Intel Architecture Software Developer's Manual

Volume 3: System Programming

NOTE: The *Intel Architecture Software Developer's Manual* consists of three volumes: *Basic Architecture*, Order Number 243190; *Instruction Set Reference*, Order Number 243191; and the *System Programming Guide*, Order Number 243192.
Please refer to all three volumes when evaluating your design needs.

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1

About This Manual

CHAPTER 1
ABOUT THIS MANUAL

The *Intel Architecture Software Developer's Manual, Volume 2*: *Instruction Set Reference* (Order Number 243191) is part of a three-volume set that describes the architecture and programming environment of all Intel Architecture processors. The other two volumes in this set are:

- The *Intel Architecture Software Developer's Manual, Volume 1: Basic Architecture* (Order Number 243190).
- The *Intel Architecture Software Developer's Manual, Volume 3*: *System Programing Guide* (Order Number 243192).

The *Intel Architecture Software Developer's Manual, Volume 1*, describes the basic architecture and programming environment of an Intel Architecture processor; the *Intel Architecture Software Developer's Manual, Volume 2*, describes the instructions set of the processor and the opcode structure. These two volumes are aimed at application programmers who are writing programs to run under existing operating systems or executives. The *Intel Architecture Software Developer's Manual, Volume 3*, describes the operating-system support environment of an Intel Architecture processor, including memory management, protection, task management, interrupt and exception handling, and system management mode. It also provides Intel Architecture processor compatibility information. This volume is aimed at operating-system and BIOS designers and programmers.

1.1. P6 FAMILY PROCESSOR TERMINOLOGY

This manual includes information pertaining primarily to the 32-bit Intel Architecture processors, which include the Intel386™, Intel486™, and Pentium® processors, and the P6 family processors. The P6 family processors are those Intel Architecture processors based on the P6 family microarchitecture. This family includes the Pentium® Pro, Pentium® II, Pentium® III processor, and any future processors based on the P6 family microarchitecture.

1.2. OVERVIEW OF THE *INTEL ARCHITECTURE SOFTWARE DEVELOPER'S MANUAL, VOLUME 3*: *SYSTEM PROGRAMMING GUIDE*

The contents of this manual are as follows:

Chapter 1 — About This Manual. Gives an overview of all three volumes of the *Intel Architecture Software Developer's Manual.* It also describes the notational conventions in these manuals and lists related Intel manuals and documentation of interest to programmers and hardware designers.

Chapter 2 — System Architecture Overview. Describes the modes of operation of an Intel Architecture processor and the mechanisms provided in the Intel Architecture to support operating systems and executives, including the system-oriented registers and data structures and the system-oriented instructions. The steps necessary for switching between real-address and protected modes are also identified.

Chapter 3 — Protected-Mode Memory Management. Describes the data structures, registers, and instructions that support segmentation and paging and explains how they can be used to implement a "flat" (unsegmented) memory model or a segmented memory model.

Chapter 4 — Protection. Describes the support for page and segment protection provided in the Intel Architecture. This chapter also explains the implementation of privilege rules, stack switching, pointer validation, user and supervisor modes.

Chapter 5 — Interrupt and Exception Handling. Describes the basic interrupt mechanisms defined in the Intel Architecture, shows how interrupts and exceptions relate to protection, and describes how the architecture handles each exception type. Reference information for each Intel Architecture exception is given at the end of this chapter.

Chapter 6 — Task Management. Describes the mechanisms the Intel Architecture provides to support multitasking and inter-task protection.

Chapter 7 — Multiple-Processor Management. Describes the instructions and flags that support multiple processors with shared memory, memory ordering, and the advanced programmable interrupt controller (APIC).

Chapter 8 — Processor Management and Initialization. Defines the state of an Intel Architecture processor and its floating-point and SIMD floating-point units after reset initialization. This chapter also explains how to set up an Intel Architecture processor for real-address mode operation and protected- mode operation, and how to switch between modes.

Chapter 9 — Memory Cache Control. Describes the general concept of caching and the caching mechanisms supported by the Intel Architecture. This chapter also describes the memory type range registers (MTRRs) and how they can be used to map memory types of physical memory. MTRRs were introduced into the Intel Architecture with the Pentium® Pro processor. It also presents information on using the new cache control and memory streaming instructions introduced with the Pentium® III processor.

Chapter 10 — MMX™ Technology System Programming. Describes those aspects of the Intel MMX™ technology that must be handled and considered at the system programming level, including task switching, exception handling, and compatibility with existing system environments. The MMX™ technology was introduced into the Intel Architecture with the Pentium® processor.

Chapter 11 — Streaming SIMD Extensions System Programming. Describes those aspects of Streaming SIMD Extensions that must be handled and considered at the system programming level, including task switching, exception handling, and compatibility with existing system environments. Streaming SIMD Extensions were introduced into the Intel Architecture with the Pentium® processor.

Chapter 12 — System Management Mode (SMM). Describes the Intel Architecture's system management mode (SMM), which can be used to implement power management functions.

Chapter 13 — Machine-Check Architecture. Describes the machine-check architecture, which was introduced into the Intel Architecture with the Pentium® processor.

Chapter 14 — Code Optimization. Discusses general optimization techniques for programming an Intel Architecture processor.

Chapter 15 — Debugging and Performance Monitoring. Describes the debugging registers and other debug mechanism provided in the Intel Architecture. This chapter also describes the time-stamp counter and the performance-monitoring counters.

Chapter 16 — 8086 Emulation. Describes the real-address and virtual-8086 modes of the Intel Architecture.

Chapter 17 — Mixing 16-Bit and 32-Bit Code. Describes how to mix 16-bit and 32-bit code modules within the same program or task.

Chapter 18 — Intel Architecture Compatibility. Describes the programming differences between the Intel 286, Intel386™, Intel486™, Pentium®, and P6 family processors. The differences among the 32-bit Intel Architecture processors (the Intel386™, Intel486™, Pentium®, and P6 family processors) are described throughout the three volumes of the *Intel Architecture Software Developer's Manual*, as relevant to particular features of the architecture. This chapter provides a collection of all the relevant compatibility information for all Intel Architecture processors and also describes the basic differences with respect to the 16-bit Intel Architecture processors (the Intel 8086 and Intel 286 processors).

Appendix A — Performance-Monitoring Events. Lists the events that can be counted with the performance-monitoring counters and the codes used to select these events. Both Pentium® processor and P6 family processor events are described.

Appendix B — Model-Specific Registers (MSRs). Lists the MSRs available in the Pentium® and P6 family processors and their functions.

Appendix C — Dual-Processor (DP) Bootup Sequence Example (Specific to Pentium® Processors). Gives an example of how to use the DP protocol to boot two Pentium® processors (a primary processor and a secondary processor) in a DP system and initialize their APICs.

Appendix D — Multiple-Processor (MP) Bootup Sequence Example (Specific to P6 Family Processors). Gives an example of how to use of the MP protocol to boot two P6 family processors in a MP system and initialize their APICs.

Appendix E — Programming the LINT0 and LINT1 Inputs. Gives an example of how to program the LINT0 and LINT1 pins for specific interrupt vectors.

1.3. OVERVIEW OF THE *INTEL ARCHITECTURE SOFTWARE DEVELOPER'S MANUAL, VOLUME 1: BASIC ARCHITECTURE*

The contents of the *Intel Architecture Software Developer's Manual, Volume 1* are as follows:

Chapter 1 — About This Manual. Gives an overview of all three volumes of the *Intel Architecture Software Developer's Manual.* It also describes the notational conventions in these

manuals and lists related Intel manuals and documentation of interest to programmers and hardware designers.

Chapter 2 — Introduction to the Intel Architecture. Introduces the Intel Architecture and the families of Intel processors that are based on this architecture. It also gives an overview of the common features found in these processors and brief history of the Intel Architecture.

Chapter 3 — Basic Execution Environment. Introduces the models of memory organization and describes the register set used by applications.

Chapter 4 — Procedure Calls, Interrupts, and Exceptions. Describes the procedure stack and the mechanisms provided for making procedure calls and for servicing interrupts and exceptions.

Chapter 5 — Data Types and Addressing Modes. Describes the data types and addressing modes recognized by the processor.

Chapter 6 — Instruction Set Summary. Gives an overview of all the Intel Architecture instructions except those executed by the processor's floating-point unit. The instructions are presented in functionally related groups.

Chapter 7 — Floating-Point Unit. Describes the Intel Architecture floating-point unit, including the floating-point registers and data types; gives an overview of the floating-point instruction set; and describes the processor's floating-point exception conditions.

Chapter 8 — Programming with the Intel MMX™ Technology. Describes the Intel MMX™ technology, including MMX™ registers and data types, and gives an overview of the MMX™ instruction set.

Chapter 9 — Programming with the Streaming SIMD Extensions. Describes the Intel Streaming SIMD Extensions, including the registers and data types.

Chapter 10— Input/Output. Describes the processor's I/O architecture, including I/O port addressing, the I/O instructions, and the I/O protection mechanism.

Chapter 11 — Processor Identification and Feature Determination. Describes how to determine the CPU type and the features that are available in the processor.

Appendix A — EFLAGS Cross-Reference. Summarizes how the Intel Architecture instructions affect the flags in the EFLAGS register.

Appendix B — EFLAGS Condition Codes. Summarizes how the conditional jump, move, and byte set on condition code instructions use the condition code flags (OF, CF, ZF, SF, and PF) in the EFLAGS register.

Appendix C — Floating-Point Exceptions Summary. Summarizes the exceptions that can be raised by floating-point instructions.

Appendix D — SIMD Floating-Point Exceptions Summary. Provides the Streaming SIMD Extensions mnemonics, and the exceptions that each instruction can cause.

Appendix E — Guidelines for Writing FPU Exception Handlers. Describes how to design and write MS-DOS* compatible exception handling facilities for FPU and SIMD floating-point exceptions, including both software and hardware requirements and assembly-language code

examples. This appendix also describes general techniques for writing robust FPU exception handlers.

Appendix F — Guidelines for Writing SIMD-FP Exception Handlers. Provides guidelines for the Streaming SIMD Extensions instructions that can generate numeric (floating-point) exceptions, and gives an overview of the necessary support for handling such exceptions.

1.4. OVERVIEW OF THE *INTEL ARCHITECTURE SOFTWARE DEVELOPER'S MANUAL, VOLUME 2: INSTRUCTION SET REFERENCE*

The contents of the *Intel Architecture Software Developer's Manual, Volume 2*, are as follows:

Chapter 1 — About This Manual. Gives an overview of all three volumes of the *Intel Architecture Software Developer's Manual.* It also describes the notational conventions in these manuals and lists related Intel manuals and documentation of interest to programmers and hardware designers.

Chapter 2 — Instruction Format. Describes the machine-level instruction format used for all Intel Architecture instructions and gives the allowable encodings of prefixes, the operand-identifier byte (ModR/M byte), the addressing-mode specifier byte (SIB byte), and the displacement and immediate bytes.

Chapter 3 — Instruction Set Reference. Describes each of the Intel Architecture instructions in detail, including an algorithmic description of operations, the effect on flags, the effect of operand- and address-size attributes, and the exceptions that may be generated. The instructions are arranged in alphabetical order. The FPU, MMX™ Technology instructions, and Streaming SIMD Extensions are included in this chapter.

Appendix A — Opcode Map. Gives an opcode map for the Intel Architecture instruction set.

Appendix B — Instruction Formats and Encodings. Gives the binary encoding of each form of each Intel Architecture instruction.

Appendix C — Compiler Intrinsics and Functional Equivalents. Gives the Intel C/C++ compiler intrinsics and functional equivalents for the MMX™ Technology instructions and Streaming SIMD Extensions.

1.5. NOTATIONAL CONVENTIONS

This manual uses special notation for data-structure formats, for symbolic representation of instructions, and for hexadecimal numbers. A review of this notation makes the manual easier to read.

1.5.1. Bit and Byte Order

In illustrations of data structures in memory, smaller addresses appear toward the bottom of the figure; addresses increase toward the top. Bit positions are numbered from right to left. The numerical value of a set bit is equal to two raised to the power of the bit position. Intel Architecture processors are “little endian” machines; this means the bytes of a word are numbered starting from the least significant byte. Figure 1-1 illustrates these conventions.

1.5.2. Reserved Bits and Software Compatibility

In many register and memory layout descriptions, certain bits are marked as **reserved**. When bits are marked as reserved, it is essential for compatibility with future processors that software treat these bits as having a future, though unknown, effect. The behavior of reserved bits should be regarded as not only undefined, but unpredictable. Software should follow these guidelines in dealing with reserved bits:

- Do not depend on the states of any reserved bits when testing the values of registers which contain such bits. Mask out the reserved bits before testing.
- Do not depend on the states of any reserved bits when storing to memory or to a register.
- Do not depend on the ability to retain information written into any reserved bits.
- When loading a register, always load the reserved bits with the values indicated in the documentation, if any, or reload them with values previously read from the same register.

NOTE

Avoid any software dependence upon the state of reserved bits in Intel Architecture registers. Depending upon the values of reserved register bits will make software dependent upon the unspecified manner in which the processor handles these bits. Programs that depend upon reserved values risk incompatibility with future processors.

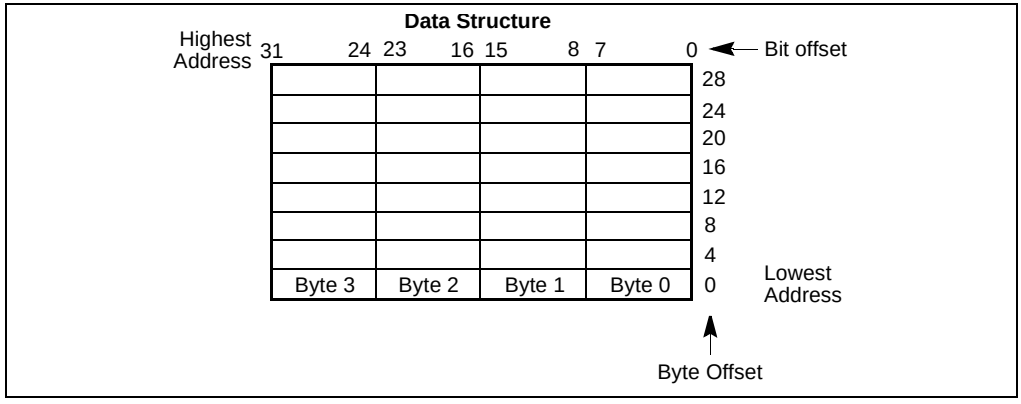


Figure 1-1. Bit and Byte Order

1.5.3. Instruction Operands

When instructions are represented symbolically, a subset of the Intel Architecture assembly language is used. In this subset, an instruction has the following format:

label: mnemonic argument1, argument2, argument3

where:

- A **label** is an identifier which is followed by a colon.
- A **mnemonic** is a reserved name for a class of instruction opcodes which have the same function.
- The operands **argument1**, **argument2**, and **argument3** are optional. There may be from zero to three operands, depending on the opcode. When present, they take the form of either literals or identifiers for data items. Operand identifiers are either reserved names of registers or are assumed to be assigned to data items declared in another part of the program (which may not be shown in the example).

When two operands are present in an arithmetic or logical instruction, the right operand is the source and the left operand is the destination.

For example:

LOADREG: MOV EAX, SUBTOTAL

In this example, LOADREG is a label, MOV is the mnemonic identifier of an opcode, EAX is the destination operand, and SUBTOTAL is the source operand. Some assembly languages put the source and destination in reverse order.

1.5.4. Hexadecimal and Binary Numbers

Base 16 (hexadecimal) numbers are represented by a string of hexadecimal digits followed by the character H (for example, F82EH). A hexadecimal digit is a character from the following set: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, and F.

Base 2 (binary) numbers are represented by a string of 1s and 0s, sometimes followed by the character B (for example, 1010B). The “B” designation is only used in situations where confusion as to the type of number might arise.

1.5.5. Segmented Addressing

The processor uses byte addressing. This means memory is organized and accessed as a sequence of bytes. Whether one or more bytes are being accessed, a byte address is used to locate the byte or bytes of memory. The range of memory that can be addressed is called an **address space**.

The processor also supports segmented addressing. This is a form of addressing where a program may have many independent address spaces, called **segments**. For example, a program can keep its code (instructions) and stack in separate segments. Code addresses would always

refer to the code space, and stack addresses would always refer to the stack space. The following notation is used to specify a byte address within a segment:

Segment-register:Byte-address

For example, the following segment address identifies the byte at address FF79H in the segment pointed by the DS register:

DS:FF79H

The following segment address identifies an instruction address in the code segment. The CS register points to the code segment and the EIP register contains the address of the instruction.

CS:EIP

1.5.6. Exceptions

An exception is an event that typically occurs when an instruction causes an error. For example, an attempt to divide by zero generates an exception. However, some exceptions, such as breakpoints, occur under other conditions. Some types of exceptions may provide error codes. An error code reports additional information about the error. An example of the notation used to show an exception and error code is shown below.

#PF(fault code)

This example refers to a page-fault exception under conditions where an error code naming a type of fault is reported. Under some conditions, exceptions which produce error codes may not be able to report an accurate code. In this case, the error code is zero, as shown below for a general-protection exception.

#GP(0)

Refer to Chapter 5, *Interrupt and Exception Handling*, for a list of exception mnemonics and their descriptions.

1.6. RELATED LITERATURE

The following books contain additional material related to Intel processors:

- *Intel Pentium® II Processor Specification Update*, Order Number 243337-010.
- *Intel Pentium® Pro Processor Specification Update*, Order Number 242689-031.
- *Intel Pentium® Processor Specification Update*, Order Number 242480.
- AP-485, *Intel Processor Identification and the CPUID Instruction*, Order Number 241618-006.
- AP-578, *Software and Hardware Considerations for FPU Exception Handlers for Intel Architecture Processors*, Order Number 243291.
- *Pentium® Pro Processor Data Book*, Order Number 242690.
- *Pentium® Pro BIOS Writer's Guide*, http://www.intel.com/procs/ppro/info/index.htm.
- *Pentium® Processor Data Book*, Order Number 241428.
- *82496 Cache Controller and 82491 Cache SRAM Data Book For Use With the Pentium® Processor*, Order Number 241429.
- *Intel486™ Microprocessor Data Book*, Order Number 240440.
- *Intel486™ SX CPU/Intel487™ SX Math Coprocessor Data Book*, Order Number 240950.
- *Intel486™ DX2 Microprocessor Data Book*, Order Number 241245.
- *Intel486™ Microprocessor Product Brief Book*, Order Number 240459.
- *Intel386™ Processor Hardware Reference Manual*, Order Number 231732.
- *Intel386™ Processor System Software Writer's Guide*, Order Number 231499.
- *Intel386™ High-Performance 32-Bit CHMOS Microprocessor with Integrated Memory Management*, Order Number 231630.
- *376 Embedded Processor Programmer's Reference Manual*, Order Number 240314.
- *80387 DX User's Manual Programmer's Reference*, Order Number 231917.
- *376 High-Performance 32-Bit Embedded Processor*, Order Number 240182.
- *Intel386™ SX Microprocessor*, Order Number 240187.
- *Intel Architecture Optimization Manual*, Order Number 242816-002.

2

System Architecture Overview

CHAPTER 2
SYSTEM ARCHITECTURE OVERVIEW

The 32-bit members of the Intel Architecture family of processors provide extensive support for operating-system and system-development software. This support is part of the processor's system-level architecture and includes features to assist in the following operations:

- Memory management
- Protection of software modules
- Multitasking
- Exception and interrupt handling
- Multiprocessing
- Cache management
- Hardware resource and power management
- Debugging and performance monitoring

This chapter provides a brief overview of the processor's system-level architecture; a detailed description of each part of this architecture given in the following chapters. This chapter also describes the system registers that are used to set up and control the processor at the system level and gives a brief overview of the processor's system-level (operating system) instructions.

Many of the system-level architectural features of the processor are used only by system programmers. Application programmers may need to read this chapter, and the following chapters which describe the use of these features, in order to understand the hardware facilities used by system programmers to create a reliable and secure environment for application programs.

NOTE

This overview and most of the subsequent chapters of this book focus on the "native" or protected-mode operation of the 32-bit Intel Architecture processors. As described in Chapter 8, *Processor Management and Initialization*, all Intel Architecture processors enter real-address mode following a power-up or reset. Software must then initiate a switch from real-address mode to protected mode.

2.1. OVERVIEW OF THE SYSTEM-LEVEL ARCHITECTURE

The Intel Architecture's system architecture consists of a set of registers, data structures, and instructions designed to support basic system-level operations such as memory management, interrupt and exception handling, task management, and control of multiple processors (multiprocessing). Figure 2-1 provides a generalized summary of the system registers and data structures.

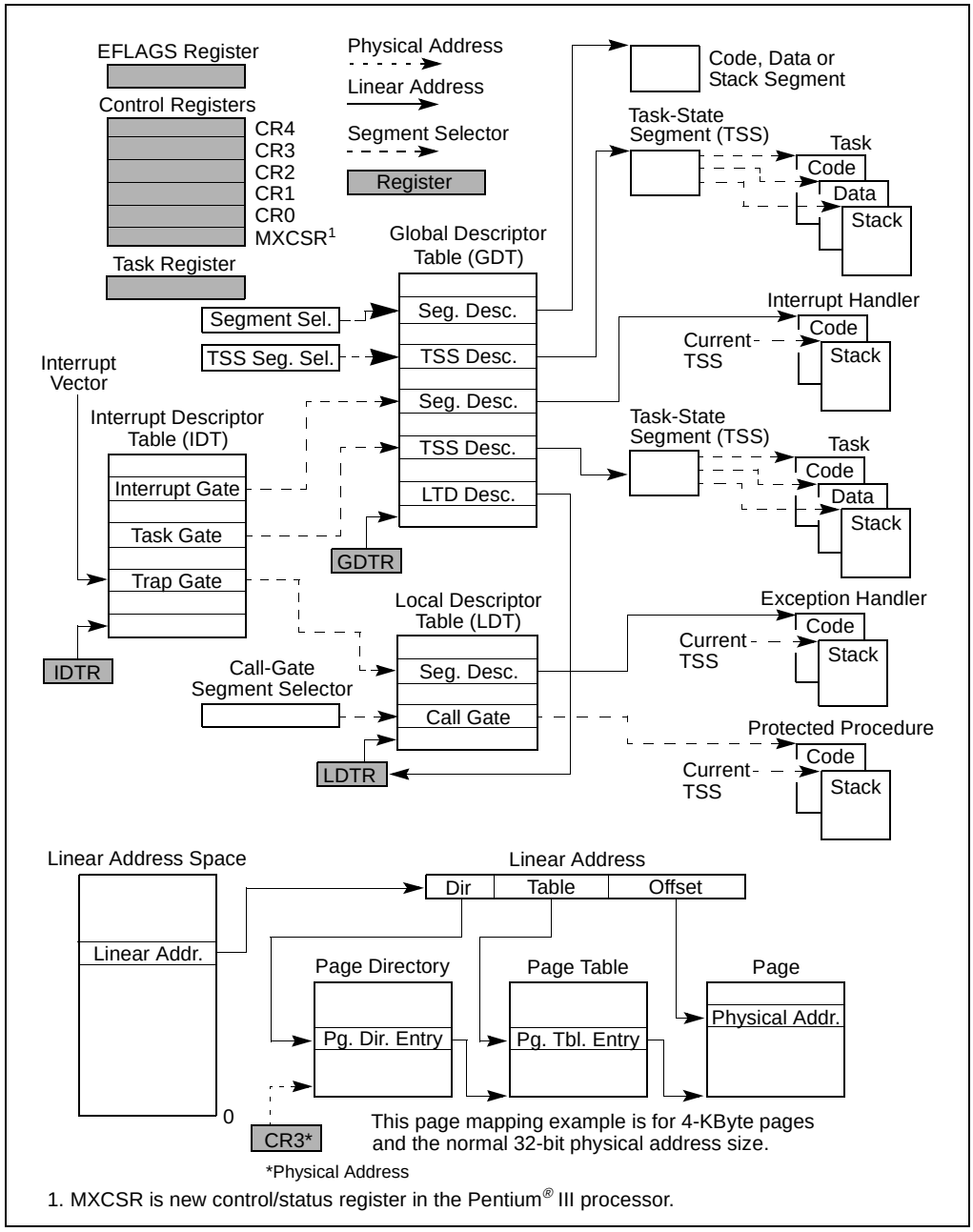


Figure 2-1. System-Level Registers and Data Structures

2.1.1. Global and Local Descriptor Tables

When operating in protected mode, all memory accesses pass through either the global descriptor table (GDT) or the (optional) local descriptor table (LDT), shown in Figure 2-1. These tables contain entries called segment descriptors. A segment descriptor provides the base address of a segment and access rights, type, and usage information. Each segment descriptor has a segment selector associated with it. The segment selector provides an index into the GDT or LDT (to its associated segment descriptor), a global/local flag (that determines whether the segment selector points to the GDT or the LDT), and access rights information.

To access a byte in a segment, both a segment selector and an offset must be supplied. The segment selector provides access to the segment descriptor for the segment (in the GDT or LDT). From the segment descriptor, the processor obtains the base address of the segment in the linear address space. The offset then provides the location of the byte relative to the base address. This mechanism can be used to access any valid code, data, or stack segment in the GDT or LDT, provided the segment is accessible from the current privilege level (CPL) at which the processor is operating. (The CPL is defined as the protection level of the currently executing code segment.)

In Figure 2-1 the solid arrows indicate a linear address, the dashed lines indicate a segment selector, and the dotted arrows indicate a physical address. For simplicity, many of the segment selectors are shown as direct pointers to a segment. However, the actual path from a segment selector to its associated segment is always through the GDT or LDT.

The linear address of the base of the GDT is contained in the GDT register (GDTR); the linear address of the LDT is contained in the LDT register (LDTR).

2.1.2. System Segments, Segment Descriptors, and Gates

Besides the code, data, and stack segments that make up the execution environment of a program or procedure, the system architecture also defines two system segments: the task-state segment (TSS) and the LDT. (The GDT is not considered a segment because it is not accessed by means of a segment selector and segment descriptor.) Each of these segment types has a segment descriptor defined for it.

The system architecture also defines a set of special descriptors called gates (the call gate, interrupt gate, trap gate, and task gate) that provide protected gateways to system procedures and handlers that operate at different privilege levels than application programs and procedures. For example, a CALL to a call gate provides access to a procedure in a code segment that is at the same or numerically lower privilege level (more privileged) than the current code segment. To access a procedure through a call gate, the calling procedure[1] must supply the selector of the call gate. The processor than performs an access rights check on the call gate, comparing the CPL with the privilege level of the call gate and the destination code segment pointed to by the call gate. If access to the destination code segment is allowed, the processor gets the segment selector for the destination code segment and an offset into that code segment from the call gate.

1. The word “procedure” is commonly used in this document as a general term for a logical unit or block of code (such as a program, procedure, function, or routine). The term is not restricted to the definition of a procedure in the Intel Architecture assembly language.

If the call requires a change in privilege level, the processor also switches to the stack for that privilege level. (The segment selector for the new stack is obtained from the TSS for the currently running task.) Gates also facilitate transitions between 16-bit and 32-bit code segments, and vice versa.

2.1.3. Task-State Segments and Task Gates

The TSS (refer to Figure 2-1) defines the state of the execution environment for a task. It includes the state of the general-purpose registers, the segment registers, the EFLAGS register, the EIP register, and segment selectors and stack pointers for three stack segments (one stack each for privilege levels 0, 1, and 2). It also includes the segment selector for the LDT associated with the task and the page-table base address.

All program execution in protected mode happens within the context of a task, called the current task. The segment selector for the TSS for the current task is stored in the task register. The simplest method of switching to a task is to make a call or jump to the task. Here, the segment selector for the TSS of the new task is given in the CALL or JMP instruction. In switching tasks, the processor performs the following actions:

1. Stores the state of the current task in the current TSS.
2. Loads the task register with the segment selector for the new task.
3. Accesses the new TSS through a segment descriptor in the GDT.
4. Loads the state of the new task from the new TSS into the general-purpose registers, the segment registers, the LDTR, control register CR3 (page-table base address), the EFLAGS register, and the EIP register.
5. Begins execution of the new task.

A task can also be accessed through a task gate. A task gate is similar to a call gate, except that it provides access (through a segment selector) to a TSS rather than a code segment.

2.1.4. Interrupt and Exception Handling

External interrupts, software interrupts, and exceptions are handled through the interrupt descriptor table (IDT), refer to Figure 2-1. The IDT contains a collection of gate descriptors, which provide access to interrupt and exception handlers. Like the GDT, the IDT is not a segment. The linear address of the base of the IDT is contained in the IDT register (IDTR).

The gate descriptors in the IDT can be of the interrupt-, trap-, or task-gate type. To access an interrupt or exception handler, the processor must first receive an interrupt vector (interrupt number) from internal hardware, an external interrupt controller, or from software by means of an INT, INTO, INT 3, or BOUND instruction. The interrupt vector provides an index into the IDT to a gate descriptor. If the selected gate descriptor is an interrupt gate or a trap gate, the associated handler procedure is accessed in a manner very similar to calling a procedure through a call gate. If the descriptor is a task gate, the handler is accessed through a task switch.

2.1.5. Memory Management

The system architecture supports either direct physical addressing of memory or virtual memory (through paging). When physical addressing is used, a linear address is treated as a physical address. When paging is used, all the code, data, stack, and system segments and the GDT and IDT can be paged, with only the most recently accessed pages being held in physical memory.

The location of pages (or page frames as they are sometimes called in the Intel Architecture) in physical memory is contained in two types of system data structures (a page directory and a set of page tables), both of which reside in physical memory (refer to Figure 2-1). An entry in a page directory contains the physical address of the base of a page table, access rights, and memory management information. An entry in a page table contains the physical address of a page frame, access rights, and memory management information. The base physical address of the page directory is contained in control register CR3.

To use this paging mechanism, a linear address is broken into three parts, providing separate offsets into the page directory, the page table, and the page frame.

A system can have a single page directory or several. For example, each task can have its own page directory.

2.1.6. System Registers

To assist in initializing the processor and controlling system operations, the system architecture provides system flags in the EFLAGS register and several system registers:

- The system flags and IOPL field in the EFLAGS register control task and mode switching, interrupt handling, instruction tracing, and access rights. Refer to Section 2.3., “System Flags and Fields in the EFLAGS Register” for a description of these flags.
- The control registers (CR0, CR2, CR3, and CR4) contain a variety of flags and data fields for controlling system-level operations. With the introduction of the Pentium® III processor, CR4 now contains bits indicating support Pentium® III processor specific capabilities within the OS. Refer to Section 2.5., “Control Registers” for a description of these flags.
- The debug registers (not shown in Figure 2-1) allow the setting of breakpoints for use in debugging programs and systems software. Refer to Chapter 15, *Debugging and Performance Monitoring*, for a description of these registers.
- The GDTR, LDTR, and IDTR registers contain the linear addresses and sizes (limits) of their respective tables. Refer to Section 2.4., “Memory-Management Registers” for a description of these registers.
- The task register contains the linear address and size of the TSS for the current task. Refer to Section 2.4., “Memory-Management Registers” for a description of this register.
- Model-specific registers (not shown in Figure 2-1).

The model-specific registers (MSRs) are a group of registers available primarily to operating-system or executive procedures (that is, code running at privilege level 0). These registers control items such as the debug extensions, the performance-monitoring counters, the machine-check architecture, and the memory type ranges (MTRRs). The number and functions of these

registers varies among the different members of the Intel Architecture processor families. Section 8.4., “Model-Specific Registers (MSRs)” in Chapter 8, *Processor Management and Initialization* for more information about the MSRs and Appendix B, *Model-Specific Registers* for a complete list of the MSRs.

Most systems restrict access to all system registers (other than the EFLAGS register) by application programs. Systems can be designed, however, where all programs and procedures run at the most privileged level (privilege level 0), in which case application programs are allowed to modify the system registers.

2.1.7. Other System Resources

Besides the system registers and data structures described in the previous sections, the system architecture provides the following additional resources:

- Operating system instructions (refer to Section 2.6., “System Instruction Summary”).
- Performance-monitoring counters (not shown in Figure 2-1).
- Internal caches and buffers (not shown in Figure 2-1).

The performance-monitoring counters are event counters that can be programmed to count processor events such as the number of instructions decoded, the number of interrupts received, or the number of cache loads. Refer to Section 15.6., “Performance-Monitoring Counters”, in Chapter 15, *Debugging and Performance Monitoring*, for more information about these counters.

The processor provides several internal caches and buffers. The caches are used to store both data and instructions. The buffers are used to store things like decoded addresses to system and application segments and write operations waiting to be performed. Refer to Chapter 9, *Memory Cache Control*, for a detailed discussion of the processor’s caches and buffers.

2.2. MODES OF OPERATION

The Intel Architecture supports three operating modes and one quasi-operating mode:

- **Protected mode.** This is the native operating mode of the processor. In this mode all instructions and architectural features are available, providing the highest performance and capability. This is the recommended mode for all new applications and operating systems.
- **Real-address mode.** This operating mode provides the programming environment of the Intel 8086 processor, with a few extensions (such as the ability to switch to protected or system management mode).
- **System management mode (SMM).** The system management mode (SMM) is a standard architectural feature in all Intel Architecture processors, beginning with the Intel386™ SL processor. This mode provides an operating system or executive with a transparent mechanism for implementing power management and OEM differentiation features. SMM is entered through activation of an external system interrupt pin (SMI#), which generates a

system management interrupt (SMI). In SMM, the processor switches to a separate address space while saving the context of the currently running program or task. SMM-specific code may then be executed transparently. Upon returning from SMM, the processor is placed back into its state prior to the SMI.

- **Virtual-8086 mode.** In protected mode, the processor supports a quasi-operating mode known as **virtual-8086 mode**. This mode allows the processor to execute 8086 software in a protected, multitasking environment.

Figure 2-2 shows how the processor moves among these operating modes.

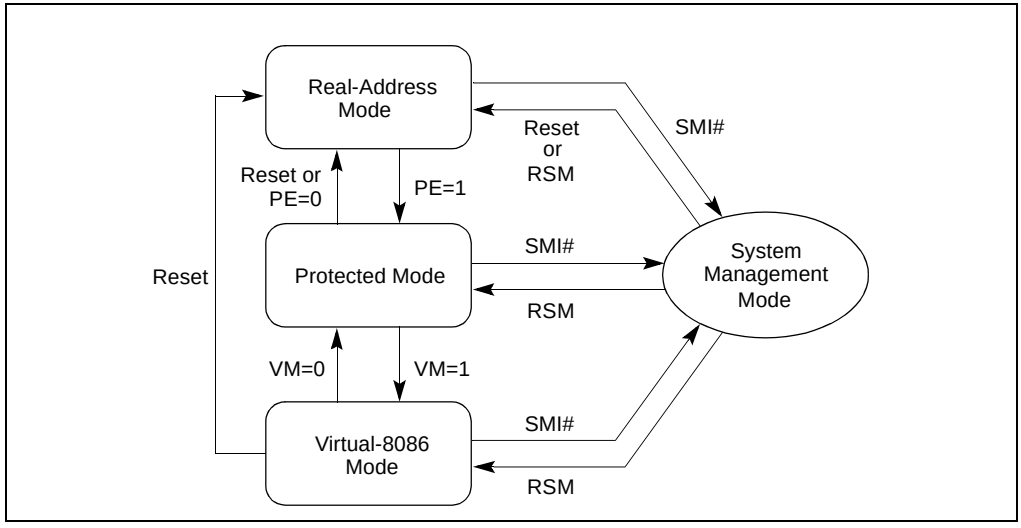


Figure 2-2. Transitions Among the Processor's Operating Modes

The processor is placed in real-address mode following power-up or a reset. Thereafter, the PE flag in control register CR0 controls whether the processor is operating in real-address or protected mode (refer to Section 2.5., "Control Registers"). Refer to Section 8.8., "Mode Switching" in Chapter 8, *Processor Management and Initialization* for detailed information on switching between real-address mode and protected mode.

The VM flag in the EFLAGS register determines whether the processor is operating in protected mode or virtual-8086 mode. Transitions between protected mode and virtual-8086 mode are generally carried out as part of a task switch or a return from an interrupt or exception handler (refer to Section 16.2.5., "Entering Virtual-8086 Mode" in Chapter 16, *8086 Emulation*).

The processor switches to SMM whenever it receives an SMI while the processor is in real-address, protected, or virtual-8086 modes. Upon execution of the RSM instruction, the processor always returns to the mode it was in when the SMI occurred.

2.3. SYSTEM FLAGS AND FIELDS IN THE EFLAGS REGISTER

The system flags and IOPL field of the EFLAGS register control I/O, maskable hardware interrupts, debugging, task switching, and the virtual-8086 mode (refer to Figure 2-3). Only privileged code (typically operating system or executive code) should be allowed to modify these bits.

The functions of the system flags and IOPL are as follows:

TF **Trap (bit 8).** Set to enable single-step mode for debugging; clear to disable single-step mode. In single-step mode, the processor generates a debug exception after each instruction, which allows the execution state of a program to be inspected after each instruction. If an application program sets the TF flag using a POPF, POPFD, or IRET instruction, a debug exception is generated after the instruction that follows the POPF, POPFD, or IRET instruction.

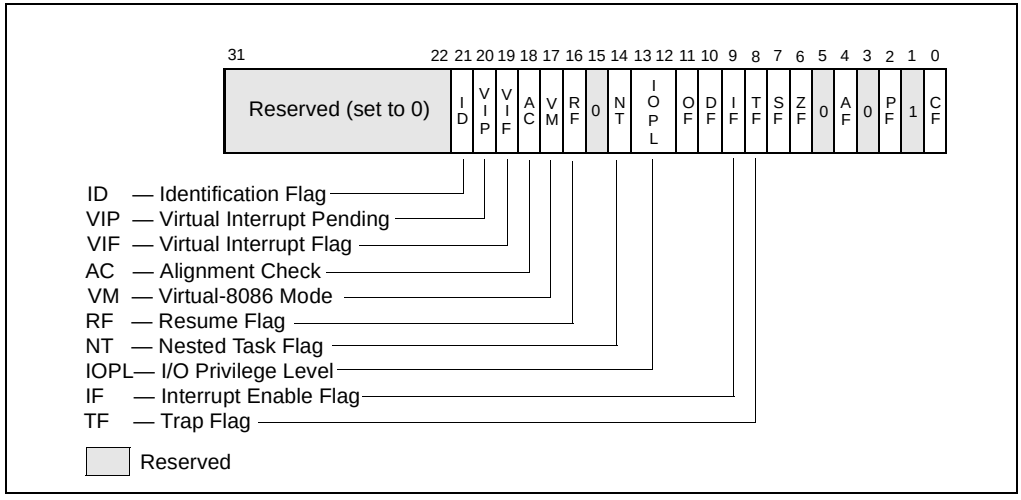


Figure 2-3. System Flags in the EFLAGS Register

IF **Interrupt enable (bit 9).** Controls the response of the processor to maskable hardware interrupt requests (refer to Section 5.1.1.2., "Maskable Hardware Interrupts" in Chapter 5, *Interrupt and Exception Handling*). Set to respond to maskable hardware interrupts; cleared to inhibit maskable hardware interrupts. The IF flag does not affect the generation of exceptions or nonmaskable interrupts (NMI interrupts). The CPL, IOPL, and the state of the VME flag in control register CR4 determine whether the IF flag can be modified by the CLI, STI, POPF, POPFD, and IRET instructions.

IOPL **I/O privilege level field (bits 12 and 13).** Indicates the I/O privilege level (IOPL) of the currently running program or task. The CPL of the currently running program or task must be less than or equal to the IOPL to access the I/O address space. This field can only be modified by the POPF and IRET instructions when operating at a CPL of 0. Refer to Chapter 10, *Input/Output*, of the *Intel Architecture Software Developer's Manual, Volume 1*, for more information on the relationship of the IOPL to I/O operations.

The IOPL is also one of the mechanisms that controls the modification of the IF flag and the handling of interrupts in virtual-8086 mode when the virtual mode extensions are in effect (the VME flag in control register CR4 is set).

NT **Nested task (bit 14).** Controls the chaining of interrupted and called tasks. The processor sets this flag on calls to a task initiated with a CALL instruction, an interrupt, or an exception. It examines and modifies this flag on returns from a task initiated with the IRET instruction. The flag can be explicitly set or cleared with the POPF/POPFD instructions; however, changing to the state of this flag can generate unexpected exceptions in application programs. Refer to Section 6.4., "Task Linking" in Chapter 6, *Task Management* for more information on nested tasks.

RF **Resume (bit 16).** Controls the processor's response to instruction-breakpoint conditions. When set, this flag temporarily disables debug exceptions (#DE) from being generated for instruction breakpoints; although, other exception conditions can cause an exception to be generated. When clear, instruction breakpoints will generate debug exceptions.

The primary function of the RF flag is to allow the restarting of an instruction following a debug exception that was caused by an instruction breakpoint condition. Here, debugger software must set this flag in the EFLAGS image on the stack just prior to returning to the interrupted program with the IRETD instruction, to prevent the instruction breakpoint from causing another debug exception. The processor then automatically clears this flag after the instruction returned to has been successfully executed, enabling instruction breakpoint faults again.

Refer to Section 15.3.1.1., "Instruction-Breakpoint Exception Condition", in Chapter 15, *Debugging and Performance Monitoring,* for more information on the use of this flag.

VM **Virtual-8086 mode (bit 17).** Set to enable virtual-8086 mode; clear to return to protected mode. Refer to Section 16.2.1., "Enabling Virtual-8086 Mode" in Chapter 16, *8086 Emulation* for a detailed description of the use of this flag to switch to virtual-8086 mode.

AC **Alignment check (bit 18).** Set this flag and the AM flag in the CR0 register to enable alignment checking of memory references; clear the AC flag and/or the AM flag to disable alignment checking. An alignment-check exception is generated when reference is made to an unaligned operand, such as a word at an odd byte address or a doubleword at an address which is not an integral multiple of four. Alignment-check exceptions are generated only in user mode (privilege level 3). Memory references that default to privilege level 0, such as segment descriptor loads, do not generate this exception even when caused by instructions executed in user-mode.

The alignment-check exception can be used to check alignment of data. This is useful when exchanging data with other processors, which require all data to be aligned. The alignment-check exception can also be used by interpreters to flag some pointers as special by misaligning the pointer. This eliminates overhead of checking each pointer and only handles the special pointer when used.

VIF **Virtual Interrupt (bit 19).** Contains a virtual image of the IF flag. This flag is used in conjunction with the VIP flag. The processor only recognizes the VIF flag when either the VME flag or the PVI flag in control register CR4 is set and the IOPL is less than 3. (The VME flag enables the virtual-8086 mode extensions; the PVI flag enables the protected-mode virtual interrupts.) Refer to Section 16.3.3.5., "Method 6: Software Interrupt Handling" and Section 16.4., "Protected-Mode Virtual Interrupts" in Chapter 16, *8086 Emulation* for detailed information about the use of this flag.

VIP **Virtual interrupt pending (bit 20).** Set by software to indicate that an interrupt is pending; cleared to indicate that no interrupt is pending. This flag is used in conjunction with the VIF flag. The processor reads this flag but never modifies it. The processor only recognizes the VIP flag when either the VME flag or the PVI flag in control register CR4 is set and the IOPL is less than 3. (The VME flag enables the virtual-8086 mode extensions; the PVI flag enables the protected-mode virtual interrupts.) Refer to Section 16.3.3.5., "Method 6: Software Interrupt Handling" and Section 16.4., "Protected-Mode Virtual Interrupts" in Chapter 16, *8086 Emulation* for detailed information about the use of this flag.

ID **Identification (bit 21).** The ability of a program or procedure to set or clear this flag indicates support for the CPUID instruction.

2.4. MEMORY-MANAGEMENT REGISTERS

The processor provides four memory-management registers (GDTR, LDTR, IDTR, and TR) that specify the locations of the data structures which control segmented memory management (refer to Figure 2-4). Special instructions are provided for loading and storing these registers.

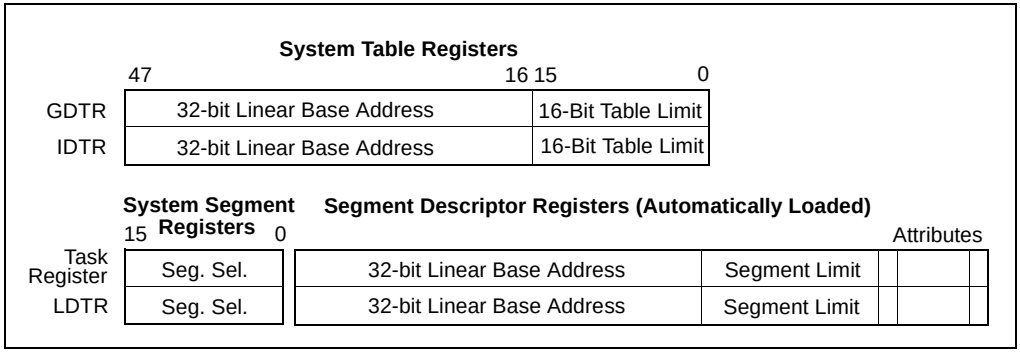


Figure 2-4. Memory Management Registers

2.4.1. Global Descriptor Table Register (GDTR)

The GDTR register holds the 32-bit base address and 16-bit table limit for the GDT. The base address specifies the linear address of byte 0 of the GDT; the table limit specifies the number of bytes in the table. The LGDT and SGDT instructions load and store the GDTR register, respectively. On power up or reset of the processor, the base address is set to the default value of 0 and

the limit is set to FFFFH. A new base address must be loaded into the GDTR as part of the processor initialization process for protected-mode operation. Refer to Section 3.5.1., “Segment Descriptor Tables” in Chapter 3, *Protected-Mode Memory Management* for more information on the base address and limit fields.

2.4.2. Local Descriptor Table Register (LDTR)

The LDTR register holds the 16-bit segment selector, 32-bit base address, 16-bit segment limit, and descriptor attributes for the LDT. The base address specifies the linear address of byte 0 of the LDT segment; the segment limit specifies the number of bytes in the segment. Refer to Section 3.5.1., “Segment Descriptor Tables” in Chapter 3, *Protected-Mode Memory Management* for more information on the base address and limit fields.

The LLDT and SLDT instructions load and store the segment selector part of the LDTR register, respectively. The segment that contains the LDT must have a segment descriptor in the GDT. When the LLDT instruction loads a segment selector in the LDTR, the base address, limit, and descriptor attributes from the LDT descriptor are automatically loaded into the LDTR.

When a task switch occurs, the LDTR is automatically loaded with the segment selector and descriptor for the LDT for the new task. The contents of the LDTR are not automatically saved prior to writing the new LDT information into the register.

On power up or reset of the processor, the segment selector and base address are set to the default value of 0 and the limit is set to FFFFH.

2.4.3. IDTR Interrupt Descriptor Table Register

The IDTR register holds the 32-bit base address and 16-bit table limit for the IDT. The base address specifies the linear address of byte 0 of the IDT; the table limit specifies the number of bytes in the table. The LIDT and SIDT instructions load and store the IDTR register, respectively. On power up or reset of the processor, the base address is set to the default value of 0 and the limit is set to FFFFH. The base address and limit in the register can then be changed as part of the processor initialization process. Refer to Section 5.8., “Interrupt Descriptor Table (IDT)” in Chapter 5, *Interrupt and Exception Handling* for more information on the base address and limit fields.

2.4.4. Task Register (TR)

The task register holds the 16-bit segment selector, 32-bit base address, 16-bit segment limit, and descriptor attributes for the TSS of the current task. It references a TSS descriptor in the GDT. The base address specifies the linear address of byte 0 of the TSS; the segment limit specifies the number of bytes in the TSS. (Refer to Section 6.2.3., “Task Register” in Chapter 6, *Task Management* for more information about the task register.)

The LTR and STR instructions load and store the segment selector part of the task register, respectively. When the LTR instruction loads a segment selector in the task register, the base

address, limit, and descriptor attributes from the TSS descriptor are automatically loaded into the task register. On power up or reset of the processor, the base address is set to the default value of 0 and the limit is set to FFFFH.

When a task switch occurs, the task register is automatically loaded with the segment selector and descriptor for the TSS for the new task. The contents of the task register are not automatically saved prior to writing the new TSS information into the register.

2.5. CONTROL REGISTERS

The control registers (CR0, CR1, CR2, CR3, and CR4) determine operating mode of the processor and the characteristics of the currently executing task (refer to Figure 2-5).

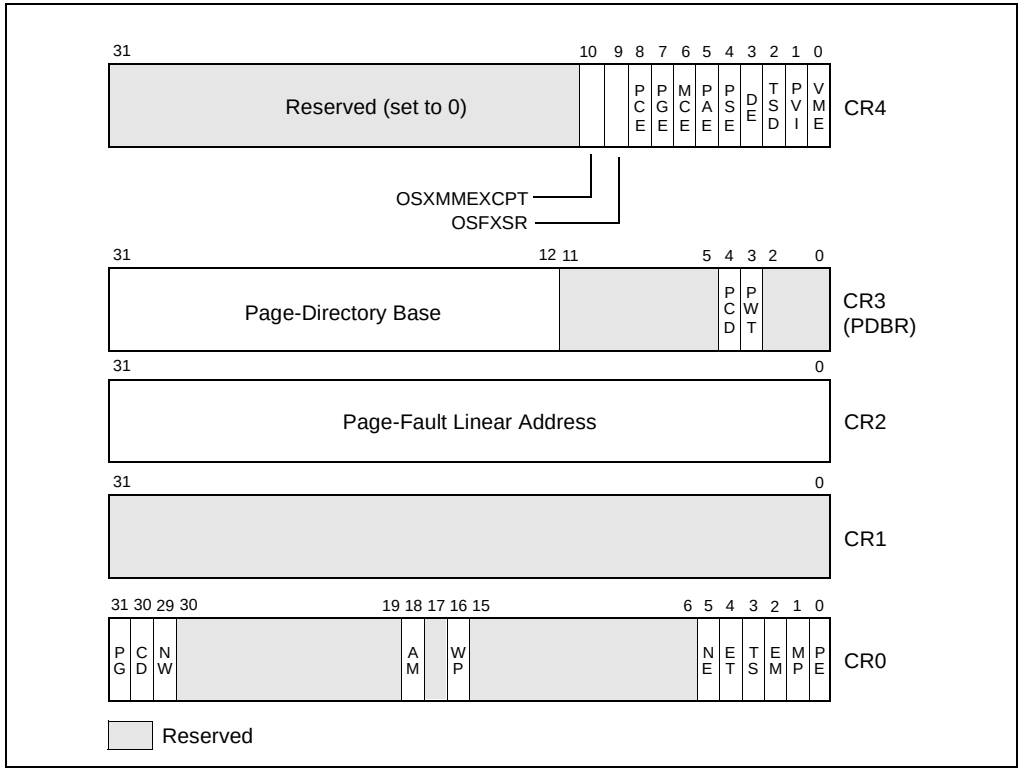


Figure 2-5. Control Registers

The control registers:

- CR0—Contains system control flags that control operating mode and states of the processor.
- CR1—Reserved.
- CR2—Contains the page-fault linear address (the linear address that caused a page fault).
- CR3—Contains the physical address of the base of the page directory and two flags (PCD and PWT). This register is also known as the page-directory base register (PDBR). Only the 20 most-significant bits of the page-directory base address are specified; the lower 12 bits of the address are assumed to be 0. The page directory must thus be aligned to a page (4-KByte) boundary. The PCD and PWT flags control caching of the page directory in the processor's internal data caches (they do not control TLB caching of page-directory information).

  When using the physical address extension, the CR3 register contains the base address of the page-directory-pointer table (refer to Section 3.8., "Physical Address Extension" in Chapter 3, *Protected-Mode Memory Management*).
- CR4—Contains a group of flags that enable several architectural extensions, as well as indicating the level of OS support for the Streaming SIMD Extensions.

In protected mode, the move-to-or-from-control-registers forms of the MOV instruction allow the control registers to be read (at privilege level 0 only) or loaded (at privilege level 0 only). These restrictions mean that application programs (running at privilege levels 1, 2, or 3) are prevented from reading or loading the control registers.

A program running at privilege level 1, 2, or 3 should not attempt to read or write the control registers. An attempt to read or write these registers will result in a general protection fault (GP(0)). The functions of the flags in the control registers are as follows:

PG **Paging (bit 31 of CR0).** Enables paging when set; disables paging when clear. When paging is disabled, all linear addresses are treated as physical addresses. The PG flag has no effect if the PE flag (bit 0 of register CR0) is not also set; in fact, setting the PG flag when the PE flag is clear causes a general-protection exception (#GP) to be generated. Refer to Section 3.6., "Paging (Virtual Memory)" in Chapter 3, *Protected-Mode Memory Management* for a detailed description of the processor's paging mechanism.

CD **Cache Disable (bit 30 of CR0).** When the CD and NW flags are clear, caching of memory locations for the whole of physical memory in the processor's internal (and external) caches is enabled. When the CD flag is set, caching is restricted as described in Table 9-4, in Chapter 9, *Memory Cache Control*. To prevent the processor from accessing and updating its caches, the CD flag must be set and the caches must be invalidated so that no cache hits can occur (refer to Section 9.5.2., "Preventing Caching", in Chapter 9, *Memory Cache Control*). Refer to Section 9.5., "Cache Control", Chapter 9, *Memory Cache Control*, for a detailed description of the additional restrictions that can be placed on the caching of selected pages or regions of memory.

NW **Not Write-through (bit 29 of CR0).** When the NW and CD flags are clear, write-back (for Pentium® and P6 family processors) or write-through (for Intel486™ processors) is enabled for writes that hit the cache and invalidation cycles are enabled. Refer to

Table 9-4, in Chapter 9, *Memory Cache Control*, for detailed information about the affect of the NW flag on caching for other settings of the CD and NW flags.

AM **Alignment Mask (bit 18 of CR0).** Enables automatic alignment checking when set; disables alignment checking when clear. Alignment checking is performed only when the AM flag is set, the AC flag in the EFLAGS register is set, the CPL is 3, and the processor is operating in either protected or virtual-8086 mode.

WP **Write Protect (bit 16 of CR0).** Inhibits supervisor-level procedures from writing into user-level read-only pages when set; allows supervisor-level procedures to write into user-level read-only pages when clear. This flag facilitates implementation of the copy-on-write method of creating a new process (forking) used by operating systems such as UNIX*.

NE **Numeric Error (bit 5 of CR0).** Enables the native (internal) mechanism for reporting FPU errors when set; enables the PC-style FPU error reporting mechanism when clear. When the NE flag is clear and the IGNNE# input is asserted, FPU errors are ignored. When the NE flag is clear and the IGNNE# input is deasserted, an unmasked FPU error causes the processor to assert the FERR# pin to generate an external interrupt and to stop instruction execution immediately before executing the next waiting floating-point instruction or WAIT/FWAIT instruction. The FERR# pin is intended to drive an input to an external interrupt controller (the FERR# pin emulates the ERROR# pin of the Intel 287 and Intel 387 DX math coprocessors). The NE flag, IGNNE# pin, and FERR# pin are used with external logic to implement PC-style error reporting. (Refer to “Software Exception Handling” in Chapter 7, and Appendix D in the *Intel Architecture Software Developer’s Manual, Volume 1*, for more information about FPU error reporting and for detailed information on when the FERR# pin is asserted, which is implementation dependent.)

ET **Extension Type (bit 4 of CR0).** Reserved in the P6 family and Pentium® processors. (In the P6 family processors, this flag is hardcoded to 1.) In the Intel386™ and Intel486™ processors, this flag indicates support of Intel 387 DX math coprocessor instructions when set.

TS **Task Switched (bit 3 of CR0).** Allows the saving of FPU context on a task switch to be delayed until the FPU is actually accessed by the new task. The processor sets this flag on every task switch and tests it when interpreting floating-point arithmetic instructions.

- If the TS flag is set, a device-not-available exception (#NM) is raised prior to the execution of a floating-point instruction.
- If the TS flag and the MP flag (also in the CR0 register) are both set, an #NM exception is raised prior to the execution of floating-point instruction or a WAIT/FWAIT instruction.

Table 2-1 shows the actions taken for floating-point, WAIT/FWAIT, MMX™, and Streaming SIMD Extensions based on the settings of the TS, EM, and MP flags.

Table 2-1. Action Taken for Combinations of EM, MP, TS, CR4.OSFXSR, and CPUID.XMM

CR0 Flags			CR4	CPUID	Instruction Type			
EM	MP	TS	OSFXSR	XMM	Floating-Point	WAIT/FWAIT	MMX™ Technology	Streaming SIMD Extensions
0	0	0	-	-	Execute	Execute	Execute	-
0	0	1	-	-	#NM Exception	Execute	#NM Exception	-
0	1	0	-	-	Execute	Execute	Execute	-
0	1	1	-	-	#NM Exception	#NM Exception	#NM Exception	-
1	0	0	-	-	#NM Exception	Execute	#UD Exception	-
1	0	1	-	-	#NM Exception	Execute	#UD Exception	-
1	1	0	-	-	#NM Exception	Execute	#UD Exception	-
EM	MP	TS	OSFXSR	XMM	Floating-Point	WAIT/FWAIT	MMX™ Technology	Streaming SIMD Extensions
1	1	1	-	-	#NM Exception	#NM Exception	#UD Exception	-
1	-	-	-	-	-	-	-	#UD Interrupt 6
0	-	1	1	1	-	-	-	#NM Interrupt 7
-	-	-	0	-	-	-	-	#UD Interrupt 6
-	-	-	-	0	-	-	-	#UD Interrupt 6

The processor does not automatically save the context of the FPU on a task switch. Instead it sets the TS flag, which causes the processor to raise an #NM exception whenever it encounters a floating-point instruction in the instruction stream for the new task. The fault handler for the #NM exception can then be used to clear the TS flag (with the CLTS instruction) and save the context of the FPU. If the task never encounters a floating-point instruction, the FPU context is never saved.

EM **Emulation (bit 2 of CR0).** Indicates that the processor does not have an internal or external FPU when set; indicates an FPU is present when clear. When the EM flag is set, execution of a floating-point instruction generates a device-not-available exception (#NM). This flag must be set when the processor does not have an internal FPU or is not connected to a math coprocessor. If the processor does have an internal FPU, setting this flag would force all floating-point instructions to be handled by software emulation. Table 8-2 in Chapter 8, *Processor Management and Initialization* shows the recommended setting of this flag, depending on the Intel Architecture processor and

FPU or math coprocessor present in the system. Table 2-1 shows the interaction of the EM, MP, and TS flags.

Note that the EM flag also affects the execution of the MMX™ instructions (refer to Table 2-1). When this flag is set, execution of an MMX™ instruction causes an invalid opcode exception (#UD) to be generated. Thus, if an Intel Architecture processor incorporates MMX™ technology, the EM flag must be set to 0 to enable execution of MMX™ instructions.

Similarly for the Streaming SIMD Extensions, when this flag is set, execution of a Streaming SIMD Extensions instruction causes an invalid opcode exception (#UD) to be generated. Thus, if an Intel Architecture processor incorporates Streaming SIMD Extensions, the EM flag must be set to 0 to enable execution of Streaming SIMD Extensions. The exception to this is the PREFETCH and SFENCE instructions. These instructions are not affected by the EM flag.

MP **Monitor Coprocessor (bit 1 of CR0).** Controls the interaction of the WAIT (or FWAIT) instruction with the TS flag (bit 3 of CR0). If the MP flag is set, a WAIT instruction generates a device-not-available exception (#NM) if the TS flag is set. If the MP flag is clear, the WAIT instruction ignores the setting of the TS flag. Table 8-2 in Chapter 8, *Processor Management and Initialization* shows the recommended setting of this flag, depending on the Intel Architecture processor and FPU or math coprocessor present in the system. Table 2-1 shows the interaction of the MP, EM, and TS flags.

PE **Protection Enable (bit 0 of CR0).** Enables protected mode when set; enables real-address mode when clear. This flag does not enable paging directly. It only enables segment-level protection. To enable paging, both the PE and PG flags must be set. Refer to Section 8.8., “Mode Switching” in Chapter 8, *Processor Management and Initialization* for information using the PE flag to switch between real and protected mode.

PCD **Page-level Cache Disable (bit 4 of CR3).** Controls caching of the current page directory. When the PCD flag is set, caching of the page-directory is prevented; when the flag is clear, the page-directory can be cached. This flag affects only the processor’s internal caches (both L1 and L2, when present). The processor ignores this flag if paging is not used (the PG flag in register CR0 is clear) or the CD (cache disable) flag in CR0 is set. Refer to Chapter 9, *Memory Cache Control*, for more information about the use of this flag. Refer to Section 3.6.4., “Page-Directory and Page-Table Entries” in Chapter 3, *Protected-Mode Memory Management* for a description of a companion PCD flag in the page-directory and page-table entries.

PWT **Page-level Writes Transparent (bit 3 of CR3).** Controls the write-through or write-back caching policy of the current page directory. When the PWT flag is set, write-through caching is enabled; when the flag is clear, write-back caching is enabled. This flag affects only the internal caches (both L1 and L2, when present). The processor ignores this flag if paging is not used (the PG flag in register CR0 is clear) or the CD (cache disable) flag in CR0 is set. Refer to Section 9.5., “Cache Control”, in Chapter 9, *Memory Cache Control*, for more information about the use of this flag. Refer to Section 3.6.4., “Page-Directory and Page-Table Entries” in Chapter 3, *Protected-Mode*

Memory Management for a description of a companion PCD flag in the page-directory and page-table entries.

VME **Virtual-8086 Mode Extensions (bit 0 of CR4).** Enables interrupt- and exception-handling extensions in virtual-8086 mode when set; disables the extensions when clear. Use of the virtual mode extensions can improve the performance of virtual-8086 applications by eliminating the overhead of calling the virtual-8086 monitor to handle interrupts and exceptions that occur while executing an 8086 program and, instead, redirecting the interrupts and exceptions back to the 8086 program's handlers. It also provides hardware support for a virtual interrupt flag (VIF) to improve reliability of running 8086 programs in multitasking and multiple-processor environments. Refer to Section 16.3., "Interrupt and Exception Handling in Virtual-8086 Mode" in Chapter 16, *8086 Emulation* for detailed information about the use of this feature.

PVI **Protected-Mode Virtual Interrupts (bit 1 of CR4).** Enables hardware support for a virtual interrupt flag (VIF) in protected mode when set; disables the VIF flag in protected mode when clear. Refer to Section 16.4., "Protected-Mode Virtual Interrupts" in Chapter 16, *8086 Emulation* for detailed information about the use of this feature.

TSD **Time Stamp Disable (bit 2 of CR4).** Restricts the execution of the RDTSC instruction to procedures running at privilege level 0 when set; allows RDTSC instruction to be executed at any privilege level when clear.

DE **Debugging Extensions (bit 3 of CR4).** References to debug registers DR4 and DR5 cause an undefined opcode (#UD) exception to be generated when set; when clear, processor aliases references to registers DR4 and DR5 for compatibility with software written to run on earlier Intel Architecture processors. Refer to Section 15.2.2., "Debug Registers DR4 and DR5", in Chapter 15, *Debugging and Performance Monitoring*, for more information on the function of this flag.

PSE **Page Size Extensions (bit 4 of CR4).** Enables 4-MByte pages when set; restricts pages to 4 KBytes when clear. Refer to Section 3.6.1., "Paging Options" in Chapter 3, *Protected-Mode Memory Management* for more information about the use of this flag.

PAE **Physical Address Extension (bit 5 of CR4).** Enables paging mechanism to reference 36-bit physical addresses when set; restricts physical addresses to 32 bits when clear. Refer to Section 3.8., "Physical Address Extension" in Chapter 3, *Protected-Mode Memory Management* for more information about the physical address extension.

MCE **Machine-Check Enable (bit 6 of CR4).** Enables the machine-check exception when set; disables the machine-check exception when clear. Refer to Chapter 13, *Machine-Check Architecture*, for more information about the machine-check exception and machine- check architecture.

PGE **Page Global Enable (bit 7 of CR4).** (Introduced in the P6 family processors.) Enables the global page feature when set; disables the global page feature when clear. The global page feature allows frequently used or shared pages to be marked as global to all users (done with the global flag, bit 8, in a page-directory or page-table entry). Global pages are not flushed from the translation-lookaside buffer (TLB) on a task switch or a write to register CR3. In addition, the bit must not be enabled before paging

is enabled via CR0.PG. Program correctness may be affected by reversing this sequence, and processor performance will be impacted. Refer to Section 3.7., "Translation Lookaside Buffers (TLBs)" in Chapter 3, *Protected-Mode Memory Management* for more information on the use of this bit.

PCE **Performance-Monitoring Counter Enable (bit 8 of CR4).** Enables execution of the RDPMC instruction for programs or procedures running at any protection level when set; RDPMC instruction can be executed only at protection level 0 when clear.

OSFXSR

Operating Sytsem FXSAVE/FXRSTOR Support (bit 9 of CR4). The operating system will set this bit if both the CPU and the OS support the use of FXSAVE/FXRSTOR for use during context switches.

OSXMMEXCPT

Operating System Unmasked Exception Support (bit 10 of CR4). The operating system will set this bit if it provides support for unmasked SIMD floating-point exceptions.

2.5.1. CPUID Qualification of Control Register Flags

The VME, PVI, TSD, DE, PSE, PAE, MCE, PGE, PCE, OSFXSR, and OSXMMCEPT flags in control register CR4 are model specific. All of these flags (except PCE) can be qualified with the CPUID instruction to determine if they are implemented on the processor before they are used.

2.6. SYSTEM INSTRUCTION SUMMARY

The system instructions handle system-level functions such as loading system registers, managing the cache, managing interrupts, or setting up the debug registers. Many of these instructions can be executed only by operating-system or executive procedures (that is, procedures running at privilege level 0). Others can be executed at any privilege level and are thus available to application programs. Table 2-2 lists the system instructions and indicates whether they are available and useful for application programs. These instructions are described in detail in Chapter 3, *Instruction Set Reference*, of the *Intel Architecture Software Developer's Manual, Volume 2*.

Table 2-2. Summary of System Instructions

Instruction	Description	Useful to Application?	Protected from Application?
LLDT	Load LDT Register	No	Yes
SLDT	Store LDT Register	No	No
LGDT	Load GDT Register	No	Yes
SGDT	Store GDT Register	No	No
LTR	Load Task Register	No	Yes
STR	Store Task Register	No	No
LIDT	Load IDT Register	No	Yes
SIDT	Store IDT Register	No	No
MOV CR*n*	Load and store control registers	Yes	Yes (load only)
SMSW	Store MSW	Yes	No
LMSW	Load MSW	No	Yes
CLTS	Clear TS flag in CR0	No	Yes
ARPL	Adjust RPL	Yes[1]	No
LAR	Load Access Rights	Yes	No
LSL	Load Segment Limit	Yes	No
VERR	Verify for Reading	Yes	No
VERW	Verify for Writing	Yes	No
MOV DB*n*	Load and store debug registers	No	Yes
INVD	Invalidate cache, no writeback	No	Yes
WBINVD	Invalidate cache, with writeback	No	Yes
INVLPG	Invalidate TLB entry	No	Yes
HLT	Halt Processor	No	Yes
LOCK (Prefix)	Bus Lock	Yes	No
RSM	Return from system management mode	No	Yes
RDMSR[3]	Read Model-Specific Registers	No	Yes
WRMSR[3]	Write Model-Specific Registers	No	Yes
RDPMC[4]	Read Performance-Monitoring Counter	Yes	Yes[2]
RDTSC[3]	Read Time-Stamp Counter	Yes	Yes[2]
LDMXCSR[5]	Load MXCSR Register	Yes	No
STMXCSR[5]	Store MXCSR Resister	Yes	No

NOTES:

1. Useful to application programs running at a CPL of 1 or 2.
2. The TSD and PCE flags in control register CR4 control access to these instructions by application programs running at a CPL of 3.
3. These instructions were introduced into the Intel Architecture with the Pentium® processor.
4. This instruction was introduced into the Intel Architecture with the Pentium® Pro processor and the Pentium processor with MMX™ technology.
5. This instruction was introduced into the Intel Architecture with the Pentium® III processor.

2.6.1. Loading and Storing System Registers

The GDTR, LDTR, IDTR, and TR registers each have a load and store instruction for loading data into and storing data from the register:

LGDT (Load GDTR Register) Loads the GDT base address and limit from memory into the GDTR register.

SGDT (Store GDTR Register) Stores the GDT base address and limit from the GDTR register into memory.

LIDT (Load IDTR Register) Loads the IDT base address and limit from memory into the IDTR register.

SIDT (Load IDTR Register Stores the IDT base address and limit from the IDTR register into memory.

LLDT (Load LDT Register) Loads the LDT segment selector and segment descriptor from memory into the LDTR. (The segment selector operand can also be located in a general-purpose register.)

SLDT (Store LDT Register) Stores the LDT segment selector from the LDTR register into memory or a general-purpose register.

LTR (Load Task Register) Loads segment selector and segment descriptor for a TSS from memory into the task register. (The segment selector operand can also be located in a general-purpose register.)

STR (Store Task Register) Stores the segment selector for the current task TSS from the task register into memory or a general-purpose register.

The LMSW (load machine status word) and SMSW (store machine status word) instructions operate on bits 0 through 15 of control register CR0. These instructions are provided for compatibility with the 16-bit Intel 286 processor. Program written to run on 32-bit Intel Architecture processors should not use these instructions. Instead, they should access the control register CR0 using the MOV instruction.

The CLTS (clear TS flag in CR0) instruction is provided for use in handling a device-not-available exception (#NM) that occurs when the processor attempts to execute a floating-point instruction when the TS flag is set. This instruction allows the TS flag to be cleared after the FPU context has been saved, preventing further #NM exceptions. Refer to Section 2.5., “Control Registers” for more information about the TS flag.

The control registers (CR0, CR1, CR2, CR3, and CR4) are loaded with the MOV instruction. This instruction can load a control register from a general-purpose register or store the contents of the control register in a general-purpose register.

2.6.2. Verifying of Access Privileges

The processor provides several instructions for examining segment selectors and segment descriptors to determine if access to their associated segments is allowed. These instructions

duplicate some of the automatic access rights and type checking done by the processor, thus allowing operating-system or executive software to prevent exceptions from being generated.

The ARPL (adjust RPL) instruction adjusts the RPL (requestor privilege level) of a segment selector to match that of the program or procedure that supplied the segment selector. Refer to Section 4.10.4., “Checking Caller Access Privileges (ARPL Instruction)” in Chapter 4, *Protection* for a detailed explanation of the function and use of this instruction.

The LAR (load access rights) instruction verifies the accessibility of a specified segment and loads the access rights information from the segment’s segment descriptor into a general-purpose register. Software can then examine the access rights to determine if the segment type is compatible with its intended use. Refer to Section 4.10.1., “Checking Access Rights (LAR Instruction)” in Chapter 4, *Protection* for a detailed explanation of the function and use of this instruction.

The LSL (load segment limit) instruction verifies the accessibility of a specified segment and loads the segment limit from the segment’s segment descriptor into a general-purpose register. Software can then compare the segment limit with an offset into the segment to determine whether the offset lies within the segment. Refer to Section 4.10.3., “Checking That the Pointer Offset Is Within Limits (LSL Instruction)” in Chapter 4, *Protection* for a detailed explanation of the function and use of this instruction.

The VERR (verify for reading) and VERW (verify for writing) instructions verify if a selected segment is readable or writable, respectively, at the CPL. Refer to Section 4.10.2., “Checking Read/Write Rights (VERR and VERW Instructions)” in Chapter 4, *Protection* for a detailed explanation of the function and use of this instruction.

2.6.3. Loading and Storing Debug Registers

The internal debugging facilities in the processor are controlled by a set of 8 debug registers (DR0 through DR7). The MOV instruction allows setup data to be loaded into and stored from these registers.

2.6.4. Invalidating Caches and TLBs

The processor provides several instructions for use in explicitly invalidating its caches and TLB entries. The INVD (invalidate cache with no writeback) instruction invalidates all data and instruction entries in the internal caches and TLBs and sends a signal to the external caches indicating that they should be invalidated also.

The WBINVD (invalidate cache with writeback) instruction performs the same function as the INVD instruction, except that it writes back any modified lines in its internal caches to memory before it invalidates the caches. After invalidating the internal caches, it signals the external caches to write back modified data and invalidate their contents.

The INVLPG (invalidate TLB entry) instruction invalidates (flushes) the TLB entry for a specified page.

2.6.5. Controlling the Processor

The HLT (halt processor) instruction stops the processor until an enabled interrupt (such as NMI or SMI, which are normally enabled), the BINIT# signal, the INIT# signal, or the RESET# signal is received. The processor generates a special bus cycle to indicate that the halt mode has been entered. Hardware may respond to this signal in a number of ways. An indicator light on the front panel may be turned on. An NMI interrupt for recording diagnostic information may be generated. Reset initialization may be invoked. (Note that the BINIT# pin was introduced with the Pentium® Pro processor.)

The LOCK prefix invokes a locked (atomic) read-modify-write operation when modifying a memory operand. This mechanism is used to allow reliable communications between processors in multiprocessor systems. In the Pentium® and earlier Intel Architecture processors, the LOCK prefix causes the processor to assert the LOCK# signal during the instruction, which always causes an explicit bus lock to occur. In the P6 family processors, the locking operation is handled with either a cache lock or bus lock. If a memory access is cacheable and affects only a single cache line, a cache lock is invoked and the system bus and the actual memory location in system memory are not locked during the operation. Here, other P6 family processors on the bus write-back any modified data and invalidate their caches as necessary to maintain system memory coherency. If the memory access is not cacheable and/or it crosses a cache line boundary, the processor's LOCK# signal is asserted and the processor does not respond to requests for bus control during the locked operation.

The RSM (return from SMM) instruction restores the processor (from a context dump) to the state it was in prior to an system management mode (SMM) interrupt.

2.6.6. Reading Performance-Monitoring and Time-Stamp Counters

The RDPMC (read performance-monitoring counter) and RDTSC (read time-stamp counter) instructions allow an application program to read the processors performance-monitoring and time-stamp counters, respectively.

The P6 family processors have two 40-bit performance counters that record either the occurrence of events or the duration of events. The events that can be monitored include the number of instructions decoded, number of interrupts received, of number of cache loads. Each counter can be set up to monitor a different event, using the system instruction WRMSR to set up values in the model-specific registers PerfEvtSel0 and PerfEvtSel1. The RDPMC instruction loads the current count in counter 0 or 1 into the EDX:EAX registers.

The time-stamp counter is a model-specific 64-bit counter that is reset to zero each time the processor is reset. If not reset, the counter will increment ~6.3 x 10^{15} times per year when the processor is operating at a clock rate of 200 MHz. At this clock frequency, it would take over 2000 years for the counter to wrap around. The RDTSC instruction loads the current count of the time-stamp counter into the EDX:EAX registers.

Refer to Section 15.5., “Time-Stamp Counter”, and Section 15.6., “Performance-Monitoring Counters”, in Chapter 15, *Debugging and Performance Monitoring*, for more information about the performance monitoring and time-stamp counters.

The RDTSC instruction was introduced into the Intel Architecture with the Pentium® processor. The RDPMC instruction was introduced into the Intel Architecture with the Pentium® Pro processor and the Pentium® processor with MMX™ technology. Earlier Pentium® processors have two performance-monitoring counters, but they can be read only with the RDMSR instruction, and only at privilege level 0.

2.6.7. Reading and Writing Model-Specific Registers

The RDMSR (read model-specific register) and WRMSR (write model-specific register) allow the processor’s 64-bit model-specific registers (MSRs) to be read and written to, respectively. The MSR to be read or written to is specified by the value in the ECX register. The RDMSR instruction reads the value from the specified MSR into the EDX:EAX registers; the WRMSR writes the value in the EDX:EAX registers into the specified MSR. Refer to Section 8.4., “Model-Specific Registers (MSRs)” in Chapter 8, *Processor Management and Initialization* for more information about the MSRs.

The RDMSR and WRMSR instructions were introduced into the Intel Architecture with the Pentium® processor.

2.6.8. Loading and Storing the Streaming SIMD Extensions Control/Status Word

The LDMXCSR (load Streaming SIMD Extensions control/status word from memory) and STMXCSR (store Streaming SIMD Extensions control/status word to memory) allow the Pentium® III processor’s 32-bit control/status word to be read and written to, respectively. The MXCSR control/status register is used to enable masked/unmasked exception handling, to set rounding modes, to set flush-to-zero mode, and to view exception status flags. For more information on the LDMXCSR and STMXCSR instructions, refer to the *Intel Architecture Software Developer’s Manual, Vol 2*, for a complete description of these instructions.

3

Protected-Mode Memory Management

CHAPTER 3
PROTECTED-MODE MEMORY MANAGEMENT

This chapter describes the Intel Architecture's protected-mode memory management facilities, including the physical memory requirements, the segmentation mechanism, and the paging mechanism. Refer to Chapter 4, *Protection* for a description of the processor's protection mechanism. Refer to Chapter 16, *8086 Emulation* for a description of memory addressing protection in real-address and virtual-8086 modes.

3.1. MEMORY MANAGEMENT OVERVIEW

The memory management facilities of the Intel Architecture are divided into two parts: segmentation and paging. Segmentation provides a mechanism of isolating individual code, data, and stack modules so that multiple programs (or tasks) can run on the same processor without interfering with one another. Paging provides a mechanism for implementing a conventional demand-paged, virtual-memory system where sections of a program's execution environment are mapped into physical memory as needed. Paging can also be used to provide isolation between multiple tasks. When operating in protected mode, some form of segmentation must be used. **There is no mode bit to disable segmentation.** The use of paging, however, is optional.

These two mechanisms (segmentation and paging) can be configured to support simple single-program (or single-task) systems, multitasking systems, or multiple-processor systems that used shared memory.

As shown in Figure 3-1, segmentation provides a mechanism for dividing the processor's addressable memory space (called the **linear address space**) into smaller protected address spaces called **segments**. Segments can be used to hold the code, data, and stack for a program or to hold system data structures (such as a TSS or LDT). If more than one program (or task) is running on a processor, each program can be assigned its own set of segments. The processor then enforces the boundaries between these segments and insures that one program does not interfere with the execution of another program by writing into the other program's segments. The segmentation mechanism also allows typing of segments so that the operations that may be performed on a particular type of segment can be restricted.

All of the segments within a system are contained in the processor's linear address space. To locate a byte in a particular segment, a **logical address** (sometimes called a far pointer) must be provided. A logical address consists of a segment selector and an offset. The segment selector is a unique identifier for a segment. Among other things it provides an offset into a descriptor table (such as the global descriptor table, GDT) to a data structure called a segment descriptor. Each segment has a segment descriptor, which specifies the size of the segment, the access rights and privilege level for the segment, the segment type, and the location of the first byte of the segment in the linear address space (called the base address of the segment). The offset part of the logical address is added to the base address for the segment to locate a byte within the segment. The base address plus the offset thus forms a **linear address** in the processor's linear

address space.

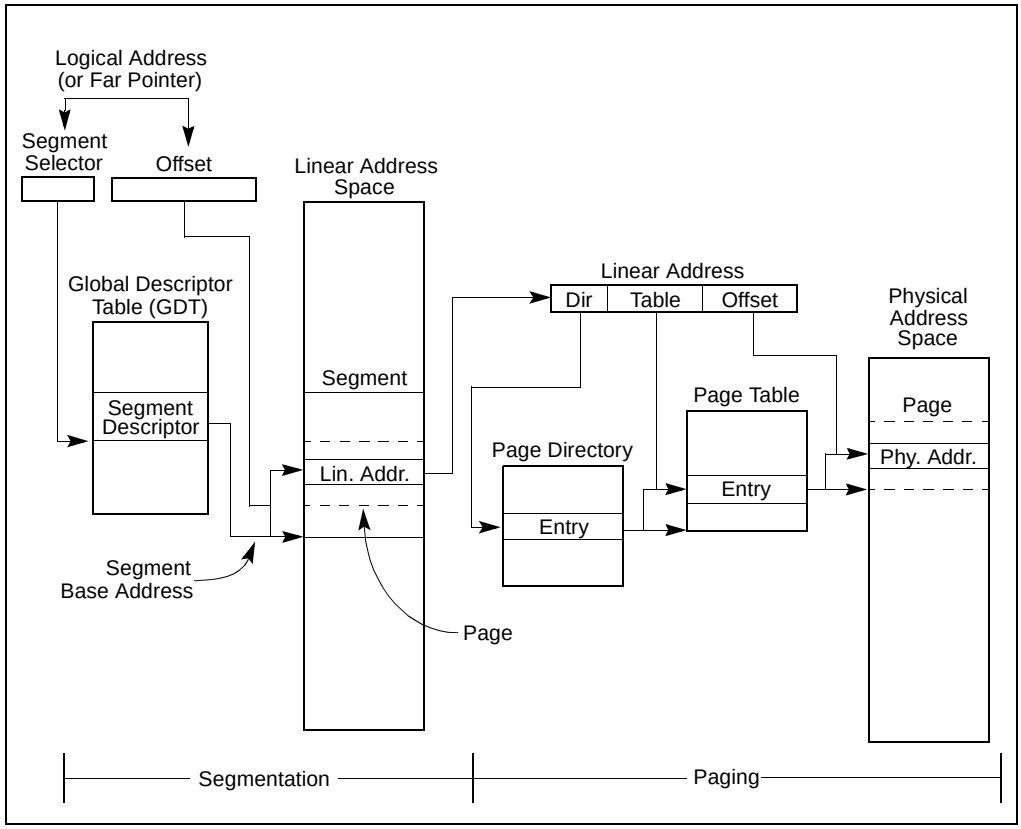


Figure 3-1. Segmentation and Paging

If paging is not used, the linear address space of the processor is mapped directly into the physical address space of processor. The physical address space is defined as the range of addresses that the processor can generate on its address bus.

Because multitasking computing systems commonly define a linear address space much larger than it is economically feasible to contain all at once in physical memory, some method of "virtualizing" the linear address space is needed. This virtualization of the linear address space is handled through the processor's paging mechanism.

Paging supports a "virtual memory" environment where a large linear address space is simulated with a small amount of physical memory (RAM and ROM) and some disk storage. When using paging, each segment is divided into pages (ordinarily 4 KBytes each in size), which are stored either in physical memory or on the disk. The operating system or executive maintains a page directory and a set of page tables to keep track of the pages. When a program (or task) attempts to access an address location in the linear address space, the processor uses the page directory

and page tables to translate the linear address into a physical address and then performs the requested operation (read or write) on the memory location. If the page being accessed is not currently in physical memory, the processor interrupts execution of the program (by generating a page-fault exception). The operating system or executive then reads the page into physical memory from the disk and continues executing the program.

When paging is implemented properly in the operating-system or executive, the swapping of pages between physical memory and the disk is transparent to the correct execution of a program. Even programs written for 16-bit Intel Architecture processors can be paged (transparently) when they are run in virtual-8086 mode.

3.2. USING SEGMENTS

The segmentation mechanism supported by the Intel Architecture can be used to implement a wide variety of system designs. These designs range from flat models that make only minimal use of segmentation to protect programs to multisegmented models that employ segmentation to create a robust operating environment in which multiple programs and tasks can be executed reliably.

The following sections give several examples of how segmentation can be employed in a system to improve memory management performance and reliability.

3.2.1. Basic Flat Model

The simplest memory model for a system is the basic “flat model,” in which the operating system and application programs have access to a continuous, unsegmented address space. To the greatest extent possible, this basic flat model hides the segmentation mechanism of the architecture from both the system designer and the application programmer.

To implement a basic flat memory model with the Intel Architecture, at least two segment descriptors must be created, one for referencing a code segment and one for referencing a data segment (refer to Figure 3-2). Both of these segments, however, are mapped to the entire linear address space: that is, both segment descriptors have the same base address value of 0 and the same segment limit of 4 GBytes. By setting the segment limit to 4 GBytes, the segmentation mechanism is kept from generating exceptions for out of limit memory references, even if no physical memory resides at a particular address. ROM (EPROM) is generally located at the top of the physical address space, because the processor begins execution at FFFF_FFF0H. RAM (DRAM) is placed at the bottom of the address space because the initial base address for the DS data segment after reset initialization is 0.

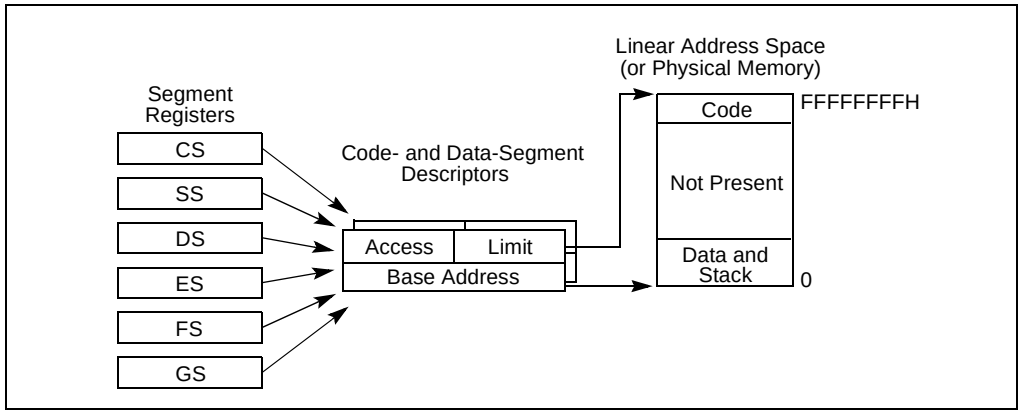


Figure 3-2. Flat Model

3.2.2. Protected Flat Model

The protected flat model is similar to the basic flat model, except the segment limits are set to include only the range of addresses for which physical memory actually exists (refer to Figure 3-3). A general-protection exception (#GP) is then generated on any attempt to access nonexistent memory. This model provides a minimum level of hardware protection against some kinds of program bugs.

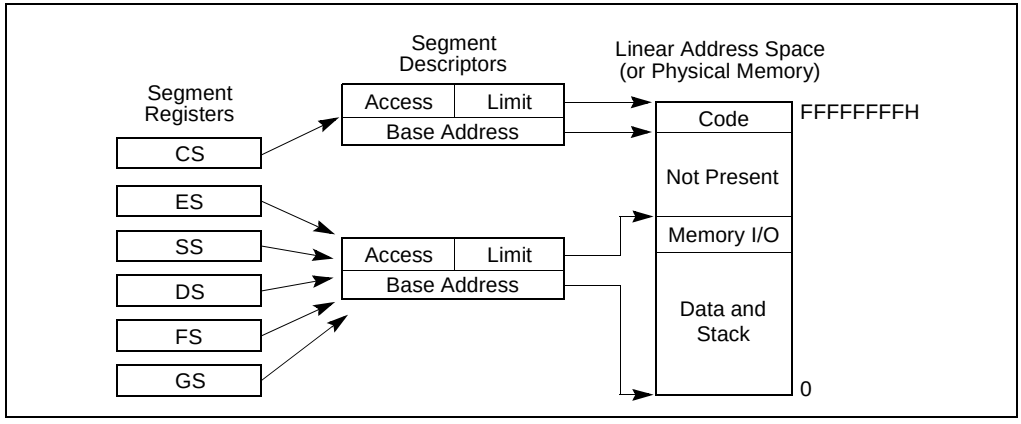


Figure 3-3. Protected Flat Model

More complexity can be added to this protected flat model to provide more protection. For example, for the paging mechanism to provide isolation between user and supervisor code and data, four segments need to be defined: code and data segments at privilege level 3 for the user, and code and data segments at privilege level 0 for the supervisor. Usually these segments all overlay each other and start at address 0 in the linear address space. This flat segmentation

model along with a simple paging structure can protect the operating system from applications, and by adding a separate paging structure for each task or process, it can also protect applications from each other. Similar designs are used by several popular multitasking operating systems.

3.2.3. Multisegment Model

A multisegment model (such as the one shown in Figure 3-4) uses the full capabilities of the segmentation mechanism to provided hardware enforced protection of code, data structures, and programs and tasks. Here, each program (or task) is given its own table of segment descriptors and its own segments. The segments can be completely private to their assigned programs or shared among programs. Access to all segments and to the execution environments of individual programs running on the system is controlled by hardware.

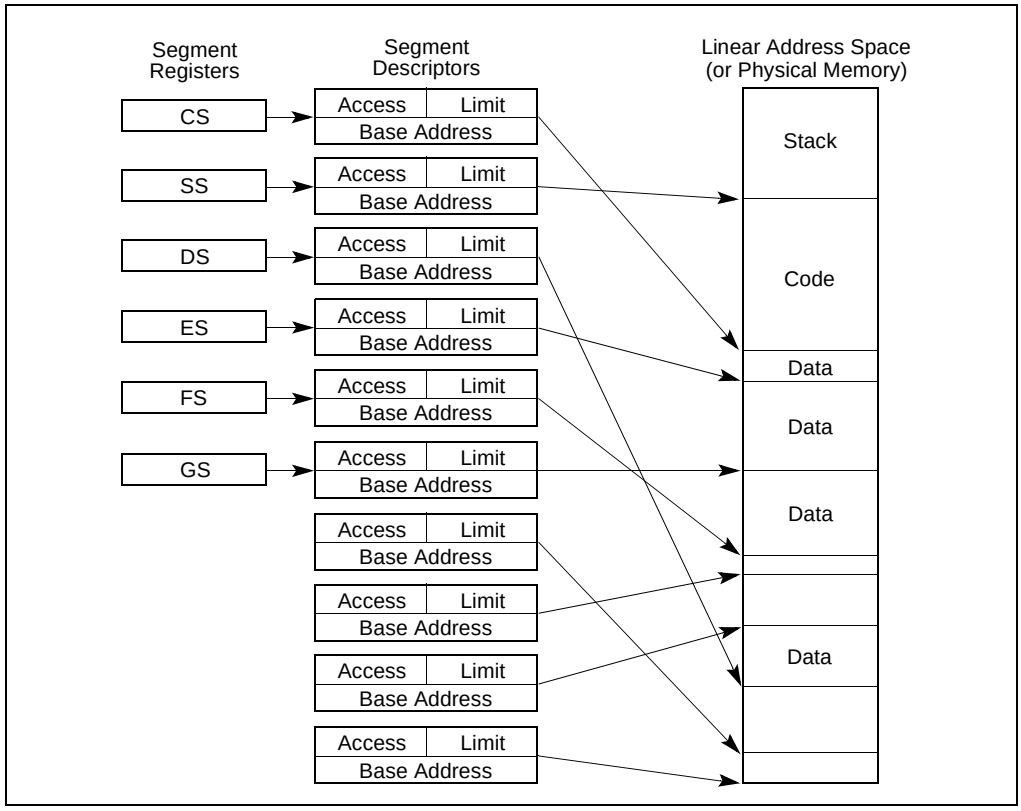


Figure 3-4. Multisegment Model

Access checks can be used to protect not only against referencing an address outside the limit of a segment, but also against performing disallowed operations in certain segments. For example, since code segments are designated as read-only segments, hardware can be used to prevent writes into code segments. The access rights information created for segments can also be used to set up protection rings or levels. Protection levels can be used to protect operating-system procedures from unauthorized access by application programs.

3.2.4. Paging and Segmentation

Paging can be used with any of the segmentation models described in Figures 3-2, 3-3, and 3-4. The processor's paging mechanism divides the linear address space (into which segments are mapped) into pages (as shown in Figure 3-1). These linear-address-space pages are then mapped to pages in the physical address space. The paging mechanism offers several page-level protection facilities that can be used with or instead of the segment-protection facilities. For example, it lets read-write protection be enforced on a page-by-page basis. The paging mechanism also provides two-level user-supervisor protection that can also be specified on a page-by-page basis.

3.3. PHYSICAL ADDRESS SPACE

In protected mode, the Intel Architecture provides a normal physical address space of 4 GBytes (2^{32} bytes). This is the address space that the processor can address on its address bus. This address space is flat (unsegmented), with addresses ranging continuously from 0 to FFFFFFFFH. This physical address space can be mapped to read-write memory, read-only memory, and memory mapped I/O. The memory mapping facilities described in this chapter can be used to divide this physical memory up into segments and/or pages.

(Introduced in the Pentium® Pro processor.) The Intel Architecture also supports an extension of the physical address space to 2^{36} bytes (64 GBytes), with a maximum physical address of FFFFFFFFFH. This extension is invoked with the physical address extension (PAE) flag, located in bit 5 of control register CR4. (Refer to Section 3.8., "Physical Address Extension" for more information about extended physical addressing.)

3.4. LOGICAL AND LINEAR ADDRESSES

At the system-architecture level in protected mode, the processor uses two stages of address translation to arrive at a physical address: logical-address translation and linear address space paging.

Even with the minimum use of segments, every byte in the processor's address space is accessed with a logical address. A logical address consists of a 16-bit segment selector and a 32-bit offset (refer to Figure 3-5). The segment selector identifies the segment the byte is located in and the offset specifies the location of the byte in the segment relative to the base address of the segment.

The processor translates every logical address into a linear address. A linear address is a 32-bit address in the processor's linear address space. Like the physical address space, the linear address space is a flat (unsegmented), 2^{32}-byte address space, with addresses ranging from 0 to

FFFFFFFH. The linear address space contains all the segments and system tables defined for a system.

To translate a logical address into a linear address, the processor does the following:

1. Uses the offset in the segment selector to locate the segment descriptor for the segment in the GDT or LDT and reads it into the processor. (This step is needed only when a new segment selector is loaded into a segment register.)
2. Examines the segment descriptor to check the access rights and range of the segment to insure that the segment is accessible and that the offset is within the limits of the segment.
3. Adds the base address of the segment from the segment descriptor to the offset to form a linear address.

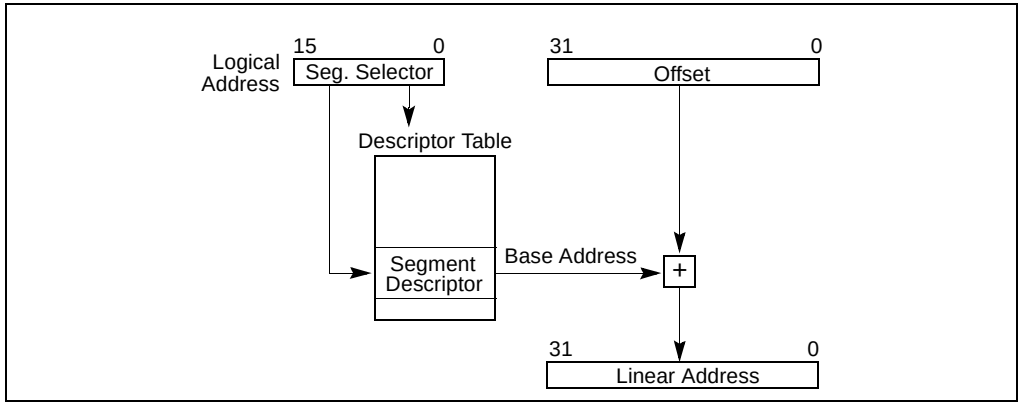


Figure 3-5. Logical Address to Linear Address Translation

If paging is not used, the processor maps the linear address directly to a physical address (that is, the linear address goes out on the processor's address bus). If the linear address space is paged, a second level of address translation is used to translate the linear address into a physical address. Page translation is described in Section 3.6., "Paging (Virtual Memory)"

3.4.1. Segment Selectors

A segment selector is a 16-bit identifier for a segment (refer to Figure 3-6). It does not point directly to the segment, but instead points to the segment descriptor that defines the segment. A segment selector contains the following items:

Index (Bits 3 through 15). Selects one of 8192 descriptors in the GDT or LDT. The processor multiplies the index value by 8 (the number of bytes in a segment descriptor) and adds the result to the base address of the GDT or LDT (from the GDTR or LDTR register, respectively).

TI (table indicator) flag

(Bit 2). Specifies the descriptor table to use: clearing this flag selects the GDT; setting this flag selects the current LDT.

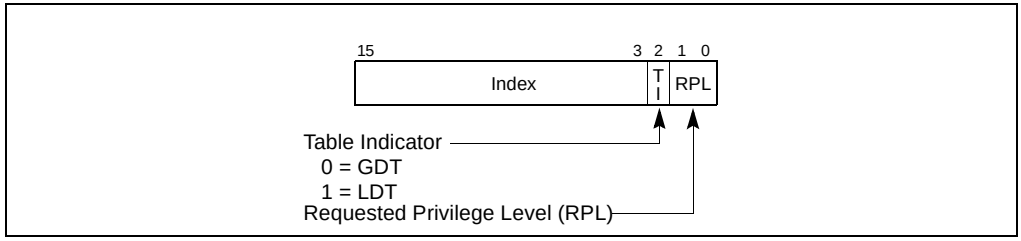


Figure 3-6. Segment Selector

Requested Privilege Level (RPL)

(Bits 0 and 1). Specifies the privilege level of the selector. The privilege level can range from 0 to 3, with 0 being the most privileged level. Refer to Section 4.5., "Privilege Levels" in Chapter 4, *Protection* for a description of the relationship of the RPL to the CPL of the executing program (or task) and the descriptor privilege level (DPL) of the descriptor the segment selector points to.

The first entry of the GDT is not used by the processor. A segment selector that points to this entry of the GDT (that is, a segment selector with an index of 0 and the TI flag set to 0) is used as a "null segment selector." The processor does not generate an exception when a segment register (other than the CS or SS registers) is loaded with a null selector. It does, however, generate an exception when a segment register holding a null selector is used to access memory. A null selector can be used to initialize unused segment registers. Loading the CS or SS register with a null segment selector causes a general-protection exception (#GP) to be generated.

Segment selectors are visible to application programs as part of a pointer variable, but the values of selectors are usually assigned or modified by link editors or linking loaders, not application programs.

3.4.2. Segment Registers

To reduce address translation time and coding complexity, the processor provides registers for holding up to 6 segment selectors (refer to Figure 3-7). Each of these segment registers support a specific kind of memory reference (code, stack, or data). For virtually any kind of program execution to take place, at least the code-segment (CS), data-segment (DS), and stack-segment (SS) registers must be loaded with valid segment selectors. The processor also provides three additional data-segment registers (ES, FS, and GS), which can be used to make additional data segments available to the currently executing program (or task).

For a program to access a segment, the segment selector for the segment must have been loaded in one of the segment registers. So, although a system can define thousands of segments, only 6

can be available for immediate use. Other segments can be made available by loading their segment selectors into these registers during program execution.

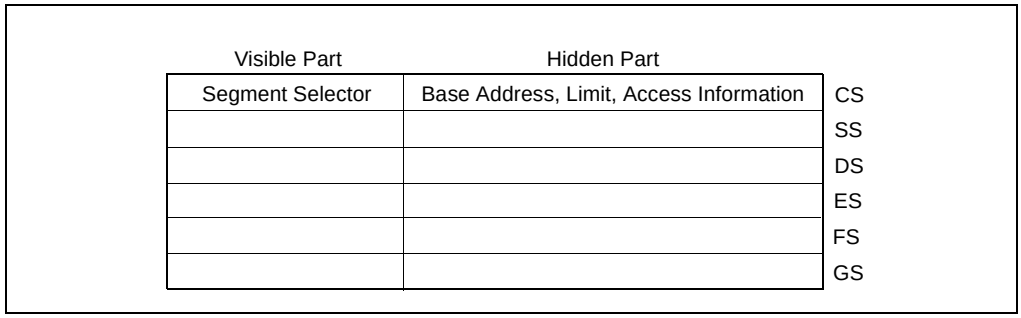


Figure 3-7. Segment Registers

Every segment register has a “visible” part and a “hidden” part. (The hidden part is sometimes referred to as a “descriptor cache” or a “shadow register.”) When a segment selector is loaded into the visible part of a segment register, the processor also loads the hidden part of the segment register with the base address, segment limit, and access control information from the segment descriptor pointed to by the segment selector. The information cached in the segment register (visible and hidden) allows the processor to translate addresses without taking extra bus cycles to read the base address and limit from the segment descriptor. In systems in which multiple processors have access to the same descriptor tables, it is the responsibility of software to reload the segment registers when the descriptor tables are modified. If this is not done, an old segment descriptor cached in a segment register might be used after its memory-resident version has been modified.

Two kinds of load instructions are provided for loading the segment registers:

1. Direct load instructions such as the MOV, POP, LDS, LES, LSS, LGS, and LFS instructions. These instructions explicitly reference the segment registers.
2. Implied load instructions such as the far pointer versions of the CALL, JMP, and RET instructions and the IRET, INT*n*, INTO and INT3 instructions. These instructions change the contents of the CS register (and sometimes other segment registers) as an incidental part of their operation.

The MOV instruction can also be used to store visible part of a segment register in a general-purpose register.

3.4.3. Segment Descriptors

A segment descriptor is a data structure in a GDT or LDT that provides the processor with the size and location of a segment, as well as access control and status information. Segment descriptors are typically created by compilers, linkers, loaders, or the operating system or exec-

utive, but not application programs. Figure 3-8 illustrates the general descriptor format for all types of segment descriptors.

The flags and fields in a segment descriptor are as follows:

Segment limit field

Specifies the size of the segment. The processor puts together the two segment limit fields to form a 20-bit value. The processor interprets the segment limit in one of two ways, depending on the setting of the G (granularity) flag:

- If the granularity flag is clear, the segment size can range from 1 byte to 1 MByte, in byte increments.
- If the granularity flag is set, the segment size can range from 4 KBytes to 4 GBytes, in 4-KByte increments.

The processor uses the segment limit in two different ways, depending on whether the segment is an expand-up or an expand-down segment. Refer to Section 3.4.3.1., “Code- and Data-Segment Descriptor Types” for more information about segment types. For expand-up segments, the offset in a logical address can range from 0 to the segment limit. Offsets greater than the segment limit generate general-protection exceptions (#GP). For expand-down segments, the segment limit has the reverse function; the offset can range from the segment limit to FFFFFFFFH or FFFFH, depending on the setting of the B flag. Offsets less than the segment limit generate general-protection exceptions. Decreasing the value in the segment limit field for an expand-down segment allocates new memory at the bottom of the segment's address space, rather than at the top. Intel Architecture stacks always grow downwards, making this mechanism is convenient for expandable stacks.

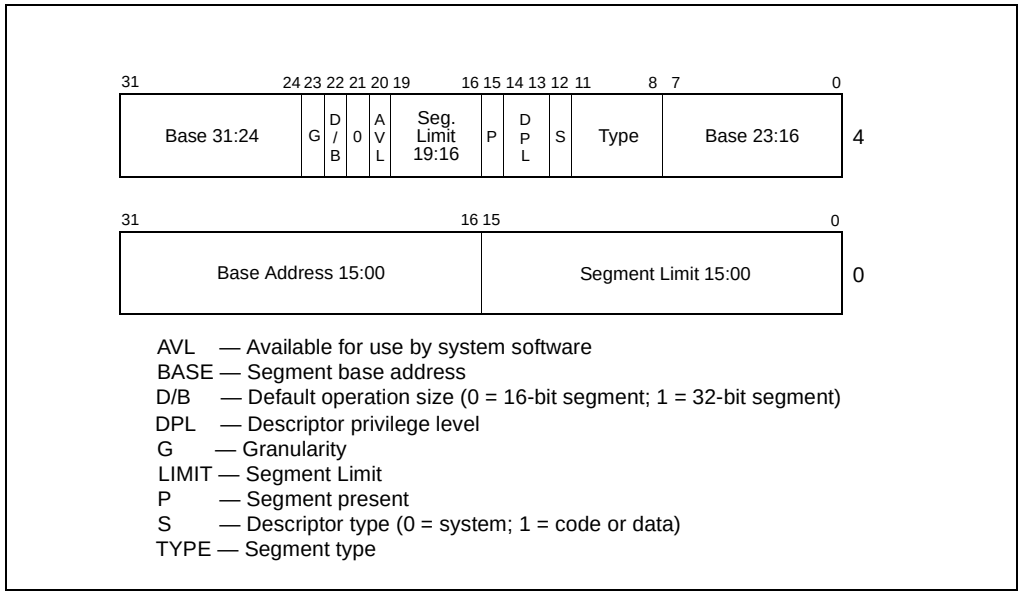


Figure 3-8. Segment Descriptor

Base address fields

Defines the location of byte 0 of the segment within the 4-GByte linear address space. The processor puts together the three base address fields to form a single 32-bit value. Segment base addresses should be aligned to 16-byte boundaries. Although 16-byte alignment is not required, this alignment allows programs to maximize performance by aligning code and data on 16-byte boundaries.

Type field Indicates the segment or gate type and specifies the kinds of access that can be made to the segment and the direction of growth. The interpretation of this field depends on whether the descriptor type flag specifies an application (code or data) descriptor or a system descriptor. The encoding of the type field is different for code, data, and system descriptors (refer to Figure 4-1 in Chapter 4, *Protection*). Refer to Section 3.4.3.1., “Code- and Data-Segment Descriptor Types” for a description of how this field is used to specify code and data-segment types.

S (descriptor type) flag

Specifies whether the segment descriptor is for a system segment (S flag is clear) or a code or data segment (S flag is set).

DPL (descriptor privilege level) field

Specifies the privilege level of the segment. The privilege level can range from 0 to 3, with 0 being the most privileged level. The DPL is used to control access to the segment. Refer to Section 4.5., "Privilege Levels" in Chapter 4, *Protection* for a description of the relationship of the DPL to the CPL of the executing code segment and the RPL of a segment selector.

P (segment-present) flag

Indicates whether the segment is present in memory (set) or not present (clear). If this flag is clear, the processor generates a segment-not-present exception (#NP) when a segment selector that points to the segment descriptor is loaded into a segment register. Memory management software can use this flag to control which segments are actually loaded into physical memory at a given time. It offers a control in addition to paging for managing virtual memory.

Figure 3-9 shows the format of a segment descriptor when the segment-present flag is clear. When this flag is clear, the operating system or executive is free to use the locations marked "Available" to store its own data, such as information regarding the whereabouts of the missing segment.

D/B (default operation size/default stack pointer size and/or upper bound) flag

Performs different functions depending on whether the segment descriptor is an executable code segment, an expand-down data segment, or a stack segment. (This flag should always be set to 1 for 32-bit code and data segments and to 0 for 16-bit code and data segments.)

- **Executable code segment.** The flag is called the D flag and it indicates the default length for effective addresses and operands referenced by instructions in the segment. If the flag is set, 32-bit addresses and 32-bit or 8-bit operands are assumed; if it is clear, 16-bit addresses and 16-bit or 8-bit operands are assumed. The instruction prefix 66H can be used to select an operand size other than the default, and the prefix 67H can be used select an address size other than the default.
- **Stack segment (data segment pointed to by the SS register).** The flag is called the B (big) flag and it specifies the size of the stack pointer used for implicit stack operations (such as pushes, pops, and calls). If the flag is set, a 32-bit stack pointer is used, which is stored in the 32-bit ESP register; if the flag is clear, a 16-bit stack pointer is used, which is stored in the 16-bit SP register. If the stack segment is set up to be an expand-down data segment (described in the next paragraph), the B flag also specifies the upper bound of the stack segment.
- **Expand-down data segment.** The flag is called the B flag and it specifies the upper bound of the segment. If the flag is set, the upper bound is FFFFFFFFH (4 GBytes); if the flag is clear, the upper bound is FFFFH (64 KBytes).

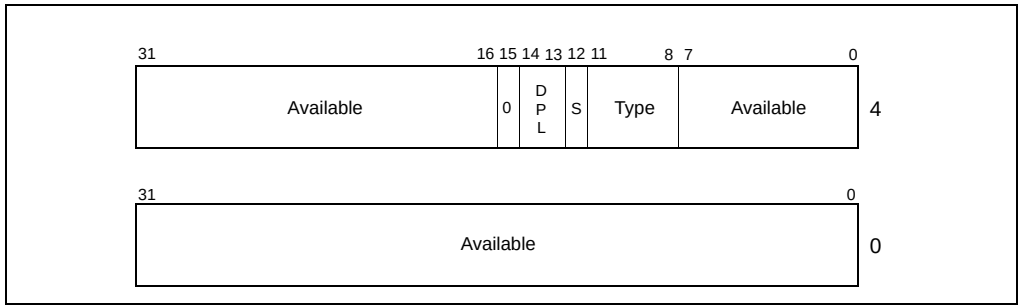


Figure 3-9. Segment Descriptor When Segment-Present Flag Is Clear

G (granularity) flag

Determines the scaling of the segment limit field. When the granularity flag is clear, the segment limit is interpreted in byte units; when flag is set, the segment limit is interpreted in 4-KByte units. (This flag does not affect the granularity of the base address; it is always byte granular.) When the granularity flag is set, the twelve least significant bits of an offset are not tested when checking the offset against the segment limit. For example, when the granularity flag is set, a limit of 0 results in valid offsets from 0 to 4095.

Available and reserved bits

Bit 20 of the second doubleword of the segment descriptor is available for use by system software; bit 21 is reserved and should always be set to 0.

3.4.3.1. CODE- AND DATA-SEGMENT DESCRIPTOR TYPES

When the S (descriptor type) flag in a segment descriptor is set, the descriptor is for either a code or a data segment. The highest order bit of the type field (bit 11 of the second double word of the segment descriptor) then determines whether the descriptor is for a data segment (clear) or a code segment (set).

For data segments, the three low-order bits of the type field (bits 8, 9, and 10) are interpreted as accessed (A), write-enable (W), and expansion-direction (E). Refer to Table 3-1 for a description of the encoding of the bits in the type field for code and data segments. Data segments can be read-only or read/write segments, depending on the setting of the write-enable bit.

Table 3-1. Code- and Data-Segment Types

Type Field					Descriptor Type	Description
Decimal	11	10 E	9 W	8 A		
0	0	0	0	0	Data	Read-Only
1	0	0	0	1	Data	Read-Only, accessed
2	0	0	1	0	Data	Read/Write
3	0	0	1	1	Data	Read/Write, accessed
4	0	1	0	0	Data	Read-Only, expand-down
5	0	1	0	1	Data	Read-Only, expand-down, accessed
6	0	1	1	0	Data	Read/Write, expand-down
7	0	1	1	1	Data	Read/Write, expand-down, accessed
		C	R	A		
8	1	0	0	0	Code	Execute-Only
9	1	0	0	1	Code	Execute-Only, accessed
10	1	0	1	0	Code	Execute/Read
11	1	0	1	1	Code	Execute/Read, accessed
12	1	1	0	0	Code	Execute-Only, conforming
13	1	1	0	1	Code	Execute-Only, conforming, accessed
14	1	1	1	0	Code	Execute/Read-Only, conforming
15	1	1	1	1	Code	Execute/Read-Only, conforming, accessed

Stack segments are data segments which must be read/write segments. Loading the SS register with a segment selector for a nonwritable data segment generates a general-protection exception (#GP). If the size of a stack segment needs to be changed dynamically, the stack segment can be an expand-down data segment (expansion-direction flag set). Here, dynamically changing the segment limit causes stack space to be added to the bottom of the stack. If the size of a stack segment is intended to remain static, the stack segment may be either an expand-up or expand-down type.

The accessed bit indicates whether the segment has been accessed since the last time the operating-system or executive cleared the bit. The processor sets this bit whenever it loads a segment selector for the segment into a segment register. The bit remains set until explicitly cleared. This bit can be used both for virtual memory management and for debugging.

For code segments, the three low-order bits of the type field are interpreted as accessed (A), read enable (R), and conforming (C). Code segments can be execute-only or execute/read, depending on the setting of the read-enable bit. An execute/read segment might be used when constants or other static data have been placed with instruction code in a ROM. Here, data can be read from the code segment either by using an instruction with a CS override prefix or by loading a segment selector for the code segment in a data-segment register (the DS, ES, FS, or GS registers). In protected mode, code segments are not writable.

Code segments can be either conforming or nonconforming. A transfer of execution into a more-privileged conforming segment allows execution to continue at the current privilege level. A transfer into a nonconforming segment at a different privilege level results in a general-protection exception (#GP), unless a call gate or task gate is used (refer to Section 4.8.1., “Direct Calls or Jumps to Code Segments” in Chapter 4, *Protection* for more information on conforming and

nonconforming code segments). System utilities that do not access protected facilities and handlers for some types of exceptions (such as, divide error or overflow) may be loaded in conforming code segments. Utilities that need to be protected from less privileged programs and procedures should be placed in nonconforming code segments.

NOTE

Execution cannot be transferred by a call or a jump to a less-privileged (numerically higher privilege level) code segment, regardless of whether the target segment is a conforming or nonconforming code segment. Attempting such an execution transfer will result in a general-protection exception.

All data segments are nonconforming, meaning that they cannot be accessed by less privileged programs or procedures (code executing at numerically high privilege levels). Unlike code segments, however, data segments can be accessed by more privileged programs or procedures (code executing at numerically lower privilege levels) without using a special access gate.

The processor may update the Type field when a segment is accessed, even if the access is a read cycle. If the descriptor tables have been put in ROM, it may be necessary for hardware to prevent the ROM from being enabled onto the data bus during a write cycle. It also may be necessary to return the READY# signal to the processor when a write cycle to ROM occurs, otherwise the cycle will not terminate. These features of the hardware design are necessary for using ROM-based descriptor tables with the Intel386™ DX processor, which always sets the Accessed bit when a segment descriptor is loaded. The P6 family, Pentium®, and Intel486™ processors, however, only set the accessed bit if it is not already set. Writes to descriptor tables in ROM can be avoided by setting the accessed bits in every descriptor.

3.5. SYSTEM DESCRIPTOR TYPES

When the S (descriptor type) flag in a segment descriptor is clear, the descriptor type is a system descriptor. The processor recognizes the following types of system descriptors:

- Local descriptor-table (LDT) segment descriptor.
- Task-state segment (TSS) descriptor.
- Call-gate descriptor.
- Interrupt-gate descriptor.
- Trap-gate descriptor.
- Task-gate descriptor.

These descriptor types fall into two categories: system-segment descriptors and gate descriptors. System-segment descriptors point to system segments (LDT and TSS segments). Gate descriptors are in themselves “gates,” which hold pointers to procedure entry points in code segments (call, interrupt, and trap gates) or which hold segment selectors for TSS’s (task gates). Table 3-2 shows the encoding of the type field for system-segment descriptors and gate descriptors.

Table 3-2. System-Segment and Gate-Descriptor Types

Type Field					Description
Decimal	11	10	9	8	
0	0	0	0	0	Reserved
1	0	0	0	1	16-Bit TSS (Available)
2	0	0	1	0	LDT
3	0	0	1	1	16-Bit TSS (Busy)
4	0	1	0	0	16-Bit Call Gate
5	0	1	0	1	Task Gate
6	0	1	1	0	16-Bit Interrupt Gate
7	0	1	1	1	16-Bit Trap Gate
8	1	0	0	0	Reserved
9	1	0	0	1	32-Bit TSS (Available)
10	1	0	1	0	Reserved
11	1	0	1	1	32-Bit TSS (Busy)
12	1	1	0	0	32-Bit Call Gate
13	1	1	0	1	Reserved
14	1	1	1	0	32-Bit Interrupt Gate
15	1	1	1	1	32-Bit Trap Gate

For more information on the system-segment descriptors, refer to Section 3.5.1., “Segment Descriptor Tables”, and Section 6.2.2., “TSS Descriptor” in Chapter 6, *Task Management*. For more information on the gate descriptors, refer to Section 4.8.2., “Gate Descriptors” in Chapter 4, *Protection*; Section 5.9., “IDT Descriptors” in Chapter 5, *Interrupt and Exception Handling*; and Section 6.2.4., “Task-Gate Descriptor” in Chapter 6, *Task Management*.

3.5.1. Segment Descriptor Tables

A segment descriptor table is an array of segment descriptors (refer to Figure 3-10). A descriptor table is variable in length and can contain up to 8192 (2^{13}) 8-byte descriptors. There are two kinds of descriptor tables:

- The global descriptor table (GDT)
- The local descriptor tables (LDT)

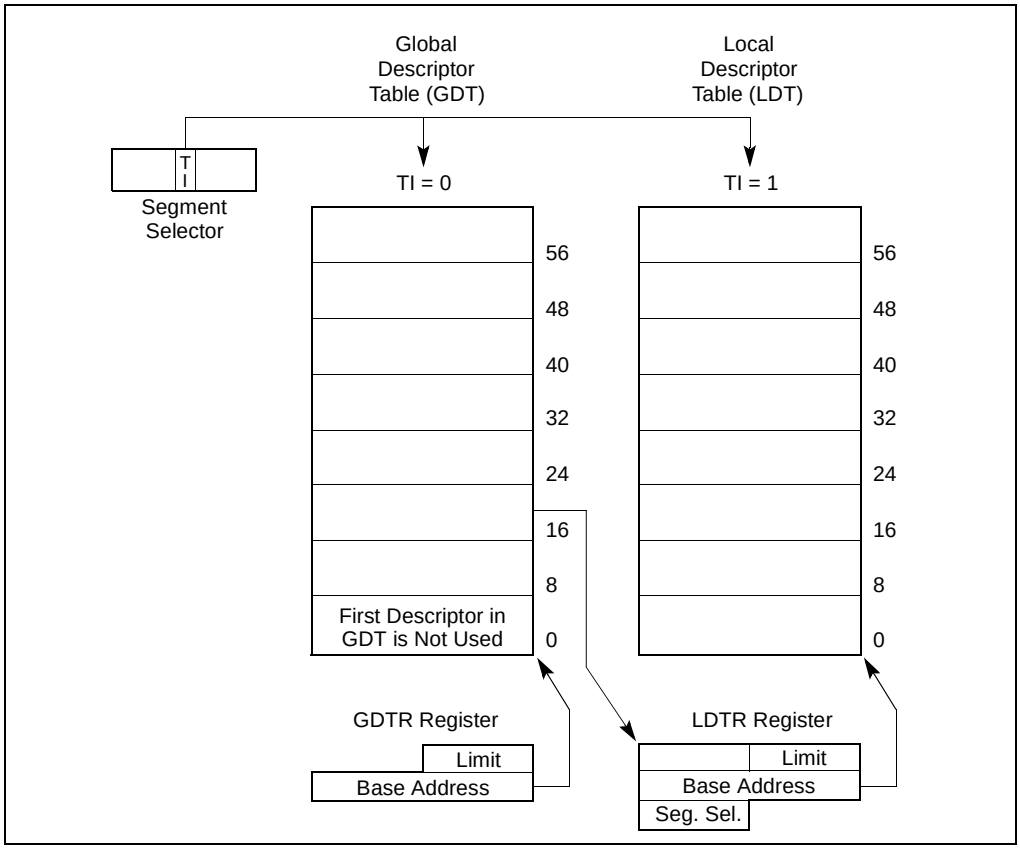


Figure 3-10. Global and Local Descriptor Tables

Each system must have one GDT defined, which may be used for all programs and tasks in the system. Optionally, one or more LDTs can be defined. For example, an LDT can be defined for each separate task being run, or some or all tasks can share the same LDT.

The GDT is not a segment itself; instead, it is a data structure in the linear address space. The base linear address and limit of the GDT must be loaded into the GDTR register (refer to Section 2.4., "Memory-Management Registers" in Chapter 2, *System Architecture Overview*). The base addresses of the GDT should be aligned on an eight-byte boundary to yield the best processor performance. The limit value for the GDT is expressed in bytes. As with segments, the limit value is added to the base address to get the address of the last valid byte. A limit value of 0 results in exactly one valid byte. Because segment descriptors are always 8 bytes long, the GDT limit should always be one less than an integral multiple of eight (that is, 8N – 1).

The first descriptor in the GDT is not used by the processor. A segment selector to this "null descriptor" does not generate an exception when loaded into a data-segment register (DS, ES, FS, or GS), but it always generates a general-protection exception (#GP) when an attempt is

made to access memory using the descriptor. By initializing the segment registers with this segment selector, accidental reference to unused segment registers can be guaranteed to generate an exception.

The LDT is located in a system segment of the LDT type. The GDT must contain a segment descriptor for the LDT segment. If the system supports multiple LDTs, each must have a separate segment selector and segment descriptor in the GDT. The segment descriptor for an LDT can be located anywhere in the GDT. Refer to Section 3.5., "System Descriptor Types" for information on the LDT segment-descriptor type.

An LDT is accessed with its segment selector. To eliminate address translations when accessing the LDT, the segment selector, base linear address, limit, and access rights of the LDT are stored in the LDTR register (refer to Section 2.4., "Memory-Management Registers" in Chapter 2, *System Architecture Overview*).

When the GDTR register is stored (using the SGDT instruction), a 48-bit "pseudo-descriptor" is stored in memory (refer to Figure 3-11). To avoid alignment check faults in user mode (privilege level 3), the pseudo-descriptor should be located at an odd word address (that is, address MOD 4 is equal to 2). This causes the processor to store an aligned word, followed by an aligned doubleword. User-mode programs normally do not store pseudo-descriptors, but the possibility of generating an alignment check fault can be avoided by aligning pseudo-descriptors in this way. The same alignment should be used when storing the IDTR register using the SIDT instruction. When storing the LDTR or task register (using the SLTR or STR instruction, respectively), the pseudo-descriptor should be located at a doubleword address (that is, address MOD 4 is equal to 0).

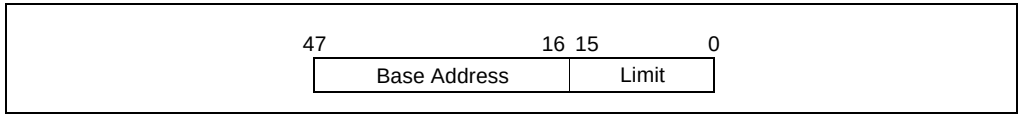


Figure 3-11. Pseudo-Descriptor Format

3.6. PAGING (VIRTUAL MEMORY)

When operating in protected mode, the Intel Architecture permits the linear address space to be mapped directly into a large physical memory (for example, 4 GBytes of RAM) or indirectly (using paging) into a smaller physical memory and disk storage. This latter method of mapping the linear address space is commonly referred to as virtual memory or demand-paged virtual memory.

When paging is used, the processor divides the linear address space into fixed-size pages (generally 4 KBytes in length) that can be mapped into physical memory and/or disk storage. When a program (or task) references a logical address in memory, the processor translates the address into a linear address and then uses its paging mechanism to translate the linear address into a corresponding physical address. If the page containing the linear address is not currently in physical memory, the processor generates a page-fault exception (#PF). The exception handler for the page-fault exception typically directs the operating system or executive to load the page from disk storage into physical memory (perhaps writing a different page from physical memory

out to disk in the process). When the page has been loaded in physical memory, a return from the exception handler causes the instruction that generated the exception to be restarted. The information that the processor uses to map linear addresses into the physical address space and to generate page-fault exceptions (when necessary) is contained in page directories and page tables stored in memory.

Paging is different from segmentation through its use of fixed-size pages. Unlike segments, which usually are the same size as the code or data structures they hold, pages have a fixed size. If segmentation is the only form of address translation used, a data structure present in physical memory will have all of its parts in memory. If paging is used, a data structure can be partly in memory and partly in disk storage.

To minimize the number of bus cycles required for address translation, the most recently accessed page-directory and page-table entries are cached in the processor in devices called translation lookaside buffers (TLBs). The TLBs satisfy most requests for reading the current page directory and page tables without requiring a bus cycle. Extra bus cycles occur only when the TLBs do not contain a page-table entry, which typically happens when a page has not been accessed for a long time. Refer to Section 3.7., “Translation Lookaside Buffers (TLBs)” for more information on the TLBs.

3.6.1. Paging Options

Paging is controlled by three flags in the processor’s control registers:

- PG (paging) flag, bit 31 of CR0 (available in all Intel Architecture processors beginning with the Intel386™ processor).
- PSE (page size extensions) flag, bit 4 of CR4 (introduced in the Pentium® and Pentium® Pro processors).
- PAE (physical address extension) flag, bit 5 of CR4 (introduced in the Pentium® Pro processors).

The PG flag enables the page-translation mechanism. The operating system or executive usually sets this flag during processor initialization. The PG flag must be set if the processor’s page-translation mechanism is to be used to implement a demand-paged virtual memory system or if the operating system is designed to run more than one program (or task) in virtual-8086 mode.

The PSE flag enables large page sizes: 4-MByte pages or 2-MByte pages (when the PAE flag is set). When the PSE flag is clear, the more common page length of 4 KBytes is used. Refer to Chapter 3.6.2.2., *Linear Address Translation (4-MByte Pages)* and Section 3.8.2., “Linear Address Translation With Extended Addressing Enabled (2-MByte or 4-MByte Pages)” for more information about the use of the PSE flag.

The PAE flag enables 36-bit physical addresses. This physical address extension can only be used when paging is enabled. It relies on page directories and page tables to reference physical addresses above FFFFFFFFH. Refer to Section 3.8., “Physical Address Extension” for more information about the physical address extension.

3.6.2. Page Tables and Directories

The information that the processor uses to translate linear addresses into physical addresses (when paging is enabled) is contained in four data structures:

- Page directory—An array of 32-bit page-directory entries (PDEs) contained in a 4-KByte page. Up to 1024 page-directory entries can be held in a page directory.
- Page table—An array of 32-bit page-table entries (PTEs) contained in a 4-KByte page. Up to 1024 page-table entries can be held in a page table. (Page tables are not used for 2-MByte or 4-MByte pages. These page sizes are mapped directly from one or more page-directory entries.)
- Page—A 4-KByte, 2-MByte, or 4-MByte flat address space.
- Page-Directory-Pointer Table—An array of four 64-bit entries, each of which points to a page directory. This data structure is only used when the physical address extension is enabled (refer to Section 3.8., “Physical Address Extension”).

These tables provide access to either 4-KByte or 4-MByte pages when normal 32-bit physical addressing is being used and to either 4-KByte, 2-MByte, or 4-MByte pages when extended (36-bit) physical addressing is being used. Table 3-3 shows the page size and physical address size obtained from various settings of the paging control flags. Each page-directory entry contains a PS (page size) flag that specifies whether the entry points to a page table whose entries in turn point to 4-KByte pages (PS set to 0) or whether the page-directory entry points directly to a 4-MByte or 2-MByte page (PSE or PAE set to 1 and PS set to 1).

Table 3-3. Page Sizes and Physical Address Sizes

PG Flag, CR0	PAE Flag, CR4	PSE Flag, CR4	PS Flag, PDE	Page Size	Physical Address Size
0	X	X	X	—	Paging Disabled
1	0	0	X	4 KBytes	32 Bits
1	0	1	0	4 KBytes	32 Bits
1	0	1	1	4 MBytes	32 Bits
1	1	X	0	4 KBytes	36 Bits
1	1	X	1	2 MBytes	36 Bits

3.6.2.1. LINEAR ADDRESS TRANSLATION (4-KBYTE PAGES)

Figure 3-12 shows the page directory and page-table hierarchy when mapping linear addresses to 4-KByte pages. The entries in the page directory point to page tables, and the entries in a page table point to pages in physical memory. This paging method can be used to address up to 2^{20} pages, which spans a linear address space of 2^{32} bytes (4 GBytes).

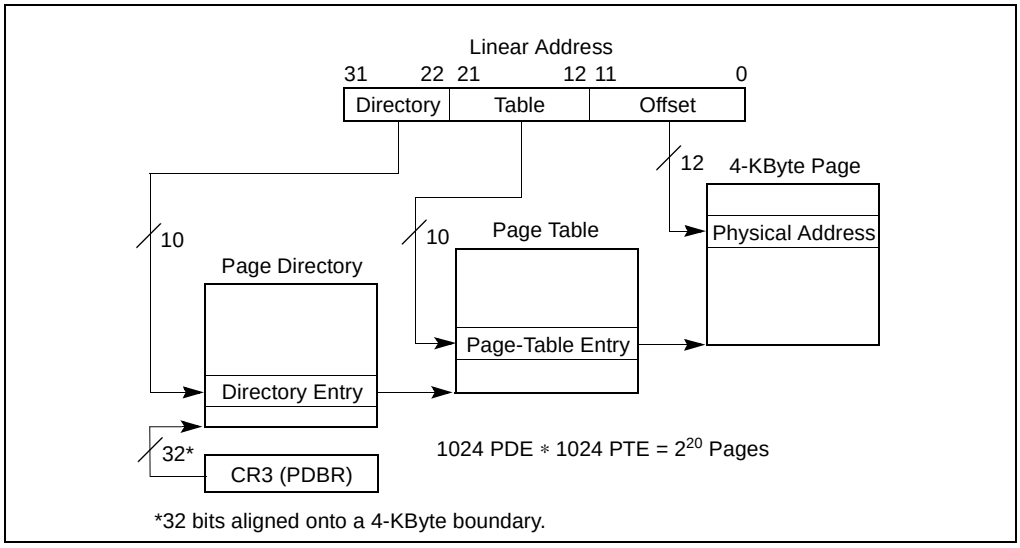


Figure 3-12. Linear Address Translation (4-KByte Pages)

To select the various table entries, the linear address is divided into three sections:

- Page-directory entry—Bits 22 through 31 provide an offset to an entry in the page directory. The selected entry provides the base physical address of a page table.
- Page-table entry—Bits 12 through 21 of the linear address provide an offset to an entry in the selected page table. This entry provides the base physical address of a page in physical memory.
- Page offset—Bits 0 through 11 provides an offset to a physical address in the page.

Memory management software has the option of using one page directory for all programs and tasks, one page directory for each task, or some combination of the two.

3.6.2.2. LINEAR ADDRESS TRANSLATION (4-MBYTE PAGES)

Figure 3-12 shows how a page directory can be used to map linear addresses to 4-MByte pages. The entries in the page directory point to 4-MByte pages in physical memory. This paging method can be used to map up to 1024 pages into a 4-GByte linear address space.

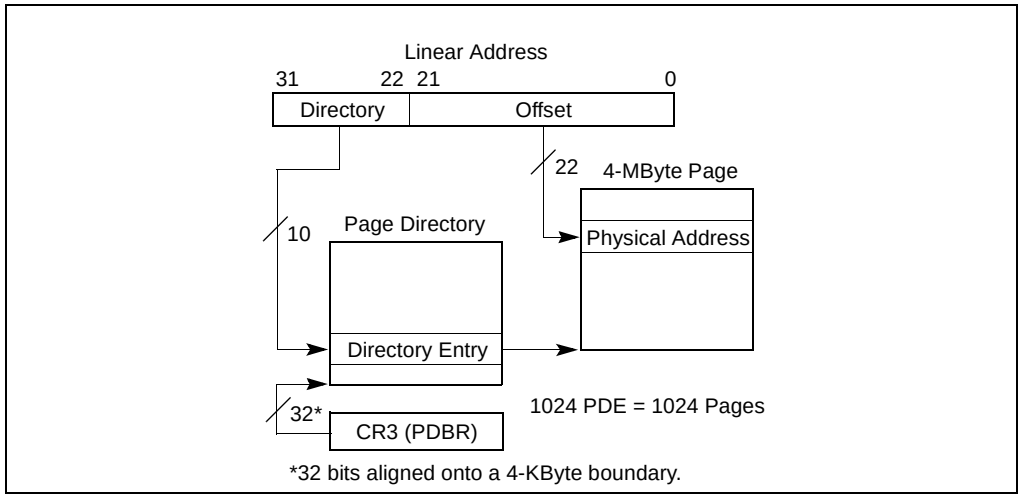


Figure 3-13. Linear Address Translation (4-MByte Pages)

The 4-MByte page size is selected by setting the PSE flag in control register CR4 and setting the page size (PS) flag in a page-directory entry (refer to Figure 3-14). With these flags set, the linear address is divided into two sections:

- Page directory entry—Bits 22 through 31 provide an offset to an entry in the page directory. The selected entry provides the base physical address of a 4-MByte page.
- Page offset—Bits 0 through 21 provides an offset to a physical address in the page.

NOTE

(For the Pentium® processor only.) When enabling or disabling large page sizes, the TLBs must be invalidated (flushed) after the PSE flag in control register CR4 has been set or cleared. Otherwise, incorrect page translation might occur due to the processor using outdated page translation information stored in the TLBs. Refer to Section 9.10., "Invalidating the Translation Lookaside Buffers (TLBs)", in Chapter 9, *Memory Cache Control*, for information on how to invalidate the TLBs.

3.6.2.3. MIXING 4-KBYTE AND 4-MBYTE PAGES

When the PSE flag in CR4 is set, both 4-MByte pages and page tables for 4-KByte pages can be accessed from the same page directory. If the PSE flag is clear, only page tables for 4-KByte pages can be accessed (regardless of the setting of the PS flag in a page-directory entry).

A typical example of mixing 4-KByte and 4-MByte pages is to place the operating system or executive's kernel in a large page to reduce TLB misses and thus improve overall system performance. The processor maintains 4-MByte page entries and 4-KByte page entries in separate

TLBs. So, placing often used code such as the kernel in a large page, frees up 4-KByte-page TLB entries for application programs and tasks.

3.6.3. Base Address of the Page Directory

The physical address of the current page directory is stored in the CR3 register (also called the page directory base register or PDBR). (Refer to Figure 2-5 and Section 2.5., “Control Registers” in Chapter 2, *System Architecture Overview* for more information on the PDBR.) If paging is to be used, the PDBR must be loaded as part of the processor initialization process (prior to enabling paging). The PDBR can then be changed either explicitly by loading a new value in CR3 with a MOV instruction or implicitly as part of a task switch. (Refer to Section 6.2.1., “Task-State Segment (TSS)” in Chapter 6, *Task Management* for a description of how the contents of the CR3 register is set for a task.)

There is no present flag in the PDBR for the page directory. The page directory may be not-present (paged out of physical memory) while its associated task is suspended, but the operating system must ensure that the page directory indicated by the PDBR image in a task's TSS is present in physical memory before the task is dispatched. The page directory must also remain in memory as long as the task is active.

3.6.4. Page-Directory and Page-Table Entries

Figure 3-14 shows the format for the page-directory and page-table entries when 4-KByte pages and 32-bit physical addresses are being used. Figure 3-14 shows the format for the page-directory entries when 4-MByte pages and 32-bit physical addresses are being used. Refer to Section 3.8., “Physical Address Extension” for the format of page-directory and page-table entries when the physical address extension is being used.

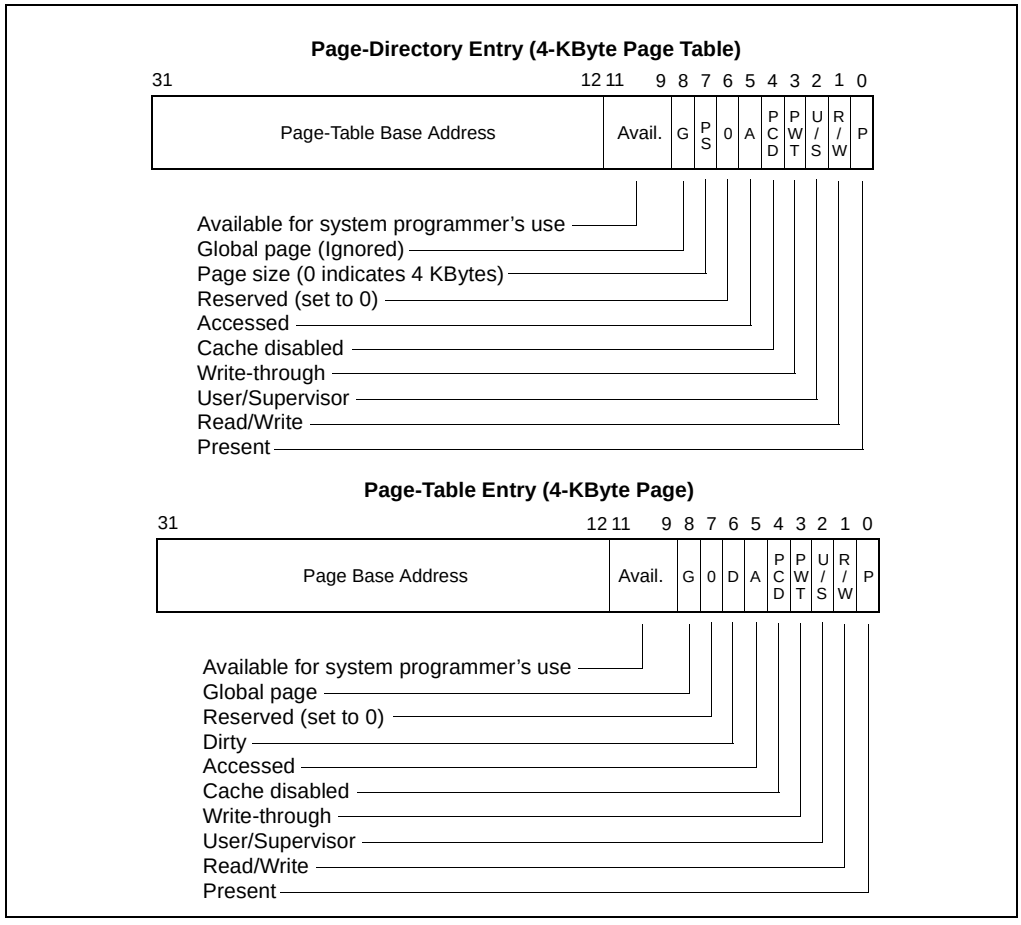


Figure 3-14. Format of Page-Directory and Page-Table Entries for 4-KByte Pages and 32-Bit Physical Addresses

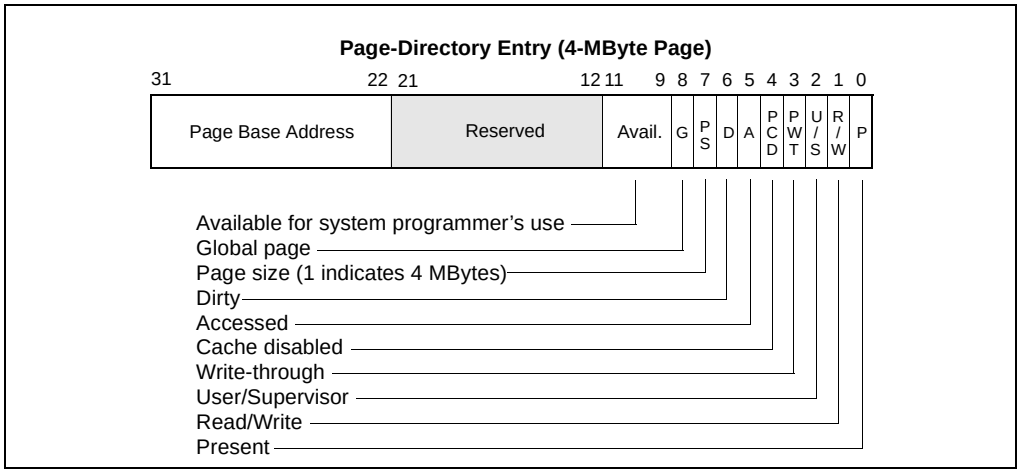


Figure 3-15. Format of Page-Directory Entries for 4-MByte Pages and 32-Bit Addresses

The functions of the flags and fields in the entries in Figures 3-14 and 3-15 are as follows:

Page base address, bits 12 through 32

(Page-table entries for 4-KByte pages.) Specifies the physical address of the first byte of a 4-KByte page. The bits in this field are interpreted as the 20 most-significant bits of the physical address, which forces pages to be aligned on 4-KByte boundaries.

(Page-directory entries for 4-KByte page tables.) Specifies the physical address of the first byte of a page table. The bits in this field are interpreted as the 20 most-significant bits of the physical address, which forces page tables to be aligned on 4-KByte boundaries.

(Page-directory entries for 4-MByte pages.) Specifies the physical address of the first byte of a 4-MByte page. Only bits 22 through 31 of this field are used (and bits 12 through 21 are reserved and must be set to 0, for Intel Architecture processors through the Pentium® II processor). The base address bits are interpreted as the 10 most-significant bits of the physical address, which forces 4-MByte pages to be aligned on 4-MByte boundaries.

Present (P) flag, bit 0

Indicates whether the page or page table being pointed to by the entry is currently loaded in physical memory. When the flag is set, the page is in physical memory and address translation is carried out. When the flag is clear, the page is not in memory and, if the processor attempts to access the page, it generates a page-fault exception (#PF).

The processor does not set or clear this flag; it is up to the operating system or executive to maintain the state of the flag.

The bit must be set to 1 whenever extended physical addressing mode is enabled.

If the processor generates a page-fault exception, the operating system must carry out the following operations in the order below:

1. Copy the page from disk storage into physical memory, if needed.
2. Load the page address into the page-table or page-directory entry and set its present flag. Other bits, such as the dirty and accessed flags, may also be set at this time.
3. Invalidate the current page-table entry in the TLB (refer to Section 3.7., "Translation Lookaside Buffers (TLBs)" for a discussion of TLBs and how to invalidate them).
4. Return from the page-fault handler to restart the interrupted program or task.

Read/write (R/W) flag, bit 1

Specifies the read-write privileges for a page or group of pages (in the case of a page-directory entry that points to a page table). When this flag is clear, the page is read only; when the flag is set, the page can be read and written into. This flag interacts with the U/S flag and the WP flag in register CR0. Refer to Section 4.11., "Page-Level Protection" and Table 4-2 in Chapter 4, *Protection* for a detailed discussion of the use of these flags.

User/supervisor (U/S) flag, bit 2

Specifies the user-supervisor privileges for a page or group of pages (in the case of a page-directory entry that points to a page table). When this flag is clear, the page is assigned the supervisor privilege level; when the flag is set, the page is assigned the user privilege level. This flag interacts with the R/W flag and the WP flag in register CR0. Refer to Section 4.11., "Page-Level Protection" and Table 4-2 in Chapter 4, *Protection* for a detail discussion of the use of these flags.

Page-level write-through (PWT) flag, bit 3

Controls the write-through or write-back caching policy of individual pages or page tables. When the PWT flag is set, write-through caching is enabled for the associated page or page table; when the flag is clear, write-back caching is enabled for the associated page or page table. The processor ignores this flag if the CD (cache disable) flag in CR0 is set. Refer to Section 9.5., "Cache Control", in Chapter 9, *Memory Cache Control*, for more information about the use of this flag. Refer to Section 2.5., "Control Registers" in Chapter 2, *System Architecture Overview* for a description of a companion PWT flag in control register CR3.

Page-level cache disable (PCD) flag, bit 4

Controls the caching of individual pages or page tables. When the PCD flag is set, caching of the associated page or page table is prevented; when the flag is clear, the page or page table can be cached. This flag permits caching to be

disabled for pages that contain memory-mapped I/O ports or that do not provide a performance benefit when cached. The processor ignores this flag (assumes it is set) if the CD (cache disable) flag in CR0 is set. Refer to Chapter 9, *Memory Cache Control*, for more information about the use of this flag. Refer to Section 2.5. in Chapter 2, *System Architecture Overview* for a description of a companion PCD flag in control register CR3.

Accessed (A) flag, bit 5

Indicates whether a page or page table has been accessed (read from or written to) when set. Memory management software typically clears this flag when a page or page table is initially loaded into physical memory. The processor then sets this flag the first time a page or page table is accessed. This flag is a "sticky" flag, meaning that once set, the processor does not implicitly clear it. Only software can clear this flag. The accessed and dirty flags are provided for use by memory management software to manage the transfer of pages and page tables into and out of physical memory.

Dirty (D) flag, bit 6

Indicates whether a page has been written to when set. (This flag is not used in page-directory entries that point to page tables.) Memory management software typically clears this flag when a page is initially loaded into physical memory. The processor then sets this flag the first time a page is accessed for a write operation. This flag is "sticky," meaning that once set, the processor does not implicitly clear it. Only software can clear this flag. The dirty and accessed flags are provided for use by memory management software to manage the transfer of pages and page tables into and out of physical memory.

Page size (PS) flag, bit 7

Determines the page size. This flag is only used in page-directory entries. When this flag is clear, the page size is 4 KBytes and the page-directory entry points to a page table. When the flag is set, the page size is 4 MBytes for normal 32-bit addressing (and 2 MBytes if extended physical addressing is enabled) and the page-directory entry points to a page. If the page-directory entry points to a page table, all the pages associated with that page table will be 4-KByte pages.

Global (G) flag, bit 8

(Introduced in the Pentium® Pro processor.) Indicates a global page when set. When a page is marked global and the page global enable (PGE) flag in register CR4 is set, the page-table or page-directory entry for the page is not invalidated in the TLB when register CR3 is loaded or a task switch occurs. This flag is provided to prevent frequently used pages (such as pages that contain kernel or other operating system or executive code) from being flushed from the TLB. Only software can set or clear this flag. For page-directory entries that point to page tables, this flag is ignored and the global characteristics of a page are set in the page-table entries. Refer to Section 3.7., "Translation Lookaside Buffers (TLBs)" for more information about the use of this flag. (This bit is reserved in Pentium® and earlier Intel Architecture processors.)

Reserved and available-to-software bits

In a page-table entry, bit 7 is reserved and should be set to 0; in a page-directory entry that points to a page table, bit 6 is reserved and should be set to 0. For a page-directory entry for a 4-MByte page, bits 12 through 21 are reserved and must be set to 0, for Intel Architecture processors through the Pentium® II processor. For both types of entries, bits 9, 10, and 11 are available for use by software. (When the present bit is clear, bits 1 through 31 are available to software—refer to Figure 3-16.) When the PSE and PAE flags in control register CR4 are set, the processor generates a page fault if reserved bits are not set to 0.

3.6.5. Not Present Page-Directory and Page-Table Entries

When the present flag is clear for a page-table or page-directory entry, the operating system or executive may use the rest of the entry for storage of information such as the location of the page in the disk storage system (refer to).

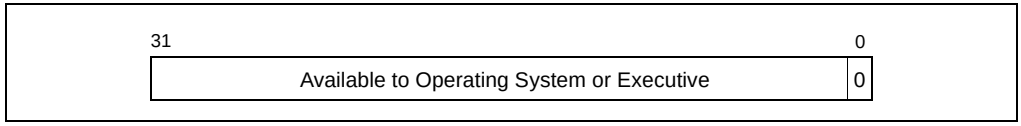


Figure 3-16. Format of a Page-Table or Page-Directory Entry for a Not-Present Page

3.7. TRANSLATION LOOKASIDE BUFFERS (TLBS)

The processor stores the most recently used page-directory and page-table entries in on-chip caches called translation lookaside buffers or TLBs. The P6 family and Pentium® processors have separate TLBs for the data and instruction caches. Also, the P6 family processors maintain separate TLBs for 4-KByte and 4-MByte page sizes. The CPUID instruction can be used to determine the sizes of the TLBs provided in the P6 family and Pentium® processors.

Most paging is performed using the contents of the TLBs. Bus cycles to the page directory and page tables in memory are performed only when the TLBs do not contain the translation information for a requested page.

The TLBs are inaccessible to application programs and tasks (privilege level greater than 0); that is, they cannot invalidate TLBs. Only operating system or executive procedures running at privilege level of 0 can invalidate TLBs or selected TBL entries. Whenever a page-directory or page-table entry is changed (including when the present flag is set to zero), the operating-system must immediately invalidate the corresponding entry in the TLB so that it can be updated the next time the entry is referenced. However, if the physical address extension (PAE) feature is enabled to use 36-bit addressing, a new table is added to the paging hierarchy. This new table is called the page directory pointer table (as described in Section 3.8., “Physical Address Extension”). If an entry is changed in this table (to point to another page directory), the TLBs must then be flushed by writing to CR3.

All (nonglobal) TLBs are automatically invalidated any time the CR3 register is loaded (unless the G flag for a page or page-table entry is set, as describe later in this section). The CR3 register can be loaded in either of two ways:

- Explicitly, using the MOV instruction, for example:

  ```
  MOV CR3, EAX
  ```

  where the EAX register contains an appropriate page-directory base address.

- Implicitly by executing a task switch, which automatically changes the contents of the CR3 register.

The INVLPG instruction is provided to invalidate a specific page-table entry in the TLB. Normally, this instruction invalidates only an individual TLB entry; however, in some cases, it may invalidate more than the selected entry and may even invalidate all of the TLBs. This instruction ignores the setting of the G flag in a page-directory or page-table entry (refer to the following paragraph).

(Introduced in the Pentium® Pro processor.) The page global enable (PGE) flag in register CR4 and the global (G) flag of a page-directory or page-table entry (bit 8) can be used to prevent frequently used pages from being automatically invalidated in the TLBs on a task switch or a load of register CR3. (Refer to Section 3.6.4., “Page-Directory and Page-Table Entries” for more information about the global flag.) When the processor loads a page-directory or page-table entry for a global page into a TLB, the entry will remain in the TLB indefinitely. The only way to deterministically invalidate global page entries is to clear the PGE flag and then invalidate the TLBs or to use the INVLPG instruction to invalidate individual page-directory or page-table entries in the TLBs.

For additional information about invalidation of the TLBs, refer to Section 9.10., “Invalidating the Translation Lookaside Buffers (TLBs)”, in Chapter 9, *Memory Cache Control*.

3.8. PHYSICAL ADDRESS EXTENSION

The physical address extension (PAE) flag in register CR4 enables an extension of physical addresses from 32 bits to 36 bits. (This feature was introduced into the Intel Architecture in the Pentium® Pro processors.) Here, the processor provides 4 additional address line pins to accommodate the additional address bits. This option can only be used when paging is enabled (that is, when both the PG flag in register CR0 and the PAE flag in register CR4 are set).

When the physical address extension is enabled, the processor allows several sizes of pages: 4-KByte, 2-MByte, or 4-MByte. As with 32-bit addressing, these page sizes can be addressed within the same set of paging tables (that is, a page-directory entry can point to either a 2-MByte or 4-MByte page or a page table that in turn points to 4-KByte pages). To support the 36-bit physical addresses, the following changes are made to the paging data structures:

- The paging table entries are increased to 64 bits to accommodate 36-bit base physical addresses. Each 4-KByte page directory and page table can thus have up to 512 entries.

- A new table, called the page-directory-pointer table, is added to the linear-address translation hierarchy. This table has 4 entries of 64-bits each, and it lies above the page directory in the hierarchy. With the physical address extension mechanism enabled, the processor supports up to 4 page directories.
- The 20-bit page-directory base address field in register CR3 (PDPR) is replaced with a 27-bit page-directory-pointer-table base address field (refer to Figure 3-17). (In this case, register CR3 is called the PDPTR.) This field provides the 27 most-significant bits of the physical address of the first byte of the page-directory-pointer table, which forces the table to be located on a 32-byte boundary.
- Linear address translation is changed to allow mapping 32-bit linear addresses into the larger physical address space.

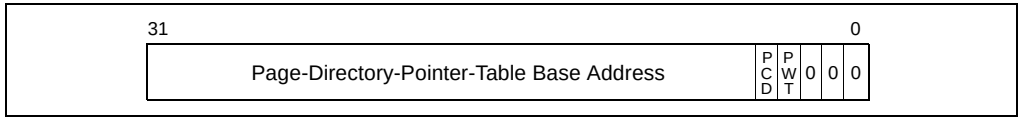


Figure 3-17. Register CR3 Format When the Physical Address Extension is Enabled

3.8.1. Linear Address Translation With Extended Addressing Enabled (4-KByte Pages)

Figure 3-12 shows the page-directory-pointer, page-directory, and page-table hierarchy when mapping linear addresses to 4-KByte pages with extended physical addressing enabled. This paging method can be used to address up to 2^{20} pages, which spans a linear address space of 2^{32} bytes (4 GBytes).

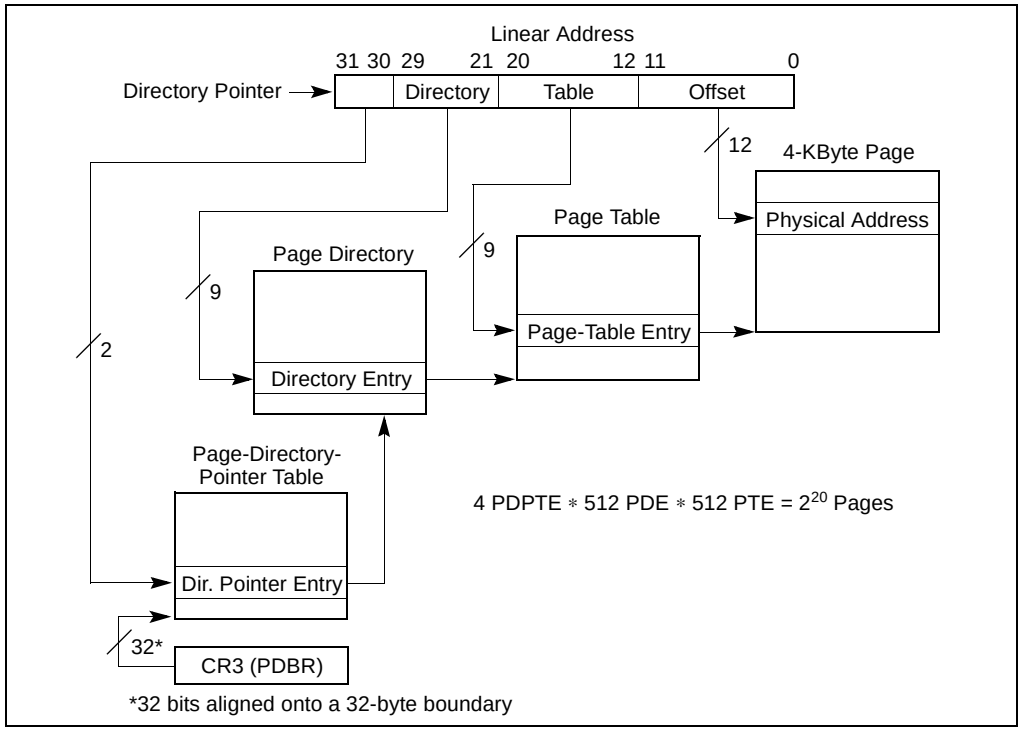


Figure 3-18. Linear Address Translation With Extended Physical Addressing Enabled (4-KByte Pages)

To select the various table entries, the linear address is divided into three sections:

- Page-directory-pointer-table entry—Bits 30 and 31 provide an offset to one of the 4 entries in the page-directory-pointer table. The selected entry provides the base physical address of a page directory.
- Page-directory entry—Bits 21 through 29 provide an offset to an entry in the selected page directory. The selected entry provides the base physical address of a page table.
- Page-table entry—Bits 12 through 20 provide an offset to an entry in the selected page table. This entry provides the base physical address of a page in physical memory.
- Page offset—Bits 0 through 11 provide an offset to a physical address in the page.

3.8.2. Linear Address Translation With Extended Addressing Enabled (2-MByte or 4-MByte Pages)

Figure 3-12 shows how a page-directory-pointer table and page directories can be used to map linear addresses to 2-MByte or 4-MByte pages. This paging method can be used to map up to 2048 pages (4 page-directory-pointer-table entries times 512 page-directory entries) into a 4-GByte linear address space.

The 2-MByte or 4-MByte page size is selected by setting the PSE flag in control register CR4 and setting the page size (PS) flag in a page-directory entry (refer to Figure 3-14). With these flags set, the linear address is divided into three sections:

- Page-directory-pointer-table entry—Bits 30 and 31 provide an offset to an entry in the page-directory-pointer table. The selected entry provides the base physical address of a page directory.
- Page-directory entry—Bits 21 through 29 provide an offset to an entry in the page directory. The selected entry provides the base physical address of a 2-MByte or 4-MByte page.
- Page offset—Bits 0 through 20 provides an offset to a physical address in the page.

3.8.3. Accessing the Full Extended Physical Address Space With the Extended Page-Table Structure

The page-table structure described in the previous two sections allows up to 4 GBytes of the 64-GByte extended physical address space to be addressed at one time. Additional 4-GByte sections of physical memory can be addressed in either of two way:

- Change the pointer in register CR3 to point to another page-directory-pointer table, which in turn points to another set of page directories and page tables.
- Change entries in the page-directory-pointer table to point to other page directories, which in turn point to other sets of page tables.

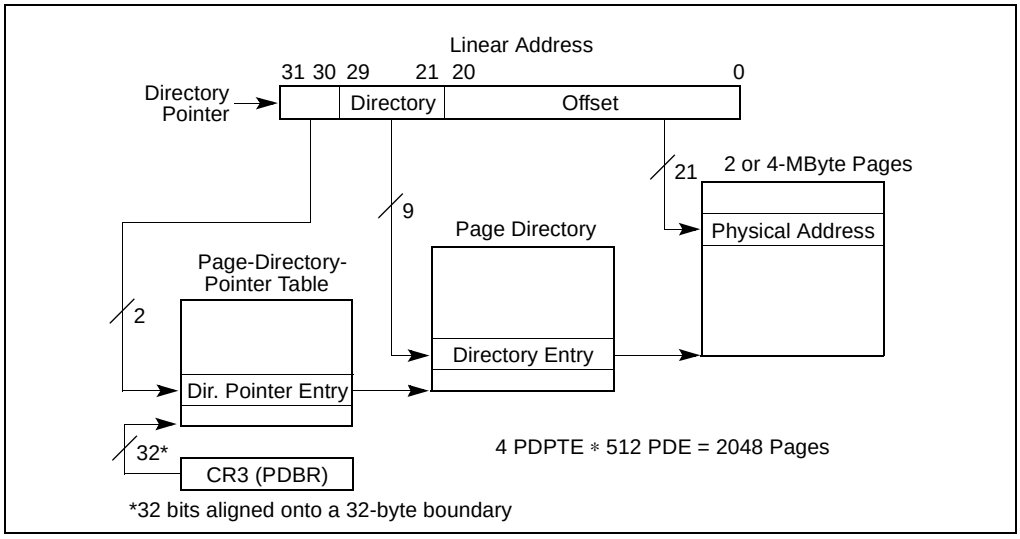


Figure 3-19. Linear Address Translation With Extended Physical Addressing Enabled (2-MByte or 4-MByte Pages)

3.8.4. Page-Directory and Page-Table Entries With Extended Addressing Enabled

Figure 3-20 shows the format for the page-directory-pointer-table, page-directory, and page-table entries when 4-KByte pages and 36-bit extended physical addresses are being used. Figure 3-21 shows the format for the page-directory-pointer-table and page-directory entries when 2-MByte or 4-MByte pages and 36-bit extended physical addresses are being used. The functions of the flags in these entries are the same as described in Section 3.6.4., "Page-Directory and Page-Table Entries". The major differences in these entries are as follows:

- A page-directory-pointer-table entry is added.
- The size of the entries are increased from 32 bits to 64 bits.
- The maximum number of entries in a page directory or page table is 512.
- The base physical address field in each entry is extended to 24 bits.

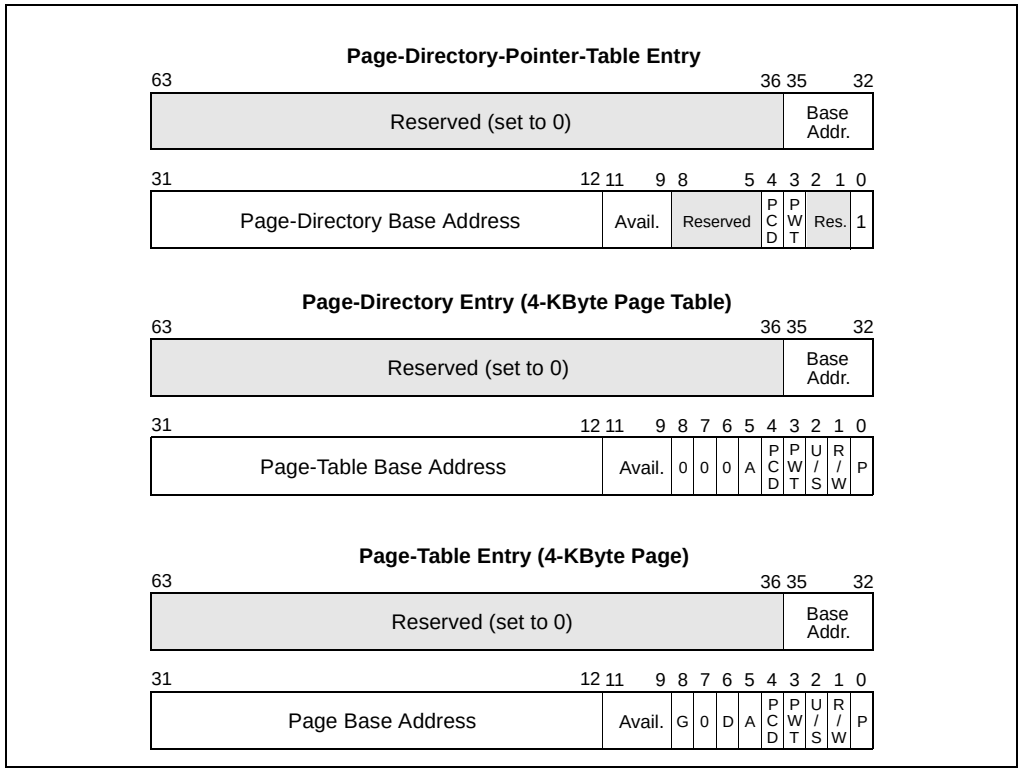


Figure 3-20. Format of Page-Directory-Pointer-Table, Page-Directory, and Page-Table Entries for 4-KByte Pages and 36-Bit Extended Physical Addresses

The base physical address in an entry specifies the following, depending on the type of entry:

- Page-directory-pointer-table entry—the physical address of the first byte of a 4-KByte page directory.
- Page-directory entry—the physical address of the first byte of a 4-KByte page table or a 2-MByte page.
- Page-table entry—the physical address of the first byte of a 4-KByte page.

For all table entries (except for page-directory entries that point to 2-MByte or 4-MByte pages), the bits in the page base address are interpreted as the 24 most-significant bits of a 36-bit physical address, which forces page tables and pages to be aligned on 4-KByte boundaries. When a page-directory entry points to a 2-MByte or 4-MByte page, the base address is interpreted as the 15 most-significant bits of a 36-bit physical address, which forces pages to be aligned on 2-MByte or 4-MByte boundaries.

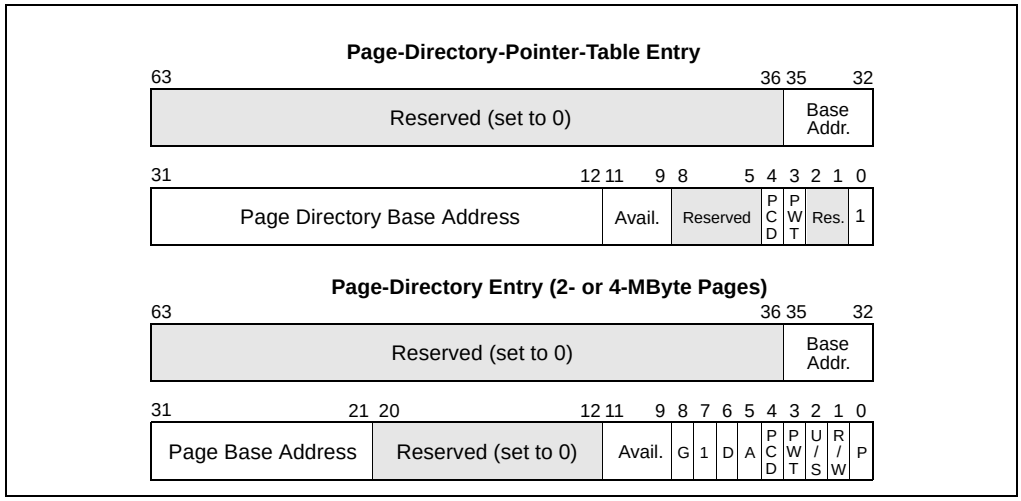


Figure 3-21. Format of Page-Directory-Pointer-Table and Page-Directory Entries for 2- or 4-MByte Pages and 36-Bit Extended Physical Addresses

The present (P) flag (bit 0) in all page-directory-pointer-table entries must be set to 1 anytime extended physical addressing mode is enabled; that is, whenever the PAE flag (bit 5 in register CR4) and the PG flag (bit 31 in register CR0) are set. If the P flag is not set in all 4 page-directory-pointer-table entries in the page-directory-pointer table when extended physical addressing is enabled, a general-protection exception (#GP) is generated.

The page size (PS) flag (bit 7) in a page-directory entry determines if the entry points to a page table or a 2-MByte or 4-MByte page. When this flag is clear, the entry points to a page table; when the flag is set, the entry points to a 2-MByte or 4-MByte page. This flag allows 4-KByte, 2-MByte, or 4-MByte pages to be mixed within one set of paging tables.

Access (A) and dirty (D) flags (bits 5 and 6) are provided for table entries that point to pages.

Bits 9, 10, and 11 in all the table entries for the physical address extension are available for use by software. (When the present flag is clear, bits 1 through 63 are available to software.) All bits in Figure 3-14 that are marked reserved or 0 should be set to 0 by software and not accessed by software. When the PSE and/or PAE flags in control register CR4 are set, the processor generates a page fault (#PF) if reserved bits in page-directory and page-table entries are not set to 0, and it generates a general-protection exception (#GP) if reserved bits in a page-directory-pointer-table entry are not set to 0.

3.9. 36-BIT PAGE SIZE EXTENSION (PSE)

The 36-bit PSE extends 36-bit physical address support to 4-MByte pages while maintaining a 4-byte page-directory entry. This approach provides a simple mechanism for operating system

vendors to address physical memory above 4-GBytes without requiring major design changes, but has practical limitations with respect to demand paging.

The P6 family of processors' physical address extension (PAE) feature provides generic access to a 36-bit physical address space. However, it requires expansion of the page-directory and page-table entries to an 8-byte format (64 bit), and the addition of a page-directory-pointer table, resulting in another level of indirection to address translation.

For P6-family processors that support the 36-bit PSE feature, the virtual memory architecture is extended to support 4-MByte page size granularity in combination with 36-bit physical addressing. Note that some P6-family processors do not support this feature. For information about determining a processor's feature support, refer to the following documents:

- AP-485, *Intel Processor Identification and the CPUID Instruction*
- Addendum—Intel Architecture Software Developer's Manual, Volume1: Basic Architecture

For information about the virtual memory architecture features of P6-family processors, refer to Chapter 3 of the *Intel Architecture Software Developer's Manual, Volume3: System Programming Guide*.

3.9.1. Description of the 36-bit PSE Feature

The 36-bit PSE feature (PSE-36) is detected by an operating system through the CPUID instruction. Specifically, the operating system executes the CPUID instruction with the value 1 in the EAX register and then determines support for the feature by inspecting bit 17 of the EDX register return value (see *Addendum—Intel Architecture Software Developer's Manual, Volume1: Basic Architecture*). If the PSE-36 feature is supported, an operating system is permitted to utilize the feature, as well as use certain formerly reserved bits. To use the 36-bit PSE feature, the PSE flag must be enabled by the operating system (bit 4 of CR4). Note that a separate control bit in CR 4 does not exist to regulate the use of 36-bit MByte pages, because this feature becomes the example for 4-MByte pages on processors that support it.

Table 3-8 shows the page size and physical address size obtained from various settings of the page-control flags for the P6-family processors that support the 36-bit PSE feature. Shaded in gray is the change to this table resulting from the 36-bit PSE feature.

Table 3-4. Paging Modes and Physical Address Size

PG Flag (in CR0)	PAE Flag (in CR4)	PSE Flag (in CR4)	PS Flag (in the PDE)	Page Size	Physical Address Size
0	X	X	X	—	Paging Disabled
1	0	0	X	4 KB	32 bits
1	0	1	0	4 KB	32 bits
1	**0**	**1**	**1**	**4 KB**	**36 bits**
1	1	X	0	4 KB	36 bits
1	1	X	1	2 KB	36 bits

To use the 36-bit PSE feature, the PAE feature must be cleared (as indicated in Table 3-4). However, the 36-bit PSE in no way affects the PAE feature. Existing operating systems and softwware that use the PAE will continue to have compatible functionality and features with P6-family processors that support 36-bit PSE. Specifically, the Page-Directory Entry (PDE) format when PAE is enabled for 2-MByte or 4-MByte pages is exactly as depicted in Figure 3-21 of the *Intel Architecture Software Developer's Manual, Volume3: System Programming Guide.*

No matter which 36-bit addressing feature is used (PAE or 36-bit PSE), the linear address space of the processor remains at 32 bits. Applications must partition the address space of their work loads across multiple operating system process to take advantage of the additonal physical memory provided in the system.

The 36-bit PSE feature estends the PDE format of the Intel Architecture for 4-MByte pages and 32-bit addresses by utilizing bits 16-13 (formerly reserved bits that were required to be zero) to extend the physical address without requiring an 8-byte page-directory entry. Therefore, with the 36-bit PSE feature, a page directory can contain up to 1024 entries, each pointing to a 4-MByte page that can exist anywhere in the 36-bit physical address space of the processor.

Figure 3-22 shows the difference between PDE formats for 4-MByte pages on P6-family processors that support the 36-bit PSE feature compared to P6-family processors that do not support the 36-bit PSE feature (i.e., 32-bit addressing).

Figure 3-22 also shows the linear address mapping to 4-MByte pages when the 36-bit PSE is enabled. The base physical address of the 4-MByte page is contained in the PDE. PA-2 (bits 13-16) is used to provide the upper four bits (bits 32-35) of the 36-bit physical address. PA-1 (bits 22-31) continues to provide the next ten bits (bits 22-31) of the physical address for the 4-MByte page. The offset into the page is provided by the lower 22 bits of the linear address. This scheme eliminates the second level of indirection caused by the use of 4-KByte page tables.

Page Directory Entry format for processors that support 36-bit addressing for 4-MByte pages

31 22	21 17	16 13	12	11 8	7	6 0
PA - 1	Reserved	PA - 2	PAT		PS=1	

Page Directory Entry format for processors that support 32-bit addressing for 4-MByte pages

31 22	21 12	11 8	7	6 0
Base Page Address	Reserved		PS=1	

Figure 3-22. PDE Format Differences between 36-bit and 32-bit addressing

Notes:

1. PA-2 = Bits 35-32 of thebase physical address for the 4-MByte page (correspond to bits 16-13)
2. PA-2 = Bits 31-22 of thebase physical address for the 4-MByte page
3. PAT = Bit 12 used as the Most Significant Bit of the index into Page Attribute Table (PAT); see Section 10.2.
4. PS = Bit 7 is the Page Size Bit—indicates 4-MByte page (must be set to 1)
5. Reserved = Bits 21-17 are reserved for future expansion
6. No change in format or meaning of bits 11-8 and 6-0; refer to Figure 3-15 for details.

The PSE-36 feature is transparent to existing operating systems that utilize 4-MByte pages, because unused bits in PA-2 are currently enforced as zero by Intel processors. The feature requires 4-MByte pages aligned on a 4-MByte boundary and 4 MBytes of physically contiguous memory. Therefore, the ten bits of PA-1 are sufficient to specify the base physical address of any 4-MByte page below 4 GBytes. An operating system can easily support addresses greater than 4 GBytes simply by providing the upper 4 bits of the physical address in PA-2 when creating a PDE for a 4-MByte page.

Figure 3-23 shows the linear address mapping to 4 MB pages when the 36-bit PSE is enabled. The base physical address of the 4 MB page is contained in the PDE. PA-2 (bits 13-16) is used to provide the upper four bits (bits 32-35) of the 36-bit physical address. PA-1 (bits 22-31) continues to provide the next ten bits (bits 22-31) of the physical address for the 4 MB page. The offset into the page is provided by the lower 22 bits of the linear address. This scheme eliminates the second level of indirection caused by the use of 4 KB page tables.

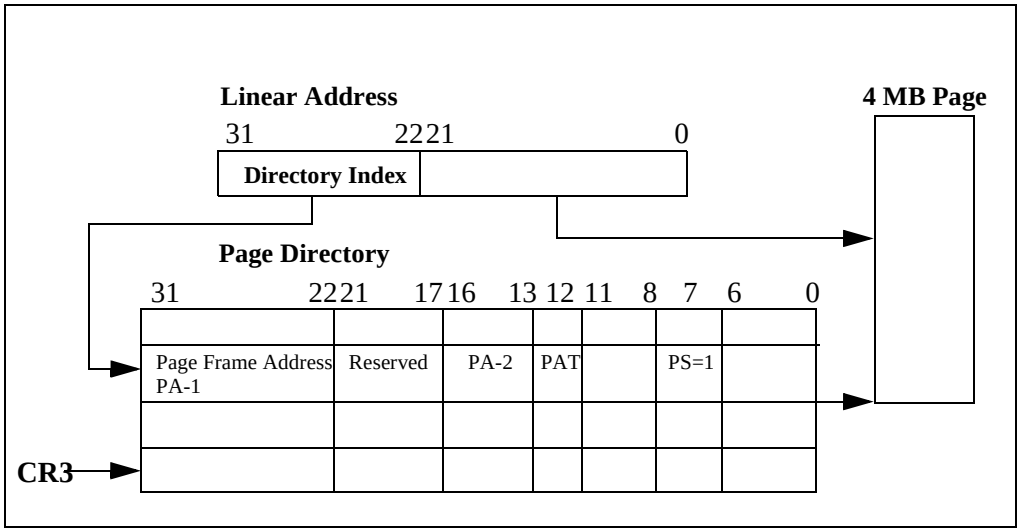


Figure 3-23. Page Size Extension Linear to Physical Translation

The PSE-36 feature is transparent to existing operating systems that utilize 4 MB pages because unused bits in PA-2 are currently enforced as zero by Intel processors. The feature requires 4 MB pages aligned on a 4 MB boundary and 4 MB of physically contiguous memory. Therefore, the ten bits of PA-1 are sufficient to specify the base physical address of any 4 MB page below 4GB. An operating system easily can support addresses greater than 4 GB simply by providing the upper 4 bits of the physical address in PA-2 when creating a PDE for a 4 MB page.

3.9.2. Fault Detection

There are several conditions that can cause P6-family processors that support this feature to generate a page fault (PF) fault. These conditions are related to the use of, or switching between, various memory management features:

- If the PSE feature is enabled, a nonzero value in any of the remaining reserved bits (17-21) of a 4-MByte PDE causes a page fault, with the reserved bit (bit 3) set in the error code.
- If the PAE feature is enabled and set to use 2-MByte or 4-MByte pages (that is, 8-byte page-directory table entries are being used), a nonzero value in any of the reserved bits 13-20 causes a page fault, with the reserved bit (bit 3) set in the error code. Note that bit 12 is now being used to support the Page Attribute Table feature (refer to Section 9.13., “Page Attribute Table (PAT)”).

3.10. MAPPING SEGMENTS TO PAGES

The segmentation and paging mechanisms provide in the Intel Architecture support a wide variety of approaches to memory management. When segmentation and paging is combined, segments can be mapped to pages in several ways. To implement a flat (unsegmented) addressing environment, for example, all the code, data, and stack modules can be mapped to one or more large segments (up to 4-GBytes) that share same range of linear addresses (refer to Figure 3-2). Here, segments are essentially invisible to applications and the operating-system or executive. If paging is used, the paging mechanism can map a single linear address space (contained in a single segment) into virtual memory. Or, each program (or task) can have its own large linear address space (contained in its own segment), which is mapped into virtual memory through its own page directory and set of page tables.

Segments can be smaller than the size of a page. If one of these segments is placed in a page which is not shared with another segment, the extra memory is wasted. For example, a small data structure, such as a 1-byte semaphore, occupies 4K bytes if it is placed in a page by itself. If many semaphores are used, it is more efficient to pack them into a single page.

The Intel Architecture does not enforce correspondence between the boundaries of pages and segments. A page can contain the end of one segment and the beginning of another. Likewise, a segment can contain the end of one page and the beginning of another.

Memory-management software may be simpler and more efficient if it enforces some alignment between page and segment boundaries. For example, if a segment which can fit in one page is placed in two pages, there may be twice as much paging overhead to support access to that segment.

One approach to combining paging and segmentation that simplifies memory-management software is to give each segment its own page table, as shown in Figure 3-24. This convention gives the segment a single entry in the page directory that provides the access control information for paging the entire segment.

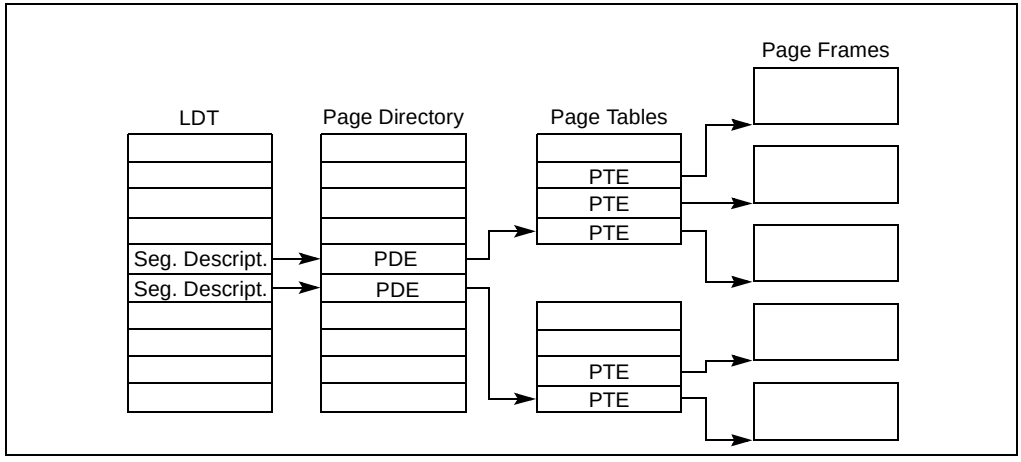


Figure 3-24. Memory Management Convention That Assigns a Page Table to Each Segment

4

Protection

CHAPTER 4
PROTECTION

In protected mode, the Intel Architecture provides a protection mechanism that operates at both the segment level and the page level. This protection mechanism provides the ability to limit access to certain segments or pages based on privilege levels (four privilege levels for segments and two privilege levels for pages). For example, critical operating-system code and data can be protected by placing them in more privileged segments than those that contain applications code. The processor's protection mechanism will then prevent application code from accessing the operating-system code and data in any but a controlled, defined manner.

Segment and page protection can be used at all stages of software development to assist in localizing and detecting design problems and bugs. It can also be incorporated into end-products to offer added robustness to operating systems, utilities software, and applications software.

When the protection mechanism is used, each memory reference is checked to verify that it satisfies various protection checks. All checks are made before the memory cycle is started; any violation results in an exception. Because checks are performed in parallel with address translation, there is no performance penalty. The protection checks that are performed fall into the following categories:

- Limit checks.
- Type checks.
- Privilege level checks.
- Restriction of addressable domain.
- Restriction of procedure entry-points.
- Restriction of instruction set.

All protection violation results in an exception being generated. Refer to Chapter 5, *Interrupt and Exception Handling* for an explanation of the exception mechanism. This chapter describes the protection mechanism and the violations which lead to exceptions.

The following sections describe the protection mechanism available in protected mode. Refer to Chapter 16, *8086 Emulation* for information on protection in real-address and virtual-8086 mode.

4.1. ENABLING AND DISABLING SEGMENT AND PAGE PROTECTION

Setting the PE flag in register CR0 causes the processor to switch to protected mode, which in turn enables the segment-protection mechanism. Once in protected mode, there is no control bit for turning the protection mechanism on or off. The part of the segment-protection mechanism that is based on privilege levels can essentially be disabled while still in protected mode by assigning a privilege level of 0 (most privileged) to all segment selectors and segment descriptors. This action disables the privilege level protection barriers between segments, but other protection checks such as limit checking and type checking are still carried out.

Page-level protection is automatically enabled when paging is enabled (by setting the PG flag in register CR0). Here again there is no mode bit for turning off page-level protection once paging is enabled. However, page-level protection can be disabled by performing the following operations:

- Clear the WP flag in control register CR0.
- Set the read/write (R/W) and user/supervisor (U/S) flags for each page-directory and page-table entry.

This action makes each page a writable, user page, which in effect disables page-level protection.

4.2. FIELDS AND FLAGS USED FOR SEGMENT-LEVEL AND PAGE-LEVEL PROTECTION

The processor's protection mechanism uses the following fields and flags in the system data structures to control access to segments and pages:

- Descriptor type (S) flag—(Bit 12 in the second doubleword of a segment descriptor.) Determines if the segment descriptor is for a system segment or a code or data segment.
- Type field—(Bits 8 through 11 in the second doubleword of a segment descriptor.) Determines the type of code, data, or system segment.
- Limit field—(Bits 0 through 15 of the first doubleword and bits 16 through 19 of the second doubleword of a segment descriptor.) Determines the size of the segment, along with the G flag and E flag (for data segments).
- G flag—(Bit 23 in the second doubleword of a segment descriptor.) Determines the size of the segment, along with the limit field and E flag (for data segments).
- E flag—(Bit 10 in the second doubleword of a data-segment descriptor.) Determines the size of the segment, along with the limit field and G flag.
- Descriptor privilege level (DPL) field—(Bits 13 and 14 in the second doubleword of a segment descriptor.) Determines the privilege level of the segment.
- Requested privilege level (RPL) field. (Bits 0 and 1 of any segment selector.) Specifies the requested privilege level of a segment selector.

- Current privilege level (CPL) field. (Bits 0 and 1 of the CS segment register.) Indicates the privilege level of the currently executing program or procedure. The term current privilege level (CPL) refers to the setting of this field.
- User/supervisor (U/S) flag. (Bit 2 of a page-directory or page-table entry.) Determines the type of page: user or supervisor.
- Read/write (R/W) flag. (Bit 1 of a page-directory or page-table entry.) Determines the type of access allowed to a page: read only or read-write.

Figure 4-1 shows the location of the various fields and flags in the data, code, and system-segment descriptors; Figure 3-6 in Chapter 3, *Protected-Mode Memory Management* shows the location of the RPL (or CPL) field in a segment selector (or the CS register); and Figure 3-14 in Chapter 3, *Protected-Mode Memory Management* shows the location of the U/S and R/W flags in the page-directory and page-table entries.

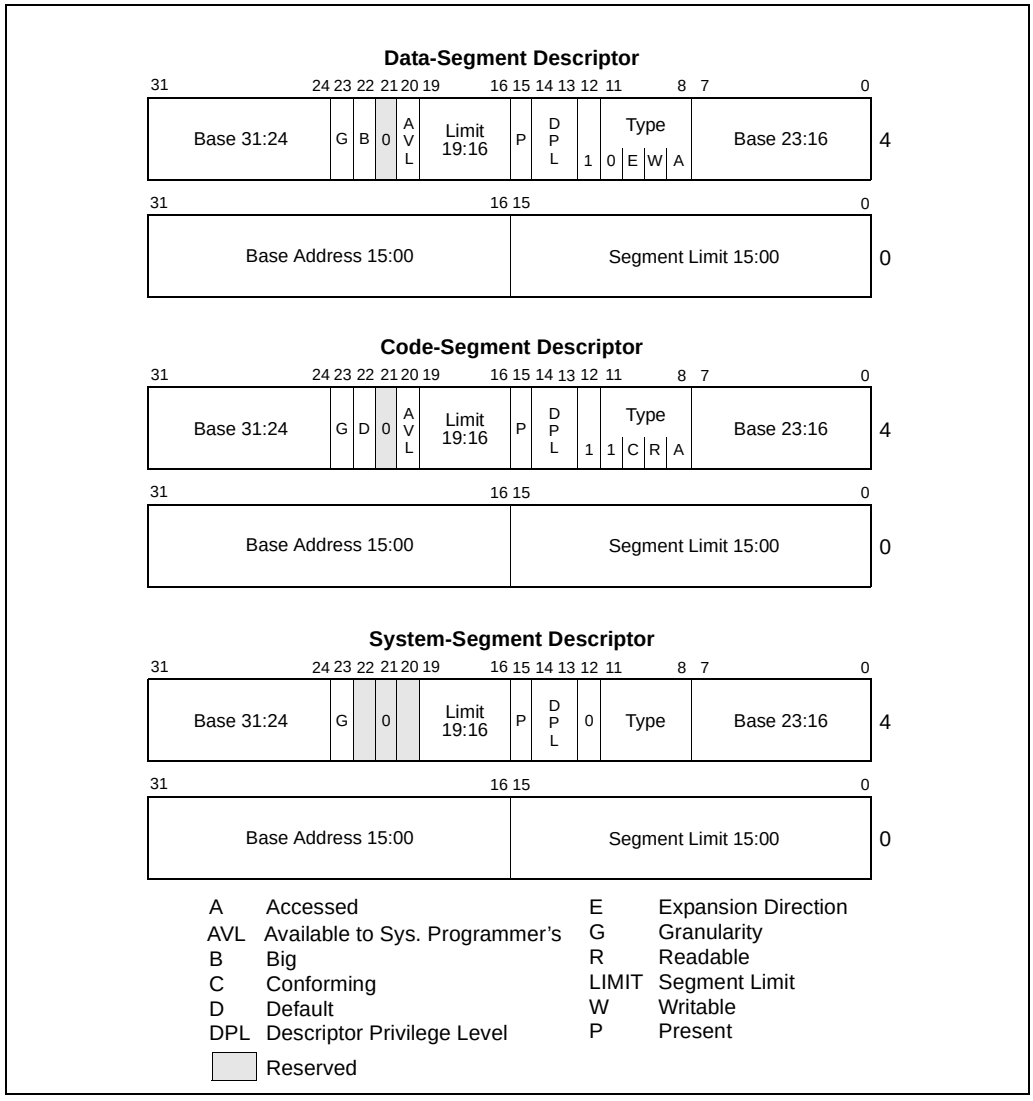


Figure 4-1. Descriptor Fields Used for Protection

Many different styles of protection schemes can be implemented with these fields and flags. When the operating system creates a descriptor, it places values in these fields and flags in keeping with the particular protection style chosen for an operating system or executive. Application program do not generally access or modify these fields and flags.

The following sections describe how the processor uses these fields and flags to perform the various categories of checks described in the introduction to this chapter.

4.3. LIMIT CHECKING

The limit field of a segment descriptor prevents programs or procedures from addressing memory locations outside the segment. The effective value of the limit depends on the setting of the G (granularity) flag (refer to Figure 4-1). For data segments, the limit also depends on the E (expansion direction) flag and the B (default stack pointer size and/or upper bound) flag. The E flag is one of the bits in the type field when the segment descriptor is for a data-segment type.

When the G flag is clear (byte granularity), the effective limit is the value of the 20-bit limit field in the segment descriptor. Here, the limit ranges from 0 to FFFFFH (1 MByte). When the G flag is set (4-KByte page granularity), the processor scales the value in the limit field by a factor of 2^12 (4 KBytes). In this case, the effective limit ranges from FFFH (4 KBytes) to FFFFFFFFH (4 GBytes). Note that when scaling is used (G flag is set), the lower 12 bits of a segment offset (address) are not checked against the limit; for example, note that if the segment limit is 0, offsets 0 through FFFH are still valid.

For all types of segments except expand-down data segments, the effective limit is the last address that is allowed to be accessed in the segment, which is one less than the size, in bytes, of the segment. The processor causes a general-protection exception any time an attempt is made to access the following addresses in a segment:

- A byte at an offset greater than the effective limit
- A word at an offset greater than the (effective-limit – 1)
- A doubleword at an offset greater than the (effective-limit – 3)
- A quadword at an offset greater than the (effective-limit – 7)

For expand-down data segments, the segment limit has the same function but is interpreted differently. Here, the effective limit specifies the last address that is not allowed to be accessed within the segment; the range of valid offsets is from (effective-limit + 1) to FFFFFFFFH if the B flag is set and from (effective-limit + 1) to FFFFH if the B flag is clear. An expand-down segment has maximum size when the segment limit is 0.

Limit checking catches programming errors such as runaway code, runaway subscripts, and invalid pointer calculations. These errors are detected when they occur, so identification of the cause is easier. Without limit checking, these errors could overwrite code or data in another segment.

In addition to checking segment limits, the processor also checks descriptor table limits. The GDTR and IDTR registers contain 16-bit limit values that the processor uses to prevent programs from selecting a segment descriptors outside the respective descriptor tables. The LDTR and task registers contain 32-bit segment limit value (read from the segment descriptors for the current LDT and TSS, respectively). The processor uses these segment limits to prevent accesses beyond the bounds of the current LDT and TSS. Refer to Section 3.5.1., “Segment Descriptor Tables” in Chapter 3, *Protected-Mode Memory Management* for more information on the GDT and LDT limit fields; refer to Section 5.8., “Interrupt Descriptor Table (IDT)” in Chapter 5, *Interrupt and Exception Handling* for more information on the IDT limit field; and refer to Section 6.2.3., “Task Register” in Chapter 6, *Task Management* for more information on the TSS segment limit field.

4.4. TYPE CHECKING

Segment descriptors contain type information in two places:

- The S (descriptor type) flag.
- The type field.

The processor uses this information to detect programming errors that result in an attempt to use a segment or gate in an incorrect or unintended manner.

The S flag indicates whether a descriptor is a system type or a code or data type. The type field provides 4 additional bits for use in defining various types of code, data, and system descriptors. Table 3-1 in Chapter 3, *Protected-Mode Memory Management* shows the encoding of the type field for code and data descriptors; Table 3-2 in Chapter 3, *Protected-Mode Memory Management* shows the encoding of the field for system descriptors.

The processor examines type information at various times while operating on segment selectors and segment descriptors. The following list gives examples of typical operations where type checking is performed. This list is not exhaustive.

- **When a segment selector is loaded into a segment register.** Certain segment registers can contain only certain descriptor types, for example:
  - The CS register only can be loaded with a selector for a code segment.
  - Segment selectors for code segments that are not readable or for system segments cannot be loaded into data-segment registers (DS, ES, FS, and GS).
  - Only segment selectors of writable data segments can be loaded into the SS register.
- **When a segment selector is loaded into the LDTR or task register.**
  - The LDTR can only be loaded with a selector for an LDT.
  - The task register can only be loaded with a segment selector for a TSS.
- **When instructions access segments whose descriptors are already loaded into segment registers.** Certain segments can be used by instructions only in certain predefined ways, for example:
  - No instruction may write into an executable segment.
  - No instruction may write into a data segment if it is not writable.
  - No instruction may read an executable segment unless the readable flag is set.
- **When an instruction operand contains a segment selector.** Certain instructions can access segment or gates of only a particular type, for example:
  - A far CALL or far JMP instruction can only access a segment descriptor for a conforming code segment, nonconforming code segment, call gate, task gate, or TSS.
  - The LLDT instruction must reference a segment descriptor for an LDT.
  - The LTR instruction must reference a segment descriptor for a TSS.

— The LAR instruction must reference a segment or gate descriptor for an LDT, TSS, call gate, task gate, code segment, or data segment.

— The LSL instruction must reference a segment descriptor for a LDT, TSS, code segment, or data segment.

— IDT entries must be interrupt, trap, or task gates.

- **During certain internal operations.** For example:

  — On a far call or far jump (executed with a far CALL or far JMP instruction), the processor determines the type of control transfer to be carried out (call or jump to another code segment, a call or jump through a gate, or a task switch) by checking the type field in the segment (or gate) descriptor pointed to by the segment (or gate) selector given as an operand in the CALL or JMP instruction. If the descriptor type is for a code segment or call gate, a call or jump to another code segment is indicated; if the descriptor type is for a TSS or task gate, a task switch is indicated.

  — On a call or jump through a call gate (or on an interrupt- or exception-handler call through a trap or interrupt gate), the processor automatically checks that the segment descriptor being pointed to by the gate is for a code segment.

  — On a call or jump to a new task through a task gate (or on an interrupt- or exception-handler call to a new task through a task gate), the processor automatically checks that the segment descriptor being pointed to by the task gate is for a TSS.

  — On a call or jump to a new task by a direct reference to a TSS, the processor automatically checks that the segment descriptor being pointed to by the CALL or JMP instruction is for a TSS.

  — On return from a nested task (initiated by an IRET instruction), the processor checks that the previous task link field in the current TSS points to a TSS.

4.4.1. Null Segment Selector Checking

Attempting to load a null segment selector (refer to Section 3.4.1. in Chapter 3, *Protected-Mode Memory Management*) into the CS or SS segment register generates a general-protection exception (#GP). A null segment selector can be loaded into the DS, ES, FS, or GS register, but any attempt to access a segment through one of these registers when it is loaded with a null segment selector results in a #GP exception being generated. Loading unused data-segment registers with a null segment selector is a useful method of detecting accesses to unused segment registers and/or preventing unwanted accesses to data segments.

4.5. PRIVILEGE LEVELS

The processor's segment-protection mechanism recognizes 4 privilege levels, numbered from 0 to 3. The greater numbers mean lesser privileges. Figure 4-2 shows how these levels of privilege can be interpreted as rings of protection. The center (reserved for the most privileged code, data, and stacks) is used for the segments containing the critical software, usually the kernel of an operating system. Outer rings are used for less critical software. (Systems that use only 2 of the 4 possible privilege levels should use levels 0 and 3.)

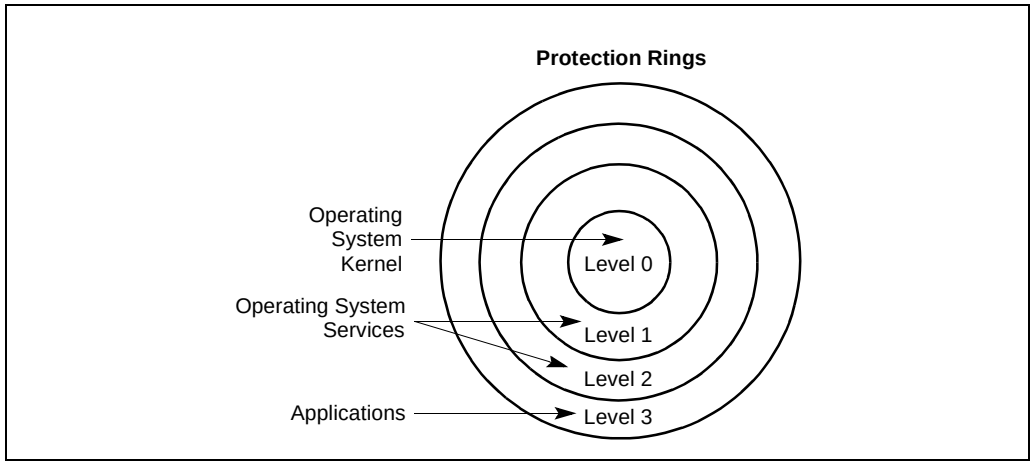


Figure 4-2. Protection Rings

The processor uses privilege levels to prevent a program or task operating at a lesser privilege level from accessing a segment with a greater privilege, except under controlled situations. When the processor detects a privilege level violation, it generates a general-protection exception (#GP).

To carry out privilege-level checks between code segments and data segments, the processor recognizes the following three types of privilege levels:

- **Current privilege level (CPL).** The CPL is the privilege level of the currently executing program or task. It is stored in bits 0 and 1 of the CS and SS segment registers. Normally, the CPL is equal to the privilege level of the code segment from which instructions are being fetched. The processor changes the CPL when program control is transferred to a code segment with a different privilege level. The CPL is treated slightly differently when accessing conforming code segments. Conforming code segments can be accessed from any privilege level that is equal to or numerically greater (less privileged) than the DPL of the conforming code segment. Also, the CPL is not changed when the processor accesses a conforming code segment that has a different privilege level than the CPL.
- **Descriptor privilege level (DPL).** The DPL is the privilege level of a segment or gate. It is stored in the DPL field of the segment or gate descriptor for the segment or gate. When the currently executing code segment attempts to access a segment or gate, the DPL of the

segment or gate is compared to the CPL and RPL of the segment or gate selector (as described later in this section). The DPL is interpreted differently, depending on the type of segment or gate being accessed:

— **Data segment.** The DPL indicates the numerically highest privilege level that a program or task can have to be allowed to access the segment. For example, if the DPL of a data segment is 1, only programs running at a CPL of 0 or 1 can access the segment.

— **Nonconforming code segment (without using a call gate).** The DPL indicates the privilege level that a program or task must be at to access the segment. For example, if the DPL of a nonconforming code segment is 0, only programs running at a CPL of 0 can access the segment.

— **Call gate.** The DPL indicates the numerically highest privilege level that the currently executing program or task can be at and still be able to access the call gate. (This is the same access rule as for a data segment.)

— **Conforming code segment and nonconforming code segment accessed through a call gate.** The DPL indicates the numerically lowest privilege level that a program or task can have to be allowed to access the segment. For example, if the DPL of a conforming code segment is 2, programs running at a CPL of 0 or 1 cannot access the segment.

— **TSS.** The DPL indicates the numerically highest privilege level that the currently executing program or task can be at and still be able to access the TSS. (This is the same access rule as for a data segment.)

- **Requested privilege level (RPL).** The RPL is an override privilege level that is assigned to segment selectors. It is stored in bits 0 and 1 of the segment selector. The processor checks the RPL along with the CPL to determine if access to a segment is allowed. Even if the program or task requesting access to a segment has sufficient privilege to access the segment, access is denied if the RPL is not of sufficient privilege level. That is, if the RPL of a segment selector is numerically greater than the CPL, the RPL overrides the CPL, and vice versa. The RPL can be used to insure that privileged code does not access a segment on behalf of an application program unless the program itself has access privileges for that segment. Refer to Section 4.10.4., “Checking Caller Access Privileges (ARPL Instruction)” for a detailed description of the purpose and typical use of the RPL.

Privilege levels are checked when the segment selector of a segment descriptor is loaded into a segment register. The checks used for data access differ from those used for transfers of program control among code segments; therefore, the two kinds of accesses are considered separately in the following sections.

4.6. PRIVILEGE LEVEL CHECKING WHEN ACCESSING DATA SEGMENTS

To access operands in a data segment, the segment selector for the data segment must be loaded into the data-segment registers (DS, ES, FS, or GS) or into the stack-segment register (SS).

(Segment registers can be loaded with the MOV, POP, LDS, LES, LFS, LGS, and LSS instructions.) Before the processor loads a segment selector into a segment register, it performs a privilege check (refer to Figure 4-3) by comparing the privilege levels of the currently running program or task (the CPL), the RPL of the segment selector, and the DPL of the segment's segment descriptor. The processor loads the segment selector into the segment register if the DPL is numerically greater than or equal to both the CPL and the RPL. Otherwise, a general-protection fault is generated and the segment register is not loaded.

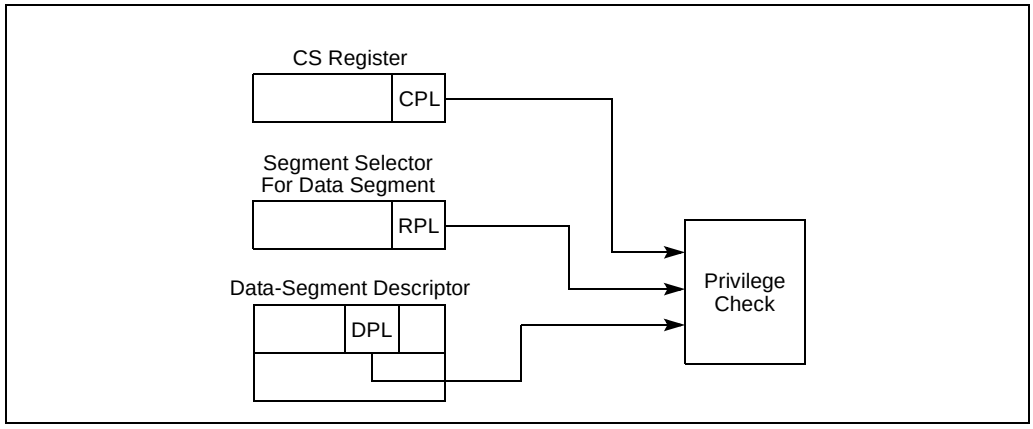


Figure 4-3. Privilege Check for Data Access

Figure 4-4 shows four procedures (located in codes segments A, B, C, and D), each running at different privilege levels and each attempting to access the same data segment.

- The procedure in code segment A is able to access data segment E using segment selector E1, because the CPL of code segment A and the RPL of segment selector E1 are equal to the DPL of data segment E.
- The procedure in code segment B is able to access data segment E using segment selector E2, because the CPL of code segment A and the RPL of segment selector E2 are both numerically lower than (more privileged) than the DPL of data segment E. A code segment B procedure can also access data segment E using segment selector E1.
- The procedure in code segment C is not able to access data segment E using segment selector E3 (dotted line), because the CPL of code segment C and the RPL of segment selector E3 are both numerically greater than (less privileged) than the DPL of data segment E. Even if a code segment C procedure were to use segment selector E1 or E2, such that the RPL would be acceptable, it still could not access data segment E because its CPL is not privileged enough.
- The procedure in code segment D should be able to access data segment E because code segment D's CPL is numerically less than the DPL of data segment E. However, the RPL of segment selector E3 (which the code segment D procedure is using to access data segment E) is numerically greater than the DPL of data segment E, so access is not

allowed. If the code segment D procedure were to use segment selector E1 or E2 to access the data segment, access would be allowed.

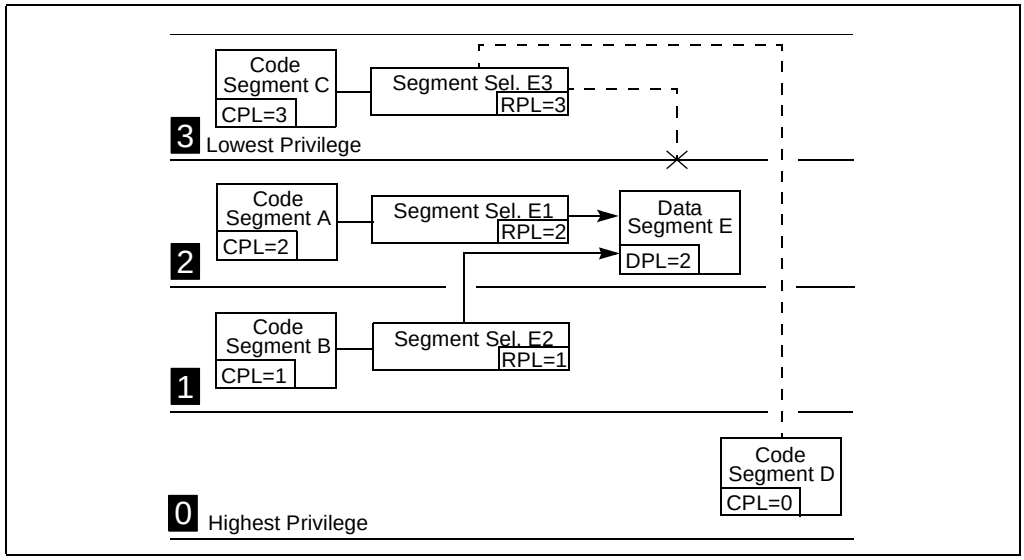


Figure 4-4. Examples of Accessing Data Segments From Various Privilege Levels

As demonstrated in the previous examples, the addressable domain of a program or task varies as its CPL changes. When the CPL is 0, data segments at all privilege levels are accessible; when the CPL is 1, only data segments at privilege levels 1 through 3 are accessible; when the CPL is 3, only data segments at privilege level 3 are accessible.

The RPL of a segment selector can always override the addressable domain of a program or task. When properly used, RPLs can prevent problems caused by accidental (or intensional) use of segment selectors for privileged data segments by less privileged programs or procedures.

It is important to note that the RPL of a segment selector for a data segment is under software control. For example, an application program running at a CPL of 3 can set the RPL for a data-segment selector to 0. With the RPL set to 0, only the CPL checks, not the RPL checks, will provide protection against deliberate, direct attempts to violate privilege-level security for the data segment. To prevent these types of privilege-level-check violations, a program or procedure can check access privileges whenever it receives a data-segment selector from another procedure (refer to Section 4.10.4., “Checking Caller Access Privileges (ARPL Instruction)”).

4.6.1. Accessing Data in Code Segments

In some instances it may be desirable to access data structures that are contained in a code segment. The following methods of accessing data in code segments are possible:

- Load a data-segment register with a segment selector for a nonconforming, readable, code segment.
- Load a data-segment register with a segment selector for a conforming, readable, code segment.
- Use a code-segment override prefix (CS) to read a readable, code segment whose selector is already loaded in the CS register.

The same rules for accessing data segments apply to method 1. Method 2 is always valid because the privilege level of a conforming code segment is effectively the same as the CPL, regardless of its DPL. Method 3 is always valid because the DPL of the code segment selected by the CS register is the same as the CPL.

4.7. PRIVILEGE LEVEL CHECKING WHEN LOADING THE SS REGISTER

Privilege level checking also occurs when the SS register is loaded with the segment selector for a stack segment. Here all privilege levels related to the stack segment must match the CPL; that is, the CPL, the RPL of the stack-segment selector, and the DPL of the stack-segment descriptor must be the same. If the RPL and DPL are not equal to the CPL, a general-protection exception (#GP) is generated.

4.8. PRIVILEGE LEVEL CHECKING WHEN TRANSFERRING PROGRAM CONTROL BETWEEN CODE SEGMENTS

To transfer program control from one code segment to another, the segment selector for the destination code segment must be loaded into the code-segment register (CS). As part of this loading process, the processor examines the segment descriptor for the destination code segment and performs various limit, type, and privilege checks. If these checks are successful, the CS register is loaded, program control is transferred to the new code segment, and program execution begins at the instruction pointed to by the EIP register.

Program control transfers are carried out with the JMP, CALL, RET, INT *n*, and IRET instructions, as well as by the exception and interrupt mechanisms. Exceptions, interrupts, and the IRET instruction are special cases discussed in Chapter 5, *Interrupt and Exception Handling.* This chapter discusses only the JMP, CALL, and RET instructions.

A JMP or CALL instruction can reference another code segment in any of four ways:

- The target operand contains the segment selector for the target code segment.
- The target operand points to a call-gate descriptor, which contains the segment selector for the target code segment.

- The target operand points to a TSS, which contains the segment selector for the target code segment.
- The target operand points to a task gate, which points to a TSS, which in turn contains the segment selector for the target code segment.

The following sections describe first two types of references. Refer to Section 6.3., “Task Switching” in Chapter 6, *Task Management* for information on transferring program control through a task gate and/or TSS.

4.8.1. Direct Calls or Jumps to Code Segments

The near forms of the JMP, CALL, and RET instructions transfer program control within the current code segment, so privilege-level checks are not performed. The far forms of the JMP, CALL, and RET instructions transfer control to other code segments, so the processor does perform privilege-level checks.

When transferring program control to another code segment without going through a call gate, the processor examines four kinds of privilege level and type information (refer to Figure 4-5):

- The CPL. (Here, the CPL is the privilege level of the calling code segment; that is, the code segment that contains the procedure that is making the call or jump.)

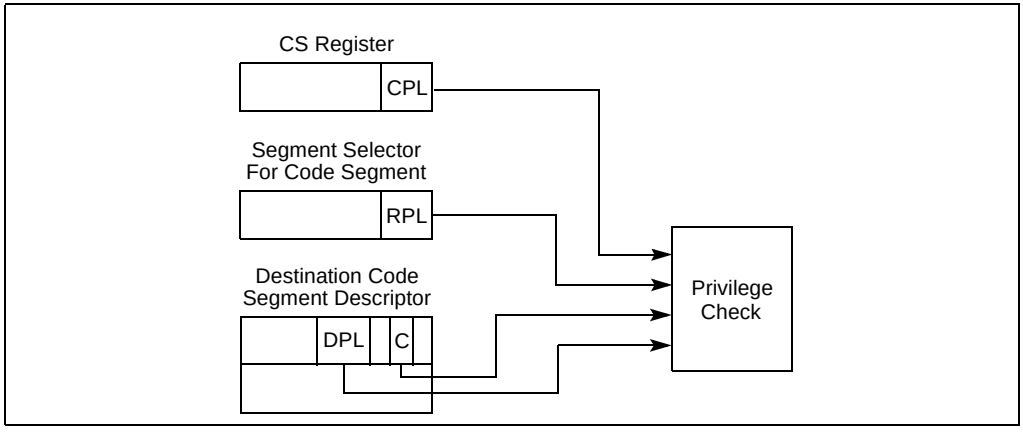


Figure 4-5. Privilege Check for Control Transfer Without Using a Gate

- The DPL of the segment descriptor for the destination code segment that contains the called procedure.
- The RPL of the segment selector of the destination code segment.
- The conforming (C) flag in the segment descriptor for the destination code segment, which determines whether the segment is a conforming (C flag is set) or nonconforming (C flag is clear) code segment. (Refer to Section 3.4.3.1., “Code- and Data-Segment Descriptor

Types" in Chapter 3, *Protected-Mode Memory Management* for more information about this flag.)

The rules that the processor uses to check the CPL, RPL, and DPL depends on the setting of the C flag, as described in the following sections.

4.8.1.1. ACCESSING NONCONFORMING CODE SEGMENTS

When accessing nonconforming code segments, the CPL of the calling procedure must be equal to the DPL of the destination code segment; otherwise, the processor generates a general-protection exception (#GP).

For example, in Figure 4-6, code segment C is a nonconforming code segment. Therefore, a procedure in code segment A can call a procedure in code segment C (using segment selector C1), because they are at the same privilege level (the CPL of code segment A is equal to the DPL of code segment C). However, a procedure in code segment B cannot call a procedure in code segment C (using segment selector C2 or C1), because the two code segments are at different privilege levels.

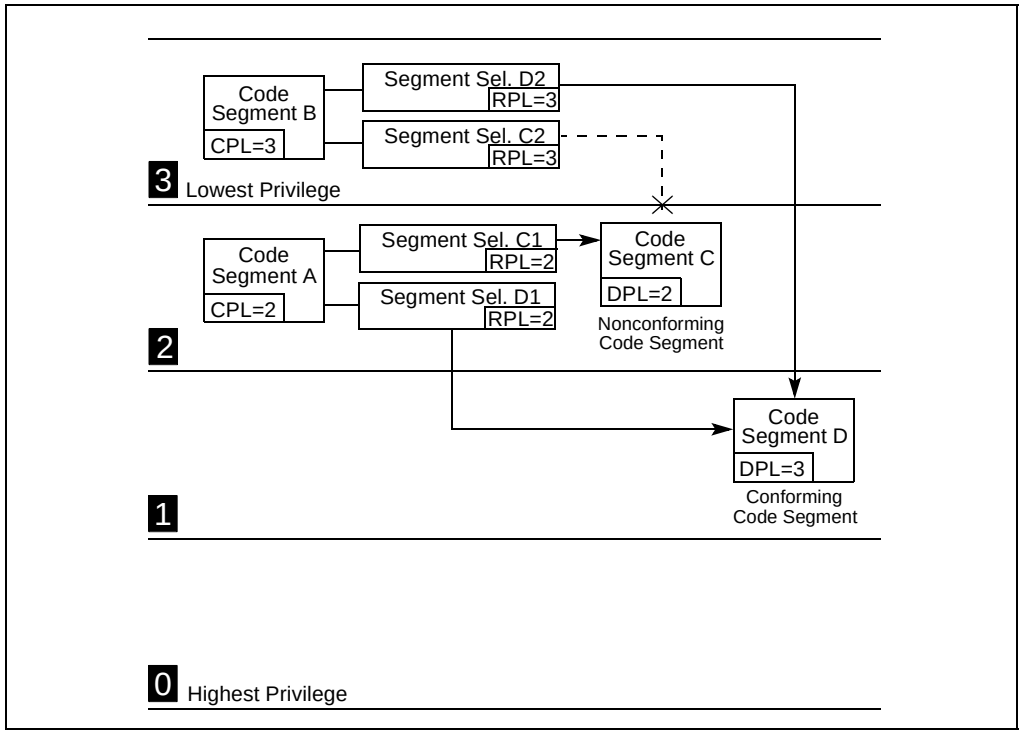


Figure 4-6. Examples of Accessing Conforming and Nonconforming Code Segments From Various Privilege Levels

The RPL of the segment selector that points to a nonconforming code segment has a limited effect on the privilege check. The RPL must be numerically less than or equal to the CPL of the calling procedure for a successful control transfer to occur. So, in the example in Figure 4-6, the RPLs of segment selectors C1 and C2 could legally be set to 0, 1, or 2, but not to 3.

When the segment selector of a nonconforming code segment is loaded into the CS register, the privilege level field is not changed; that is, it remains at the CPL (which is the privilege level of the calling procedure). This is true, even if the RPL of the segment selector is different from the CPL.

4.8.1.2. ACCESSING CONFORMING CODE SEGMENTS

When accessing conforming code segments, the CPL of the calling procedure may be numerically equal to or greater than (less privileged) the DPL of the destination code segment; the processor generates a general-protection exception (#GP) only if the CPL is less than the DPL. (The segment selector RPL for the destination code segment is not checked if the segment is a conforming code segment.)

In the example in Figure 4-6, code segment D is a conforming code segment. Therefore, calling procedures in both code segment A and B can access code segment D (using either segment selector D1 or D2, respectively), because they both have CPLs that are greater than or equal to the DPL of the conforming code segment. **For conforming code segments, the DPL represents the numerically lowest privilege level that a calling procedure may be at to successfully make a call to the code segment.**

(Note that segments selectors D1 and D2 are identical except for their respective RPLs. But since RPLs are not checked when accessing conforming code segments, the two segment selectors are essentially interchangeable.)

When program control is transferred to a conforming code segment, the CPL does not change, even if the DPL of the destination code segment is less than the CPL. This situation is the only one where the CPL may be different from the DPL of the current code segment. Also, since the CPL does not change, no stack switch occurs.

Conforming segments are used for code modules such as math libraries and exception handlers, which support applications but do not require access to protected system facilities. These modules are part of the operating system or executive software, but they can be executed at numerically higher privilege levels (less privileged levels). Keeping the CPL at the level of a calling code segment when switching to a conforming code segment prevents an application program from accessing nonconforming code segments while at the privilege level (DPL) of a conforming code segment and thus prevents it from accessing more privileged data.

Most code segments are nonconforming. For these segments, program control can be transferred only to code segments at the same level of privilege, unless the transfer is carried out through a call gate, as described in the following sections.

4.8.2. Gate Descriptors

To provide controlled access to code segments with different privilege levels, the processor provides special set of descriptors called gate descriptors. There are four kinds of gate descriptors:

- Call gates
- Trap gates
- Interrupt gates
- Task gates

Task gates are used for task switching and are discussed in Chapter 6, *Task Management*. Trap and interrupt gates are special kinds of call gates used for calling exception and interrupt handlers. The are described in Chapter 5, *Interrupt and Exception Handling*. This chapter is concerned only with call gates.

4.8.3. Call Gates

Call gates facilitate controlled transfers of program control between different privilege levels. They are typically used only in operating systems or executives that use the privilege-level protection mechanism. Call gates are also useful for transferring program control between 16-bit and 32-bit code segments, as described in Section 17.4., "Transferring Control Among Mixed-Size Code Segments" in Chapter 17, *Mixing 16-Bit and 32-Bit Code*.

Figure 4-7 shows the format of a call-gate descriptor. A call-gate descriptor may reside in the GDT or in an LDT, but not in the interrupt descriptor table (IDT). It performs six functions:

- It specifies the code segment to be accessed.
- It defines an entry point for a procedure in the specified code segment.
- It specifies the privilege level required for a caller trying to access the procedure.
- If a stack switch occurs, it specifies the number of optional parameters to be copied between stacks.
- It defines the size of values to be pushed onto the target stack: 16-bit gates force 16-bit pushes and 32-bit gates force 32-bit pushes.
- It specifies whether the call-gate descriptor is valid.

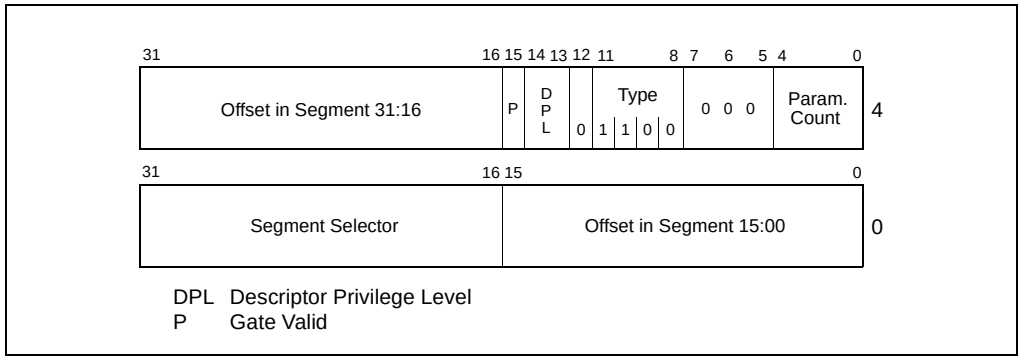


Figure 4-7. Call-Gate Descriptor

The segment selector field in a call gate specifies the code segment to be accessed. The offset field specifies the entry point in the code segment. This entry point is generally to the first instruction of a specific procedure. The DPL field indicates the privilege level of the call gate, which in turn is the privilege level required to access the selected procedure through the gate. The P flag indicates whether the call-gate descriptor is valid. (The presence of the code segment to which the gate points is indicated by the P flag in the code segment's descriptor.) The parameter count field indicates the number of parameters to copy from the calling procedures stack to the new stack if a stack switch occurs (refer to Section 4.8.5., "Stack Switching"). The parameter count specifies the number of words for 16-bit call gates and doublewords for 32-bit call gates.

Note that the P flag in a gate descriptor is normally always set to 1. If it is set to 0, a not present (#NP) exception is generated when a program attempts to access the descriptor. The operating system can use the P flag for special purposes. For example, it could be used to track the number of times the gate is used. Here, the P flag is initially set to 0 causing a trap to the not-present exception handler. The exception handler then increments a counter and sets the P flag to 1, so that on returning from the handler, the gate descriptor will be valid.

4.8.4. Accessing a Code Segment Through a Call Gate

To access a call gate, a far pointer to the gate is provided as a target operand in a CALL or JMP instruction. The segment selector from this pointer identifies the call gate (refer to Figure 4-8); the offset from the pointer is required, but not used or checked by the processor. (The offset can be set to any value.)

When the processor has accessed the call gate, it uses the segment selector from the call gate to locate the segment descriptor for the destination code segment. (This segment descriptor can be in the GDT or the LDT.) It then combines the base address from the code-segment descriptor with the offset from the call gate to form the linear address of the procedure entry point in the code segment.

As shown in Figure 4-9, four different privilege levels are used to check the validity of a program control transfer through a call gate:

- The CPL (current privilege level).
- The RPL (requestor's privilege level) of the call gate's selector.
- The DPL (descriptor privilege level) of the call gate descriptor.
- The DPL of the segment descriptor of the destination code segment.

The C flag (conforming) in the segment descriptor for the destination code segment is also checked.

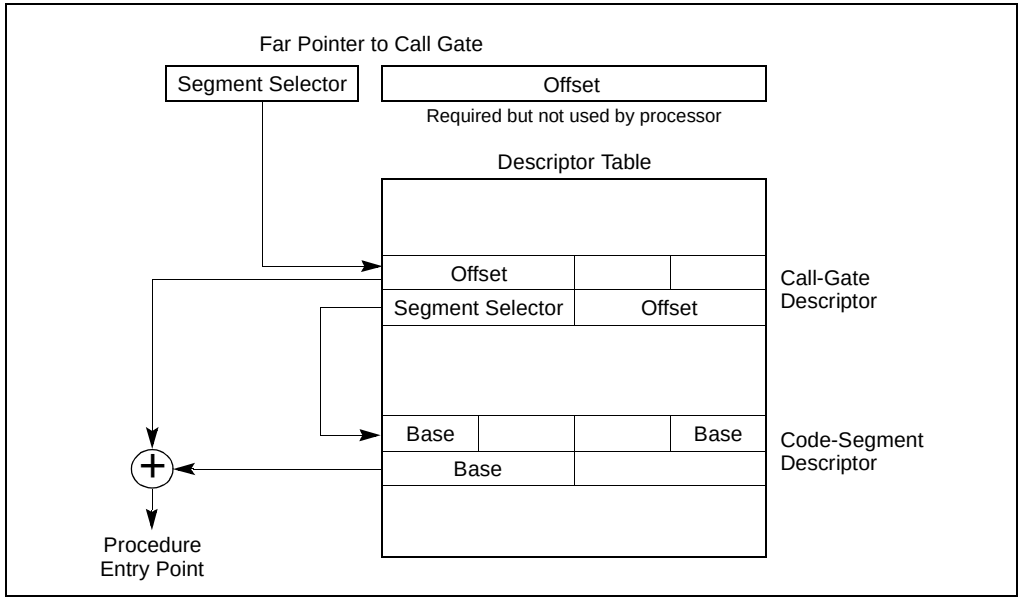


Figure 4-8. Call-Gate Mechanism

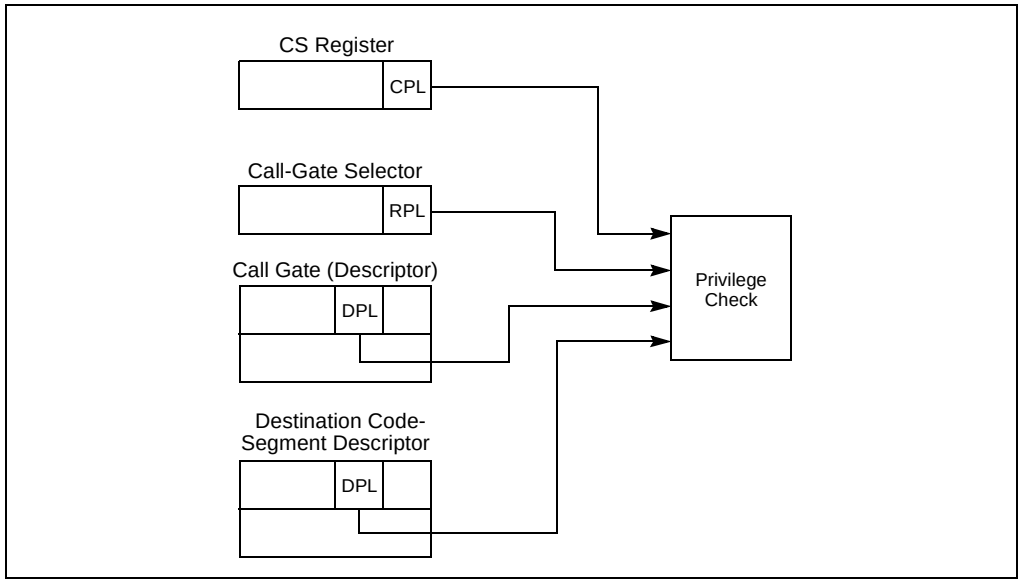


Figure 4-9. Privilege Check for Control Transfer with Call Gate

The privilege checking rules are different depending on whether the control transfer was initiated with a CALL or a JMP instruction, as shown in Table 4-1.

Table 4-1. Privilege Check Rules for Call Gates

Instruction	Privilege Check Rules
CALL	CPL ≤ call gate DPL; RPL ≤ call gate DPL
	Destination conforming code segment DPL ≤ CPL
	Destination nonconforming code segment DPL ≤ CPL
JMP	CPL ≤ call gate DPL; RPL ≤ call gate DPL
	Destination conforming code segment DPL ≤ CPL
	Destination nonconforming code segment DPL = CPL

The DPL field of the call-gate descriptor specifies the numerically highest privilege level from which a calling procedure can access the call gate; that is, to access a call gate, the CPL of a calling procedure must be equal to or less than the DPL of the call gate. For example, in Figure 4-12, call gate A has a DPL of 3. So calling procedures at all CPLs (0 through 3) can access this call gate, which includes calling procedures in code segments A, B, and C. Call gate B has a DPL of 2, so only calling procedures at a CPL or 0, 1, or 2 can access call gate B, which includes calling procedures in code segments B and C. The dotted line shows that a calling procedure in code segment A cannot access call gate B.

The RPL of the segment selector to a call gate must satisfy the same test as the CPL of the calling procedure; that is, the RPL must be less than or equal to the DPL of the call gate. In the example in Figure 4-12, a calling procedure in code segment C can access call gate B using gate selector B2 or B1, but it could not use gate selector B3 to access call gate B.

If the privilege checks between the calling procedure and call gate are successful, the processor then checks the DPL of the code-segment descriptor against the CPL of the calling procedure. Here, the privilege check rules vary between CALL and JMP instructions. Only CALL instructions can use call gates to transfer program control to more privileged (numerically lower privilege level) nonconforming code segments; that is, to nonconforming code segments with a DPL less than the CPL. A JMP instruction can use a call gate only to transfer program control to a nonconforming code segment with a DPL equal to the CPL. CALL and JMP instruction can both transfer program control to a more privileged conforming code segment; that is, to a conforming code segment with a DPL less than or equal to the CPL.

If a call is made to a more privileged (numerically lower privilege level) nonconforming destination code segment, the CPL is lowered to the DPL of the destination code segment and a stack switch occurs (refer to Section 4.8.5., “Stack Switching”). If a call or jump is made to a more privileged conforming destination code segment, the CPL is not changed and no stack switch occurs.

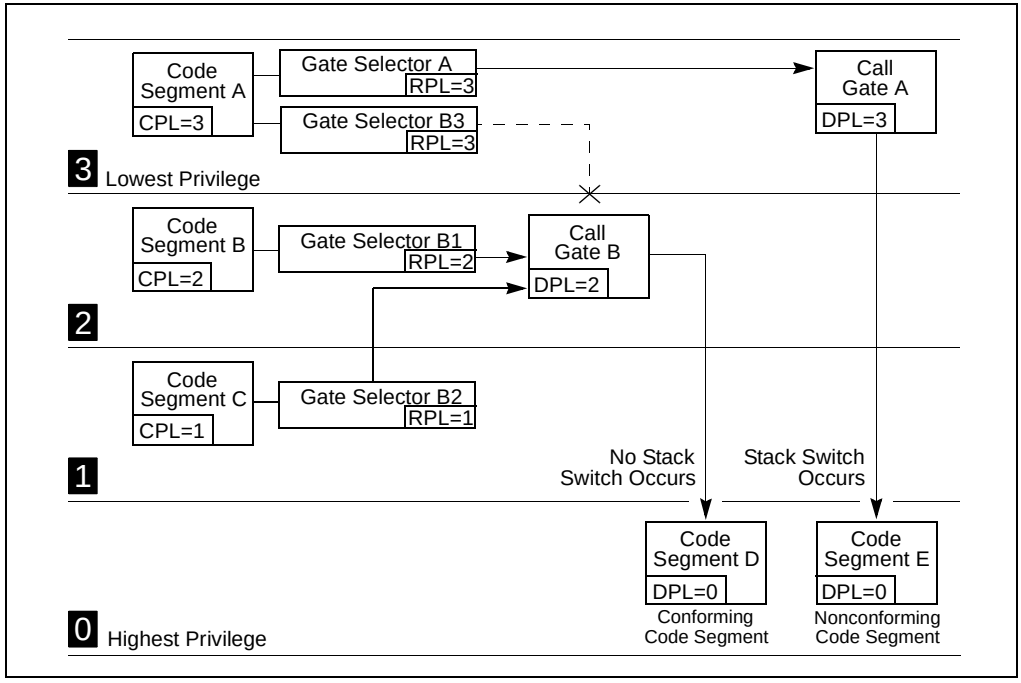


Figure 4-10. Example of Accessing Call Gates At Various Privilege Levels

Call gates allow a single code segment to have procedures that can be accessed at different privilege levels. For example, an operating system located in a code segment may have some services which are intended to be used by both the operating system and application software (such as procedures for handling character I/O). Call gates for these procedures can be set up that allow access at all privilege levels (0 through 3). More privileged call gates (with DPLs of 0 or 1) can then be set up for other operating system services that are intended to be used only by the operating system (such as procedures that initialize device drivers).

4.8.5. Stack Switching

Whenever a call gate is used to transfer program control to a more privileged nonconforming code segment (that is, when the DPL of the nonconforming destination code segment is less than the CPL), the processor automatically switches to the stack for the destination code segment's privilege level. This stack switching is carried out to prevent more privileged procedures from crashing due to insufficient stack space. It also prevents less privileged procedures from interfering (by accident or intent) with more privileged procedures through a shared stack.

Each task must define up to 4 stacks: one for applications code (running at privilege level 3) and one for each of the privilege levels 2, 1, and 0 that are used. (If only two privilege levels are used [3 and 0], then only two stacks must be defined.) Each of these stacks is located in a separate segment and is identified with a segment selector and an offset into the stack segment (a stack pointer).

The segment selector and stack pointer for the privilege level 3 stack is located in the SS and ESP registers, respectively, when privilege-level-3 code is being executed and is automatically stored on the called procedure's stack when a stack switch occurs.

Pointers to the privilege level 0, 1, and 2 stacks are stored in the TSS for the currently running task (refer to Figure 6-2 in Chapter 6, *Task Management*). Each of these pointers consists of a segment selector and a stack pointer (loaded into the ESP register). These initial pointers are strictly read-only values. The processor does not change them while the task is running. They are used only to create new stacks when calls are made to more privileged levels (numerically lower privilege levels). These stacks are disposed of when a return is made from the called procedure. The next time the procedure is called, a new stack is created using the initial stack pointer. (The TSS does not specify a stack for privilege level 3 because the processor does not allow a transfer of program control from a procedure running at a CPL of 0, 1, or 2 to a procedure running at a CPL of 3, except on a return.)

The operating system is responsible for creating stacks and stack-segment descriptors for all the privilege levels to be used and for loading initial pointers for these stacks into the TSS. Each stack must be read/write accessible (as specified in the type field of its segment descriptor) and must contain enough space (as specified in the limit field) to hold the following items:

- The contents of the SS, ESP, CS, and EIP registers for the calling procedure.
- The parameters and temporary variables required by the called procedure.
- The EFLAGS register and error code, when implicit calls are made to an exception or interrupt handler.

The stack will need to require enough space to contain many frames of these items, because procedures often call other procedures, and an operating system may support nesting of multiple interrupts. Each stack should be large enough to allow for the worst case nesting scenario at its privilege level.

(If the operating system does not use the processor's multitasking mechanism, it still must create at least one TSS for this stack-related purpose.)

When a procedure call through a call gate results in a change in privilege level, the processor performs the following steps to switch stacks and begin execution of the called procedure at a new privilege level:

1. Uses the DPL of the destination code segment (the new CPL) to select a pointer to the new stack (segment selector and stack pointer) from the TSS.
2. Reads the segment selector and stack pointer for the stack to be switched to from the current TSS. Any limit violations detected while reading the stack-segment selector, stack pointer, or stack-segment descriptor cause an invalid TSS (#TS) exception to be generated.
3. Checks the stack-segment descriptor for the proper privileges and type and generates an invalid TSS (#TS) exception if violations are detected.
4. Temporarily saves the current values of the SS and ESP registers.
5. Loads the segment selector and stack pointer for the new stack in the SS and ESP registers.
6. Pushes the temporarily saved values for the SS and ESP registers (for the calling procedure) onto the new stack (refer to Figure 4-11).
7. Copies the number of parameter specified in the parameter count field of the call gate from the calling procedure's stack to the new stack. If the count is 0, no parameters are copied.
8. Pushes the return instruction pointer (the current contents of the CS and EIP registers) onto the new stack.
9. Loads the segment selector for the new code segment and the new instruction pointer from the call gate into the CS and EIP registers, respectively, and begins execution of the called procedure.

Refer to the description of the CALL instruction in Chapter 3, *Instruction Set Reference*, in the *Intel Architecture Software Developer's Manual, Volume 2*, for a detailed description of the privilege level checks and other protection checks that the processor performs on a far call through a call gate.

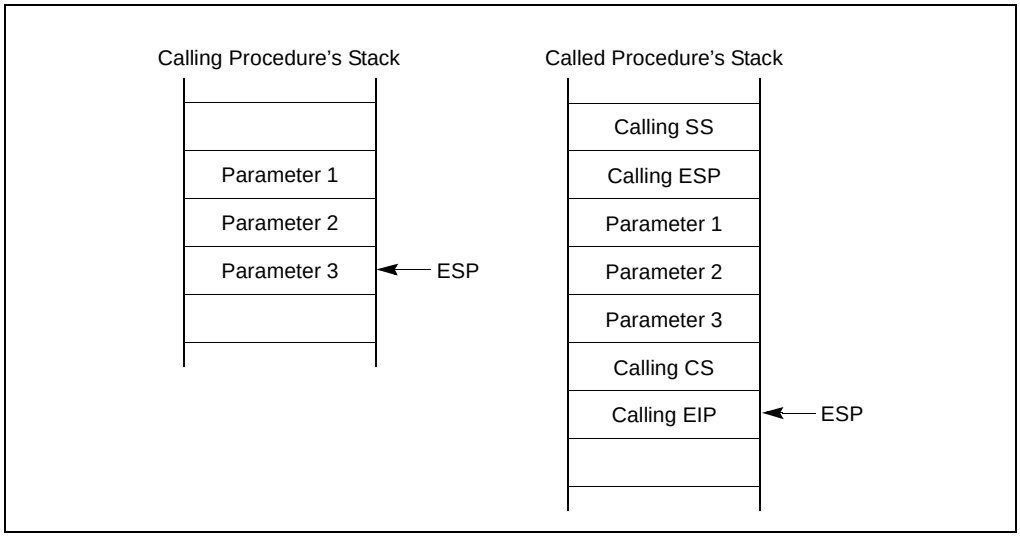


Figure 4-11. Stack Switching During an Interprivilege-Level Call

The parameter count field in a call gate specifies the number of data items (up to 31) that the processor should copy from the calling procedure's stack to the stack of the called procedure. If more than 31 data items need to be passed to the called procedure, one of the parameters can be a pointer to a data structure, or the saved contents of the SS and ESP registers may be used to access parameters in the old stack space. The size of the data items passed to the called procedure depends on the call gate size, as described in Section 4.8.3., "Call Gates"

4.8.6. Returning from a Called Procedure

The RET instruction can be used to perform a near return, a far return at the same privilege level, and a far return to a different privilege level. This instruction is intended to execute returns from procedures that were called with a CALL instruction. It does not support returns from a JMP instruction, because the JMP instruction does not save a return instruction pointer on the stack.

A near return only transfers program control within the current code segment; therefore, the processor performs only a limit check. When the processor pops the return instruction pointer from the stack into the EIP register, it checks that the pointer does not exceed the limit of the current code segment.

On a far return at the same privilege level, the processor pops both a segment selector for the code segment being returned to and a return instruction pointer from the stack. Under normal conditions, these pointers should be valid, because they were pushed on the stack by the CALL instruction. However, the processor performs privilege checks to detect situations where the current procedure might have altered the pointer or failed to maintain the stack properly.

A far return that requires a privilege-level change is only allowed when returning to a less privileged level (that is, the DPL of the return code segment is numerically greater than the CPL). The processor uses the RPL field from the CS register value saved for the calling procedure (refer to Figure 4-11) to determine if a return to a numerically higher privilege level is required. If the RPL is numerically greater (less privileged) than the CPL, a return across privilege levels occurs.

The processor performs the following steps when performing a far return to a calling procedure (refer to Figures 4-2 and 4-4 in the *Intel Architecture Software Developer's Manual, Volume 1*, for an illustration of the stack contents prior to and after a return):

1. Checks the RPL field of the saved CS register value to determine if a privilege level change is required on the return.
2. Loads the CS and EIP registers with the values on the called procedure's stack. (Type and privilege level checks are performed on the code-segment descriptor and RPL of the code-segment selector.)
3. (If the RET instruction includes a parameter count operand and the return requires a privilege level change.) Adds the parameter count (in bytes obtained from the RET instruction) to the current ESP register value (after popping the CS and EIP values), to step past the parameters on the called procedure's stack. The resulting value in the ESP register points to the saved SS and ESP values for the calling procedure's stack. (Note that the byte count in the RET instruction must be chosen to match the parameter count in the call gate that the calling procedure referenced when it made the original call multiplied by the size of the parameters.)
4. (If the return requires a privilege level change.) Loads the SS and ESP registers with the saved SS and ESP values and switches back to the calling procedure's stack. The SS and ESP values for the called procedure's stack are discarded. Any limit violations detected while loading the stack-segment selector or stack pointer cause a general-protection exception (#GP) to be generated. The new stack-segment descriptor is also checked for type and privilege violations.
5. (If the RET instruction includes a parameter count operand.) Adds the parameter count (in bytes obtained from the RET instruction) to the current ESP register value, to step past the parameters on the calling procedure's stack. The resulting ESP value is not checked against the limit of the stack segment. If the ESP value is beyond the limit, that fact is not recognized until the next stack operation.
6. (If the return requires a privilege level change.) Checks the contents of the DS, ES, FS, and GS segment registers. If any of these registers refer to segments whose DPL is less than the new CPL (excluding conforming code segments), the segment register is loaded with a null segment selector.

Refer to the description of the RET instruction in Chapter 3, *Instruction Set Reference*, of the *Intel Architecture Software Developer's Manual, Volume 2*, for a detailed description of the privilege level checks and other protection checks that the processor performs on a far return.

4.9. PRIVILEGED INSTRUCTIONS

Some of the system instructions (called “privileged instructions” are protected from use by application programs. The privileged instructions control system functions (such as the loading of system registers). They can be executed only when the CPL is 0 (most privileged). If one of these instructions is executed when the CPL is not 0, a general-protection exception (#GP) is generated. The following system instructions are privileged instructions:

- LGDT—Load GDT register.
- LLDT—Load LDT register.
- LTR—Load task register.
- LIDT—Load IDT register.
- MOV (control registers)—Load and store control registers.
- LMSW—Load machine status word.
- CLTS—Clear task-switched flag in register CR0.
- MOV (debug registers)—Load and store debug registers.
- INVD—Invalidate cache, without writeback.
- WBINVD—Invalidate cache, with writeback.
- INVLPG—Invalidate TLB entry.
- HLT—Halt processor.
- RDMSR—Read Model-Specific Registers.
- WRMSR—Write Model-Specific Registers.
- RDPMC—Read Performance-Monitoring Counter.
- RDTSC—Read Time-Stamp Counter.

Some of the privileged instructions are available only in the more recent families of Intel Architecture processors (refer to Section 18.7., “New Instructions In the Pentium® and Later Intel Architecture Processors”, in Chapter 18, *Intel Architecture Compatibility*).

The PCE and TSD flags in register CR4 (bits 4 and 2, respectively) enable the RDPMC and RDTSC instructions, respectively, to be executed at any CPL.

4.10. POINTER VALIDATION

When operating in protected mode, the processor validates all pointers to enforce protection between segments and maintain isolation between privilege levels. Pointer validation consists of the following checks:

1. Checking access rights to determine if the segment type is compatible with its use.
2. Checking read/write rights

3. Checking if the pointer offset exceeds the segment limit.
4. Checking if the supplier of the pointer is allowed to access the segment.
5. Checking the offset alignment.

The processor automatically performs first, second, and third checks during instruction execution. Software must explicitly request the fourth check by issuing an ARPL instruction. The fifth check (offset alignment) is performed automatically at privilege level 3 if alignment checking is turned on. Offset alignment does not affect isolation of privilege levels.

4.10.1. Checking Access Rights (LAR Instruction)

When the processor accesses a segment using a far pointer, it performs an access rights check on the segment descriptor pointed to by the far pointer. This check is performed to determine if type and privilege level (DPL) of the segment descriptor are compatible with the operation to be performed. For example, when making a far call in protected mode, the segment-descriptor type must be for a conforming or nonconforming code segment, a call gate, a task gate, or a TSS. Then, if the call is to a nonconforming code segment, the DPL of the code segment must be equal to the CPL, and the RPL of the code segment's segment selector must be less than or equal to the DPL. If type or privilege level are found to be incompatible, the appropriate exception is generated.

To prevent type incompatibility exceptions from being generated, software can check the access rights of a segment descriptor using the LAR (load access rights) instruction. The LAR instruction specifies the segment selector for the segment descriptor whose access rights are to be checked and a destination register. The instruction then performs the following operations:

1. Check that the segment selector is not null.
2. Checks that the segment selector points to a segment descriptor that is within the descriptor table limit (GDT or LDT).
3. Checks that the segment descriptor is a code, data, LDT, call gate, task gate, or TSS segment-descriptor type.
4. If the segment is not a conforming code segment, checks if the segment descriptor is visible at the CPL (that is, if the CPL and the RPL of the segment selector are less than or equal to the DPL).
5. If the privilege level and type checks pass, loads the second doubleword of the segment descriptor into the destination register (masked by the value 00FXFF00H, where X indicates that the corresponding 4 bits are undefined) and sets the ZF flag in the EFLAGS register. If the segment selector is not visible at the current privilege level or is an invalid type for the LAR instruction, the instruction does not modify the destination register and clears the ZF flag.

Once loaded in the destination register, software can preform additional checks on the access rights information.

4.10.2. Checking Read/Write Rights (VERR and VERW Instructions)

When the processor accesses any code or data segment it checks the read/write privileges assigned to the segment to verify that the intended read or write operation is allowed. Software can check read/write rights using the VERR **(**verify for reading) and VERW (verify for writing**)** instructions. Both these instructions specify the segment selector for the segment being checked. The instructions then perform the following operations:

1. Check that the segment selector is not null.
2. Checks that the segment selector points to a segment descriptor that is within the descriptor table limit (GDT or LDT).
3. Checks that the segment descriptor is a code or data-segment descriptor type.
4. If the segment is not a conforming code segment, checks if the segment descriptor is visible at the CPL (that is, if the CPL and the RPL of the segment selector are less than or equal to the DPL).
5. Checks that the segment is readable (for the VERR instruction) or writable (for the VERW) instruction.

The VERR instruction sets the ZF flag in the EFLAGS register if the segment is visible at the CPL and readable; the VERW sets the ZF flag if the segment is visible and writable. (Code segments are never writable.) The ZF flag is cleared if any of these checks fail.

4.10.3. Checking That the Pointer Offset Is Within Limits (LSL Instruction)

When the processor accesses any segment it performs a limit check to insure that the offset is within the limit of the segment. Software can perform this limit check using the LSL (load segment limit) instruction. Like the LAR instruction, the LSL instruction specifies the segment selector for the segment descriptor whose limit is to be checked and a destination register. The instruction then performs the following operations:

1. Check that the segment selector is not null.
2. Checks that the segment selector points to a segment descriptor that is within the descriptor table limit (GDT or LDT).
3. Checks that the segment descriptor is a code, data, LDT, or TSS segment-descriptor type.
4. If the segment is not a conforming code segment, checks if the segment descriptor is visible at the CPL (that is, if the CPL and the RPL of the segment selector less than or equal to the DPL).
5. If the privilege level and type checks pass, loads the unscrambled limit (the limit scaled according to the setting of the G flag in the segment descriptor) into the destination register and sets the ZF flag in the EFLAGS register. If the segment selector is not visible at the current privilege level or is an invalid type for the LSL instruction, the instruction does not modify the destination register and clears the ZF flag.

Once loaded in the destination register, software can compare the segment limit with the offset of a pointer.

4.10.4. Checking Caller Access Privileges (ARPL Instruction)

The requestor's privilege level (RPL) field of a segment selector is intended to carry the privilege level of a calling procedure (the calling procedure's CPL) to a called procedure. The called procedure then uses the RPL to determine if access to a segment is allowed. The RPL is said to "weaken" the privilege level of the called procedure to that of the RPL.

Operating-system procedures typically use the RPL to prevent less privileged application programs from accessing data located in more privileged segments. When an operating-system procedure (the called procedure) receives a segment selector from an application program (the calling procedure), it sets the segment selector's RPL to the privilege level of the calling procedure. Then, when the operating system uses the segment selector to access its associated segment, the processor performs privilege checks using the calling procedure's privilege level (stored in the RPL) rather than the numerically lower privilege level (the CPL) of the operating-system procedure. The RPL thus insures that the operating system does not access a segment on behalf of an application program unless that program itself has access to the segment.

Figure 4-12 shows an example of how the processor uses the RPL field. In this example, an application program (located in code segment A) possesses a segment selector (segment selector D1) that points to a privileged data structure (that is, a data structure located in a data segment D at privilege level 0). The application program cannot access data segment D, because it does

not have sufficient privilege, but the operating system (located in code segment C) can. So, in an attempt to access data segment D, the application program executes a call to the operating system and passes segment selector D1 to the operating system as a parameter on the stack. Before passing the segment selector, the (well behaved) application program sets the RPL of the segment selector to its current privilege level (which in this example is 3). If the operating system attempts to access data segment D using segment selector D1, the processor compares the CPL (which is now 0 following the call), the RPL of segment selector D1, and the DPL of data segment D (which is 0). Since the RPL is greater than the DPL, access to data segment D is denied. The processor's protection mechanism thus protects data segment D from access by the operating system, because application program's privilege level (represented by the RPL of segment selector B) is greater than the DPL of data segment D.

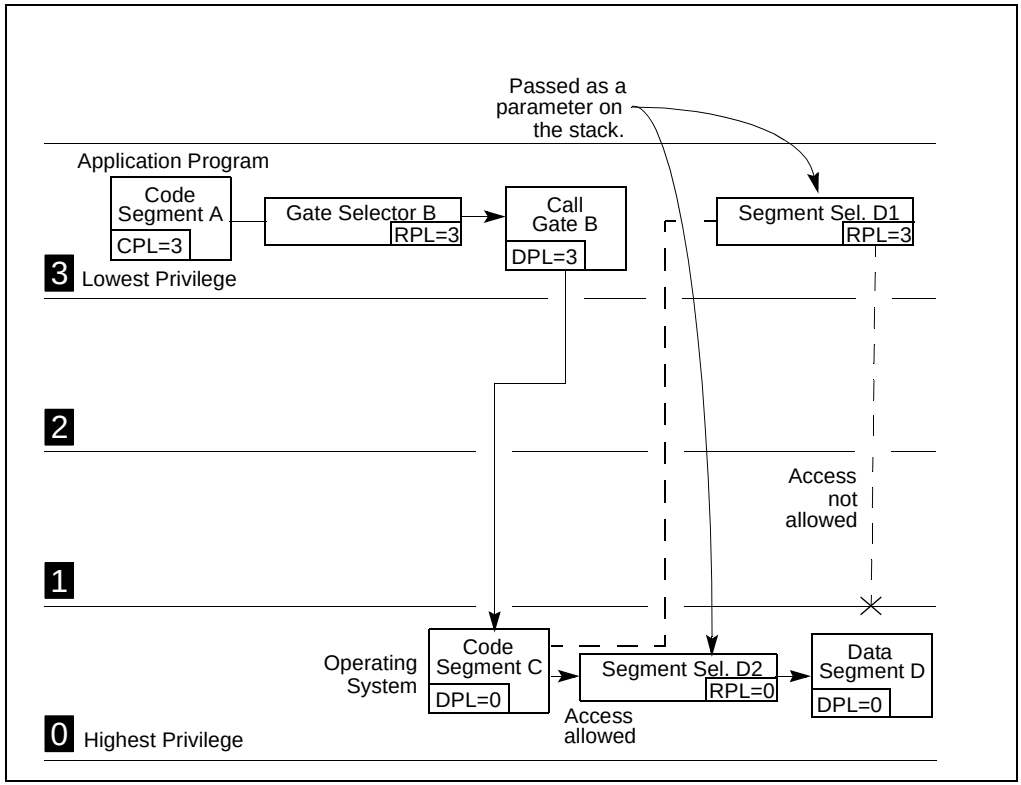


Figure 4-12. Use of RPL to Weaken Privilege Level of Called Procedure

Now assume that instead of setting the RPL of the segment selector to 3, the application program sets the RPL to 0 (segment selector D2). The operating system can now access data segment D, because its CPL and the RPL of segment selector D2 are both equal to the DPL of data segment D. Because the application program is able to change the RPL of a segment selector to any value, it can potentially use a procedure operating at a numerically lower privilege level to access a

protected data structure. This ability to lower the RPL of a segment selector breaches the processor's protection mechanism.

Because a called procedure cannot rely on the calling procedure to set the RPL correctly, operating-system procedures (executing at numerically lower privilege-levels) that receive segment selectors from numerically higher privilege-level procedures need to test the RPL of the segment selector to determine if it is at the appropriate level. The ARPL (adjust requested privilege level) instruction is provided for this purpose. This instruction adjusts the RPL of one segment selector to match that of another segment selector.

The example in Figure 4-12 demonstrates how the ARPL instruction is intended to be used. When the operating-system receives segment selector D2 from the application program, it uses the ARPL instruction to compare the RPL of the segment selector with the privilege level of the application program (represented by the code-segment selector pushed onto the stack). If the RPL is less than application program's privilege level, the ARPL instruction changes the RPL of the segment selector to match the privilege level of the application program (segment selector D1). Using this instruction thus prevents a procedure running at a numerically higher privilege level from accessing numerically lower privilege-level (more privileged) segments by lowering the RPL of a segment selector.

Note that the privilege level of the application program can be determined by reading the RPL field of the segment selector for the application-program's code segment. This segment selector is stored on the stack as part of the call to the operating system. The operating system can copy the segment selector from the stack into a register for use as an operand for the ARPL instruction.

4.10.5. Checking Alignment

When the CPL is 3, alignment of memory references can be checked by setting the AM flag in the CR0 register and the AC flag in the EFLAGS register. Unaligned memory references generate alignment exceptions (#AC). The processor does not generate alignment exceptions when operating at privilege level 0, 1, or 2. Refer to Table 5-7 in Chapter 5, *Interrupt and Exception Handling* for a description of the alignment requirements when alignment checking is enabled.

4.11. PAGE-LEVEL PROTECTION

Page-level protection can be used alone or applied to segments. When page-level protection is used with the flat memory model, it allows supervisor code and data (the operating system or executive) to be protected from user code and data (application programs). It also allows pages containing code to be write protected. When the segment- and page-level protection are combined, page-level read/write protection allows more protection granularity within segments.

With page-level protection (as with segment-level protection) each memory reference is checked to verify that protection checks are satisfied. All checks are made before the memory cycle is started, and any violation prevents the cycle from starting and results in a page-fault

exception being generated. Because checks are performed in parallel with address translation, there is no performance penalty.

The processor performs two page-level protection checks:

- Restriction of addressable domain (supervisor and user modes).
- Page type (read only or read/write).

Violations of either of these checks results in a page-fault exception being generated. Refer to Chapter 5, *Interrupt and Exception Handling* for an explanation of the page-fault exception mechanism. This chapter describes the protection violations which lead to page-fault exceptions.

4.11.1. Page-Protection Flags

Protection information for pages is contained in two flags in a page-directory or page-table entry (refer to Figure 3-14 in Chapter 3, *Protected-Mode Memory Management*): the read/write flag (bit 1) and the user/supervisor flag (bit 2). The protection checks are applied to both first- and second-level page tables (that is, page directories and page tables).

4.11.2. Restricting Addressable Domain

The page-level protection mechanism allows restricting access to pages based on two privilege levels:

- Supervisor mode (U/S flag is 0)—(Most privileged) For the operating system or executive, other system software (such as device drivers), and protected system data (such as page tables).
- User mode (U/S flag is 1)—(Least privileged) For application code and data.

The segment privilege levels map to the page privilege levels as follows. If the processor is currently operating at a CPL of 0, 1, or 2, it is in supervisor mode; if it is operating at a CPL of 3, it is in user mode. When the processor is in supervisor mode, it can access all pages; when in user mode, it can access only user-level pages. (Note that the WP flag in control register CR0 modifies the supervisor permissions, as described in Section 4.11.3., “Page Type”)

Note that to use the page-level protection mechanism, code and data segments must be set up for at least two segment-based privilege levels: level 0 for supervisor code and data segments and level 3 for user code and data segments. (In this model, the stacks are placed in the data segments.) To minimize the use of segments, a flat memory model can be used (refer to Section 3.2.1., “Basic Flat Model” in Section 3, “Protected-Mode Memory Management”). Here, the user and supervisor code and data segments all begin at address zero in the linear address space and overlay each other. With this arrangement, operating-system code (running at the supervisor level) and application code (running at the user level) can execute as if there are no segments. Protection between operating-system and application code and data is provided by the processor’s page-level protection mechanism.

4.11.3. Page Type

The page-level protection mechanism recognizes two page types:

- Read-only access (R/W flag is 0).
- Read/write access (R/W flag is 1).

When the processor is in supervisor mode and the WP flag in register CR0 is clear (its state following reset initialization), all pages are both readable and writable (write-protection is ignored). When the processor is in user mode, it can write only to user-mode pages that are read/write accessible. User-mode pages which are read/write or read-only are readable; supervisor-mode pages are neither readable nor writable from user mode. A page-fault exception is generated on any attempt to violate the protection rules.

The P6 family, Pentium®, and Intel486™ processors allow user-mode pages to be write-protected against supervisor-mode access. Setting the WP flag in register CR0 to 1 enables supervisor-mode sensitivity to user-mode, write-protected pages. This supervisor write-protect feature is useful for implementing a “copy-on-write” strategy used by some operating systems, such as UNIX*, for task creation (also called forking or spawning). When a new task is created, it is possible to copy the entire address space of the parent task. This gives the child task a complete, duplicate set of the parent's segments and pages. An alternative copy-on-write strategy saves memory space and time by mapping the child's segments and pages to the same segments and pages used by the parent task. A private copy of a page gets created only when one of the tasks writes to the page. By using the WP flag and marking the shared pages as read-only, the supervisor can detect an attempt to write to a user-level page, and can copy the page at that time.

4.11.4. Combining Protection of Both Levels of Page Tables

For any one page, the protection attributes of its page-directory entry (first-level page table) may differ from those of its page-table entry (second-level page table). The processor checks the protection for a page in both its page-directory and the page-table entries. Table 4-2 shows the protection provided by the possible combinations of protection attributes when the WP flag is clear.

4.11.5. Overrides to Page Protection

The following types of memory accesses are checked as if they are privilege-level 0 accesses, regardless of the CPL at which the processor is currently operating:

- Access to segment descriptors in the GDT, LDT, or IDT.
- Access to an inner-privilege-level stack during an inter-privilege-level call or a call to in exception or interrupt handler, when a change of privilege level occurs.

4.12. COMBINING PAGE AND SEGMENT PROTECTION

When paging is enabled, the processor evaluates segment protection first, then evaluates page protection. If the processor detects a protection violation at either the segment level or the page level, the memory access is not carried out and an exception is generated. If an exception is generated by segmentation, no paging exception is generated.

Page-level protections cannot be used to override segment-level protection. For example, a code segment is by definition not writable. If a code segment is paged, setting the R/W flag for the pages to read-write does not make the pages writable. Attempts to write into the pages will be blocked by segment-level protection checks.

Page-level protection can be used to enhance segment-level protection. For example, if a large read-write data segment is paged, the page-protection mechanism can be used to write-protect individual pages.

Table 4-2. Combined Page-Directory and Page-Table Protection

Page-Directory Entry		Page-Table Entry		Combined Effect	
Privilege	**Access Type**	**Privilege**	**Access Type**	**Privilege**	**Access Type**
User	Read-Only	User	Read-Only	User	Read-Only
User	Read-Only	User	Read-Write	User	Read-Only
User	Read-Write	User	Read-Only	User	Read-Only
User	Read-Write	User	Read-Write	User	Read/Write
User	Read-Only	Supervisor	Read-Only	Supervisor	Read/Write*
User	Read-Only	Supervisor	Read-Write	Supervisor	Read/Write*
User	Read-Write	Supervisor	Read-Only	Supervisor	Read/Write*
User	Read-Write	Supervisor	Read-Write	Supervisor	Read/Write
Supervisor	Read-Only	User	Read-Only	Supervisor	Read/Write*
Supervisor	Read-Only	User	Read-Write	Supervisor	Read/Write*
Supervisor	Read-Write	User	Read-Only	Supervisor	Read/Write*
Supervisor	Read-Write	User	Read-Write	Supervisor	Read/Write
Supervisor	Read-Only	Supervisor	Read-Only	Supervisor	Read/Write*
Supervisor	Read-Only	Supervisor	Read-Write	Supervisor	Read/Write*
Supervisor	Read-Write	Supervisor	Read-Only	Supervisor	Read/Write*
Supervisor	Read-Write	Supervisor	Read-Write	Supervisor	Read/Write

NOTE:

* If the WP flag of CR0 is set, the access type is determined by the R/W flags of the page-directory and page-table entries.

5

Interrupt and Exception Handling

CHAPTER 5
INTERRUPT AND EXCEPTION HANDLING

This chapter describes the processor's interrupt and exception-handling mechanism, when operating in protected mode. Most of the information provided here also applies to the interrupt and exception mechanism used in real-address or virtual-8086 mode. Refer to Chapter 16, *8086 Emulation* for a description of the differences in the interrupt and exception mechanism for real-address and virtual-8086 mode.

5.1. INTERRUPT AND EXCEPTION OVERVIEW

Interrupts and exceptions are forced transfers of execution from the currently running program or task to a special procedure or task called a **handler**. Interrupts typically occur at random times during the execution of a program, in response to signals from hardware. They are used to handle events external to the processor, such as requests to service peripheral devices. Software can also generate interrupts by executing the INT *n* instruction. Exceptions occur when the processor detects an error condition while executing an instruction, such as division by zero. The processor detects a variety of error conditions including protection violations, page faults, and internal machine faults. The **machine-check architecture** of the P6 family and Pentium® processors also permits a machine-check exception to be generated when internal hardware errors and bus errors are detected.

The processor's interrupt and exception-handling mechanism allows interrupts and exceptions to be handled transparently to application programs and the operating system or executive. When an interrupt is received or an exception is detected, the currently running procedure or task is automatically suspended while the processor executes an interrupt or exception handler. When execution of the handler is complete, the processor resumes execution of the interrupted procedure or task. The resumption of the interrupted procedure or task happens without loss of program continuity, unless recovery from an exception was not possible or an interrupt caused the currently running program to be terminated.

This chapter describes the processor's interrupt and exception-handling mechanism, when operating in protected mode. A detailed description of the exceptions and the conditions that cause them to be generated is given at the end of this chapter. Refer to Chapter 16, *8086 Emulation* for a description of the interrupt and exception mechanism for real-address and virtual-8086 mode.

5.1.1. Sources of Interrupts

The processor receives interrupts from two sources:

- External (hardware generated) interrupts.
- Software-generated interrupts.

5.1.1.1. EXTERNAL INTERRUPTS

External interrupts are received through pins on the processor or through the local APIC serial bus. The primary interrupt pins on a P6 family or Pentium® processor are the LINT[1:0] pins, which are connected to the local APIC (refer to Section 7.5., "Advanced Programmable Interrupt Controller (APIC)" in Chapter 7, *Multiple-Processor Management*). When the local APIC is disabled, these pins are configured as INTR and NMI pins, respectively. Asserting the INTR pin signals the processor that an external interrupt has occurred, and the processor reads from the system bus the interrupt vector number provided by an external interrupt controller, such as an 8259A (refer to Section 5.2., "Exception and Interrupt Vectors"). Asserting the NMI pin signals a nonmaskable interrupt (NMI), which is assigned to interrupt vector 2.

When the local APIC is enabled, the LINT[1:0] pins can be programmed through the APIC's vector table to be associated with any of the processor's exception or interrupt vectors.

The processor's local APIC can be connected to a system-based I/O APIC. Here, external interrupts received at the I/O APIC's pins can be directed to the local APIC through the APIC serial bus (pins PICD[1:0]). The I/O APIC determines the vector number of the interrupt and sends this number to the local APIC. When a system contains multiple processors, processors can also send interrupts to one another by means of the APIC serial bus.

The LINT[1:0] pins are not available on the Intel486™ processor and the earlier Pentium® processors that do not contain an on-chip local APIC. Instead these processors have dedicated NMI and INTR pins. With these processors, external interrupts are typically generated by a system-based interrupt controller (8259A), with the interrupts being signaled through the INTR pin.

Note that several other pins on the processor cause a processor interrupt to occur; however, these interrupts are not handled by the interrupt and exception mechanism described in this chapter. These pins include the RESET#, FLUSH#, STPCLK#, SMI#, R/S#, and INIT# pins. Which of these pins are included on a particular Intel Architecture processor is implementation dependent. The functions of these pins are described in the data books for the individual processors. The SMI# pin is also described in Chapter 12, *System Management Mode (SMM)*.

5.1.1.2. MASKABLE HARDWARE INTERRUPTS

Any external interrupt that is delivered to the processor by means of the INTR pin or through the local APIC is called a **maskable hardware interrupt**. The maskable hardware interrupts that can be delivered through the INTR pin include all Intel Architecture defined interrupt vectors from 0 through 255; those that can be delivered through the local APIC include interrupt vectors 16 through 255.

All maskable hardware interrupts can be masked as a group. Use the single IF flag in the EFLAGS register (refer to Section 5.6.1., "Masking Maskable Hardware Interrupts") to mask these maskable interrupts. Note that when interrupts 0 through 15 are delivered through the local APIC, the APIC indicates the receipt of an illegal vector.

5.1.1.3. SOFTWARE-GENERATED INTERRUPTS

The INT *n* instruction permits interrupts to be generated from within software by supplying the interrupt vector number as an operand. For example, the INT 35 instruction forces an implicit call to the interrupt handler for interrupt 35.

Any of the interrupt vectors from 0 to 255 can be used as a parameter in this instruction. If the processor's predefined NMI vector is used, however, the response of the processor will not be the same as it would be from an NMI interrupt generated in the normal manner. If vector number 2 (the NMI vector) is used in this instruction, the NMI interrupt handler is called, but the processor's NMI-handling hardware is not activated.

Note that interrupts generated in software with the INT *n* instruction cannot be masked by the IF flag in the EFLAGS register.

5.1.2. Sources of Exceptions

The processor receives exceptions from three sources:

- Processor-detected program-error exceptions.
- Software-generated exceptions.
- Machine-check exceptions.

5.1.2.1. PROGRAM-ERROR EXCEPTIONS

The processor generates one or more exceptions when it detects program errors during the execution in an application program or the operating system or executive. The Intel Architecture defines a vector number for each processor-detectable exception. The exceptions are further classified as **faults**, **traps**, and **aborts** (refer to Section 5.3., "Exception Classifications").

5.1.2.2. SOFTWARE-GENERATED EXCEPTIONS

The INTO, INT 3, and BOUND instructions permit exceptions to be generated in software. These instructions allow checks for specific exception conditions to be performed at specific points in the instruction stream. For example, the INT 3 instruction causes a breakpoint exception to be generated.

The INT *n* instruction can be used to emulate a specific exception in software, with one limitation. If the *n* operand in the INT *n* instruction contains a vector for one of the Intel Architecture exceptions, the processor will generate an interrupt to that vector, which will in turn invoke the exception handler associated with that vector. Because this is actually an interrupt, however, the processor does not push an error code onto the stack, even if a hardware-generated exception for that vector normally produces one. For those exceptions that produce an error code, the exception handler will attempt to pop an error code from the stack while handling the exception. If the INT *n* instruction was used to emulate the generation of an exception, the handler will pop off and discard the EIP (in place of the missing error code), sending the return to the wrong location.

5.1.2.3. MACHINE-CHECK EXCEPTIONS

The P6 family and Pentium® processors provide both internal and external machine-check mechanisms for checking the operation of the internal chip hardware and bus transactions. These mechanisms constitute extended (implementation dependent) exception mechanisms. When a machine-check error is detected, the processor signals a machine-check exception (vector 18) and returns an error code. Refer to "Interrupt 18—Machine Check Exception (#MC)" at the end of this chapter and Chapter 13, *Machine-Check Architecture*, for a detailed description of the machine-check mechanism.

5.2. EXCEPTION AND INTERRUPT VECTORS

The processor associates an identification number, called a **vector**, with each exception and interrupt. Table 5-1 shows the assignment of exception and interrupt vectors. This table also gives the exception type for each vector, indicates whether an error code is saved on the stack for an exception, and gives the source of the exception or interrupt.

The vectors in the range 0 through 31 are assigned to the exceptions and the NMI interrupt. Not all of these vectors are currently used by the processor. Unassigned vectors in this range are reserved for possible future uses. **Do not use the reserved vectors.**

The vectors in the range 32 to 255 are designated as user-defined interrupts. These interrupts are not reserved by the Intel Architecture and are generally assigned to external I/O devices and to permit them to signal the processor through one of the external hardware interrupt mechanisms described in Section 5.1.1., "Sources of Interrupts"

5.3. EXCEPTION CLASSIFICATIONS

Exceptions are classified as **faults**, **traps**, or **aborts** depending on the way they are reported and whether the instruction that caused the exception can be restarted with no loss of program or task continuity.

Faults

A fault is an exception that can generally be corrected and that, once corrected, allows the program to be restarted with no loss of continuity. When a fault is reported, the processor restores the machine state to the state prior to the beginning of execution of the faulting instruction. The return address (saved contents of the CS and EIP registers) for the fault handler points to the faulting instruction, rather than the instruction following the faulting instruction.

Note: There are a small subset of exceptions that are normally reported as faults, but under architectural corner cases, they are not restartable and some processor context will be lost. An example of these cases is the execution of the POPAD instruction where the stack frame crosses over the the end of the stack segment. The exception handler will see that the CS:EIP has been restored as if the POPAD instruction had not executed however internal processor state (general purpose registers) will have been modified. These corner cases are

considered programming errors and an application causeing this class of exceptions will likely be terminated by the operating system.

Traps — A trap is an exception that is reported immediately following the execution of the trapping instruction. Traps allow execution of a program or task to be continued without loss of program continuity. The return address for the trap handler points to the instruction to be executed after the trapping instruction.

Aborts — An abort is an exception that does not always report the precise location of the instruction causing the exception and does not allow restart of the program or task that caused the exception. Aborts are used to report severe errors, such as hardware errors and inconsistent or illegal values in system tables.

Table 5-1. Protected-Mode Exceptions and Interrupts

Vector No.	Mnemonic	Description	Type	Error Code	Source
0	#DE	Divide Error	Fault	No	DIV and IDIV instructions.
1	#DB	Debug	Fault/ Trap	No	Any code or data reference or the INT 1 instruction.
2	—	NMI Interrupt	Interrupt	No	Nonmaskable external interrupt.
3	#BP	Breakpoint	Trap	No	INT 3 instruction.
4	#OF	Overflow	Trap	No	INTO instruction.
5	#BR	BOUND Range Exceeded	Fault	No	BOUND instruction.
6	#UD	Invalid Opcode (Undefined Opcode)	Fault	No	UD2 instruction or reserved opcode.[1]
7	#NM	Device Not Available (No Math Coprocessor)	Fault	No	Floating-point or WAIT/FWAIT instruction.
8	#DF	Double Fault	Abort	Yes (Zero)	Any instruction that can generate an exception, an NMI, or an INTR.
9		Coprocessor Segment Overrun (reserved)	Fault	No	Floating-point instruction.[2]
10	#TS	Invalid TSS	Fault	Yes	Task switch or TSS access.
11	#NP	Segment Not Present	Fault	Yes	Loading segment registers or accessing system segments.
12	#SS	Stack-Segment Fault	Fault	Yes	Stack operations and SS register loads.
13	#GP	General Protection	Fault	Yes	Any memory reference and other protection checks.
14	#PF	Page Fault	Fault	Yes	Any memory reference.
15	—	(Intel reserved. Do not use.)		No	
16	#MF	Floating-Point Error (Math Fault)	Fault	No	Floating-point or WAIT/FWAIT instruction.
17	#AC	Alignment Check	Fault	Yes (Zero)	Any data reference in memory.[3]
18	#MC	Machine Check	Abort	No	Error codes (if any) and source are model dependent.[4]
19	#XF	Streaming SIMD Extensions	Fault	No	SIMD floating-point instructions[5]
20-31	—	Intel reserved. Do not use.			
32-255	—	User Defined (Nonreserved) Interrupts	Interrupt		External interrupt or INT *n* instruction.

NOTES:
1. The UD2 instruction was introduced in the Pentium® Pro processor.
2. Intel Architecture processors after the Intel386™ processor do not generate this exception.
3. This exception was introduced in the Intel486™ processor.
4. This exception was introduced in the Pentium® processor and enhanced in the P6 family processors.
5. This exception was introduced in the Pentium® III processor.

5.4. PROGRAM OR TASK RESTART

To allow restarting of program or task following the handling of an exception or an interrupt, all exceptions except aborts are guaranteed to report the exception on a precise instruction boundary, and all interrupts are guaranteed to be taken on an instruction boundary.

For fault-class exceptions, the return instruction pointer that the processor saves when it generates the exception points to the faulting instruction. So, when a program or task is restarted following the handling of a fault, the faulting instruction is restarted (re-executed). Restarting the faulting instruction is commonly used to handle exceptions that are generated when access to an operand is blocked. The most common example of a fault is a page-fault exception (#PF) that occurs when a program or task references an operand in a page that is not in memory. When a page-fault exception occurs, the exception handler can load the page into memory and resume execution of the program or task by restarting the faulting instruction. To insure that this instruction restart is handled transparently to the currently executing program or task, the processor saves the necessary registers and stack pointers to allow it to restore itself to its state prior to the execution of the faulting instruction.

For trap-class exceptions, the return instruction pointer points to the instruction following the trapping instruction. If a trap is detected during an instruction which transfers execution, the return instruction pointer reflects the transfer. For example, if a trap is detected while executing a JMP instruction, the return instruction pointer points to the destination of the JMP instruction, not to the next address past the JMP instruction. All trap exceptions allow program or task restart with no loss of continuity. For example, the overflow exception is a trapping exception. Here, the return instruction pointer points to the instruction following the INTO instruction that tested the OF (overflow) flag in the EFLAGS register. The trap handler for this exception resolves the overflow condition. Upon return from the trap handler, program or task execution continues at the next instruction following the INTO instruction.

The abort-class exceptions do not support reliable restarting of the program or task. Abort handlers generally are designed to collect diagnostic information about the state of the processor when the abort exception occurred and then shut down the application and system as gracefully as possible.

Interrupts rigorously support restarting of interrupted programs and tasks without loss of continuity. The return instruction pointer saved for an interrupt points to the next instruction to be executed at the instruction boundary where the processor took the interrupt. If the instruction just executed has a repeat prefix, the interrupt is taken at the end of the current iteration with the registers set to execute the next iteration.

The ability of a P6 family processor to speculatively execute instructions does not affect the taking of interrupts by the processor. Interrupts are taken at instruction boundaries located during the retirement phase of instruction execution; so they are always taken in the “in-order” instruction stream. Refer to Chapter 2, *Introduction to the Intel Architecture*, in the *Intel Architecture Software Developer’s Manual, Volume 1*, for more information about the P6 family processors’ microarchitecture and its support for out-of-order instruction execution.

Note that the Pentium® processor and earlier Intel Architecture processors also perform varying amounts of prefetching and preliminary decoding of instructions; however, here also exceptions and interrupts are not signaled until actual “in-order” execution of the instructions. For a given

code sample, the signaling of exceptions will occur uniformly when the code is executed on any family of Intel Architecture processors (except where new exceptions or new opcodes have been defined).

5.5. NONMASKABLE INTERRUPT (NMI)

The nonmaskable interrupt (NMI) can be generated in either of two ways:

- External hardware asserts the NMI pin.
- The processor receives a message on the APIC serial bus of delivery mode NMI.

When the processor receives a NMI from either of these sources, the processor handles it immediately by calling the NMI handler pointed to by interrupt vector number 2. The processor also invokes certain hardware conditions to insure that no other interrupts, including NMI interrupts, are received until the NMI handler has completed executing (refer to Section 5.5.1., “Handling Multiple NMIs”).

Also, when an NMI is received from either of the above sources, it cannot be masked by the IF flag in the EFLAGS register.

It is possible to issue a maskable hardware interrupt (through the INTR pin) to vector 2 to invoke the NMI interrupt handler; however, this interrupt will not truly be an NMI interrupt. A true NMI interrupt that activates the processor’s NMI-handling hardware can only be delivered through one of the mechanisms listed above.

5.5.1. Handling Multiple NMIs

While an NMI interrupt handler is executing, the processor disables additional calls to the NMI handler until the next IRET instruction is executed. This blocking of subsequent NMIs prevents stacking up calls to the NMI handler. It is recommended that the NMI interrupt handler be accessed through an interrupt gate to disable maskable hardware interrupts (refer to Section 5.6.1., “Masking Maskable Hardware Interrupts”).

5.6. ENABLING AND DISABLING INTERRUPTS

The processor inhibits the generation of some interrupts, depending on the state of the processor and of the IF and RF flags in the EFLAGS register, as described in the following sections.

5.6.1. Masking Maskable Hardware Interrupts

The IF flag can disable the servicing of maskable hardware interrupts received on the processor’s INTR pin or through the local APIC (refer to Section 5.1.1.2., “Maskable Hardware Interrupts”). When the IF flag is clear, the processor inhibits interrupts delivered to the INTR pin or through the local APIC from generating an internal interrupt request; when the IF flag is set, interrupts delivered to the INTR or through the local APIC pin are processed as normal

external interrupts. The IF flag does not affect nonmaskable interrupts (NMIs) delivered to the NMI pin or delivery mode NMI messages delivered through the APIC serial bus, nor does it affect processor generated exceptions. As with the other flags in the EFLAGS register, the processor clears the IF flag in response to a hardware reset.

The fact that the group of maskable hardware interrupts includes the reserved interrupt and exception vectors 0 through 32 can potentially cause confusion. Architecturally, when the IF flag is set, an interrupt for any of the vectors from 0 through 32 can be delivered to the processor through the INTR pin and any of the vectors from 16 through 32 can be delivered through the local APIC. The processor will then generate an interrupt and call the interrupt or exception handler pointed to by the vector number. So for example, it is possible to invoke the page-fault handler through the INTR pin (by means of vector 14); however, this is not a true page-fault exception. It is an interrupt. As with the INT *n* instruction (refer to Section 5.1.2.2., "Software-Generated Exceptions"), when an interrupt is generated through the INTR pin to an exception vector, the processor does not push an error code on the stack, so the exception handler may not operate correctly.

The IF flag can be set or cleared with the STI (set interrupt-enable flag) and CLI (clear interrupt-enable flag) instructions, respectively. These instructions may be executed only if the CPL is equal to or less than the IOPL. A general-protection exception (#GP) is generated if they are executed when the CPL is greater than the IOPL. (The effect of the IOPL on these instructions is modified slightly when the virtual mode extension is enabled by setting the VME flag in control register CR4, refer to Section 16.3., "Interrupt and Exception Handling in Virtual-8086 Mode" in Chapter 16, *8086 Emulation*.)

The IF flag is also affected by the following operations:

- The PUSHF instruction stores all flags on the stack, where they can be examined and modified. The POPF instruction can be used to load the modified flags back into the EFLAGS register.
- Task switches and the POPF and IRET instructions load the EFLAGS register; therefore, they can be used to modify the setting of the IF flag.
- When an interrupt is handled through an interrupt gate, the IF flag is automatically cleared, which disables maskable hardware interrupts. (If an interrupt is handled through a trap gate, the IF flag is not cleared.)

Refer to the descriptions of the CLI, STI, PUSHF, POPF, and IRET instructions in Chapter 3, *Instruction Set Reference*, of the *Intel Architecture Software Developer's Manual, Volume 2*, for a detailed description of the operations these instructions are allowed to perform on the IF flag.

5.6.2. Masking Instruction Breakpoints

The RF (resume) flag in the EFLAGS register controls the response of the processor to instruction-breakpoint conditions (refer to the description of the RF flag in Section 2.3., "System Flags and Fields in the EFLAGS Register" in Chapter 2, *System Architecture Overview*). When set, it prevents an instruction breakpoint from generating a debug exception (#DB); when clear, instruction breakpoints will generate debug exceptions. The primary function of the RF flag is

to prevent the processor from going into a debug exception loop on an instruction-breakpoint. Refer to Section 15.3.1.1., “Instruction-Breakpoint Exception Condition”, in Chapter 15, *Debugging and Performance Monitoring*, for more information on the use of this flag.

5.6.3. Masking Exceptions and Interrupts When Switching Stacks

To switch to a different stack segment, software often uses a pair of instructions, for example:

```
MOV SS, AX
MOV ESP, StackTop
```

If an interrupt or exception occurs after the segment selector has been loaded into the SS register but before the ESP register has been loaded, these two parts of the logical address into the stack space are inconsistent for the duration of the interrupt or exception handler.

To prevent this situation, the processor inhibits interrupts, debug exceptions, and single-step trap exceptions after either a MOV to SS instruction or a POP to SS instruction, until the instruction boundary following the next instruction is reached. All other faults may still be generated. If the LSS instruction is used to modify the contents of the SS register (which is the recommended method of modifying this register), this problem does not occur.

5.7. PRIORITY AMONG SIMULTANEOUS EXCEPTIONS AND INTERRUPTS

If more than one exception or interrupt is pending at an instruction boundary, the processor services them in a predictable order. Table 5-3 shows the priority among classes of exception and interrupt sources. While priority among these classes is consistent throughout the architecture, exceptions within each class are implementation-dependent and may vary from processor to processor. The processor first services a pending exception or interrupt from the class which has the highest priority, transferring execution to the first instruction of the handler. Lower priority exceptions are discarded; lower priority interrupts are held pending. Discarded exceptions are re-generated when the interrupt handler returns execution to the point in the program or task where the exceptions and/or interrupts occurred.

The Pentium® III processor added the SIMD floating-point execution unit. The SIMD floating-point execution unit can generate exceptions as well. Since the SIMD floating-point execution unit utilizes a 4-wide register set an exception may result from more than one operand within a SIMD floating-point register. Hence the Pentium® III processor handles these exceptions according to a predetermined precedence. When a sub-operand of a packed instruction generates two or more exception conditions, the exception precedence sometimes results in the higher priority exception being handled and the lower priority exceptions being ignored. Prioritization of exceptions is performed only on a sub-operand basis, and not between suboperands. For example, an invalid exception generated by one sub-operand will not prevent the reporting of a divide-by-zero exception generated by another sub-operand. Table 5-2 shows the precedence for Streaming SIMD Extensions numeric exceptions. The table reflects the order in which interrupts are handled upon simultaneous recognition by the processor (for example, when multiple interrupts are pending at an instruction boundary). However, the table does not necessarily reflect the

order in which interrupts will be recognized by the processor if received simultaneously at the processor pins.

Table 5-2. SIMD Floating-Point Exceptions Priority

Priority	Description
1(Highest)	Invalid operation exception due to SNaN operand (or any NaN operand for max, min, or certain compare and convert operations)
2	QNaN operand[1]
3	Any other invalid operation exception not mentioned above or a divide-by-zero exception[2]
4	Denormal operand exception[2]
5	Numeric overflow and underflow exceptions possibly in conjunction with the inexact result exception[2]
6(Lowest)	Inexact result exception

1. Though this is not an exception, the handling of a QNaN operand has precedence over lower priority exceptions. For example, a QNaN divided by zero results in a QNaN, not a zero-divide exception.
2. If masked, then instruction execution continues, and a lower priority exception can occur as well.

5.8. INTERRUPT DESCRIPTOR TABLE (IDT)

The interrupt descriptor table (IDT) associates each exception or interrupt vector with a gate descriptor for the procedure or task used to service the associated exception or interrupt. Like the GDT and LDTs, the IDT is an array of 8-byte descriptors (in protected mode). Unlike the GDT, the first entry of the IDT may contain a descriptor. To form an index into the IDT, the processor scales the exception or interrupt vector by eight (the number of bytes in a gate descriptor). Because there are only 256 interrupt or exception vectors, the IDT need not contain more than 256 descriptors. It can contain fewer than 256 descriptors, because descriptors are required only for the interrupt and exception vectors that may occur. All empty descriptor slots in the IDT should have the present flag for the descriptor set to 0.

Table 5-3. Priority Among Simultaneous Exceptions and Interrupts

Priority	Descriptions
1 (Highest)	Hardware Reset and Machine Checks - RESET - Machine Check
2	Trap on Task Switch - T flag in TSS is set
3	External Hardware Interventions - FLUSH - STOPCLK - SMI - INIT
4	Traps on the Previous Instruction - Breakpoints - Debug Trap Exceptions (TF flag set or data/I-O breakpoint)
5	External Interrupts - NMI Interrupts - Maskable Hardware Interrupts
6	Faults from Fetching Next Instruction - Code Breakpoint Fault - Code-Segment Limit Violation[1] - Code Page Fault[1]
7	Faults from Decoding the Next Instruction - Instruction length > 15 bytes - Illegal Opcode - Coprocessor Not Available
8 (Lowest)	Faults on Executing an Instruction - Floating-point exception - Overflow - Bound error - Invalid TSS - Segment Not Present - Stack fault - General Protection - Data Page Fault - Alignment Check - SIMD floating-point exception

NOTE:

1. For the Pentium® and Intel486™ processors, the Code Segment Limit Violation and the Code Page Fault exceptions are assigned to the priority 7.

The base addresses of the IDT should be aligned on an 8-byte boundary to maximize performance of cache line fills. The limit value is expressed in bytes and is added to the base address to get the address of the last valid byte. A limit value of 0 results in exactly 1 valid byte. Because IDT entries are always eight bytes long, the limit should always be one less than an integral multiple of eight (that is, 8N – 1).

The IDT may reside anywhere in the linear address space. As shown in Figure 5-1, the processor locates the IDT using the IDTR register. This register holds both a 32-bit base address and 16-bit limit for the IDT.

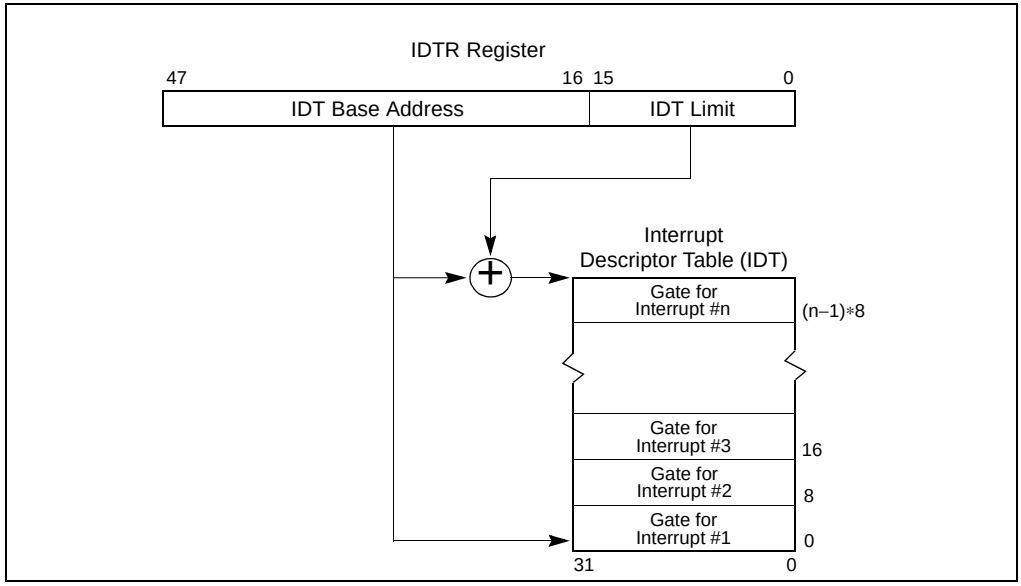


Figure 5-1. Relationship of the IDTR and IDT

The LIDT (load IDT register) and SIDT (store IDT register) instructions load and store the contents of the IDTR register, respectively. The LIDT instruction loads the IDTR register with the base address and limit held in a memory operand. This instruction can be executed only when the CPL is 0. It normally is used by the initialization code of an operating system when creating an IDT. An operating system also may use it to change from one IDT to another. The SIDT instruction copies the base and limit value stored in IDTR to memory. This instruction can be executed at any privilege level.

If a vector references a descriptor beyond the limit of the IDT, a general-protection exception (#GP) is generated.

5.9. IDT DESCRIPTORS

The IDT may contain any of three kinds of gate descriptors:

- Task-gate descriptor
- Interrupt-gate descriptor
- Trap-gate descriptor

Figure 5-2 shows the formats for the task-gate, interrupt-gate, and trap-gate descriptors. The format of a task gate used in an IDT is the same as that of a task gate used in the GDT or an LDT (refer to Section 6.2.4., "Task-Gate Descriptor" in Chapter 6, *Task Management*). The task gate contains the segment selector for a TSS for an exception and/or interrupt handler task.

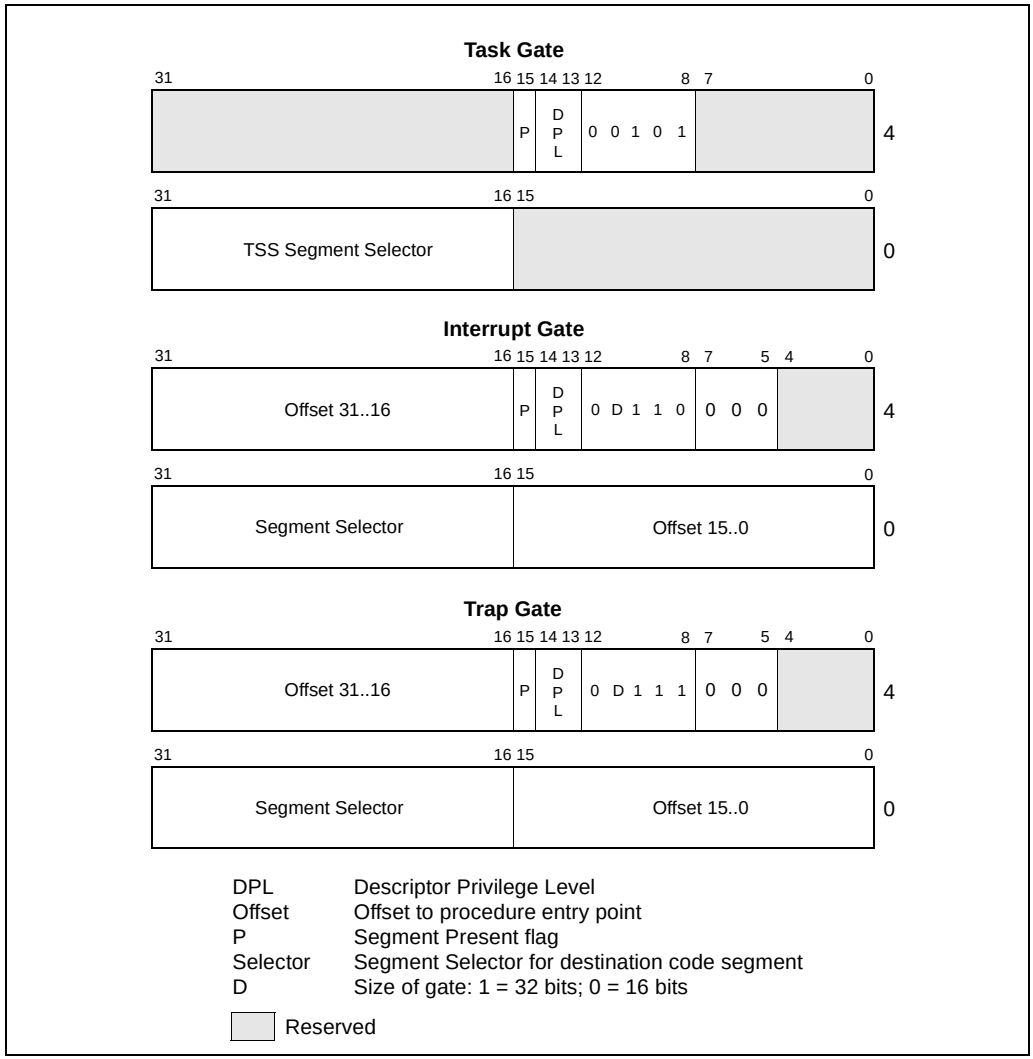


Figure 5-2. IDT Gate Descriptors

Interrupt and trap gates are very similar to call gates (refer to Section 4.8.3., "Call Gates" in Chapter 4, *Protection*). They contain a far pointer (segment selector and offset) that the processor uses to transfer execution to a handler procedure in an exception- or interrupt-handler

code segment. These gates differ in the way the processor handles the IF flag in the EFLAGS register (refer to Section 5.10.1.2., “Flag Usage By Exception- or Interrupt-Handler Procedure”).

5.10. EXCEPTION AND INTERRUPT HANDLING

The processor handles calls to exception- and interrupt-handlers similar to the way it handles calls with a CALL instruction to a procedure or a task. When responding to an exception or interrupt, the processor uses the exception or interrupt vector as an index to a descriptor in the IDT. If the index points to an interrupt gate or trap gate, the processor calls the exception or interrupt handler in a manner similar to a CALL to a call gate (refer to Section 4.8.2., “Gate Descriptors” through Section 4.8.6., “Returning from a Called Procedure” in Chapter 4, *Protection*). If index points to a task gate, the processor executes a task switch to the exception- or interrupt-handler task in a manner similar to a CALL to a task gate (refer to Section 6.3., “Task Switching” in Chapter 6, *Task Management*).

5.10.1. Exception- or Interrupt-Handler Procedures

An interrupt gate or trap gate references an exception- or interrupt-handler procedure that runs in the context of the currently executing task (refer to Figure 5-3). The segment selector for the gate points to a segment descriptor for an executable code segment in either the GDT or the current LDT. The offset field of the gate descriptor points to the beginning of the exception- or interrupt-handling procedure.

When the processor performs a call to the exception- or interrupt-handler procedure, it saves the current states of the EFLAGS register, CS register, and EIP register on the stack (refer to Figure 5-4). (The CS and EIP registers provide a return instruction pointer for the handler.) If an exception causes an error code to be saved, it is pushed on the stack after the EIP value.

If the handler procedure is going to be executed at the same privilege level as the interrupted procedure, the handler uses the current stack.

If the handler procedure is going to be executed at a numerically lower privilege level, a stack switch occurs. When a stack switch occurs, a stack pointer for the stack to be returned to is also saved on the stack. (The SS and ESP registers provide a return stack pointer for the handler.) The segment selector and stack pointer for the stack to be used by the handler is obtained from the TSS for the currently executing task. The processor copies the EFLAGS, SS, ESP, CS, EIP, and error code information from the interrupted procedure’s stack to the handler’s stack.

To return from an exception- or interrupt-handler procedure, the handler must use the IRET (or IRETD) instruction. The IRET instruction is similar to the RET instruction except that it restores the saved flags into the EFLAGS register. The IOPL field of the EFLAGS register is restored only if the CPL is 0. The IF flag is changed only if the CPL is less than or equal to the IOPL. Refer to “IRET/IRETD—Interrupt Return” in Chapter 3 of the *Intel Architecture Software Developer’s Manual, Volume 2,* for the complete operation performed by the IRET instruction.

If a stack switch occurred when calling the handler procedure, the IRET instruction switches back to the interrupted procedure’s stack on the return.

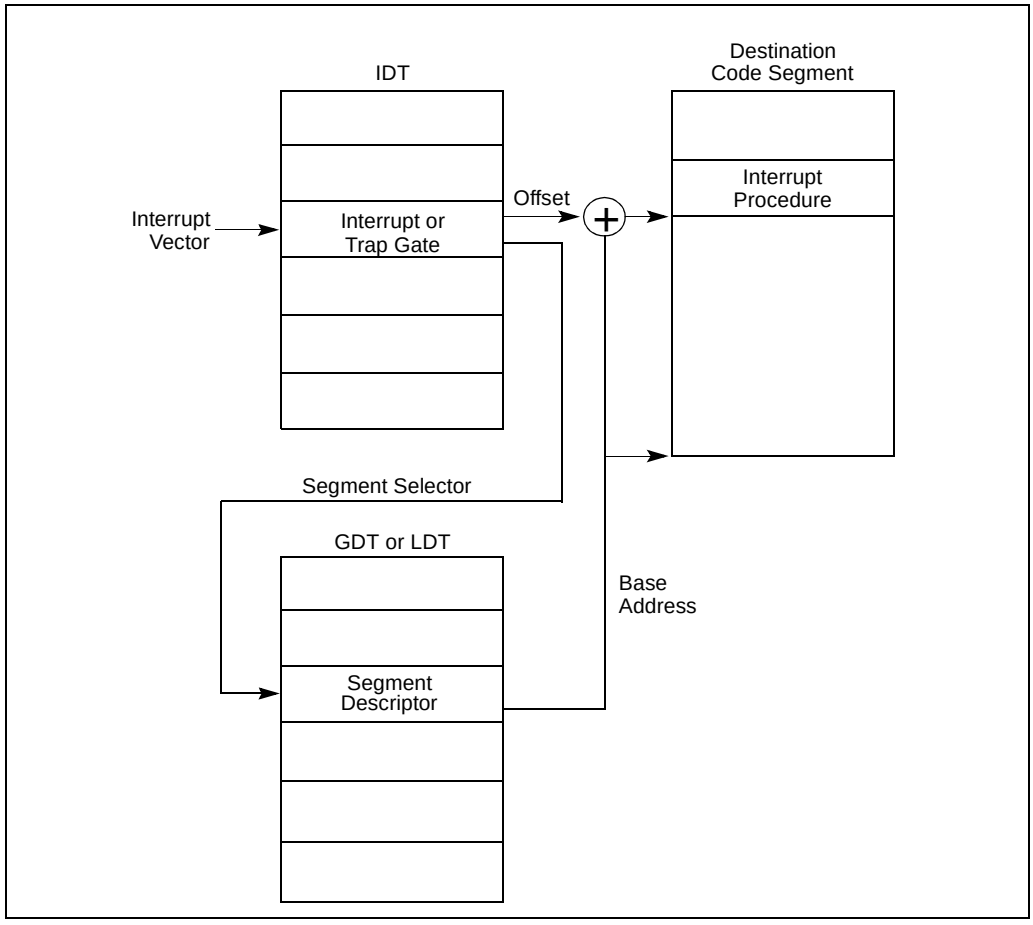


Figure 5-3. Interrupt Procedure Call

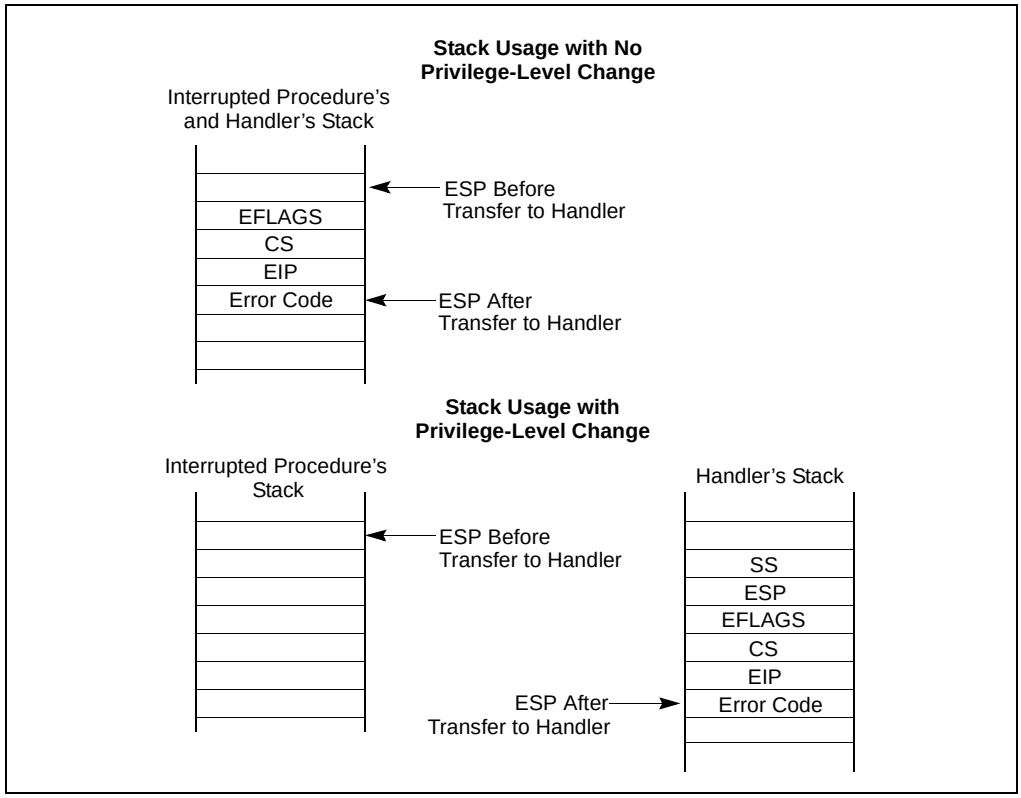


Figure 5-4. Stack Usage on Transfers to Interrupt and Exception-Handling Routines

5.10.1.1. PROTECTION OF EXCEPTION- AND INTERRUPT-HANDLER PROCEDURES

The privilege-level protection for exception- and interrupt-handler procedures is similar to that used for ordinary procedure calls when called through a call gate (refer to Section 4.8.4., "Accessing a Code Segment Through a Call Gate" in Chapter 4, *Protection*). The processor does not permit transfer of execution to an exception- or interrupt-handler procedure in a less privileged code segment (numerically greater privilege level) than the CPL. An attempt to violate this rule results in a general-protection exception (#GP). The protection mechanism for exception- and interrupt-handler procedures is different in the following ways:

- Because interrupt and exception vectors have no RPL, the RPL is not checked on implicit calls to exception and interrupt handlers.
- The processor checks the DPL of the interrupt or trap gate only if an exception or interrupt is generated with an INT *n*, INT 3, or INTO instruction. Here, the CPL must be less than or equal to the DPL of the gate. This restriction prevents application programs or procedures running at privilege level 3 from using a software interrupt to access critical exception

handlers, such as the page-fault handler, providing that those handlers are placed in more privileged code segments (numerically lower privilege level). For hardware-generated interrupts and processor-detected exceptions, the processor ignores the DPL of interrupt and trap gates.

Because exceptions and interrupts generally do not occur at predictable times, these privilege rules effectively impose restrictions on the privilege levels at which exception and interrupt-handling procedures can run. Either of the following techniques can be used to avoid privilege-level violations.

- The exception or interrupt handler can be placed in a conforming code segment. This technique can be used for handlers that only need to access data available on the stack (for example, divide error exceptions). If the handler needs data from a data segment, the data segment needs to be accessible from privilege level 3, which would make it unprotected.
- The handler can be placed in a nonconforming code segment with privilege level 0. This handler would always run, regardless of the CPL that the interrupted program or task is running at.

5.10.1.2. FLAG USAGE BY EXCEPTION- OR INTERRUPT-HANDLER PROCEDURE

When accessing an exception or interrupt handler through either an interrupt gate or a trap gate, the processor clears the TF flag in the EFLAGS register after it saves the contents of the EFLAGS register on the stack. (On calls to exception and interrupt handlers, the processor also clears the VM, RF, and NT flags in the EFLAGS register, after they are saved on the stack.) Clearing the TF flag prevents instruction tracing from affecting interrupt response. A subsequent IRET instruction restores the TF (and VM, RF, and NT) flags to the values in the saved contents of the EFLAGS register on the stack.

The only difference between an interrupt gate and a trap gate is the way the processor handles the IF flag in the EFLAGS register. When accessing an exception- or interrupt-handling procedure through an interrupt gate, the processor clears the IF flag to prevent other interrupts from interfering with the current interrupt handler. A subsequent IRET instruction restores the IF flag to its value in the saved contents of the EFLAGS register on the stack. Accessing a handler procedure through a trap gate does not affect the IF flag.

5.10.2. Interrupt Tasks

When an exception or interrupt handler is accessed through a task gate in the IDT, a task switch results. Handling an exception or interrupt with a separate task offers several advantages:

- The entire context of the interrupted program or task is saved automatically.
- A new TSS permits the handler to use a new privilege level 0 stack when handling the exception or interrupt. If an exception or interrupt occurs when the current privilege level 0 stack is corrupted, accessing the handler through a task gate can prevent a system crash by providing the handler with a new privilege level 0 stack.

- The handler can be further isolated from other tasks by giving it a separate address space. This is done by giving it a separate LDT.

The disadvantage of handling an interrupt with a separate task is that the amount of machine state that must be saved on a task switch makes it slower than using an interrupt gate, resulting in increased interrupt latency.

A task gate in the IDT references a TSS descriptor in the GDT (refer to Figure 5-5). A switch to the handler task is handled in the same manner as an ordinary task switch (refer to Section 6.3., "Task Switching" in Chapter 6, *Task Management*). The link back to the interrupted task is stored in the previous task link field of the handler task's TSS. If an exception caused an error code to be generated, this error code is copied to the stack of the new task.

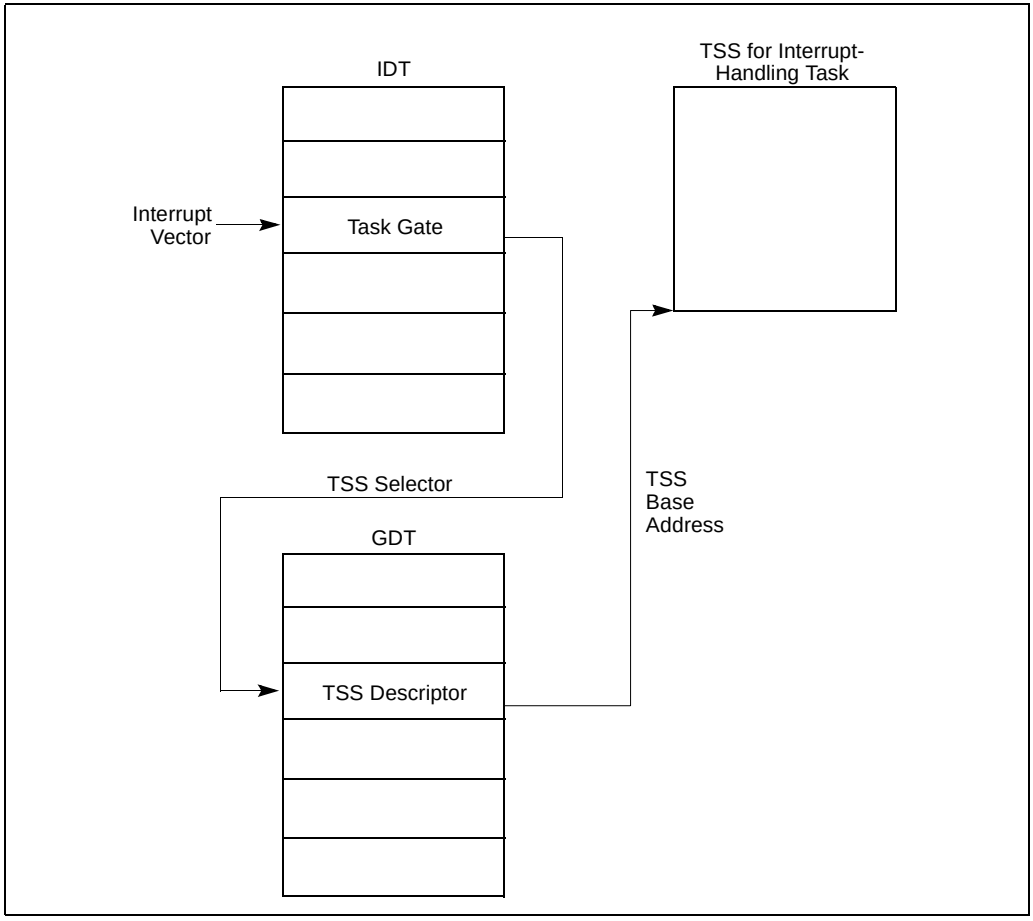


Figure 5-5. Interrupt Task Switch

When exception- or interrupt-handler tasks are used in an operating system, there are actually two mechanisms that can be used to dispatch tasks: the software scheduler (part of the operating system) and the hardware scheduler (part of the processor's interrupt mechanism). The software scheduler needs to accommodate interrupt tasks that may be dispatched when interrupts are enabled.

5.11. ERROR CODE

When an exception condition is related to a specific segment, the processor pushes an error code onto the stack of the exception handler (whether it is a procedure or task). The error code has the format shown in Figure 5-6. The error code resembles a segment selector; however, instead of a TI flag and RPL field, the error code contains 3 flags:

EXT **External event (bit 0).** When set, indicates that an event external to the program caused the exception, such as a hardware interrupt.

IDT **Descriptor location (bit 1).** When set, indicates that the index portion of the error code refers to a gate descriptor in the IDT; when clear, indicates that the index refers to a descriptor in the GDT or the current LDT.

TI **GDT/LDT (bit 2).** Only used when the IDT flag is clear. When set, the TI flag indicates that the index portion of the error code refers to a segment or gate descriptor in the LDT; when clear, it indicates that the index refers to a descriptor in the current GDT.

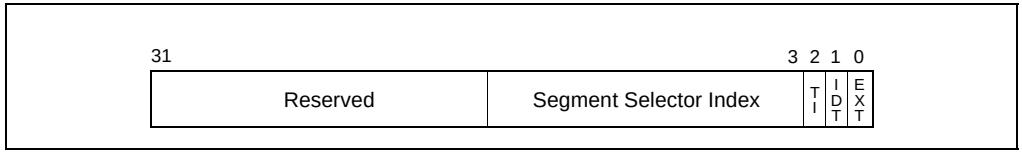


Figure 5-6. Error Code

The segment selector index field provides an index into the IDT, GDT, or current LDT to the segment or gate selector being referenced by the error code. In some cases the error code is null (that is, all bits in the lower word are clear). A null error code indicates that the error was not caused by a reference to a specific segment or that a null segment descriptor was referenced in an operation.

The format of the error code is different for page-fault exceptions (#PF), refer to "Interrupt 14—Page-Fault Exception (#PF)" in this chapter.

The error code is pushed on the stack as a doubleword or word (depending on the default interrupt, trap, or task gate size). To keep the stack aligned for doubleword pushes, the upper half of the error code is reserved. Note that the error code is not popped when the IRET instruction is executed to return from an exception handler, so the handler must remove the error code before executing a return.

Error codes are not pushed on the stack for exceptions that are generated externally (with the INTR or LINT[1:0] pins) or the INT *n* instruction, even if an error code is normally produced for those exceptions.

5.12. EXCEPTION AND INTERRUPT REFERENCE

The following sections describe conditions which generate exceptions and interrupts. They are arranged in the order of vector numbers. The information contained in these sections are as follows:

Exception Class	Indicates whether the exception class is a fault, trap, or abort type. Some exceptions can be either a fault or trap type, depending on when the error condition is detected. (This section is not applicable to interrupts.)
Description	Gives a general description of the purpose of the exception or interrupt type. It also describes how the processor handles the exception or interrupt.
Exception Error Code	Indicates whether an error code is saved for the exception. If one is saved, the contents of the error code are described. (This section is not applicable to interrupts.)
Saved Instruction Pointer	Describes which instruction the saved (or return) instruction pointer points to. It also indicates whether the pointer can be used to restart a faulting instruction.
Program State Change	Describes the effects of the exception or interrupt on the state of the currently running program or task and the possibilities of restarting the program or task without loss of continuity.

Interrupt 0—Divide Error Exception (#DE)

Exception Class Fault.

Description

Indicates the divisor operand for a DIV or IDIV instruction is 0 or that the result cannot be represented in the number of bits specified for the destination operand.

Exception Error Code

None.

Saved Instruction Pointer

Saved contents of CS and EIP registers point to the instruction that generated the exception.

Program State Change

A program-state change does not accompany the divide error, because the exception occurs before the faulting instruction is executed.

Interrupt 1—Debug Exception (#DB)

Exception Class Trap or Fault. The exception handler can distinguish between traps or faults by examining the contents of DR6 and the other debug registers.

Description

Indicates that one or more of several debug-exception conditions has been detected. Whether the exception is a fault or a trap depends on the condition, as shown below:

Exception Condition	Exception Class
Instruction fetch breakpoint	Fault
Data read or write breakpoint	Trap
I/O read or write breakpoint	Trap
General detect condition (in conjunction with in-circuit emulation)	Fault
Single-step	Trap
Task-switch	Trap
Execution of INT 1 instruction	Trap

Refer to Chapter 15, *Debugging and Performance Monitoring*, for detailed information about the debug exceptions.

Exception Error Code

None. An exception handler can examine the debug registers to determine which condition caused the exception.

Saved Instruction Pointer

Fault—Saved contents of CS and EIP registers point to the instruction that generated the exception.

Trap—Saved contents of CS and EIP registers point to the instruction following the instruction that generated the exception.

Program State Change

Fault—A program-state change does not accompany the debug exception, because the exception occurs before the faulting instruction is executed. The program can resume normal execution upon returning from the debug exception handler

Trap—A program-state change does accompany the debug exception, because the instruction or task switch being executed is allowed to complete before the exception is generated. However, the new state of the program is not corrupted and execution of the program can continue reliably.

Interrupt 2—NMI Interrupt

Exception Class Not applicable.

Description

The nonmaskable interrupt (NMI) is generated externally by asserting the processor's NMI pin or through an NMI request set by the I/O APIC to the local APIC on the APIC serial bus. This interrupt causes the NMI interrupt handler to be called.

Exception Error Code

Not applicable.

Saved Instruction Pointer

The processor always takes an NMI interrupt on an instruction boundary. The saved contents of CS and EIP registers point to the next instruction to be executed at the point the interrupt is taken. Refer to Section 5.4., "Program or Task Restart" for more information about when the processor takes NMI interrupts.

Program State Change

The instruction executing when an NMI interrupt is received is completed before the NMI is generated. A program or task can thus be restarted upon returning from an interrupt handler without loss of continuity, provided the interrupt handler saves the state of the processor before handling the interrupt and restores the processor's state prior to a return.

Interrupt 3—Breakpoint Exception (#BP)

Exception Class Trap.

Description

Indicates that a breakpoint instruction (INT 3) was executed, causing a breakpoint trap to be generated. Typically, a debugger sets a breakpoint by replacing the first opcode byte of an instruction with the opcode for the INT 3 instruction. (The INT 3 instruction is one byte long, which makes it easy to replace an opcode in a code segment in RAM with the breakpoint opcode.) The operating system or a debugging tool can use a data segment mapped to the same physical address space as the code segment to place an INT 3 instruction in places where it is desired to call the debugger.

With the P6 family, Pentium®, Intel486™, and Intel386™ processors, it is more convenient to set breakpoints with the debug registers. (Refer to Section 15.3.2., "Breakpoint Exception (#BP)—Interrupt Vector 3", in Chapter 15, *Debugging and Performance Monitoring*, for information about the breakpoint exception.) If more breakpoints are needed beyond what the debug registers allow, the INT 3 instruction can be used.

The breakpoint (#BP) exception can also be generated by executing the INT *n* instruction with an operand of 3. The action of this instruction (INT 3) is slightly different than that of the INT 3 instruction (refer to "INTn/INTO/INT3—Call to Interrupt Procedure" in Chapter 3 of the *Intel Architecture Software Developer's Manual, Volume 2*).

Exception Error Code

None.

Saved Instruction Pointer

Saved contents of CS and EIP registers point to the instruction following the INT 3 instruction.

Program State Change

Even though the EIP points to the instruction following the breakpoint instruction, the state of the program is essentially unchanged because the INT 3 instruction does not affect any register or memory locations. The debugger can thus resume the suspended program by replacing the INT 3 instruction that caused the breakpoint with the original opcode and decrementing the saved contents of the EIP register. Upon returning from the debugger, program execution resumes with the replaced instruction.

Interrupt 4—Overflow Exception (#OF)

Exception Class Trap.

Description

Indicates that an overflow trap occurred when an INTO instruction was executed. The INTO instruction checks the state of the OF flag in the EFLAGS register. If the OF flag is set, an overflow trap is generated.

Some arithmetic instructions (such as the ADD and SUB) perform both signed and unsigned arithmetic. These instructions set the OF and CF flags in the EFLAGS register to indicate signed overflow and unsigned overflow, respectively. When performing arithmetic on signed operands, the OF flag can be tested directly or the INTO instruction can be used. The benefit of using the INTO instruction is that if the overflow exception is detected, an exception handler can be called automatically to handle the overflow condition.

Exception Error Code

None.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the instruction following the INTO instruction.

Program State Change

Even though the EIP points to the instruction following the INTO instruction, the state of the program is essentially unchanged because the INTO instruction does not affect any register or memory locations. The program can thus resume normal execution upon returning from the overflow exception handler.

Interrupt 5—BOUND Range Exceeded Exception (#BR)

Exception Class Fault.

Description

Indicates that a BOUND-range-exceeded fault occurred when a BOUND instruction was executed. The BOUND instruction checks that a signed array index is within the upper and lower bounds of an array located in memory. If the array index is not within the bounds of the array, a BOUND-range-exceeded fault is generated.

Exception Error Code

None.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the BOUND instruction that generated the exception.

Program State Change

A program-state change does not accompany the bounds-check fault, because the operands for the BOUND instruction are not modified. Returning from the BOUND-range-exceeded exception handler causes the BOUND instruction to be restarted.

Interrupt 6—Invalid Opcode Exception (#UD)

Exception Class Fault.

Description

Indicates that the processor did one of the following things:

- Attempted to execute a Streaming SIMD Extensions instruction in an Intel Architecture processor that does not support the Streaming SIMD Extensions.
- Attempted to execute a Streaming SIMD Extensions instruction when the OSFXSR bit is not set (0) in CR4. Note this does not include the following Streaming SIMD Extensions: PAVGB, PAVGW, PEXTRW, PINSRW, PMAXSW, PMAXUB, PMINSW, PMINUB, PMOVMSKB, PMULHUW, PSADBW, PSHUFW, MASKMOVQ, MOVNTQ, PREFETCH and SFENCE.
- Attempted to execute a Streaming SIMD Extensions instruction in an Intel Architecture processor which causes a numeric exception when the OSXMMEXCPT bit is not set (0) in CR4.
- Attempted to execute an invalid or reserved opcode, including any MMX™ instruction in an Intel Architecture processor that does not support the MMX™ architecture.
- Attempted to execute an MMX™ instruction or SIMD floating-point instruction when the EM flag in register CR0 is set. Note this does not include the following Streaming SIMD Extensions: SFENCE and PREFETCH.
- Attempted to execute an instruction with an operand type that is invalid for its accompanying opcode; for example, the source operand for a LES instruction is not a memory location.
- Executed a UD2 instruction.
- Detected a LOCK prefix that precedes an instruction that may not be locked or one that may be locked but the destination operand is not a memory location.
- Attempted to execute an LLDT, SLDT, LTR, STR, LSL, LAR, VERR, VERW, or ARPL instruction while in real-address or virtual-8086 mode.
- Attempted to execute the RSM instruction when not in SMM mode.

In the P6 family processors, this exception is not generated until an attempt is made to retire the result of executing an invalid instruction; that is, decoding and speculatively attempting to execute an invalid opcode does not generate this exception. Likewise, in the Pentium® processor and earlier Intel Architecture processors, this exception is not generated as the result of prefetching and preliminary decoding of an invalid instruction. (Refer to Section 5.4., “Program or Task Restart” for general rules for taking of interrupts and exceptions.)

The opcodes D6 and F1 are undefined opcodes that are reserved by Intel. These opcodes, even though undefined, do not generate an invalid opcode exception.

The UD2 instruction is guaranteed to generate an invalid opcode exception.

Exception Error Code

None.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the instruction that generated the exception.

Program State Change

A program-state change does not accompany an invalid-opcode fault, because the invalid instruction is not executed.

Interrupt 7—Device Not Available Exception (#NM)

Exception Class Fault.

Description

Indicates one of the following things:

The device-not-available fault is generated by either of three conditions:

- The processor executed a floating-point instruction while the EM flag of register CR0 was set.
- The processor executed a floating-point, MMX™ or SIMD floating-point (excluding prefetch, sfence or streaming store instructions) instruction while the TS flag of register CR0 was set.
- The processor executed a WAIT or FWAIT instruction while the MP and TS flags of register CR0 were set.

The EM flag is set when the processor does not have an internal floating-point unit. An exception is then generated each time a floating-point instruction is encountered, allowing an exception handler to call floating-point instruction emulation routines.

The TS flag indicates that a context switch (task switch) has occurred since the last time a floating-point, MMX™ or SIMD floating-point (excluding prefetch, sfence or streaming store instructions) instruction was executed, but that the context of the FPU was not saved. When the TS flag is set, the processor generates a device-not-available exception each time a floating-point, MMX™ or SIMD floating-point (excluding prefetch, sfence or streaming store instructions) instruction is encountered. The exception handler can then save the context of the FPU before it executes the instruction. Refer to Section 2.5., “Control Registers”, in Chapter 2, *System Architecture Overview*, for more information about the TS flag.

The MP flag in control register CR0 is used along with the TS flag to determine if WAIT or FWAIT instructions should generate a device-not-available exception. It extends the function of the TS flag to the WAIT and FWAIT instructions, giving the exception handler an opportunity to save the context of the FPU before the WAIT or FWAIT instruction is executed. The MP flag is provided primarily for use with the Intel286 and Intel386™ DX processors. For programs running on the P6 family, Pentium®, or Intel486™ DX processors, or the Intel 487 SX coprocessors, the MP flag should always be set; for programs running on the Intel486™ SX processor, the MP flag should be clear.

Exception Error Code

None.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the floating-point instruction or the WAIT/FWAIT instruction that generated the exception.

Program State Change

A program-state change does not accompany a device-not-available fault, because the instruction that generated the exception is not executed.

If the EM flag is set, the exception handler can then read the floating-point instruction pointed to by the EIP and call the appropriate emulation routine.

If the MP and TS flags are set or the TS flag alone is set, the exception handler can save the context of the FPU, clear the TS flag, and continue execution at the interrupted floating-point or WAIT/FWAIT instruction.

Interrupt 8—Double Fault Exception (#DF)

Exception Class Abort.

Description

Indicates that the processor detected a second exception while calling an exception handler for a prior exception. Normally, when the processor detects another exception while trying to call an exception handler, the two exceptions can be handled serially. If, however, the processor cannot handle them serially, it signals the double-fault exception. To determine when two faults need to be signaled as a double fault, the processor divides the exceptions into three classes: benign exceptions, contributory exceptions, and page faults (refer to Table 5-4).

Table 5-4. Interrupt and Exception Classes

Class	Vector Number	Description
Benign Exceptions and Interrupts	1 2 3 4 5 6 7 9 16 17 18 19 All All	Debug Exception NMI Interrupt Breakpoint Overflow BOUND Range Exceeded Invalid Opcode Device Not Available Coprocessor Segment Overrun Floating-Point Error Alignment Check Machine Check SIMD floating-point extensions INT *n* INTR
Contributory Exceptions	0 10 11 12 13	Divide Error Invalid TSS Segment Not Present Stack Fault General Protection
Page Faults	14	Page Fault

Table 5-5 shows the various combinations of exception classes that cause a double fault to be generated. A double-fault exception falls in the abort class of exceptions. The program or task cannot be restarted or resumed. The double-fault handler can be used to collect diagnostic information about the state of the machine and/or, when possible, to shut the application and/or system down gracefully or restart the system.

A segment or page fault may be encountered while prefetching instructions; however, this behavior is outside the domain of Table 5-5. Any further faults generated while the processor is attempting to transfer control to the appropriate fault handler could still lead to a double-fault sequence.

Table 5-5. Conditions for Generating a Double Fault

First Exception	Second Exception		
	Benign	**Contributory**	**Page Fault**
Benign	Handle Exceptions Serially	Handle Exceptions Serially	Handle Exceptions Serially
Contributory	Handle Exceptions Serially	Generate a Double Fault	Handle Exceptions Serially
Page Fault	Handle Exceptions Serially	Generate a Double Fault	Generate a Double Fault

If another exception occurs while attempting to call the double-fault handler, the processor enters shutdown mode. This mode is similar to the state following execution of an HLT instruction. In this mode, the processor stops executing instructions until an NMI interrupt, SMI interrupt, hardware reset, or INIT# is received. The processor generates a special bus cycle to indicate that it has entered shutdown mode. Software designers may need to be aware of the response of hardware to receiving this signal. For example, hardware may turn on an indicator light on the front panel, generate an NMI interrupt to record diagnostic information, invoke reset initialization, generate an INIT initialization, or generate an SMI.

If the shutdown occurs while the processor is executing an NMI interrupt handler, then only a hardware reset can restart the processor.

Exception Error Code

Zero. The processor always pushes an error code of 0 onto the stack of the double-fault handler.

Saved Instruction Pointer

The saved contents of CS and EIP registers are undefined.

Program State Change

A program-state following a double-fault exception is undefined. The program or task cannot be resumed or restarted. The only available action of the double-fault exception handler is to collect all possible context information for use in diagnostics and then close the application and/or shut down or reset the processor.

Interrupt 9—Coprocessor Segment Overrun

Exception Class Abort. **(Intel reserved; do not use. Recent Intel Architecture processors do not generate this exception.)**

Description

Indicates that an Intel386™ CPU-based systems with an Intel 387 math coprocessor detected a page or segment violation while transferring the middle portion of an Intel 387 math coprocessor operand. The P6 family, Pentium®, and Intel486™ processors do not generate this exception; instead, this condition is detected with a general protection exception (#GP), interrupt 13.

Exception Error Code

None.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the instruction that generated the exception.

Program State Change

A program-state following a coprocessor segment-overrun exception is undefined. The program or task cannot be resumed or restarted. The only available action of the exception handler is to save the instruction pointer and reinitialize the FPU using the FNINIT instruction.

Interrupt 10—Invalid TSS Exception (#TS)

Exception Class Fault.

Description

Indicates that a task switch was attempted and that invalid information was detected in the TSS for the target task. Table 5-6 shows the conditions that will cause an invalid-TSS exception to be generated. In general, these invalid conditions result from protection violations for the TSS descriptor; the LDT pointed to by the TSS; or the stack, code, or data segments referenced by the TSS.

Table 5-6. Invalid TSS Conditions

Error Code Index	Invalid Condition
TSS segment selector index	TSS segment limit less than 67H for 32-bit TSS or less than 2CH for 16-bit TSS.
LDT segment selector index	Invalid LDT or LDT not present
Stack-segment selector index	Stack-segment selector exceeds descriptor table limit
Stack-segment selector index	Stack segment is not writable
Stack-segment selector index	Stack segment DPL ≠ CPL
Stack-segment selector index	Stack-segment selector RPL ≠ CPL
Code-segment selector index	Code-segment selector exceeds descriptor table limit
Code-segment selector index	Code segment is not executable
Code-segment selector index	Nonconforming code segment DPL ≠ CPL
Code-segment selector index	Conforming code segment DPL greater than CPL
Data-segment selector index	Data-segment selector exceeds descriptor table limit
Data-segment selector index	Data segment not readable

This exception can generated either in the context of the original task or in the context of the new task (refer to Section 6.3., “Task Switching” in Chapter 6, *Task Management*). Until the processor has completely verified the presence of the new TSS, the exception is generated in the context of the original task. Once the existence of the new TSS is verified, the task switch is considered complete. Any invalid-TSS conditions detected after this point are handled in the context of the new task. (A task switch is considered complete when the task register is loaded with the segment selector for the new TSS and, if the switch is due to a procedure call or interrupt, the previous task link field of the new TSS references the old TSS.)

To insure that a valid TSS is available to process the exception, the invalid-TSS exception handler must be a task called using a task gate.

Exception Error Code

An error code containing the segment selector index for the segment descriptor that caused the violation is pushed onto the stack of the exception handler. If the EXT flag is set, it indicates that the exception was caused by an event external to the currently running program (for example, if an external interrupt handler using a task gate attempted a task switch to an invalid TSS).

Saved Instruction Pointer

If the exception condition was detected before the task switch was carried out, the saved contents of CS and EIP registers point to the instruction that invoked the task switch. If the exception condition was detected after the task switch was carried out, the saved contents of CS and EIP registers point to the first instruction of the new task.

Program State Change

The ability of the invalid-TSS handler to recover from the fault depends on the error condition than causes the fault. Refer to Section 6.3., “Task Switching” in Chapter 6, *Task Management* for more information on the task switch process and the possible recovery actions that can be taken.

If an invalid TSS exception occurs during a task switch, it can occur before or after the commit-to-new-task point. If it occurs before the commit point, no program state change occurs. If it occurs after the commit point (when the segment descriptor information for the new segment selectors have been loaded in the segment registers), the processor will load all the state information from the new TSS before it generates the exception. During a task switch, the processor first loads all the segment registers with segment selectors from the TSS, then checks their contents for validity. If an invalid TSS exception is discovered, the remaining segment registers are loaded but not checked for validity and therefore may not be usable for referencing memory. The invalid TSS handler should not rely on being able to use the segment selectors found in the CS, SS, DS, ES, FS, and GS registers without causing another exception. The exception handler should load all segment registers before trying to resume the new task; otherwise, general-protection exceptions (#GP) may result later under conditions that make diagnosis more difficult. The Intel recommended way of dealing situation is to use a task for the invalid TSS exception handler. The task switch back to the interrupted task from the invalid-TSS exception-handler task will then cause the processor to check the registers as it loads them from the TSS.

Interrupt 11—Segment Not Present (#NP)

Exception Class Fault.

Description

Indicates that the present flag of a segment or gate descriptor is clear. The processor can generate this exception during any of the following operations:

- While attempting to load CS, DS, ES, FS, or GS registers. [Detection of a not-present segment while loading the SS register causes a stack fault exception (#SS) to be generated.] This situation can occur while performing a task switch.
- While attempting to load the LDTR using an LLDT instruction. Detection of a not-present LDT while loading the LDTR during a task switch operation causes an invalid-TSS exception (#TS) to be generated.
- When executing the LTR instruction and the TSS is marked not present.
- While attempting to use a gate descriptor or TSS that is marked segment-not-present, but is otherwise valid.

An operating system typically uses the segment-not-present exception to implement virtual memory at the segment level. If the exception handler loads the segment and returns, the interrupted program or task resumes execution.

A not-present indication in a gate descriptor, however, does not indicate that a segment is not present (because gates do not correspond to segments). The operating system may use the present flag for gate descriptors to trigger exceptions of special significance to the operating system.

Exception Error Code

An error code containing the segment selector index for the segment descriptor that caused the violation is pushed onto the stack of the exception handler. If the EXT flag is set, it indicates that the exception resulted from an external event (NMI or INTR) that caused an interrupt, which subsequently referenced a not-present segment. The IDT flag is set if the error code refers to an IDT entry (e.g., an INT instruction referencing a not-present gate).

Saved Instruction Pointer

The saved contents of CS and EIP registers normally point to the instruction that generated the exception. If the exception occurred while loading segment descriptors for the segment selectors in a new TSS, the CS and EIP registers point to the first instruction in the new task. If the exception occurred while accessing a gate descriptor, the CS and EIP registers point to the instruction that invoked the access (for example a CALL instruction that references a call gate).

Program State Change

If the segment-not-present exception occurs as the result of loading a register (CS, DS, SS, ES, FS, GS, or LDTR), a program-state change does accompany the exception, because the register is not loaded. Recovery from this exception is possible by simply loading the missing segment into memory and setting the present flag in the segment descriptor.

If the segment-not-present exception occurs while accessing a gate descriptor, a program-state change does not accompany the exception. Recovery from this exception is possible merely by setting the present flag in the gate descriptor.

If a segment-not-present exception occurs during a task switch, it can occur before or after the commit-to-new-task point (refer to Section 6.3., “Task Switching” in Chapter 6, *Task Management*). If it occurs before the commit point, no program state change occurs. If it occurs after the commit point, the processor will load all the state information from the new TSS (without performing any additional limit, present, or type checks) before it generates the exception. The segment-not-present exception handler should thus not rely on being able to use the segment selectors found in the CS, SS, DS, ES, FS, and GS registers without causing another exception. (Refer to the Program State Change description for “Interrupt 10—Invalid TSS Exception (#TS)” in this chapter for additional information on how to handle this situation.)

Interrupt 12—Stack Fault Exception (#SS)

Exception Class Fault.

Description

Indicates that one of the following stack related conditions was detected:

- A limit violation is detected during an operation that refers to the SS register. Operations that can cause a limit violation include stack-oriented instructions such as POP, PUSH, CALL, RET, IRET, ENTER, and LEAVE, as well as other memory references which implicitly or explicitly use the SS register (for example, MOV AX, [BP+6] or MOV AX, SS:[EAX+6]). The ENTER instruction generates this exception when there is not enough stack space for allocating local variables.
- A not-present stack segment is detected when attempting to load the SS register. This violation can occur during the execution of a task switch, a CALL instruction to a different privilege level, a return to a different privilege level, an LSS instruction, or a MOV or POP instruction to the SS register.

Recovery from this fault is possible by either extending the limit of the stack segment (in the case of a limit violation) or loading the missing stack segment into memory (in the case of a not-present violation.

Exception Error Code

If the exception is caused by a not-present stack segment or by overflow of the new stack during an inter-privilege-level call, the error code contains a segment selector for the segment that caused the exception. Here, the exception handler can test the present flag in the segment descriptor pointed to by the segment selector to determine the cause of the exception. For a normal limit violation (on a stack segment already in use) the error code is set to 0.

Saved Instruction Pointer

The saved contents of CS and EIP registers generally point to the instruction that generated the exception. However, when the exception results from attempting to load a not-present stack segment during a task switch, the CS and EIP registers point to the first instruction of the new task.

Program State Change

A program-state change does not generally accompany a stack-fault exception, because the instruction that generated the fault is not executed. Here, the instruction can be restarted after the exception handler has corrected the stack fault condition.

If a stack fault occurs during a task switch, it occurs after the commit-to-new-task point (refer to Section 6.3., “Task Switching” Chapter 6, *Task Management*). Here, the processor loads all the state information from the new TSS (without performing any additional limit, present, or

type checks) before it generates the exception. The stack fault handler should thus not rely on being able to use the segment selectors found in the CS, SS, DS, ES, FS, and GS registers without causing another exception. The exception handler should check all segment registers before trying to resume the new task; otherwise, general protection faults may result later under conditions that are more difficult to diagnose. (Refer to the Program State Change description for “Interrupt 10—Invalid TSS Exception (#TS)” in this chapter for additional information on how to handle this situation.)

Interrupt 13—General Protection Exception (#GP)

Exception Class Fault.

Description

Indicates that the processor detected one of a class of protection violations called "general-protection violations." The conditions that cause this exception to be generated comprise all the protection violations that do not cause other exceptions to be generated (such as, invalid-TSS, segment-not-present, stack-fault, or page-fault exceptions). The following conditions cause general-protection exceptions to be generated:

- Exceeding the segment limit when accessing the CS, DS, ES, FS, or GS segments.
- Exceeding the segment limit when referencing a descriptor table (except during a task switch or a stack switch).
- Transferring execution to a segment that is not executable.
- Writing to a code segment or a read-only data segment.
- Reading from an execute-only code segment.
- Loading the SS register with a segment selector for a read-only segment (unless the selector comes from a TSS during a task switch, in which case an invalid-TSS exception occurs).
- Loading the SS, DS, ES, FS, or GS register with a segment selector for a system segment.
- Loading the DS, ES, FS, or GS register with a segment selector for an execute-only code segment.
- Loading the SS register with the segment selector of an executable segment or a null segment selector.
- Loading the CS register with a segment selector for a data segment or a null segment selector.
- Accessing memory using the DS, ES, FS, or GS register when it contains a null segment selector.
- Switching to a busy task during a call or jump to a TSS.
- Switching to an available (nonbusy) task during the execution of an IRET instruction.
- Using a segment selector on task switch that points to a TSS descriptor in the current LDT. TSS descriptors can only reside in the GDT.
- Violating any of the privilege rules described in Chapter 4, *Protection*.
- Exceeding the instruction length limit of 15 bytes (this only can occur when redundant prefixes are placed before an instruction).

- Loading the CR0 register with a set PG flag (paging enabled) and a clear PE flag (protection disabled).
- Loading the CR0 register with a set NW flag and a clear CD flag.
- Referencing an entry in the IDT (following an interrupt or exception) that is not an interrupt, trap, or task gate.
- Attempting to access an interrupt or exception handler through an interrupt or trap gate from virtual-8086 mode when the handler's code segment DPL is greater than 0.
- Attempting to write a 1 into a reserved bit of CR4.
- Attempting to execute a privileged instruction when the CPL is not equal to 0 (refer to Section 4.9., "Privileged Instructions" in Chapter 4, *Protection* for a list of privileged instructions).
- Writing to a reserved bit in an MSR.
- Accessing a gate that contains a null segment selector.
- Executing the INT *n* instruction when the CPL is greater than the DPL of the referenced interrupt, trap, or task gate.
- The segment selector in a call, interrupt, or trap gate does not point to a code segment.
- The segment selector operand in the LLDT instruction is a local type (TI flag is set) or does not point to a segment descriptor of the LDT type.
- The segment selector operand in the LTR instruction is local or points to a TSS that is not available.
- The target code-segment selector for a call, jump, or return is null.
- If the PAE and/or PSE flag in control register CR4 is set and the processor detects any reserved bits in a page-directory-pointer-table entry set to 1. These bits are checked during a write to control registers CR0, CR3, or CR4 that causes a reloading of the page-directory-pointer-table entry.

A program or task can be restarted following any general-protection exception. If the exception occurs while attempting to call an interrupt handler, the interrupted program can be restartable, but the interrupt may be lost.

Exception Error Code

The processor pushes an error code onto the exception handler's stack. If the fault condition was detected while loading a segment descriptor, the error code contains a segment selector to or IDT vector number for the descriptor; otherwise, the error code is 0. The source of the selector in an error code may be any of the following:

- An operand of the instruction.
- A selector from a gate which is the operand of the instruction.
- A selector from a TSS involved in a task switch.

- IDT vector number.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the instruction that generated the exception.

Program State Change

In general, a program-state change does not accompany a general-protection exception, because the invalid instruction or operation is not executed. An exception handler can be designed to correct all of the conditions that cause general-protection exceptions and restart the program or task without any loss of program continuity.

If a general-protection exception occurs during a task switch, it can occur before or after the commit-to-new-task point (refer to Section 6.3., “Task Switching” in Chapter 6, *Task Management*). If it occurs before the commit point, no program state change occurs. If it occurs after the commit point, the processor will load all the state information from the new TSS (without performing any additional limit, present, or type checks) before it generates the exception. The general-protection exception handler should thus not rely on being able to use the segment selectors found in the CS, SS, DS, ES, FS, and GS registers without causing another exception. (Refer to the Program State Change description for “Interrupt 10—Invalid TSS Exception (#TS)” in this chapter for additional information on how to handle this situation.)

Interrupt 14—Page-Fault Exception (#PF)

Exception Class Fault.

Description

Indicates that, with paging enabled (the PG flag in the CR0 register is set), the processor detected one of the following conditions while using the page-translation mechanism to translate a linear address to a physical address:

- The P (present) flag in a page-directory or page-table entry needed for the address translation is clear, indicating that a page table or the page containing the operand is not present in physical memory.
- The procedure does not have sufficient privilege to access the indicated page (that is, a procedure running in user mode attempts to access a supervisor-mode page).
- Code running in user mode attempts to write to a read-only page. In the Intel486™ and later processors, if the WP flag is set in CR0, the page fault will also be triggered by code running in supervisor mode that tries to write to a read-only user-mode page.

The exception handler can recover from page-not-present conditions and restart the program or task without any loss of program continuity. It can also restart the program or task after a privilege violation, but the problem that caused the privilege violation may be uncorrectable.

Exception Error Code

Yes (special format). The processor provides the page-fault handler with two items of information to aid in diagnosing the exception and recovering from it:

- An error code on the stack. The error code for a page fault has a format different from that for other exceptions (refer to Figure 5-7). The error code tells the exception handler four things:
  - — The P flag indicates whether the exception was due to a not-present page (0) or to either an access rights violation or the use of a reserved bit (1).
  - — The W/R flag indicates whether the memory access that caused the exception was a read (0) or write (1).
  - — The U/S flag indicates whether the processor was executing at user mode (1) or supervisor mode (0) at the time of the exception.
  - — The RSVD flag indicates that the processor detected 1s in reserved bits of the page directory, when the PSE or PAE flags in control register CR4 are set to 1. (The PSE flag is only available in the P6 family and Pentium® processors, and the PAE flag is only available on the P6 family processors. In earlier Intel Architecture processor families, the bit position of the RSVD flag is reserved.)

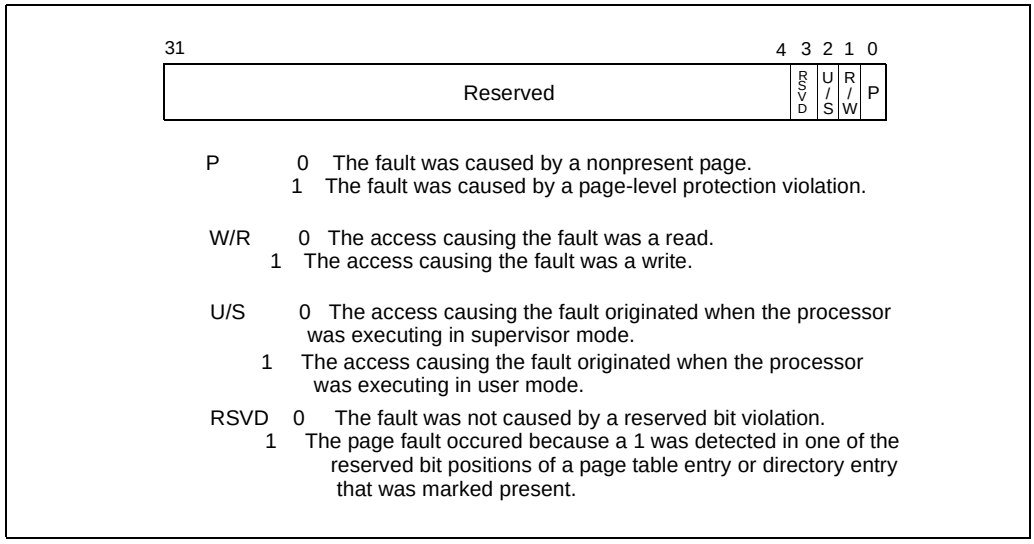


Figure 5-7. Page-Fault Error Code

- The contents of the CR2 register. The processor loads the CR2 register with the 32-bit linear address that generated the exception. The page-fault handler can use this address to locate the corresponding page directory and page-table entries. If another page fault can potentially occur during execution of the page-fault handler, the handler must push the contents of the CR2 register onto the stack before the second page fault occurs.

If a page fault is caused by a page-level protection violation, the access flag in the page-directory entry is set when the fault occurs. The behavior of Intel Architecture processors regarding the access flag in the corresponding page-table entry is model specific and not architecturally defined.

Saved Instruction Pointer

The saved contents of CS and EIP registers generally point to the instruction that generated the exception. If the page-fault exception occurred during a task switch, the CS and EIP registers may point to the first instruction of the new task (as described in the following “Program State Change” section).

Program State Change

A program-state change does not normally accompany a page-fault exception, because the instruction that causes the exception to be generated is not executed. After the page-fault exception handler has corrected the violation (for example, loaded the missing page into memory), execution of the program or task can be resumed.

When a page-fault exception is generated during a task switch, the program-state may change, as follows. During a task switch, a page-fault exception can occur during any of following operations:

- While writing the state of the original task into the TSS of that task.
- While reading the GDT to locate the TSS descriptor of the new task.
- While reading the TSS of the new task.
- While reading segment descriptors associated with segment selectors from the new task.
- While reading the LDT of the new task to verify the segment registers stored in the new TSS.

In the last two cases the exception occurs in the context of the new task. The instruction pointer refers to the first instruction of the new task, not to the instruction which caused the task switch (or the last instruction to be executed, in the case of an interrupt). If the design of the operating system permits page faults to occur during task-switches, the page-fault handler should be called through a task gate.

If a page fault occurs during a task switch, the processor will load all the state information from the new TSS (without performing any additional limit, present, or type checks) before it generates the exception. The page-fault handler should thus not rely on being able to use the segment selectors found in the CS, SS, DS, ES, FS, and GS registers without causing another exception. (Refer to the Program State Change description for “Interrupt 10—Invalid TSS Exception (#TS)” in this chapter for additional information on how to handle this situation.)

Additional Exception-Handling Information

Special care should be taken to ensure that an exception that occurs during an explicit stack switch does not cause the processor to use an invalid stack pointer (SS:ESP). Software written for 16-bit Intel Architecture processors often use a pair of instructions to change to a new stack, for example:

```
MOV SS, AX
MOV SP, StackTop
```

When executing this code on one of the 32-bit Intel Architecture processors, it is possible to get a page fault, general-protection fault (#GP), or alignment check fault (#AC) after the segment selector has been loaded into the SS register but before the ESP register has been loaded. At this point, the two parts of the stack pointer (SS and ESP) are inconsistent. The new stack segment is being used with the old stack pointer.

The processor does not use the inconsistent stack pointer if the exception handler switches to a well defined stack (that is, the handler is a task or a more privileged procedure). However, if the exception handler is called at the same privilege level and from the same task, the processor will attempt to use the inconsistent stack pointer.

In systems that handle page-fault, general-protection, or alignment check exceptions within the faulting task (with trap or interrupt gates), software executing at the same privilege level as the exception handler should initialize a new stack by using the LSS instruction rather than a pair

of MOV instructions, as described earlier in this note. When the exception handler is running at privilege level 0 (the normal case), the problem is limited to procedures or tasks that run at privilege level 0, typically the kernel of the operating system.

Interrupt 16—Floating-Point Error Exception (#MF)

Exception Class Fault.

Description

Indicates that the FPU has detected a floating-point-error exception. The NE flag in the register CR0 must be set and the appropriate exception must be unmasked (clear mask bit in the control register) for an interrupt 16, floating-point-error exception to be generated. (Refer to Section 2.5., “Control Registers” in Chapter 2, *System Architecture Overview* for a detailed description of the NE flag.)

While executing floating-point instructions, the FPU detects and reports six types of floating-point errors:

- Invalid operation (#I)
  - — Stack overflow or underflow (#IS)
  - — Invalid arithmetic operation (#IA)
- Divide-by-zero (#Z)
- Denormalized operand (#D)
- Numeric overflow (#O)
- Numeric underflow (#U)
- Inexact result (precision) (#P)

For each of these error types, the FPU provides a flag in the FPU status register and a mask bit in the FPU control register. If the FPU detects a floating-point error and the mask bit for the error is set, the FPU handles the error automatically by generating a predefined (default) response and continuing program execution. The default responses have been designed to provide a reasonable result for most floating-point applications.

If the mask for the error is clear and the NE flag in register CR0 is set, the FPU does the following:

1. Sets the necessary flag in the FPU status register.
2. Waits until the next “waiting” floating-point instruction or WAIT/FWAIT instruction is encountered in the program’s instruction stream. (The FPU checks for pending floating-point exceptions on “waiting” instructions prior to executing them. All the floating-point instructions except the FNINIT, FNCLEX, FNSTSW, FNSTSW AX, FNSTCW, FNSTENV, and FNSAVE instructions are “waiting” instructions.)
3. Generates an internal error signal that causes the processor to generate a floating-point-error exception.

All of the floating-point-error conditions can be recovered from. The floating-point-error exception handler can determine the error condition that caused the exception from the settings of the flags in the FPU status word. Refer to “Software Exception Handling” in Chapter 7 of the *Intel Architecture Software Developer’s Manual, Volume 1*, for more information on handling floating-point-error exceptions.

Exception Error Code

None. The FPU provides its own error information.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the floating-point or WAIT/FWAIT instruction that was about to be executed when the floating-point-error exception was generated. This is not the faulting instruction in which the error condition was detected. The address of the faulting instruction is contained in the FPU instruction pointer register. Refer to “The FPU Instruction and Operand (Data) Pointers” in Chapter 7 of the *Intel Architecture Software Developer’s Manual, Volume 1*, for more information about information the FPU saves for use in handling floating-point-error exceptions.

Program State Change

A program-state change generally accompanies a floating-point-error exception because the handling of the exception is delayed until the next waiting floating-point or WAIT/FWAIT instruction following the faulting instruction. The FPU, however, saves sufficient information about the error condition to allow recovery from the error and re-execution of the faulting instruction if needed.

In situations where nonfloating-point instructions depend on the results of a floating-point instruction, a WAIT or FWAIT instruction can be inserted in front of a dependent instruction to force a pending floating-point-error exception to be handled before the dependent instruction is executed. Refer to “Floating-Point Exception Synchronization” in Chapter 7 of the *Intel Architecture Software Developer’s Manual, Volume 1*, for more information about synchronization of floating-point-error exceptions.

Interrupt 17—Alignment Check Exception (#AC)

Exception Class Fault.

Description

Indicates that the processor detected an unaligned memory operand when alignment checking was enabled. Alignment checks are only carried out in data (or stack) segments (not in code or system segments). An example of an alignment-check violation is a word stored at an odd byte address, or a doubleword stored at an address that is not an integer multiple of 4. Table 5-7 lists the alignment requirements various data types recognized by the processor.

Table 5-7. Alignment Requirements by Data Type

Data Type	Address Must Be Divisible By
Word	2
Doubleword	4
Single Real	4
Double Real	8
Extended Real	8
Segment Selector	2
32-bit Far Pointer	2
48-bit Far Pointer	4
32-bit Pointer	4
GDTR, IDTR, LDTR, or Task Register Contents	4
FSTENV/FLDENV Save Area	4 or 2, depending on operand size
FSAVE/FRSTOR Save Area	4 or 2, depending on operand size
Bit String	2 or 4 depending on the operand-size attribute.
128-bit[1]	16

1. 128-bit datatype introduced with the Pentium® III processor. This type of alignment check is done for operands less than 128-bits in size: 32-bit scalar single and 16-bit/32-bit/64-bit integer MMX™ technology; 2, 4, or 8 byte alignments checks are possible when #AC is enabled. Some exceptional cases are:
   - The MOVUPS instruction, which performs a 128-bit unaligned load or store. In this case, 2/4/8-byte misalignments will be detected, but detection of 16-byte misalignment is not guaranteed and may vary with implementation.
   - The FXSAVE/FXRSTOR instructions - refer to instruction descriptions

To enable alignment checking, the following conditions must be true:

- AM flag in CR0 register is set.
- AC flag in the EFLAGS register is set.
- The CPL is 3 (protected mode or virtual-8086 mode).

Alignment-check faults are generated only when operating at privilege level 3 (user mode). Memory references that default to privilege level 0, such as segment descriptor loads, do not generate alignment-check faults, even when caused by a memory reference made from privilege level 3.

Storing the contents of the GDTR, IDTR, LDTR, or task register in memory while at privilege level 3 can generate an alignment-check fault. Although application programs do not normally store these registers, the fault can be avoided by aligning the information stored on an even word-address.

FSAVE and FRSTOR instructions generate unaligned references which can cause alignment-check faults. These instructions are rarely needed by application programs.

Exception Error Code

Yes (always zero).

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the instruction that generated the exception.

Program State Change

A program-state change does not accompany an alignment-check fault, because the instruction is not executed.

Interrupt 18—Machine-Check Exception (#MC)

Exception Class Abort.

Description

Indicates that the processor detected an internal machine error or a bus error, or that an external agent detected a bus error. The machine-check exception is model-specific, available only on the P6 family and Pentium® processors. The implementation of the machine-check exception is different between the P6 family and Pentium® processors, and these implementations may not be compatible with future Intel Architecture processors. (Use the CPUID instruction to determine whether this feature is present.)

Bus errors detected by external agents are signaled to the processor on dedicated pins: the BINIT# pin on the P6 family processors and the BUSCHK# pin on the Pentium® processor. When one of these pins is enabled, asserting the pin causes error information to be loaded into machine-check registers and a machine-check exception is generated.

The machine-check exception and machine-check architecture are discussed in detail in Chapter 13, *Machine-Check Architecture*. Also, refer to the data books for the individual processors for processor-specific hardware information.

Exception Error Code

None. Error information is provide by machine-check MSRs.

Saved Instruction Pointer

For the P6 family processors, if the EIPV flag in the MCG_STATUS MSR is set, the saved contents of CS and EIP registers are directly associated with the error that caused the machine-check exception to be generated; if the flag is clear, the saved instruction pointer may not be associated with the error (refer to Section 13.3.1.2., “MCG_STATUS MSR”, in Chapter 13, *Machine-Check Architecture*).

For the Pentium® processor, contents of the CS and EIP registers may not be associated with the error.

Program State Change

A program-state change always accompanies a machine-check exception. If the machine-check mechanism is enabled (the MCE flag in control register CR4 is set), a machine-check exception results in an abort; that is, information about the exception can be collected from the machine-check MSRs, but the program cannot be restarted. If the machine-check mechanism is not enabled, a machine-check exception causes the processor to enter the shutdown state.

Interrupt 19—SIMD Floating-Point Exception (#XF)

Exception Class Fault.

Description

Indicates the processor has detected a SIMD floating-point execution unit exception. The appropriate status flag in the MXCSR register must be set and the particular exception unmasked for this interrupt to be generated.

There are six classes of numeric exception conditions that can occur while executing Streaming SIMD Extensions:

1. Invalid operation (#I)
2. Divide-by-zero (#Z)
3. Denormalized operand (#D)
4. Numeric overflow (#O)
5. Numeric underflow (#U)
6. Inexact result (Precision) (#P)

Invalid, Divide-by-zero, and Denormal exceptions are pre-computation exceptions, i.e., they are detected before any arithmetic operation occurs. Underflow, Overflow, and Precision exceptions are post-computational exceptions.

When numeric exceptions occur, a processor supporting Streaming SIMD Extensions takes one of two possible courses of action:

- The processor can handle the exception by itself, producing the most reasonable result and allowing numeric program execution to continue undisturbed (i.e., masked exception response).
- A software exception handler can be invoked to handle the exception (i.e., unmasked exception response).

Each of the six exception conditions described above has corresponding flag and mask bits in the MXCSR. If an exception is masked (the corresponding mask bit in MXCSR = 1), the processor takes an appropriate default action and continues with the computation. If the exception is unmasked (mask bit = 0) and the OS supports SIMD floating-point exceptions (i.e. CR4.OSXMMEXCPT = 1), a software exception handler is invoked immediately through SIMD floating-point exception interrupt vector 19. If the exception is unmasked (mask bit = 0) and the OS does not support SIMD floating-point exceptions (i.e. CR4.OSXMMEXCPT = 0), an invalid opcode exception is signaled instead of a SIMD floating-point exception.

Note that because SIMD floating-point exceptions are precise and occur immediately, the situation does not arise where an x87-FP instruction, an FWAIT instruction, or another Streaming SIMD Extensions instruction will catch a pending unmasked SIMD floating-point exception.

Exception Error Code

None. The Streaming SIMD Extensions provide their own error information.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the Streaming SIMD Extensions instruction that was executed when the SIMD floating-point exception was generated. This is the faulting instruction in which the error condition was detected.

Program State Change

A program-state change generally accompanies a SIMD floating-point exception because the handling of the exception is immediate unless the particular exception is masked. The Pentium® III processor contains sufficient information about the error condition to allow recovery from the error and re-execution of the faulting instruction if needed.

In situations where a SIMD floating-point exception occurred while the SIMD floating-point exceptions were masked, SIMD floating-point exceptions were then unmasked, and a Streaming SIMD Extensions instruction was executed, then no exception is raised.

Interrupts 32 to 255—User Defined Interrupts

Exception Class Not applicable.

Description

Indicates that the processor did one of the following things:

- Executed an INT *n* instruction where the instruction operand is one of the vector numbers from 32 through 255.
- Responded to an interrupt request at the INTR pin or from the local APIC when the interrupt vector number associated with the request is from 32 through 255.

Exception Error Code

Not applicable.

Saved Instruction Pointer

The saved contents of CS and EIP registers point to the instruction that follows the INT *n* instruction or instruction following the instruction on which the INTR signal occurred.

Program State Change

A program-state change does not accompany interrupts generated by the INT *n* instruction or the INTR signal. The INT *n* instruction generates the interrupt within the instruction stream. When the processor receives an INTR signal, it commits all state changes for all previous instructions before it responds to the interrupt; so, program execution can resume upon returning from the interrupt handler.

6

Task Management

CHAPTER 6
TASK MANAGEMENT

This chapter describes the Intel Architecture's task management facilities. These facilities are only available when the processor is running in protected mode.

6.1. TASK MANAGEMENT OVERVIEW

A task is a unit of work that a processor can dispatch, execute, and suspend. It can be used to execute a program, a task or process, an operating-system service utility, an interrupt or exception handler, or a kernel or executive utility.

The Intel Architecture provides a mechanism for saving the state of a task, for dispatching tasks for execution, and for switching from one task to another. When operating in protected mode, all processor execution takes place from within a task. Even simple systems must define at least one task. More complex systems can use the processor's task management facilities to support multitasking applications.

6.1.1. Task Structure

A task is made up of two parts: a task execution space and a task-state segment (TSS). The task execution space consists of a code segment, a stack segment, and one or more data segments (refer to Figure 6-1). If an operating system or executive uses the processor's privilege-level protection mechanism, the task execution space also provides a separate stack for each privilege level.

The TSS specifies the segments that make up the task execution space and provides a storage place for task state information. In multitasking systems, the TSS also provides a mechanism for linking tasks.

NOTE

This chapter describes primarily 32-bit tasks and the 32-bit TSS structure. For information on 16-bit tasks and the 16-bit TSS structure, refer to Section 6.6., "16-Bit Task-State Segment (TSS)".

A task is identified by the segment selector for its TSS. When a task is loaded into the processor for execution, the segment selector, base address, limit, and segment descriptor attributes for the TSS are loaded into the task register (refer to Section 2.4.4., "Task Register (TR)" in Chapter 2, *System Architecture Overview*).

If paging is implemented for the task, the base address of the page directory used by the task is loaded into control register CR3.

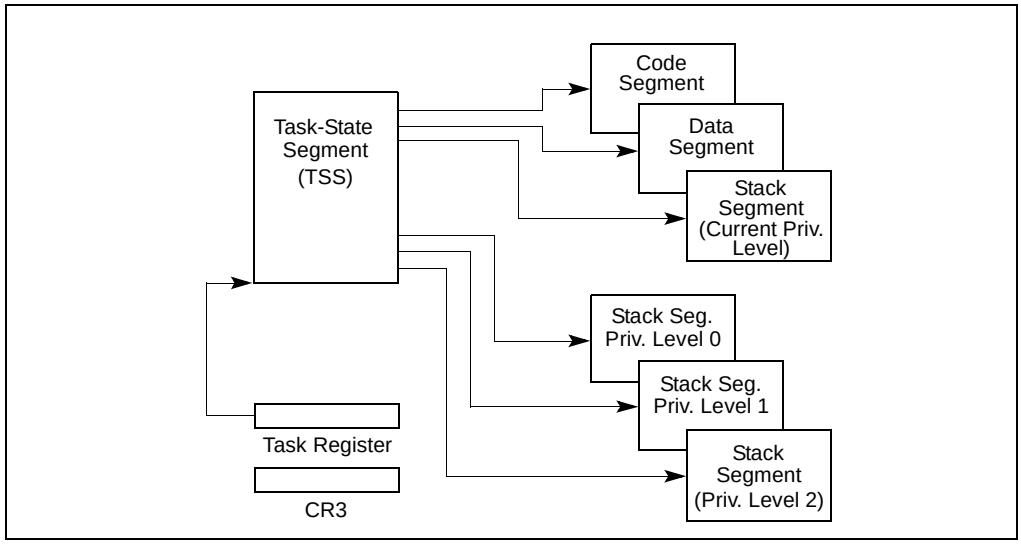


Figure 6-1. Structure of a Task

6.1.2. Task State

The following items define the state of the currently executing task:

- The task's current execution space, defined by the segment selectors in the segment registers (CS, DS, SS, ES, FS, and GS).
- The state of the general-purpose registers.
- The state of the EFLAGS register.
- The state of the EIP register.
- The state of control register CR3.
- The state of the task register.
- The state of the LDTR register.
- The I/O map base address and I/O map (contained in the TSS).
- Stack pointers to the privilege 0, 1, and 2 stacks (contained in the TSS).
- Link to previously executed task (contained in the TSS).

Prior to dispatching a task, all of these items are contained in the task's TSS, except the state of the task register. Also, the complete contents of the LDTR register are not contained in the TSS, only the segment selector for the LDT.

6.1.3. Executing a Task

Software or the processor can dispatch a task for execution in one of the following ways:

- A explicit call to a task with the CALL instruction.
- A explicit jump to a task with the JMP instruction.
- An implicit call (by the processor) to an interrupt-handler task.
- An implicit call to an exception-handler task.
- A return (initiated with an IRET instruction) when the NT flag in the EFLAGS register is set.

All of these methods of dispatching a task identify the task to be dispatched with a segment selector that points either to a task gate or the TSS for the task. When dispatching a task with a CALL or JMP instruction, the selector in the instruction may select either the TSS directly or a task gate that holds the selector for the TSS. When dispatching a task to handle an interrupt or exception, the IDT entry for the interrupt or exception must contain a task gate that holds the selector for the interrupt- or exception-handler TSS.

When a task is dispatched for execution, a task switch automatically occurs between the currently running task and the dispatched task. During a task switch, the execution environment of the currently executing task (called the task's state or **context**) is saved in its TSS and execution of the task is suspended. The context for the dispatched task is then loaded into the processor and execution of that task begins with the instruction pointed to by the newly loaded EIP register. If the task has not been run since the system was last initialized, the EIP will point to the first instruction of the task's code; otherwise, it will point to the next instruction after the last instruction that the task executed when it was last active.

If the currently executing task (the calling task) called the task being dispatched (the called task), the TSS segment selector for the calling task is stored in the TSS of the called task to provide a link back to the calling task.

For all Intel Architecture processors, tasks are not recursive. A task cannot call or jump to itself.

Interrupts and exceptions can be handled with a task switch to a handler task. Here, the processor not only can perform a task switch to handle the interrupt or exception, but it can automatically switch back to the interrupted task upon returning from the interrupt- or exception-handler task. This mechanism can handle interrupts that occur during interrupt tasks.

As part of a task switch, the processor can also switch to another LDT, allowing each task to have a different logical-to-physical address mapping for LDT-based segments. The page-directory base register (CR3) also is reloaded on a task switch, allowing each task to have its own set of page tables. These protection facilities help isolate tasks and prevent them from interfering with one another. If one or both of these protection mechanisms are not used, the processor provides no protection between tasks. This is true even with operating systems that use multiple privilege levels for protection. Here, a task running at privilege level 3 that uses the same LDT and page tables as other privilege-level-3 tasks can access code and corrupt data and the stack of other tasks.

Use of task management facilities for handling multitasking applications is optional. Multitasking can be handled in software, with each software defined task executed in the context of a single Intel Architecture task.

6.2. TASK MANAGEMENT DATA STRUCTURES

The processor defines five data structures for handling task-related activities:

- Task-state segment (TSS).
- Task-gate descriptor.
- TSS descriptor.
- Task register.
- NT flag in the EFLAGS register.

When operating in protected mode, a TSS and TSS descriptor must be created for at least one task, and the segment selector for the TSS must be loaded into the task register (using the LTR instruction).

6.2.1. Task-State Segment (TSS)

The processor state information needed to restore a task is saved in a system segment called the task-state segment (TSS). Figure 6-2 shows the format of a TSS for tasks designed for 32-bit CPUs. (Compatibility with 16-bit Intel 286 processor tasks is provided by a different kind of TSS, refer to Figure 6-9.) The fields of a TSS are divided into two main categories: dynamic fields and static fields.

The processor updates the dynamic fields when a task is suspended during a task switch. The following are dynamic fields:

General-purpose register fields
: State of the EAX, ECX, EDX, EBX, ESP, EBP, ESI, and EDI registers prior to the task switch.

Segment selector fields
: Segment selectors stored in the ES, CS, SS, DS, FS, and GS registers prior to the task switch.

EFLAGS register field
: State of the EFAGS register prior to the task switch.

EIP (instruction pointer) field
: State of the EIP register prior to the task switch.

Previous task link field
: Contains the segment selector for the TSS of the previous task (updated on a task switch that was initiated by a call, interrupt, or exception). This field

(which is sometimes called the back link field) permits a task switch back to the previous task to be initiated with an IRET instruction.

The processor reads the static fields, but does not normally change them. These fields are set up when a task is created. The following are static fields:

LDT segment selector field
Contains the segment selector for the task's LDT.

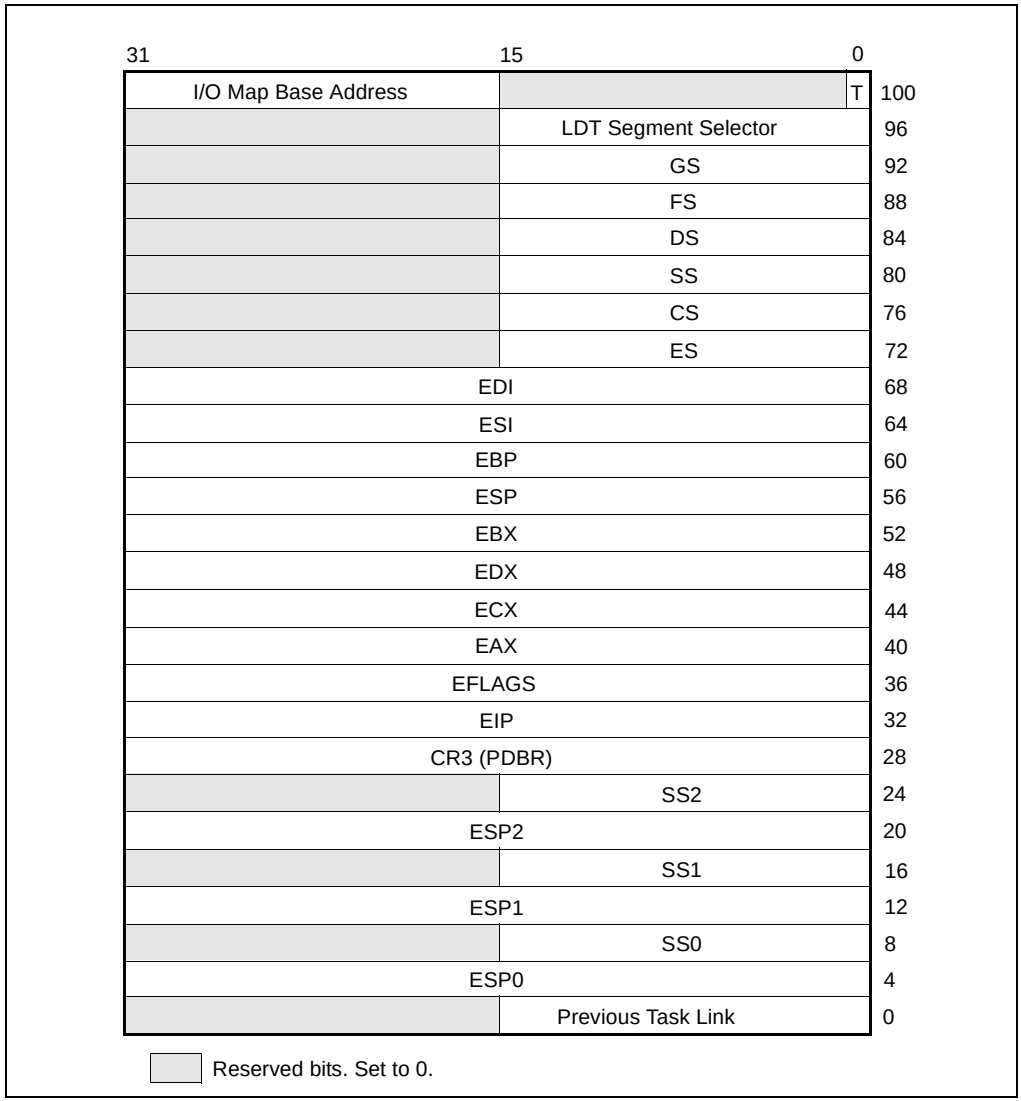


Figure 6-2. 32-Bit Task-State Segment (TSS)

CR3 control register field

Contains the base physical address of the page directory to be used by the task. Control register CR3 is also known as the page-directory base register (PDBR).

Privilege level-0, -1, and -2 stack pointer fields

These stack pointers consist of a logical address made up of the segment selector for the stack segment (SS0, SS1, and SS2) and an offset into the stack (ESP0, ESP1, and ESP2). Note that the values in these fields are static for a particular task; whereas, the SS and ESP values will change if stack switching occurs within the task.

T (debug trap) flag (byte 100, bit 0)

When set, the T flag causes the processor to raise a debug exception when a task switch to this task occurs (refer to Section 15.3.1.5., "Task-Switch Exception Condition", in Chapter 15, *Debugging and Performance Monitoring*).

I/O map base address field

Contains a 16-bit offset from the base of the TSS to the I/O permission bit map and interrupt redirection bitmap. When present, these maps are stored in the TSS at higher addresses. The I/O map base address points to the beginning of the I/O permission bit map and the end of the interrupt redirection bit map. Refer to Chapter 9, *Input/Output*, in the *Intel Architecture Software Developer's Manual, Volume 1*, for more information about the I/O permission bit map. Refer to Section 16.3., "Interrupt and Exception Handling in Virtual-8086 Mode" in Chapter 16, *8086 Emulation* for a detailed description of the interrupt redirection bit map.

If paging is used, care should be taken to avoid placing a page boundary within the part of the TSS that the processor reads during a task switch (the first 104 bytes). If a page boundary is placed within this part of the TSS, the pages on either side of the boundary must be present at the same time and contiguous in physical memory. The reason for this restriction is that when accessing a TSS during a task switch, the processor reads and writes into the first 104 bytes of each TSS from contiguous physical addresses beginning with the physical address of the first byte of the TSS. It may not perform address translations at a page boundary if one occurs within this area. So, after the TSS access begins, if a part of the 104 bytes is not both present and physically contiguous, the processor will access incorrect TSS information, without generating a page-fault exception. The reading of this incorrect information will generally lead to an unrecoverable exception later in the task switch process.

Also, if paging is used, the pages corresponding to the previous task's TSS, the current task's TSS, and the descriptor table entries for each should be marked as read/write. The task switch will be carried out faster if the pages containing these structures are also present in memory before the task switch is initiated.

6.2.2. TSS Descriptor

The TSS, like all other segments, is defined by a segment descriptor. Figure 6-3 shows the format of a TSS descriptor. TSS descriptors may only be placed in the GDT; they cannot be placed in an LDT or the IDT. An attempt to access a TSS using a segment selector with its TI

flag set (which indicates the current LDT) causes a general-protection exception (#GP) to be generated. A general-protection exception is also generated if an attempt is made to load a segment selector for a TSS into a segment register.

The busy flag (B) in the type field indicates whether the task is busy. A busy task is currently running or is suspended. A type field with a value of 1001B indicates an inactive task; a value of 1011B indicates a busy task. Tasks are not recursive. The processor uses the busy flag to detect an attempt to call a task whose execution has been interrupted. To insure that there is only one busy flag is associated with a task, each TSS should have only one TSS descriptor that points to it.

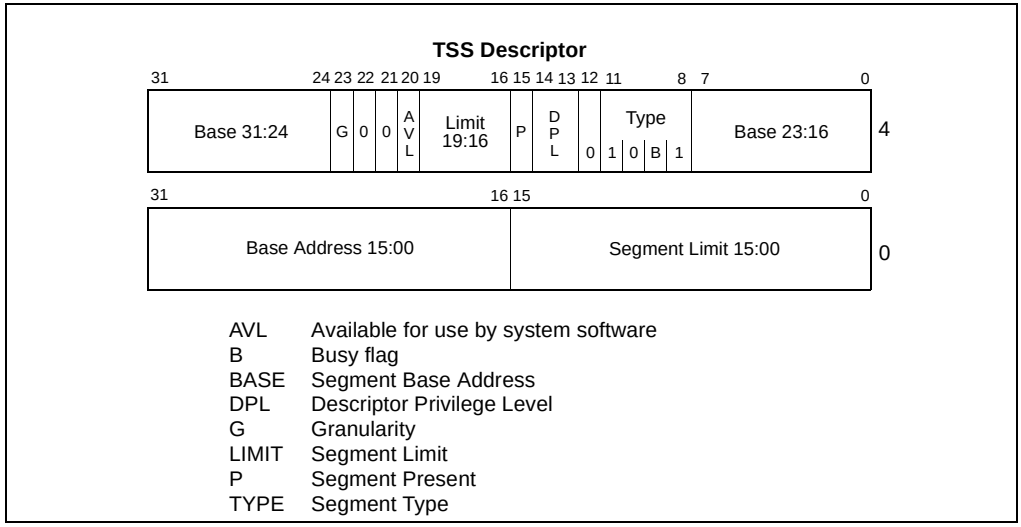


Figure 6-3. TSS Descriptor

The base, limit, and DPL fields and the granularity and present flags have functions similar to their use in data-segment descriptors (refer to Section 3.4.3., “Segment Descriptors” in Chapter 3, *Protected-Mode Memory Management*). The limit field must have a value equal to or greater than 67H (for a 32-bit TSS), one byte less than the minimum size of a TSS. Attempting to switch to a task whose TSS descriptor has a limit less than 67H generates an invalid-TSS exception (#TS). A larger limit is required if an I/O permission bit map is included in the TSS. An even larger limit would be required if the operating system stores additional data in the TSS. The processor does not check for a limit greater than 67H on a task switch; however, it does when accessing the I/O permission bit map or interrupt redirection bit map.

Any program or procedure with access to a TSS descriptor (that is, whose CPL is numerically equal to or less than the DPL of the TSS descriptor) can dispatch the task with a call or a jump. In most systems, the DPLs of TSS descriptors should be set to values less than 3, so that only privileged software can perform task switching. However, in multitasking applications, DPLs for some TSS descriptors can be set to 3 to allow task switching at the application (or user) privilege level.

6.2.3. Task Register

The task register holds the 16-bit segment selector and the entire segment descriptor (32-bit base address, 16-bit segment limit, and descriptor attributes) for the TSS of the current task (refer to Figure 2-4 in Chapter 2, *System Architecture Overview*). This information is copied from the TSS descriptor in the GDT for the current task. Figure 6-4 shows the path the processor uses to accesses the TSS, using the information in the task register.

The task register has both a visible part (that can be read and changed by software) and an invisible part (that is maintained by the processor and is inaccessible by software). The segment selector in the visible portion points to a TSS descriptor in the GDT. The processor uses the invisible portion of the task register to cache the segment descriptor for the TSS. Caching these values in a register makes execution of the task more efficient, because the processor does not need to fetch these values from memory to reference the TSS of the current task.

The LTR (load task register) and STR (store task register) instructions load and read the visible portion of the task register. The LTR instruction loads a segment selector (source operand) into the task register that points to a TSS descriptor in the GDT, and then loads the invisible portion of the task register with information from the TSS descriptor. This instruction is a privileged instruction that may be executed only when the CPL is 0. The LTR instruction generally is used during system initialization to put an initial value in the task register. Afterwards, the contents of the task register are changed implicitly when a task switch occurs.

The STR (store task register) instruction stores the visible portion of the task register in a general-purpose register or memory. This instruction can be executed by code running at any privilege level, to identify the currently running task; however, it is normally used only by operating system software.

On power up or reset of the processor, the segment selector and base address are set to the default value of 0 and the limit is set to FFFFH.

6.2.4. Task-Gate Descriptor

A task-gate descriptor provides an indirect, protected reference to a task. Figure 6-5 shows the format of a task-gate descriptor. A task-gate descriptor can be placed in the GDT, an LDT, or the IDT.

The TSS segment selector field in a task-gate descriptor points to a TSS descriptor in the GDT. The RPL in this segment selector is not used.

The DPL of a task-gate descriptor controls access to the TSS descriptor during a task switch. When a program or procedure makes a call or jump to a task through a task gate, the CPL and the RPL field of the gate selector pointing to the task gate must be less than or equal to the DPL of the task-gate descriptor. (Note that when a task gate is used, the DPL of the destination TSS descriptor is not used.)

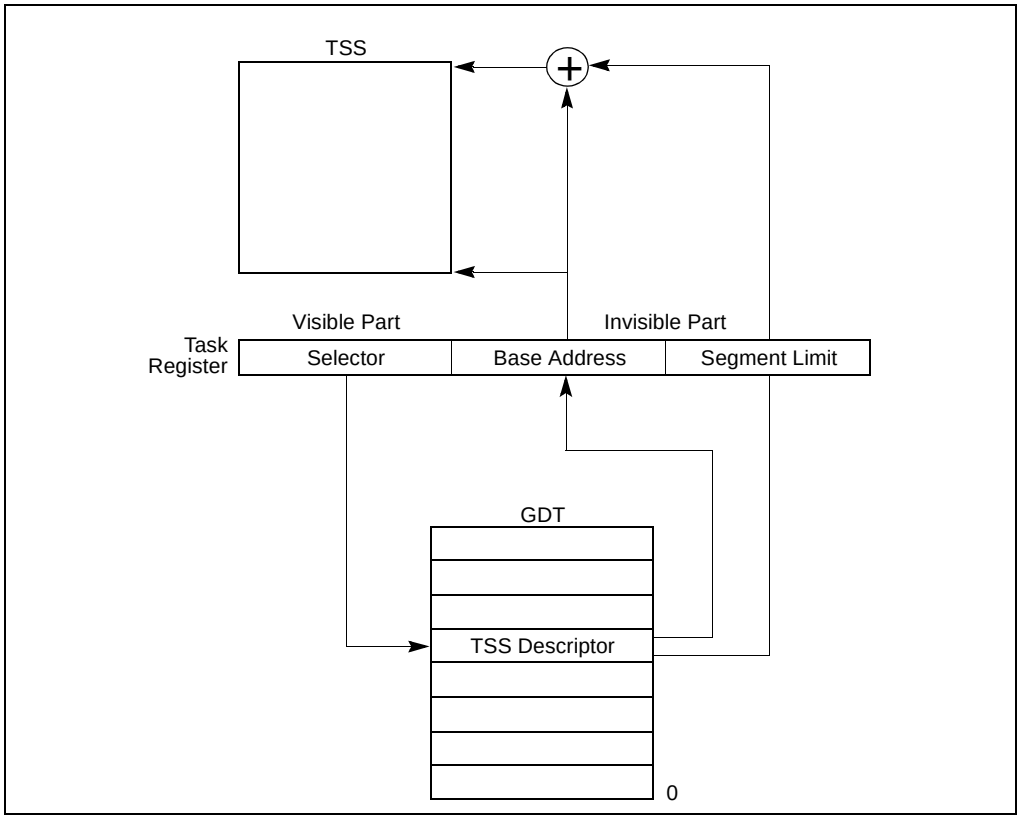


Figure 6-4. Task Register

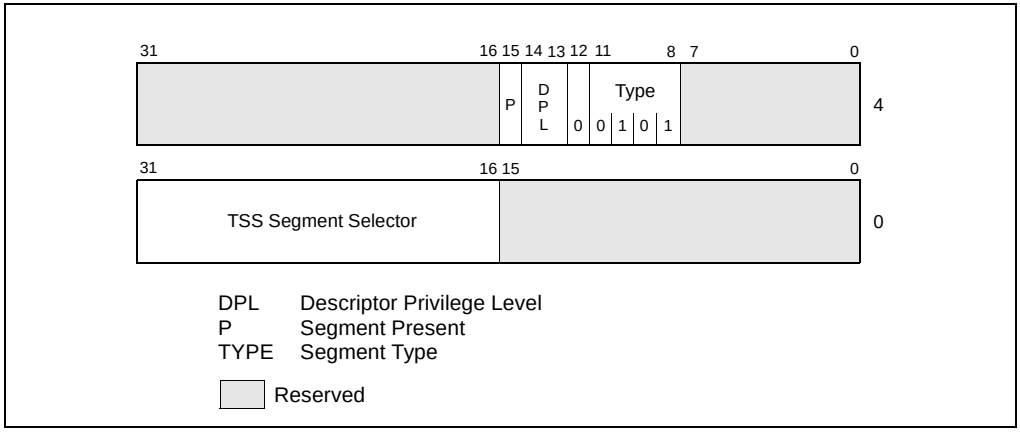


Figure 6-5. Task-Gate Descriptor

A task can be accessed either through a task-gate descriptor or a TSS descriptor. Both of these structures are provided to satisfy the following needs:

- The need for a task to have only one busy flag. Because the busy flag for a task is stored in the TSS descriptor, each task should have only one TSS descriptor. There may, however, be several task gates that reference the same TSS descriptor.
- The need to provide selective access to tasks. Task gates fill this need, because they can reside in an LDT and can have a DPL that is different from the TSS descriptor's DPL. A program or procedure that does not have sufficient privilege to access the TSS descriptor for a task in the GDT (which usually has a DPL of 0) may be allowed access to the task through a task gate with a higher DPL. Task gates give the operating system greater latitude for limiting access to specific tasks.
- The need for an interrupt or exception to be handled by an independent task. Task gates may also reside in the IDT, which allows interrupts and exceptions to be handled by handler tasks. When an interrupt or exception vector points to a task gate, the processor switches to the specified task.

Figure 6-6 illustrates how a task gate in an LDT, a task gate in the GDT, and a task gate in the IDT can all point to the same task.

6.3. TASK SWITCHING

The processor transfers execution to another task in any of four cases:

- The current program, task, or procedure executes a JMP or CALL instruction to a TSS descriptor in the GDT.
- The current program, task, or procedure executes a JMP or CALL instruction to a task-gate descriptor in the GDT or the current LDT.
- An interrupt or exception vector points to a task-gate descriptor in the IDT.
- The current task executes an IRET when the NT flag in the EFLAGS register is set.

The JMP, CALL, and IRET instructions, as well as interrupts and exceptions, are all generalized mechanisms for redirecting a program. The referencing of a TSS descriptor or a task gate (when calling or jumping to a task) or the state of the NT flag (when executing an IRET instruction) determines whether a task switch occurs.

The processor performs the following operations when switching to a new task:

1. Obtains the TSS segment selector for the new task as the operand of the JMP or CALL instruction, from a task gate, or from the previous task link field (for a task switch initiated with an IRET instruction).

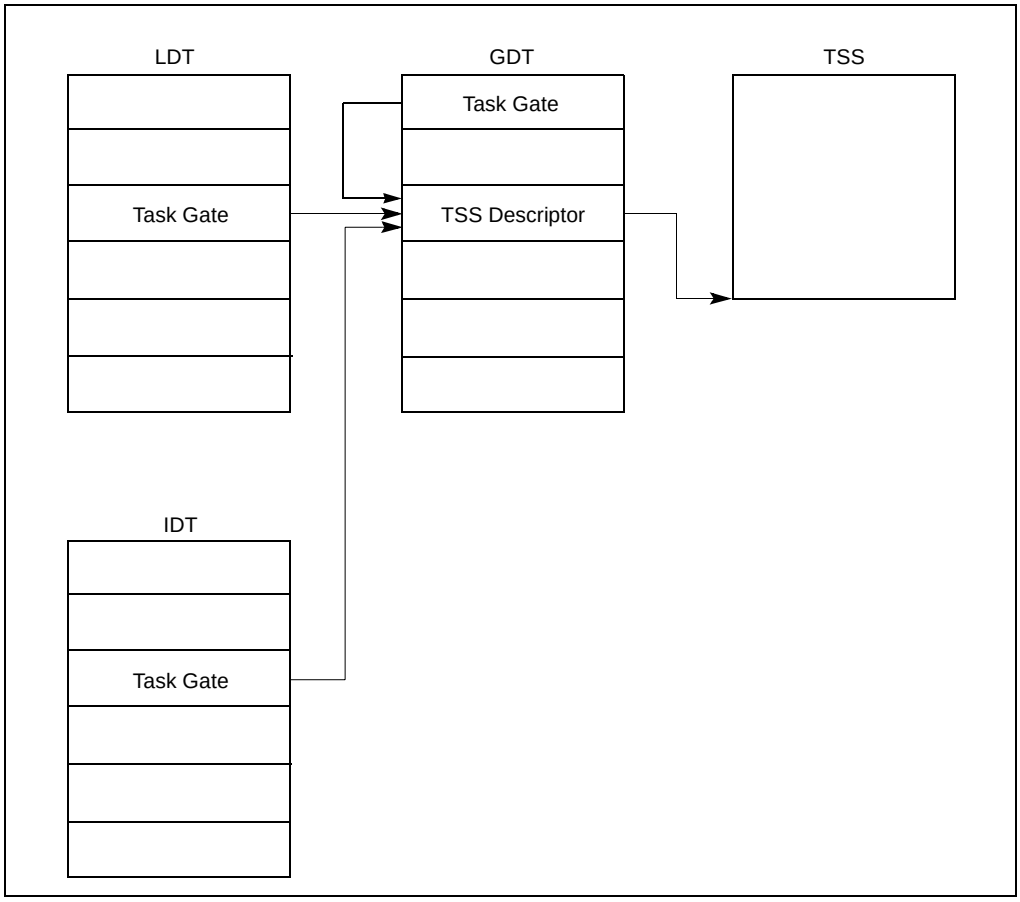


Figure 6-6. Task Gates Referencing the Same Task

2. Checks that the current (old) task is allowed to switch to the new task. Data-access privilege rules apply to JMP and CALL instructions. The CPL of the current (old) task and the RPL of the segment selector for the new task must be less than or equal to the DPL of the TSS descriptor or task gate being referenced. Exceptions, interrupts (except for interrupts generated by the INT *n* instruction), and the IRET instruction are permitted to switch tasks regardless of the DPL of the destination task-gate or TSS descriptor. For interrupts generated by the INT *n* instruction, the DPL is checked.
3. Checks that the TSS descriptor of the new task is marked present and has a valid limit (greater than or equal to 67H).
4. Checks that the new task is available (call, jump, exception, or interrupt) or busy (IRET return).

5. Checks that the current (old) TSS, new TSS, and all segment descriptors used in the task switch are paged into system memory.
6. If the task switch was initiated with a JMP or IRET instruction, the processor clears the busy (B) flag in the current (old) task's TSS descriptor; if initiated with a CALL instruction, an exception, or an interrupt, the busy (B) flag is left set. (Refer to Table 6-2.)
7. If the task switch was initiated with an IRET instruction, the processor clears the NT flag in a temporarily saved image of the EFLAGS register; if initiated with a CALL or JMP instruction, an exception, or an interrupt, the NT flag is left unchanged in the saved EFLAGS image.
8. Saves the state of the current (old) task in the current task's TSS. The processor finds the base address of the current TSS in the task register and then copies the states of the following registers into the current TSS: all the general-purpose registers, segment selectors from the segment registers, the temporarily saved image of the EFLAGS register, and the instruction pointer register (EIP).

NOTE

At this point, if all checks and saves have been carried out successfully, the processor commits to the task switch. If an unrecoverable error occurs in steps 1 through 8, the processor does not complete the task switch and insures that the processor is returned to its state prior to the execution of the instruction that initiated the task switch. If an unrecoverable error occurs after the commit point (in steps 9 through 14), the processor completes the task switch (without performing additional access and segment availability checks) and generates the appropriate exception prior to beginning execution of the new task. If exceptions occur after the commit point, the exception handler must finish the task switch itself before allowing the processor to begin executing the task. Refer to Chapter 5, *Interrupt and Exception Handling* for more information about the affect of exceptions on a task when they occur after the commit point of a task switch.

9. If the task switch was initiated with a CALL instruction, an exception, or an interrupt, the processor sets the NT flag in the EFLAGS image stored in the new task's TSS; if initiated with an IRET instruction, the processor restores the NT flag from the EFLAGS image stored on the stack. If initiated with a JMP instruction, the NT flag is left unchanged. (Refer to Table 6-2.)
10. If the task switch was initiated with a CALL instruction, JMP instruction, an exception, or an interrupt, the processor sets the busy (B) flag in the new task's TSS descriptor; if initiated with an IRET instruction, the busy (B) flag is left set.
11. Sets the TS flag in the control register CR0 image stored in the new task's TSS.
12. Loads the task register with the segment selector and descriptor for the new task's TSS.

13. Loads the new task's state from its TSS into processor. Any errors associated with the loading and qualification of segment descriptors in this step occur in the context of the new task. The task state information that is loaded here includes the LDTR register, the PDBR (control register CR3), the EFLAGS register, the EIP register, the general-purpose registers, and the segment descriptor parts of the segment registers.
14. Begins executing the new task. (To an exception handler, the first instruction of the new task appears not to have been executed.)

The state of the currently executing task is always saved when a successful task switch occurs. If the task is resumed, execution starts with the instruction pointed to by the saved EIP value, and the registers are restored to the values they held when the task was suspended.

When switching tasks, the privilege level of the new task does not inherit its privilege level from the suspended task. The new task begins executing at the privilege level specified in the CPL field of the CS register, which is loaded from the TSS. Because tasks are isolated by their separate address spaces and TSSs and because privilege rules control access to a TSS, software does not need to perform explicit privilege checks on a task switch.

Table 6-1 shows the exception conditions that the processor checks for when switching tasks. It also shows the exception that is generated for each check if an error is detected and the segment that the error code references. (The order of the checks in the table is the order used in the P6 family processors. The exact order is model specific and may be different for other Intel Architecture processors.) Exception handlers designed to handle these exceptions may be subject to recursive calls if they attempt to reload the segment selector that generated the exception. The cause of the exception (or the first of multiple causes) should be fixed before reloading the selector.

Table 6-1. Exception Conditions Checked During a Task Switch

Condition Checked	Exception[1]	Error Code Reference[2]
Segment selector for a TSS descriptor references the GDT and is within the limits of the table.	#GP	New Task's TSS
TSS descriptor is present in memory.	#NP	New Task's TSS
TSS descriptor is not busy (for task switch initiated by a call, interrupt, or exception).	#GP (for JMP, CALL, INT)	Task's back-link TSS
TSS descriptor is not busy (for task switch initiated by an IRET instruction).	#TS (for IRET)	New Task's TSS
TSS segment limit greater than or equal to 108 (for 32-bit TSS) or 44 (for 16-bit TSS).	#TS	New Task's TSS
Registers are loaded from the values in the TSS.		
LDT segment selector of new task is valid [3].	#TS	New Task's LDT
Code segment DPL matches segment selector RPL.	#TS	New Code Segment
SS segment selector is valid [2].	#TS	New Stack Segment
Stack segment is present in memory.	#SF	New Stack Segment

Table 6-1. Exception Conditions Checked During a Task Switch (Contd.)

Stack segment DPL matches CPL.	#TS	New stack segment
LDT of new task is present in memory.	#TS	New Task's LDT
CS segment selector is valid [3].	#TS	New Code Segment
Code segment is present in memory.	#NP	New Code Segment
Stack segment DPL matches selector RPL.	#TS	New Stack Segment
DS, ES, FS, and GS segment selectors are valid [3].	#TS	New Data Segment
DS, ES, FS, and GS segments are readable.	#TS	New Data Segment
DS, ES, FS, and GS segments are present in memory.	#NP	New Data Segment
DS, ES, FS, and GS segment DPL greater than or equal to CPL (unless these are conforming segments).	#TS	New Data Segment

NOTES:

1. #NP is segment-not-present exception, #GP is general-protection exception, #TS is invalid-TSS exception, and #SF is stack-fault exception.
2. The error code contains an index to the segment descriptor referenced in this column.
3. A segment selector is valid if it is in a compatible type of table (GDT or LDT), occupies an address within the table's segment limit, and refers to a compatible type of descriptor (for example, a segment selector in the CS register only is valid when it points to a code-segment descriptor).

The TS (task switched) flag in the control register CR0 is set every time a task switch occurs. System software uses the TS flag to coordinate the actions of floating-point unit when generating floating-point exceptions with the rest of the processor. The TS flag indicates that the context of the floating-point unit may be different from that of the current task. Refer to Section 2.5., "Control Registers" in Chapter 2, *System Architecture Overview* for a detailed description of the function and use of the TS flag.

6.4. TASK LINKING

The previous task link field of the TSS (sometimes called the "backlink") and the NT flag in the EFLAGS register are used to return execution to the previous task. The NT flag indicates whether the currently executing task is nested within the execution of another task, and the previous task link field of the current task's TSS holds the TSS selector for the higher-level task in the nesting hierarchy, if there is one (refer to Figure 6-7).

When a CALL instruction, an interrupt, or an exception causes a task switch, the processor copies the segment selector for the current TSS into the previous task link field of the TSS for the new task, and then sets the NT flag in the EFLAGS register. The NT flag indicates that the previous task link field of the TSS has been loaded with a saved TSS segment selector. If software uses an IRET instruction to suspend the new task, the processor uses the value in the previous task link field and the NT flag to return to the previous task; that is, if the NT flag is set, the processor performs a task switch to the task specified in the previous task link field.

NOTE

When a JMP instruction causes a task switch, the new task is not nested; that is, the NT flag is set to 0 and the previous task link field is not used. A JMP instruction is used to dispatch a new task when nesting is not desired.

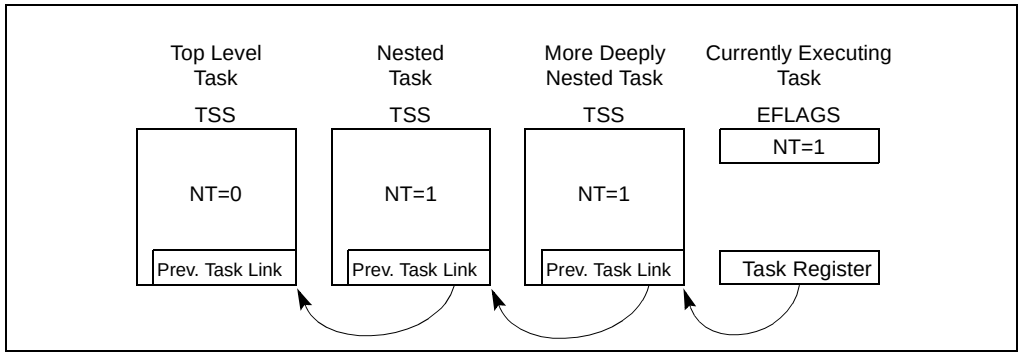


Figure 6-7. Nested Tasks

Table 6-2 summarizes the uses of the busy flag (in the TSS segment descriptor), the NT flag, the previous task link field, and TS flag (in control register CR0) during a task switch. Note that the NT flag may be modified by software executing at any privilege level. It is possible for a program to set its NT flag and execute an IRET instruction, which would have the effect of invoking the task specified in the previous link field of the current task's TSS. To keep spurious task switches from succeeding, the operating system should initialize the previous task link field for every TSS it creates to 0.

Table 6-2. Effect of a Task Switch on Busy Flag, NT Flag, Previous Task Link Field, and TS Flag

Flag or Field	Effect of JMP instruction	Effect of CALL Instruction or Interrupt	Effect of IRET Instruction
Busy (B) flag of new task.	Flag is set. Must have been clear before.	Flag is set. Must have been clear before.	No change. Must have been set.
Busy flag of old task.	Flag is cleared.	No change. Flag is currently set.	Flag is cleared.
NT flag of new task.	No change.	Flag is set.	Restored to value from TSS of new task.
NT flag of old task.	No change.	No change.	Flag is cleared.
Previous task link field of new task.	No change.	Loaded with selector for old task's TSS.	No change.
Previous task link field of old task.	No change.	No change.	No change.
TS flag in control register CR0.	Flag is set.	Flag is set.	Flag is set.

6.4.1. Use of Busy Flag To Prevent Recursive Task Switching

A TSS allows only one context to be saved for a task; therefore, once a task is called (dispatched), a recursive (or re-entrant) call to the task would cause the current state of the task to be lost. The busy flag in the TSS segment descriptor is provided to prevent re-entrant task switching and subsequent loss of task state information. The processor manages the busy flag as follows:

1. When dispatching a task, the processor sets the busy flag of the new task.
2. If during a task switch, the current task is placed in a nested chain (the task switch is being generated by a CALL instruction, an interrupt, or an exception), the busy flag for the current task remains set.
3. When switching to the new task (initiated by a CALL instruction, interrupt, or exception), the processor generates a general-protection exception (#GP) if the busy flag of the new task is already set. (If the task switch is initiated with an IRET instruction, the exception is not raised because the processor expects the busy flag to be set.)
4. When a task is terminated by a jump to a new task (initiated with a JMP instruction in the task code) or by an IRET instruction in the task code, the processor clears the busy flag, returning the task to the “not busy” state.

In this manner the processor prevents recursive task switching by preventing a task from switching to itself or to any task in a nested chain of tasks. The chain of nested suspended tasks may grow to any length, due to multiple calls, interrupts, or exceptions. The busy flag prevents a task from being invoked if it is in this chain.

The busy flag may be used in multiprocessor configurations, because the processor follows a LOCK protocol (on the bus or in the cache) when it sets or clears the busy flag. This lock keeps two processors from invoking the same task at the same time. (Refer to Section 7.1.2.1., “Automatic Locking” in Chapter 7, *Multiple-Processor Management* for more information about setting the busy flag in a multiprocessor applications.)

6.4.2. Modifying Task Linkages

In a uniprocessor system, in situations where it is necessary to remove a task from a chain of linked tasks, use the following procedure to remove the task:

1. Disable interrupts.
2. Change the previous task link field in the TSS of the pre-empting task (the task that suspended the task to be removed). It is assumed that the pre-empting task is the next task (newer task) in the chain from the task to be removed. Change the previous task link field should to point to the TSS of the next oldest or to an even older task in the chain.
3. Clear the busy (B) flag in the TSS segment descriptor for the task being removed from the chain. If more than one task is being removed from the chain, the busy flag for each task being remove must be cleared.
4. Enable interrupts.

In a multiprocessing system, additional synchronization and serialization operations must be added to this procedure to insure that the TSS and its segment descriptor are both locked when the previous task link field is changed and the busy flag is cleared.

6.5. TASK ADDRESS SPACE

The address space for a task consists of the segments that the task can access. These segments include the code, data, stack, and system segments referenced in the TSS and any other segments accessed by the task code. These segments are mapped into the processor's linear address space, which is in turn mapped into the processor's physical address space (either directly or through paging).

The LDT segment field in the TSS can be used to give each task its own LDT. Giving a task its own LDT allows the task address space to be isolated from other tasks by placing the segment descriptors for all the segments associated with the task in the task's LDT.

It also is possible for several tasks to use the same LDT. This is a simple and memory-efficient way to allow some tasks to communicate with or control each other, without dropping the protection barriers for the entire system.

Because all tasks have access to the GDT, it also is possible to create shared segments accessed through segment descriptors in this table.

If paging is enabled, the CR3 register (PDBR) field in the TSS allows each task can also have its own set of page tables for mapping linear addresses to physical addresses. Or, several tasks can share the same set of page tables.

6.5.1. Mapping Tasks to the Linear and Physical Address Spaces

Tasks can be mapped to the linear address space and physical address space in either of two ways:

- One linear-to-physical address space mapping is shared among all tasks. When paging is not enabled, this is the only choice. Without paging, all linear addresses map to the same physical addresses. When paging is enabled, this form of linear-to-physical address space mapping is obtained by using one page directory for all tasks. The linear address space may exceed the available physical space if demand-paged virtual memory is supported.
- Each task has its own linear address space that is mapped to the physical address space. This form of mapping is accomplished by using a different page directory for each task. Because the PDBR (control register CR3) is loaded on each task switch, each task may have a different page directory.

The linear address spaces of different tasks may map to completely distinct physical addresses. If the entries of different page directories point to different page tables and the page tables point to different pages of physical memory, then the tasks do not share any physical addresses.

With either method of mapping task linear address spaces, the TSSs for all tasks must lie in a shared area of the physical space, which is accessible to all tasks. This mapping is required so that the mapping of TSS addresses does not change while the processor is reading and updating the TSSs during a task switch. The linear address space mapped by the GDT also should be mapped to a shared area of the physical space; otherwise, the purpose of the GDT is defeated. Figure 6-8 shows how the linear address spaces of two tasks can overlap in the physical space by sharing page tables.

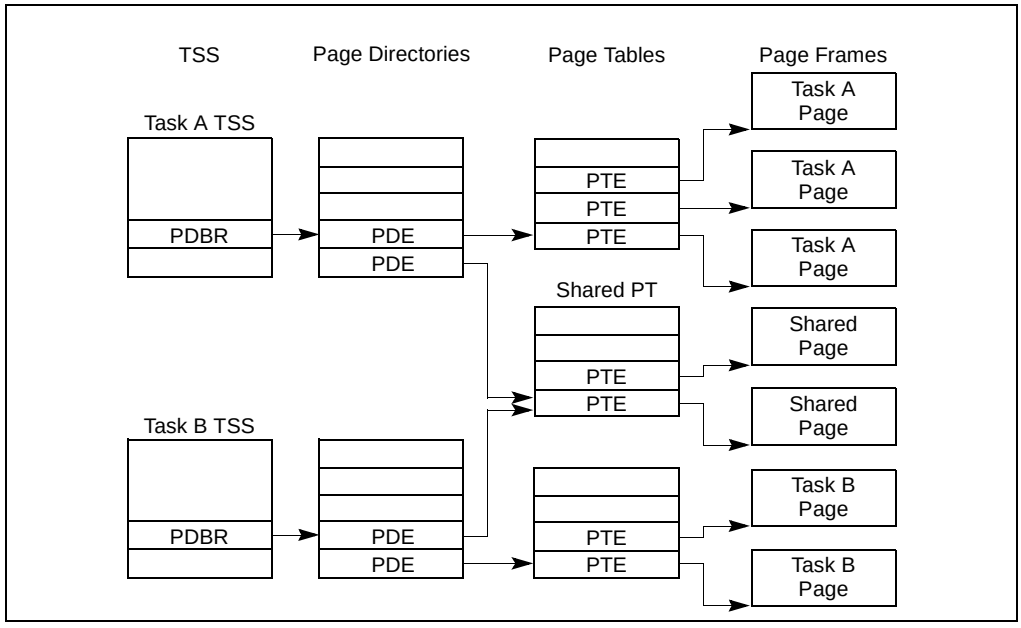


Figure 6-8. Overlapping Linear-to-Physical Mappings

6.5.2. Task Logical Address Space

To allow the sharing of data among tasks, use any of the following techniques to create shared logical-to-physical address-space mappings for data segments:

- Through the segment descriptors in the GDT. All tasks must have access to the segment descriptors in the GDT. If some segment descriptors in the GDT point to segments in the linear-address space that are mapped into an area of the physical-address space common to all tasks, then all tasks can share the data and code in those segments.
- Through a shared LDT. Two or more tasks can use the same LDT if the LDT fields in their TSSs point to the same LDT. If some segment descriptors in a shared LDT point to segments that are mapped to a common area of the physical address space, the data and code in those segments can be shared among the tasks that share the LDT. This method of sharing is more selective than sharing through the GDT, because the sharing can be limited

to specific tasks. Other tasks in the system may have different LDTs that do not give them access to the shared segments.

- Through segment descriptors in distinct LDTs that are mapped to common addresses in the linear address space. If this common area of the linear address space is mapped to the same area of the physical address space for each task, these segment descriptors permit the tasks to share segments. Such segment descriptors are commonly called aliases. This method of sharing is even more selective than those listed above, because, other segment descriptors in the LDTs may point to independent linear addresses which are not shared.

6.6. 16-BIT TASK-STATE SEGMENT (TSS)

The 32-bit Intel Architecture processors also recognize a 16-bit TSS format like the one used in Intel 286 processors (refer to Figure 6-9). It is supported for compatibility with software written to run on these earlier Intel Architecture processors.

The following additional information is important to know about the 16-bit TSS.

- Do not use a 16-bit TSS to implement a virtual-8086 task.
- The valid segment limit for a 16-bit TSS is 2CH.
- The 16-bit TSS does not contain a field for the base address of the page directory, which is loaded into control register CR3. Therefore, a separate set of page tables for each task is not supported for 16-bit tasks. If a 16-bit task is dispatched, the page-table structure for the previous task is used.
- The I/O base address is not included in the 16-bit TSS, so none of the functions of the I/O map are supported.
- When task state is saved in a 16-bit TSS, the upper 16 bits of the EFLAGS register and the EIP register are lost.
- When the general-purpose registers are loaded or saved from a 16-bit TSS, the upper 16 bits of the registers are modified and not maintained.

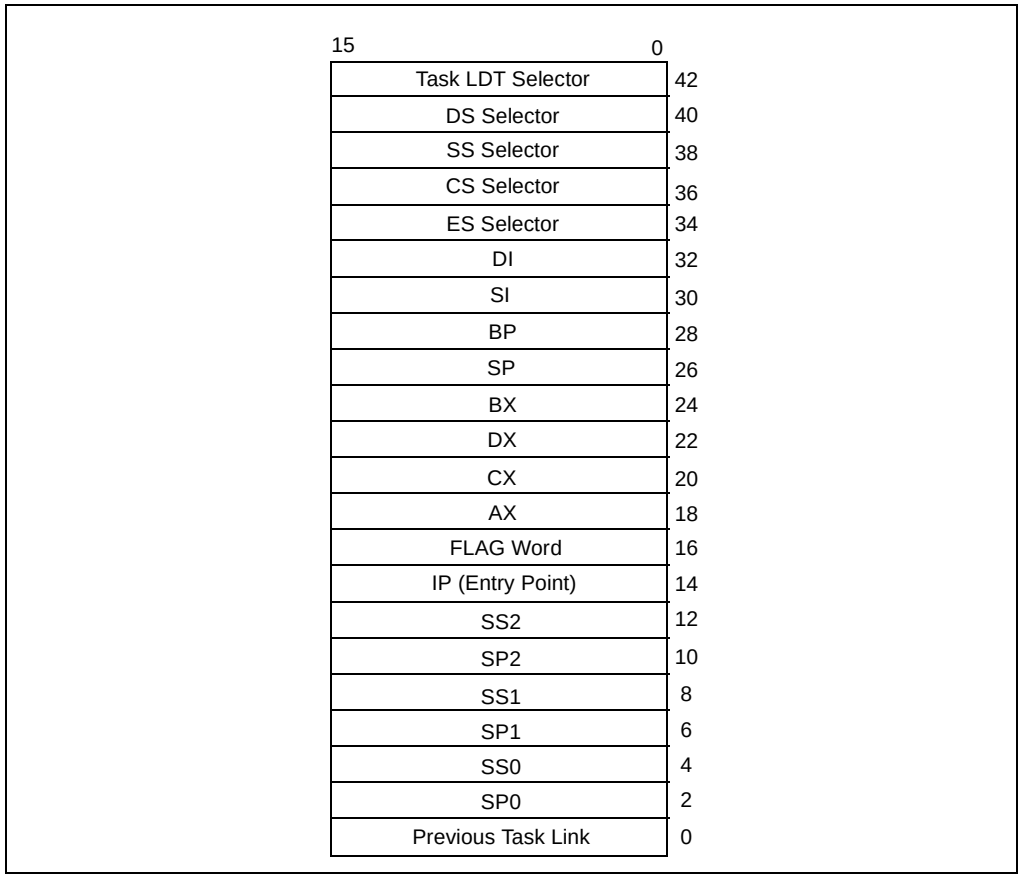


Figure 6-9. 16-Bit TSS Format

7

Multiple-Processor Management

CHAPTER 7
MULTIPLE-PROCESSOR MANAGEMENT

The Intel Architecture provides several mechanisms for managing and improving the performance of multiple processors connected to the same system bus. These mechanisms include:

- Bus locking and/or cache coherency management for performing atomic operations on system memory.
- Serializing instructions. (These instructions apply only to the Pentium® and P6 family processors.)
- Advance programmable interrupt controller (APIC) located on the processor chip. (The APIC architecture was introduced into the Intel Architecture with the Pentium® processor.)
- A secondary (level 2, L2) cache. For the P6 family processors, the L2 cache is included in the processor package and is tightly coupled to the processor. For the Pentium® and Intel486™ processors, pins are provided to support an external L2 cache.

These mechanisms are particularly useful in symmetric-multiprocessing systems; however, they can also be used in applications where a Intel Architecture processor and a special-purpose processor (such as a communications, graphics, or video processor) share the system bus.

The main goals of these multiprocessing mechanisms are as follows:

- To maintain system memory coherency—When two or more processors are attempting simultaneously to access the same address in system memory, some communication mechanism or memory access protocol must be available to promote data coherency and, in some instances, to allow one processor to temporarily lock a memory location.
- To maintain cache consistency—When one processor accesses data cached in another processor, it must not receive incorrect data. If it modifies data, all other processors that access that data must receive the modified data.
- To allow predictable ordering of writes to memory—In some circumstances, it is important that memory writes be observed externally in precisely the same order as programmed.
- To distribute interrupt handling among a group of processors—When several processors are operating in a system in parallel, it is useful to have a centralized mechanism for receiving interrupts and distributing them to available processors for servicing.

The Intel Architecture's caching mechanism and cache consistency are discussed in Chapter 9, *Memory Cache Control*. Bus and memory locking, serializing instructions, memory ordering, and the processor's internal APIC are discussed in the following sections.

7.1. LOCKED ATOMIC OPERATIONS

The 32-bit Intel Architecture processors support locked atomic operations on locations in system memory. These operations are typically used to manage shared data structures (such as semaphores, segment descriptors, system segments, or page tables) in which two or more processors may try simultaneously to modify the same field or flag. The processor uses three interdependent mechanisms for carrying out locked atomic operations:

- Guaranteed atomic operations.
- Bus locking, using the LOCK# signal and the LOCK instruction prefix.
- Cache coherency protocols that insure that atomic operations can be carried out on cached data structures (cache lock). This mechanism is present in the P6 family processors.

These mechanisms are interdependent in the following ways. Certain basic memory transactions (such as reading or writing a byte in system memory) are always guaranteed to be handled atomically. That is, once started, the processor guarantees that the operation will be completed before another processor or bus agent is allowed access to the memory location. The processor also supports bus locking for performing selected memory operations (such as a read-modify-write operation in a shared area of memory) that typically need to be handled atomically, but are not automatically handled this way. Because frequently used memory locations are often cached in a processor's L1 or L2 caches, atomic operations can often be carried out inside a processor's caches without asserting the bus lock. Here the processor's cache coherency protocols insure that other processors that are caching the same memory locations are managed properly while atomic operations are performed on cached memory locations.

Note that the mechanisms for handling locked atomic operations have evolved as the complexity of Intel Architecture processors has evolved. As such, more recent Intel Architecture processors (such as the P6 family processors) provide a more refined locking mechanism than earlier Intel Architecture processors, as is described in the following sections.

7.1.1. Guaranteed Atomic Operations

The Intel386™, Intel486™, Pentium®, and P6 family processors guarantee that the following basic memory operations will always be carried out atomically:

- Reading or writing a byte.
- Reading or writing a word aligned on a 16-bit boundary.
- Reading or writing a doubleword aligned on a 32-bit boundary.

The P6 family processors guarantee that the following additional memory operations will always be carried out atomically:

- Reading or writing a quadword aligned on a 64-bit boundary. (This operation is also guaranteed on the Pentium® processor.)
- 16-bit accesses to uncached memory locations that fit within a 32-bit data bus.
- 16-, 32-, and 64-bit accesses to cached memory that fit within a 32-Byte cache line.

Accesses to cacheable memory that are split across bus widths, cache lines, and page boundaries are not guaranteed to be atomic by the Intel486™, Pentium®, or P6 family processors. The P6 family processors provide bus control signals that permit external memory subsystems to make split accesses atomic; however, nonaligned data accesses will seriously impact the performance of the processor and should be avoided where possible.

7.1.2. Bus Locking

Intel Architecture processors provide a LOCK# signal that is asserted automatically during certain critical memory operations to lock the system bus. While this output signal is asserted, requests from other processors or bus agents for control of the bus are blocked. Software can specify other occasions when the LOCK semantics are to be followed by prepending the LOCK prefix to an instruction.

In the case of the Intel386™, Intel486™, and Pentium® processors, explicitly locked instructions will result in the assertion of the LOCK# signal. It is the responsibility of the hardware designer to make the LOCK# signal available in system hardware to control memory accesses among processors.

For the P6 family processors, if the memory area being accessed is cached internally in the processor, the LOCK# signal is generally not asserted; instead, locking is only applied to the processor's caches (refer to Section 7.1.4., "Effects of a LOCK Operation on Internal Processor Caches").

7.1.2.1. AUTOMATIC LOCKING

The operations on which the processor automatically follows the LOCK semantics are as follows:

- **When executing an XCHG instruction that references memory.**
- **When setting the B (busy) flag of a TSS descriptor.** The processor tests and sets the busy flag in the type field of the TSS descriptor when switching to a task. To insure that two processors do not switch to the same task simultaneously, the processor follows the LOCK semantics while testing and setting this flag.
- **When updating segment descriptors.** When loading a segment descriptor, the processor will set the accessed flag in the segment descriptor if the flag is clear. During this operation, the processor follows the LOCK semantics so that the descriptor will not be modified by another processor while it is being updated. For this action to be effective, operating-system procedures that update descriptors should use the following steps:
  - — Use a locked operation to modify the access-rights byte to indicate that the segment descriptor is not-present, and specify a value for the type field that indicates that the descriptor is being updated.
  - — Update the fields of the segment descriptor. (This operation may require several memory accesses; therefore, locked operations cannot be used.)

— Use a locked operation to modify the access-rights byte to indicate that the segment descriptor is valid and present.

Note that the Intel386™ processor always updates the accessed flag in the segment descriptor, whether it is clear or not. The P6 family, Pentium®, and Intel486™ processors only update this flag if it is not already set.

- **When updating page-directory and page-table entries.** When updating page-directory and page-table entries, the processor uses locked cycles to set the accessed and dirty flag in the page-directory and page-table entries.
- **Acknowledging interrupts.** After an interrupt request, an interrupt controller may use the data bus to send the interrupt vector for the interrupt to the processor. The processor follows the LOCK semantics during this time to ensure that no other data appears on the data bus when the interrupt vector is being transmitted.

7.1.2.2. SOFTWARE CONTROLLED BUS LOCKING

To explicitly force the LOCK semantics, software can use the LOCK prefix with the following instructions when they are used to modify a memory location. An invalid-opcode exception (#UD) is generated when the LOCK prefix is used with any other instruction or when no write operation is made to memory (that is, when the destination operand is in a register).

- The bit test and modify instructions (BTS, BTR, and BTC).
- The exchange instructions (XADD, CMPXCHG, and CMPXCHG8B).
- The LOCK prefix is automatically assumed for XCHG instruction.
- The following single-operand arithmetic and logical instructions: INC, DEC, NOT, and NEG.
- The following two-operand arithmetic and logical instructions: ADD, ADC, SUB, SBB, AND, OR, and XOR.

A locked instruction is guaranteed to lock only the area of memory defined by the destination operand, but may be interpreted by the system as a lock for a larger memory area.

Software should access semaphores (shared memory used for signaling between multiple processors) using identical addresses and operand lengths. For example, if one processor accesses a semaphore using a word access, other processors should not access the semaphore using a byte access.

The integrity of a bus lock is not affected by the alignment of the memory field. The LOCK semantics are followed for as many bus cycles as necessary to update the entire operand. However, it is recommend that locked accesses be aligned on their natural boundaries for better system performance:

- Any boundary for an 8-bit access (locked or otherwise).
- 16-bit boundary for locked word accesses.
- 32-bit boundary for locked doubleword access.

- 64-bit boundary for locked quadword access.

Locked operations are atomic with respect to all other memory operations and all externally visible events. Only instruction fetch and page table accesses can pass locked instructions. Locked instructions can be used to synchronize data written by one processor and read by another processor.

For the P6 family processors, locked operations serialize all outstanding load and store operations (that is, wait for them to complete).

Locked instructions should not be used to insure that data written can be fetched as instructions.

NOTE

The locked instructions for the current versions of the Intel486™, Pentium®, and P6 family processors will allow data written to be fetched as instructions. However, Intel recommends that developers who require the use of self-modifying code use a different synchronizing mechanism, described in the following sections.

7.1.3. Handling Self- and Cross-Modifying Code

The act of a processor writing data into a currently executing code segment with the intent of executing that data as code is called **self-modifying code**. Intel Architecture processors exhibit model-specific behavior when executing self-modified code, depending upon how far ahead of the current execution pointer the code has been modified. As processor architectures become more complex and start to speculatively execute code ahead of the retirement point (as in the P6 family processors), the rules regarding which code should execute, pre- or post-modification, become blurred. To write self-modifying code and ensure that it is compliant with current and future Intel Architectures one of the following two coding options should be chosen.

```
(* OPTION 1 *)
Store modified code (as data) into code segment;
Jump to new code or an intermediate location;
Execute new code;

(* OPTION 2 *)
Store modified code (as data) into code segment;
Execute a serializing instruction; (* For example, CPUID instruction *)
Execute new code;
```

(The use of one of these options is not required for programs intended to run on the Pentium® or Intel486™ processors, but are recommended to insure compatibility with the P6 family processors.)

It should be noted that self-modifying code will execute at a lower level of performance than nonself-modifying or normal code. The degree of the performance deterioration will depend upon the frequency of modification and specific characteristics of the code.

The act of one processor writing data into the currently executing code segment of a second processor with the intent of having the second processor execute that data as code is called **cross-modifying code**. As with self-modifying code, Intel Architecture processors exhibit model-specific behavior when executing cross-modifying code, depending upon how far ahead of the executing processors current execution pointer the code has been modified. To write cross-modifying code and insure that it is compliant with current and future Intel Architectures, the following processor synchronization algorithm should be implemented.

```
; Action of Modifying Processor
Store modified code (as data) into code segment;
Memory_Flag ← 1;

; Action of Executing Processor
WHILE (Memory_Flag ≠ 1)
    Wait for code to update;
ELIHW;
Execute serializing instruction; (* For example, CPUID instruction *)
Begin executing modified code;
```

(The use of this option is not required for programs intended to run on the Intel486™ processor, but is recommended to insure compatibility with the Pentium®, and P6 family processors.)

Like self-modifying code, cross-modifying code will execute at a lower level of performance than noncross-modifying (normal) code, depending upon the frequency of modification and specific characteristics of the code.

7.1.4. Effects of a LOCK Operation on Internal Processor Caches

For the Intel486™ and Pentium® processors, the LOCK# signal is always asserted on the bus during a LOCK operation, even if the area of memory being locked is cached in the processor.

For the P6 family processors, if the area of memory being locked during a LOCK operation is cached in the processor that is performing the LOCK operation as write-back memory and is completely contained in a cache line, the processor may not assert the LOCK# signal on the bus. Instead, it will modify the memory location internally and allow it's cache coherency mechanism to insure that the operation is carried out atomically. This operation is called "cache locking." The cache coherency mechanism automatically prevents two or more processors that have cached the same area of memory from simultaneously modifying data in that area.

7.2. MEMORY ORDERING

The term **memory ordering** refers to the order in which the processor issues reads (loads) and writes (stores) out onto the bus to system memory. The Intel Architecture supports several memory ordering models depending on the implementation of the architecture. For example, the Intel386™ processor enforces **program ordering** (generally referred to as **strong ordering**),

where reads and writes are issued on the system bus in the order they occur in the instruction stream under all circumstances.

To allow optimizing of instruction execution, the Intel Architecture allows departures from strong-ordering model called **processor ordering** in P6-family processors. These **processor-ordering** variations allow performance enhancing operations such as allowing reads to go ahead of writes by buffering writes. The goal of any of these variations is to increase instruction execution speeds, while maintaining memory coherency, even in multiple-processor systems.

The following sections describe the memory ordering models used by the Intel486™, Pentium®, and P6 family processors.

7.2.1. Memory Ordering in the Pentium® and Intel486™ Processors

The Pentium® and Intel486™ processors follow the processor-ordered memory model; however, they operate as strongly-ordered processors under most circumstances. Reads and writes always appear in programmed order at the system bus—except for the following situation where processor ordering is exhibited. Read misses are permitted to go ahead of buffered writes on the system bus when all the buffered writes are cache hits and, therefore, are not directed to the same address being accessed by the read miss.

In the case of I/O operations, both reads and writes always appear in programmed order.

Software intended to operate correctly in processor-ordered processors (such as the P6 family processors) should not depend on the relatively strong ordering of the Pentium® or Intel486™ processors. Instead, it should insure that accesses to shared variables that are intended to control concurrent execution among processors are explicitly required to obey program ordering through the use of appropriate locking or serializing operations (refer to Section 7.2.4., “Strengthening or Weakening the Memory Ordering Model”).

7.2.2. Memory Ordering in the P6 Family Processors

The P6 family processors also use a processor-ordered memory ordering model that can be further refined defined as “write ordered with store-buffer forwarding.” This model can be characterized as follows.

In a single-processor system for memory regions defined as write-back cacheable, the following ordering rules apply:

1. Reads can be carried out speculatively and in any order.
2. Reads can pass buffered writes, but the processor is self-consistent.
3. Writes to memory are always carried out in program order.
4. Writes can be buffered.
5. Writes are not performed speculatively; they are only performed for instructions that have actually been retired.

6. Data from buffered writes can be forwarded to waiting reads within the processor.
7. Reads or writes cannot pass (be carried out ahead of) I/O instructions, locked instructions, or serializing instructions.

The second rule allows a read to pass a write. However, if the write is to the same memory location as the read, the processor's internal "snooping" mechanism will detect the conflict and update the already cached read before the processor executes the instruction that uses the value.

The sixth rule constitutes an exception to an otherwise write ordered model.

In a multiple-processor system, the following ordering rules apply:

- Individual processors use the same ordering rules as in a single-processor system.
- Writes by a single processor are observed in the same order by all processors.
- Writes from the individual processors on the system bus are globally observed and are NOT ordered with respect to each other.

The latter rule can be clarified by the example in Figure 7-1. Consider three processors in a system and each processor performs three writes, one to each of three defined locations (A, B, and C). Individually, the processors perform the writes in the same program order, but because of bus arbitration and other memory access mechanisms, the order that the three processors write the individual memory locations can differ each time the respective code sequences are executed on the processors. The final values in location A, B, and C would possibly vary on each execution of the write sequence.

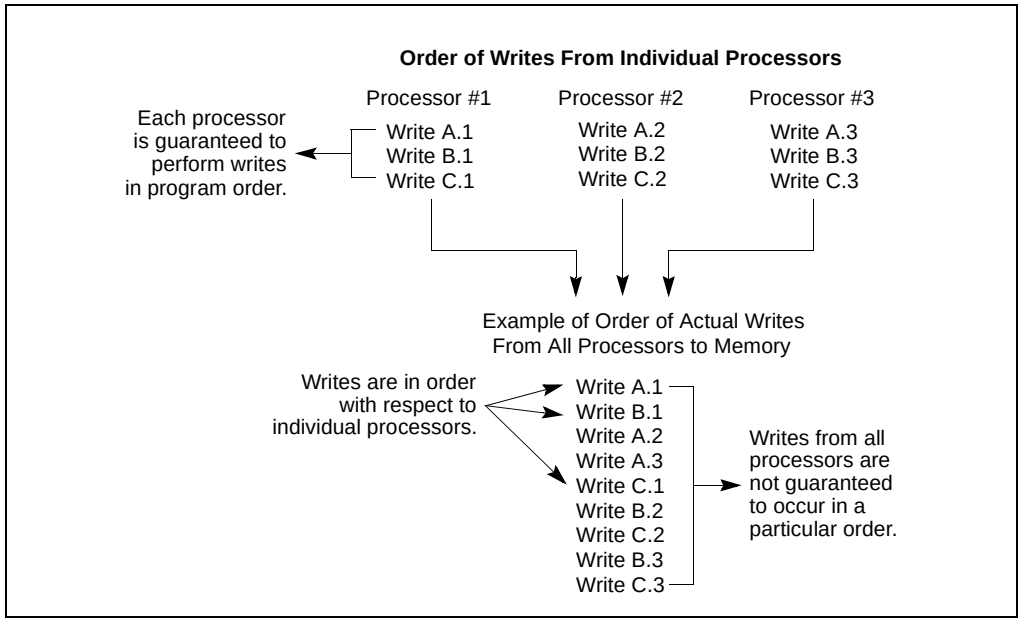


Figure 7-1. Example of Write Ordering in Multiple-Processor Systems

The processor-ordering model described in this section is virtually identical to that used by the Pentium® and Intel486™ processors. The only enhancements in the P6 family processors are:

- Added support for speculative reads.
- Store-buffer forwarding, when a read passes a write to the same memory location.
- Out of order store from long string store and string move operations (refer to Section 7.2.3., “Out of Order Stores From String Operations in P6 Family Processors” below).

7.2.3. Out of Order Stores From String Operations in P6 Family Processors

The P6 family processors modify the processors operation during the string store operations (initiated with the MOVS and STOS instructions) to maximize performance. Once the “fast string” operations initial conditions are met (as described below), the processor will essentially operate on, from an external perspective, the string in a cache line by cache line mode. This results in the processor looping on issuing a cache-line read for the source address and an invalidation on the external bus for the destination address, knowing that all bytes in the destination cache line will be modified, for the length of the string. In this mode interrupts will only be accepted by the processor on cache line boundaries. It is possible in this mode that the destination line invalidations, and therefore stores, will be issued on the external bus out of order.

Code dependent upon sequential store ordering should not use the string operations for the entire data structure to be stored. Data and semaphores should be separated. Order dependent code should use a discrete semaphore uniquely stored to after any string operations to allow correctly ordered data to be seen by all processors.

Initial conditions for “fast string” operations:

- Source and destination addresses must be 8-byte aligned.
- String operation must be performed in ascending address order.
- The initial operation counter (ECX) must be equal to or greater than 64.
- Source and destination must not overlap by less than a cache line (32 bytes).
- The memory type for both source and destination addresses must be either WB or WC.

7.2.4. Strengthening or Weakening the Memory Ordering Model

The Intel Architecture provides several mechanisms for strengthening or weakening the memory ordering model to handle special programming situations. These mechanisms include:

- The I/O instructions, locking instructions, the LOCK prefix, and serializing instructions force stronger ordering on the processor.
- The memory type range registers (MTRRs) can be used to strengthen or weaken memory ordering for specific area of physical memory (refer to Section 9.12., “Memory Type

Range Registers (MTRRs)", in Chapter 9, *Memory Cache Control*). MTRRs are available only in the P6 family processors.

These mechanisms can be used as follows.

Memory mapped devices and other I/O devices on the bus are often sensitive to the order of writes to their I/O buffers. I/O instructions can be used to (the IN and OUT instructions) impose strong write ordering on such accesses as follows. Prior to executing an I/O instruction, the processor waits for all previous instructions in the program to complete and for all buffered writes to drain to memory. Only instruction fetch and page tables walks can pass I/O instructions. Execution of subsequent instructions do not begin until the processor determines that the I/O instruction has been completed.

Synchronization mechanisms in multiple-processor systems may depend upon a strong memory-ordering model. Here, a program can use a locking instruction such as the XCHG instruction or the LOCK prefix to insure that a read-modify-write operation on memory is carried out atomically. Locking operations typically operate like I/O operations in that they wait for all previous instructions to complete and for all buffered writes to drain to memory (refer to Section 7.1.2., "Bus Locking").

Program synchronization can also be carried out with serializing instructions (refer to Section 7.4., "Serializing Instructions"). These instructions are typically used at critical procedure or task boundaries to force completion of all previous instructions before a jump to a new section of code or a context switch occurs. Like the I/O and locking instructions, the processor waits until all previous instructions have been completed and all buffered writes have been drained to memory before executing the serializing instruction.

The MTRRs were introduced in the P6 family processors to define the cache characteristics for specified areas of physical memory. The following are two examples of how memory types set up with MTRRs can be used strengthen or weaken memory ordering for the P6 family processors:

- The uncached (UC) memory type forces a strong-ordering model on memory accesses. Here, all reads and writes to the UC memory region appear on the bus and out-of-order or speculative accesses are not performed. This memory type can be applied to an address range dedicated to memory mapped I/O devices to force strong memory ordering.
- For areas of memory where weak ordering is acceptable, the write back (WB) memory type can be chosen. Here, reads can be performed speculatively and writes can be buffered and combined. For this type of memory, cache locking is performed on atomic (locked) operations that do not split across cache lines, which helps to reduce the performance penalty associated with the use of the typical synchronization instructions, such as XCHG, that lock the bus during the entire read-modify-write operation. With the WB memory type, the XCHG instruction locks the cache instead of the bus if the memory access is contained within a cache line.

It is recommended that software written to run on P6 family processors assume the processor-ordering model or a weaker memory-ordering model. The P6 family processors do not implement a strong memory-ordering model, except when using the UC memory type. Despite the fact that P6 family processors support processor ordering, Intel does not guarantee that future processors will support this model. To make software portable to future processors, it is recom-

mended that operating systems provide critical region and resource control constructs and API's (application program interfaces) based on I/O, locking, and/or serializing instructions be used to synchronize access to shared areas of memory in multiple-processor systems. Also, software should not depend on processor ordering in situations where the system hardware does not vsupport this memory-ordering model.

7.3. PROPAGATION OF PAGE TABLE ENTRY CHANGES TO MULTIPLE PROCESSORS

In a multiprocessor system, when one processor changes a page table entry or mapping, the changes must also be propagated to all the other processors. This process is also known as "TLB Shootdown." Propagation may be done by memory-based semaphores and/or interprocessor interrupts between processors. One naive but algorithmically correct TLB Shootdown sequence for the Intel Architecture is:

1. Begin barrier: Stop all processors. Cause all but one to HALT or stop in a spinloop.
2. Let the active processor change the PTE(s).
3. Let all processors invalidate the PTE(s) modified in their TLBs.
4. End barrier: Resume all processors.

Alternate, performance-optimized, TBL Shootdown algorithms may be developed; however, care must be taken by the developers to ensure that either:

- The differing TLB mappings are not actually used on different processors during the update process.

OR

- The operating system is prepared to deal with the case where processor(s) is/are using the stale mapping during the update process.

7.4. SERIALIZING INSTRUCTIONS

The Intel Architecture defines several **serializing instructions**. These instructions force the processor to complete all modifications to flags, registers, and memory by previous instructions and to drain all buffered writes to memory before the next instruction is fetched and executed. For example, when a MOV to control register instruction is used to load a new value into control register CR0 to enable protected mode, the processor must perform a serializing operation before it enters protected mode. This serializing operation insures that all operations that were started while the processor was in real-address mode are completed before the switch to protected mode is made.

The concept of serializing instructions was introduced into the Intel Architecture with the Pentium® processor to support parallel instruction execution. Serializing instructions have no meaning for the Intel486™ and earlier processors that do not implement parallel instruction execution.

It is important to note that executing of serializing instructions on P6 family processors constrain speculative execution, because the results of speculatively executed instructions are discarded.

The following instructions are serializing instructions:

- Privileged serializing instructions—MOV (to control register), MOV (to debug register), WRMSR, INVD, INVLPG, WBINVD, LGDT, LLDT, LIDT, and LTR.
- Nonprivileged serializing instructions—CPUID, IRET, and RSM.

The CPUID instruction can be executed at any privilege level to serialize instruction execution with no effect on program flow, except that the EAX, EBX, ECX, and EDX registers are modified.

Nothing can pass a serializing instruction, and serializing instructions cannot pass any other instruction (read, write, instruction fetch, or I/O).

When the processor serializes instruction execution, it ensures that all pending memory transactions are completed, including writes stored in its store buffer, before it executes the next instruction.

The following additional information is worth noting regarding serializing instructions:

- The processor does not writeback the contents of modified data in its data cache to external memory when it serializes instruction execution. Software can force modified data to be written back by executing the WBINVD instruction, which is a serializing instruction. It should be noted that frequent use of the WBINVD instruction will seriously reduce system performance.
- When an instruction is executed that enables or disables paging (that is, changes the PG flag in control register CR0), the instruction should be followed by a jump instruction. The target instruction of the jump instruction is fetched with the new setting of the PG flag (that is, paging is enabled or disabled), but the jump instruction itself is fetched with the previous setting. The P6 family processors do not require the jump operation following the move to register CR0 (because any use of the MOV instruction in a P6 family processor to write to CR0 is completely serializing). However, to maintain backwards and forward compatibility with code written to run on other Intel Architecture processors, it is recommended that the jump operation be performed.
- Whenever an instruction is executed to change the contents of CR3 while paging is enabled, the next instruction is fetched using the translation tables that correspond to the new value of CR3. Therefore the next instruction and the sequentially following instructions should have a mapping based upon the new value of CR3. (Global entries in the TLBs are not invalidated, refer to Section 9.10., “Invalidating the Translation Lookaside Buffers (TLBs)”, Chapter 9, *Memory Cache Control*.)
- The Pentium® and P6 family processors use branch-prediction techniques to improve performance by prefetching the destination of a branch instruction before the branch instruction is executed. Consequently, instruction execution is not deterministically serialized when a branch instruction is executed.

7.5. ADVANCED PROGRAMMABLE INTERRUPT CONTROLLER (APIC)

The Advanced Programmable Interrupt Controller (APIC), referred to in the following sections as the **local APIC**, was introduced into the Intel Architecture with the Pentium® processor (beginning with the 735/90 and 815/100 models) and is included in all P6 family processors. The local APIC performs two main functions for the processor:

- It processes local external interrupts that the processor receives at its interrupt pins and local internal interrupts that software generates.
- In multiple-processor systems, it communicates with an external I/O APIC chip. The external I/O APIC receives external interrupt events from the system and interprocessor interrupts from the processors on the system bus and distributes them to the processors on the system bus. The I/O APIC is part of Intel's system chip set.

Figure 7-2 shows the relationship of the local APICs on the processors in a multiple-processor (MP) system and the I/O APIC. The local APIC controls the dispatching of interrupts (to its associated processor) that it receives either locally or from the I/O APIC. It provides facilities for queuing, nesting and masking of interrupts. It handles the interrupt delivery protocol with its local processor and accesses to APIC registers, and also manages interprocessor interrupts and remote APIC register reads. A timer on the local APIC allows local generation of interrupts, and local interrupt pins permit local reception of processor-specific interrupts. The local APIC can be disabled and used in conjunction with a standard 8259A-style interrupt controller. (Disabling the local APIC can be done in hardware for the Pentium® processors or in software for the P6 family processors.)

The I/O APIC is responsible for receiving interrupts generated by I/O devices and distributing them among the local APICs by means of the APIC Bus. The I/O APIC manages interrupts using either static or dynamic distribution schemes. Dynamic distribution of interrupts allows routing of interrupts to the lowest priority processors. It also handles the distribution of interprocessor interrupts and system-wide control functions such as NMI, INIT, SMI and start-up-interprocessor interrupts. Individual pins on the I/O APIC can be programmed to generate a specific, prioritized interrupt vector when asserted. The I/O APIC also has a "virtual wire mode" that allows it to cooperate with an external 8259A in the system.

The APIC in the Pentium® and P6 family processors is an architectural subset of the Intel 82489DX external APIC. The differences are described in Section 7.5.19., "Software Visible Differences Between the Local APIC and the 82489DX"

The following sections focus on the local APIC, and its implementation in the P6 family processors. Contact Intel for the information on I/O APIC.

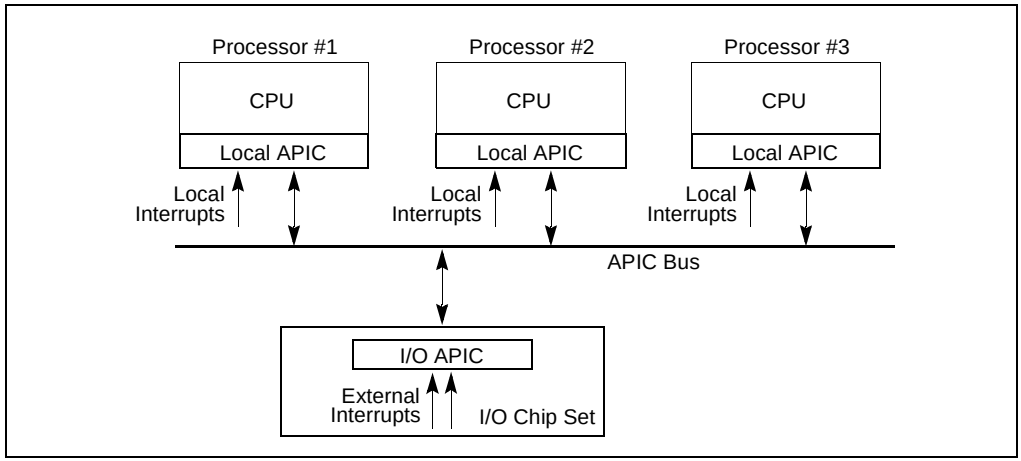


Figure 7-2. I/O APIC and Local APICs in Multiple-Processor Systems

7.5.1. Presence of APIC

Beginning with the P6 family processors, the presence or absence of an on-chip APIC can be detected using the CPUID instruction. When the CPUID instruction is executed, bit 9 of the feature flags returned in the EDX register indicates the presence (set) or absence (clear) of an on-chip local APIC.

7.5.2. Enabling or Disabling the Local APIC

For the P6 family processors, a flag (the E flag, bit 11) in the APIC_BASE_MSR register permits the local APIC to be explicitly enabled or disabled. Refer to Section 7.5.8., "Relocation of the APIC Registers Base Address" for a description of this flag. For the Pentium® processor, the APICEN pin (which is shared with the PICD1 pin) is used during reset to enable or disable the local APIC.

7.5.3. APIC Bus

All I/O APIC and local APICs communicate through the APIC bus (a 3-line inter-APIC bus). Two of the lines are open-drain (wired-OR) and are used for data transmission; the third line is a clock. **The bus and its messages are invisible to software and are not classed as architectural (that is, the APIC bus and message format may change in future implementations without having any effect on software compatibility).**

7.5.4. Valid Interrupts

The local and I/O APICs support 240 distinct vectors in the range of 16 to 255. Interrupt priority is implied by its vector, according to the following relationship:

priority = vector / 16

One is the lowest priority and 15 is the highest. Vectors 16 through 31 are reserved for exclusive use by the processor. The remaining vectors are for general use. The processor's local APIC includes an in-service entry and a holding entry for each priority level. To avoid losing interrupts, software should allocate no more than 2 interrupt vectors per priority.

7.5.5. Interrupt Sources

The local APIC can receive interrupts from the following sources:

- Interrupt pins on the processor chip, driven by locally connected I/O devices.
- A bus message from the I/O APIC, originated by an I/O device connected to the I/O APIC.
- A bus message from another processor's local APIC, originated as an interprocessor interrupt.
- The local APIC's programmable timer or the error register, through the self-interrupt generating mechanism.
- Software, through the self-interrupt generating mechanism.
- (P6 family processors.) The performance-monitoring counters.

The local APIC services the I/O APIC and interprocessor interrupts according to the information included in the bus message (such as vector, trigger type, interrupt destination, etc.). Interpretation of the processor's interrupt pins and the timer-generated interrupts is programmable, by means of the local vector table (LVT). To generate an interprocessor interrupt, the source processor programs its interrupt command register (ICR). The programming of the ICR causes generation of a corresponding interrupt bus message. Refer to Section 7.5.11., "Local Vector Table" and Section 7.5.12., "Interprocessor and Self-Interrupts" for detailed information on programming the LVT and ICR, respectively.

7.5.6. Bus Arbitration Overview

Being connected on a common bus (the APIC bus), the local and I/O APICs have to arbitrate for permission to send a message on the APIC bus. Logically, the APIC bus is a wired-OR connection, enabling more than one local APIC to send messages simultaneously. Each APIC issues its arbitration priority at the beginning of each message, and one winner is collectively selected following an arbitration round. At any given time, a local APIC's the arbitration priority is a unique value from 0 to 15. The arbitration priority of each local APIC is dynamically modified after each successfully transmitted message to preserve fairness. Refer to Section 7.5.16., "APIC Bus Arbitration Mechanism and Protocol" for a detailed discussion of bus arbitration.

Section 7.5.3., “APIC Bus” describes the existing arbitration protocols and bus message formats, while Section 7.5.12., “Interprocessor and Self-Interrupts” describes the INIT level de-assert message, used to resynchronize all local APICs’ arbitration IDs. Note that except for start-up (refer to Section 7.5.11., “Local Vector Table”), all bus messages failing during delivery are automatically retried. The software should avoid situations in which interrupt messages may be “ignored” by disabled or nonexistent “target” local APICs, and messages are being resent repeatedly.

7.5.7. The Local APIC Block Diagram

Figure 7-3 gives a functional block diagram for the local APIC. Software interacts with the local APIC by reading and writing its registers. The registers are memory-mapped to the processor’s physical address space, and for each processor they have an identical address space of 4 KBytes starting at address FEE00000H. (Refer to Section 7.5.8., “Relocation of the APIC Registers Base Address” for information on relocating the APIC registers base address for the P6 family processors.)

NOTE

For P6 family processors, the APIC handles all memory accesses to addresses within the 4-KByte APIC register space and no external bus cycles are produced. For the Pentium® processors with an on-chip APIC, bus cycles are produced for accesses to the 4-KByte APIC register space. Thus, for software intended to run on Pentium® processors, system software should explicitly not map the APIC register space to regular system memory. Doing so can result in an invalid opcode exception (#UD) being generated or unpredictable execution.

The 4-KByte APIC register address space should be mapped as uncacheable (UC), refer to Section 9, “Memory Cache Control”, in Chapter 9, *Memory Cache Control.*

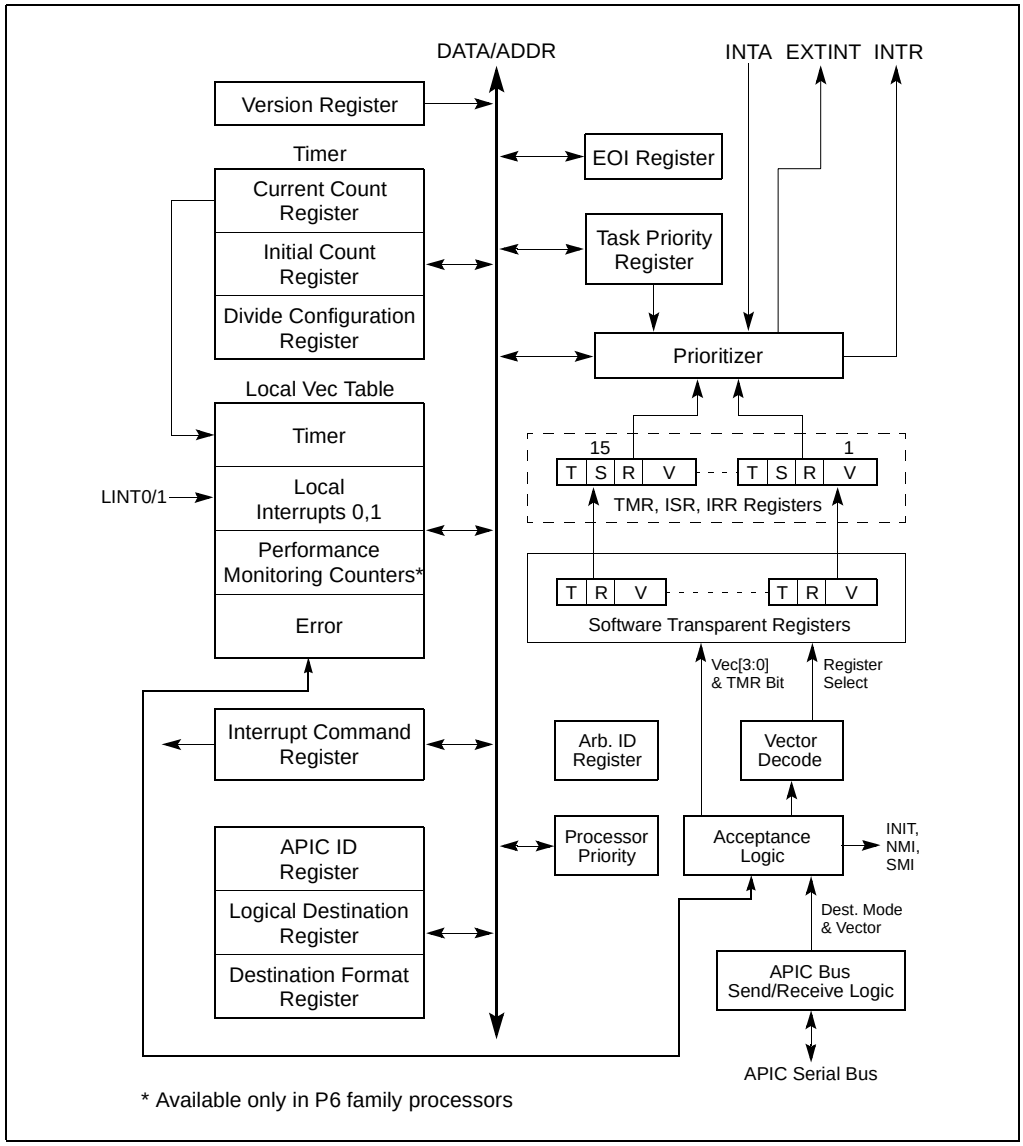


Figure 7-3. Local APIC Structure

Within the 4-KByte APIC register area, the register address allocation scheme is shown in Table 7-1. Register offsets are aligned on 128-bit boundaries. All registers must be accessed using 32-bit loads and stores. Wider registers (64-bit or 256-bit) are defined and accessed as independent multiple 32-bit registers. If a LOCK prefix is used with a MOV instruction that accesses the APIC address space, the prefix is ignored; that is, a locking operation does not take place.

Table 7-1. Local APIC Register Address Map

Address	Register Name	Software Read/Write
FEE0 0000H	Reserved	
FEE0 0010H	Reserved	
FEE0 0020H	Local APIC ID Register	Read/write
FEE0 0030H	Local APIC Version Register	Read only
FEE0 0040H	Reserved	
FEE0 0050H	Reserved	
FEE0 0060H	Reserved	
FEE0 0070H	Reserved	
FEE0 0080H	Task Priority Register	Read/Write
FEE0 0090H	Arbitration Priority Register	Read only
FEE0 00A0H	Processor Priority Register	Read only
FEE0 00B0H	EOI Register	Write only
FEE0 00C0H	Reserved	
FEE0 00D0H	Logical Destination Register	Read/Write
FEE0 00E0H	Destination Format Register	Bits 0-27 Read only. Bits 28-31 Read/Write
FEE0 00F0H	Spurious-Interrupt Vector Register	Bits 0-3 Read only. Bits 4-9 Read/Write
FEE0 0100H through FEE0 0170H	ISR 0-255	Read only
FEE0 0180H through FEE0 01F0H	TMR 0-255	Read only
FEE0 0200H through FEE0 0270H	IRR 0-255	Read only
FEE0 0280H	Error Status Register	Read only
FEE0 0290H through FEE0 02F0H	Reserved	
FEE0 0300H	Interrupt Command Reg. 0-31	Read/Write
FEE0 0310H	Interrupt Command Reg. 32-63	Read/Write
FEE0 0320H	Local Vector Table (Timer)	Read/Write
FEE0 0330H	Reserved	
FEE0 0340H	Performance Counter LVT[1]	Read/Write
FEE0 0350H	Local Vector Table (LINT0)	Read/Write
FEE0 0360H	Local Vector Table (LINT1)	Read/Write
FEE0 0370H	Local Vector Table (Error)[2]	Read/Write
FEE0 0380H	Initial Count Register for Timer	Read/Write

Table 7-1. Local APIC Register Address Map (Contd.)

Address	Register Name	Software Read/Write
FEE0 0390H	Current Count Register for Timer	Read only
FEE0 03A0H through FEE0 03D0H	Reserved	
FEE0 03E0H	Timer Divide Configuration Register	Read/Write
FEE0 03F0H	Reserved	

NOTES:

1. Introduced into the APIC Architecture in the Pentium® Pro processor.
2. Introduced into the APIC Architecture in the Pentium® processor.

7.5.8. Relocation of the APIC Registers Base Address

The P6 family processors permit the starting address of the APIC registers to be relocated from FEE00000H to another physical address. This extension of the APIC architecture is provided to help resolve conflicts with memory maps of existing systems. The P6 family processors also provide the ability to enable or disable the local APIC.

An alternate APIC base address is specified through the APIC_BASE_MSR register. This MSR is located at MSR address 27 (1BH). Figure 7-4 shows the encoding of the bits in this register. This register also provides the flag for enabling or disabling the local APIC.

The functions of the bits in the APIC_BASE_MSR register are as follows:

BSP flag, bit 8 Indicates if the processor is the bootstrap processor (BSP), determined during the MP initialization (refer to Section 7.7., "Multiple-Processor (MP) Initialization Protocol"). Following a power-up or reset, this flag is clear for all the processors in the system except the single BSP.

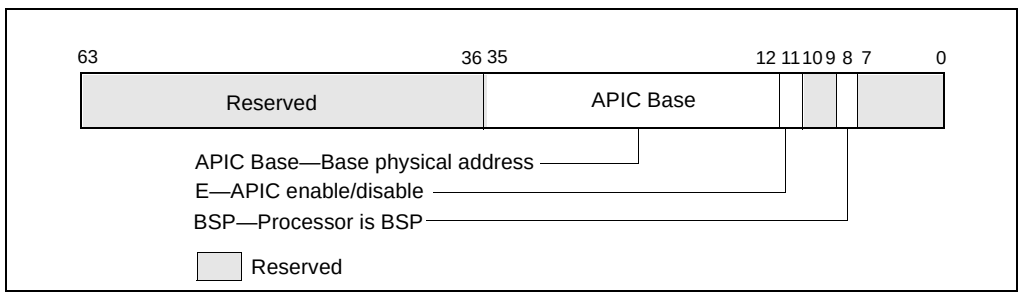


Figure 7-4. APIC_BASE_MSR

E (APIC Enabled) flag, bit 11
Permits the local APIC to be enabled (set) or disabled (clear). Following a power-up or reset, this flag is set, enabling the local APIC. When this flag is

clear, the processor is functionally equivalent to an Intel Architecture processor without an on-chip APIC (for example, an Intel486™ processor). This flag is implementation dependent and in not guaranteed to be available or available at the same location in future Intel Architecture processors.

APIC Base field, bits 12 through 35

Specifies the base address of the APIC registers. This 24-bit value is extended by 12 bits at the low end to form the base address, which automatically aligns the address on a 4-KByte boundary. Following a power-up or reset, this field is set to FEE00000H.

Bits 0 through 7, bits 9 and 10, and bits 36 through 63 in the APIC_BASE_MSR register are reserved.

7.5.9. Interrupt Destination and APIC ID

The destination of an interrupt can be one, all, or a subset of the processors in the system. The sender specifies the destination of an interrupt in one of two destination modes: physical or logical.

7.5.9.1. PHYSICAL DESTINATION MODE

In physical destination mode, the destination processor is specified by its local APIC ID. This ID is matched against the local APIC's actual physical ID, which is stored in the local APIC ID register (refer to Figure 7-5). Either a single destination (the ID is 0 through 14) or a broadcast to all (the ID is 15) can be specified in physical destination mode. Note that in this mode, up to 15 the local APICs can be individually addressed. An ID of all 1s denotes a broadcast to all local APICs. The APIC ID register is loaded at power up by sampling configuration data that is driven onto pins of the processor. For the P6 family processors, pins A11# and A12# and pins BR0# through BR3# are sampled; for the Pentium® processor, pins BE0# through BE3# are sampled. The ID portion can be read and modified by software.

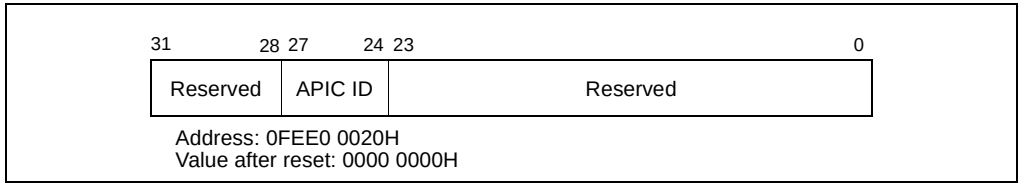


Figure 7-5. Local APIC ID Register

7.5.9.2. LOGICAL DESTINATION MODE

In logical destination mode, message destinations are specified using an 8-bit message destination address (MDA). The MDA is compared against the 8-bit logical APIC ID field of the APIC logical destination register (LDR), refer to Figure 7-6.

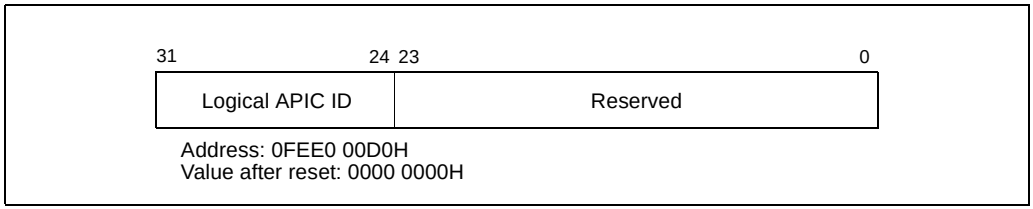


Figure 7-6. Logical Destination Register (LDR)

Destination format register (DFR) defines the interpretation of the logical destination information (refer to Figure 7-7). The DFR register can be programmed for **flat model** or **cluster model** interrupt delivery modes.

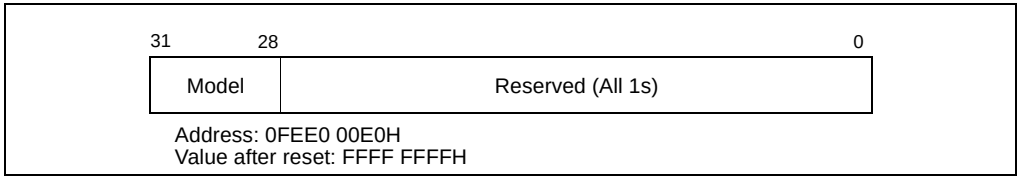


Figure 7-7. Destination Format Register (DFR)

7.5.9.3. FLAT MODEL

For the flat model, bits 28 through 31 of the DFR must be programmed to 1111. The MDA is interpreted as a decoded address. This scheme allows the specification of arbitrary groups of local APICs simply by setting each APIC's bit to 1 in the corresponding LDR. In the flat model, up to 8 local APICs can coexist in the system. Broadcast to all APICs is achieved by setting all 8 bits of the MDA to ones.

7.5.9.4. CLUSTER MODEL

For the cluster model, the DFR bits 28 through 31 should be programmed to 0000. In this model, there are two basic connection schemes: flat cluster and hierarchical cluster.

In the flat cluster connection model, all clusters are assumed to be connected on a single APIC bus. Bits 28 through 31 of the MDA contains the encoded address of the destination cluster. These bits are compared with bits 28 through 31 of the LDR to determine if the local APIC is part of the cluster. Bits 24 through 27 of the MDA are compared with Bits 24 through 27 of the LDR to identify individual local APIC unit within the cluster. Arbitrary sets of processors within a cluster can be specified by writing the target cluster address in bits 28 through 31 of the MDA and setting selected bits in bits 24 through 27 of the MDA, corresponding to the chosen members of the cluster. In this mode, 15 clusters (with cluster addresses of 0 through 14) each having 4 processors can be specified in the message. The APIC arbitration ID, however, supports only 15 agents, and hence the total number of processors supported in this mode is limited to 15.

Broadcast to all local APICs is achieved by setting all destination bits to one. This guarantees a match on all clusters, and selects all APICs in each cluster.

In the hierarchical cluster connection model, an arbitrary hierarchical network can be created by connecting different flat clusters via independent APIC buses. This scheme requires a cluster manager within each cluster, responsible for handling message passing between APIC buses. One cluster contains up to 4 agents. Thus 15 cluster managers, each with 4 agents, can form a network of up to 60 APIC agents. Note that hierarchical APIC networks requires a special cluster manager device, which is not part of the local or the I/O APIC units.

7.5.9.5. ARBITRATION PRIORITY

Each local APIC is given an arbitration priority of from 0 to 15 upon reset. The I/O APIC uses this priority during arbitration rounds to determine which local APIC should be allowed to transmit a message on the APIC bus when multiple local APICs are issuing messages. The local APIC with the highest arbitration priority wins access to the APIC bus. Upon completion of an arbitration round, the winning local APIC lowers its arbitration priority to 0 and the losing local APICs each raise theirs by 1. In this manner, the I/O APIC distributes message bus-cycles among the contesting local APICs.

The current arbitration priority for a local APIC is stored in a 4-bit, software-transparent arbitration ID (Arb ID) register. During reset, this register is initialized to the APIC ID number (stored in the local APIC ID register). The INIT-deassert command resynchronizes the arbitration priorities of the local APICs by resetting Arb ID register of each agent to its current APIC ID value.

7.5.10. Interrupt Distribution Mechanisms

The APIC supports two mechanisms for selecting the destination processor for an interrupt: static and dynamic. Static distribution is used to access a specific processor in the network. Using this mechanism, the interrupt is unconditionally delivered to all local APICs that match the destination information supplied with the interrupt. The following delivery modes fall into the static distribution category: fixed, SMI, NMI, EXTINT, and start-up.

Dynamic distribution assigns incoming interrupts to the lowest priority processor, which is generally the least busy processor. It can be programmed in the LVT for local interrupt delivery or the ICR for bus messages. Using dynamic distribution, only the “lowest priority” delivery mode is allowed. From all processors listed in the destination, the processor selected is the one whose current arbitration priority is the lowest. The latter is specified in the arbitration priority register (APR), refer to Section 7.5.13.4., “Arbitration Priority Register (APR)” If more than one processor shares the lowest priority, the processor with the highest arbitration priority (the unique value in the Arb ID register) is selected.

In lowest priority mode, if a **focus processor** exists**,** it may accept the interrupt, regardless of its priority. A processor is said to be the focus of an interrupt if it is currently servicing that interrupt or if it has a pending request for that interrupt.

7.5.11. Local Vector Table

The local APIC contains a local vector table (LVT), specifying interrupt delivery and status information for the local interrupts. The information contained in this table includes the interrupt's associated vector, delivery mode, status bits and other data as shown in Figure 7-8. The LVT incorporates five 32-bit entries: one for the timer, one each for the two local interrupt (LINT0 and LINT1) pins, one for the error interrupt, and (in the P6 family processors) one for the performance-monitoring counter interrupt.

The fields in the LVT are as follows:

Vector Interrupt vector number.

Delivery Mode Defined only for local interrupt entries 1 and 2 and the performance-monitoring counter. The timer and the error status register (ESR) generate only edge triggered maskable hardware interrupts to the local processor. The delivery mode field does not exist for the timer and error interrupts. The performance-monitoring counter LVT may be programmed with a Deliver Mode equal to Fixed or NMI only. Note that certain delivery modes will only operate as intended when used in conjunction with a specific Trigger Mode. The allowable delivery modes are as follows:

- **000 (Fixed)** Delivers the interrupt, received on the local interrupt pin, to this processor as specified in the corresponding LVT entry. The trigger mode can be edge or level. Note, if the processor is not used in conjunction with an I/O APIC, the fixed delivery mode may be software programmed for an edge-triggered interrupt, but the P6 family processors implementation will always operate in a level-triggered mode.
- **100 (NMI)** Delivers the interrupt, received on the local interrupt pin, to this processor as an NMI interrupt. The vector information is ignored. The NMI interrupt is treated as edge-triggered, even if programmed otherwise. Note that the NMI may be masked. It is the software's responsibility to program the LVT mask bit according to the desired behavior of NMI.
- **111 (ExtINT)** Delivers the interrupt, received on the local interrupt pin, to this processor and responds as if the interrupt originated in an externally connected (8259A-compatible) interrupt controller. A special INTA bus cycle corresponding to ExtINT, is routed to the external controller. The latter is expected to supply the vector information. When the delivery mode is ExtINT, the trigger-mode is

level-triggered, regardless of how the APIC triggering mode is programmed. The APIC architecture supports only one ExtINT source in a system, usually contained in the compatibility bridge.

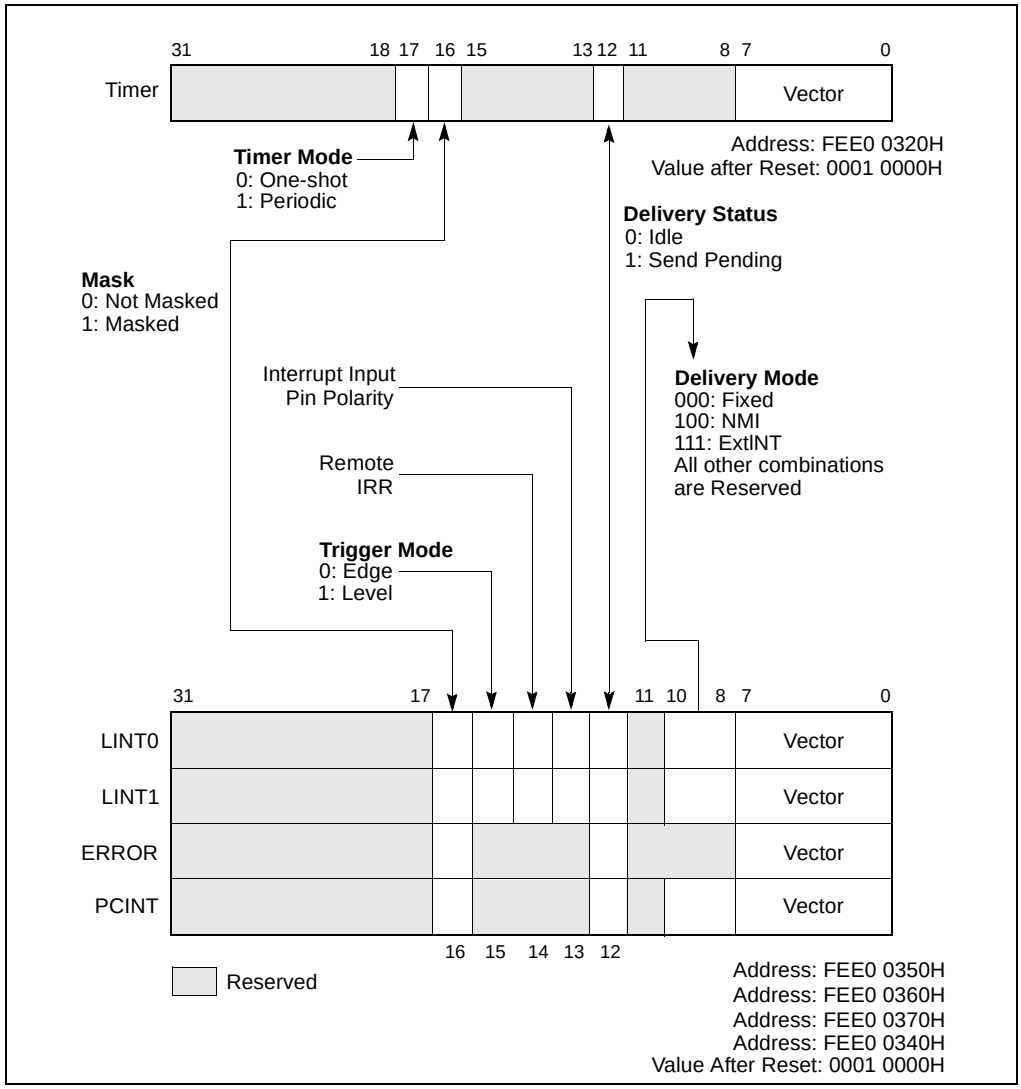


Figure 7-8. Local Vector Table (LVT)

Delivery Status (read only)

Holds the current status of interrupt delivery. Two states are defined:

0 (Idle) There is currently no activity for this interrupt, or the previous interrupt from this source has completed.

1 (Send Pending)

Indicates that the interrupt transmission has started, but has not yet been completely accepted.

Interrupt Input Pin Polarity

Specifies the polarity of the corresponding interrupt pin: (0) active high or (1) active low.

Remote Interrupt Request Register (IRR) Bit

Used for level triggered interrupts only; its meaning is undefined for edge triggered interrupts. For level triggered interrupts, the bit is set when the logic of the local APIC accepts the interrupt. The remote IRR bit is reset when an EOI command is received from the processor.

Trigger Mode Selects the trigger mode for the local interrupt pins when the delivery mode is Fixed: (0) edge sensitive and (1) level sensitive. When the delivery mode is NMI, the trigger mode is always level sensitive; when the delivery mode is ExtINT, the trigger mode is always level sensitive. The timer and error interrupts are always treated as edge sensitive.

Mask Interrupt mask: (0) enables reception of the interrupt and (1) inhibits reception of the interrupt.

Timer Mode Selects the timer mode: (0) one-shot and (1) periodic (refer to Section 7.5.18., “Timer”).

7.5.12. Interprocessor and Self-Interrupts

A processor generates interprocessor interrupts by writing into the interrupt command register (ICR) of its local APIC (refer to Figure 7-9). The processor may use the ICR for self interrupts or for interrupting other processors (for example, to forward device interrupts originally accepted by it to other processors for service). In addition, special inter-processor interrupts (IPI) such as the start-up IPI message, can only be delivered using the ICR mechanism. ICR-based interrupts are treated as edge triggered even if programmed otherwise. Note that not all combinations of options for ICR generated interrupts are valid (refer to Table 7-2).

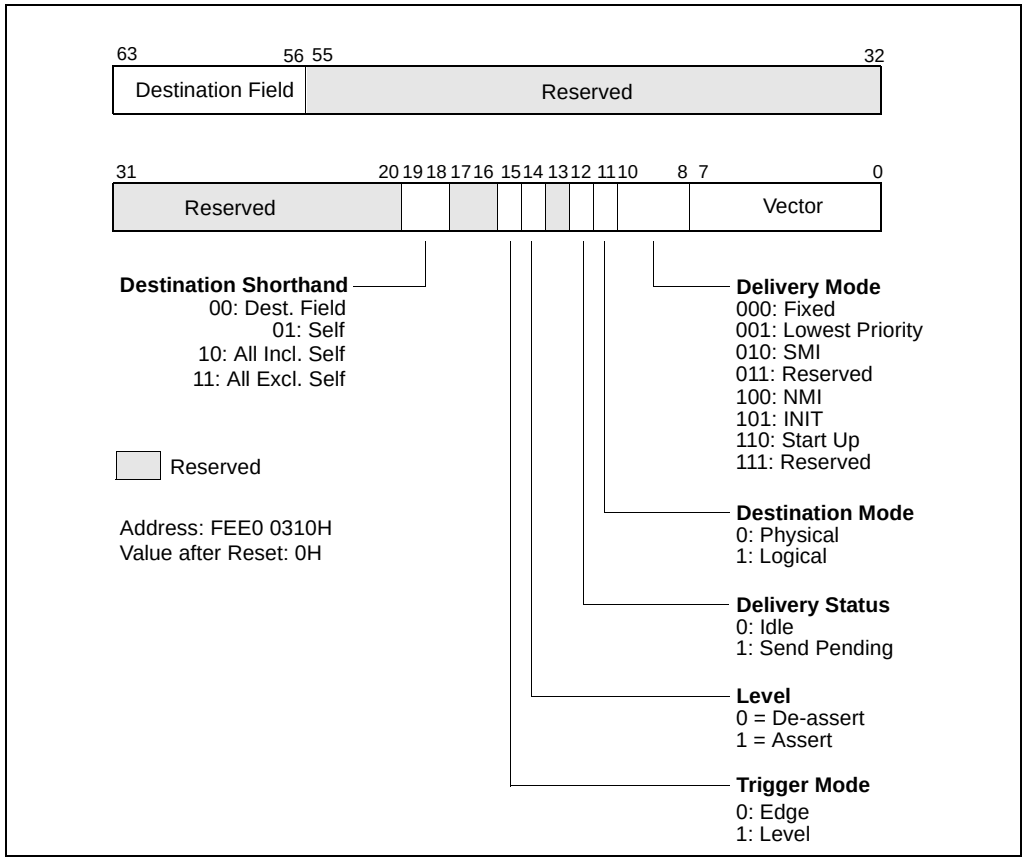


Figure 7-9. Interrupt Command Register (ICR)

All fields of the ICR are read-write by software with the exception of the delivery status field, which is read-only. Writing to the 32-bit word that contains the interrupt vector causes the interrupt message to be sent. The ICR consists of the following fields.

Vector The vector identifying the interrupt being sent. The localAPIC register addresses are summarized in Table 7-1.

Delivery Mode Specifies how the APICs listed in the destination field should act upon reception of the interrupt. Note that all interprocessor interrupts behave as edge triggered interrupts (except for INIT level de-assert message) even if they are programmed as level triggered interrupts.

000 (Fixed) Deliver the interrupt to all processors listed in the destination field according to the information provided in the ICR. The fixed interrupt is treated as

an edge-triggered interrupt even if programmed otherwise.

001 (Lowest Priority)
Same as fixed mode, except that the interrupt is delivered to the processor executing at the lowest priority among the set of processors listed in the destination.

010 (SMI) Only the edge trigger mode is allowed. The vector field must be programmed to 00B.

011 (Reserved)

100 (NMI) Delivers the interrupt as an NMI interrupt to all processors listed in the destination field. The vector information is ignored. NMI is treated as an edge triggered interrupt even if programmed otherwise.

101 (INIT) Delivers the interrupt as an INIT signal to all processors listed in the destination field. As a result, all addressed APICs will assume their INIT state. As in the case of NMI, the vector information is ignored, and INIT is treated as an edge triggered interrupt even if programmed otherwise.

101 (INIT Level De-assert)
(The trigger mode must also be set to 1 and level mode to 0.) Sends a synchronization message to all APIC agents to set their arbitration IDs to the values of their APIC IDs. Note that the INIT interrupt is sent to all agents, regardless of the destination field value. However, at least one valid destination processor should be specified. For future compatibility, the software is requested to use a broadcast-to-all ("all-incl-self" shorthand, as described below).

110 (Start-Up) Sends a special message between processors in a multiple-processor system. For details refer to the *Pentium® Pro Family Developer's Manual, Volume 1*. The Vector information contains the start-up address for the multiple-processor boot-up protocol. Start-up is treated as an edge triggered interrupt even if programmed otherwise. Note that interrupts are not automatically retried by the source APIC upon failure in delivery of the message. It is up to the software to decide whether a

retry is needed in the case of failure, and issue a retry message accordingly.

Destination Mode Selects either (0) physical or (1) logical destination mode.

Delivery Status Indicates the delivery status:

0 (Idle) There is currently no activity for this interrupt, or the previous interrupt from this source has completed.

1 (Send Pending)
Indicates that the interrupt transmission has started, but has not yet been completely accepted.

Level For INIT level de-assert delivery mode the level is 0. For all other modes the level is 1.

Trigger Mode Used for the INIT level de-assert delivery mode only.

Destination Shorthand

Indicates whether a shorthand notation is used to specify the destination of the interrupt and, if so, which shorthand is used. Destination shorthands do not use the 8-bit destination field, and can be sent by software using a single write to the lower 32-bit part of the APIC interrupt command register. Shorthands are defined for the following cases: software self interrupt, interrupt to all processors in the system including the sender, interrupts to all processors in the system excluding the sender.

00: (destination field, no shorthand)
The destination is specified in bits 56 through 63 of the ICR.

01: (self) The current APIC is the single destination of the interrupt. This is useful for software self interrupts. The destination field is ignored. Refer to Table 7-2 for description of supported modes. Note that self interrupts do not generate bus messages.

10: (all including self)
The interrupt is sent to all processors in the system including the processor sending the interrupt. The APIC will broadcast a message with the destination field set to FH. Refer to Table 7-2 for description of supported modes.

11: (all excluding self)
The interrupt is sent to all processors in the system with the exception of the processor sending the interrupt. The APIC will broadcast a message using

the physical destination mode and destination field set to FH.

Destination This field is only used when the destination shorthand field is set to "dest field". If the destination mode is physical, then bits 56 through 59 contain the APIC ID. In logical destination mode, the interpretation of the 8-bit destination field depends on the DFR and LDR of the local APIC Units.

Table 7-2 shows the valid combinations for the fields in the interrupt control register.

Table 7-2. Valid Combinations for the APIC Interrupt Command Register

Trigger Mode	Destination Mode	Delivery Mode	Valid/ Invalid	Destination Shorthand
Edge	Physical or Logical	Fixed, Lowest Priority, NMI, SMI, INIT, Start-Up	Valid	Dest. Field
Level	Physical or Logical	Fixed, Lowest Priority, NMI	1	Dest. field
Level	Physical or Logical	INIT	2	Dest. Field
Level	x[4]	SMI, Start-Up	Invalid[3]	x
Edge	x	Fixed	Valid	Self
Level	x	Fixed	1	Self
x	x	Lowest Priority, NMI, INIT, SMI, Start-Up	Invalid[3]	Self
Edge	x	Fixed	Valid	All inc Self
Level	x	Fixed	1	All inc Self
x	x	Lowest Priority, NMI, INIT, SMI, Start-Up	Invalid[3]	All inc Self
Edge	x	Fixed, Lowest Priority, NMI, INIT, SMI, Start-Up	Valid	All excl Self
Level	x	Fixed, Lowest Priority, NMI	1	All excl Self
Level	x	SMI, Start-Up	Invalid[3]	All excl Self
Level	x	INIT	2	All excl Self

NOTES:

1. Valid. Treated as edge triggered if Level = 1 (assert), otherwise ignored.
2. Valid. Treated as edge triggered when Level = 1 (assert); when Level = 0 (deassert), treated as "INIT Level Deassert" message. Only INIT level deassert messages are allowed to have level = deassert. For all other messages the level must be "assert."
3. Invalid. The behavior of the APIC is undefined.
4. X—Don't care.

7.5.13. Interrupt Acceptance

Three 256-bit read-only registers (the IRR, ISR, and TMR registers) are involved in the interrupt acceptance logic (refer to Figure 7-10). The 256 bits represents the 256 possible vectors. Because vectors 0 through 15 are reserved, so are bits 0 through 15 in these registers. The functions of the three registers are as follows:

TMR (trigger mode register)

Upon acceptance of an interrupt, the corresponding TMR bit is cleared for edge triggered interrupts and set for level interrupts. If the TMR bit is set, the local APIC sends an EOI message to all I/O APICs as a result of software issuing an EOI command (refer to Section 7.5.13.6., "End-Of-Interrupt (EOI)" for a description of the EOI register).

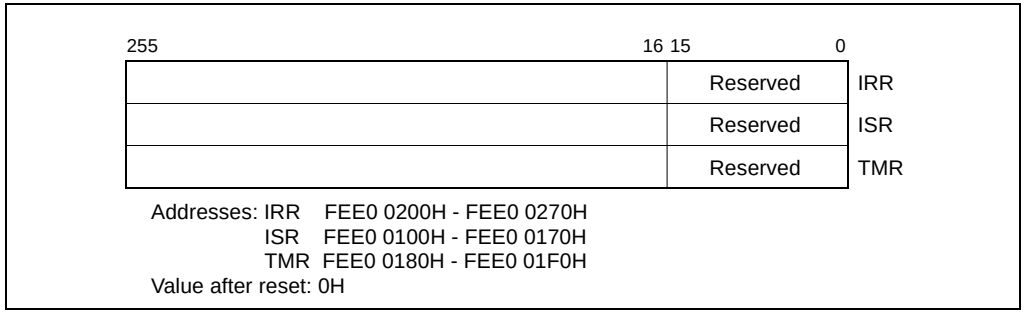


Figure 7-10. IRR, ISR and TMR Registers

IRR (interrupt request register)

Contains the active interrupt requests that have been accepted, but not yet dispensed by the current local APIC. A bit in IRR is set when the APIC accepts the interrupt. The IRR bit is cleared, and a corresponding ISR bit is set when the INTA cycle is issued.

ISR (in-service register)

Marks the interrupts that have been delivered to the processor, but have not been fully serviced yet, as an EOI has not yet been received from the processor. The ISR reflects the current state of the processor interrupt queue. The ISR bit for the highest priority IRR is set during the INTA cycle. During the EOI cycle, the highest priority ISR bit is cleared, and if the corresponding TMR bit was set, an EOI message is sent to all I/O APICs.

7.5.13.1. INTERRUPT ACCEPTANCE DECISION FLOW CHART

The process that the APIC uses to accept an interrupt is shown in the flow chart in Figure 7-11. The response of the local APIC to the start-up IPI is explained in the *Pentium® Pro Family Developer's Manual, Volume 1*.

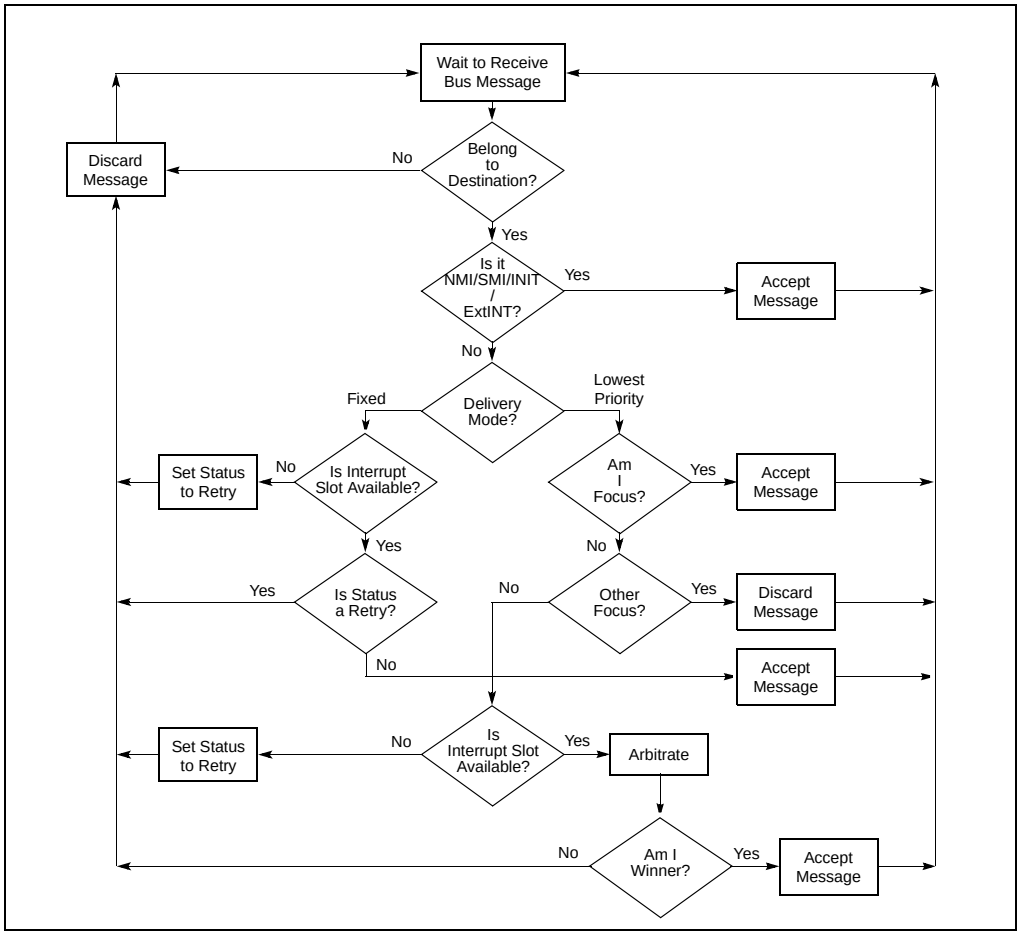


Figure 7-11. Interrupt Acceptance Flow Chart for the Local APIC

7.5.13.2. TASK PRIORITY REGISTER

Task priority register (TPR) provides a **priority threshold** mechanism for interrupting the processor (refer to Figure 7-12). Only interrupts whose priority is higher than that specified in the TPR will be serviced. Other interrupts are recorded and are serviced as soon as the TPR value is decreased enough to allow that. This enables the operating system to block temporarily specific interrupts (generally low priority) from disturbing high-priority tasks execution. The priority threshold mechanism is not applicable for delivery modes excluding the vector information (that is, for ExtINT, NMI, SMI, INIT, INIT-Deassert, and Start-Up delivery modes).

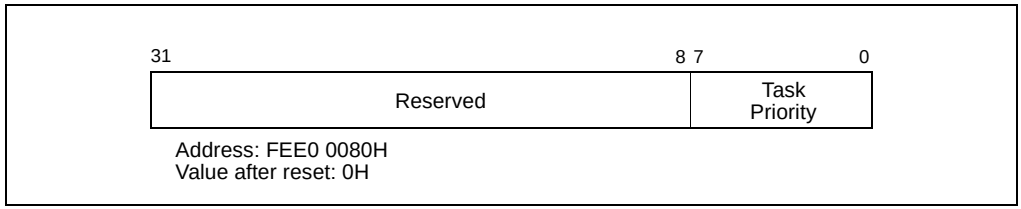


Figure 7-12. Task Priority Register (TPR)

The Task Priority is specified in the TPR. The 4 most-significant bits of the task priority correspond to the 16 interrupt priorities, while the 4 least-significant bits correspond to the sub-class priority. The TPR value is generally denoted as *x:y,* where *x* is the main priority and *y* provides more precision within a given priority class. When the x-value of the TPR is 15, the APIC will not accept any interrupts.

7.5.13.3. PROCESSOR PRIORITY REGISTER (PPR)

The processor priority register (PPR) is used to determine whether a pending interrupt can be dispensed to the processor. Its value is computed as follows:

```
IF TPR[7:4] ≥ ISRV[7:4]
    THEN
        PPR[7:0] = TPR[7:0]
    ELSE
        PPR[7:4] = ISRV[7:4] AND PPR[3:0] = 0
```

Where ISRV is the vector of the highest priority ISR bit set, or zero if no ISR bit is set. The PPR format is identical to that of the TPR. The PPR address is FEE000A0H, and its value after reset is zero.

7.5.13.4. ARBITRATION PRIORITY REGISTER (APR)

Arbitration priority register (APR) holds the current, lowest-priority of the processor, a value used during lowest priority arbitration (refer to Section 7.5.16., “APIC Bus Arbitration Mechanism and Protocol”). The APR format is identical to that of the TPR. The APR value is computed as the following.

```
IF (TPR[7:4] ≥ IRRV[7:4]) AND (TPR[7:4] > ISRV[7:4])
    THEN
        APR[7:0] = TPR[7:0]
    ELSE
        APR[7:4] = max(TPR[7:4] AND ISRV[7:4], IRRV[7:4]), APR[3:0]=0.
```

Here, IRRV is the interrupt vector with the highest priority IRR bit set or cleared (if no IRR bit is set). The APR address is FEE0 0090H, and its value after reset is 0.

7.5.13.5. SPURIOUS INTERRUPT

A special situation may occur when a processor raises its task priority to be greater than or equal to the level of the interrupt for which the processor INTR signal is currently being asserted. If at the time the INTA cycle is issued, the interrupt that was to be dispensed has become masked (programmed by software), the local APIC will return a spurious-interrupt vector to the processor. Dispensing the spurious-interrupt vector does not affect the ISR, so the handler for this vector should return without an EOI.

7.5.13.6. END-OF-INTERRUPT (EOI)

During the interrupt serving routine, software should indicate acceptance of lowest-priority, fixed, timer, and error interrupts by writing an arbitrary value into its local APIC end-of-interrupt (EOI) register (refer to Figure 7-13). This is an indication for the local APIC it can issue the next interrupt, regardless of whether the current interrupt service has been terminated or not. Note that interrupts whose priority is higher than that currently in service, do not wait for the EOI command corresponding to the interrupt in service.

Figure 7-13. EOI Register

Upon receiving end-of-interrupt, the APIC clears the highest priority bit in the ISR and selects the next highest priority interrupt for posting to the CPU. If the terminated interrupt was a level-triggered interrupt, the local APIC sends an end-of-interrupt message to all I/O APICs. Note that EOI command is supplied for the above two interrupt delivery modes regardless of the interrupt source (that is, as a result of either the I/O APIC interrupts or those issued on local pins or using the ICR). For future compatibility, the software is requested to issue the end-of-interrupt command by writing a value of 0H into the EOI register.

7.5.14. Local APIC State

In P6 family processors, all local APICs are initialized in a software-disabled state after power-up. A software-disabled local APIC unit responds only to self-interrupts and to INIT, NMI, SMI, and start-up messages arriving on the APIC Bus. The operation of local APICs during the disabled state is as follows:

- For the INIT, NMI, SMI, and start-up messages, the APIC behaves normally, as if fully enabled.

- Pending interrupts in the IRR and ISR registers are held and require masking or handling by the CPU.
- A disabled local APIC does not affect the sending of APIC messages. It is software's responsibility to avoid issuing ICR commands if no sending of interrupts is desired.
- Disabling a local APIC does not affect the message in progress. The local APIC will complete the reception/transmission of the current message and then enter the disabled state.
- A disabled local APIC automatically sets all mask bits in the LVT entries. Trying to reset these bits in the local vector table will be ignored.
- A software-disabled local APIC listens to all bus messages in order to keep its arbitration ID synchronized with the rest of the system, in the event that it is re-enabled.

For the Pentium® processor, the local APIC is enabled and disabled through a hardware mechanism. (Refer to the *Pentium® Processor Data Book* for a description of this mechanism.)

7.5.14.1. SPURIOUS-INTERRUPT VECTOR REGISTER

Software can enable or disable a local APIC at any time by programming bit 8 of the spurious-interrupt vector register (SVR), refer to Figure 7-14. The functions of the fields in the SVR are as follows:

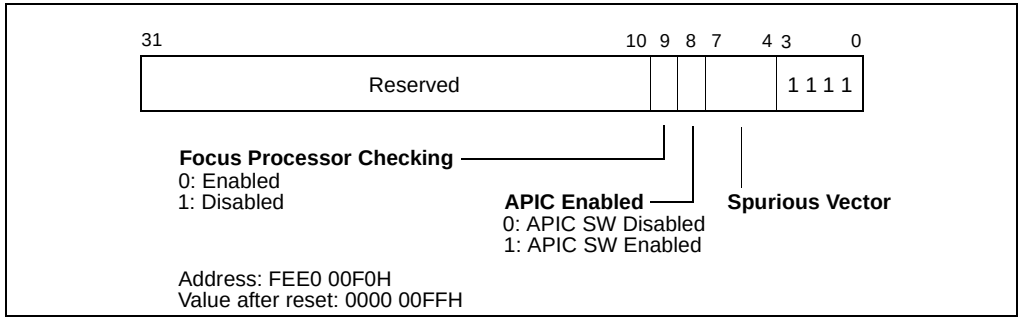


Figure 7-14. Spurious-Interrupt Vector Register (SVR)

Spurious Vector — Released during an INTA cycle when all pending interrupts are masked or when no interrupt is pending. Bits 4 through 7 of the this field are programmable by software, and bits 0 through 3 are hard-wired to logical ones. Software writes to bits 0 through 3 have no effect.

APIC Enable — Allows software to enable (1) or disable (0) the local APIC. To bypass APIC completely, use the APIC_BASE_MSR in Figure 7-4.

Focus Processor Checking — Determines if focus processor checking is enabled during the lowest Priority delivery: (0) enabled and (1) disabled.

7.5.14.2. LOCAL APIC INITIALIZATION

On a hardware reset, the processor and its local APIC are initialized simultaneously. For the P6 family processors, the local APIC obtains its initial physical ID from system hardware at the falling edge of the RESET# signal by sampling 6 lines on the system bus (the BR[3:0]) and cluster ID[1:0] lines) and storing this value into the APIC ID register; for the Pentium® processor, four lines are sampled (BE0# through BE3#). Refer to the *Pentium® Pro & Pentium II Processors Data Book* and the *Pentium® Processor Data Book* for descriptions of this mechanism.

7.5.14.3. LOCAL APIC STATE AFTER POWER-UP RESET

The state of local APIC registers and state machines after a power-up reset are as follows:

- The following registers are all reset to 0: the IRR, ISR, TMR, ICR, LDR, and TPR registers; the holding registers; the timer initial count and timer current count registers; the remote register; and the divide configuration register.
- The DFR register is reset to all 1s.
- The LVT register entries are reset to 0 except for the mask bits, which are set to 1s.
- The local APIC version register is not affected.
- The local APIC ID and Arb ID registers are loaded from processor input pins (the Arb ID register is set to the APIC ID value for the local APIC).
- All internal state machines are reset.
- APIC is software disabled (that is, bit 8 of the SVR register is set to 0).
- The spurious-interrupt vector register is initialized to FFH.

7.5.14.4. LOCAL APIC STATE AFTER AN INIT RESET

An INIT reset of the processor can be initiated in either of two ways:

- By asserting the processor's INIT# pin.
- By sending the processor an INIT IPI (sending an APIC bus-based interrupt with the delivery mode set to INIT).

Upon receiving an INIT via either of these two mechanisms, the processor responds by beginning the initialization process of the processor core and the local APIC. The state of the local APIC following an INIT reset is the same as it is after a power-up reset, except that the APIC ID and Arb ID registers are not affected.

7.5.14.5. LOCAL APIC STATE AFTER INIT-DEASSERT MESSAGE

An INIT-disassert message has no affect on the state of the APIC, other than to reload the arbitration ID register with the value in the APIC ID register.

7.5.15. Local APIC Version Register

The local APIC contains a hardwired version register, which software can use to identify the APIC version (refer to Figure 7-16). In addition, the version register specifies the size of LVT used in the specific implementation. The fields in the local APIC version register are as follows:

Version — The version numbers of the local APIC or an external 82489DX APIC controller:

- 1XH — Local APIC.
- 0XH — 82489DX.
- 20H through FFH — Reserved.

Max LVT Entry — Shows the number of the highest order LVT entry. For the P6 family processors, having 5 LVT entries, the Max LVT number is 4; for the Pentium® processor, having 4 LVT entries, the Max LVT number is 3.

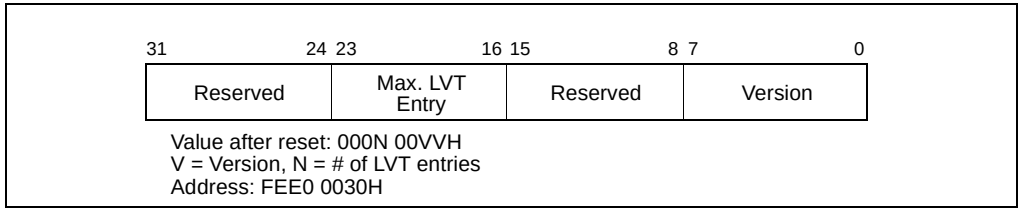


Figure 7-15. Local APIC Version Register

7.5.16. APIC Bus Arbitration Mechanism and Protocol

Because only one message can be sent at a time on the APIC bus, the I/O APIC and local APICs employ a “rotating priority” arbitration protocol to gain permission to send a message on the APIC bus. One or more APICs may start sending their messages simultaneously. At the beginning of every message, each APIC presents the type of the message it is sending and its current arbitration priority on the APIC bus. This information is used for arbitration. After each arbitration cycle (within an arbitration round, only the potential winners keep driving the bus. By the time all arbitration cycles are completed, there will be only one APIC left driving the bus. Once a winner is selected, it is granted exclusive use of the bus, and will continue driving the bus to send its actual message.

After each successfully transmitted message, all APICs increase their arbitration priority by 1. The previous winner (that is, the one that has just successfully transmitted its message) assumes a priority of 0 (lowest). An agent whose arbitration priority was 15 (highest) during arbitration, but did not send a message, adopts the previous winner’s arbitration priority, incremented by 1.

Note that the arbitration protocol described above is slightly different if one of the APICs issues a special End-Of-Interrupt (EOI). This high-priority message is granted the bus regardless of its sender’s arbitration priority, unless more than one APIC issues an EOI message simultaneously. In the latter case, the APICs sending the EOI messages arbitrate using their arbitration priorities.

If the APICs are set up to use “lowest priority” arbitration (refer to Section 7.5.10., “Interrupt Distribution Mechanisms”) and multiple APICs are currently executing at the lowest priority (the value in the APR register), the arbitration priorities (unique values in the Arb ID register) are used to break ties. All 8 bits of the APR are used for the lowest priority arbitration.

7.5.16.1. BUS MESSAGE FORMATS

The APICs use three types of messages: EOI message, short message, and non-focused lowest priority message. The purpose of each type of message and its format are described below.

EOI Message. Local APICs send 14-cycle EOI messages to the I/O APIC to indicate that a level triggered interrupt has been accepted by the processor. This interrupt, in turn, is a result of software writing into the EOI register of the local APIC. Table 7-3 shows the cycles in an EOI message.

The checksum is computed for cycles 6 through 9. It is a cumulative sum of the 2-bit (Bit1:Bit0) logical data values. The carry out of all but the last addition is added to the sum. If any APIC computes a different checksum than the one appearing on the bus in cycle 10, it signals an error, driving 11 on the APIC bus during cycle 12. In this case, the APICs disregard the message. The sending APIC will receive an appropriate error indication (refer to Section 7.5.17., “Error Handling”) and resend the message. The status cycles are defined in Table 7-6.

Short Message. Short messages (21-cycles) are used for sending fixed, NMI, SMI, INIT, start-up, ExtINT and lowest-priority-with-focus interrupts. Table 7-4 shows the cycles in a short message.

Table 7-3. EOI Message (14 Cycles)

Cycle	Bit1	Bit0	
1	1	1	11 = EOI
2	ArbID3	0	Arbitration ID bits 3 through 0
3	ArbID2	0	
4	ArbID1	0	
5	ArbID0	0	
6	V7	V6	Interrupt vector V7 - V0
7	V5	V4	
8	V3	V2	
9	V1	V0	
10	C	C	Checksum for cycles 6 - 9
11	0	0	
12	A	A	Status Cycle 0
13	A1	A1	Status Cycle 1
14	0	0	Idle

If the physical delivery mode is being used, then cycles 15 and 16 represent the APIC ID and cycles 13 and 14 are considered don't care by the receiver. If the logical delivery mode is being used, then cycles 13 through 16 are the 8-bit logical destination field. For shorthands of "all-incl-self" and "all-excl-self," the physical delivery mode and an arbitration priority of 15 (D0:D3 = 1111) are used. The agent sending the message is the only one required to distinguish between the two cases. It does so using internal information.

When using lowest priority delivery with an existing focus processor, the focus processor identifies itself by driving 10 during cycle 19 and accepts the interrupt. This is an indication to other APICs to terminate arbitration. If the focus processor has not been found, the short message is extended on-the-fly to the non-focused lowest-priority message. Note that except for the EOI message, messages generating a checksum or an acceptance error (refer to Section 7.5.17., "Error Handling") terminate after cycle 21.

Table 7-4. Short Message (21 Cycles)

Cycle	Bit1	Bit0	
1	0	1	0 1 = normal
2	ArbID3	0	Arbitration ID bits 3 through 0
3	ArbID2	0	
4	ArbID1	0	
5	ArbID0	0	
6	DM	M2	DM = Destination Mode
7	M1	M0	M2-M0 = Delivery mode
Cycle	**Bit1**	**Bit0**	
8	L	TM	L = Level, TM = Trigger Mode
9	V7	V6	V7-V0 = Interrupt Vector
10	V5	V4	
11	V3	V2	
12	V1	V0	
13	D7	D6	D7-D0 = Destination
14	D5	D4	
15	D3	D2	
16	D1	D0	
17	C	C	Checksum for cycles 6-16
18	0	0	
19	A	A	Status cycle 0
20	A1	A1	Status cycle 1
21	0	0	Idle

Nonfocused Lowest Priority Message. These 34-cycle messages (refer to Table 7-5) are used in the lowest priority delivery mode when a focus processor is not present. Cycles 1 through 20

are same as for the short message. If during the status cycle (cycle 19) the state of the (A:A) flags is 10B, a focus processor has been identified, and the short message format is used (refer to Table 7-4). If the (A:A) flags are set to 00B, lowest priority arbitration is started and the 34-cycles of the nonfocused lowest priority message are competed. For other combinations of status flags, refer to Section 7.5.16.2., “APIC Bus Status Cycles”

Table 7-5. Nonfocused Lowest Priority Message (34 Cycles)

Cycle	Bit0	Bit1	
1	0	1	0 1 = normal
2	ArbID3	0	Arbitration ID bits 3 through 0
3	ArbID2	0	
4	ArbID1	0	
5	ArbID0	0	
6	DM	M2	DM = Destination mode
7	M1	M0	M2-M0 = Delivery mode
8	L	TM	L = Level, TM = Trigger Mode
9	V7	V6	V7-V0 = Interrupt Vector
10	V5	V4	
11	V3	V2	
12	V1	V0	
13	D7	D6	D7-D0 = Destination
Cycle	**Bit0**	**Bit1**	
14	D5	D4	
15	D3	D2	
16	D1	D0	
17	C	C	Checksum for cycles 6-16
18	0	0	
19	A	A	Status cycle 0
20	A1	A1	Status cycle 1
21	P7	0	P7 - P0 = Inverted Processor Priority
22	P6	0	
23	P5	0	
24	P4	0	
25	P3	0	
26	P2	0	
27	P1	0	
28	P0	0	
29	ArbID3	0	Arbitration ID 3 -0
30	ArbID2	0	
31	ArbID1	0	
32	ArbID0	0	
33	A2	A2	Status Cycle
34	0	0	Idle

Cycles 21 through 28 are used to arbitrate for the lowest priority processor. The processors participating in the arbitration drive their inverted processor priority on the bus. Only the local APICs having free interrupt slots participate in the lowest priority arbitration. If no such APIC exists, the message will be rejected, requiring it to be tried at a later time.

Cycles 29 through 32 are also used for arbitration in case two or more processors have the same lowest priority. In the lowest priority delivery mode, all combinations of errors in cycle 33 (A2 A2) will set the “accept error” bit in the error status register (refer to Figure 7-16). Arbitration priority update is performed in cycle 20, and is not affected by errors detected in cycle 33. Only the local APIC that wins in the lowest priority arbitration, drives cycle 33. An error in cycle 33 will force the sender to resend the message.

7.5.16.2. APIC BUS STATUS CYCLES

Certain cycles within an APIC bus message are status cycles. During these cycles the status flags (A:A) and (A1:A1) are examined. Table 7-6 shows how these status flags are interpreted, depending on the current delivery mode and existence of a focus processor.

Table 7-6. APIC Bus Status Cycles Interpretation

Delivery Mode	A Status	A1 Status	A2 Status	Update ArbID and Cycle#	Message Length	Retry
EOI	00: CS_OK	10: Accept	XX:	Yes, 13	14 Cycle	No
	00: CS_OK	11: Retry	XX:	Yes, 13	14 Cycle	Yes
	00: CS_OK	0X: Accept Error	XX:	No	14 Cycle	Yes
	11: CS_Error	XX:	XX:	No	14 Cycle	Yes
	10: Error	XX:	XX:	No	14 Cycle	Yes
	01: Error	XX:	XX:	No	14 Cycle	Yes
Fixed	00: CS_OK	10: Accept	XX:	Yes, 20	21 Cycle	No
	00: CS_OK	11: Retry	XX:	Yes, 20	21 Cycle	Yes
	00: CS_OK	0X: Accept Error	XX:	No	21 Cycle	Yes
	11: CS_Error	XX:	XX:	No	21 Cycle	Yes
	10: Error	XX:	XX:	No	21 Cycle	Yes
	01: Error	XX:	XX:	No	21 Cycle	Yes
NMI, SMI, INIT, ExtINT, Start-Up	00: CS_OK	10: Accept	XX:	Yes, 20	21 Cycle	No
	00: CS_OK	11: Retry	XX:	Yes, 20	21 Cycle	Yes
	00: CS_OK	0X: Accept Error	XX:	No	21 Cycle	Yes
	11: CS_Error	XX:	XX:	No	21 Cycle	Yes
	10: Error	XX:	XX:	No	21 Cycle	Yes
	01: Error	XX:	XX:	No	21 Cycle	Yes

Table 7-6. APIC Bus Status Cycles Interpretation (Contd.)

Lowest	00: CS_OK, NoFocus	11: Do Lowest	10: Accept	Yes, 20	34 Cycle	No
	00: CS_OK, NoFocus	11: Do Lowest	11: Error	Yes, 20	34 Cycle	Yes
	00: CS_OK, NoFocus	11: Do Lowest	0X: Error	Yes, 20	34 Cycle	Yes
	00: CS_OK, NoFocus	10: End and Retry	XX:	Yes, 20	34 Cycle	Yes
	00: CS_OK, NoFocus	0X: Error	XX:	No	34 Cycle	Yes
	10: CS_OK, Focus	XX:	XX:	Yes, 20	34 Cycle	No
	11: CS_Error	XX:	XX:	No	21 Cycle	Yes
	01: Error	XX:	XX:	No	21 Cycle	Yes

7.5.17. Error Handling

The local APIC sets flags in the error status register (ESR) to record all the errors that is detects (refer to Figure 7-16). The ESR is a read/write register and is reset after being written to by the processor. A write to the ESR must be done just prior to reading the ESR to allow the register to be updated. An error interrupt is generated when one of the error bits is set. Error bits are cumulative. The ESR must be cleared by software after unmasking of the error interrupt entry in the LVT is performed (by executing back-to-back a writes). If the software, however, wishes to handle errors set in the register prior to unmasking, it should write and then read the ESR prior or immediately after the unmasking.

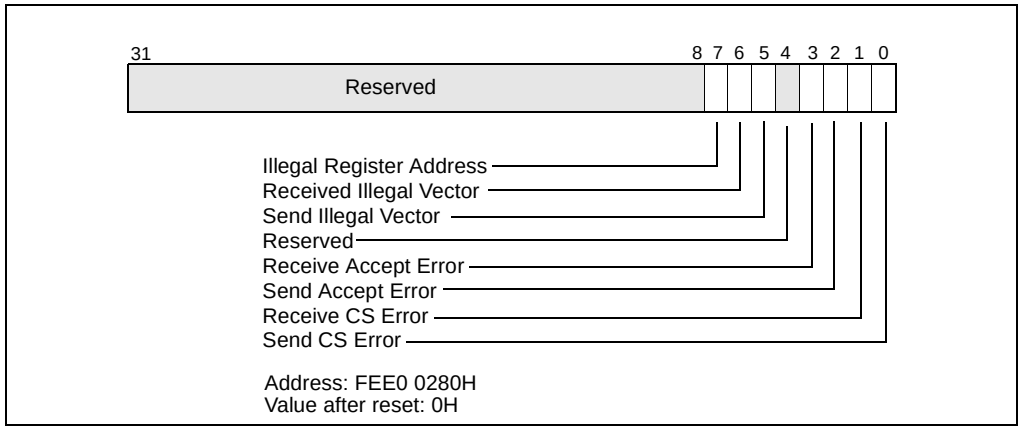


Figure 7-16. Error Status Register (ESR)

The functions of the ESR flags are as follows:

Send CS Error — Set when the local APIC detects a check sum error for a message that was sent by it.

Receive CS Error — Set when the local APIC detects a check sum error for a message that was received by it.

Send Accept Error — Set when the local APIC detects that a message it sent was not accepted by any APIC on the bus.

Receive Accept Error — Set when the local APIC detects that the message it received was not accepted by any APIC on the bus, including itself.

Send Illegal Vector — Set when the local APIC detects an illegal vector in the message that it is sending on the bus.

Receive Illegal Vector — Set when the local APIC detects an illegal vector in the message it received, including an illegal vector code in the local vector table interrupts and self-interrupts from ICR.

Illegal Reg. Address (P6 Family Processors Only) — Set when the processor is trying to access a register that is not implemented in the P6 family processors' local APIC register address space; that is, within FEE00000H (the APICBase MSR) through FEE003FFH (the APICBase MSR plus 4K Bytes).

7.5.18. Timer

The local APIC unit contains a 32-bit programmable timer for use by the local processor. This timer is configured through the timer register in the local vector table (refer to Figure 7-8). The time base is derived from the processor's bus clock, divided by a value specified in the divide configuration register (refer to Figure 7-17). After reset, the timer is initialized to zero. The timer supports one-shot and periodic modes. The timer can be configured to interrupt the local processor with an arbitrary vector.

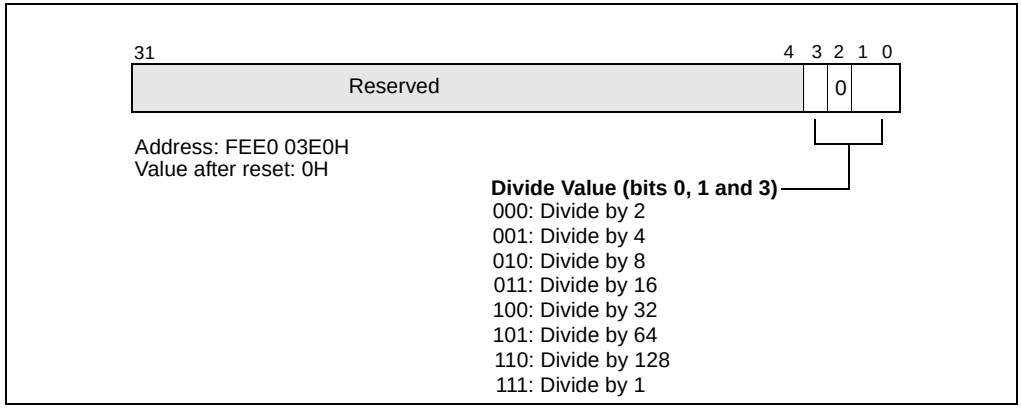


Figure 7-17. Divide Configuration Register

The timer is started by programming its initial-count register, refer to Figure 7-18. The initial count value is copied into the current-count register and count-down is begun. After the timer reaches zero in one-shot mode, an interrupt is generated and the timer remains at its 0 value until reprogrammed. In periodic mode, the current-count register is automatically reloaded from the initial-count register when the count reaches 0 and the count-down is repeated. If during the count-down process the initial-count register is set, the counting will restart and the new value will be used. The initial-count register is read-write by software, while the current-count register is read only.

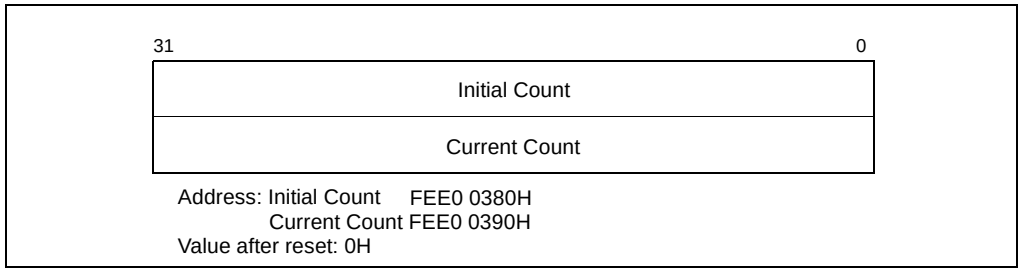


Figure 7-18. Initial Count and Current Count Registers

7.5.19. Software Visible Differences Between the Local APIC and the 82489DX

The following local APIC features differ in their definitions from the 82489DX features:

- When the local APIC is disabled, its internal registers are not cleared. Instead, setting the mask bits in the local vector table to disable the local APIC merely causes it to cease accepting the bus messages except for INIT, SMI, NMI, and start-up. In the 82489DX, when the local unit is disabled by resetting the bit 8 of the spurious vector register, all the internal registers including the IRR, ISR and TMR are cleared and the mask bits in the local vector tables are set to logical ones. In the disabled mode, 82489DX local unit will accept only the reset deassert message.
- In the local APIC, NMI and INIT (except for INIT deassert) are always treated as edge triggered interrupts, even if programmed otherwise. In the 82489DX these interrupts are always level triggered.
- In the local APIC, interrupts generated through ICR messages are always treated as edge triggered (except INIT Deassert). In the 82489DX, the ICR can be used to generate either edge or level triggered interrupts.
- Logical Destination register the local APIC supports 8 bits, where it supports 32 bits for the 82489DX.
- APIC ID register is 4 bits wide for the local APIC and 8 bits wide for the 82489DX.
- The remote read delivery mode provided in the 82489DX is not supported in the Intel Architecture local APIC.

7.5.20. Performance Related Differences between the Local APIC and the 82489DX

For the 82489DX, in the lowest priority mode, all the target local APICs specified by the destination field participate in the lowest priority arbitration. Only those local APICs which have free interrupt slots will participate in the lowest priority arbitration.

7.5.21. New Features Incorporated in the Pentium® and P6 Family Processors Local APIC

The local APIC in the Pentium® and P6 family processors have the following new features not found in the 82489DX.

- The local APIC supports cluster addressing in logical destination mode.
- Focus processor checking can be enabled/disabled in the local APIC.
- Interrupt input signal polarity can be programmed in the local APIC.
- The local APIC supports SMI through the ICR and I/O redirection table.
- The local APIC incorporates an error status register to log and report errors to the processor.

In the P6 family processors, the local APIC incorporates an additional local vector table entry to handle performance monitoring counter interrupts.

7.6. DUAL-PROCESSOR (DP) INITIALIZATION PROTOCOL

The Pentium® processor contains an internal dual-processing (DP) mechanism that permits two processors to be initialized and configured for tightly coupled symmetric multiprocessing (SMP). The DP initialization protocol supports the controlled booting and configuration of the two Pentium® processors. When configuration has been completed, the two Pentium® processors can share the processing load for the system and share the handling of interrupts received from the system's I/O APIC.

The Pentium® DP initialization protocol defines two processors:

- Primary processor (also called the bootstrap processor, BSP)—This processor boots itself, configures the APIC environment, and starts the second processor.
- Secondary processor (also called the dual processor, DP)—This processor boots itself then waits for a startup signal from the primary processor. Upon receiving the startup signal, it completes its configuration.

Appendix C, *Dual-Processor (DP) Bootup Sequence Example (Specific to Pentium® Processors)* gives an example (with code) of the bootup sequence for two Pentium® processors operating in a DP configuration.

Appendix E, *Programming the LINT0 and LINT1 Inputs* describes (with code) how to program the LINT[0:1] pins of the processor's local APICs after a dual-processor configuration has been completed.

7.7. MULTIPLE-PROCESSOR (MP) INITIALIZATION PROTOCOL

The Intel Architecture (beginning with the Pentium® Pro processors) defines a multiple-processor (MP) initialization protocol, for use with both single- and multiple-processor systems. (Here, **multiple processors** is defined as two or more processors.) The primary goals of this protocol are as follows:

- To permit sequential or controlled booting of multiple processors (from 2 to 4) with no dedicated system hardware. The initialization algorithm is not limited to 4 processors; it can support supports from 1 to 15 processors in a multiclustered system when the APIC busses are tied together. Larger systems are not supported.
- To be able to initiate the MP protocol without the need for a dedicated signal or BSP.
- To provide fault tolerance. No single processor is geographically designated the BSP. The BSP is determined dynamically during initialization.

The following sections describe an MP initialization protocol.

Appendix D, *Multiple-Processor (MP) Bootup Sequence Example (Specific to P6 Family Processors)* gives an example (with code) of the bootup sequence for two P6 family processors operating in an MP configuration.

Appendix E, *Programming the LINT0 and LINT1 Inputs* describes (with code) how to program the LINT[0:1] pins of the processor's local APICs after an MP configuration has been completed.

7.7.1. MP Initialization Protocol Requirements and Restrictions

The MP protocol imposes the following requirements and restrictions on the system:

- An APIC clock (APICLK) must be provided on all systems based on the P6 family processors (excluding mobile processors and modules).
- All interrupt mechanisms must be disabled for the duration of the MP protocol algorithm, including the window of time between the assertion of INIT# or receipt of an INIT IPI by the application processors and the receipt of a STARTUP IPI by the application processors. That is, requests generated by interrupting devices must not be seen by the local APIC unit (on board the processor) until the completion of the algorithm. Failure to disable the interrupt mechanisms may result in processor shutdown.
- The MP protocol should be initiated only after a hardware reset. After completion of the protocol algorithm, a flag is set in the APIC base MSR of the BSP (APIC_BASE.BSP) to indicate that it is the BSP. This flag is cleared for all other processors. If a processor or the complete system is subject to an INIT sequence (either through the INIT# pin or an INIT

IPI), then the MP protocol is not re-executed. Instead, each processor examines its BSP flag to determine whether the processor should boot or wait for a STARTUP IPI.

7.7.2. MP Protocol Nomenclature

The MP initialization protocol defines two classes of processors:

- The bootstrap processor (BSP)—This primary processor is dynamically selected by the MP initialization algorithm. After the BSP has been selected, it configures the APIC environment, and starts the secondary processors, under software control.
- Application processors (APs)—These secondary processors are the remainder of the processors in a MP system that were not selected as the BSP. The APs complete a minimal self-configuration, then wait for a startup signal from the BSP processor. Upon receiving a startup signal, an AP completes its configuration.

Table 7-7 describes the interrupt-style abbreviations that will be used through out the remaining description of the MP initialization protocol. These IPIs do not define new interrupt messages. They are messages that are special only by virtue of the time that they exist (that is, before the RESET sequence is complete).

Table 7-7. Types of Boot Phase IPIs

Message Type	Abbreviation	Description
Boot Inter-Processor Interrupt	BIPI	An APIC serial bus message that Symmetric Multiprocessing (SMP) agents use to dynamically determine a BSP after reset.
Final Boot Inter-Processor Interrupt	FIPI	An APIC serial bus message that the BSP issues before it fetches from the reset vector. This message has the lowest priority of all boot phase IPIs. When a BSP sees an FIPI that it issued, it fetches the reset vector because no other boot phase IPIs can follow an FIPI.
Startup Inter-Processor Interrupt	SIPI	Used to send a new reset vector to a Application Processor (non-BSP) processor in an MP system.

Table 7-8 describes the various fields of each boot phase IPI.

Table 7-8. Boot Phase IPI Message Format

Type	Destination Field	Destination Shorthand	Trigger Mode	Level	Destination Mode	Delivery Mode	Vector (Hex)
BIPI	Not used	All including self	Edge	Deassert	Don't Care	Fixed (000)	40 to 4E*
FIPI	Not used	All including self	Edge	Deassert	Don't Care	Fixed (000)	10 to 1E
SIPI	Used	All allowed	Edge	Assert	Physical or Logical	StartUp (110)	00 to FF

NOTE:

* For all P6 family processors.

For BIPI and FIPI messages, the lower 4 bits of the vector field are equal to the APIC ID of the processor issuing the message. The upper 4 bits of the vector field of a BIPI or FIPI can be thought of as the “generation ID” of the message. All processors that run symmetric to a P6 family processor will have a generation ID of 0100B or 4H. BIPIs in a system based on the P6 family processors will therefore use vector values ranging from 40H to 4EH (4FH can not be used because FH is not a valid APIC ID).

7.7.3. Error Detection During the MP Initialization Protocol

Errors may occur on the APIC bus during the MP initialization phase. These errors may be transient or permanent and can be caused by a variety of failure mechanisms (for example, broken traces, soft errors during bus usage, etc.). All serial bus related errors will result in an APIC checksum or acceptance error.

The occurrence of an APIC error causes a processor shutdown.

7.7.4. Error Handling During the MP Initialization Protocol

The MP initialization protocol makes the following assumptions:

- If any errors are detected on the APIC bus during execution of the MP initialization protocol, all processors will shutdown.
- In a system that conforms to Intel Architecture guidelines, a likely error (broken trace, check sum error during transmission) will result in no more than one processor booting.
- The MP initialization protocol will be executed by processors even if they fail their BIST sequences.

7.7.5. MP Initialization Protocol Algorithm

The MP initialization protocol uses the message passing capabilities of the processor’s local APIC to dynamically determine a boot strap processor (BSP). The algorithm used essentially implements a “race for the flag” mechanism using the APIC bus for atomicity.

The MP initialization algorithm is based on the fact that one and only one message is allowed to exist on the APIC bus at a given time and that once the message is issued, it will complete (APIC messages are atomic). Another feature of the APIC architecture that is used in the initialization algorithm is the existence of a round-robin priority mechanism between all agents that use the APIC bus.

The MP initialization protocol algorithm performs the following operations in a SMP system (refer to Figure 7-19):

1. After completing their internal BISTs, all processors start their MP initialization protocol sequence by issuing BIPIs to “all including self” (at time t=0). The four least significant bits of the vector field of the IPI contain each processor's APIC ID. The APIC hardware

observes the BNR# (block next request) pin to guarantee that the initial BIPI is not issued on the APIC bus until the BIST sequence is completed for all processors in the system.

2. When the first BIPI completes (at time t=1), the APIC hardware (in each processor) propagates an interrupt to the processor core to indicate the arrival of the BIPI.
3. The processor compares the four least significant bits of the BIPI's vector field to the processor's APIC ID. A match indicates that the processor should be the BSP and continue the initialization sequence. If the APIC ID fails to match the BIPIs vector field, the processor is essentially the "loser" or not the BSP. The processor then becomes an application processor and should enter a "wait for SIPI" loop.
4. The winner (the BSP) issues an FIPI. The FIPI is issued to "all including self" and is guaranteed to be the last IPI on the APIC bus during the initialization sequence. This is due to the fact that the round-robin priority mechanism forces the winning APIC agent's (the BSPs) arbitration priority to 0. The FIPI is therefore issued by a priority 0 agent and has to wait until all other agents have issued their BIPI's. When the BSP receives the FIPI that it issued (t=5), it will start fetching code at the reset vector (Intel Architecture address).

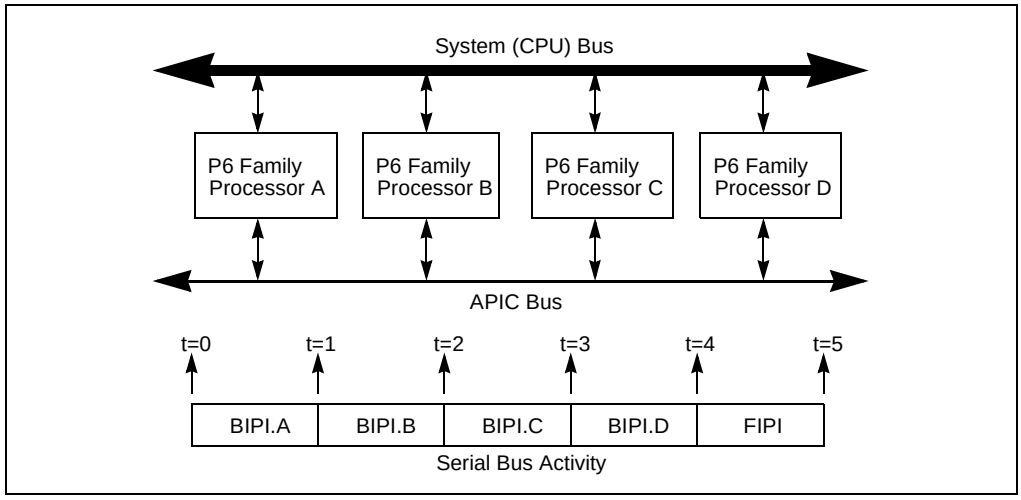


Figure 7-19. SMP System

5. All application processors (non-BSP processors) remain in a "halted" state and can only be woken up by SIPIs issued by another processor (note an AP in the startup IPI loop will also respond to BINIT and snoops).

8

Processor Management and Initialization

CHAPTER 8
PROCESSOR MANAGEMENT AND INITIALIZATION

This chapter describes the facilities provided for managing processor wide functions and for initializing the processor. The subjects covered include: processor initialization, FPU initialization, processor configuration, feature determination, mode switching, the MSRs (in the Pentium® and P6 family processors), and the MTRRs (in the P6 family processors).

8.1. INITIALIZATION OVERVIEW

Following power-up or an assertion of the RESET# pin, each processor on the system bus performs a hardware initialization of the processor (known as a hardware reset) and an optional built-in self-test (BIST). A hardware reset sets each processor's registers to a known state and places the processor in real-address mode. It also invalidates the internal caches, translation lookaside buffers (TLBs) and the branch target buffer (BTB). At this point, the action taken depends on the processor family:

- P6 family processors—All the processors on the system bus (including a single processor in a uniprocessor system) execute the multiple processor (MP) initialization protocol across the APIC bus. The processor that is selected through this protocol as the bootstrap processor (BSP) then immediately starts executing software-initialization code in the current code segment beginning at the offset in the EIP register. The application (non-BSP) processors (AP) go into a halt state while the BSP is executing initialization code. Refer to Section 7.7., "Multiple-Processor (MP) Initialization Protocol" in Chapter 7, *Multiple-Processor Management* for more details. Note that in a uniprocessor system, the single P6 family processor automatically becomes the BSP.
- Pentium® processors—In either a single- or dual- processor system, a single Pentium® processor is always pre-designated as the primary processor. Following a reset, the primary processor behaves as follows in both single- and dual-processor systems. Using the dual-processor (DP) ready initialization protocol, the primary processor immediately starts executing software-initialization code in the current code segment beginning at the offset in the EIP register. The secondary processor (if there is one) goes into a halt state. (Refer to Section 7.6., "Dual-Processor (DP) Initialization Protocol" in Chapter 7, *Multiple-Processor Management* for more details.)
- Intel486™ processor—The primary processor (or single processor in a uniprocessor system) immediately starts executing software-initialization code in the current code segment beginning at the offset in the EIP register. (The Intel486™ does not automatically execute a DP or MP initialization protocol to determine which processor is the primary processor.)

The software-initialization code performs all system-specific initialization of the BSP or primary processor and the system logic.

At this point, for MP (or DP) systems, the BSP (or primary) processor wakes up each AP (or secondary) processor to enable those processors to execute self-configuration code.

When all processors are initialized, configured, and synchronized, the BSP or primary processor begins executing an initial operating-system or executive task.

The floating-point unit (FPU) is also initialized to a known state during hardware reset. FPU software initialization code can then be executed to perform operations such as setting the precision of the FPU and the exception masks. No special initialization of the FPU is required to switch operating modes.

Asserting the INIT# pin on the processor invokes a similar response to a hardware reset. The major difference is that during an INIT, the internal caches, MSRs, MTRRs, and FPU state are left unchanged (although, the TLBs and BTB are invalidated as with a hardware reset). An INIT provides a method for switching from protected to real-address mode while maintaining the contents of the internal caches.

8.1.1. Processor State After Reset

Table 8-1 shows the state of the flags and other registers following power-up for the Pentium® Pro, Pentium®, and Intel486™ processors. The state of control register CR0 is 60000010H (refer to Figure 8-1), which places the processor is in real-address mode with paging disabled.

8.1.2. Processor Built-In Self-Test (BIST)

Hardware may request that the BIST be performed at power-up. The EAX register is cleared (0H) if the processor passes the BIST. A nonzero value in the EAX register after the BIST indicates that a processor fault was detected. If the BIST is not requested, the contents of the EAX register after a hardware reset is 0H.

The overhead for performing a BIST varies between processor families. For example, the BIST takes approximately 5.5 million processor clock periods to execute on the Pentium® Pro processor. (This clock count is model-specific, and Intel reserves the right to change the exact number of periods, for any of the Intel Architecture processors, without notification.)

Table 8-1. 32-Bit Intel Architecture Processor States Following Power-up, Reset, or INIT

Register	P6 Family Processors	Pentium® Processor	Intel486™ Processor
EFLAGS[1]	00000002H	00000002H	00000002H
EIP	0000FFF0H	0000FFF0H	0000FFF0H
CR0	60000010H[2]	60000010H[2]	60000010H[2]
CR2, CR3, CR4	00000000H	00000000H	00000000H
MXCSR	Pentium® III processor only- Pwr up or Reset: 1F80H FINIT/FNINIT: Unchanged	NA	NA
CS	Selector = F000H Base = FFFF0000H Limit = FFFFH AR = Present, R/W, Accessed	Selector = F000H Base = FFFF0000H Limit = FFFFH AR = Present, R/W, Accessed	Selector = F000H Base = FFFF0000H Limit = FFFFH AR = Present, R/W, Accessed
SS, DS, ES, FS, GS	Selector = 0000H Base = 00000000H Limit = FFFFH AR = Present, R/W, Accessed	Selector = 0000H Base = 00000000H Limit = FFFFH AR = Present, R/W, Accessed	Selector = 0000H Base = 00000000H Limit = FFFFH AR = Present, R/W, Accessed
EDX	000006xxH	000005xxH	000004xxH
EAX	0[3]	0[3]	0[3]
EBX, ECX, ESI, EDI, EBP, ESP	00000000H	00000000H	00000000H
MM0 through MM7[4]	Pentium® Pro processor - NA Pentium® II and Pentium® III processor - Pwr up or Reset: 0000000000000000H FINIT/FNINIT: Unchanged	Pwr up or Reset: 0000000000000000H FINIT/FNINIT: Unchanged	NA
XMM0 through XMM7[5]	Pentium® III processor only- Pwr up or Reset: 0000000000000000H FINIT/FNINIT: Unchanged	NA	NA
ST0 through ST7[4]	Pwr up or Reset: +0.0 FINIT/FNINIT: Unchanged	Pwr up or Reset: +0.0 FINIT/FNINIT: Unchanged	Pwr up or Reset: +0.0 FINIT/FNINIT: Unchanged
FPU Control Word[4]	Pwr up or Reset: 0040H FINIT/FNINIT: 037FH	Pwr up or Reset: 0040H FINIT/FNINIT: 037FH	Pwr up or Reset: 0040H FINIT/FNINIT: 037FH
FPU Status Word[4]	Pwr up or Reset: 0000H FINIT/FNINIT: 0000H	Pwr up or Reset: 0000H FINIT/FNINIT: 0000H	Pwr up or Reset: 0000H FINIT/FNINIT: 0000H
FPU Tag Word[4]	Pwr up or Reset: 5555H FINIT/FNINIT: FFFFH	Pwr up or Reset: 5555H FINIT/FNINIT: FFFFH	Pwr up or Reset: 5555H FINIT/FNINIT: FFFFH
FPU Data Operand and CS Seg. Selectors[4]	Pwr up or Reset: 0000H FINIT/FNINIT: 0000H	Pwr up or Reset: 0000H FINIT/FNINIT: 0000H	Pwr up or Reset: 0000H FINIT/FNINIT: 0000H

Table 8-1. 32-Bit Intel Architecture Processor States Following Power-up, Reset, or INIT (Contd.)

Register	P6 Family Processors	Pentium® Processor	Intel486™ Processor
FPU Data Operand and Inst. Pointers[4]	Pwr up or Reset: 00000000H FINIT/FNINIT: 00000000H	Pwr up or Reset: 00000000H FINIT/FNINIT: 00000000H	Pwr up or Reset: 00000000H FINIT/FNINIT: 00000000H
GDTR,IDTR	Base = 00000000H Limit = FFFFH AR = Present, R/W	Base = 00000000H Limit = FFFFH AR = Present, R/W	Base = 00000000H Limit = FFFFH AR = Present, R/W
LDTR, Task Register	Selector = 0000H Base = 00000000H Limit = FFFFH AR = Present, R/W	Selector = 0000H Base = 00000000H Limit = FFFFH AR = Present, R/W	Selector = 0000H Base = 00000000H Limit = FFFFH AR = Present, R/W
DR0, DR1, DR2, DR3	00000000H	00000000H	00000000H
DR6	FFFF0FF0H	FFFF0FF0H	FFFF1FF0H
DR7	00000400H	00000400H	00000000H
Time-Stamp Counter	Power up or Reset: 0H INIT: Unchanged	Power up or Reset: 0H INIT: Unchanged	Not Implemented
Perf. Counters and Event Select	Power up or Reset: 0H INIT: Unchanged	Power up or Reset: 0H INIT: Unchanged	Not Implemented
All Other MSRs	Pwr up or Reset: Undefined INIT: Unchanged	Pwr up or Reset: Undefined INIT: Unchanged	Not Implemented
Data and Code Cache, TLBs	Invalid	Invalid	Invalid
Fixed MTRRs	Pwr up or Reset: Disabled INIT: Unchanged	Not Implemented	Not Implemented
Variable MTRRs	Pwr up or Reset: Disabled INIT: Unchanged	Not Implemented	Not Implemented
Machine-Check Architecture	Pwr up or Reset: Undefined INIT: Unchanged	Not Implemented	Not Implemented
APIC	Pwr up or Reset: Enabled INIT: Unchanged	Pwr up or Reset: Enabled INIT: Unchanged	Not Implemented

NOTES:

1. The 10 most-significant bits of the EFLAGS register are undefined following a reset. Software should not depend on the states of any of these bits.
2. The CD and NW flags are unchanged, bit 4 is set to 1, all other bits are cleared.
3. If Built-In Self-Test (BIST) is invoked on power up or reset, EAX is 0 only if all tests passed. (BIST cannot be invoked during an INIT.)
4. The state of the FPU state and MMX™ registers is not changed by the execution of an INIT.
5. Available in the Pentium® III processor and Pentium® III Xeon™ processor only. The state of the SIMD floating-point registers is not changed by the execution of an INIT.

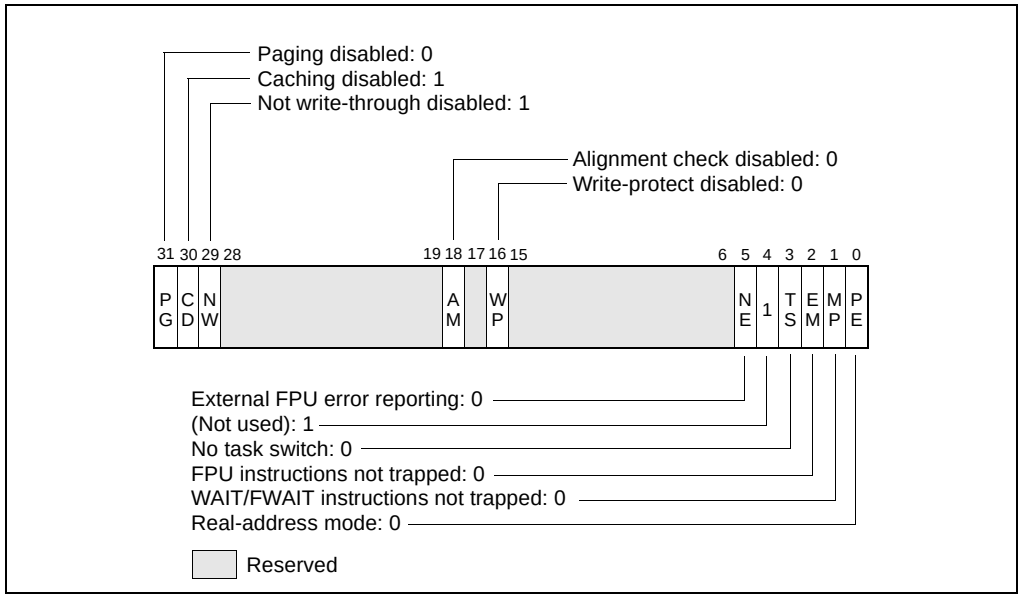


Figure 8-1. Contents of CR0 Register after Reset

8.1.3. Model and Stepping Information

Following a hardware reset, the EDX register contains component identification and revision information (refer to Figure 8-2). The device ID field is set to the value 6H, 5H, 4H, or 3H to indicate a Pentium® Pro, Pentium®, Intel486™, or Intel386™ processor, respectively. Different values may be returned for the various members of these Intel Architecture families. For example the Intel386™ SX processor returns 23H in the device ID field. Binary object code can be made compatible with other Intel processors by using this number to select the correct initialization software.

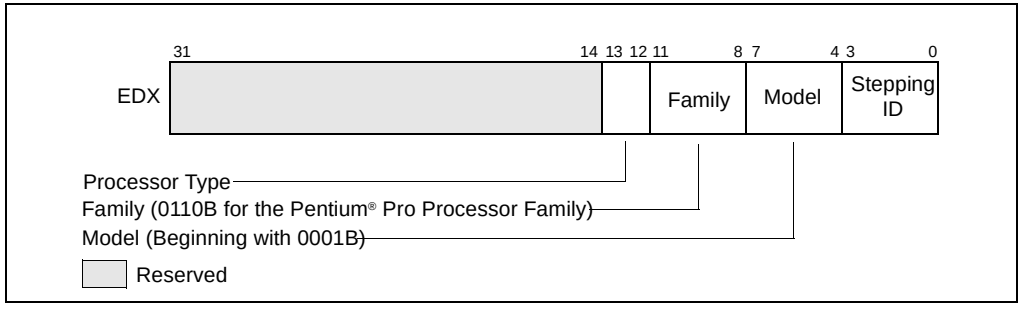


Figure 8-2. Processor Type and Signature in the EDX Register after Reset

The stepping ID field contains a unique identifier for the processor's stepping ID or revision level. The upper word of EDX is reserved following reset.

8.1.4. First Instruction Executed

The first instruction that is fetched and executed following a hardware reset is located at physical address FFFFFFF0H. This address is 16 bytes below the processor's uppermost physical address. The EPROM containing the software-initialization code must be located at this address.

The address FFFFFFF0H is beyond the 1-MByte addressable range of the processor while in real-address mode. The processor is initialized to this starting address as follows. The CS register has two parts: the visible segment selector part and the hidden base address part. In real-address mode, the base address is normally formed by shifting the 16-bit segment selector value 4 bits to the left to produce a 20-bit base address. However, during a hardware reset, the segment selector in the CS register is loaded with F000H and the base address is loaded with FFFF0000H. The starting address is thus formed by adding the base address to the value in the EIP register (that is, FFFF0000 + FFF0H = FFFFFFF0H).

The first time the CS register is loaded with a new value after a hardware reset, the processor will follow the normal rule for address translation in real-address mode (that is, [CS base address = CS segment selector * 16]). To insure that the base address in the CS register remains unchanged until the EPROM based software-initialization code is completed, the code must not contain a far jump or far call or allow an interrupt to occur (which would cause the CS selector value to be changed).

8.2. FPU INITIALIZATION

Software-initialization code can determine the whether the processor contains or is attached to an FPU by using the CPUID instruction. The code must then initialize the FPU and set flags in control register CR0 to reflect the state of the FPU environment.

A hardware reset places the Pentium® processor FPU in the state shown in Table 8-1. This state is different from the state the processor is placed in when executing an FINIT or FNINIT instruction (also shown in Table 8-1). If the FPU is to be used, the software-initialization code should execute an FINIT/FNINIT instruction following a hardware reset. These instructions, tag all data registers as empty, clear all the exception masks, set the TOP-of-stack value to 0, and select the default rounding and precision controls setting (round to nearest and 64-bit precision).

If the processor is reset by asserting the INIT# pin, the FPU state is not changed.

8.2.1. Configuring the FPU Environment

Initialization code must load the appropriate values into the MP, EM, and NE flags of control register CR0. These bits are cleared on hardware reset of the processor. Figure 8-2 shows the suggested settings for these flags, depending on the Intel Architecture processor being initial-

ized. Initialization code can test for the type of processor present before setting or clearing these flags.

Table 8-2. Recommended Settings of EM and MP Flags on Intel Architecture Processors

EM	MP	NE	Intel Architecture Processor
1	0	1	Intel486™ SX, Intel386™ DX, and Intel386™ SX processors only, without the presence of a math coprocessor.
0	1	1 or 0*	Pentium® Pro, Pentium®, Intel486™ DX, and Intel 487 SX processors, and also Intel386™ DX and Intel386™ SX processors when a companion math coprocessor is present.

NOTE:

* The setting of the NE flag depends on the operating system being used.

The EM flag determines whether floating-point instructions are executed by the FPU (EM is cleared) or generate a device-not-available exception (#NM) so that an exception handler can emulate the floating-point operation (EM = 1). Ordinarily, the EM flag is cleared when an FPU or math coprocessor is present and set if they are not present. If the EM flag is set and no FPU, math coprocessor, or floating-point emulator is present, the system will hang when a floating-point instruction is executed.

The MP flag determines whether WAIT/FWAIT instructions react to the setting of the TS flag. If the MP flag is clear, WAIT/FWAIT instructions ignore the setting of the TS flag; if the MP flag is set, they will generate a device-not-available exception (#NM) if the TS flag is set. Generally, the MP flag should be set for processors with an integrated FPU and clear for processors without an integrated FPU and without a math coprocessor present. However, an operating system can choose to save the floating-point context at every context switch, in which case there would be no need to set the MP bit.

Table 2-1 in Chapter 2, *System Architecture Overview* shows the actions taken for floating-point and WAIT/FWAIT instructions based on the settings of the EM, MP, and TS flags.

The NE flag determines whether unmasked floating-point exceptions are handled by generating a floating-point error exception internally (NE is set, native mode) or through an external interrupt (NE is cleared). In systems where an external interrupt controller is used to invoke numeric exception handlers (such as MS-DOS-based systems), the NE bit should be cleared.

8.2.2. Setting the Processor for FPU Software Emulation

Setting the EM flag causes the processor to generate a device-not-available exception (#NM) and trap to a software exception handler whenever it encounters a floating-point instruction. (Table 8-2 shows when it is appropriate to use this flag.) Setting this flag has two functions:

- It allows floating-point code to run on an Intel processor that neither has an integrated FPU nor is connected to an external math coprocessor, by using a floating-point emulator.
- It allows floating-point code to be executed using a special or nonstandard floating-point emulator, selected for a particular application, regardless of whether an FPU or math coprocessor is present.

To emulate floating-point instructions, the EM, MP, and NE flag in control register CR0 should be set as shown in Table 8-3.

Table 8-3. Software Emulation Settings of EM, MP, and NE Flags

CR0 Bit	Value
EM	1
MP	0
NE	1

Regardless of the value of the EM bit, the Intel486™ SX processor generates a device-not-available exception (#NM) upon encountering any floating-point instruction.

8.3. CACHE ENABLING

The Intel Architecture processors (beginning with the Intel486™ processor) contain internal instruction and data caches. These caches are enabled by clearing the CD and NW flags in control register CR0. (They are set during a hardware reset.) Because all internal cache lines are invalid following reset initialization, it is not necessary to invalidate the cache before enabling caching. Any external caches may require initialization and invalidation using a system-specific initialization and invalidation code sequence.

Depending on the hardware and operating system or executive requirements, additional configuration of the processor's caching facilities will probably be required. Beginning with the Intel486™ processor, page-level caching can be controlled with the PCD and PWT flags in page-directory and page-table entries. For P6 family processors, the memory type range registers (MTRRs) control the caching characteristics of the regions of physical memory. (For the Intel486™ and Pentium® processors, external hardware can be used to control the caching characteristics of regions of physical memory.) Refer to Chapter 9, *Memory Cache Control*, for detailed information on configuration of the caching facilities in the P6 family processors and system memory.

8.4. MODEL-SPECIFIC REGISTERS (MSRS)

The P6 family processors and Pentium® processors contain model-specific registers (MSRs). These registers are by definition implementation specific; that is, they are not guaranteed to be

supported on future Intel Architecture processors and/or to have the same functions. The MSRs are provided to control a variety of hardware- and software-related features, including:

- The performance-monitoring counters (refer to Section 15.6., "Performance-Monitoring Counters", in Chapter 15, *Debugging and Performance Monitoring*).
- (P6 family processors only.) Debug extensions (refer to Section 15.4., "Last Branch, Interrupt, and Exception Recording", in Chapter 15, *Debugging and Performance Monitoring*).
- (P6 family processors only.) The machine-check exception capability and its accompanying machine-check architecture (refer to Chapter 13, *Machine-Check Architecture*).
- (P6 family processors only.) The MTRRs (refer to Section 9.12., "Memory Type Range Registers (MTRRs)", in Chapter 9, *Memory Cache Control*).

The MSRs can be read and written to using the RDMSR and WRMSR instructions, respectively.

When performing software initialization of a Pentium® Pro or Pentium® processor, many of the MSRs will need to be initialized to set up things like performance-monitoring events, run-time machine checks, and memory types for physical memory.

Systems configured to implement FRC mode must write all of the processors' internal MSRs to deterministic values before performing either a read or read-modify-write operation using these registers. The following is a list of MSRs that are not initialized by the processors' reset sequences.

- All fixed and variable MTRRs.
- All Machine Check Architecture (MCA) status registers.
- Microcode update signature register.
- All L2 cache initialization MSRs.

The list of available performance-monitoring counters for the Pentium® Pro and Pentium® processors is given in Appendix A, *Performance-Monitoring Events*, and the list of available MSRs for the Pentium® Pro processor is given in Appendix B, *Model-Specific Registers*. The references earlier in this section show where the functions of the various groups of MSRs are described in this manual.

8.5. MEMORY TYPE RANGE REGISTERS (MTRRS)

Memory type range registers (MTRRs) were introduced into the Intel Architecture with the Pentium® Pro processor. They allow the type of caching (or no caching) to be specified in system memory for selected physical address ranges. They allow memory accesses to be optimized for various types of memory such as RAM, ROM, frame buffer memory, and memory-mapped I/O devices.

In general, initializing the MTRRs is normally handled by the software initialization code or BIOS and is not an operating system or executive function. At the very least, all the MTRRs must be cleared to 0, which selects the uncached (UC) memory type. Refer to Section 9.12.,

"Memory Type Range Registers (MTRRs)", in Chapter 9, *Memory Cache Control*, for detailed information on the MTRRs.

8.6. SOFTWARE INITIALIZATION FOR REAL-ADDRESS MODE OPERATION

Following a hardware reset (either through a power-up or the assertion of the RESET# pin) the processor is placed in real-address mode and begins executing software initialization code from physical address FFFFFFF0H. Software initialization code must first set up the necessary data structures for handling basic system functions, such as a real-mode IDT for handling interrupts and exceptions. If the processor is to remain in real-address mode, software must then load additional operating-system or executive code modules and data structures to allow reliable execution of application programs in real-address mode.

If the processor is going to operate in protected mode, software must load the necessary data structures to operate in protected mode and then switch to protected mode. The protected-mode data structures that must be loaded are described in Section 8.7., "Software Initialization for Protected-Mode Operation".

8.6.1. Real-Address Mode IDT

In real-address mode, the only system data structure that must be loaded into memory is the IDT (also called the "interrupt vector table"). By default, the address of the base of the IDT is physical address 0H. This address can be changed by using the LIDT instruction to change the base address value in the IDTR. Software initialization code needs to load interrupt- and exception-handler pointers into the IDT before interrupts can be enabled.

The actual interrupt- and exception-handler code can be contained either in EPROM or RAM; however, the code must be located within the 1-MByte addressable range of the processor in real-address mode. If the handler code is to be stored in RAM, it must be loaded along with the IDT.

8.6.2. NMI Interrupt Handling

The NMI interrupt is always enabled (except when multiple NMIs are nested). If the IDT and the NMI interrupt handler need to be loaded into RAM, there will be a period of time following hardware reset when an NMI interrupt cannot be handled. During this time, hardware must provide a mechanism to prevent an NMI interrupt from halting code execution until the IDT and the necessary NMI handler software is loaded.

Here are two examples of how NMIs can be handled during the initial states of processor initialization:

- A simple IDT and NMI interrupt handler can be provided in EPROM. This allows an NMI interrupt to be handled immediately after reset initialization.
- The system hardware can provide a mechanism to enable and disable NMIs by passing the NMI# signal through an AND gate controlled by a flag in an I/O port. Hardware can clear the flag when the processor is reset, and software can set the flag when it is ready to handle NMI interrupts.

8.7. SOFTWARE INITIALIZATION FOR PROTECTED-MODE OPERATION

The processor is placed in real-address mode following a hardware reset. At this point in the initialization process, some basic data structures and code modules must be loaded into physical memory to support further initialization of the processor, as described in Section 8.6., “Software Initialization for Real-Address Mode Operation”. Before the processor can be switched to protected mode, the software initialization code must load a minimum number of protected mode data structures and code modules into memory to support reliable operation of the processor in protected mode. These data structures include the following:

- A protected-mode IDT.
- A GDT.
- A TSS.
- (Optional.) An LDT.
- If paging is to be used, at least one page directory and one page table.
- A code segment that contains the code to be executed when the processor switches to protected mode.
- One or more code modules that contain the necessary interrupt and exception handlers.

Software initialization code must also initialize the following system registers before the processor can be switched to protected mode:

- The GDTR.
- (Optional.) The IDTR. This register can also be initialized immediately after switching to protected mode, prior to enabling interrupts.
- Control registers CR1 through CR4.
- (Pentium® Pro processor only.) The memory type range registers (MTRRs).

With these data structures, code modules, and system registers initialized, the processor can be switched to protected mode by loading control register CR0 with a value that sets the PE flag (bit 0).

8.7.1. Protected-Mode System Data Structures

The contents of the protected-mode system data structures loaded into memory during software initialization, depend largely on the type of memory management the protected-mode operating-system or executive is going to support: flat, flat with paging, segmented, or segmented with paging.

To implement a flat memory model without paging, software initialization code must at a minimum load a GDT with one code and one data-segment descriptor. A null descriptor in the first GDT entry is also required. The stack can be placed in a normal read/write data segment, so no dedicated descriptor for the stack is required. A flat memory model with paging also requires a page directory and at least one page table (unless all pages are 4 MBytes in which case only a page directory is required). Refer to Section 8.7.3., “Initializing Paging”

Before the GDT can be used, the base address and limit for the GDT must be loaded into the GDTR register using an LGDT instruction.

A multisegmented model may require additional segments for the operating system, as well as segments and LDTs for each application program. LDTs require segment descriptors in the GDT. Some operating systems allocate new segments and LDTs as they are needed. This provides maximum flexibility for handling a dynamic programming environment. However, many operating systems use a single LDT for all tasks, allocating GDT entries in advance. An embedded system, such as a process controller, might pre-allocate a fixed number of segments and LDTs for a fixed number of application programs. This would be a simple and efficient way to structure the software environment of a real-time system.

8.7.2. Initializing Protected-Mode Exceptions and Interrupts

Software initialization code must at a minimum load a protected-mode IDT with gate descriptor for each exception vector that the processor can generate. If interrupt or trap gates are used, the gate descriptors can all point to the same code segment, which contains the necessary exception handlers. If task gates are used, one TSS and accompanying code, data, and task segments are required for each exception handler called with a task gate.

If hardware allows interrupts to be generated, gate descriptors must be provided in the IDT for one or more interrupt handlers.

Before the IDT can be used, the base address and limit for the IDT must be loaded into the IDTR register using an LIDT instruction. This operation is typically carried out immediately after switching to protected mode.

8.7.3. Initializing Paging

Paging is controlled by the PG flag in control register CR0. When this flag is clear (its state following a hardware reset), the paging mechanism is turned off; when it is set, paging is enabled. Before setting the PG flag, the following data structures and registers must be initialized:

- Software must load at least one page directory and one page table into physical memory. The page table can be eliminated if the page directory contains a directory entry pointing to itself (here, the page directory and page table reside in the same page), or if only 4-MByte pages are used.
- Control register CR3 (also called the PDBR register) is loaded with the physical base address of the page directory.
- (Optional) Software may provide one set of code and data descriptors in the GDT or in an LDT for supervisor mode and another set for user mode.

With this paging initialization complete, paging is enabled and the processor is switched to protected mode at the same time by loading control register CR0 with an image in which the PG and PE flags are set. (Paging cannot be enabled before the processor is switched to protected mode.)

8.7.4. Initializing Multitasking

If the multitasking mechanism is not going to be used and changes between privilege levels are not allowed, it is not necessary load a TSS into memory or to initialize the task register.

If the multitasking mechanism is going to be used and/or changes between privilege levels are allowed, software initialization code must load at least one TSS and an accompanying TSS descriptor. (A TSS is required to change privilege levels because pointers to the privileged-level 0, 1, and 2 stack segments and the stack pointers for these stacks are obtained from the TSS.) TSS descriptors must not be marked as busy when they are created; they should be marked busy by the processor only as a side-effect of performing a task switch. As with descriptors for LDTs, TSS descriptors reside in the GDT.

After the processor has switched to protected mode, the LTR instruction can be used to load a segment selector for a TSS descriptor into the task register. This instruction marks the TSS descriptor as busy, but does not perform a task switch. The processor can, however, use the TSS to locate pointers to privilege-level 0, 1, and 2 stacks. The segment selector for the TSS must be loaded before software performs its first task switch in protected mode, because a task switch copies the current task state into the TSS.

After the LTR instruction has been executed, further operations on the task register are performed by task switching. As with other segments and LDTs, TSSs and TSS descriptors can be either pre-allocated or allocated as needed.

8.8. MODE SWITCHING

To use the processor in protected mode, a mode switch must be performed from real-address mode. Once in protected mode, software generally does not need to return to real-address mode. To run software written to run in real-address mode (8086 mode), it is generally more convenient to run the software in virtual-8086 mode, than to switch back to real-address mode.

8.8.1. Switching to Protected Mode

Before switching to protected mode, a minimum set of system data structures and code modules must be loaded into memory, as described in Section 8.7., “Software Initialization for Protected-Mode Operation”. Once these tables are created, software initialization code can switch into protected mode.

Protected mode is entered by executing a MOV CR0 instruction that sets the PE flag in the CR0 register. (In the same instruction, the PG flag in register CR0 can be set to enable paging.) Execution in protected mode begins with a CPL of 0.

The 32-bit Intel Architecture processors have slightly different requirements for switching to protected mode. To insure upwards and downwards code compatibility with all 32-bit Intel Architecture processors, it is recommended that the following steps be performed:

1. Disable interrupts. A CLI instruction disables maskable hardware interrupts. NMI interrupts can be disabled with external circuitry. (Software must guarantee that no exceptions or interrupts are generated during the mode switching operation.)
2. Execute the LGDT instruction to load the GDTR register with the base address of the GDT.
3. Execute a MOV CR0 instruction that sets the PE flag (and optionally the PG flag) in control register CR0.
4. Immediately following the MOV CR0 instruction, execute a far JMP or far CALL instruction. (This operation is typically a far jump or call to the next instruction in the instruction stream.)

   The JMP or CALL instruction immediately after the MOV CR0 instruction changes the flow of execution and serializes the processor.

   If paging is enabled, the code for the MOV CR0 instruction and the JMP or CALL instruction must come from a page that is identity mapped (that is, the linear address before the jump is the same as the physical address after paging and protected mode is enabled). The target instruction for the JMP or CALL instruction does not need to be identity mapped.
5. If a local descriptor table is going to be used, execute the LLDT instruction to load the segment selector for the LDT in the LDTR register.
6. Execute the LTR instruction to load the task register with a segment selector to the initial protected-mode task or to a writable area of memory that can be used to store TSS information on a task switch.
7. After entering protected mode, the segment registers continue to hold the contents they had in real-address mode. The JMP or CALL instruction in step 4 resets the CS register. Perform one of the following operations to update the contents of the remaining segment registers.

   — Reload segment registers DS, SS, ES, FS, and GS. If the ES, FS, and/or GS registers are not going to be used, load them with a null selector.

— Perform a JMP or CALL instruction to a new task, which automatically resets the values of the segment registers and branches to a new code segment.

8. Execute the LIDT instruction to load the IDTR register with the address and limit of the protected-mode IDT.
9. Execute the STI instruction to enable maskable hardware interrupts and perform the necessary hardware operation to enable NMI interrupts.

Random failures can occur if other instructions exist between steps 3 and 4 above. Failures will be readily seen in some situations, such as when instructions that reference memory are inserted between steps 3 and 4 while in System Management mode.

8.8.2. Switching Back to Real-Address Mode

The processor switches back to real-address mode if software clears the PE bit in the CR0 register with a MOV CR0 instruction. A procedure that re-enters real-address mode should perform the following steps:

1. Disable interrupts. A CLI instruction disables maskable hardware interrupts. NMI interrupts can be disabled with external circuitry.
2. If paging is enabled, perform the following operations:
   — Transfer program control to linear addresses that are identity mapped to physical addresses (that is, linear addresses equal physical addresses).
   — Insure that the GDT and IDT are in identity mapped pages.
   — Clear the PG bit in the CR0 register.
   — Move 0H into the CR3 register to flush the TLB.
3. Transfer program control to a readable segment that has a limit of 64 KBytes (FFFFH). This operation loads the CS register with the segment limit required in real-address mode.
4. Load segment registers SS, DS, ES, FS, and GS with a selector for a descriptor containing the following values, which are appropriate for real-address mode:
   — Limit = 64 KBytes (0FFFFH)
   — Byte granular (G = 0)
   — Expand up (E = 0)
   — Writable (W = 1)
   — Present (P = 1)
   — Base = any value

   The segment registers must be loaded with nonnull segment selectors or the segment registers will be unusable in real-address mode. Note that if the segment registers are not

reloaded, execution continues using the descriptor attributes loaded during protected mode.

5. Execute an LIDT instruction to point to a real-address mode interrupt table that is within the 1-MByte real-address mode address range.
6. Clear the PE flag in the CR0 register to switch to real-address mode.
7. Execute a far JMP instruction to jump to a real-address mode program. This operation flushes the instruction queue and loads the appropriate base and access rights values in the CS register.
8. Load the SS, DS, ES, FS, and GS registers as needed by the real-address mode code. If any of the registers are not going to be used in real-address mode, write 0s to them.
9. Execute the STI instruction to enable maskable hardware interrupts and perform the necessary hardware operation to enable NMI interrupts.

NOTE

All the code that is executed in steps 1 through 9 must be in a single page and the linear addresses in that page must be identity mapped to physical addresses.

8.9. INITIALIZATION AND MODE SWITCHING EXAMPLE

This section provides an initialization and mode switching example that can be incorporated into an application. This code was originally written to initialize the Intel386™ processor, but it will execute successfully on the Pentium® Pro, Pentium®, and Intel486™ processors. The code in this example is intended to reside in EPROM and to run following a hardware reset of the processor. The function of the code is to do the following:

- Establish a basic real-address mode operating environment.
- Load the necessary protected-mode system data structures into RAM.
- Load the system registers with the necessary pointers to the data structures and the appropriate flag settings for protected-mode operation.
- Switch the processor to protected mode.

Figure 8-3 shows the physical memory layout for the processor following a hardware reset and the starting point of this example. The EPROM that contains the initialization code resides at the upper end of the processor's physical memory address range, starting at address FFFFFFFFH and going down from there. The address of the first instruction to be executed is at FFFFFFF0H, the default starting address for the processor following a hardware reset.

The main steps carried out in this example are summarized in Table 8-4. The source listing for the example (with the filename STARTUP.ASM) is given in Example 8-1. The line numbers given in Table 8-4 refer to the source listing.

The following are some additional notes concerning this example:

- When the processor is switched into protected mode, the original code segment base-address value of FFFF0000H (located in the hidden part of the CS register) is retained and execution continues from the current offset in the EIP register. The processor will thus continue to execute code in the EPROM until a far jump or call is made to a new code segment, at which time, the base address in the CS register will be changed.
- Maskable hardware interrupts are disabled after a hardware reset and should remain disabled until the necessary interrupt handlers have been installed. The NMI interrupt is not disabled following a reset. The NMI# pin must thus be inhibited from being asserted until an NMI handler has been loaded and made available to the processor.
- The use of a temporary GDT allows simple transfer of tables from the EPROM to anywhere in the RAM area. A GDT entry is constructed with its base pointing to address 0 and a limit of 4 GBytes. When the DS and ES registers are loaded with this descriptor, the temporary GDT is no longer needed and can be replaced by the application GDT.
- This code loads one TSS and no LDTs. If more TSSs exist in the application, they must be loaded into RAM. If there are LDTs they may be loaded as well.

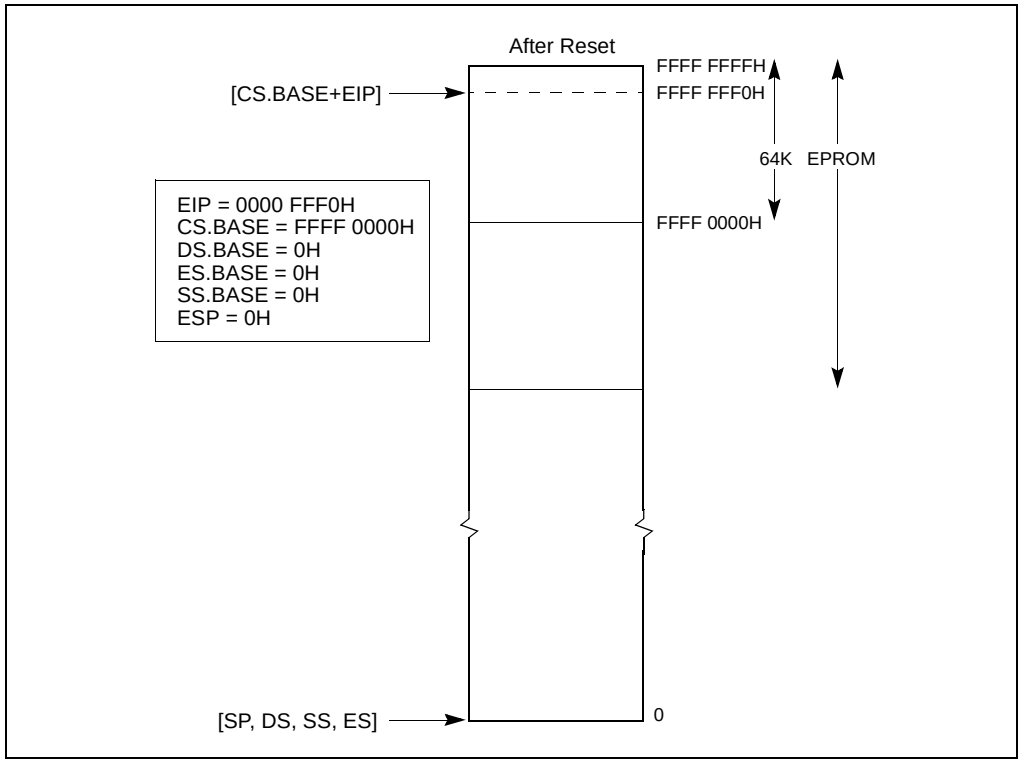


Figure 8-3. Processor State After Reset

Table 8-4. Main Initialization Steps in STARTUP.ASM Source Listing

STARTUP.ASM Line Numbers		Description
From	To	
157	157	Jump (short) to the entry code in the EPROM
162	169	Construct a temporary GDT in RAM with one entry: 0 - null 1 - R/W data segment, base = 0, limit = 4 GBytes
171	172	Load the GDTR to point to the temporary GDT
174	177	Load CR0 with PE flag set to switch to protected mode
179	181	Jump near to clear real mode instruction queue
184	186	Load DS, ES registers with GDT[1] descriptor, so both point to the entire physical memory space
188	195	Perform specific board initialization that is imposed by the new protected mode
196	218	Copy the application's GDT from ROM into RAM
220	238	Copy the application's IDT from ROM into RAM
241	243	Load application's GDTR
244	245	Load application's IDTR
247	261	Copy the application's TSS from ROM into RAM
263	267	Update TSS descriptor and other aliases in GDT (GDT alias or IDT alias)
277	277	Load the task register (without task switch) using LTR instruction
282	286	Load SS, ESP with the value found in the application's TSS
287	287	Push EFLAGS value found in the application's TSS
288	288	Push CS value found in the application's TSS
289	289	Push EIP value found in the application's TSS
290	293	Load DS, ES with the value found in the application's TSS
296	296	Perform IRET; pop the above values and enter the application code

8.9.1. Assembler Usage

In this example, the Intel assembler ASM386 and build tools BLD386 are used to assemble and build the initialization code module. The following assumptions are used when using the Intel ASM386 and BLD386 tools.

- The ASM386 will generate the right operand size opcodes according to the code-segment attribute. The attribute is assigned either by the ASM386 invocation controls or in the code-segment definition.
- If a code segment that is going to run in real-address mode is defined, it must be set to a USE 16 attribute. If a 32-bit operand is used in an instruction in this code segment (for example, MOV EAX, EBX), the assembler automatically generates an operand prefix for the instruction that forces the processor to execute a 32-bit operation, even though its default code-segment attribute is 16-bit.
- Intel's ASM386 assembler allows specific use of the 16- or 32-bit instructions, for example, LGDTW, LGDTD, IRETD. If the generic instruction LGDT is used, the default-segment attribute will be used to generate the right opcode.

8.9.2. STARTUP.ASM Listing

The source code listing to move the processor into protected mode is provided in Example 8-1. This listing does not include any opcode and offset information.

Example 8-1. STARTUP.ASM

```
MS-DOS* 5.0(045-N) 386(TM) MACRO ASSEMBLER STARTUP  09:44:51  08/19/92 PAGE 1

MS-DOS 5.0(045-N) 386(TM) MACRO ASSEMBLER V4.0, ASSEMBLY OF MODULE
STARTUP
OBJECT MODULE PLACED IN startup.obj
ASSEMBLER INVOKED BY: f:\386tools\ASM386.EXE startup.a58 pw (132 )

LINE    SOURCE

  1     NAME    STARTUP
  2
  3             ;;;
```

```
12  ;
13  ;;;
```

```
 59     EAX_reg          DD ?
 60     ECX_reg          DD ?
 61     EDX_reg          DD ?
 62     EBX_reg          DD ?
 63     ESP_reg          DD ?
 64     EBP_reg          DD ?
 65     ESI_reg          DD ?
 66     EDI_reg          DD ?
 67     ES_reg           DW ?
 68     ES_h             DW ?
 69     CS_reg           DW ?
 70     CS_h             DW ?
 71     SS_reg           DW ?
 72     SS_h             DW ?
 73     DS_reg           DW ?
 74     DS_h             DW ?
 75     FS_reg           DW ?
 76     FS_h             DW ?
 77     GS_reg           DW ?
 78     GS_h             DW ?
 79     LDT_reg          DW ?
 80     LDT_h            DW ?
 81     TRAP_reg         DW ?
 82     IO_map_base      DW ?
 83  TASK_STATE  ENDS
 84
 85  ; basic structure of a descriptor
 86  DESC    STRUC
 87     lim_0_15         DW ?
 88     bas_0_15         DW ?
 89     bas_16_23        DB ?
 90     access           DB ?
 91     gran             DB ?
 92     bas_24_31        DB ?
 93  DESC    ENDS
 94
 95  ; structure for use with LGDT and LIDT instructions
 96  TABLE_REG   STRUC
 97     table_lim        DW ?
 98     table_linear     DD ?
 99  TABLE_REG   ENDS
100
101  ; offset of GDT and IDT descriptors in builder generated GDT
102  GDT_DESC_OFF    EQU 1*SIZE(DESC)
103  IDT_DESC_OFF    EQU 2*SIZE(DESC)
104
105  ; equates for building temporary GDT in RAM
```

```
106 LINEAR_SEL         EQU     1*SIZE (DESC)
107 LINEAR_PROTO_LO     EQU     00000FFFFH  ; LINEAR_ALIAS
108 LINEAR_PROTO_HI     EQU     000CF9200H
109
110 ; Protection Enable Bit in CR0
111 PE_BIT  EQU 1B
112
113 ; -------------------------------------------------------------
114
115 ; ------------------------- DATA SEGMENT----------------------
116
117 ; Initially, this  data segment starts at linear 0, according
118 ; to the processor's power-up state.
119
120 STARTUP_DATA    SEGMENT RW
121
122 free_mem_linear_base    LABEL   DWORD
123 TEMP_GDT                LABEL   BYTE  ; must be first in segment
124 TEMP_GDT_NULL_DESC   DESC    <>
125 TEMP_GDT_LINEAR_DESC DESC    <>
126
127 ; scratch areas for LGDT and LIDT instructions
128 TEMP_GDT_SCRATCH TABLE_REG   <>
129 APP_GDT_RAM     TABLE_REG    <>
130 APP_IDT_RAM     TABLE_REG    <>
131         ; align end_data
132 fill    DW      ?
133
134 ; last thing in this segment - should be on a dword boundary
135 end_data    LABEL   BYTE
136
137 STARTUP_DATA    ENDS
138 ; -------------------------------------------------------------
139
140
141 ; ------------------------- CODE SEGMENT----------------------
142 STARTUP_CODE SEGMENT ER PUBLIC USE16
143
144 ; filled in by builder
145     PUBLIC  GDT_EPROM
146 GDT_EPROM   TABLE_REG   <>
147
148 ; filled in by builder
149     PUBLIC  IDT_EPROM
150 IDT_EPROM   TABLE_REG   <>
151
152 ; entry point into startup code - the bootstrap will vector
```

```
153  ; here  with a  near JMP  generated by  the builder.   This
154  ; label must be in the top 64K of linear memory.
155
156     PUBLIC  STARTUP
157  STARTUP:
158
159  ; DS,ES address the bottom 64K of flat linear memory
160     ASSUME  DS:STARTUP_DATA, ES:STARTUP_DATA
161  ; See Figure 8-4
162  ; load GDTR with temporary GDT
163         LEA     EBX,TEMP_GDT  ; build the TEMP_GDT in low ram,
164         MOV     DWORD PTR [EBX],0   ; where we can address
165         MOV     DWORD PTR [EBX]+4,0
166         MOV     DWORD PTR [EBX]+8, LINEAR_PROTO_LO
167         MOV     DWORD PTR [EBX]+12, LINEAR_PROTO_HI
168         MOV     TEMP_GDT_scratch.table_linear,EBX
169         MOV     TEMP_GDT_scratch.table_lim,15
170
171               DB      66H         ; execute a 32 bit LGDT
172         LGDT    TEMP_GDT_scratch
173
174  ; enter protected mode
175         MOV     EBX,CR0
176         OR      EBX,PE_BIT
177         MOV     CR0,EBX
178

179   ; clear prefetch queue
180         JMP     CLEAR_LABEL
181  CLEAR_LABEL:
182
183   ; make DS and ES address 4G of linear memory
184         MOV     CX,LINEAR_SEL
185         MOV     DS,CX
186         MOV     ES,CX
187
188    ; do board specific initialization
189    ;
190                 ;
191                 ; ......
192                 ;
193
194
195         ; See Figure 8-5
196         ; copy EPROM GDT to ram at:
197         ;               RAM_START + size (STARTUP_DATA)
198         MOV     EAX,RAM_START
```

```
199       ADD     EAX,OFFSET (end_data)
200       MOV     EBX,RAM_START
201       MOV     ECX, CS_BASE
202       ADD     ECX, OFFSET (GDT_EPROM)
203       MOV     ESI, [ECX].table_linear
204       MOV     EDI,EAX
205       MOVZX   ECX, [ECX].table_lim
206       MOV     APP_GDT_ram[EBX].table_lim,CX
207       INC     ECX
208       MOV     EDX,EAX
209       MOV     APP_GDT_ram[EBX].table_linear,EAX
210       ADD     EAX,ECX
211     REP MOVS    BYTE PTR ES:[EDI],BYTE PTR DS:[ESI]
212
213       ; fixup GDT base in descriptor
214       MOV     ECX,EDX
215       MOV     [EDX].bas_0_15+GDT_DESC_OFF,CX
216       ROR     ECX,16
217       MOV     [EDX].bas_16_23+GDT_DESC_OFF,CL
218       MOV     [EDX].bas_24_31+GDT_DESC_OFF,CH
219
220       ; copy EPROM IDT to ram at:
221       ; RAM_START+size(STARTUP_DATA)+SIZE (EPROM GDT)
222       MOV     ECX, CS_BASE
223       ADD     ECX, OFFSET (IDT_EPROM)
224       MOV     ESI, [ECX].table_linear
225       MOV     EDI,EAX
226       MOVZX   ECX, [ECX].table_lim
227       MOV     APP_IDT_ram[EBX].table_lim,CX
228       INC     ECX
229       MOV     APP_IDT_ram[EBX].table_linear,EAX
230       MOV     EBX,EAX
231       ADD     EAX,ECX
232     REP MOVS    BYTE PTR ES:[EDI],BYTE PTR DS:[ESI]
233
234             ; fixup IDT pointer in GDT
235       MOV     [EDX].bas_0_15+IDT_DESC_OFF,BX
236       ROR     EBX,16
237       MOV     [EDX].bas_16_23+IDT_DESC_OFF,BL
238       MOV     [EDX].bas_24_31+IDT_DESC_OFF,BH
239
240             ; load GDTR and IDTR
241       MOV     EBX,RAM_START
242               DB      66H         ; execute a 32 bit LGDT
243       LGDT    APP_GDT_ram[EBX]
244               DB      66H         ; execute a 32 bit LIDT
245       LIDT    APP_IDT_ram[EBX]
246
247             ; move the TSS
```

```
248       MOV     EDI,EAX
249       MOV     EBX,TSS_INDEX*SIZE(DESC)
250       MOV     ECX,GDT_DESC_OFF ;build linear address for TSS
251       MOV     GS,CX
252       MOV     DH,GS:[EBX].bas_24_31
253       MOV     DL,GS:[EBX].bas_16_23
254       ROL     EDX,16
255       MOV     DX,GS:[EBX].bas_0_15
256       MOV     ESI,EDX
257       LSL     ECX,EBX
258       INC     ECX
259       MOV     EDX,EAX
260       ADD     EAX,ECX
261     REP MOVS    BYTE PTR ES:[EDI],BYTE PTR DS:[ESI]
262
263             ; fixup TSS pointer
264       MOV     GS:[EBX].bas_0_15,DX
265       ROL     EDX,16
266       MOV     GS:[EBX].bas_24_31,DH
267       MOV     GS:[EBX].bas_16_23,DL
268       ROL     EDX,16
269     ;save start of free ram at linear location RAMSTART
270       MOV     free_mem_linear_base+RAM_START,EAX
271
272     ;assume no  LDT used in  the initial task  - if necessary,
273     ;code  to move the LDT could be added, and should resemble
274     ;that used to move the TSS
275
276     ; load task register
277       LTR     BX   ; No task switch, only descriptor loading
278     ; See Figure 8-6
279     ; load minimal set of registers necessary to simulate task
280     ; switch
281
282
283       MOV     AX,[EDX].SS_reg     ; start loading registers
284       MOV     EDI,[EDX].ESP_reg
285       MOV     SS,AX
286       MOV     ESP,EDI             ; stack now valid
287       PUSH    DWORD PTR [EDX].EFLAGS_reg
288       PUSH    DWORD PTR [EDX].CS_reg
289       PUSH    DWORD PTR [EDX].EIP_reg
290       MOV     AX,[EDX].DS_reg
291       MOV     BX,[EDX].ES_reg
292       MOV     DS,AX     ; DS and ES no longer linear memory
293       MOV     ES,BX
294
```

```
 295         ; simulate far jump to initial task
 296         IRETD
 297
 298  STARTUP_CODE  ENDS
*** WARNING #377 IN 298, (PASS 2) SEGMENT CONTAINS PRIVILEGED INSTRUCTION(S)
 299
 300  END STARTUP, DS:STARTUP_DATA, SS:STARTUP_DATA
 301
 302

ASSEMBLY COMPLETE,   1 WARNING,   NO ERRORS.
```

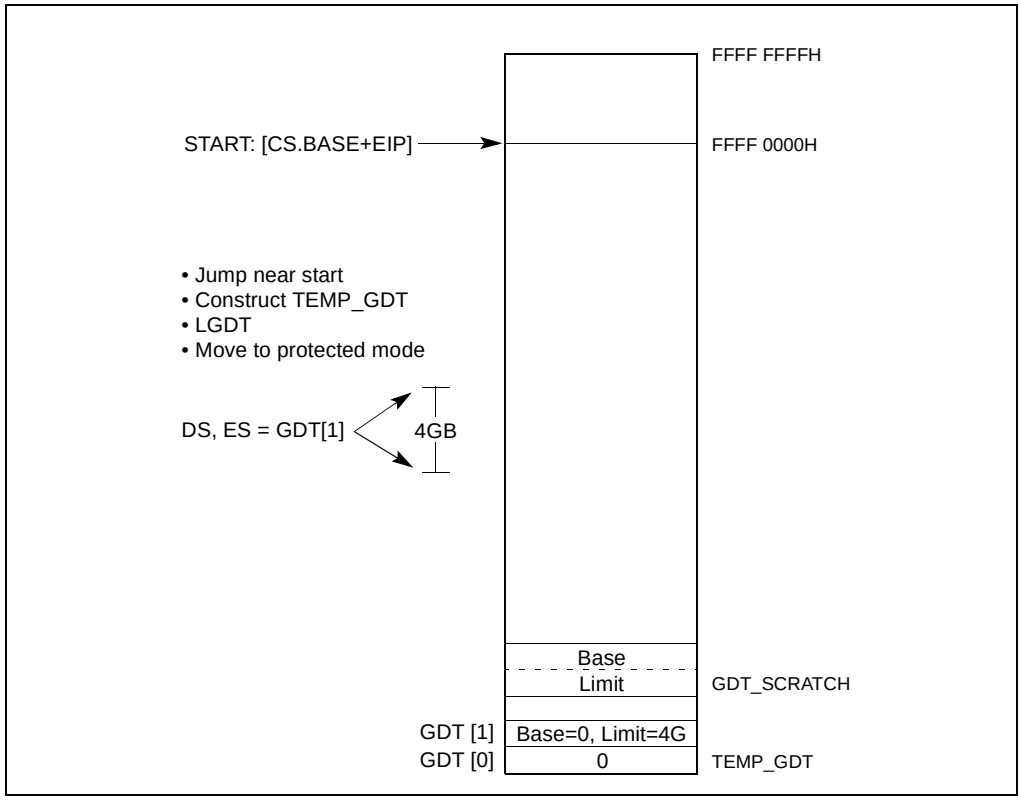


Figure 8-4. Constructing Temporary GDT and Switching to Protected Mode (Lines 162-172 of List File)

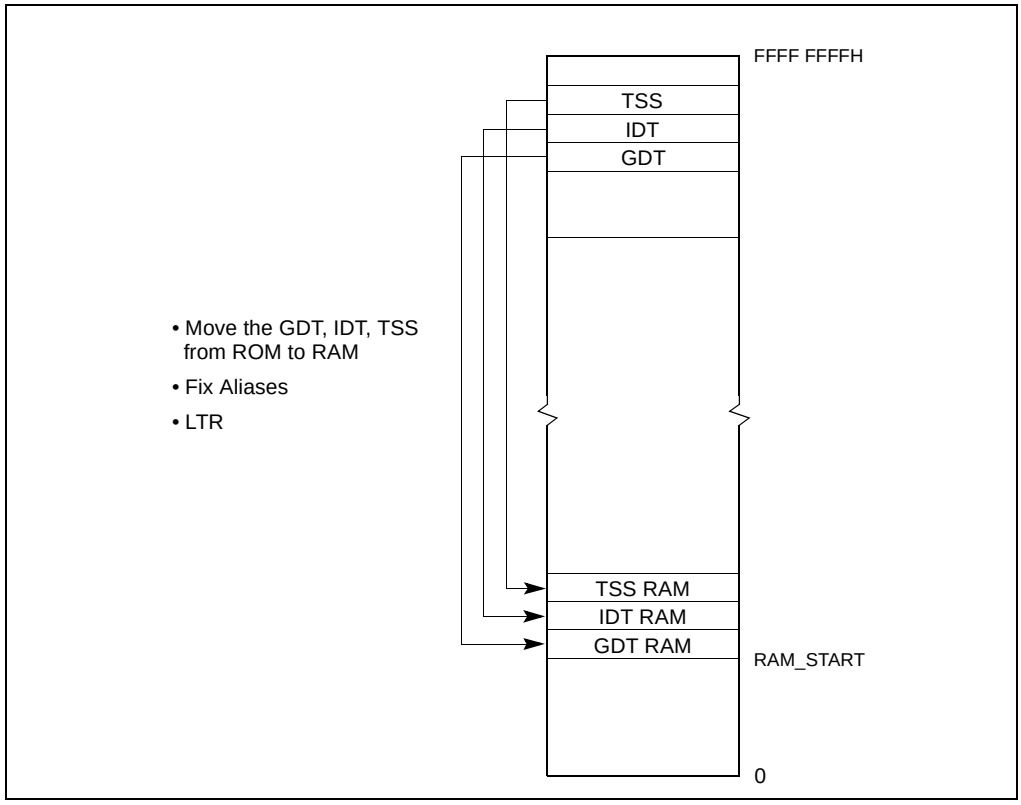


Figure 8-5. Moving the GDT, IDT and TSS from ROM to RAM (Lines 196-261 of List File)

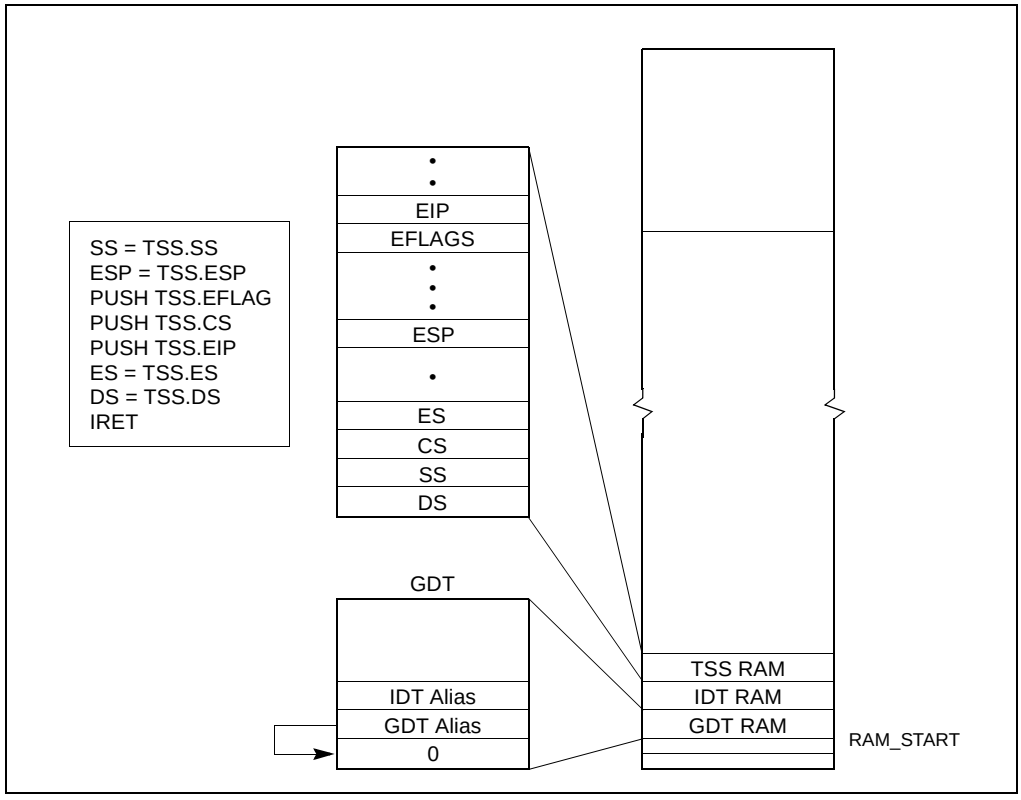


Figure 8-6. Task Switching (Lines 282-296 of List File)

8.9.3. MAIN.ASM Source Code

The file MAIN.ASM shown in Example 8-2 defines the data and stack segments for this application and can be substituted with the main module task written in a high-level language that is invoked by the IRET instruction executed by STARTUP.ASM.

Example 8-2. MAIN.ASM

```
NAME    main_module
data    SEGMENT RW
    dw 1000 dup(?)
DATA    ENDS
stack stackseg 800
CODE SEGMENT ER  use32 PUBLIC
main_start:
    nop
    nop
    nop
CODE  ENDS
END main_start, ds:data, ss:stack
```

8.9.4. Supporting Files

The batch file shown in Example 8-3 can be used to assemble the source code files STARTUP.ASM and MAIN.ASM and build the final application.

Example 8-3. Batch File to Assemble and Build the Application

```
ASM386 STARTUP.ASM
ASM386 MAIN.ASM
BLD386 STARTUP.OBJ, MAIN.OBJ buildfile(EPROM.BLD) bootstrap(STARTUP) Bootload
```

BLD386 performs several operations in this example:

- It allocates physical memory location to segments and tables.
- It generates tables using the build file and the input files.
- It links object files and resolves references.
- It generates a boot-loadable file to be programmed into the EPROM.

Example 8-4 shows the build file used as an input to BLD386 to perform the above functions.

Example 8-4. Build File

```
INIT_BLD_EXAMPLE;

SEGMENT
      *SEGMENTS(DPL = 0)
   ,  startup.startup_code(BASE = 0FFFF0000H)
   ;

TASK
      BOOT_TASK(OBJECT = startup, INITIAL,DPL = 0,
                              NOT INTENABLED)
,     PROTECTED_MODE_TASK(OBJECT = main_module,DPL = 0,
                              NOT INTENABLED)
   ;

TABLE
   GDT (
      LOCATION = GDT_EPROM
   ,  ENTRY = (
         10:   PROTECTED_MODE_TASK
   ,                 startup.startup_code
   ,      startup.startup_data
   ,      main_module.data
   ,      main_module.code
   ,      main_module.stack
           )
      ),

   IDT (
      LOCATION = IDT_EPROM
      );

MEMORY
   (
      RESERVE = (0..3FFFH
                        -- Area for the GDT, IDT, TSS copied from ROM
   ,           60000H..0FFFEFFFFH)
   ,  RANGE = (ROM_AREA = ROM (0FFFF0000H..0FFFFFFFFH))
                              -- Eprom size 64K
   ,  RANGE = (RAM_AREA = RAM (4000H..05FFFFH))
   );

END
```

Table 8-5 shows the relationship of each build item with an ASM source file.

Table 8-5. Relationship Between BLD Item and ASM Source File

Item	ASM386 and Startup.A58	BLD386 Controls and BLD file	Effect
Bootstrap	public startup startup:	bootstrap start(startup)	Near jump at 0FFFFFFF0H to start
GDT location	public GDT_EPROM GDT_EPROM TABLE_REG <>	TABLE GDT(location = GDT_EPROM)	The location of the GDT will be programmed into the GDT_EPROM location
IDT location	public IDT_EPROM IDT_EPROM TABLE_REG <>	TABLE IDT(location = IDT_EPROM	The location of the IDT will be programmed into the IDT_EPROM location
RAM start	RAM_START equ 400H	memory (reserve = (0..3FFFH))	RAM_START is used as the ram destination for moving the tables. It must be excluded from the application's segment area.
Location of the application TSS in the GDT	TSS_INDEX EQU 10	TABLE GDT(ENTRY=(10: PROTECTED_MODE_TASK))	Put the descriptor of the application TSS in GDT entry 10
EPROM size and location	size and location of the initialization code	SEGMENT startup.code (base= 0FFFF0000H) ...memory (RANGE(ROM_AREA = ROM(x..y))	Initialization code size must be less than 64K and resides at upper most 64K of the 4GB memory space.

8.10. P6 FAMILY MICROCODE UPDATE FEATURE

P6 family processors have the capability to correct specific errata through the loading of an Intel-supplied data block. This data block is referred to as a *microcode update*. This chapter describes the underlying mechanisms the BIOS needs to provide in order to utilize this feature during system initialization. It also describes a specification that provides for incorporating future releases of the microcode update into a system BIOS.

Intel considers the combination of a particular silicon revision and the microcode update as the equivalent stepping of the processor. Intel does not validate processors without the microcode update loaded. Intel completes a full-stepping level validation and testing for new releases of microcode updates.

A microcode update is used to correct specific errata in the processor. The BIOS, which incorporates an update loader, is responsible for loading the appropriate update on all processors during system initialization (refer to Figure 8-7). There are effectively two steps to this process. The first is to incorporate the necessary microcode updates into the BIOS, the second is to actually load the appropriate microcode update into the processor.

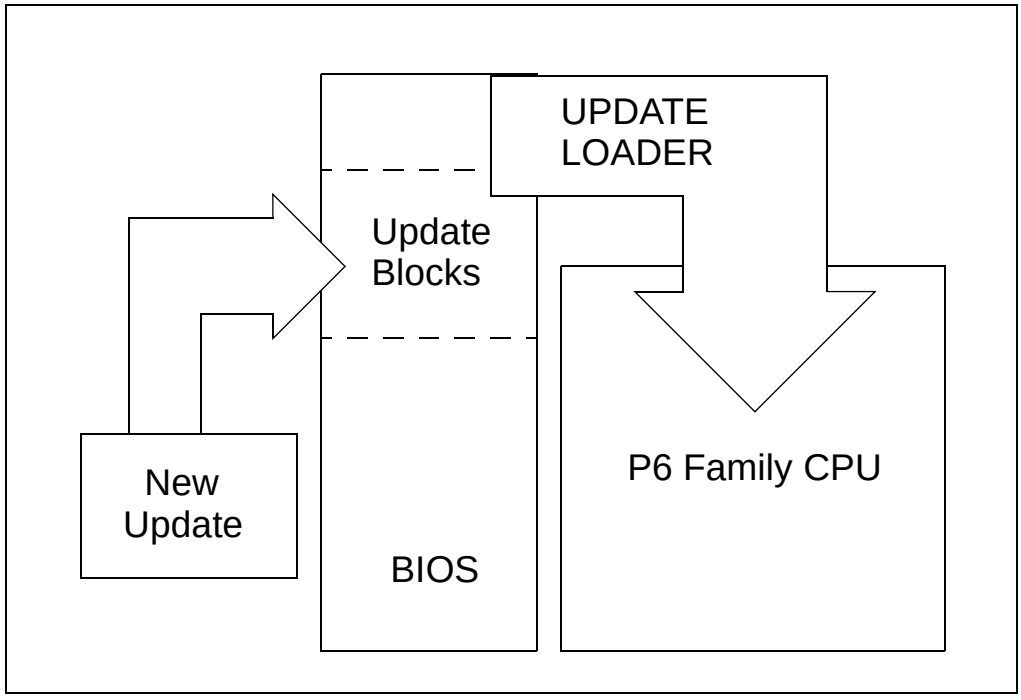


Figure 8-7. Integrating Processor Specific Updates

8.10.1. Microcode Update

A microcode update consists of an Intel-supplied binary that contains a descriptive header and data. No executable code resides within the update. This section describes the update and the structure of its data format.

Each microcode update is tailored for a particular stepping of a P6 family processor. It is designed such that a mismatch between a stepping of the processor and the update will result in a failure to load. Thus, a given microcode update is associated with a particular type, family, model, and stepping of the processor as returned by the CPUID instruction. In addition, the intended processor platform type must be determined to properly target the microcode update. The intended processor platform type is determined by reading a model-specific register MSR (17h) (refer to Table 8-6) within the P6 family processor. This is a 64-bit register that may be read using the RDMSR instruction (refer to Section 3.2., "Instruction Reference" Chapter 3, *Instruction Set Reference*, Volume 1 of the *Programmer's Reference Manua*l). The three *platform ID bits*, when read as a binary coded decimal (BCD) number indicate the bit position in the microcode update header's, *Processor Flags* field, that is associated with the installed processor.

Register Name:BBL_CR_OVRD
MSR Address:017h
Access:Read Only
BBL_CR_OVRD is a 64-bit register accessed only when referenced as a Qword through a RDMSR instruction.

Table 8-6. P6 Family Processor MSR Register Components

Bit	Descriptions
63:53	Reserved
52:50	Platform ID bits (RO). The field gives information concerning the intended platform for the processor. 52 51 50 0 0 0 Processor Flag 0 (See *Processor Flags* in Microcode Update Header) 0 0 1 Processor Flag 1 0 1 0 Processor Flag 2 0 1 1 Processor Flag 3 1 0 0 Processor Flag 4 1 0 1 Processor Flag 5 1 1 0 Processor Flag 6 1 1 1 Processor Flag 7
49:0	Reserved

The microcode update is a data block that is exactly 2048 bytes in length. The initial 48 bytes of the update contain a header with information used to identify the update. The update header and its reserved fields are interpreted by software based upon the header version. The initial version of the header is 00000001h. An encoding scheme also guards against tampering of the update data and provides a means for determining the authenticity of any given update. Table 8-7 defines each of the fields and Figure 8-8 shows the format of the microcode update data block.

Table 8-7. Microcode Update Encoding Format

Field Name	Offset (in bytes)	Length (in bytes)	Description
Header Version	0	4	Version number of the update header.
Update Revision	4	4	Unique version number for the update, the basis for the update signature provided by the processor to indicate the current update functioning within the processor. Used by the BIOS to authenticate the update and verify that it is loaded successfully by the processor. The value in this field cannot be used for processor stepping identification alone.
Date	8	4	Date of the update creation in binary format: mmddyyyy (e.g. 07/18/98 is 07181998h).
Processor	12	4	*Processor type*, *family*, *model*, and *stepping* of processor that requires this particular update revision (e.g., 00000650h). Each microcode update is designed specifically for a given *processor type*, *family*, *model*, and *stepping* of processor. The BIOS uses the Processor field in conjunction with the CPUID instruction to determine whether or not an update is appropriate to load on a processor. The information encoded within this field exactly corresponds to the bit representations returned by the CPUID instruction.
Checksum	16	4	Checksum of update data and header. Used to verify the integrity of the update header and data. Checksum is correct when the summation of the 512 double words of the update result in the value zero.
Loader Revision	20	4	Version number of the loader program needed to correctly load this update. The initial version is 00000001h.
Processor Flags	24	4	Platform type information is encoded in the lower 8 bits of this 4-byte field. Each bit represents a particular platform type for a given CPUID. The BIOS uses the Processor Flags field in conjunction with the platform ID bits in MSR (17h) to determine whether or not an update is appropriate to load on a processor.
Reserved	28	20	Reserved Fields for future expansion.
Update Data	48	2000	Update data.

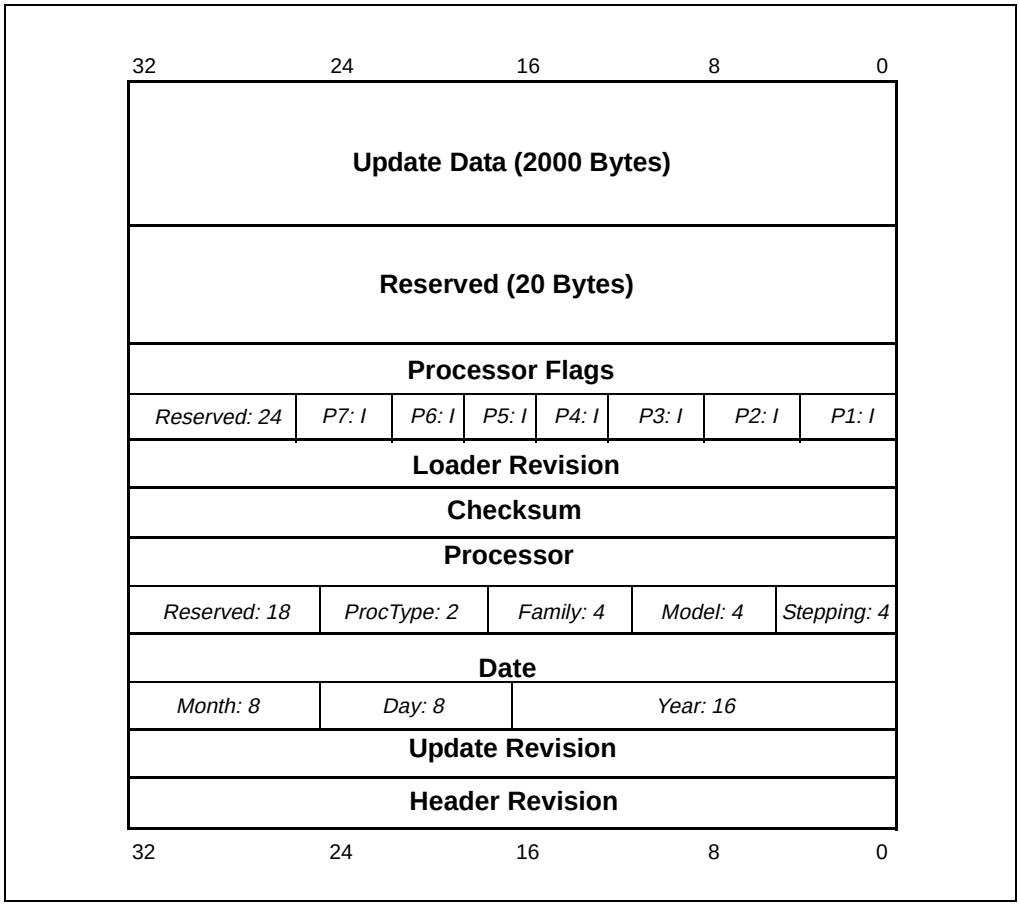


Figure 8-8. Format of the Microcode Update Data Block

8.10.2. Microcode Update Loader

This section describes the update loader used to load a microcode update into a P6 family processor. It also discusses the requirements placed upon the BIOS to ensure proper loading of an update.

The update loader contains the minimal instructions needed to load an update. The specific instruction sequence that is required to load an update is dependent upon the loader revision field contained within the update header. The revision of the update loader is expected to change very infrequently, potentially only when new processor models are introduced.

The code below represents the update loader with a loader revision of 00000001h:

```
mov     ecx,79h                 ; MSR to read in ECX
xor eax,eax             ; clear EAX
xor ebx,ebx             ; clear EBX
movax,cs                ; Segment of microcode update
shl eax,4
movbx,offset Update ; Offset of microcode update
addeax,ebx              ; Linear Address of Update in EAX
addeax,48d              ; Offset of the Update Data within the Update
xor edx,edx             ; Zero in EDX
WRMSR                   ; microcode update trigger
```

8.10.2.1. UPDATE LOADING PROCEDURE

The simple loader previously described assumes that *Update* is the address of a microcode update (header and data) embedded within the code segment of the BIOS. It also assumes that the processor is operating in real mode. The data may reside anywhere in memory that is accessible by the processor within its current operating mode (real, protected).

Before the BIOS executes the microcode update trigger (WRMSR) instruction the following must be true:

- EAX contains the linear address of the start of the update data
- EDX contains zero
- ECX contains 79h

Other requirements to keep in mind are:

- The microcode update must be loaded to the processor early on in the POST, and always prior to the initialization of the P6 family processors L2 cache controller.
- If the update is loaded while the processor is in real mode, then the update data may not cross a segment boundary.
- If the update is loaded while the processor is in real mode, then the update data may not exceed a segment limit.
- If paging is enabled, pages that are currently present must map the update data.
- The microcode update data does not require any particular byte or word boundary alignment.

8.10.2.2. HARD RESETS IN UPDATE LOADING

The effects of a loaded update are cleared from the processor upon a hard reset. Therefore, each time a hard reset is asserted during the BIOS POST, the update must be reloaded on all processors that observed the reset. The effects of a loaded update are, however, maintained across a processor INIT. There are no side effects caused by loading an update into a processor multiple times.

8.10.2.3. UPDATE IN A MULTIPROCESSOR SYSTEM

A multiprocessor (MP) system requires loading each processor with update data appropriate for its CPUID and platform ID bits. The BIOS is responsible for ensuring that this requirement is met, and that the loader is located in a module that is executed by all processors in the system. If a system design permits multiple steppings of P6 family processors to exist concurrently, then the BIOS must verify each individual processor against the update header information to ensure appropriate loading. Given these considerations, it is most practical to load the update during MP initialization.

8.10.2.4. UPDATE LOADER ENHANCEMENTS

The update loader presented in Section 8.10.2.1., "Update Loading Procedure" is a minimal implementation that can be enhanced to provide additional functionality and features. Some potential enhancements are described below:

- The BIOS can incorporate multiple updates to support multiple steppings of the P6 family processor. This feature provides for operating in a mixed stepping environment on an MP system and enables a user to upgrade to a later version of the processor. In this case, modify the loader to check the CPUID and platform ID bits of the processor that it is running on against the available headers before loading a particular update. The number of updates is only limited by the available space in the BIOS.
- A loader can load the update and test the processor to determine if the update was loaded correctly. This can be done as described in the Section 8.10.3., "Update Signature and Verification".
- A loader can verify the integrity of the update data by performing a checksum on the double words of the update summing to zero, and can reject the update.
- A loader can provide power-on messages indicating successful loading of an update.

8.10.3. Update Signature and Verification

The P6 family processor provides capabilities to verify the authenticity of a particular update and to identify the current update revision. This section describes the model-specific extensions of the processor that support this feature. The update verification method below assumes that the BIOS will only verify an update that is more recent than the revision currently loaded into the processor.

The CPUID instruction returns a value in a model specific register in addition to its usual register return values. The semantics of the CPUID instruction cause it to deposit an update ID value in the 64-bit model-specific register (MSR) at address 08Bh. If no update is present in the processor, the value in the MSR remains unmodified. Normally a zero value is preloaded into the MSR by software before executing the CPUID instruction. If the MSR still contains zero after executing CPUID, this indicates that no update is present.

The update ID value returned in the EDX register after a RDMSR instruction indicates the revision of the update loaded in the processor. This value, in combination with the normal CPUID

value returned in the EAX register, uniquely identifies a particular update. The signature ID can be directly compared with the update revision field in the microcode update header for verification of a correct update load. No consecutive updates released for a given stepping of the P6 family processor may share the same signature. Updates for different steppings are differentiated by the CPUID value.

8.10.3.1. DETERMINING THE SIGNATURE

An update that is successfully loaded into the processor provides a signature that matches the update revision of the currently functioning revision. This signature is available any time after the actual update has been loaded, and requesting this signature does not have any negative impact upon any currently loaded update. The procedure for determining this signature is:

```
mov ecx, 08Bh;Model Specific Register to Read in ECX
xor eax,eax ;clear EAX
xor edx,edx ;clear EDX
WRMSR      ;Load 0 to MSR at 8Bh
mov eax,1
CPUID
mov ecx, 08BH;Model Specific Register to Read
RDMSR      ;Read Model Specific Register
```

If there is an update currently active in the processor, its update revision is returned in the EDX register after the RDMSR instruction has completed.

8.10.3.2. AUTHENTICATING THE UPDATE

An update may be authenticated by the BIOS using the signature primitive, described above, with the following algorithm:

```
Z = Update revision from the update header to be authenticated;
X = Current Update Signature from MSR 8Bh;
If (Z > X) Then
    Load Update that is to be authenticated;
    Y = New Signature from MSR 8Bh;
    If (Z == Y) then Success
    Else Fail
Else Fail
```

The algorithm requires that the BIOS only authenticate updates that contain a numerically larger revision than the currently loaded revision, where Current Signature (X) < New Update Revision (Z). A processor with no update loaded should be considered to have a revision equal to zero. This authentication procedure relies upon the decoding provided by the processor to verify an update from a potentially hostile source. As an example, this mechanism in conjunction with other safeguards provides security for dynamically incorporating field updates into the BIOS.

8.10.4. P6 Family Processor Microcode Update Specifications

This section describes the interface that an application can use to dynamically integrate processor-specific updates into the system BIOS. In this discussion, the application is referred to as the *calling program* or *caller.*

The real mode INT15 call specification described here is an Intel extension to an OEM BIOS. This extension allows an application to read and modify the contents of the microcode update data in NVRAM. The update loader, which is part of the system BIOS, cannot be updated by the interface. All of the functions defined in the specification must be implemented for a system to be considered compliant with the specification. The INT15 functions are accessible only from real mode.

8.10.4.1. RESPONSIBILITIES OF THE BIOS

If a BIOS passes the presence test (INT 15h, AX=0D042h, BL=0h) it must implement all of the sub-functions defined in the INT 15h, AX= 0D042h specification. There are no optional functions. The BIOS must load the appropriate update for each processor during system initialization.

A header version of an update block containing the value 0FFFFFFFFh indicates that the update block is unused and available for storing a new update.

The BIOS is responsible for providing a 2048 byte region of non-volatile storage (NVRAM) for each potential processor stepping within a system. This storage unit is referred to as an *update block.* The BIOS for a single processor system need only provide one update block to store the microcode update data. The BIOS for a multiple processor capable system needs to provide one update block for each unique processor stepping supported by the OEM's system. The BIOS is responsible for managing the NVRAM update blocks. This includes garbage collection, such as removing update blocks that exist in NVRAM for which a corresponding processor does not exist in the system. This specification only provides the mechanism for ensuring security, the uniqueness of an entry, and that stale entries are not loaded. The actual update block management is implementation specific on a per-BIOS basis. As an example, the BIOS may use update blocks sequentially in ascending order with CPU signatures sorted versus the first available block. In addition, garbage collection may be implemented as a setup option to clear all NVRAM slots or as BIOS code that searches and eliminates unused entries during boot.

The following algorithm describes the steps performed during BIOS initialization used to load the updates into the processor(s). It assumes that the BIOS ensures that no update contained within NVRAM has a header version or loader version that does not match one currently supported by the BIOS and that the update block contains a correct checksum. It also assumes that the BIOS ensures that at most one update exists for each processor stepping and that older update revisions are not allowed to overwrite more recent ones. These requirements are checked by the BIOS during the execution of the write update function of this interface. The BIOS sequentially scans through all of the update blocks in NVRAM starting with index 0. The BIOS scans until it finds an update where the processor fields in the header match the family, model, and stepping as well as the platform ID bits of the current processor.

```
For each processor in the system {
Determine the ProcType, Family, Model and Stepping via CPUID;
Determine the Platform ID Bits by reading the BBL_CR_OVRD[52:50] MSR;
for (I = UpdateBlock 0, I < NumOfUpdates;  I++) {
    If ((UpdateHeader.Processor ==
         ProcType, Family, Model and Stepping) &&
       (UpdateHeader.ProcessorFlags == Platform ID Bits)) {
    Load UpdateHeader.UpdateData into the Processor;
    Verify that update was correctly loaded into the processor
    Go on to next processor
         Break;
    }
}
```

> Programmer's Note: The platform ID bits in the BBL_CR_OVRD MSR are encoded as a three-bit binary coded decimal field. The platform ID bits in the microcode update header are individually bit encoded. The algorithm must do a translation from one format to the other prior to doing the comparison.

When performing the INT 15h, 0D042h functions, the BIOS must assume that the caller has no knowledge about platform specific requirements. It is the responsibility of the BIOS calls to manage all chipset and platform specific prerequisites for managing the NVRAM device. When writing the update data via the write update sub-function, the BIOS must maintain implementation specific data requirements, such as the update of NVRAM checksum. The BIOS should also attempt to verify the success of write operations on the storage device used to record the update.

8.10.4.2. RESPONSIBILITIES OF THE CALLING PROGRAM

This section of the document lists the responsibilities of the calling program using the interface specifications to load microcode update(s) into BIOS NVRAM.

The calling program should call the INT 15h, 0D042h functions from a pure real mode program and should be executing on a system that is running in pure real mode. The caller should issue the presence test function (sub function 0) and verify the signature and return codes of that function. It is important that the calling program provides the required scratch RAM buffers for the BIOS and the proper stack size as specified in the interface definition.

The calling program should read any update data that already exists in the BIOS in order to make decisions about the appropriateness of loading the update. The BIOS refuses to overwrite a newer update with an older version. The update header contains information about version and processor specifics for the calling program to make an intelligent decision about loading.

There can be no ambiguous updates. The BIOS refuses to allow multiple updates for the same CPUID to exist at the same time. The BIOS also refuses to load an update for a processor that does not exist in the system.

The calling application should implement a verify function that is run after the update write function successfully completes. This function reads back the update and verifies that the BIOS

returned an image identical to the one that was written. The following pseudo-code represents a calling program.

INT 15 D042 Calling Program Pseudo-code

```
//
//    We must be in real mode
//
If the system is not in Real mode
then Exit
//
//    Detect the presence of Genuine Intel processor(s) that can be updated (CPUID)
//
If no Intel processors exist that can be updated
    then Exit
//
//    Detect the presence of the Intel microcode update extensions
//
If the BIOS fails the PresenceTest
then Exit
//
// If the APIC is enabled, see if any other processors are out there
//
Read APICBaseMSR
If APIC enabled {
    Send Broadcast Message to all processors except self via APIC;
    Have all processors execute CPUID and record Type, Family, Model, Stepping
    Have all processors read BBL_CR_OVRD[52:50] and record platform ID bits
    If current processor is not updatable
        then Exit
    }
//
// Determine the number of unique update slots needed for this system
//
NumSlots = 0;
For each processor {
    If ((this is a unique processor stepping) and
    (we have an update in the database for this processor)) {
        Checksum the update from the database;
        If Checksum fails
            then Exit;
        Increment NumSlots;
        }
    }
//
// Do we have enough update slots for all CPUs?
//
If there are more unique processor steppings than update slots provided by the BIOS
    then Exit
```

```
//
// Do we need any update slots at all?  If not, then we're all done
//
If (NumSlots == 0)
    then Exit

//
//    Record updates for processors in NVRAM.
//
For (I=0; I<NumSlots; I++) {
        //
        //    Load each Update
        //
    Issue the WriteUpdate function

    If (STORAGE_FULL) returned {
        Display Error -- BIOS is not managing NVRAM appropriately
        exit
        }
    If (INVALID_REVISION) returned {
        Display Message: More recent update already loaded in NVRAM for this stepping
        continue;
        }

    If any other error returned {
        Display Diagnostic
        exit
        }
        //
        //    Verify the update was loaded correctly
        //
    Issue the ReadUpdate function

    If an error occurred {
        Display Diagnostic
        exit
        }
        //
        //    Compare the Update read to that written
        //
        if (Update read != Update written) {
        Display Diagnostic
        exit
        }
    }
//
```

// Enable Update Loading, and inform user
//
Issue the *ControlUpdate* function with *Task=Enable*.

8.10.4.3. MICROCODE UPDATE FUNCTIONS

Table 8-8 defines the current P6 family Processor microcode update functions.

Table 8-8. Microcode Update Functions

Microcode Update Function	Function Number	Description	Required/Optional
Presence test	00h	Returns information about the supported functions.	Required
Write update data	01h	Writes one of the update data areas (slots).	Required
Update control	02h	Globally controls the loading of updates.	Required
Read update data	03h	Reads one of the update data areas (slots).	Required

8.10.4.4. INT 15H-BASED INTERFACE

Intel recommends that a BIOS interface be provided that allows additional microcode updates to be added to the system flash. The INT15 interface is an Intel-defined method for doing this.

The program that calls this interface is responsible for providing three 64-kilobyte RAM areas for BIOS use during calls to the read and write functions. These RAM scratch pads can be used by the BIOS for any purpose, but only for the duration of the function call. The calling routine places real mode segments pointing to the RAM blocks in the CX, DX and SI registers. Calls to functions in this interface must be made with a minimum of 32 kilobytes of stack available to the BIOS.

In general, each function returns with CF cleared and AH contains the returned status. The general return codes and other constant definitions are listed in Section 8.10.4.5., “Return Codes”.

The OEM Error (AL) is provided for the OEM to return additional error information specific to the platform. If the BIOS provides no additional information about the error, the OEM Error must be set to SUCCESS. The OEM Error field is undefined if AH contains either SUCCESS (00) or NOT_IMPLEMENTED (86h). In all other cases it must be set with either SUCCESS or a value meaningful to the OEM.

The following text details the functions provided by the INT15h-based interface.

Function 00h - Presence Test

This function verifies that the BIOS has implemented the required microcode update functions. Table 8-3 lists the parameters and return codes for the function.

Table 8-9. Parameters for the Presence Test

Input:		
AX	Function Code	0D042h
BL	Sub-function	00h - Presence Test
Output:		
CF	Carry Flag	Carry Set - Failure - AH Contains Status. Carry Clear - All return values are valid.
AH	Return Code	
AL	OEM Error	Additional OEM Information.
EBX	Signature Part 1	'INTE' - Part one of the signature.
ECX	Signature Part 2	'LPEP'- Part two of the signature.
EDX	Loader Version	Version number of the microcode update loader.
SI	Update Count	Number of update blocks the system can record in NVRAM.
Return Codes: (See Table 8-8 for code definitions)		
SUCCESS		Function completed successfully.
NOT_IMPLEMENTED		Function not implemented.

In order to assure that the BIOS function is present, the caller must verify the Carry Flag, the Return Code, and the 64-bit signature. Each update block is exactly 2048 bytes in length. The update count reflects the number of update blocks available for storage within non-volatile RAM. The update count must return with a value greater than or equal to the number of unique processor steppings currently installed within the system.

The loader version number refers to the revision of the update loader program that is included in the system BIOS image.

Function 01h - Write Microcode Update Data

This function integrates a new microcode update into the BIOS storage device. Table 8-4 lists the parameters and return codes for the function.

Table 8-10. Parameters for the Write Update Data Function

Input:		
AX	Function Code	0D042h
BL	Sub-function	01h - Write Update
ED:DI	Update Address	Real Mode pointer to the Intel Update structure. This buffer is 2048 bytes in length
CX	Scratch Pad1	Real Mode Segment address of 64 kilobytes of RAM Block.
DX	Scratch Pad2	Real Mode Segment address of 64 kilobytes of RAM Block.
SI	Scratch Pad3	Real Mode Segment address of 64 kilobytes of RAM Block.
SS:SP	Stack pointer	32 kilobytes of Stack Minimum.
Output:		
CF	Carry Flag	Carry Set - Failure - AH Contains Status. Carry Clear - All return values are valid.
AH	Return Code	Status of the Call
AL	OEM Error	Additional OEM Information.
Return Codes: (See Table 8-8 for code definitions)		
SUCCESS		Function completed successfully.
WRITE_FAILURE		A failure because of the inability to write the storage device.
ERASE_FAILURE		A failure because of the inability to erase the storage device.
READ_FAILURE		A failure because of the inability to read the storage device.
STORAGE_FULL		The BIOS non-volatile storage area is unable to accommodate the update because all available update blocks are filled with updates that are needed for processors in the system.
CPU_NOT_PRESENT		The processor stepping does not currently exist in the system.
INVALID_HEADER		The update header contains a header or loader version that is not recognized by the BIOS.
INVALID_HEADER_CS		The update does not checksum correctly.
SECURITY_FAILURE		The processor rejected the update.
INVALID_REVISION		The same or more recent revision of the update exists in the storage device.

The BIOS is responsible for selecting an appropriate update block in the non-volatile storage for storing the new update. This BIOS is also responsible for ensuring the integrity of the information provided by the caller, including authenticating the proposed update before incorporating it into storage.

Before writing the update block into NVRAM, the BIOS should ensure that the update structure meets the following criteria in the following order:

1. The update header version should be equal to an update header version recognized by the BIOS.
2. The update loader version in the update header should be equal to the update loader version contained within the BIOS image.
3. The update block should checksum to zero. This checksum is computed as a 32-bit summation of all 512 double words in the structure, including the header.

The BIOS selects an update block in non-volatile storage for storing the candidate update. The BIOS can select any available update block as long as it guarantees that only a single update exists for any given processor stepping in non-volatile storage. If the update block selected already contains an update, the following additional criteria apply to overwrite it:

- The processor signature in the proposed update should be equal to the processor signature in the header of the current update in NVRAM (CPUID + platform ID bits).
- The update revision in the proposed update should be greater than the update revision in the header of the current update in NVRAM.

If no unused update blocks are available and the above criteria are not met, the BIOS can overwrite an update block for a processor stepping that is no longer present in the system. This can be done by scanning the update blocks and comparing the processor steppings, identified in the MP Specification table, to the processor steppings that currently exist in the system.

Finally, before storing the proposed update into NVRAM, the BIOS should verify the authenticity of the update via the mechanism described in Section 8.10.2., “Microcode Update Loader”. This includes loading the update into the current processor, executing the CPUID instruction, reading MSR 08Bh, and comparing a calculated value with the update revision in the proposed update header for equality.

When performing the write update function, the BIOS should record the entire update, including the header and the update data. When writing an update, the original contents may be overwritten, assuming the above criteria have been met. It is the responsibility of the BIOS to ensure that more recent updates are not overwritten through the use of this BIOS call, and that only a single update exists within the NVRAM for any processor stepping.

Figure 8-9 shows the process the BIOS follows to choose an update block and ensure the integrity of the data when it stores the new microcode update.

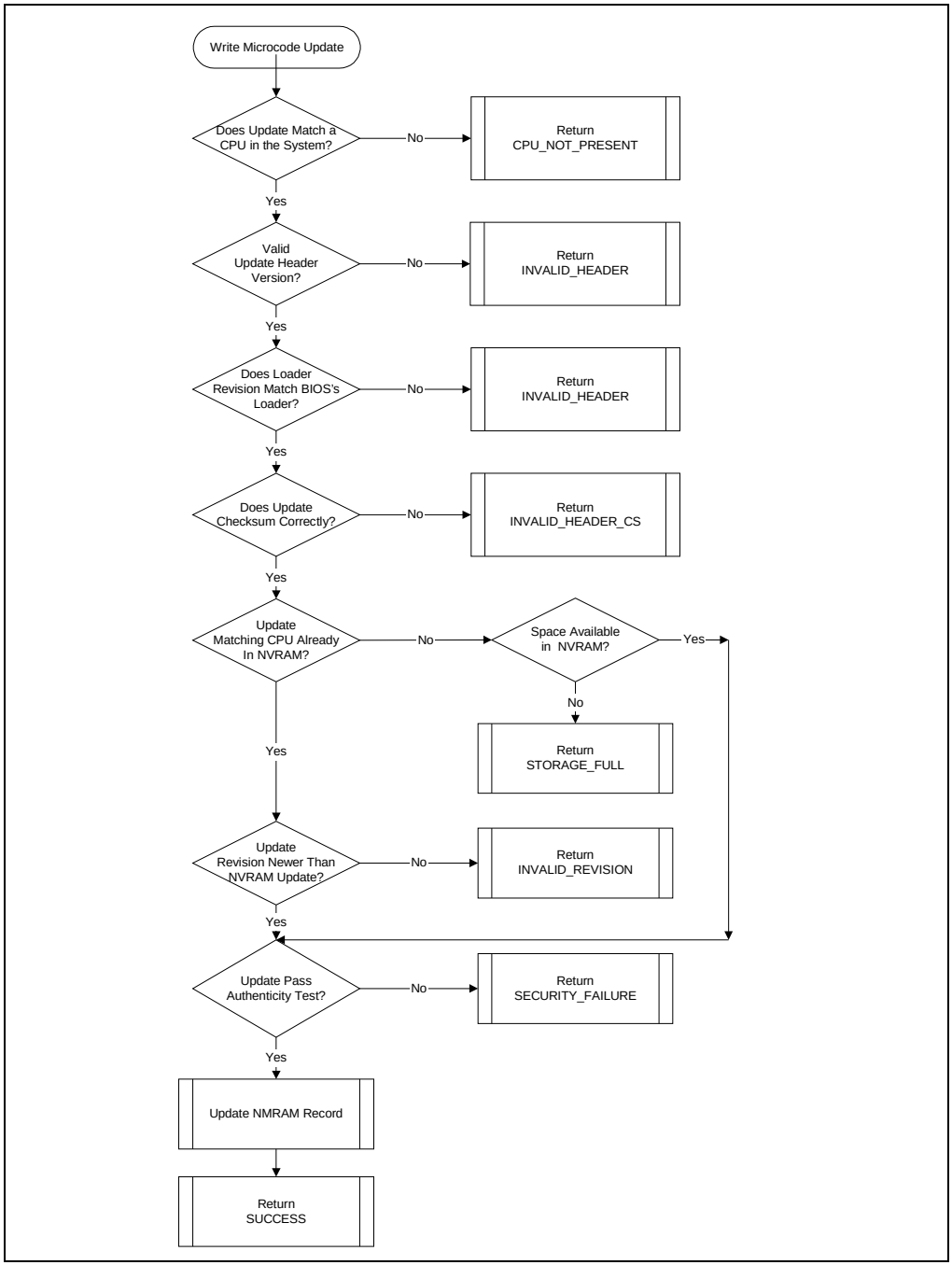


Figure 8-9. Write Operation Flow Chart

Function 02h - Microcode Update Control

This function enables loading of binary updates into the processor. Table 8-5 lists the parameters and return codes for the function.

Table 8-11. Parameters for the Control Update Sub-function

Input:		
AX	Function Code	0D042h
BL	Sub-function	02h - Control Update
BH	Task	See Description.
CX	Scratch Pad1	Real Mode Segment of 64 kilobytes of RAM Block.
DX	Scratch Pad2	Real Mode Segment of 64 kilobytes of RAM Block.
SI	Scratch Pad3	Real Mode Segment of 64 kilobytes of RAM Block.
SS:SP	Stack pointer	32 kilobytes of Stack Minimum.
Output:		
CF	Carry Flag	Carry Set - Failure - AH contains Status. Carry Clear - All return values are valid.
AH	Return Code	Status of the Call.
AL	OEM Error	Additional OEM Information.
BL	Update Status	Either Enable or Disable indicator.
Return Codes: (See Table 8-8 for code definitions)		
SUCCESS		Function completed successfully.
READ_FAILURE		A failure because of the inability to read the storage device.

This control is provided on a global basis for all updates and processors. The caller can determine the current status of update loading (enabled or disabled) without changing the state. The function does not allow the caller to disable loading of binary updates, as this poses a security risk.

The caller specifies the requested operation by placing one of the values from Table 8-6 in the BH register. After successfully completing this function the BL register contains either the enable or the disable designator. Note that if the function fails, the update status return value is undefined.

Table 8-12. Mnemonic Values

Mnemonic	Value	Meaning
Enable	1	Enable the Update loading at initialization time
Query	2	Determine the current state of the update control without changing its status.

The READ_FAILURE error code returned by this function has meaning only if the control function is implemented in the BIOS NVRAM. The state of this feature (enabled/disabled) can also be implemented using CMOS RAM bits where READ failure errors cannot occur.

Function 03h - Read Microcode Update Data

This function reads a currently installed microcode update from the BIOS storage into a caller-provided RAM buffer. Section 8-13, “Parameters for the Read Microcode Update Data Function” lists the parameters and return codes for the function.

Table 8-13. Parameters for the Read Microcode Update Data Function

Input:		
AX	Function Code	0D042h
BL	Sub-function	03h - Read Update
ES:DI	Buffer Address	Real Mode pointer to the Intel Update structure that will be written with the binary data.
ECX	Scratch Pad1	Real Mode Segment address of 64 kilobytes of RAM Block (lower 16 bits).
ECX	Scratch Pad2	Real Mode Segment address of 64 kilobytes of RAM Block (upper 16 bits).
DX	Scratch Pad3	Real Mode Segment address of 64 kilobytes of RAM Block.
SS:SP	Stack pointer	32 kilobytes of Stack Minimum.
SI	Update Number	The index number of the update block to be read. This value is zero based and must be less than the update count returned from the presence test function.
Output:		
CF	Carry Flag	Carry Set - Failure - AH contains Status.
Carry Clear - All return values are valid.		
AH	Return Code	Status of the Call.
AL	OEM Error	Additional OEM Information.
Return Codes: (See Table 8-8 for code definitions)		
SUCCESS		Function completed successfully.
READ_FAILURE		A failure because of the inability to read the storage device.
UPDATE_NUM_INVALID		Update number exceeds the maximum number of update blocks implemented by the BIOS.

The read function enables the caller to read any update data that already exists in a BIOS and make decisions about the addition of new updates. As a result of a successful call, the BIOS copies exactly 2048 bytes into the location pointed to by ES:DI, with the contents of the update block represented by update number.

An update block is considered unused and available for storing a new update if its header version contains the value 0FFFFFFFFh after return from this function call. The actual implementation of NVRAM storage management is not specified here and is BIOS dependent. As an example, the actual data value used to represent an empty block by the BIOS may be zero, rather than

0FFFFFFFh. The BIOS is responsible for translating this information into the header provided by this function.

8.10.4.5. RETURN CODES

After the call has been made, the return codes listed in Table 8-8 are available in the AH register.

Table 8-14. Return Code Definitions

Return Code	Value	Description
SUCCESS	00h	Function completed successfully
NOT_IMPLEMENTED	86h	Function not implemented
ERASE_FAILURE	90h	A failure because of the inability to erase the storage device
WRITE_FAILURE	91h	A failure because of the inability to write the storage device
READ_FAILURE	92h	A failure because of the inability to read the storage device
STORAGE_FULL	93h	The BIOS non-volatile storage area is unable to accommodate the update because all available update blocks are filled with updates that are needed for processors in the system
CPU_NOT_PRESENT	94h	The processor stepping does not currently exist in the system
INVALID_HEADER	95h	The update header contains a header or loader version that is not recognized by the BIOS
INVALID_HEADER_CS	96h	The update does not checksum correctly
SECURITY_FAILURE	97h	The update was rejected by the processor
INVALID_REVISION	98h	The same or more recent revision of the update exists in the storage device
UPDATE_NUM_INVALID	99h	The update number exceeds the maximum number of update blocks implemented by the BIOS

9

Memory Cache Control

CHAPTER 9
MEMORY CACHE CONTROL

This chapter describes the Intel Architecture's memory cache and cache control mechanisms, the TLBs, and the write buffer. It also describes the memory type range registers (MTRRs) found in the P6 family processors and how they are used to control caching of physical memory locations.

9.1. INTERNAL CACHES, TLBS, AND BUFFERS

The Intel Architecture supports caches, translation look aside buffers (TLBs), and write buffers for temporary on-chip (and external) storage of instructions and data (see Figure 9-1). Table 9-1 shows the characteristics of these caches and buffers for the P6 family, Pentium®, and Intel486™ processors. **The sizes and characteristics of these units are machine specific and may change in future versions of the processor.** The CPUID instruction returns the sizes and characteristics of the caches and buffers for the processor on which the instruction is executed. For more information, see "CPUID—CPU Identification" in Chapter 3 of the *Intel Architecture Software Developer's Manual, Volume 2*.

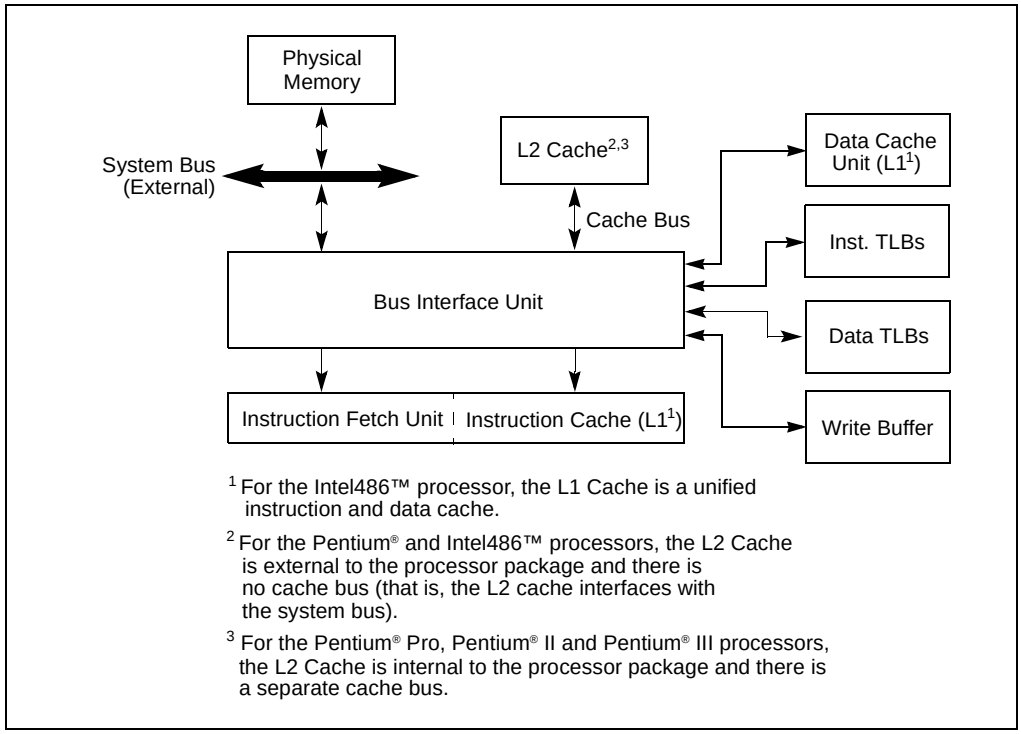


Figure 9-1. Intel Architecture Caches

The Intel Architecture defines two separate caches: the level 1 (L1) cache and the level 2 (L2) cache (see Figure 9-1). The L1 cache is closely coupled to the instruction fetch unit and execution units of the processor. For the Pentium® and P6 family processors, the L1 cache is divided into two sections: one dedicated to caching instructions and one to caching data. For the Intel486™ processor, the L1 cache is a unified instruction and data cache.

Table 9-1. Characteristics of the Caches, TLBs, and Write Buffer in Intel Architecture Processors

Cache or Buffer	Characteristics
L1 Instruction Cache[1]	- P6 family and Pentium® processors: 8 or 16 KBytes, 4-way set associative, 32-byte cache line size; 2-way set associative for earlier Pentium® processors. - Intel486™ processor: 8 or 16 KBytes, 4-way set associative, 16-byte cache line size, instruction and data cache combined.
L1 Data Cache[1]	- P6 family processors: 16 KBytes, 4-way set associative, 32-byte cache line size; 8 KBytes, 2-way set associative for earlier P6 family processors. - Pentium® processors: 16 KBytes, 4-way set associative, 32-byte cache line size; 8 KBytes, 2-way set associative for earlier Pentium® processors. - Intel486™ processor: (see L1 instruction cache).
L2 Unified Cache[2,3]	- P6 family processors: 128 KBytes, 256 KBytes, 512 KBytes, 1 MByte, or 2 MByte, 4-way set associative, 32-byte cache line size. - Pentium® processor: System specific, typically 256 or 512 KBytes, 4-way set associative, 32-byte cache line size. - Intel486™ processor: System specific.
Instruction TLB (4-KByte Pages)[1]	- P6 family processors: 32 entries, 4-way set associative. - Pentium® processor: 32 entries, 4-way set associative; fully set associative for Pentium® processors with MMX™ technology. - Intel486™ processor: 32 entries, 4-way set associative, instruction and data TLB combined.
Data TLB (4-KByte Pages)[1]	- Pentium® and P6 family processors: 64 entries, 4-way set associative; fully set associative for Pentium® processors with MMX™ technology. - Intel486™ processor: (see Instruction TLB).
Instruction TLB (Large Pages)	- P6 family processors: 2 entries, fully associative - Pentium® processor: Uses same TLB as used for 4-KByte pages. - Intel486™ processor: None (large pages not supported).
Data TLB (Large Pages)	- P6 family processors: 8 entries, 4-way set associative. - Pentium® processor: 8 entries, 4-way set associative; uses same TLB as used for 4-KByte pages in Pentium® processors with MMX™ technology. - Intel486™ processor: None (large pages not supported).
Write Buffer	- P6 family processors: 12 entries. - Pentium® processor: 2 buffers, 1 entry each (Pentium® processors with MMX™ technology have 4 buffers for 4 entries). - Intel486™ processor: 4 entries.

NOTES:

1. In the Intel486™ processor, the L1 cache is a unified instruction and data cache, and the TLB is a unified instruction and data TLB.
2. In the Intel486™ and Pentium® processors, the L2 cache is external to the processor package and optional.
3. In the Pentium® Pro, Pentium® II, and Pentium® III processors, the L2 cache is internal to the processor package.

The L2 cache is a unified cache for storage of both instructions and data. It is closely coupled to the L1 cache through the processor's cache bus (for the P6 family processors) or the system bus (for the Pentium® and Intel486™ processors).

The cache lines for the P6 family and Pentium® processors' L1 and L2 caches are 32 bytes wide. The processor always reads a cache line from system memory beginning on a 32-byte boundary. (A 32-byte aligned cache line begins at an address with its 5 least-significant bits clear.) A cache line can be filled from memory with a 4-transfer burst transaction. The caches do not support partially-filled cache lines, so caching even a single doubleword requires caching an entire line. (The cache line size for the Intel486™ processor is 16 bytes.)

The L1 and L2 caches are available in all execution modes. Using these caches greatly improves the performance of the processor both in single- and multiple-processor systems. Caching can also be used in system management mode (SMM); however, it must be handled carefully. For more information, see Section 12.4.2., "SMRAM Caching", in Chapter 12, *System Management Mode (SMM)*.

The TLBs store the most recently used page-directory and page-table entries. They speed up memory accesses when paging is enabled by reducing the number of memory accesses that are required to read the page tables stored in system memory. The TLBs are divided into four groups: instruction TLBs for 4-KByte pages, data TLBs for 4-KByte pages; instruction TLBs for large pages (2-MByte or 4-MByte pages), and data TLBs for large pages. (Only 4-KByte pages are supported for Intel386™ and Intel486™ processors.) The TLBs are normally active only in protected mode with paging enabled. When paging is disabled or the processor is in real-address mode, the TLBs maintain their contents until explicitly or implicitly flushed. For more information, see Section 9.10., "Invalidating the Translation Lookaside Buffers (TLBs)".

The write buffer is associated with the processors instruction execution units. It allows writes to system memory and/or the internal caches to be saved and in some cases combined to optimize the processor's bus accesses. The write buffer is always enabled in all execution modes.

The processor's caches are for the most part transparent to software. When enabled, instructions and data flow through these caches without the need for explicit software control. However, knowledge of the behavior of these caches may be useful in optimizing software performance. For example, knowledge of cache dimensions and replacement algorithms gives an indication of how large of a data structure can be operated on at once without causing cache thrashing.

In multiprocessor systems, maintenance of cache consistency may, in rare circumstances, require intervention by system software. For these rare cases, the processor provides privileged cache control instructions for use in flushing caches.

9.2. CACHING TERMINOLOGY

The Intel Architecture (beginning with the Pentium® processor) uses the MESI (modified, exclusive, shared, invalid) cache protocol to maintain consistency with internal caches and caches in other processors. For more information, see Section 9.4., "Cache Control Protocol". (The Intel486™ processor uses an implementation defined caching protocol that operates in a similar manner to the MESI protocol.)

When the processor recognizes that an operand being read from memory is cacheable, the processor reads an entire cache line into the appropriate cache (L1, L2, or both). This operation is called a **cache line fill**. If the memory location containing that operand is still cached the next time the processor attempts to access the operand, the processor can read the operand from the cache instead of going back to memory. This operation is called a **cache hit**.

When the processor attempts to write an operand to a cacheable area of memory, it first checks if a cache line for that memory location exists in the cache. If a valid cache line does exist, the processor (depending on the write policy currently in force) can write the operand into the cache instead of writing it out to system memory. This operation is called a **write hit**. If a write misses the cache (that is, a valid cache line is not present for the area of memory being written to), the processor performs a cache line fill, write allocation. Then it writes the operand into the cache line and (depending on the write policy currently in force) can also write it out to memory. If the operand is to be written out to memory, it is written first into the write buffer, and then written from the write buffer to memory when the system bus is available. (Note that for the Intel486™ and Pentium® processors, write misses do not result in a cache line fill; they always result in a write to memory. For these processors, only read misses result in cache line fills.)

When operating in a multiple-processor system, Intel Architecture processors (beginning with the Intel486™ processor) have the ability to **snoop** other processor's accesses to system memory and to their internal caches. They use this snooping ability to keep their internal caches consistent both with system memory and with the caches in other processors on the bus. For example, in the Pentium® and P6 family processors, if through snooping one processor detects that another processor intends to write to a memory location that it currently has cached in **shared state**, the snooping processor will invalidate its cache line forcing it to perform a cache line fill the next time it accesses the same memory location.

Beginning with the P6 family processors, if a processor detects (through snooping) that another processor is trying to access a memory location that it has modified in its cache, but has not yet written back to system memory, the snooping processor will signal the other processor (by means of the HITM# signal) that the cache line is held in modified state and will preform an implicit write-back of the modified data. The implicit write-back is transferred directly to the initial requesting processor and snooped by the memory controller to assure that system memory has been updated. Here, the processor with the valid data may pass the data to the other processors without actually writing it to system memory; however, it is the responsibility of the memory controller to snoop this operation and update memory.

9.3. METHODS OF CACHING AVAILABLE

The processor allows any area of system memory to be cached in the L1 and L2 caches. Within individual pages or regions of system memory, it also allows the type of caching (also called **memory type**) to be specified, using a variety of system flags and registers. For more information, see Section 9.5., "Cache Control". The caching methods currently defined for the Intel Architecture are as follows. (Table 9-2 lists which types of caching are available on specific Intel Architecture processors.)

- Uncacheable (UC)—System memory locations are not cached. All reads and writes appear on the system bus and are executed in program order, without reordering. No speculative

memory accesses, page-table walks, or prefetches of speculated branch targets are made. This type of cache-control is useful for memory-mapped I/O devices. When used with normal RAM, it greatly reduces processor performance.

Table 9-2. Methods of Caching Available in P6 Family, Pentium®, and Intel486™ Processors

Caching Method	P6 Family Processors	Pentium® Processor	Intel486™ Processor
Uncacheable (UC)	Yes	Yes	Yes
Write Combining (WC)	Yes[1]	No	No
Write Through (WT)	Yes	Yes[2]	Yes[2]
Write Back (WB)	Yes	Yes[2]	No
Write Protected (WP)	Yes[1]	No	No

NOTES:

1. Requires programming of MTRRs to implement.
2. Speculative reads not supported.

- Write Combining (WC)—System memory locations are not cached (as with uncacheable memory) and coherency is not enforced by the processor's bus coherency protocol. Speculative reads are allowed. Writes may be delayed and combined in the write buffer to reduce memory accesses. The writes may be delayed until the next occurrence of a buffer or processor serialization event, e.g., CPUID execution, a read or write to uncached memory, interrupt occurrence, LOCKed instruction execution, etc. if the WC buffer is partially filled. This type of cache-control is appropriate for video frame buffers, where the order of writes is unimportant as long as the writes update memory so they can be seen on the graphics display. See Section 9.3.1., "Buffering of Write Combining Memory Locations", for more information about caching the WC memory type. The preferred method is to use the new SFENCE (store fence) instruction introduced in the Pentium® III processor. The SFENCE instruction ensures weakly ordered writes are written to memory in order, i.e., it serializes only the store operations.

- Write-through (WT)—Writes and reads to and from system memory are cached. Reads come from cache lines on cache hits; read misses cause cache fills. Speculative reads are allowed. All writes are written to a cache line (when possible) and through to system memory. When writing through to memory, invalid cache lines are never filled, and valid cache lines are either filled or invalidated. Write combining is allowed. This type of cache-control is appropriate for frame buffers or when there are devices on the system bus that access system memory, but do not perform snooping of memory accesses. It enforces coherency between caches in the processors and system memory.

- Write-back (WB)—Writes and reads to and from system memory are cached. Reads come from cache lines on cache hits; read misses cause cache fills. Speculative reads are allowed. Write misses cause cache line fills (in the P6 family processors), and writes are performed entirely in the cache, when possible. Write combining is allowed. The write-back memory type reduces bus traffic by eliminating many unnecessary writes to system memory. Writes to a cache line are not immediately forwarded to system memory; instead,

they are accumulated in the cache. The modified cache lines are written to system memory later, when a write-back operation is performed. Write-back operations are triggered when cache lines need to be deallocated, such as when new cache lines are being allocated in a cache that is already full. They also are triggered by the mechanisms used to maintain cache consistency. This type of cache-control provides the best performance, but it requires that all devices that access system memory on the system bus be able to snoop memory accesses to insure system memory and cache coherency.

- Write protected (WP)—Reads come from cache lines when possible, and read misses cause cache fills. Writes are propagated to the system bus and cause corresponding cache lines on all processors on the bus to be invalidated. Speculative reads are allowed. This caching option is available in the P6 family processors by programming the MTRRs (seeTable 9-5).

9.3.1. Buffering of Write Combining Memory Locations

Writes to WC memory are not cached in the typical sense of the word cached. They are retained in an internal buffer that is separate from the internal L1 and L2 caches. The buffer is not snooped and thus does not provide data coherency. The write buffering is done to allow software a small window of time to supply more modified data to the buffer while remaining as nonintrusive to software as possible. The size of the buffer is not architecturally defined, However the Pentium® Pro and Pentium® II processors implement a single concurrent 32-byte buffer. The size of this buffer was chosen by implementation convenience. In the Pentium® III processor there are 4 write combine buffers. The size is the same as for the Pentium® Pro and Pentium® II processors. Buffer size and quantity changes may occur in future generations of the P6 family processors and so software should not rely upon the current 32-byte WC buffer size or the existence of a single concurrent buffer or the 4 buffers in the Penitum III processor. The WC buffering of writes also causes data to be collapsed (for example, multiple writes to the same location will leave the last data written in the location and the other writes will be lost).

For the Pentium® Pro and Pentium® II processors, once software writes to a region of memory that is addressed outside of the range of the current 32-byte buffer, the data in the buffer is automatically forwarded to the system bus and written to memory. Therefore software that writes more than one 32-byte buffers worth of data will ensure that the data from the first buffers address range is forwarded to memory. The last buffer written in the sequence may be delayed by the processor longer unless the buffers are deliberately emptied. Software developers should not rely on the fact that there is only one active WC buffer at a time. Software developers creating software that is sensitive to data being delayed **must** deliberately empty the WC buffers and not assume the hardware will.

Once the processor has started to move data into the WC buffer, it will make a bus transaction style decision based on how much of the buffer contains valid data. If the buffer is full (for example, all 32 bytes are valid) the processor will execute a burst write transaction on the bus that will result in all 32 bytes being transmitted on the data bus in a single transaction. If one or more of the WC buffer's bytes are invalid (for example, have not been written by software) then the processor will start to move the data to memory using "partial write" transactions on the system bus. There will be a maximum of 4 partial write transactions for one WC buffer of data sent to memory. Once data in the WC buffer has started to be propagated to memory, the data is

subject to the weak ordering semantics of its definition. Ordering is not maintained between the successive allocation/deallocation of WC buffers (for example, writes to WC buffer 1 followed by writes to WC buffer 2 may appear as buffer 2 followed by buffer 1 on the system bus. When a WC buffer is propagated to memory as partial writes there is no guaranteed ordering between successive partial writes (for example, a partial write for chunk 2 may appear on the bus before the partial write for chunk 1 or vice versa). The only elements of WC propagation to the system bus that are guaranteed are those provided by transaction atomicity. For the P6 family processors, a completely full WC buffer will always be propagated as a single burst transaction using any of the chunk orders. In a WC buffer propagation where the data will be propagated as partials, all data contained in the same chunk (0 mod 8 aligned) will be propagated simultaneously.

9.3.2. Choosing a Memory Type

The simplest system memory model does not use memory-mapped I/O with read or write side effects, does not include a frame buffer, and uses the write-back memory type for all memory. An I/O agent can perform direct memory access (DMA) to write-back memory and the cache protocol maintains cache coherency.

A system can use uncacheable memory for other memory-mapped I/O, and should always use uncacheable memory for memory-mapped I/O with read side effects.

Dual-ported memory can be considered a write side effect, making relatively prompt writes desirable, because those writes cannot be observed at the other port until they reach the memory agent. A system can use uncacheable, write-through, or write-combining memory for frame buffers or dual-ported memory that contains pixel values displayed on a screen. Frame buffer memory is typically large (a few megabytes) and is usually written more than it is read by the processor. Using uncacheable memory for a frame buffer generates very large amounts of bus traffic, because operations on the entire buffer are implemented using partial writes rather than line writes. Using write-through memory for a frame buffer can displace almost all other useful cached lines in the processor's L2 cache and L1 data cache. Therefore, systems should use write-combining memory for frame buffers whenever possible.

Software can use page-level cache control, to assign appropriate effective memory types when software will not access data structures in ways that benefit from write-back caching. For example, software may read a large data structure once and not access the structure again until the structure is rewritten by another agent. Such a large data structure should be marked as uncacheable, or reading it will evict cached lines that the processor will be referencing again. A similar example would be a write-only data structure that is written to (to export the data to another agent), but never read by software. Such a structure can be marked as uncacheable, because software never reads the values that it writes (though as uncacheable memory, it will be written using partial writes, while as write-back memory, it will be written using line writes, which may not occur until the other agent reads the structure and triggers implicit write-backs).

On the Pentium® III processor, new capabilities exist that may allow the programmer to perform similar functions with the prefetch and streaming store instructions. For more information on these instructions, see Section 3.2., "Instruction Reference" in Chapter 3, *Instruction Set Reference*.

9.4. CACHE CONTROL PROTOCOL

The following section describes the cache control protocol currently defined for the Intel Architecture processors. This protocol is used by the P6 family and Pentium® processors. The Intel486™ processor uses an implementation defined protocol that does not support the MESI four-state protocol, but instead uses a two-state protocol with valid and invalid states defined.

In the L1 data cache and the P6 family processors' L2 cache, the MESI (modified, exclusive, shared, invalid) cache protocol maintains consistency with caches of other processors. The L1 data cache and the L2 cache has two MESI status flags per cache line. Each line can thus be marked as being in one of the states defined in Table 9-3. In general, the operation of the MESI protocol is transparent to programs.

The L1 instruction cache implements only the "SI" part of the MESI protocol, because the instruction cache is not writable. The instruction cache monitors changes in the data cache to maintain consistency between the caches when instructions are modified. See Section 9.7., "Self-Modifying Code", for more information on the implications of caching instructions.

Table 9-3. MESI Cache Line States

Cache Line State	M (Modified)	E (Exclusive)	S (Shared)	I (Invalid)
This cache line is valid?	Yes	Yes	Yes	No
The memory copy is…	…out of date	…valid	…valid	—
Copies exist in caches of other processors?	No	No	Maybe	Maybe
A write to this line …	…does not go to bus	…does not go to bus	…causes the processor to gain exclusive ownership of the line	…goes directly to bus

9.5. CACHE CONTROL

The current Intel Architecture provides the following cache-control mechanisms for use in enabling caching and/or restricting caching to various pages or regions in memory (see Figure 9-2):

- CD flag, bit 30 of control register CR0—Controls caching of system memory locations. For more information, see Section 2.5., "Control Registers", in Chapter 2, *System Architecture Overview*. If the CD flag is clear, caching is enabled for the whole of system memory, but may be restricted for individual pages or regions of memory by other cache-control mechanisms. When the CD flag is set, caching is restricted in the L1 and L2 caches for the P6 family processors and prevented for the Pentium® and Intel486™ processors (see note below). With the CD flag set, however, the caches will still respond to snoop traffic. Caches should be explicitly flushed to insure memory coherency. For highest processor performance, both the CD and the NW flags in control register CR0 should be cleared. Table 9-4 shows the interaction of the CD and NW flags.

NOTE

The effect of setting the CD flag is somewhat different for the P6 family, Pentium®, and Intel486™ processors (see Table 9-4). To insure memory coherency after the CD flag is set, the caches should be explicitly flushed. For more information, see Section 9.5.2., “Preventing Caching”. Setting the CD flag for the P6 family processors modifies cache line fill and update behaviour. Also for the P6 family processors, setting the CD flag does not force strict ordering of memory accesses unless the MTRRs are disabled and/or all memory is referenced as uncached. For more information, see Section 7.2.4., “Strengthening or Weakening the Memory Ordering Model”, in Chapter 7, *Multiple-Processor Management*.

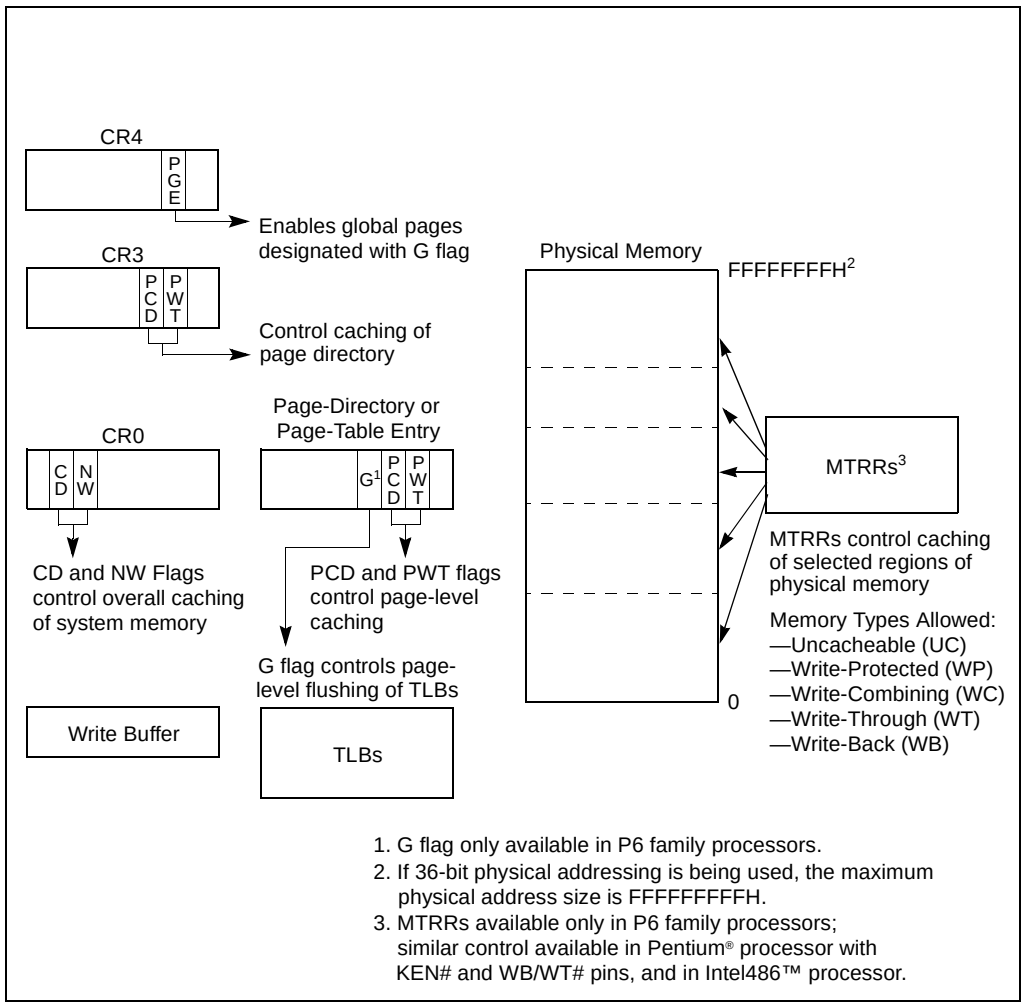


Figure 9-2. Cache-Control Mechanisms Available in the Intel Architecture Processors

Table 9-4. Cache Operating Modes

CD	NW	Caching and Read/Write Policy	L1	L2[1]
0	0	Normal highest performance cache operation.		
		- Read hits access the cache; read misses may cause replacement.	Yes	Yes
		- Write hits update the cache.	Yes	Yes
		- (Pentium® and P6 family processors.) Only writes to shared lines and write misses update system memory.	Yes	Yes
		- (P6 family processors.) Write misses cause cache line fills; write hits can change shared lines to exclusive under control of the MTRRs	Yes	Yes
		- (Pentium® processor.) Write misses do not cause cache line fills; write hits can change shared lines to exclusive under control of WB/WT#.	Yes	
		- (Intel486™ processor.) All writes update system memory; write misses do not cause cache line fills.	Yes	
		- Invalidation is allowed.	Yes	Yes
		- External snoop traffic is supported.	Yes	Yes
0	1	Invalid setting. A general-protection exception (#GP) with an error code of 0 is generated.	NA	NA
1	0	Memory coherency is maintained.		
		- Read hits access the cache; read misses do not cause replacement.	Yes	Yes
		- Write hits update the cache.	Yes	Yes
		- (Pentium® and P6 family processors.) Only writes to shared lines and write misses update system memory.	Yes	Yes
		- (Intel486™ processor.) All writes update system memory	Yes	
		- (Pentium® processor.) Write hits can change shared lines to exclusive under control of the WB/WT#.	Yes	
		- (P6 family processors.) Strict memory ordering is not enforced unless the MTRRs are disabled and/or all memory is referenced as uncached. For more information, see Section 7.2.4., “Strengthening or Weakening the Memory Ordering Model”.	Yes	Yes
		- Invalidation is allowed.	Yes	Yes
		- External snoop traffic is supported.	Yes	Yes
1	1	Memory coherency is not maintained. This is the state of the processor after a power up or reset.		
		- Read hits access the cache; read misses do not cause replacement.	Yes	Yes
		- Write hits update the cache.	Yes	Yes
		- (Pentium® and P6 family processors.) Write hits change exclusive lines to modified.	Yes	Yes
		- (Pentium® and P6 family processors.) Shared lines remain shared after write hit.	Yes	Yes
		- Write misses access memory.	Yes	Yes
		- (P6 family processors.) Strict memory ordering is not enforced unless the MTRRs are disabled and/or all memory is referenced as uncached. For more information, see Section 7.2.4., “Strengthening or Weakening the Memory Ordering Model”.	Yes	Yes
		- Invalidation is inhibited when snooping; but is allowed with INVD and WBINVD instructions.	Yes No	Yes Yes
		- External snoop traffic is supported.		

NOTE:

1. The P6 family processors are the only Intel Architecture processors that contain an integrated L2 cache. The L2 column in this table is definitive for the P6 family processors. It is intended to represent what could be implemented in a Pentium® processor based system with a platform specific write-back L2 cache.

- NW flag, bit 29 of control register CR0—Controls the write policy for system memory locations. For more information, see Section 2.5., “Control Registers”, in Chapter 2, *System Architecture Overview*. If the NW and CD flags are clear, write-back is enabled for the whole of system memory (write-through for the Intel486™ processor), but may be restricted for individual pages or regions of memory by other cache-control mechanisms. Table 9-4 shows how the other combinations of CD and NW flags affects caching.

NOTE

For the Pentium® processor, when the L1 cache is disabled (the CD and NW flags in control register CR0 are set), external snoops are accepted in DP (dual-processor) systems and inhibited in uniprocessor systems. When snoops are inhibited, address parity is not checked and APCHK# is not asserted for a corrupt address; however, when snoops are accepted, address parity is checked and APCHK# is asserted for corrupt addresses.

- PCD flag in the page-directory and page-table entries—Controls caching for individual page tables and pages, respectively. For more information, see Section 3.6.4., “Page-Directory and Page-Table Entries”, in Chapter 3, *Protected-Mode Memory Management*. This flag only has effect when paging is enabled and the CD flag in control register CR0 is clear. The PCD flag enables caching of the page table or page when clear and prevents caching when set.
- PWT flag in the page-directory and page-table entries—Controls the write policy for individual page tables and pages, respectively. For more information, see Section 3.6.4., “Page-Directory and Page-Table Entries”, in Chapter 3, *Protected-Mode Memory Management*. This flag only has effect when paging is enabled and the NW flag in control register CR0 is clear. The PWT flag enables write-back caching of the page table or page when clear and write-through caching when set.
- PCD and PWT flags in control register CR3. Control the global caching and write policy for the page directory. For more information, see Section 2.5., “Control Registers”, in Chapter 2, *System Architecture Overview*. The PCD flag enables caching of the page directory when clear and prevents caching when set. The PWT flag enables write-back caching of the page directory when clear and write-through caching when set. These flags do not affect the caching and write policy for individual page tables. These flags only have effect when paging is enabled and the CD flag in control register CR0 is clear.
- G (global) flag in the page-directory and page-table entries (introduced to the Intel Architecture in the P6 family processors)—Controls the flushing of TLB entries for individual pages. See Section 3.7., “Translation Lookaside Buffers (TLBs)”, in Chapter 3, *Protected-Mode Memory Management*, for more information about this flag.
- PGE (page global enable) flag in control register CR4—Enables the establishment of global pages with the G flag. See Section 3.7., “Translation Lookaside Buffers (TLBs)”, in Chapter 3, *Protected-Mode Memory Management*, for more information about this flag.
- Memory type range registers (MTRRs) (introduced in the P6 family processors)—Control the type of caching used in specific regions of physical memory. Any of the caching types described in Section 9.3., “Methods of Caching Available”, can be selected. See Section

9.12., “Memory Type Range Registers (MTRRs)”, for a detailed description of the MTRRs.

- KEN# and WB/WT# pins on Pentium® processor and KEN# pin alone on the Intel486™ processor—These pins allow external hardware to control the caching method used for specific areas of memory. They perform similar (but not identical) functions to the MTRRs in the P6 family processors.
- PCD and PWT pins on the Pentium® and Intel486™ processors—These pins (which are associated with the PCD and PWT flags in control register CR3 and in the page-directory and page-table entries) permit caching in an external L2 cache to be controlled on a page-by-page basis, consistent with the control exercised on the L1 cache of these processors. The P6 family processors do not provide these pins because the L2 cache in internal to the chip package.

9.5.1. Precedence of Cache Controls (P6 Family Processor)

In the P6 family processors, the cache control flags and MTRRs operate hierarchically for restricting caching. That is, if the CD flag is set, caching is prevented globally (see Table 9-4). If the CD flag is clear, either the PCD flags and/or the MTRRs can be used to restrict caching. If there is an overlap of page-level caching control and MTRR caching control, the mechanism that prevents caching has precedence. For example, if an MTRR makes a region of system memory uncachable, a PCD flag cannot be used to enable caching for a page in that region. The converse is also true; that is, if the PCD flag is set, an MTRR cannot be used to make a region of system memory cacheable.

In cases where there is a overlap in the assignment of the write-back and write-through caching policies to a page and a region of memory, the write-through policy takes precedence. The write-combining policy (which can only be assigned through an MTRR) takes precedence over either write-through or write-back.

Table 9-5 describes the mapping from MTRR memory types and page-level caching attributes to effective memory types, when normal caching is in effect (the CD and NW flags in control register CR0 are clear). Combinations that appear in gray are implementation-defined and may be implemented differently on future Intel Architecture processors. System designers are encouraged to avoid these implementation-defined combinations.

When normal caching is in effect, the effective memory type is determined using the following rules:

1. If the PCD and PWT attributes for the page are both 0, then the effective memory type is identical to the MTRR-defined memory type.
2. If the PCD flag is set, then the effective memory type is UC.
3. If the PCD flag is clear and the PWT flag is set, the effective memory type is WT for the WB memory type and the MTRR-defined memory type for all other memory types.
4. Setting the PCD and PWT flags to opposite values is considered model-specific for the WP and WC memory types and architecturally-defined for the WB, WT, and UC memory types.

Table 9-5. Effective Memory Type Depending on MTRR, PCD, and PWT Settings

MTRR Memory Type	PCD Value	PWT Value	Effective Memory Type
UC	X	X	UC
WC	0	0	WC
	0	1	WC
	1	0	WC
	1	1	UC
WT	0	X	WT
	1	X	UC
WP	0	0	WP
	0	1	WP
	1	0	WC
	1	1	UC
WB	0	0	WB
	0	1	WT
	1	X	UC

NOTE:

This table assumes that the CD and NW flags in register CR0 are set to 0. The effective memory types in the grey areas are implementation defined and may be different in future Intel Architecture processors.

9.5.2. Preventing Caching

To prevent the L1 and L2 caches from performing caching operations after they have been enabled and have received cache fills, perform the following steps:

1. Enter the no-fill cache mode. (Set the CD flag in control register CR0 to 1 and the NW flag to 0.
2. Flush all caches using the WBINVD instruction.
3. Disable the MTRRs and set the default memory type to uncached or set all MTRRs for the uncached memory type. For more information, see the discussion of the TYPE field and the E flag in Section 9.12.2.1., “MTRRdefType Register”.

The caches must be flushed when the CD flag is cleared to insure system memory coherency. If the caches are not flushed in step 2, cache hits on reads will still occur and data will be read from valid cache lines.

9.6. CACHE MANAGEMENT INSTRUCTIONS

The INVD and WBINVD instructions are used to invalidate the contents of the L1 and L2 caches. The INVD instruction invalidates all internal cache entries, then generates a special-function bus cycle that indicates that external caches also should be invalidated. The INVD instruction should be used with care. It does not force a write-back of modified cache lines; therefore, data stored in the caches and not written back to system memory will be lost. Unless there is a specific requirement or benefit to invalidating the caches without writing back the modified lines (such as, during testing or fault recovery where cache coherency with main memory is not a concern), software should use the WBINVD instruction.

The WBINVD instruction first writes back any modified lines in all the internal caches, then invalidates the contents of both L1 and L2 caches. It ensures that cache coherency with main memory is maintained regardless of the write policy in effect (that is, write-through or write-back). Following this operation, the WBINVD instruction generates one (P6 family processors) or two (Pentium® and Intel486™ processors) special-function bus cycles to indicate to external cache controllers that write-back of modified data followed by invalidation of external caches should occur.

9.7. SELF-MODIFYING CODE

A write to a memory location in a code segment that is currently cached in the processor causes the associated cache line (or lines) to be invalidated. This check is based on the physical address of the instruction. In addition, the P6 family and Pentium® processors check whether a write to a code segment may modify an instruction that has been prefetched for execution. If the write affects a prefetched instruction, the prefetch queue is invalidated. This latter check is based on the linear address of the instruction.

In practice, the check on linear addresses should not create compatibility problems among Intel Architecture processors. Applications that include self-modifying code use the same linear address for modifying and fetching the instruction. Systems software, such as a debugger, that might possibly modify an instruction using a different linear address than that used to fetch the instruction, will execute a serializing operation, such as a CPUID instruction, before the modified instruction is executed, which will automatically resynchronize the instruction cache and prefetch queue. See Section 7.1.3., “Handling Self- and Cross-Modifying Code”, in Chapter 7, *Multiple-Processor Management*, for more information about the use of self-modifying code.

For Intel486™ processors, a write to an instruction in the cache will modify it in both the cache and memory, but if the instruction was prefetched before the write, the old version of the instruction could be the one executed. To prevent the old instruction from being executed, flush the instruction prefetch unit by coding a jump instruction immediately after any write that modifies an instruction.

9.8. IMPLICIT CACHING (P6 FAMILY PROCESSORS)

Implicit caching occurs when a memory element is made potentially cacheable, although the element may never have been accessed in the normal von Neumann sequence. Implicit caching occurs on the P6 family processors due to aggressive prefetching, branch prediction, and TLB miss handling. Implicit caching is an extension of the behavior of existing Intel386™, Intel486™, and Pentium® processor systems, since software running on these processor families also has not been able to deterministically predict the behavior of instruction prefetch.

To avoid problems related to implicit caching, the operating system must explicitly invalidate the cache when changes are made to cacheable data that the cache coherency mechanism does not automatically handle. This includes writes to dual-ported or physically aliased memory boards that are not detected by the snooping mechanisms of the processor, and changes to page-table entries in memory.

The code in Example 9-1 shows the effect of implicit caching on page-table entries. The linear address F000H points to physical location B000H (the page-table entry for F000H contains the value B000H), and the page-table entry for linear address F000 is PTE_F000.

Example 9-1. Effect of Implicit Caching on Page-Table Entries

```
mov EAX, CR3       ; Invalidate the TLB
mov CR3, EAX       ; by copying CR3 to itself
mov PTE_F000, A000H; Change F000H to point to A000H
mov EBX, [F000H];
```

Because of speculative execution in the P6 family processors, the last MOV instruction performed would place the value at physical location B000H into EBX, rather than the value at the new physical address A000H. This situation is remedied by placing a TLB invalidation between the load and the store.

9.9. EXPLICIT CACHING

The Pentium® III processor introduced a new instruction designed to provide some control over caching of data. The prefetch instruction is a “hint” to the processor that the data requested by the prefetch instruction should be read into cache, even though it is not needed yet. The processor assumes it will be needed soon.

Explicit caching occurs when the application program executes a prefetch instruction. The programmer must be judicious in the use of the prefetch instruction. Overuse can lead to resource conflicts and hence reduce the performance of an application. For more detailed information on the proper use of the prefetch instruction, refer to Chapter 6, *“Optimizing Cache Utilization for Pentium® III Processors”*, in the *Intel Architecture Optimization Reference Manual* (Order Number 245127-001).

Prefetch can be used to read data into the cache prior to the application actually requiring it. This helps to reduce the long latency typically associated with reading data from memory and causing the processor to “stall”. It is important to remember that prefetch is only a hint to the processor

to fetch the data now or as soon as possible. It will be used soon. The prefetch instruction has different variations that allow the programmer to control into which cache level the data will be read. For more information on the variations of the prefetch instruction refer to Section 9.5.3.1., "Cacheability Hint Instructions", Chapter 9, *Programming with the Streaming SIMD Extensions*, if the *Intel Architecture Software Developer's Manual, Volume 2*.

9.10. INVALIDATING THE TRANSLATION LOOKASIDE BUFFERS (TLBS)

The processor updates its address translation caches (TLBs) transparently to software. Several mechanisms are available, however, that allow software and hardware to invalidate the TLBs either explicitly or as a side effect of another operation.

The INVLPG instruction invalidates the TLB for a specific page. This instruction is the most efficient in cases where software only needs to invalidate a specific page, because it improves performance over invalidating the whole TLB. This instruction is not affected by the state of the G flag in a page-directory or page-table entry.

The following operations invalidate all TLB entries except global entries. (A global entry is one for which the G (global) flag is set in its corresponding page-directory or page-table entry. The global flag was introduced into the Intel Architecture in the P6 family processors, see Section 9.5., "Cache Control".)

- Writing to control register CR3.
- A task switch that changes control register CR3.

The following operations invalidate all TLB entries, irrespective of the setting of the G flag:

- Asserting or de-asserting the FLUSH# pin.
- (P6 family processors only.) Writing to an MTRR (with a WRMSR instruction).
- Writing to control register CR0 to modify the PG or PE flag.
- (P6 family processors only.) Writing to control register CR4 to modify the PSE, PGE, or PAE flag.

See Section 3.7., "Translation Lookaside Buffers (TLBs)", in Chapter 3, *Protected-Mode Memory Management*, for additional information about the TLBs.

9.11. WRITE BUFFER

Intel Architecture processors temporarily store each write (store) to memory in a write buffer. The write buffer improves processor performance by allowing the processor to continue executing instructions without having to wait until a write to memory and/or to a cache is complete. It also allows writes to be delayed for more efficient use of memory-access bus cycles.

In general, the existence of the write buffer is transparent to software, even in systems that use multiple processors. The processor ensures that write operations are always carried out in program order. It also insures that the contents of the write buffer are always drained to memory in the following situations:

- When an exception or interrupt is generated.
- (P6 family processors only.) When a serializing instruction is executed.
- When an I/O instruction is executed.
- When a LOCK operation is performed.
- (P6 family processors only.) When a BINIT operation is performed.
- (Pentium® III processors only.) When using SFENCE to order stores.

The discussion of write ordering in Section 7.2., “Memory Ordering”, in Chapter 7, *Multiple-Processor Management*, gives a detailed description of the operation of the write buffer.

9.12. MEMORY TYPE RANGE REGISTERS (MTRRS)

The following section pertains only to the P6 family processors.

The memory type range registers (MTRRs) provide a mechanism for associating the memory types with physical-address ranges in system memory. For more information, see Section 9.3., “Methods of Caching Available”. They allow the processor to optimize operations for different types of memory such as RAM, ROM, frame-buffer memory, and memory-mapped I/O devices. They also simplify system hardware design by eliminating the memory control pins used for this function on earlier Intel Architecture processors and the external logic needed to drive them.

The MTRR mechanism allows up to 96 memory ranges to be defined in physical memory, and it defines a set of model-specific registers (MSRs) for specifying the type of memory that is contained in each range. Table 9-6 shows the memory types that can be specified and their properties; Figure 9-3 shows the mapping of physical memory with MTRRs. See Section 9.3., “Methods of Caching Available”, for a more detailed description of each memory type.

Following a hardware reset, a P6 family processor disables all the fixed and variable MTRRs, which in effect makes all of physical memory uncachable. Initialization software should then set the MTRRs to a specific, system-defined memory map. Typically, the BIOS (basic input/output system) software configures the MTRRs. The operating system or executive is then free to modify the memory map using the normal page-level cacheability attributes.

In a multiprocessor system, different P6 family processors MUST use the identical MTRR memory map so that software has a consistent view of memory, independent of the processor executing a program.

Table 9-6. MTRR Memory Types and Their Properties

Mnemonic	Encoding in MTRR	Cacheable in L1 and L2 Caches	Writeback Cacheable	Allows Speculative Reads	Memory Ordering Model
Uncacheable (UC)	0	No	No	No	Strong Ordering
Write Combining (WC)	1	No	No	Yes	Weak Ordering
Write-through (WT)	4	Yes	No	Yes	Speculative Processor Ordering
Write-protected (WP)	5	Yes for reads, no for writes	No	Yes	Speculative Processor Ordering
Writeback (WB)	6	Yes	Yes	Yes	Speculative Processor Ordering
Reserved Encodings*	2, 3, 7 through 255				

NOTE:

* Using these encoding result in a general-protection exception (#GP) being generated.

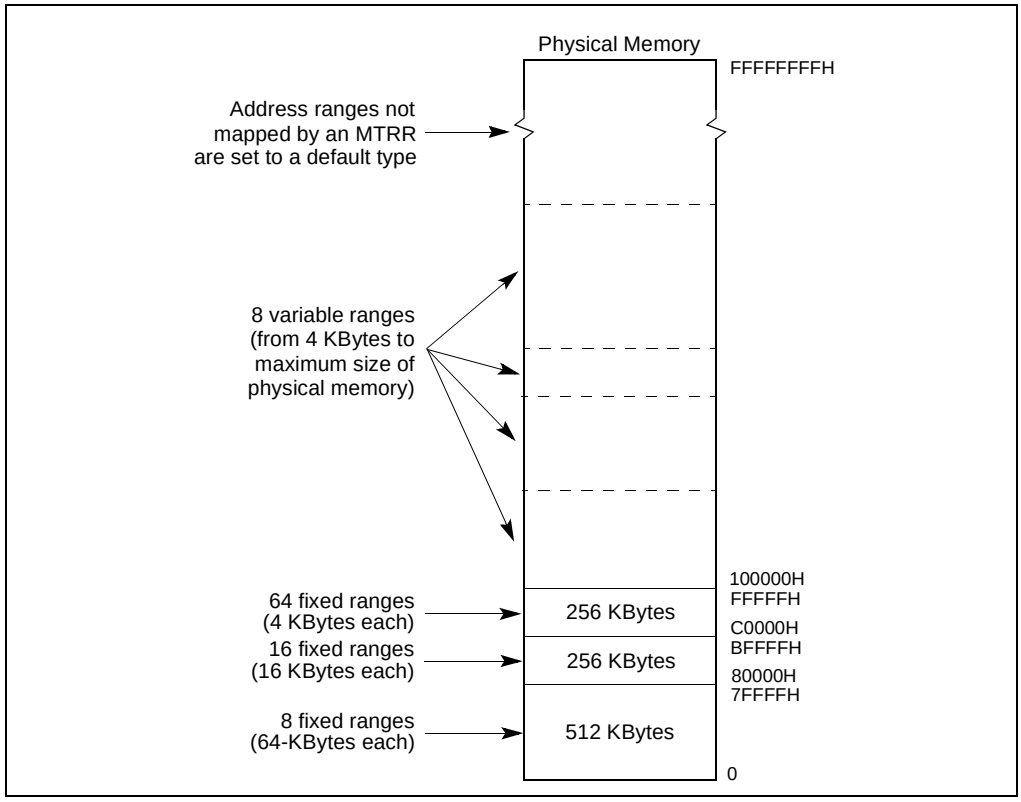


Figure 9-3. Mapping Physical Memory With MTRRs

9.12.1. MTRR Feature Identification

The availability of the MTRR feature is model-specific. Software can determine if MTRRs are supported on a processor by executing the CPUID instruction and reading the state of the MTRR flag (bit 12) in the feature information register (EDX).

If the MTRR flag is set (indicating that the processor implements MTRRs), additional information about MTRRs can be obtained from the 64-bit MTRRcap register. The MTRRcap register is a read-only MSR that can be read with the RDMSR instruction. Figure 9-4 shows the contents of the MTRRcap register. The functions of the flags and field in this register are as follows:

VCNT (variable range registers count) field, bits 0 through 7

Indicates the number of variable ranges implemented on the processor. The P6 family processors have eight pairs of MTRRs for setting up eight variable ranges.

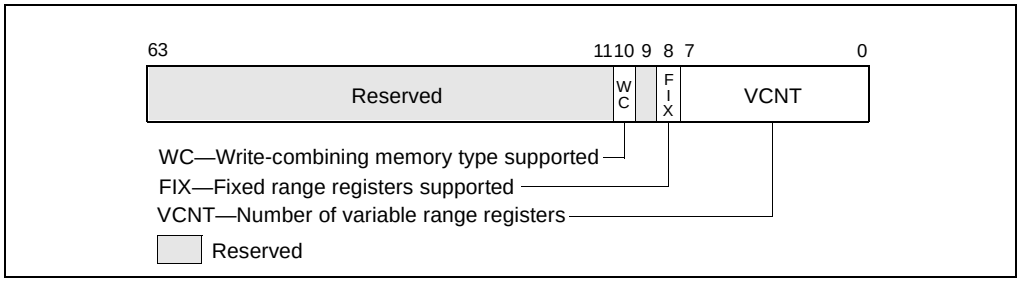


Figure 9-4. MTRRcap Register

FIX (fixed range registers supported) flag, bit 8
Fixed range MTRRs (MTRRfix64K_00000 through MTRRfix4K_0F8000) are supported when set; no fixed range registers are supported when clear.

WC (write combining) flag, bit 10
The write-combining (WC) memory type is supported when set; the WC type is not supported when clear.

Bit 9 and bits 11 through 63 in the MTRRcap register are reserved. If software attempts to write to the MTRRcap registers, a general-protection exception (#GP) is generated.

For the P6 family processors, the MTRRcap register always contains the value 508H.

9.12.2. Setting Memory Ranges with MTRRs

The memory ranges and the types of memory specified in each range are set by three groups of registers: the MTRRdefType register, the fixed-range MTRRs, and the variable range MTRRs. These registers can be read and written to using the RDMSR and WRMSR instructions, respectively. The MTRRcap register indicates the availability of these registers on the processor. For more information, see Section 9.12.1., “MTRR Feature Identification”.

9.12.2.1. MTRRDEFTYPE REGISTER

The MTRRdefType register (see Figure 9-4) sets the default properties of the regions of physical memory that are not encompassed by MTRRs. For more information, see Section 9.4., “Cache Control Protocol”. The functions of the flags and field in this register are as follows:

Type field, bits 0 through 7
Indicates the default memory type used for those physical memory address ranges that do not have a memory type specified for them by an MTRR. See Table 9-6 for the encoding of this field. If the MTRRs are disabled, this field defines the memory type for all of physical memory. The legal values for this field are 0, 1, 4, 5, and 6. All other values result in a general-protection exception (#GP) being generated.

Intel recommends the use of the UC (uncached) memory type for all physical memory addresses where memory does not exist. To assign the UC type to nonexistent memory locations, it can either be specified as the default type in the Type field or be explicitly assigned with the fixed and variable MTRRs.

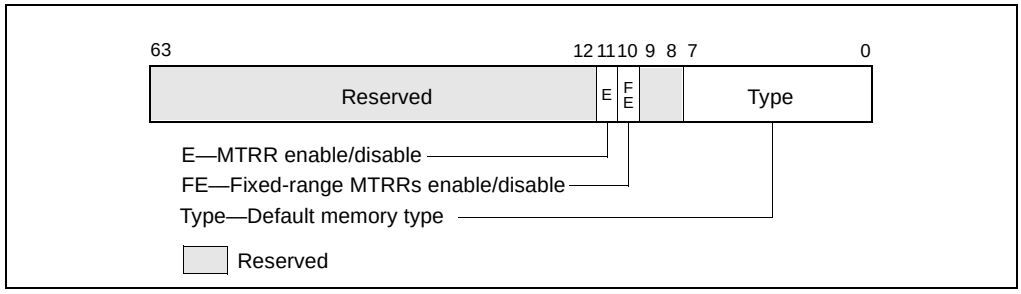


Figure 9-5. MTRRdefType Register

FE (fixed MTRRs enabled) flag, bit 10

Fixed-range MTRRs are enabled when set; fixed-range MTRRs are disabled when clear. When the fixed-range MTRRs are enabled, they take priority over the variable-range MTRRs when overlaps in ranges occur. If the fixed-range MTRRs are disabled, the variable-range MTRRs can still be used and can map the range ordinarily covered by the fixed-range MTRRs.

E (MTRRs enabled) flag, bit 11

MTRRs are enabled when set; all MTRRs are disabled when clear, and the UC memory type is applied to all of physical memory. When this flag is set, the FE flag can disable the fixed-range MTRRs; when the flag is clear, the FE flag has no affect. When the E flag is set, the type specified in the default memory type field is used for areas of memory not already mapped by either a fixed or variable MTRR.

Bits 8 and 9, and bits 12 through 63, in the MTRRdefType register are reserved; the processor generates a general-protection exception (#GP) if software attempts to write nonzero values to them.

9.12.2.2. FIXED RANGE MTRRS

The fixed memory ranges are mapped with 8 fixed-range registers of 64 bits each. Each of these registers is divided into 8-bit fields that are used to specify the memory type for each of the sub-ranges the register controls. Table 9-7 shows the relationship between the fixed physical-address ranges and the corresponding fields of the fixed-range MTRRs; Table 9-6 shows the encoding of these field:

- **Register MTRRfix64K_00000.** Maps the 512-KByte address range from 0H to 7FFFFH. This range is divided into eight 64-KByte sub-ranges.

- **Registers MTRRfix16K_80000 and MTRRfix16K_A0000.** Maps the two 128-KByte address ranges from 80000H to BFFFFH. This range is divided into sixteen 16-KByte sub-ranges, 8 ranges per register.
- **Registers MTRRfix4K_C0000. and MTRRfix4K_F8000.** Maps eight 32-KByte address ranges from C0000H to FFFFFH. This range is divided into sixty-four 4-KByte sub-ranges, 8 ranges per register.

See the *Pentium® Pro BIOS Writer's Guide* for examples of assigning memory types with fixed-range MTRRs.

Table 9-7. Address Mapping for Fixed-Range MTRRs

Address Range (hexadecimal)								Register
63 56	55 48	47 40	39 32	31 24	23 16	15 8	7 0	
70000-7FFFF	60000-6FFFF	50000-5FFFF	40000-4FFFF	30000-3FFFF	20000-2FFFF	10000-1FFFF	00000-0FFFF	MTRRfix64K_00000
9C000 9FFFF	98000-98FFF	94000-97FFF	90000-93FFF	8C000-8FFFF	88000-8BFFF	84000-87FFF	80000-83FFF	MTRRfix16K_80000
BC000 BFFFF	B8000-BBFFF	B4000-B7FFF	B0000-B3FFF	AC000-AFFFF	A8000-ABFFF	A4000-A7FFF	A0000-A3FFF	MTRRfix16K_A0000
C7000 C7FFF	C6000-C6FFF	C5000-C5FFF	C4000-C4FFF	C3000-C3FFF	C2000-C2FFF	C1000-C1FFF	C0000-C0FFF	MTRRfix4K_C0000
CF000 CFFFF	CE000-CEFFF	CD000-CDFFF	CC000-CCFFF	CB000-CBFFF	CA000-CAFFF	C9000-C9FFF	C8000-C8FFF	MTRRfix4K_C8000
D7000 D7FFF	D6000-D6FFF	D5000-D5FFF	D4000-D4FFF	D3000-D3FFF	D2000-D2FFF	D1000-D1FFF	D0000-D0FFF	MTRRfix4K_D0000
DF000 DFFFF	DE000-DEFFF	DD000-DDFFF	DC000-DCFFF	DB000-DBFFF	DA000-DAFFF	D9000-D9FFF	D8000-D8FFF	MTRRfix4K_D8000
E7000 E7FFF	E6000-E6FFF	E5000-E5FFF	E4000-E4FFF	E3000-E3FFF	E2000-E2FFF	E1000-E1FFF	E0000-E0FFF	MTRRfix4K_E0000
EF000 EFFFF	EE000-EEFFF	ED000-EDFFF	EC000-ECFFF	EB000-EBFFF	EA000-EAFFF	E9000-E9FFF	E8000-E8FFF	MTRRfix4K_E8000
F7000 F7FFF	F6000-F6FFF	F5000-F5FFF	F4000-F4FFF	F3000-F3FFF	F2000-F2FFF	F1000-F1FFF	F0000-F0FFF	MTRRfix4K_F0000
FF000 FFFFF	FE000-FEFFF	FD000-FDFFF	FC000-FCFFF	FB000-FBFFF	FA000-FAFFF	F9000-F9FFF	F8000-F8FFF	MTRRfix4K_F8000

9.12.2.3. VARIABLE RANGE MTRRS

The P6 family processors permit software to specify the memory type for eight variable-size address ranges, using a pair of MTRRs for each range. The first of each pair (MTRRphysBase*n*) defines the base address and memory type for the range, and the second (MTRRphysMask*n*) contains a mask that is used to determine the address range. The "*n*" suffix indicates registers pairs 0 through 7. Figure 9-6 shows flags and fields in these registers. The functions of the flags and fields in these registers are as follows:

Type field, bits 0 through 7
Specifies the memory type for the range. See Table 9-6 for the encoding of this field.

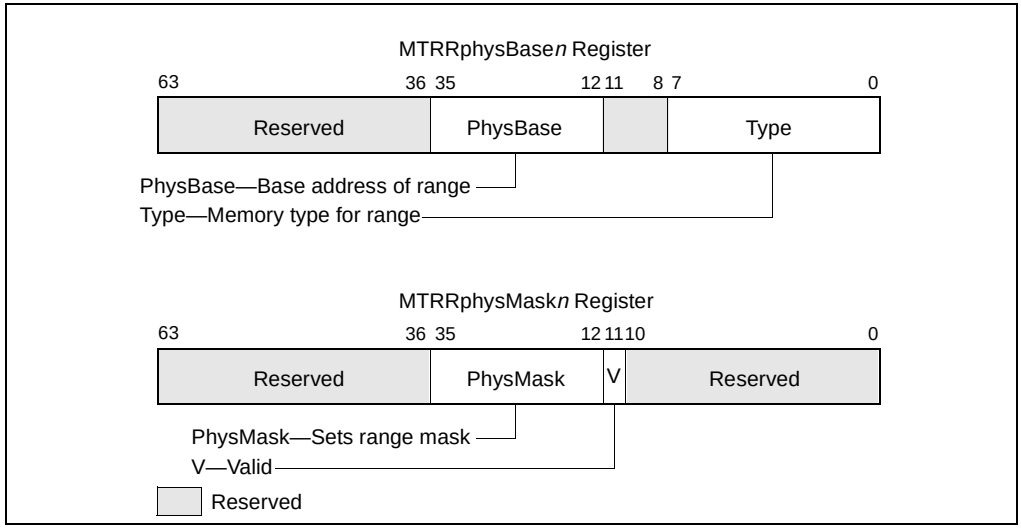


Figure 9-6. MTRRphysBase*n* and MTRRphysMaskn Variable-Range Register Pair

PhysBase field, bits 12 through 35
Specifies the base address of the address range. This 24-bit value is extended by 12 bits at the low end to form the base address, which automatically aligns the address on a 4-KByte boundary.

PhysMask field, bits 12 through 35
Specifies a 24-bit mask that determines the range of the region being mapped, according to the following relationship:

Address_Within_Range AND PhysMask = PhysBase AND PhysMask

This 24-bit value is extended by 12 bits at the low end to form the mask value. See Section 9.12.3., “Example Base and Mask Calculations”, for more information and some examples of base address and mask computations.

V (valid) flag, bit 11
Enables the register pair when set; disables register pair when clear.

All other bits in the MTRRphysBase*n* and MTRRphysMask*n* registers are reserved; the processor generates a general-protection exception (#GP) if software attempts to write to them.

Overlapping variable MTRR ranges are not supported generically. However, two variable ranges are allowed to overlap, if the following conditions are present:

- If both of them are UC (uncached).

- If one range is of type UC and the other is of type WB (write back).

In both cases above, the effective type for the overlapping region is UC. The processor's behavior is undefined for all other cases of overlapping variable ranges.

A variable range can overlap a fixed range (provided the fixed range MTRR's are enabled). Here, the memory type specified in the fixed range register overrides the one specified in variable-range register pair.

NOTE

Some mask values can result in discontinuous ranges. In a discontinuous range, the area not mapped by the mask value is set to the default memory type. Intel does not encourage the use of discontinuous ranges, because they could require physical memory to be present throughout the entire 4-GByte physical memory map. If memory is not provided for the complete memory map, the behaviour of the processor is undefined.

9.12.3. Example Base and Mask Calculations

The base and mask values entered into the variable-range MTRR pairs are 24-bit values that the processor extends to 36-bits. For example, to enter a base address of 2 MBytes (200000H) to the MTRRphysBase3 register, the 12 least-significant bits are truncated and the value 000200H is entered into the PhysBase field. The same operation must be performed on mask values. For instance, to map the address range from 200000H to 3FFFFFH (2 MBytes to 4 MBytes), a mask value of FFFE00000H is required. Here again, the 12 least-significant bits of this mask value are truncated, so that the value entered in the PhysMask field of the MTRRphysMask3 register is FFFE00H. This mask is chosen so that when any address in the 200000H to 3FFFFFH range is ANDed with the mask value it will return the same value as when the base address is ANDed with the mask value (which is 200000H).

To map the address range from 400000H 7FFFFFH (4 MBytes to 8 MBytes), a base value of 000400H is entered in the PhysBase field and a mask value of FFFC00H is entered in the PhysMask field.

Here is a real-life example of setting up the MTRRs for an entire system. Assume that the system has the following characteristics:

- 96 MBytes of system memory is mapped as write-back memory (WB) for highest system performance.
- A custom 4-MByte I/O card is mapped to uncached memory (UC) at a base address of 64 MBytes. This restriction forces the 96 MBytes of system memory to be addressed from 0 to 64 MBytes and from 68 MBytes to 100 MBytes, leaving a 4-MByte hole for the I/O card.
- An 8-MByte graphics card is mapped to write-combining memory (WC) beginning at address A0000000H.
- The BIOS area from 15 MBytes to 16 MBytes is mapped to UC memory.

The following settings for the MTRRs will yield the proper mapping of the physical address space for this system configuration. The x0_0x notation is used below to add clarity to the large numbers represented.

MTRRPhysBase0 = 0000_0000_0000_0006h
MTRRPhysMask0 = 0000_000F_FC00_0800h Caches 0-64 MB as WB cache type.
MTRRPhysBase1 = 0000_0000_0400_0006h
MTRRPhysMask1 = 0000_000F_FE00_0800h Caches 64-96 MB as WB cache type.
MTRRPhysBase2 = 0000_0000_0600_0006h
MTRRPhysMask2 = 0000_000F_FFC0_0800h Caches 96-100 MB as WB cache type.
MTRRPhysBase3 = 0000_0000_0400_0000h
MTRRPhysMask3 = 0000_000F_FFC0_0800h Caches 64-68 MB as UC cache type.
MTRRPhysBase4 = 0000_0000_00F0_0000h
MTRRPhysMask4 = 0000_000F_FFF0_0800h Caches 15-16 MB as UC cache type
MTRRPhysBase5 = 0000_0000_A000_0001h
MTRRPhysMask5 = 0000_000F_FF80_0800h Cache A0000000h-A0800000 as WC type.

This MTRR setup uses the ability to overlap any two memory ranges (as long as the ranges are mapped to WB and UC memory types) to minimize the number of MTRR registers that are required to configure the memory environment. This setup also fulfills the requirement that two register pairs are left for operating system usage.

9.12.4. Range Size and Alignment Requirement

The range that is to be mapped to a variable-range MTRR must meet the following “power of 2” size and alignment rules:

1. The minimum range size is 4 KBytes, and the base address of this range must be on at least a 4-KByte boundary.
2. For ranges greater than 4 KBytes, each range must be of length 2^n and its base address must be aligned on a 2^n boundary, where *n* is a value equal to or greater than 12. The base-address alignment value cannot be less than its length. For example, an 8-KByte range cannot be aligned on a 4-KByte boundary. It must be aligned on at least an 8-KByte boundary.

9.12.4.1. MTRR PRECEDENCES

If the MTRRs are not enabled (by setting the E flag in the MTRRdefType register), then all memory accesses are of the UC memory type. If the MTRRs are enabled, then the memory type used for a memory access is determined as follows:

1. If the physical address falls within the first 1 MByte of physical memory and fixed MTRRs are enabled, the processor uses the memory type stored for the appropriate fixed-range MTRR.

2. Otherwise, the processor attempts to match the physical address with a memory type range set with a pair of variable-range MTRRs:
   a. If one variable memory range matches, the processor uses the memory type stored in the MTRRphysBase*n* register for that range.
   b. If two or more variable memory ranges match and the memory types are identical, then that memory type is used.
   c. If two or more variable memory ranges match and one of the memory types is UC, the UC memory type used.
   d. If two or more variable memory ranges match and the memory types are WT and WB, the WT memory type is used.
   e. If two or more variable memory ranges match and the memory types are other than UC and WB, the behaviour of the processor is undefined.
3. If no fixed or variable memory range matches, the processor uses the default memory type.

9.12.5. MTRR Initialization

On a hardware reset, a P6 family processor clears the valid flags in the variable-range MTRRs and clears the E flag in the MTRRdefType register to disable all MTRRs. All other bits in the MTRRs are undefined. Prior to initializing the MTRRs, software (normally the system BIOS) must initialize all fixed-range and variable-range MTRR registers fields to 0. Software can then initialize the MTRRs according to the types of memory known to it, including memory on devices that it auto-configures. This initialization is expected to occur prior to booting the operating system.

See Section 9.12.8., “Multiple-Processor Considerations”, for information on initializing MTRRs in multiple-processor systems.

9.12.6. Remapping Memory Types

A system designer may re-map memory types to tune performance or because a future processor may not implement all memory types supported by the P6 family processors. The following rules support coherent memory-type re-mappings:

1. A memory type should not be mapped into another memory type that has a weaker memory ordering model. For example, the uncacheable type cannot be mapped into any other type, and the write-back, write-through, and write-protected types cannot be mapped into the weakly ordered write-combining type.
2. A memory type that does not delay writes should not be mapped into a memory type that does delay writes, because applications of such a memory type may rely on its write-through behavior. Accordingly, the write-back type cannot be mapped into the write-through type.

3. A memory type that views write data as not necessarily stored and read back by a subsequent read, such as the write-protected type, can only be mapped to another type with the same behaviour (and there are no others for the P6 family processors) or to the uncacheable type.

In many specific cases, a system designer can have additional information about how a memory type is used, allowing additional mappings. For example, write-through memory with no associated write side effects can be mapped into write-back memory.

9.12.7. MTRR Maintenance Programming Interface

The operating system maintains the MTRRs after booting and sets up or changes the memory types for memory-mapped devices. The operating system should provide a driver and application programming interface (API) to access and set the MTRRs. The function calls MemTypeGet() and MemTypeSet() define this interface.

9.12.7.1. MEMTYPEGET() FUNCTION

The MemTypeGet() function returns the memory type of the physical memory range specified by the parameters base and size. The base address is the starting physical address and the size is the number of bytes for the memory range. The function automatically aligns the base address and size to 4-KByte boundaries. Pseudocode for the MemTypeGet() function is given in Example 9-2.

Example 9-2. MemTypeGet() Pseudocode

```
#define MIXED_TYPES -1     /* 0 < MIXED_TYPES || MIXED_TYPES > 256 */

IF CPU_FEATURES.MTRR /* processor supports MTRRs */
    THEN
        Align BASE and SIZE to 4-KByte boundary;
        IF (BASE + SIZE) wrap 64-GByte address space
            THEN return INVALID;
        FI;
        IF MTRRdefType.E = 0
            THEN return UC;
        FI;
        FirstType ← Get4KMemType (BASE);
        /* Obtains memory type for first 4-KByte range */
        /* See Get4KMemType (4KByteRange) in Example 9-3 */
        FOR each additional 4-KByte range specified in SIZE
            NextType ← Get4KMemType (4KByteRange);
            IF NextType ≠ FirstType
                THEN return MixedTypes;
            FI;
        ROF;
        return FirstType;
```

```
    ELSE return UNSUPPORTED;
FI;
```

If the processor does not support MTRRs, the function returns UNSUPPORTED. If the MTRRs are not enabled, then the UC memory type is returned. If more than one memory type corresponds to the specified range, a status of MIXED_TYPES is returned. Otherwise, the memory type defined for the range (UC, WC, WT, WB, or WP) is returned.

The pseudocode for the Get4KMemType() function in Example 9-3 obtains the memory type for a single 4-KByte range at a given physical address. The sample code determines whether an PHY_ADDRESS falls within a fixed range by comparing the address with the known fixed ranges: 0 to 7FFFFH (64-KByte regions), 80000H to BFFFFH (16-KByte regions), and C0000H to FFFFFH (4-KByte regions). If an address falls within one of these ranges, the appropriate bits within one of its MTRRs determine the memory type.

Example 9-3. Get4KMemType() Pseudocode

```
IF MTRRcap.FIX AND MTRRdefType.FE /* fixed registers enabled */
    THEN IF PHY_ADDRESS is within a fixed range
        return MTRRfixed.Type;
FI;
FOR each variable-range MTRR in MTRRcap.VCNT
    IF MTRRphysMask.V = 0
        THEN continue;
    FI;
    IF (PHY_ADDRESS AND MTRRphysMask.Mask) = (MTRRphysBase.Base
            AND MTRRphysMask.Mask)
        THEN
            return MTRRphysBase.Type;
    FI;
ROF;
return MTRRdefType.Type;
```

9.12.7.2. MEMTYPESET() FUNCTION

The MemTypeSet() function in Example 9-4 sets a MTRR for the physical memory range specified by the parameters base and size to the type specified by type. The base address and size are multiples of 4 KBytes and the size is not 0.

Example 9-4. MemTypeSet Pseudocode

```
IF CPU_FEATURES.MTRR (* processor supports MTRRs *)
    THEN
        IF BASE and SIZE are not 4-KByte aligned or size is 0
            THEN return INVALID;
        FI;
        IF (BASE + SIZE) wrap 4-GByte address space
            THEN return INVALID;
```

```
        FI;
        IF TYPE is invalid for P6 family processors
            THEN return UNSUPPORTED;
        FI;
        IF TYPE is WC and not supported
            THEN return UNSUPPORTED;
        FI;
        IF MTRRcap.FIX is set AND range can be mapped using a fixed-range MTRR
            THEN
                pre_mtrr_change();
                update affected MTRR;
                post_mtrr_change();
        FI;

    ELSE (* try to map using a variable MTRR pair *)
        IF MTRRcap.VCNT = 0
            THEN return UNSUPPORTED;
        FI;
        IF conflicts with current variable ranges
            THEN return RANGE_OVERLAP;
        FI;
        IF no MTRRs available
            THEN return VAR_NOT_AVAILABLE;
        FI;
        IF BASE and SIZE do not meet the power of 2 requirements for variable MTRRs
            THEN return INVALID_VAR_REQUEST;
        FI;
        pre_mtrr_change();
        Update affected MTRRs;
        post_mtrr_change();
FI;

pre_mtrr_change()
    BEGIN
        disable interrupts;
        Save current value of CR4;
        disable and flush caches;
        flush TLBs;
        disable MTRRs;
        IF multiprocessing
            THEN maintain consistency through IPIs;
        FI;
    END
post_mtrr_change()
    BEGIN
        flush caches and TLBs;
        enable MTRRs;
```

```
        enable caches;
        restore value of CR4;
        enable interrupts;
    END
```

The physical address to variable range mapping algorithm in the MemTypeSet function detects conflicts with current variable range registers by cycling through them and determining whether the physical address in question matches any of the current ranges. During this scan, the algorithm can detect whether any current variable ranges overlap and can be concatenated into a single range.

The pre_mtrr_change() function disables interrupts prior to changing the MTRRs, to avoid executing code with a partially valid MTRR setup. The algorithm disables caching by setting the CD flag and clearing the NW flag in control register CR0. The caches are invalidated using the WBINVD instruction. The algorithm disables the page global flag (PGE) in control register CR4, if necessary, then flushes all TLB entries by updating control register CR3. Finally, it disables MTRRs by clearing the E flag in the MTRRdefType register.

After the memory type is updated, the post_mtrr_change() function re-enables the MTRRs and again invalidates the caches and TLBs. This second invalidation is required because of the processor's aggressive prefetch of both instructions and data. The algorithm restores interrupts and re-enables caching by setting the CD flag.

An operating system can batch multiple MTRR updates so that only a single pair of cache invalidations occur.

9.12.8. Multiple-Processor Considerations

In multiple-processor systems, the operating systems must maintain MTRR consistency between all the processors in the system. The P6 family processors provide no hardware support to maintain this consistency. In general, all processors must have the same MTRR values.

This requirement implies that when the operating system initializes a multiple-processor system, it must load the MTRRs of the boot processor while the E flag in register MTRRdefType is 0. The operating system then directs other processors to load their MTRRs with the same memory map. After all the processors have loaded their MTRRs, the operating system signals them to enable their MTRRs. Barrier synchronization is used to prevent further memory accesses until all processors indicate that the MTRRs are enabled. This synchronization is likely to be a shoot-down style algorithm, with shared variables and interprocessor interrupts.

Any change to the value of the MTRRs in a multiple-processor system requires the operating system to repeat the loading and enabling process to maintain consistency, using the following procedure:

1. Broadcast to all processors to execute the following code sequence.
2. Disable interrupts.
3. Wait for all processors to reach this point.

4. Enter the no-fill cache mode. (Set the CD flag in control register CR0 to 1 and the NW flag to 0.)
5. Flush all caches using the WBINVD instruction.
6. Clear the PGE flag in control register CR4 (if set).
7. Flush all TLBs. (Execute a MOV from control register CR3 to another register and then a MOV from that register back to CR3.)
8. Disable all range registers (by clearing the E flag in register MTRRdefType). If only variable ranges are being modified, software may clear the valid bits for the affected register pairs instead.
9. Update the MTRRs.
10. Enable all range registers (by setting the E flag in register MTRRdefType). If only variable-range registers were modified and their individual valid bits were cleared, then set the valid bits for the affected ranges instead.
11. Flush all caches and all TLBs a second time. (The TLB flush is required for P6 family processors. Executing the WBINVD instruction is not needed when using P6 family processors, but it may be needed in future systems.)
12. Enter the normal cache mode to re-enable caching. (Set the CD and NW flags in control register CR0 to 0.)
13. Set PGE flag in control register CR4, if previously cleared.
14. Wait for all processors to reach this point.
15. Enable interrupts.

9.12.9. Large Page Size Considerations

The MTRRs provide memory typing for a limited number of regions that have a 4 KByte granularity (the same granularity as 4-KByte pages). The memory type for a given page is cached in the processor's TLBs. When using large pages (2 or 4 MBytes), a single page-table entry covers multiple 4-KByte granules, each with a single memory type. Because the memory type for a large page is cached in the TLB, the processor can behave in an undefined manner if a large page is mapped to a region of memory that MTRRs have mapped with multiple memory types.

Undefined behavior can be avoided by insuring that all MTRR memory-type ranges within a large page are of the same type. If a large page maps to a region of memory containing different MTRR-defined memory types, the PCD and PWT flags in the page-table entry should be set for the most conservative memory type for that range. For example, a large page used for memory mapped I/O and regular memory is mapped as UC memory. Alternatively, the operating system can map the region using multiple 4-KByte pages each with its own memory type. The requirement that all 4-KByte ranges in a large page are of the same memory type implies that large pages with different memory types may suffer a performance penalty, since they must be marked with the lowest common denominator memory type.

The P6 family processors provide special support for the physical memory range from 0 to 4 MBytes, which is potentially mapped by both the fixed and variable MTRRs. This support is invoked when a P6 family processor detects a large page overlapping the first 1 MByte of this memory range with a memory type that conflicts with the fixed MTRRs. Here, the processor maps the memory range as multiple 4-KByte pages within the TLB. This operation insures correct behavior at the cost of performance. To avoid this performance penalty, operating-system software should reserve the large page option for regions of memory at addresses greater than or equal to 4 MBytes.

9.13. PAGE ATTRIBUTE TABLE (PAT)

The Page Attribute Table (PAT) is an extension to Intel's 32-bit processor virtual memory architecture for certain P6 family processors. Specifically, the PAT is an extension of the page-table format, which allows the specification of memory types to regions of physical memory based on linear address mappings. The PAT provides the equivalent functionality of an unlimited number of Memory Type Range Registers (MTRRs).

Using the PAT in conjunction with the MTRRs of the P6 family of processors extends the memory type information present in the current Intel Architecture page-table format. It combines the extendable and programmable qualities of the MTRRs with the flexibility of the page tables, allowing operating systems or applications to select the best memory type for their needs. The ability to apply the best memory type in a flexible way enables higher levels of performance.

NOTE

In multiple processor systems, the operating system(s) must maintain MTRR consistency between all the processors in the system. The P6 family processors provide no hardware support for maintaining this consistency. In general, all processors must have the same MTRR values.

9.13.1. Background

The P6 family of processors support the assignment of specific memory types to physical addresses. Memory type support is provided through the use of Memory Type Range Registers (MTRRs). Currently there are two interacting mechanisms that work together to set the effective memory type: the MTRRs and the page tables. Refer to the *Intel Architecture Software Developer's Manual, Volume 3: System Programming Guide*.

The MTRRs define the memory types for physical address ranges. MTRRs have specific alignment and length requirements for the memory regions they describe. Therefore, they are useful for statically describing memory types for physical ranges, and are typically set up by the system BIOS. However, they are incapable of describing memory types for the dynamic, linearly addressed data structures of programs. The MTRRs are an expandable and programmable way to encode memory types, but are inflexible because they can only apply those memory types to physical address ranges.

The page tables allow memory types to be assigned dynamically to linearly addressed pages of memory. This gives the operating system the maximum amount of flexibility in applying memory types to any data structure. However, the page tables only offer three of the five basic P6 processor family memory type encodings: Write-back (WB), Write-through (WT) and Uncached (UC). The PAT extends the existing page-table format to enable the specification of additional memory types.

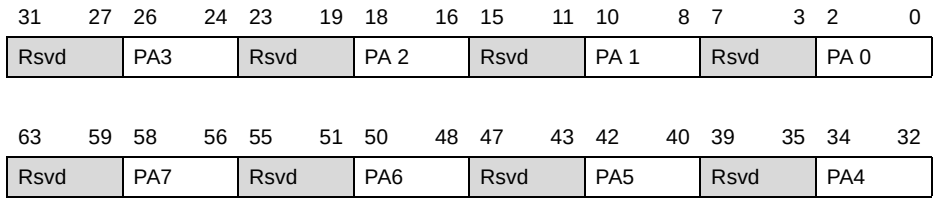
9.13.2. Detecting Support for the PAT Feature

The page attribute table (PAT) feature is detected by an operating system through the use of the CPUID instruction. Specifically, the operating system executes the CPUID instruction with the value 1 in the EAX register, and then determines support for the feature by inspecting bit 16 of the EDX register return value. If the PAT is supported, an operating system is permitted to utilize the model specific register (MSR) specified for programming the PAT, as well as make use of the PAT-index bit (PAT*i*), which was formerly a reserved bit in the page tables.

Note that there is not a separate flag or control bit in any of the control registers that enables the use of this feature. The PAT is always enabled on all processors that support it, and the table lookup always occurs whenever paging is enabled and for all paging modes (e.g., PSE, PAE).

9.13.3. Technical Description of the PAT

The Page Attribute Table is a Model Specific Register (MSR) at address 277H (for information about the MSRs, refer to Appendix B, *Model-Specific Registers*. The model specific register address for the PAT is defined and will remain at the same address on future Intel processors that support this feature. Figure 9-7 shows the format of the 64-bit register containing the PAT.



NOTES:

1. PA0-7 = Specifies the eight page attribute locations contained within the PAT
2. Rsvd = Most significant bits for each Page Attribute are reserved for future expansion

Figure 9-7. Page Attribute Table Model Specific Register

Each of the eight page attribute fields can contain any of the available memory type encodings, or indexes, as specified in Table 9-1.

9.13.4. Accessing the PAT

Access to the memory types that have been programmed into the PAT register fields is accomplished with a 3-bit index consisting of the PAT*i*, PCD, and PWT bits. Table 9-8 shows how the PAT register fields are indexed. The last column of the table shows which memory type the processor assigns to each PAT field at processor reset and initialization. These initial values provide complete backward compatibility with previous Intel processors and existing software that use the previously existing page-table memory types and MTRRs.

Table 9-8. PAT Indexing and Values After Reset

PAT*i*[1]	PCD	PWT	PAT Entry	Memory Type at Reset
0	0	0	0	WB
0	0	1	1	WT
0	1	0	2	UC-[2]
0	1	1	3	UC[3]
1	0	0	4	WB
1	0	1	5	WT
1	1	0	6	UC-[2]
1	1	1	7	UC[3]

NOTES:

1. PAT*i* bit is defined as bit 7 for 4 KB PTEs, bit 12 for PDEs mapping 2 MB/4 MB pages.
2. UC- is the page encoding PCD, PWT = 10 on P6 family processors that do not support this feature. UC- in the page table is overridden by WC in the MTRRs.
3. UC is the page encoding PCD, PWT = 11 on P6 family processors that do not support this feature. UC in the page-table overrides WC in the MTRRs.

In P6 family processors that do not support the PAT, the PCD and PWT bits are used to determine the page-table memory types of a given physical page. The PAT feature redefines these two bits and combines them with a newly defined PAT-index bit (PAT*i*) in the page-directory and page-table entries. These three bits create an index into the 8-entry Page Attribute Table. The memory type from the PAT is used in place of PCD and PWT for computing the effective memory type.

The bit used for PAT*i* differs depending upon the level of the paging hierarchy. PAT*i* is bit 7 for page-table entries, and bit 12 for page-directory entries that map to large pages. Reserved bit faults are disabled for nonzero values for PAT*i*, but remain present for all other reserved bits. This is true for 4 KB/2 MB pages when PAE is enabled. The PAT index scheme for each level of the paging hierarchy is shown in Figure 9-8.

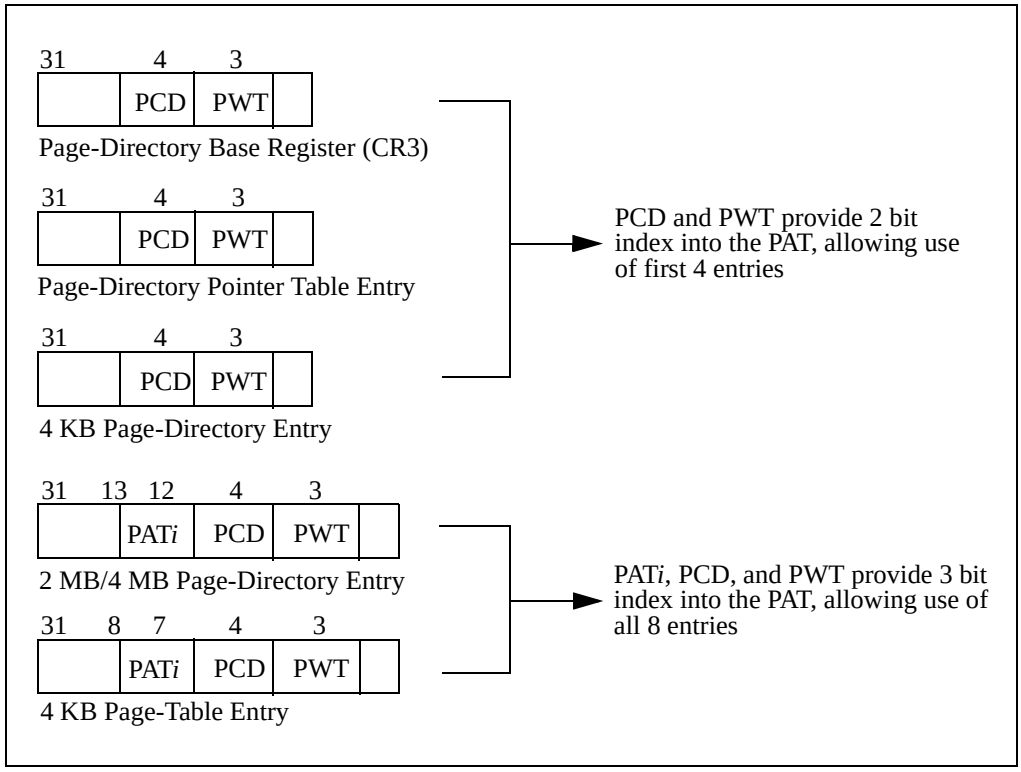


Figure 9-8. Page Attribute Table Index Scheme for Paging Hierarchy

NOTE:

This figure only shows the format of the lower 32 bits of the PDE, PDEPTR, and PTEs when in PAE mode Refer to Figure 3-21 from Chapter 3, *Protected-Mode Memory Management* of the *Intel Architecture Software Developer's Manual, Volume 3: System Programming Guide*. Additionally, the formats shown in this figure are not meant to accurately represent the entire structure, but only the labeled bits.

Figure 9-8 shows that the PAT bit is not defined in CR3, the Page-Directory-Pointer Tables when PAE is enabled, or the Page Directory when it doesn't describe a large page. In these cases, only PCD and PWT are used to index into the PAT, limiting the operating system to using only the first 4 entries of PAT for describing the memory attributes of the paging hierarchy. Note that all 8 PAT entries are available for describing a 4 KB/2 MB/4 MB page.

The memory type as now defined by PAT interacts with the MTRR memory type to determine the effective memory type as outlined in Table 9-9. Compare this to Table 9-5.

Table 9-9. Effective Memory Type Depending on MTRRs and PAT

PAT Memory Type	MTRR Memory Type	Effective Memory Type
UC-	WB, WT	UC_PAGE
	WC	WC
	UC	UC_MTRR
	WP	Undefined
UC	WB, WT, WP, WC	UC_PAGE
	UC	UC_MTRR
WC	X	WC
WT	WB, WT	WT
	UC	UC_MTRR
	WC	Undefined
	WP	Undefined
WP	WB, WP	WP
	UC	UC_MTRR
	WC, WT	Undefined
WB	WB	WB
	UC	UC_MTRR
	WC	WC
	WT	WT
	WP	WP

NOTES:

- This table assumes that the CD and NW flags in register CR0 are set to 0. If CR0.CD = 1, then the effective memory type returned is UC, regardless of what is indicated in the table. However, this does not force strict ordering. To ensure strict ordering, the MTRRs also must be disabled.
- The effective memory types in the gray areas are implementation dependent and may be different between implementations of Intel Architecture processors.
- UC_MTRR indicates that the UC attribute came from the MTRRs and the processor(s) are not required to snoop their caches since the data could never have been cached. This is preferred for performance reasons.
- UC_PAGE indicates that the UC attribute came from the page tables and processors are required to check their caches because the data may be cached due to page aliasing, which is not recommended.
- UC- is the page encoding PCD, PWT = 10 on P6 family processors that do not support this feature. UC- in the PTE/PDE is overridden by WC in the MTRRs.
- UC is the page encoding PCD, PWT = 11 on P6 family processors that do not support this feature. UC in the PTE/PDE overrides WC in the MTRRs.

Whenever the MTRRs are disabled, via bit 11 (E) in the MTRRDefType register, the effective memory type is UC for all memory ranges.

An operating system can program the PAT and select the 8 most useful attribute combinations. The PAT allows an operating system to offer performance-enhancing memory types to applications.

The page attribute for addresses containing a page directory or page table supports only the first four entries in the PAT, since a PAT-index bit is not defined for these mappings. The page attribute is determined by using the two-bit value specified by PCD and PWT in CR3 (for page directory) or the page-directory entry (for page tables). The same applies to Page-Directory-Pointer Tables when PAE is enabled.

9.13.5. Programming the PAT

The Page Attribute Table is read/write accessible to software operating at ring 0 through the use of the `rdmsr` and `wrmsr` instructions. Accesses are directed to the PAT through use of model specific register address 277H. Refer to Figure 9-7 for the format of the 64-bit register containing the PAT.

The PAT implementation on processors that support the feature defines only the 3 least significant bits for page attributes. These bits are used to specify the memory type with the same encoding as used for the P6 family MTRRs as shown in Table 9-6. Processors that support the PAT feature modify those encodings slightly, in that encoding 0 is UC and encoding 7 is UC-, as indicated in the Table 9-10. Encoding 7 remains undefined for the fixed and variable MTRRs, and any attempt to write an undefined memory type encoding continues to generate a GP fault. Attempting to write an undefined memory type encoding into the PAT generates a GP fault.

Table 9-10. PAT Memory Types and Their Properties

Mnemonic	Encoding	Cacheable	Writeback Cacheable	Allows Speculative Reads	Memory Ordering Model
Uncacheable (UC)	0	No	No	No	Strong Ordering
Write Combining (WC)	1	No	No	Yes	Weak Ordering
Write-through (WT)	4	Yes	No	Yes	Speculative Processor Ordering
Write-protect (WP)	5	Yes for reads, no for writes	No	Yes	Speculative Processor Ordering
Write-back (WB)	6	Yes	Yes	Yes	Speculative Processor Ordering
Uncached (UC-)	7	No	No	No	Strong Ordered, but can be overridden by WC in the MTRRs
Reserved	2, 3, 87-255				

The operating system is responsible for ensuring that changes to a PAT entry occur in a manner that maintains the consistency of the processor caches and translation lookaside buffers (TLB). This is accomplished by following the procedure as specified in the *Intel Architecture Software*

Developer's Manual, Volume 3: System Programming Guide, for changing the value of an MTRR. It involves a specific sequence of operations that includes flushing the processor(s) caches and TLBs. An operating system must ensure that the PAT of all processors in a multiprocessing system have the same values.

The PAT allows any memory type to be specified in the page tables, and therefore it is possible to have a single physical page mapped by two different linear addresses with differing memory types. This practice is strongly discouraged by Intel and should be avoided as it may lead to undefined results. In particular, a WC page must never be aliased to a cacheable page because WC writes may not check the processor caches. When remapping a page that was previously mapped as a cacheable memory type to a WC page, an operating system can avoid this type of aliasing by:

- Removing the previous mapping to a cacheable memory type in the page tables; that is, make them not present.
- Flushing the TLBs of processors that may have used the mapping, even speculatively.
- Creating a new mapping to the same physical address with a new memory type, for instance, WC.
- Flushing the caches on all processors that may have used the mapping previously.

Operating systems that use a Page Directory as a Page Table and enable Page Size Extensions must carefully scrutinize the use of the PAT*i* index bit for the 4 KB Page-Table Entries. The PAT*i* index bit for a PTE (bit 7) corresponds to the page size bit in a PDE. Therefore, the operating system can only utilize PAT entries PA0-3 when setting the caching type for a page table that is also used as a page directory. If the operating system attempts to use PAT entries PA4-7 when using this memory as a page table, it effectively sets the PS bit for the access to this memory as a page directory.

10

MMX™ Technology System Programming

CHAPTER 10
MMX™ TECHNOLOGY SYSTEM PROGRAMMING

This chapter describes those features of the MMX™ technology that must be considered when designing or enhancing an operating system to support MMX™ technology. It covers MMX™ instruction set emulation, the MMX™ state, aliasing of MMX™ registers, saving MMX™ state, task and context switching considerations, exception handling, and debugging.

10.1. EMULATION OF THE MMX™ INSTRUCTION SET

The Intel Architecture does not support emulation of the MMX™ technology, as it does for floating-point instructions. The EM flag in control register CR0 (provided to invoke emulation of floating-point instructions) cannot be used for MMX™ technology emulation. If an MMX™ instruction is executed when the EM flag is set, an invalid opcode (UD#) exception is generated.

10.2. THE MMX™ STATE AND MMX™ REGISTER ALIASING

The MMX™ state consists of eight 64-bit registers (MM0 through MM7). These registers are aliased to the 64-bit mantissas (bits 0 through 63) of floating-point registers R0 through R7 (see Figure 10-2). Note that the MMX™ registers are mapped to the physical locations of the floating-point registers (R0 through R7), not to the relative locations of the registers in the floating-point register stack (ST0 through ST7). As a result, the MMX™ register mapping is fixed and is not affected by value in the Top Of Stack (TOS) field in the floating-point status word (bits 11 through 13).

When a value is written into an MMX™ register using an MMX™ instruction, the value also appears in the corresponding floating-point register in bits 0 through 63. Likewise, when a floating-point value written into a floating-point register by a floating-point instruction, the mantissa of that value also appears in a the corresponding MMX™ register.

The execution of MMX™ instructions have several side effects on the FPU state contained in the floating-point registers, the FPU tag word, and the FPU the status word. These side effects are as follows:

- When an MMX™ instruction writes a value into an MMX™ register, at the same time, bits 64 through 79 of the corresponding floating-point register (the exponent field and the sign bit) are set to all 1s.
- When an MMX™ instruction (other than the EMMS instruction) is executed, each of the tag fields in the FPU tag word is set to 00B (valid). (See also Section 10.2.1., “Effect of MMX™ and Floating-Point Instructions on the FPU Tag Word”.)
- When the EMMS instruction is executed, each tag field in the FPU tag word is set to 11B (empty).

- Each time an MMX™ instruction is executed, the TOS value is set to 000B.

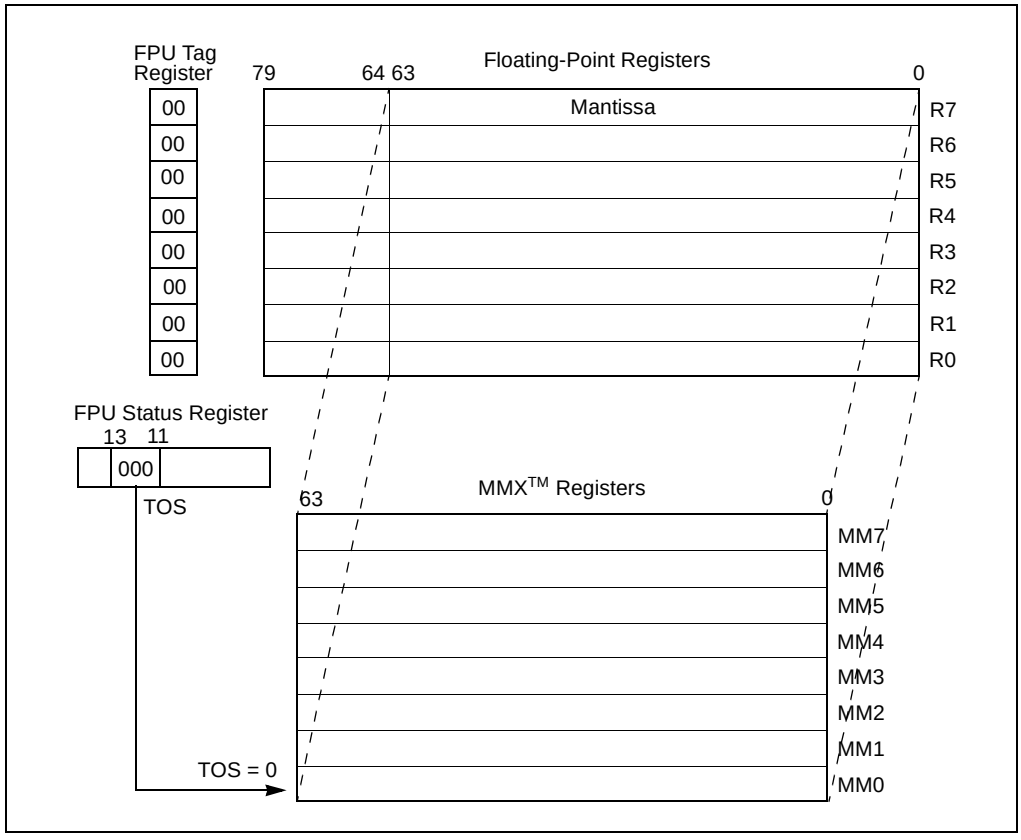


Figure 10-1. Mapping of MMX™ Registers to Floating-Point Registers

Execution of MMX™ instructions does not affect the other bits in the FPU status word (bits 0 through 10 and bits 14 and 15) or the contents of the other FPU registers that comprise the FPU state (the FPU control word, instruction pointer, data pointer, or opcode registers).

Table 10-1 summarizes the effects of the MMX™ instructions on the FPU state.

Table 10-1. Effects of MMX™ Instructions on FPU State

MMX™ Instruction Type	FPU Tag Word	TOS Field of FPU Status Word	Other FPU Registers	Exponent Bits and Sign Bit of R*n*	Mantissa of R*n*
Read from MM*n* register	All tags set to 00B (Valid)	000B	Unchanged	Unchanged	Unchanged
Write to MM*n* register	All tags set to 00B (Valid)	000B	Unchanged	Set to all 1s	Overwritten with MMX™ data
EMMS	All fields set to 11B (Empty)	000B	Unchanged	Unchanged	Unchanged

NOTE:

MM*n* refers to one MMX™ register; R*n* refers to corresponding floating-point register.

10.2.1. Effect of MMX™ and Floating-Point Instructions on the FPU Tag Word

Table 10-2 summarizes the effect of MMX™ and floating-point instructions on the tags in the FPU tag word and the corresponding tags in an image of the tag word stored in memory.

Table 10-2. Effect of the MMX™ and Floating-Point Instructions on the FPU Tag Word

Instruction Type	Instruction	FPU Tag Word	Image of FPU Tag Word Stored in Memory
MMX™ Instruction	All (except EMMS)	All tags are set to 00B (valid).	Not affected.
MMX™ Instruction	EMMS	All tags are set to 11B (empty).	Not affected.
Floating-Point Instruction	All (except FXSAVE/FSAVE, FSTENV, FXRSTOR/FRSTOR, FLDENV)	Tag for modified floating-point register is set to 00B or 11B.	Not affected.
Floating-Point Instruction	FXSAVE/FSAVE, FSTENV	Tags and register values are read and interpreted; then all tags are set to 11B.	Tags are set according to the actual values in the floating-point registers; that is, empty registers are marked 11B and valid registers are marked 00B (nonzero), 01B (zero), or 10B (special).
Floating-Point Instruction	FXRSTOR/FRSTOR, FLDENV	All tags marked 11B in memory are set to 11B; all other tags are set according to the value in the corresponding floating-point register: 00B (nonzero), 01B (zero), or 10B (special).	Tags are read and interpreted, but not modified.

The values in the fields of the FPU tag word do not affect the contents of the MMX™ registers or the execution of MMX™ instructions. However, the MMX™ instructions do modify the contents of the FPU tag word, as is described in Section 10.2., "The MMX™ State and MMX™ Register Aliasing". These modifications may affect the operation of the FPU when executing floating-point instructions, if the FPU state is not initialized or restored prior to beginning floating-point instruction execution.

Note that the FXSAVE/FSAVE and FSTENV instructions (which save FPU state information) read the FPU tag register and contents of each of the floating-point registers, determine the actual tag values for each register (empty, nonzero, zero, or special), and store the updated tag word in memory. After executing these instructions, all the tags in the FPU tag word are set to empty (11B). Likewise, the EMMS instruction clears MMX™ state from the MMX™/floating-point registers by setting all the tags in the FPU tag word to 11B.

10.3. SAVING AND RESTORING THE MMX™ STATE AND REGISTERS

The recommended method of saving and restoring the MMX™ technology state is as follows:

- Execute an FXSAVE/FSAVE/FNSAVE instruction to write the entire state of the MMX™/FPU, the SIMD floating-point registers and the SIMD floating-point MXCSR to memory.
- Execute an FXRSTOR/FRSTOR instruction to read the entire saved state of the MMX™/FPU, the SIMD floating-point registers and the SIMD floating-point MXCSR from memory into the FPU registers, the aliased MMX™ registers, the SIMD floating-point registers and the SIMD floating-point MXCSR.

This save and restore method is required for operating systems (refer to Section 10.4., "Designing Operating System Task and Context Switching Facilities").

Applications can in some cases save and restore only the MMX™ registers, in the following way:

- Execute eight MOVQ instructions to write the contents of the MMX™ registers MM0 through MM7 to memory. An EMMS instruction may then (optionally) be executed to clear the MMX™ state in the FPU.
- Execute eight MOVQ instructions to read the saved contents of the MMX™ registers from memory into the MM0 through MM7 registers.

NOTE

Intel does not support scanning the FPU tag word and then only saving valid entries.

10.4. DESIGNING OPERATING SYSTEM TASK AND CONTEXT SWITCHING FACILITIES

When switching from one task or context to another, it is often necessary to save the MMX™ state (just as it is often necessary to save the state of the FPU). As a general rule, if the existing task switching code for an operating system includes facilities for saving the state of the FPU, these facilities can also be relied upon to save the MMX™ state, without rewriting the task switch code. This reliance is possible because the MMX™ state is aliased to the FPU state (refer to Section 10.2., "The MMX™ State and MMX™ Register Aliasing").

When designing new MMX™ (and/or FPU) state saving facilities for an operating system, several approaches are available:

- The operating system can require that applications (which will be run as tasks) take responsibility for saving the state of the MMX™/FPU prior to a task suspension during a task switch and for restoring the MMX™/FPU state when the task is resumed. The application can use either of the state saving and restoring techniques given in Section 10.3., "Saving and Restoring the MMX™ State and Registers". This approach to saving MMX™/FPU state is appropriate for cooperative multitasking operating systems, where the application has control over (or is able to determine) when a task switch is about to occur and can save state prior to the task switch.
- The operating system can take the responsibility for automatically saving the MMX™/FPU state as part of the task switch process (using an FXSAVE/FSAVE instruction) and automatically restoring the MMX™/FPU state when a suspended task is resumed (using an FXRSTOR/FRSTOR instruction). Here, the MMX™/FPU state must be saved as part of the task state. This approach is appropriate for preemptive multitasking operating systems, where the application cannot know when it is going to be preempted and cannot prepare in advance for task switching. The operating system is responsible for saving and restoring the task and MMX™/FPU state when necessary.
- The operating system can take the responsibility for saving the MMX™/FPU state as part of the task switch process, but delay the saving of the MMX™/FPU state until an MMX™ or floating-point instruction is actually executed by the new task. Using this approach, the MMX™/FPU state is saved only if an MMX™ or floating-point instruction needs to be executed in the new task. (Refer to Section 10.4.1., "Using the TS Flag in Control Register CR0 to Control MMX™/FPU State Saving", for more information on this MMX™/FPU state saving technique.)

10.4.1. Using the TS Flag in Control Register CR0 to Control MMX™/FPU State Saving

Saving the MMX™/FPU state using the FXSAVE/FSAVE instruction is a relatively high-overhead operation. If a task being switched to will not access the FPU (by executing an MMX™ or a floating-point instruction), this overhead can be avoided by not automatically saving the MMX™/FPU state on a task switch.

The TS flag in control register CR0 is provided to allow the operating system to delay saving the MMX™/FPU state until the FPU is actually accessed in the new task. When this flag is set, the processor monitors the instruction stream for MMX™ or floating-point instructions. When the processor detects an MMX™ or floating-point instruction, it raises a device-not-available exception (#NM) prior to executing the instruction. The device-not-available exception handler can then be used to save the MMX™/FPU state for the previous task (using an FXSAVE/FSAVE instruction) and load the MMX™/FPU state for the current task (using an FXRSTOR/FRSTOR instruction). If the task never encounters an MMX™ or floating-point instruction, the device-not-available exception will not be raised and the MMX™/FPU state will not be saved unnecessarily.

The TS flag can be set either explicitly (by executing a MOV instruction to control register CR0) or implicitly (using the processors native task switching mechanism). When the native task switching mechanism is used, the processor automatically sets the TS flag on a task switch. After the device-not-available handler has saved the MMX™/FPU state, it should execute the CLTS instruction to clear the TS flag in CR0.

Figure 10-2 gives an example of an operating system that implements MMX™/FPU state saving using the TS flag. In this example, task A is the currently running task and task B is the task being switched to.

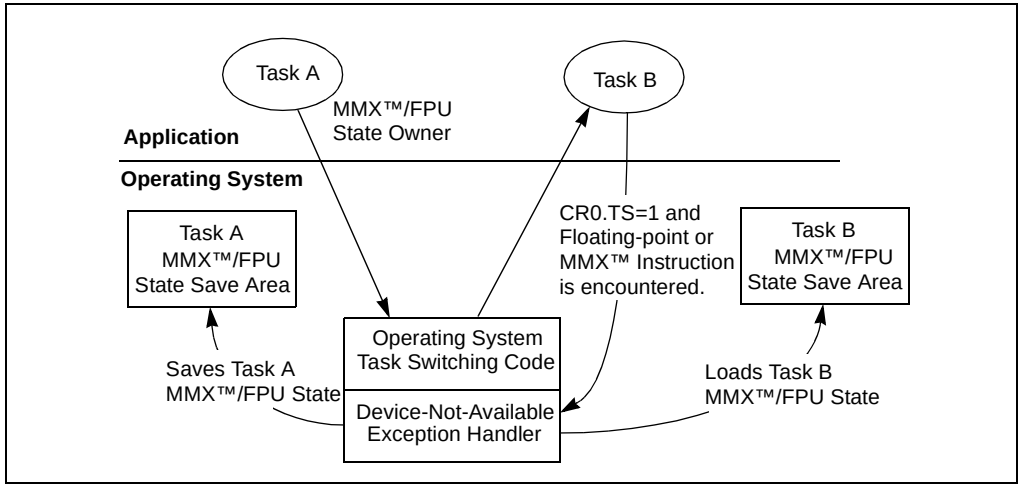


Figure 10-2. Example of MMX™/FPU State Saving During an Operating System-Controlled Task Switch

The operating system maintains an MMX™/FPU save area for each task and defines a variable (MMX™/FPUStateOwner) that indicates which task “owns” the MMX™/FPU state. In this example, task A is the current MMX™/FPU state owner.

On a task switch, the operating system task switching code must execute the following pseudo-code to set the TS flag according to who is the current MMX™/FPU state owner. If the new task

(task B in this example) is not the current MMX™/FPU state owner, the TS flag is set to 1; otherwise, it is set to 0.

```
IF Task_Being_Switched_To ≠ MMX/FPUStateOwner
   THEN
      CR0.TS ← 1;
   ELSE
      CR0.TS ← 0;
FI;
```

If a new task attempts to use an MMX™ or floating-point instruction while the TS flag is set to 1, a device-not-available exception (#NM) is generated and the device-not-available exception handler executes the following pseudo-code.

```
CR0.TS ← 0;
FSAVE “To MMX/FPU State Save Area for Current MMX/FPU State Owner”;
FRSTOR “MMX/FPU State From Current Task’s MMX/FPU State Save Area”;
MMX/FPUStateOwner ← Current_Task;
```

This handler code performs the following tasks:

- Clears the TS flag.
- Saves the MMX™/FPU state in the state save area for the current MMX™/FPU state owner.
- Restores the MMX™/FPU state from the new task’s MMX™/FPU state save area.
- Updates the current MMX™/FPU state owner to be the current task.

10.5. EXCEPTIONS THAT CAN OCCUR WHEN EXECUTING MMX™ INSTRUCTIONS

MMX™ instructions do not generate floating-point exceptions, nor do they affect the processor’s status flags in the EFLAGS register or the FPU status word. The following exceptions can be generated during the execution of an MMX™ instruction:

- Exceptions during memory accesses:
  - — Stack-segment fault (#SS).
  - — General protection (#GP).
  - — Page fault (#PF).
  - — Alignment check (#AC), if alignment checking is enabled.
- System exceptions:
  - — Invalid Opcode (#UD), if the EM flag in control register CR0 is set when an MMX™ instruction is executed. (Refer to Section 10.1., “Emulation of the MMX™ Instruction Set”).

— Device not available (#NM), if an MMX™ instruction is executed when the TS flag in control register CR0 is set. (See Refer to Section 10.4.1., “Using the TS Flag in Control Register CR0 to Control MMX™/FPU State Saving”.)

- Floating-point error (#MF). (See Refer to Section 10.5.1., “Effect of MMX™ Instructions on Pending Floating-Point Exceptions”.)
- Other exceptions can occur indirectly due to the faulty execution of the exception handlers for the above exceptions. For example, if a stack-segment fault (#SS) occurs due to MMX™ instructions, the interrupt gate for the stack-segment fault can direct the processor to invalid TSS, causing an invalid TSS exception (#TS) to be generated.

10.5.1. Effect of MMX™ Instructions on Pending Floating-Point Exceptions

If a floating-point exception is pending and the processor encounters an MMX™ instruction, the processor generates a floating-point error (#MF) prior to executing the MMX™ instruction, to allow the exception to be handled by the floating-point error exception handler. While the handler is executing, the FPU state is maintained and is visible to the handler. Upon returning from the exception handler, the MMX™ instruction is executed, which will alter the FPU state, as described in Section 10.2., “The MMX™ State and MMX™ Register Aliasing”.

10.6. DEBUGGING

The debug facilities of the Intel Architecture operate in the same manner when executing MMX™ instructions as when executing other Intel Architecture instructions. These facilities enable debuggers to debug MMX™ technology code.

To correctly interpret the contents of the MMX™ or FPU registers from the FXSAVE/FSAVE image in memory, a debugger needs to take account of the relationship between the floating-point register’s logical locations relative to TOS and the MMX™ register’s physical locations.

In the floating-point context, ST*n* refers to a floating-point register at location *n* relative to the TOS. However, the tags in the FPU tag word are associated with the physical locations of the floating-point registers (R0 through R7). The MMX™ registers always refer to the physical locations of the registers (with MM0 through MM7 being mapped to R0 through R7).

In Figure 10-2, the inner circle refers to the physical location of the floating-point and MMX™ registers. The outer circle refers to the floating-point registers’s relative location to the current TOS.

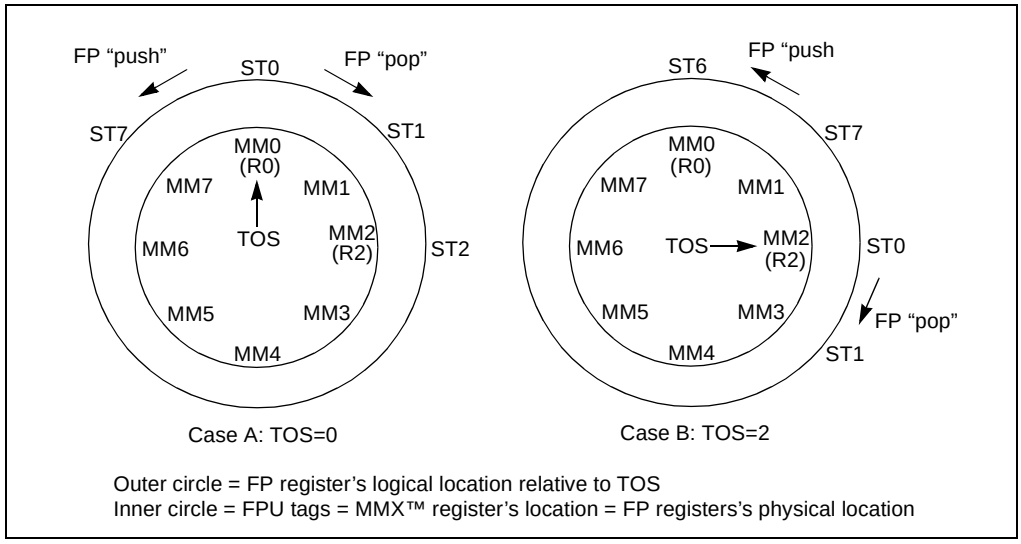


Figure 10-3. Mapping of MMX™ Registers to Floating-Point (FP) Registers

When the TOS equals 0 (case A in Figure 10-2), ST0 points to the physical location R0 on the floating-point stack. MM0 maps to ST0, MM1 maps to ST1, and so on.

When the TOS equals 2 (case B in Figure 10-2), ST0 points to the physical location R2. MM0 maps to ST6, MM1 maps to ST7, MM2 maps to ST0, and so on.

11

Streaming SIMD Extensions System Programming

CHAPTER 11
STREAMING SIMD EXTENSIONS SYSTEM PROGRAMMING

This chapter describes those features of the Streaming SIMD Extensions that must be considered when designing or enhancing an operating system to support the Pentium® III processor. It covers extensions emulation, the new SIMD floating-point architectural state, similarities to MMX™ technology, task and context switching considerations, exception handling, and debugging.

11.1. EMULATION OF THE STREAMING SIMD EXTENSIONS

The Intel Architecture does not support emulation of the Streaming SIMD Extensions, as it does for floating-point instructions. The EM flag in control register CR0 (provided to invoke emulation of floating-point instructions) cannot be used for Streaming SIMD Extensions emulation. If a Streaming SIMD Extensions instruction is executed when the EM flag is set (CR0.EM), an invalid opcode (UD#/INT6) exception is generated instead of a device not available exception (NM#/INT7).

11.2. MMX™ STATE AND STREAMING SIMD EXTENSIONS

The SIMD-integer instructions of the Streaming SIMD Extensions use the same registers as the MMX™ technology instructions. In addition they have been implemented so the same rules for MMX™ technology instructions apply to the Streaming SIMD Extensions. Hence everything referenced in chapter 10 relating to MMX™ technology and system programming is applicable to the SIMD-integer instructions in the Streaming SIMD Extensions.

11.3. NEW PENTIUM® III PROCESSOR REGISTERS

The Pentium® III Processor introduced a set of 128-bit general-purpose registers. These registers are directly addressable and can be used to hold data only. In addition, the Pentium® III Processor also introduced a new control/status register (MXCSR) that is used to flag exceptions resulting from computations involving the SIMD floating-point registers, mask/unmask exceptions, and control the rounding and flush-to-zero modes. These registers are described more completely in the following sections.

11.3.1. SIMD Floating-point Registers

Streaming SIMD Extensions provides eight 128-bit general-purpose registers, each of which can be directly addressed. These registers are new state, and require support from the operating system to use them.

The SIMD floating-point registers can hold packed 128-bit data. The SIMD floating-point instructions access the SIMD floating-point registers directly using the register names XMM0 to XMM7 (Table 11-1). These registers can be used to perform calculations on data. They cannot be used to address memory; addressing is accomplished by using the integer registers and existing IA addressing modes.

The contents of SIMD floating-point registers are cleared upon reset.

There is a new control/status register MXCSR which is used to mask/unmask numerical exception handling, to set rounding modes, to set the flush-to-zero mode, and to view status flags.

Table 11-1. SIMD Floating-point Register Set

128 97	96 64	63 32	31 0	
				XMM0
				XMM1
				XMM2
				XMM3
				XMM4
				XMM5
				XMM6
				XMM7

11.3.2. SIMD Floating-point Control/Status Registers

The control/status register is used to enable masked/unmasked numerical exception handling, to set rounding modes, to set the flush-to-zero mode, and to view status flags. The contents of this register can be loaded with the LDMXCSR and FXRSTOR instructions and stored in memory with the STMXCSR and FXSAVE instructions. Figure 11-1 shows the format and encoding of the fields in the MXCSR.

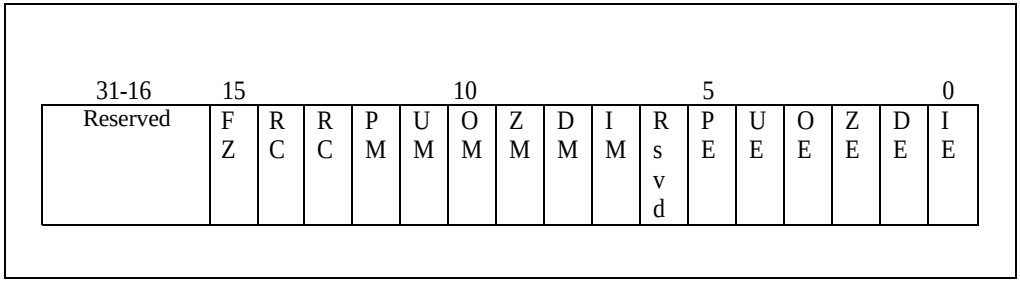


Figure 11-1. Streaming SIMD Extensions Control/Status Register Format

Bits 5-0 indicate whether a Streaming SIMD Extensions numerical exception has been detected. They are "sticky" flags, and can be cleared by using the LDMXCSR instruction to write zeroes to these fields. If a LDMXCSR instruction clears a mask bit and sets the corresponding exception flag bit, an exception will not be generated because of this change. This type of exception will occur only upon the next Streaming SIMD Extensions instruction to cause it. Streaming SIMD Extensions use only one exception flag for each exception. There is no provision for individual exception reporting within a packed data type. In situations where multiple identical exceptions occur within the same instruction, the associated exception flag is updated and indicates that at least one of these conditions happened. These flags are cleared upon reset.

Bits 12-7 configure numerical exception masking; an exception type is masked if the corresponding bit is set and it is unmasked if the bit is clear. These bits are set upon reset, meaning that all numerical exceptions are masked.

Bits 14-13 encode the rounding control, which provides for the common round to nearest mode, as well as directed rounding and true chop (refer to Section 11.3.2.1., "Rounding Control Field"). The rounding control is set to round to nearest upon reset.

Bit 15 (FZ) is used to turn on the flush-to-zero mode (refer to Section 11.3.2.2., "Flush-to-Zero"). This bit is cleared upon reset, disabling the flush-to-zero mode.

The other bits of MXCSR (bits 31-16 and bit 6) are defined as reserved and cleared; attempting to write a non-zero value to these bits, using either the FXRSTOR or LDMXCSR instructions, will result in a general protection exception.

11.3.2.1. ROUNDING CONTROL FIELD

The rounding control (RC) field of MXCSR (bits 13 and 14) controls how the results of floating-point instructions are rounded. Four rounding modes are supported: round to nearest, round up, round down, and round toward zero (see Table 11-2). Round to nearest is the default rounding mode and is suitable for most applications. It provides the most accurate and statistically unbiased estimate of the true result.

Table 11-2. Rounding Control Field (RC)

Rounding Mode	RC Field Setting	Description
Round to nearest (even)	00B	Rounded result is the closest to the infinitely precise result. If two values are equally close, the result is the even value (that is, the one with the least-significant bit of zero).
Round down (toward $-\infty$)	01B	Rounded result is closest to, but no greater than the infinitely precise result.
Round up (toward $+\infty$)	10B	Rounded result is closest to, but no less than the infinitely precise result.
Round toward zero (truncate)	11B	Rounded result is closest to, but no greater in absolute value than the infinitely precise result.

The round up and round down modes are termed *directed rounding* and can be used to implement interval arithmetic. Interval arithmetic is used to determine upper and lower bounds for the true result of a multistep computation, when the intermediate results of the computation are subject to rounding.

The round toward zero mode (sometimes called the “chop” mode) is commonly used when performing integer arithmetic with the processor.

Whenever possible, the processor produces an infinitely precise result. However, it is often the case that the infinitely precise result of an arithmetic or store operation cannot be encoded exactly in the format of the destination operand. For example, the following value (*a*) has a 24-bit fraction. The least-significant bit of this fraction (the underlined bit) cannot be encoded exactly in the single-real format (which has only a 23-bit fraction):

(*a*) $1.0001\ 0000\ 1000\ 0011\ 1001\ 011\underline{1}E_2\ 101$

To round this result (*a*), the processor first selects two representable fractions *b* and *c* that most closely bracket *a* in value ($b < a < c$).

(*b*) $1.0001\ 0000\ 1000\ 0011\ 1001\ 011E_2\ 101$

(*c*) $1.0001\ 0000\ 1000\ 0011\ 1001\ 100E_2\ 101$

The processor then sets the result to *b* or to *c* according to the rounding mode selected in the RC field. Rounding introduces an error in a result that is less than one unit in the last place to which the result is rounded.

The rounded result is called the inexact result. When the processor produces an inexact result, the floating-point precision (inexact) flag (PE) is set in MXCSR.

When the infinitely precise result is between the largest positive finite value allowed in a particular format and $+\infty$, the processor rounds the result as shown in Table 11-3.

Table 11-3. Rounding of Positive Numbers Greater than the Maximum Positive Finite Value

Rounding Mode	Result
Rounding to nearest (even)	+∞
Rounding down (toward –∞)	Maximum, positive finite value
Rounding up (toward +∞)	+∞
Rounding toward zero (Truncate)	Maximum, positive finite value

When the infinitely precise result is between the largest negative finite value allowed in a particular format and –∞, the processor rounds the result as shown in Table 11-4.

Table 11-4. Rounding of Negative Numbers Smaller than the Maximum Negative Finite Value

Rounding Mode	Result
Rounding to nearest (even)	-∞
Rounding toward zero (Truncate)	Maximum, negative finite value
Rounding up (toward +∞)	Maximum, negative finite value
Rounding down (toward –∞)	-∞

The rounding modes have no effect on comparison operations, operations that produce exact results, or operations that produce NaN results.

11.3.2.2. FLUSH-TO-ZERO

Turning on the Flush-To-Zero mode has the following effects when tiny results occur (i.e. when the infinitely precise result rounded to the destination precision with an unbounded exponent, is smaller in absolute value than the smallest normal number that can be represented; this is similar to the underflow condition when underflow traps are unmasked):

- Zero results are returned with the sign of the true result
- Precision and underflow exception flags are set

The IEEE mandated masked response to underflow is to deliver the denormalized result (i.e., gradual underflow); consequently, the flush-to-zero mode is not compatible with IEEE Standard 754. It is provided primarily for performance reasons. At the cost of a slight precision loss, faster execution can be achieved for applications where underflow is common. Underflow for flush-to-zero is defined to occur when the exponent for a computed result, prior to denormalization scaling, falls in the denormal range; this is regardless of whether a loss of accuracy has occurred. Unmasking the underflow exception takes precedence over flush-to-zero mode; this means that an exception handler will be invoked for a Streaming SIMD Extensions instruction that generates an underflow condition while this exception is unmasked, regardless of whether flush-to-zero is enabled.

11.4. ENABLING STREAMING SIMD EXTENSIONS SUPPORT

This section describes the interface of the Intel Architecture Streaming SIMD Extensions with the operating system.

11.4.1. Enabling Streaming SIMD Extensions Support

Certain steps must be taken in both the application and the OS to check if the CPU supports Streaming SIMD Extensions and associated unmasked exceptions. This section describes this process, which is conducted using the bits described in Table 11-5 and Table 11-6.

If the OS wants to use FXSAVE/FXRSTOR, it will first check CPUID.FXSR to determine if the CPU supports these instructions. If the CPU does support FXSAVE/FXRSTOR, then the OS can set CR4.OSFXSR without faulting and enable code for context switching that utilizes FXSAVE/FXRSTOR instead of FSAVE/FRSTOR.

At this point, if the OS also supports unmasked SIMD floating-point exceptions, it should check CPUID.XMM to see if this is a Streaming SIMD Extensions-enabled processor. If CPUID.XMM is set, this verifies that the OS can set CR4.OSXMMEXCPT without faulting.

The process by which an application detects the existence of Streaming SIMD Extensions as discussed in Section 9.5.1., “Detecting Support for Streaming SIMD Extensions Using the CPUID Instruction” Chapter 9, *Programming with the Streaming SIMD Extensions*, in the *Intel Architecture Software Developer’s Manual, Volume 1*. For additional information and examples, see AP-900, *Identifying Support for Streaming SIMD Extensions in the Processor and Operating System.*

Table 11-5. CPUID Bits for Streaming SIMD Extensions Support

CPUID bit (EAX = 1)	Meaning
FXSR (EDX bit24)	If set, CPU supports FXSAVE/FXRSTOR. The OS can read this bit to determine if it can use FXSAVE/FXRSTOR in place of FSAVE/FRSTOR for context switches.
XMM (EDX bit25)	If set, the Streaming SIMD Extensions set is supported by the processor.

Table 11-6. CR4 Bits for Streaming SIMD Extensions Support

CR4 bit	Meaning
OSFXSR (bit9)	Defaults to clear. If both the CPU and the OS support FXSAVE/FXRSTOR for use during context switches, then the OS will set this bit.
OSXMMEXCPT (bit10)	Defaults to clear. The OS will set this bit if it supports unmasked SIMD floating-point exceptions.

11.4.2. Device Not Available (DNA) Exceptions

Streaming SIMD Extensions will cause a DNA Exception (#NM) if the processor attempts to execute a SIMD floating-point instruction while CR0.TS is set. If CPUID.XMM is clear, execu-

tion of any Streaming SIMD Extensions instruction will cause an invalid opcode fault regardless of the state of CR0.TS.

11.4.3. FXSAVE/FXRSTOR as a Replacement for FSAVE/FRSTOR

The FXSAVE and FXRSTOR instructions are designed to be a replacement for FSAVE/FRSTOR, to be used by the OS for context switches. These have been optimized to be faster than FSAVE/FRSTOR, while still saving/restoring the additional SIMD floating-point state. To meet this goal, FXSAVE differs from FSAVE in that it does not cause an FINIT to be performed, nor does FXSAVE initialize the SIMD floating-point registers in any way. While FXSAVE/FXRSTOR does save/restore the x87-FP state, FSAVE/FRSTOR does not affect the SIMD floating-point state. This allows for FXSAVE/FXRSTOR and FSAVE/FRSTOR to be nested. State saved with FXSAVE and restored with FRSTOR (and vice versa) will result in incorrect restoration of state in the processor. FXSAVE will not save the SIMD floating-point state (SIMD floating-point registers and MXCSR register) if the CR4.OSFXSR bit is not set.

11.4.4. Numeric Error flag and IGNNE#

Streaming SIMD Extensions ignore CR0.NE (treats it as if it were always set) and the IGNNE# pin and always use the vector 19 software exception for error reporting.

11.5. SAVING AND RESTORING THE STREAMING SIMD EXTENSIONS STATE

The recommended method of saving and restoring the Streaming SIMD Extensions state is as follows:

- Execute an FXSAVE instruction to write the entire state of the MMX™/FPU, the SIMD floating-point registers, and the SIMD floating-point MXCSR to memory.
- Execute an FXRSTOR instruction to read the entire saved state of the MMX™/FPU, the SIMDP floating-point registers and the SIMD floating-point MXCSR from memory into the FPU registers and the aliased MMX™ registers.

This save and restore method is required for operating systems (see Section 10.6., “Designing Operating System Task and Context Switching Facilities”).

Applications can in some cases save and restore only the SIMD floating-point registers, in the following way:

- Execute eight MOVAPS instructions to write the contents of the SIMD floating-point registers XMM0 through XMM7 to memory. Execute a STMXCSR instruction to save the MXCSR register to memory.
- Execute eight MOVAPS instructions to read the saved contents of the SIMD floating-point registers from memory into the XMM0 through XMM7 registers. Execute a LDMXCSR

instruction to read the saved contents of the MXCSR register from memory into the MXCSR register.

11.6. DESIGNING OPERATING SYSTEM TASK AND CONTEXT SWITCHING FACILITIES

When switching from one task or context to another, it is often necessary to save the SIMD floating-point state (just as it is often necessary to save the state of the FPU). As mentioned in the previous chapter, the MMX™ state is aliased on the FPU state. The SIMD floating-point registers in the Pentium® III processor introduce a new state. When designing new SIMD floating-point state saving facilities for an operating system, several approaches are available:

- The operating system can require that applications (which will be run as tasks) take responsibility for saving the SIMD floating-point state prior to a task suspension during a task switch and for restoring the SIMD floating-point state when the task is resumed. The application can use either of the state saving and restoring techniques given in Section 10.5., “Saving and Restoring the Streaming SIMD Extensions state”. This approach to saving the SIMD floating-point state is appropriate for cooperative multitasking operating systems, where the application has control over (or is able to determine) when a task switch is about to occur and can save state prior to the task switch.
- The operating system can take the responsibility for automatically saving the SIMD floating-point state as part of the task switch process (using an FXSAVE instruction) and automatically restoring the SIMD floating-point state when a suspended task is resumed (using an FXRSTOR instruction). Here, the SIMD floating-point state must be saved as part of the task state. This approach is appropriate for preemptive multitasking operating systems, where the application cannot know when it is going to be preempted and cannot prepare in advance for task switching. The operating system is responsible for saving and restoring the task and SIMD floating-point state when necessary.
- The operating system can take the responsibility for saving the SIMD floating-point state as part of the task switch process, but delay the saving of the SIMD floating-point state until a Streaming SIMD Extensions instruction is actually executed by the new task. Using this approach, the SIMD floating-point state is saved only if a Streaming SIMD Extensions instruction needs to be executed in the new task. (See Section 10.6.1., “Using the TS Flag in Control Register CR0 to Control SIMD Floating-Point State Saving”, for more information on this SIMD floating-point state saving technique.)

11.6.1. Using the TS Flag in Control Register CR0 to Control SIMD Floating-Point State Saving

Saving the SIMD floating-point state using the FXSAVE instruction is not as high-overhead operation as FSAVE. However an operating system may choose to wait to save the SIMD floating-point state to avoid this overhead. If a task being switched to will not access the SIMD floating-point registers (by executing a Streaming SIMD Extensions instruction), this overhead can be avoided by not automatically saving the SIMD floating-point state on a task switch.

The TS flag in control register CR0 is provided to allow the operating system to delay saving the SIMD floating-point state until the SIMD floating-point registers are actually accessed in the new task. When this flag is set, the processor monitors the instruction stream for Streaming SIMD Extensions instructions. When the processor detects a Streaming SIMD Extensions instruction, it raises a device-not-available exception (#NM) prior to executing the instruction. The device-not-available exception handler can then be used to save the SIMD floating-point state for the previous task (using an FXSAVE instruction) and load the SIMD floating-point state for the current task (using an FXRSTOR instruction). If the task never encounters a Streaming SIMD Extensions instruction, the device-not-available exception will not be raised and the SIMD floating-point state will not be saved unnecessarily.

The TS flag can be set either explicitly (by executing a MOV instruction to control register CR0) or implicitly (using the processor's native task switching mechanism). When the native task switching mechanism is used, the processor automatically sets the TS flag on a task switch. After the device-not-available handler has saved the SIMD floating-point state, it should execute the CLTS instruction to clear the TS flag in CR0.

Figure 10-2 gives an example of an operating system that implements SIMD floating-point state saving using the TS flag. In this example, task A is the currently running task and task B is the task being switched to.

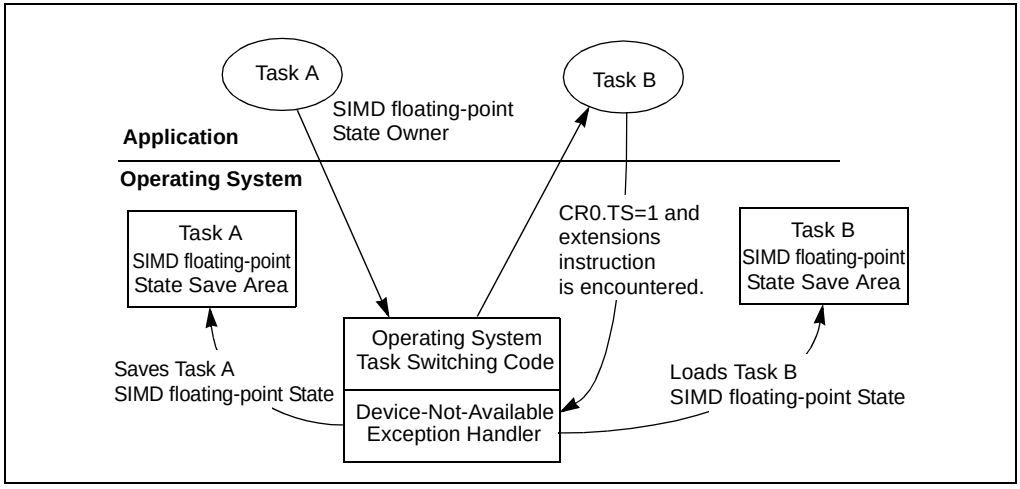


Figure 11-2. Example of SIMD Floating-Point State Saving During an Operating System-Controlled Task Switch

The operating system maintains a SIMD floating-point save area for each task and defines a variable (SIMD-fpStateOwner) that indicates which task "owns" the SIMD floating-point state. In this example, task A is the current SIMD floating-point state owner.

On a task switch, the operating system task switching code must execute the following pseudo-code to set the TS flag according to the current SIMD floating-point state owner. If the new task

(task B in this example) is not the current SIMD floating-point state owner, the TS flag is set to 1; otherwise, it is set to 0.

```
IF Task_Being_Switched_To ≠ SIMD-fpStateOwner
   THEN
      CR0.TS ← 1;
   ELSE
      CR0.TS ← 0;
FI;
```

If a new task attempts to use a Streaming SIMD Extensions instruction while the TS flag is set to 1, a device-not-available exception (#NM) is generated and the device-not-available exception handler executes the following pseudo-code.

```
CR0.TS ← 0;
FXSAVE “To SIMD floating-point State Save Area for Current SIMD Floating-point State Owner”;
FXRSTOR “SIMD floating-point State From Current Task’s SIMD Floating-point State Save Area”;
SIMF-fpStateOwner ← Current_Task;
```

This handler code performs the following tasks:

- Clears the TS flag.
- Saves the SIMD floating-point state in the state save area for the current SIMD floating-point state owner.
- Restores the SIMD floating-point state from the new task's SIMD floating-point state save area.
- Updates the current SIMD floating-point state owner to be the current task.

11.7. EXCEPTIONS THAT CAN OCCUR WHEN EXECUTING STREAMING SIMD EXTENSIONS INSTRUCTIONS

Streaming SIMD Extensions can generate two kinds of exceptions:

- Non-numeric exceptions
- Numeric exceptions

Streaming SIMD Extensions can generate the same type of memory access exceptions as the Intel Architecture instructions do. Some examples are: page fault, segment not present, and limit violations. Existing exception handlers can handle these types of exceptions without any code modification. The SIMD floating-point PREFETCH instruction hints will not generate any kind of exception and instead will be ignored.

Streaming SIMD Extensions can generate the same six numeric exceptions that x87-FP instructions can generate. All Streaming SIMD Extensions numeric exceptions are reported independently of x87-FP numeric exceptions. Independent masking and unmasking of Streaming SIMD Extensions numeric exceptions is achieved by setting/resetting specific bits in the MXCSR register.

The application must ensure that the OS can support unmasked SIMD floating-point exceptions before unmasking them. For more details, refer to Section 9.5.1., "Detecting Support for Streaming SIMD Extensions Using the CPUID Instruction" Chapter 9, *Programming with the Streaming SIMD Extensions*, in the *Intel Architecture Software Developer's Manual, Volume 1* and AP-900, *Identifying Support for Streaming SIMD Extensions in the Processor and Operating System*. If an application unmasks exceptions using either FXRSTOR or LDMXCSR without the required OS support being enabled, then an invalid opcode fault, instead of a SIMD floating-point exception, will be generated on the first faulting SIMD floating-point instruction.

11.7.1. SIMD Floating-point Non-Numeric Exceptions

- Exceptions during memory accesses:
  - — Invalid opcode (#UD).
  - — Stack exception (#SS).
  - — General protection (#GP).
  - — Page fault (#PF).
  - — Alignment check (#AC), if alignment checking is enabled.
- System exceptions:
  - — Invalid Opcode (#UD), if the EM flag in control register CR0 is set, the CPUID.XMM bit is not set, or the CR4.OSFXSR* bit is not set, when a Streaming SIMD Extensions instruction is executed (see Section 10.1., “Emulation of the Streaming SIMD Extensions”).
  - — Device not available (#NM), if a Streaming SIMD Extensions instruction is executed when the TS flag in control register CR0 is set. (See Section 10.6.1., “Using the TS Flag in Control Register CR0 to Control SIMD Floating-Point State Saving”.)
- Other exceptions can occur indirectly due to the faulty execution of the exception handlers for the above exceptions. For example, if a stack-segment fault (#SS) occurs due to Streaming SIMD Extensions instructions, the interrupt gate for the stack-segment fault can direct the processor to invalid TSS, causing an invalid TSS exception (#TS) to be generated.

Table 11-7 lists the causes for Interrupt 6 and Interrupt 7 with Streaming SIMD Extensions.

Table 11-7. Streaming SIMD Extensions Faults

CR0.EM	CR4.OSFXSR	CPUID.XMM	CR0.TS	EXCEPTION
1	-	-	-	#UD Interrupt 6
-	0	-	-	#UD Interrupt 6
-	-	0	-	#UD Interrupt 6
0	1	1	1	#NM Interrupt 7

11.7.2. SIMD Floating-point Numeric Exceptions

There are six classes of numeric exception conditions that can occur while executing Streaming SIMD Extensions:

- Invalid operation (#I)
- Divide-by-zero (#Z)
- Denormal operand (#D)
- Numeric overflow (#O)
- Numeric underflow (#U)
- Inexact result (Precision) (#P)

Invalid, Divide-by-zero and Denormal exceptions are pre-computation exceptions, i.e., they are detected before any arithmetic operation occurs. Underflow, Overflow and Precision exceptions are post-computation exceptions.

When numeric exceptions occur, a processor supporting Streaming SIMD Extensions takes one of two possible courses of action:

- The processor can handle the exception by itself, producing the most reasonable result and allowing numeric program execution to continue undisturbed (i.e., masked exception response).
- A software exception handler can be invoked to handle the exception (i.e., unmasked exception response).

Each of the six exception conditions described above has corresponding flag and mask bits in the MXCSR. If an exception is masked (the corresponding mask bit in MXCSR = 1), the processor takes an appropriate default action and continues with the computation. If the exception is unmasked (mask bit = 0) and the OS supports SIMD floating-point exceptions (i.e. CR4.OSXMMEXCPT = 1), a software exception handler is invoked immediately through SIMD floating-point exception interrupt vector 19. If the exception is unmasked (mask bit = 0) and the OS does not support SIMD floating-point exceptions (i.e. CR4.OSXMMEXCPT = 0), an invalid opcode exception is signaled instead of a SIMD floating-point exception.

Note that because SIMD floating-point exceptions are precise and occur immediately, the situation does not arise where an x87-FP instruction, an FWAIT instruction, or another Streaming SIMD Extensions instruction will catch a pending unmasked SIMD floating-point exception.

11.7.2.1. EXCEPTION PRIORITY

The processor handles exceptions according to a predetermined precedence. When a sub-operand of a packed instruction generates two or more exception conditions, the exception precedence sometimes results in the higher-priority exception being handled and the lower-priority exceptions being ignored. For example, dividing an SNaN by zero could potentially signal an invalid-arithmetic-operand exception (due to the SNaN operand) and a divide-by-zero exception. Here, if both exceptions are masked, the processor handles the higher-priority exception only (the invalid-arithmetic-operand exception), returning the quiet version of the SNaN to

the destination. The prioritization policy also applies for unmasked exceptions; if both invalid and divide-by-zero are unmasked for the previous example, only the invalid flag will be set. Prioritization of exceptions is performed only on an individual sub-operand basis, and not between suboperands; for example, an invalid exception generated by one sub-operand will not prevent the reporting of a divide-by-zero exception generated by another sub-operand.

The precedence for SIMD floating-point numeric exceptions is as follows:

1. Invalid operation exception due to NaN operands (refer to Table 11-8).
2. QNaN operand. Though this is not an exception, the handling of a QNaN operand has precedence over lower-priority exceptions. For example, a QNaN divided by zero results in a QNaN, not a zero-divide exception.
3. Any other invalid operation exception not mentioned above or a divide-by-zero exception (refer to Table 11-8).
4. Denormal operand exception. If masked, then instruction execution continues, and a lower-priority exception can occur as well.
5. Numeric overflow and underflow exceptions possibly in conjunction with the inexact result exception.
6. Inexact result exception.

11.7.2.2. AUTOMATIC MASKED EXCEPTION HANDLING

If the processor detects an exception condition for a masked exception (an exception with its mask bit set), it delivers a predefined (default) response and continues executing instructions. The masked (default) responses to exceptions have been chosen to deliver a reasonable result for each exception condition and are generally satisfactory for most application code. By masking or unmasking specific floating-point exceptions in the MXCSR, programmers can delegate responsibility for most exceptions to the processor and reserve the most severe exception conditions for software exception handlers.

Because the exception flags are “sticky,” they provide a cumulative record of the exceptions that have occurred since they were last cleared. A programmer can thus mask all exceptions, run a calculation, and then inspect the exception flags to see if any exceptions were detected during the calculation.

Note that when exceptions are masked, the processor may detect multiple exceptions in a single instruction, because:

- It continues executing the instruction after performing its masked response; for example, the processor could detect a denormalized operand, perform its masked response to this exception, and then detect an underflow
- Exceptions may occur naturally in pairs, such as numeric underflow and inexact result (precision)
- Packed instructions can produce independent exceptions for each pair of operands.

Updating of exception flags is generated by a logical-OR of exception conditions for all sub-operand computations, where the OR is done independently for each type of exception; for packed computations this means 4 sub-operands and for scalar computations this means 1 sub-operand (the lowest one).

11.7.2.3. SOFTWARE EXCEPTION HANDLING - UNMASKED EXCEPTIONS

An application must ensure that the operating system supports unmasked exceptions before unmasking any of the exceptions in the MXCSR (refer to Section 9.5.1., "Detecting Support for Streaming SIMD Extensions Using the CPUID Instruction" Chapter 9, *Programming with the Streaming SIMD Extensions*, Volume 1 of the *Programmer's Reference Manua*l).

If the processor detects a condition for an unmasked SIMD floating-point application exception, a software handler is invoked immediately at the end of the excepting instruction. The handler is invoked through the SIMD floating-point exception interrupt (vector 19), irrespective of the state of the CR0.NE flag. If an exception is unmasked, but SIMD floating-point unmasked exceptions are not enabled (CR4.OSXMMEXCPT = 0), an invalid opcode fault is generated. However, the corresponding exception bit will still be set in the MXCSR, as it would be if CR4.OSXMMEXCPT =1, since the invalid opcode handler or the user needs to determine the cause of the exception.

A typical action of the exception handler is to store x87-FP and SIMD floating-point state information in memory (with the FXSAVE/FXRSTOR instructions) so that it can evaluate the exception and formulate an appropriate response. Other typical exception handler actions can include:

- Examine stored x87-FP and SIMD floating-point state information (control/status) to determine the nature of the error.
- Taking action to correct the condition that caused the error.
- Clear the exception bits in the x87-FP status word (FSW) or the SIMD floating-point control register (MXCSR)
- Return to the interrupted program and resume normal execution.

In lieu of writing recovery procedures, the exception handler can do one or more of the following:

- Increment in software an exception counter for later display or printing.
- Print or display diagnostic information (such as the SIMD floating-point register state).
- Halt further program execution.

When an unmasked exception occurs, the processor will not alter the contents of the source register operands prior to invoking the unmasked handler. Similarly, the integer EFLAGS will also not be modified if an unmasked exception occurs while executing the COMISS or UCOMISS instructions. Exception flags will be updated according to the following rules:

- Updating of exception flags is generated by a logical-OR of exception conditions for all sub-operand computations, where the OR is done independently for each type of

exception; for packed computations this means 4 sub-operands and for scalar computations this means 1 sub-operand (the lowest one).

- In the case of only masked exception conditions, all flags will be updated,
- In the case of an unmasked pre-computation type of exception condition (e.g., denormal input), all flags relating to all pre-computation conditions (masked or unmasked) will be updated, and no subsequent computation is performed (i.e., no post-computation condition can occur if there is an unmasked pre-computation condition).
- In the case of an unmasked post-computation exception condition, all flags relating to all post-computation conditions (masked or unmasked) will be updated; all pre-computation conditions, which must be masked-only will also be reported.

11.7.2.4. INTERACTION WITH X87 NUMERIC EXCEPTIONS

The Streaming SIMD Extensions control/status register was separated from its x87-FP counterparts to allow for maximum flexibility. Consequently, the Streaming SIMD Extensions architecture is independent of the x87-FP architecture, but has the following implications for x87-FP applications that call Streaming SIMD Extensions-enabled libraries:

- The x87-FP rounding mode specified in FCW will not apply to calls in a Streaming SIMD Extensions library (unless the rounding control in MXCSR is explicitly set to the same mode).
- x87-FP exception observability may not apply to a Streaming SIMD Extensions library.
    - An application that expects to catch x87-FP exceptions that occur in an x87-FP library will not be notified if an exception occurs in a Streaming SIMD Extensions library, unless the exception masks enabled in FCW have also been enabled in MXCSR.
    - An application will not be able to unmask exceptions after returning from a Streaming SIMD Extensions library call to detect if an error occurred. A SIMD floating-point exception flag that is already set when the corresponding exception is unmasked will not generate a fault; only the next occurrence of that exception will generate an unmasked fault.
    - An application which checks FSW to determine if any masked exception flags were set during an x87-FP library call will also need to check MXCSR in order to observe a similar occurrence of a masked exception within a Streaming SIMD Extensions library.

11.7.3. SIMD Floating-point Numeric Exception Conditions and Masked/Unmasked Responses

The following sections describe the various conditions that cause a SIMD floating-point numeric exception to be generated and the masked response of the processor when these conditions are detected.

11.7.3.1. INVALID OPERATION EXCEPTION(#IA)

The invalid operation exception occurs in response to an invalid arithmetic operand, or to an invalid combination of operands.

If the invalid operation exception is masked, the processor sets the IE flag in MXCSR and returns the single-precision QNaN indefinite value or another QNaN value (derived from a NaN input operand) to the destination operand. This value overwrites the destination register specified by the instruction.

If the invalid operation exception is not masked, the processor sets the IE flag in MXCSR and an exception handler is invoked (see Section 11.7.2.3., “Software Exception Handling - Unmasked Exceptions”) and the operands remain unchanged.

The processor can detect a variety of invalid arithmetic operations that can be coded in a program. These operations generally indicate a programming error, such as dividing ∞ by ∞. Table 11-8 lists the SIMD floating-point invalid arithmetic operations that the processor detects. This group includes the invalid operations defined in IEEE Std. 854.

The flag (IE) for this exception is bit 0 of MXCSR, and the mask bit (IM) is bit 7 of MXCSR.

The invalid operation exception is not affected by the flush-to-zero mode.

Table 11-8. Invalid Arithmetic Operations and the Masked Responses to Them

Condition	Masked Response
ADDPS/ADDSS/DIVPS/DIVSS/ MULPS/MULSS/SUBPS/SUBSS with a SNaN operand.	Return the Signaling NaN converted to a quiet NaN; Refer to Table 7-18, in Chapter 7, *Floating-Point Unit*, for more details; set #IA flag.
CMPPS/CMPSS with QNaN/SNaN operands (QNaN applies only for predicates "lt", "le", "nlt", "nle")	Return a mask of all 0's for predicates "eq", "lt", "le", and "ord", and a mask of all 1's for predicates "neq", "nlt", "nle", and "unord"; set #IA flag.
COMISS with QNaN/SNaN operand(s).	Set EFLAGS values to 'not comparable'; set #IA flag.
UCOMISS with SNaN operand(s).	Set EFLAGS values to 'not comparable'; set #IA flag.
SQRTPS/SQRTSS with SNaN operand(s).	Return the SNan converted to a QNaN; set #IA flag;
Addition of opposite signed infinities or subtraction of like-signed infinities.	Return the QNaN Indefinite; set #IA flag.
Multiplication of infinity by zero.	Return the QNaN Indefinite; set #IA flag.
Divide of (0/0) or(∞ / ∞ .)	Return the QNaN Indefinite; set #IA flag.
SQRTPS/SQRTSS of negative operands (except negative zero).	Return the QNaN Indefinite; set #IA flag.
Conversion to integer when the source register is a NaN, Infinity or exceeds the representable range.	Return the Integer Indefinite; set #IA flag.

NOTE:

RCPPS/RCPSS/RSQRTPS/RSQRTSS with QNaN/SNaN operand(s) do not raise an invalid exception. They return either the SNaN operand converted to QNaN, or the original QNaN operand. RSQRTPS/RSQRTSS with negative operands (but not for negative zero) do not raise an invalid exception, and return QNaN Indefinite.

11.7.3.2. DIVISION-BY-ZERO EXCEPTION (#Z)

The processor reports a divide-by-zero exception whenever an instruction attempts to divide a finite non-zero operand by 0. This is possible with DIVPS, DIVSS.

The masked response for DIVPS, DIVSS is to set the ZE flag in MXCSR and return an infinity signed with the exclusive OR of the signs of the operands. If the divide-by-zero exception is not masked, the ZE flag is set, a software exception handler is invoked (see Section 11.7.2.3., "Software Exception Handling - Unmasked Exceptions") and the source operands remain unchanged.

Note that the response for RCPPS, RSQRTPS, RCPSS and RSQRTSS is to return an infinity of the same sign as the operand. These instructions do not set any exception flags and thus are not affected by the exception masks.

The flag (ZE) for the divide-by-zero exception is bit 2 of MXCSR, and the mask bit (ZM) is bit 9 of MXCSR.

The divide-by-zero exception is not affected by the flush-to-zero mode.

11.7.3.3. DENORMAL OPERAND EXCEPTION (#D)

The processor signals the denormal operand exception if an arithmetic instruction attempts to operate on a denormal operand.

When a denormal operand exception occurs and the exception is masked, the processor sets the DE flag in MXCSR, then proceeds with the instruction. Operating on denormal numbers will produce results at least as good as, and often better than, what can be obtained when denormal numbers are flushed to zero. Programmers can mask this exception so that a computation may proceed, then analyze any loss of accuracy when the final result is delivered.

When a denormal operand exception occurs and the exception is not masked, the processor sets the DE bit in MXCSR and a software exception handler is invoked (see Section 11.7.2.3., “Software Exception Handling - Unmasked Exceptions”). The source operands remain unchanged. When denormal operands have reduced significance due to loss of low-order bits, it may be advisable to not operate on them. Precluding denormal operands from computations can be accomplished by an exception handler that responds to unmasked denormal operand exceptions.

Note that the response for RCPPS, RSQRTPS, RCPSS and RSQRTSS is to return an infinity of the same sign as the operand. These instructions do not set any exception flags and thus are not affected by the exception masks.

Conversion instructions (CVTPI2PS, CVTPS2PI, CVTTPS2PI, CVTSI2SS, CVTSS2SI, CVTTSS2SI) do not signal denormal exceptions.

The flag (DE) for this exception is bit 1 of MXCSR, and the mask bit (DM) is bit 8 of MXCSR.

The denormal operand exception is not affected by the flush-to-zero mode.

11.7.3.4. NUMERIC OVERFLOW EXCEPTION (#O)

The processor reports a floating-point numeric overflow exception whenever the result of an instruction rounded to the destination precision with unbounded exponent exceeds the largest allowable finite value that will fit into the destination operand. This is possible with ADDPS, ADDSS, SUBPS, SUBSS, MULPS, MULSS, DIVPS, DIVSS.

When a numeric overflow exception occurs and the exception is masked, the processor sets the MXCSR.OE and MXCSR.PE flags and returns one of the values shown in Table 11-9 according to the current rounding mode of the processor (see Section 11.3.2.1., “Rounding Control Field”).

When a numeric overflow exception occurs and the exception is unmasked, the operands are left unaltered and a software exception handler is invoked (see Section 11.7.2.3., “Software Exception Handling - Unmasked Exceptions”). The MXCSR.OE flag is set; the MXCSR.PE flag is only set if a loss of accuracy has occurred in addition to overflow when rounding the result to the destination precision, with unbounded exponent.

The flag (OE) for the numeric overflow exception is bit 3 of MXCSR, and the mask bit (OM) is bit 10 of MXCSR.

The numeric overflow exception is not affected by the flush-to-zero mode.

Note that the overflow status flag is not set by RCPPS/RCPSS, since these instructions are combinatorial and are not affected by exception masks.

Table 11-9. Masked Responses to Numeric Overflow

Rounding Mode	Sign of True Result	Result
To nearest	+	+∞
	–	–∞
Toward –∞	+	Largest finite positive number
	–	–∞
Toward +∞	+	+∞
	–	Largest finite negative number
Toward zero	+	Largest finite positive number
	–	Largest finite negative number

11.7.3.5. NUMERIC UNDERFLOW EXCEPTION (#U)

The processor might report a floating-point numeric underflow exception whenever the rounded result of an arithmetic instruction is tiny; that is, the result rounded to the destination precision with unbounded exponent is less than the smallest possible normalized, finite value that will fit into the destination operand. The Underflow exception can occur in the execution of the instructions ADDPS, ADDSS, SUBPS, SUBSS, MULPS, MULSS, DIVPS and DIVSS.

Two related events contribute to underflow:

- Creation of a tiny result which, because it is so small, may cause some other exception later (such as overflow upon division).
- Creation of an inexact result; i.e. the delivered result differs from what would have been computed were both the exponent and precision unbounded.

Which of these events triggers the underflow exception depends on whether the underflow exception is masked:

- Underflow exceptions masked. The underflow exception is signaled when the result is both tiny and inexact.
- Underflow exceptions not masked: The underflow exception is signaled when the result is tiny, regardless of inexactness.

The response to an underflow exception also depends on whether the exception is masked:

- Masked response: The result is normal, denormal or zero. The precision exception is also triggered. The OE and PE flags are set in MXCSR.
- Unmasked response: The UE flag is set in MXCSR. If the original computation generated an imprecise mantissa, the inexact (#P) status flag PE will also be set in the MXCSR. In either case (result imprecise or not), the underflow (#U) status flag is set, the operands are

left unaltered, and a software exception handler is invoked (see Section 11.7.2.3., “Software Exception Handling - Unmasked Exceptions”).

If underflow is masked and flush-to-zero mode is enabled, an underflow condition will set the underflow (#U) and inexact (#P) status flags UE and PE in MXCSR and a correctly signed zero result will be returned; this will avoid the performance penalty associated with generating a denormalized result. If underflow is unmasked, the flush-to-zero mode is ignored and an underflow condition will be handled as described above.

Note that the underflow status flag is not set by RCPPS/RCPSS, since these instructions are combinatorial and are not affected by exception masks.

The flag (UE) for the numeric underflow exception is bit 4 of MXCSR and the mask bit (UM) is bit 11 of MXCSR.

11.7.3.6. INEXACT RESULT (PRECISION) EXCEPTION (#P)

The inexact result exception (also called the precision exception) occurs if the result of an operation is not exactly representable in the destination format. For example, the fraction 1/3 cannot be precisely represented in binary form. This exception occurs frequently and indicates that some (normally acceptable) accuracy has been lost. The exception is supported for applications that need to perform exact arithmetic only. Because the rounded result is generally satisfactory for most applications, this exception is commonly masked.

If the inexact result exception is masked when an inexact result condition occurs and a numeric overflow or underflow condition has not occurred, the processor sets the inexact (#P) status flag (PE flag) and stores the rounded result in the destination operand. The current rounding mode determines the method used to round the result (refer to Section 11.3.2.1., “Rounding Control Field”).

If the inexact result exception is not masked when an inexact result occurs and numeric overflow or underflow has not occurred, the operands are left unaltered, the PE flag is set in MXCSR, the inexact (#P) status flag is set, and a software exception handler is invoked (see Section 11.7.2.3., “Software Exception Handling - Unmasked Exceptions”).

If an inexact result occurs in conjunction with numeric overflow or underflow, one of the following operations is carried out:

- If an inexact result occurs along with masked overflow or underflow, the OE or UE flag and the PE flag are set in MXCSR and the result is stored as described for the overflow or underflow exceptions (see Section 11.7.3.4., “Numeric Overflow Exception (#O)”. or Section 11.7.3.5., “Numeric Underflow Exception (#U)”). If the inexact result exception is unmasked, the processor also invokes the software exception handler.
- If an inexact result occurs along with unmasked overflow or underflow, the OE or UE flag and the PE flag are set and the software exception handler is invoked.

Note that the inexact result flag is not set by RCPPS, RSQRTPS, RCPSS and RSQRTSS, since these instructions are combinatorial and are not affected by the exception masks.

The inexact result exception flag (PE) is bit 5 of MXCSR, and the mask bit (PM) is bit 12 of MXCSR.

In flush-to-zero mode, the inexact result exception is reported along with the underflow exception (the latter must be masked).

11.7.4. Effect of Streaming SIMD Extensions Instructions on Pending Floating-Point Exceptions

Unlike MMX™ instructions which will generate a floating-point error (#MF) prior to executing the MMX™ instruction, execution of a Streaming SIMD Extensions instruction does not generate a floating-point error (#MF) prior to executing the instruction. Hence they will not catch pending x87 floating-point exceptions. In addition, they will not cause assertion of FERR# (independent of the value of CR0.NE) and they ignore the assertion/de-assertion of IGNNE#.

11.8. DEBUGGING

The debug facilities of the Intel Architecture operate in the same manner when executing Streaming SIMD Extensions as when executing other Intel Architecture instructions. These facilities enable debuggers to debug code utilizing these instructions.

To correctly interpret the contents of the Pentium® III processor registers from the FXSAVE image in memory, a debugger needs to take account of the relationship between the floating-point register's logical locations relative to TOS and the MMX™ register's physical locations (refer to Section 10.6., "Debugging", Chapter 10, *MMX™ Technology System Programming*). In addition it needs to have knowledge of the SIMD floating-point registers and the state save data area used by the FXSAVE instruction.

Comparisons of the Streaming SIMD Extensions and x87 results can be performed within the Pentium® III processor at the internal single precision format and/or externally at the memory single precision format. The internal format comparison is required to allow the partitioning of the data space to reduce test time.

12

System Management Mode

CHAPTER 12
SYSTEM MANAGEMENT MODE (SMM)

This chapter describes the Intel Architecture's System Management Mode (SMM) architecture. SMM was introduced into the Intel Architecture in the Intel386™ SL processor (a mobile specialized version of the Intel386™ processor). It is also available in the Intel486™ processors (beginning with the Intel486™ SL and Intel486™ enhanced versions) and in the Intel Pentium® and P6 family processors. For a detailed description of the hardware that supports SMM, refer to the developer's manuals for each of the Intel Architecture processors.

12.1. SYSTEM MANAGEMENT MODE OVERVIEW

SMM is a special-purpose operating mode provided for handling system-wide functions like power management, system hardware control, or proprietary OEM-designed code. It is intended for use only by system firmware, not by applications software or general-purpose systems software. The main benefit of SMM is that it offers a distinct and easily isolated processor environment that operates transparently to the operating system or executive and software applications.

When SMM is invoked through a system management interrupt (SMI), the processor saves the current state of the processor (the processor's context), then switches to a separate operating environment contained in system management RAM (SMRAM). While in SMM, the processor executes SMI handler code to perform operations such as powering down unused disk drives or monitors, executing proprietary code, or placing the whole system in a suspended state. When the SMI handler has completed its operations, it executes a resume (RSM) instruction. This instruction causes the processor to reload the saved context of the processor, switch back to protected or real mode, and resume executing the interrupted application or operating-system program or task.

The following SMM mechanisms make it transparent to applications programs and operating systems:

- The only way to enter SMM is by means of an SMI.
- The processor executes SMM code in a separate address space (SMRAM) that can be made inaccessible from the other operating modes.
- Upon entering SMM, the processor saves the context of the interrupted program or task.
- All interrupts normally handled by the operating system are disabled upon entry into SMM.
- The RSM instruction can be executed only in SMM.

SMM is similar to real-address mode in that there are no privilege levels or address mapping. An SMM program can address up to 4 GBytes of memory and can execute all I/O and applicable system instructions. Refer to Section 12.5., "SMI Handler Execution Environment" for more information about the SMM execution environment.

NOTE

The physical address extension (PAE) mechanism available in the P6 family processors is not supported when a processor is in SMM.

12.2. SYSTEM MANAGEMENT INTERRUPT (SMI)

The only way to enter SMM is by signaling an SMI through the SMI# pin on the processor or through an SMI message received through the APIC bus. The SMI is a nonmaskable external interrupt that operates independently from the processor's interrupt- and exception-handling mechanism and the local APIC. The SMI takes precedence over an NMI and a maskable interrupt. SMM is nonreentrant; that is, the SMI is disabled while the processor is in SMM.

NOTE

In the P6 family processors, when a processor that is designated as the application processor during an MP initialization protocol is waiting for a startup IPI, it is in a mode where SMIs are masked.

12.3. SWITCHING BETWEEN SMM AND THE OTHER PROCESSOR OPERATING MODES

Figure 2-2 in Chapter 2, *System Architecture Overview* shows how the processor moves between SMM and the other processor operating modes (protected, real-address, and virtual-8086). Signaling an SMI while the processor is in real-address, protected, or virtual-8086 modes always causes the processor to switch to SMM. Upon execution of the RSM instruction, the processor always returns to the mode it was in when the SMI occurred.

12.3.1. Entering SMM

The processor always handles an SMI on an architecturally defined "interruptible" point in program execution (which is commonly at an Intel Architecture instruction boundary). When the processor receives an SMI, it waits for all instructions to retire and for all stores to complete. The processor then saves its current context in SMRAM (refer to Section 12.4., "SMRAM"), enters SMM, and begins to execute the SMI handler.

Upon entering SMM, the processor signals external hardware that SMM handling has begun. The signaling mechanism used is implementation dependent. For the P6 family processors, an SMI acknowledge transaction is generated on the system bus and the multiplexed status signal EXF4 is asserted each time a bus transaction is generated while the processor is in SMM. For the Pentium® and Intel486™ processors, the SMIACT# pin is asserted.

An SMI has a greater priority than debug exceptions and external interrupts. Thus, if an NMI, maskable hardware interrupt, or a debug exception occurs at an instruction boundary along with an SMI, only the SMI is handled. Subsequent SMI requests are not acknowledged while the processor is in SMM. The first SMI interrupt request that occurs while the processor is in SMM

(that is, after SMM has been acknowledged to external hardware) is latched and serviced when the processor exits SMM with the RSM instruction. The processor will latch only one SMI while in SMM.

Refer to Section 12.5., “SMI Handler Execution Environment” for a detailed description of the execution environment when in SMM.

12.3.1.1. EXITING FROM SMM

The only way to exit SMM is to execute the RSM instruction. The RSM instruction is only available to the SMI handler; if the processor is not in SMM, attempts to execute the RSM instruction result in an invalid-opcode exception (#UD) being generated.

The RSM instruction restores the processor’s context by loading the state save image from SMRAM back into the processor’s registers. The processor then returns an SMIACK transaction on the system bus and returns program control back to the interrupted program.

Upon successful completion of the RSM instruction, the processor signals external hardware that SMM has been exited. For the P6 family processors, an SMI acknowledge transaction is generated on the system bus and the multiplexed status signal EXF4 is no longer generated on bus cycles. For the Pentium® and Intel486™ processors, the SMIACT# pin is deserted.

If the processor detects invalid state information saved in the SMRAM, it enters the shutdown state and generates a special bus cycle to indicate it has entered shutdown state. Shutdown happens only in the following situations:

- A reserved bit in control register CR4 is set to 1 on a write to CR4. This error should not happen unless SMI handler code modifies reserved areas of the SMRAM saved state map (refer to Section 12.4.1., “SMRAM State Save Map”). Note that CR4 is not distinctly part of the saved state map.
- An illegal combination of bits is written to control register CR0, in particular PG set to 1 and PE set to 0, or NW set to 1 and CD set to 0.
- (For the Pentium® and Intel486™ processors only.) If the address stored in the SMBASE register when an RSM instruction is executed is not aligned on a 32-KByte boundary. This restriction does not apply to the P6 family processors.

In shutdown state, the processor stops executing instructions until a RESET#, INIT# or NMI# is asserted. The processor also recognizes the FLUSH# signal while in the shutdown state. In addition, the Pentium® processor recognizes the SMI# signal while in shutdown state, but the P6 family and Intel486™ processors do not. (It is not recommended that the SMI# pin be asserted on a Pentium® processor to bring the processor out of shutdown state, because the action of the processor in this circumstance is not well defined.)

If the processor is in the HALT state when the SMI is received, the processor handles the return from SMM slightly differently (refer to Section 12.10., “Auto HALT Restart”). Also, the SMBASE address can be changed on a return from SMM (refer to Section 12.11., “SMBASE Relocation”).

12.4. SMRAM

While in SMM, the processor executes code and stores data in the SMRAM space. The SMRAM space is mapped to the physical address space of the processor and can be up to 4 GBytes in size. The processor uses this space to save the context of the processor and to store the SMI handler code, data and stack. It can also be used to store system management information (such as the system configuration and specific information about powered-down devices) and OEM-specific information.

The default SMRAM size is 64 KBytes beginning at a base physical address in physical memory called the SMBASE (refer to Figure 12-1). The SMBASE default value following a hardware reset is 30000H. The processor looks for the first instruction of the SMI handler at the address [SMBASE + 8000H]. It stores the processor's state in the area from [SMBASE + FE00H] to [SMBASE + FFFFH]. Refer to Section 12.4.1., "SMRAM State Save Map" for a description of the mapping of the state save area.

The system logic is minimally required to decode the physical address range for the SMRAM from [SMBASE + 8000H] to [SMBASE + FFFFH]. A larger area can be decoded if needed. The size of this SMRAM can be between 32 KBytes and 4 GBytes.

The location of the SMRAM can be changed by changing the SMBASE value (refer to Section 12.11., "SMBASE Relocation"). It should be noted that all processors in a multiple-processor system are initialized with the same SMBASE value (30000H). Initialization software must sequentially place each processor in SMM and change its SMBASE so that it does not overlap those of other processors.

The actual physical location of the SMRAM can be in system memory or in a separate RAM memory. The processor generates an SMI acknowledge transaction (P6 family processors) or asserts the SMIACT# pin (Pentium® and Intel486™ processors) when the processor receives an SMI (refer to Section 12.3.1., "Entering SMM"). System logic can use the SMI acknowledge transaction or the assertion of the SMIACT# pin to decode accesses to the SMRAM and redirect them (if desired) to specific SMRAM memory. If a separate RAM memory is used for SMRAM, system logic should provide a programmable method of mapping the SMRAM into system memory space when the processor is not in SMM. This mechanism will enable start-up procedures to initialize the SMRAM space (that is, load the SMI handler) before executing the SMI handler during SMM.

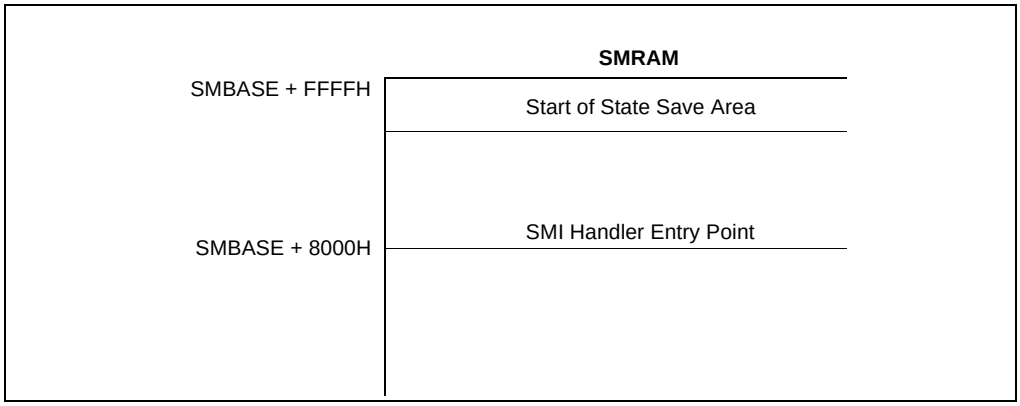


Figure 12-1. SMRAM Usage

12.4.1. SMRAM State Save Map

When the processor initially enters SMM, it writes its state to the state save area of the SMRAM. The state save area begins at [SMBASE + 8000H + 7FFFH] and extends down to [SMBASE + 8000H + 7E00H]. Table 12-1 shows the state save map. The offset in column 1 is relative to the SMBASE value plus 8000H. Reserved spaces should not be used by software.

Some of the registers in the SMRAM state save area (marked YES in column 3) may be read and changed by the SMI handler, with the changed values restored to the processor registers by the RSM instruction. Some register images are read-only, and must not be modified (modifying these registers will result in unpredictable behavior). An SMI handler should not rely on any values stored in an area that is marked as reserved.

Table 12-1. SMRAM State Save Map

Offset (Added to SMBASE + 8000H)	Register	Writable?
7FFCH	CR0	No
7FF8H	CR3	No
7FF4H	EFLAGS	Yes
7FF0H	EIP	Yes
7FECH	EDI	Yes
7FE8H	ESI	Yes
7FE4H	EBP	Yes
7FE0H	ESP	Yes
7FDCH	EBX	Yes
7FD8H	EDX	Yes
7FD4H	ECX	Yes

Table 12-1. SMRAM State Save Map (Contd.)

Offset (Added to SMBASE + 8000H)	Register	Writable?
7FD0H	EAX	Yes
7FCCH	DR6	No
7FC8H	DR7	No
7FC4H	TR*	No
7FC0H	LDT Base*	No
7FBCH	GS*	No
7FB8H	FS*	No
7FB4H	DS*	No
7FB0H	SS*	No
7FACH	CS*	No
7FA8H	ES*	No
7FA7H - 7F04H	Reserved	No
7F02H	Auto HALT Restart Field (Word)	Yes
7F00H	I/O Instruction Restart Field (Word)	Yes
7EFCH	SMM Revision Identifier Field (Doubleword)	No
7EF8H	SMBASE Field (Doubleword)	Yes
7EF7H - 7E00H	Reserved	No

NOTE:

* Upper two bytes are reserved.

The following registers are saved (but not readable) and restored upon exiting SMM:

- Control register CR4 (CR4 is set to “0” while in the SMM handler).
- The hidden segment descriptor information stored in segment registers CS, DS, ES, FS, GS, and SS.

If an SMI request is issued for the purpose of powering down the processor, the values of all reserved locations in the SMM state save must be saved to nonvolatile memory.

The following state is not automatically saved and restored following an SMI and the RSM instruction, respectively:

- Debug registers DR0 through DR3.
- The FPU registers.
- The MTRRs.
- Control register CR2.
- The model-specific registers (for the P6 family and Pentium® processors) or test registers TR3 through TR7 (for the Pentium® and Intel486™ processors).

- The state of the trap controller.
- The machine-check architecture registers.
- The APIC internal interrupt state (ISR, IRR, etc.).
- The microcode update state.

If an SMI is used to power down the processor, a power-on reset will be required before returning to SMM, which will reset much of this state back to its default values. So an SMI handler that is going to trigger power down should first read these registers listed above directly, and save them (along with the rest of RAM) to nonvolatile storage. After the power-on reset, the continuation of the SMI handler should restore these values, along with the rest of the system's state. Anytime the SMI handler changes these registers in the processor, it must also save and restore them.

NOTE

A small subset of the MSRs (such as, the time-stamp counter and performance-monitoring counter) are not arbitrarily writable and therefore cannot be saved and restored. SMM-based power-down and restoration should only be performed with operating systems that do not use or rely on the values of these registers. Operating system developers should be aware of this fact and ensure that their operating-system assisted power-down and restoration software is immune to unexpected changes in these register values.

12.4.2. SMRAM Caching

An Intel Architecture processor supporting SMM does not unconditionally write back and invalidate its cache before entering SMM. Therefore, if SMRAM is in a location that is "shadowed" by any existing system memory that is visible to the application or operating system, then it is necessary for the system to flush the cache upon entering SMM. This may be accomplished by asserting the FLUSH# pin at the same time as the request to enter SMM. The priorities of the FLUSH# pin and the SMI# are such that the FLUSH# will be serviced first. To guarantee this behavior, the processor requires that the following constraints on the interaction of SMI# and FLUSH# be met.

In a system where the FLUSH# pin and SMI# pins are synchronous and the set up and hold times are met, then the FLUSH# and SMI# pins may be asserted in the same clock. In asynchronous systems, the FLUSH# pin must be asserted at least one clock before the SMI# pin to guarantee that the FLUSH# pin is serviced first. Note that in Pentium® processor systems that use the FLUSH# pin to write back and invalidate cache contents before entering SMM, the processor will prefetch at least one cache line in between when the Flush Acknowledge cycle is run, and the subsequent recognition of SMI# and the assertion of SMIACT#. It is the obligation of the system to ensure that these lines are not cached by returning KEN# inactive to the Pentium® processor.

Intel Architecture processors do not write back or invalidate their internal caches upon leaving SMM. For this reason, references to the SMRAM area must not be cached if any part of the SMRAM shadows (overlays) non-SMRAM memory; that is, system DRAM or video RAM. It is the obligation of the system to ensure that all memory references to overlapped areas are uncached; that is, the KEN# pin is sampled inactive during all references to the SMRAM area for the Pentium® processor. The WBINVD instruction should be used to ensure cache coherency at the end of a cached SMM execution in systems that have a protected SMM memory region provided by the chipset.

The P6 family of processors have no external equivalent of the KEN# pin. All memory accesses are typed via the MTRRs. It is not practical therefore to have memory access to a certain address be cached in one access and not cached in another. Intel does not recommend the caching of SMM space in any overlapping memory environment on the P6 family of processors.

12.5. SMI HANDLER EXECUTION ENVIRONMENT

After saving the current context of the processor, the processor initializes its core registers to the values shown in Table 12-2. Upon entering SMM, the PE and PG flags in control register CR0 are cleared, which places the processor is in an environment similar to real-address mode. The differences between the SMM execution environment and the real-address mode execution environment are as follows:

- The addressable SMRAM address space ranges from 0 to FFFFFFFFH (4 GBytes). (The physical address extension (enabled with the PAE flag in control register CR4) is not supported in SMM.)
- The normal 64-KByte segment limit for real-address mode is increased to 4 GBytes.
- The default operand and address sizes are set to 16 bits, which restricts the addressable SMRAM address space to the 1-MByte real-address mode limit for native real-address-mode code. However, operand-size and address-size override prefixes can be used to access the address space beyond the 1-MByte.
- Near jumps and calls can be made to anywhere in the 4-GByte address space if a 32-bit operand-size override prefix is used. Due to the real-address-mode style of base-address formation, a far call or jump cannot transfer control to a segment with a base address of more than 20 bits (1 MByte). However, since the segment limit in SMM is 4 GBytes, offsets into a segment that go beyond the 1-MByte limit are allowed when using 32-bit operand-size override prefixes. Any program control transfer that does not have a 32-bit operand-size override prefix truncates the EIP value to the 16 low-order bits.

Table 12-2. Processor Register Initialization in SMM

Register	Contents
General-purpose registers	Undefined
EFLAGS	00000002H
EIP	00008000H
CS selector	SMM Base shifted right 4 bits (default 3000H)
CS base	SMM Base (default 30000H)
DS, ES, FS, GS, SS Selectors	0000H
DS, ES, FS, GS, SS Bases	000000000H
DS, ES, FS, GS, SS Limits	0FFFFFFFFH
CR0	PE, EM, TS and PG flags set to 0; others unmodified
DR6	Undefined
DR7	00000400H

- Data and the stack can be located anywhere in the 4-GByte address space, but can be accessed only with a 32-bit address-size override if they are located above 1 MByte. As with the code segment, the base address for a data or stack segment cannot be more than 20 bits.

The value in segment register CS is automatically set to the default of 30000H for the SMBASE shifted 4 bits to the right; that is, 3000H. The EIP register is set to 8000H. When the EIP value is added to shifted CS value (the SMBASE), the resulting linear address points to the first instruction of the SMI handler.

The other segment registers (DS, SS, ES, FS, and GS) are cleared to 0 and their segment limits are set to 4 GBytes. In this state, the SMRAM address space may be treated as a single flat 4-Gbyte linear address space. If a segment register is loaded with a 16-bit value, that value is then shifted left by 4 bits and loaded into the segment base (hidden part of the segment register). The limits and attributes are not modified.

Maskable hardware interrupts, exceptions, NMI interrupts, SMI interrupts, A20M interrupts, single-step traps, breakpoint traps, and INIT operations are inhibited when the processor enters SMM. Maskable hardware interrupts, exceptions, single-step traps, and breakpoint traps can be enabled in SMM if the SMM execution environment provides and initializes an interrupt table and the necessary interrupt and exception handlers (refer to Section 12.6., “Exceptions and Interrupts Within SMM”).

12.6. EXCEPTIONS AND INTERRUPTS WITHIN SMM

When the processor enters SMM, all hardware interrupts are disabled in the following manner:

- The IF flag in the EFLAGS register is cleared, which inhibits maskable hardware interrupts from being generated.
- The TF flag in the EFLAGS register is cleared, which disables single-step traps
- Debug register DR7 is cleared, which disables breakpoint traps. (This action prevents a debugger from accidentally breaking into an SMM handler if a debug breakpoint is set in normal address space that overlays code or data in SMRAM.)
- NMI, SMI, and A20M interrupts are blocked by internal SMM logic. (Refer to Section 12.7., “NMI Handling While in SMM” for further information about how NMIs are handled in SMM.)

Software-invoked interrupts and exceptions can still occur, and maskable hardware interrupts can be enabled by setting the IF flag. Intel recommends that SMM code be written in so that it does not invoke software interrupts (with the INT *n*, INTO, INT 3, or BOUND instructions) or generate exceptions.

If the SMM handler requires interrupt and exception handling, an SMM interrupt table and the necessary exception and interrupt handlers must be created and initialized from within SMM. Until the interrupt table is correctly initialized (using the LIDT instruction), exceptions and software interrupts will result in unpredictable processor behavior.

The following restrictions apply when designing SMM interrupt and exception-handling facilities:

- The interrupt table should be located at linear address 0 and must contain real-address mode style interrupt vectors (4 bytes containing CS and IP).
- Due to the real-address mode style of base address formation, an interrupt or exception cannot transfer control to a segment with a base address of more that 20 bits.
- An interrupt or exception cannot transfer control to a segment offset of more than 16 bits (64 KBytes).
- When an exception or interrupt occurs, only the 16 least-significant bits of the return address (EIP) are pushed onto the stack. If the offset of the interrupted procedure is greater than 64 KBytes, it is not possible for the interrupt/exception handler to return control to that procedure. (One solution to this problem is for a handler to adjust the return address on the stack.)
- The SMBASE relocation feature affects the way the processor will return from an interrupt or exception generated while the SMI handler is executing. For example, if the SMBASE is relocated to above 1 MByte, but the exception handlers are below 1 MByte, a normal return to the SMI handler is not possible. One solution is to provide the exception handler with a mechanism for calculating a return address above 1 MByte from the 16-bit return address on the stack, then use a 32-bit far call to return to the interrupted procedure.

- If an SMI handler needs access to the debug trap facilities, it must insure that an SMM accessible debug handler is available and save the current contents of debug registers DR0 through DR3 (for later restoration). Debug registers DR0 through DR3 and DR7 must then be initialized with the appropriate values.
- If an SMI handler needs access to the single-step mechanism, it must insure that an SMM accessible single-step handler is available, and then set the TF flag in the EFLAGS register.
- If the SMI design requires the processor to respond to maskable hardware interrupts or software-generated interrupts while in SMM, it must ensure that SMM accessible interrupt handlers are available and then set the IF flag in the EFLAGS register (using the STI instruction). Software interrupts are not blocked upon entry to SMM, so they do not need to be enabled.

12.7. NMI HANDLING WHILE IN SMM

NMI interrupts are blocked upon entry to the SMI handler. If an NMI request occurs during the SMI handler, it is latched and serviced after the processor exits SMM. Only one NMI request will be latched during the SMI handler. If an NMI request is pending when the processor executes the RSM instruction, the NMI is serviced before the next instruction of the interrupted code sequence.

Although NMI requests are blocked when the CPU enters SMM, they may be enabled through software by executing an IRET/IRETD instruction. If the SMM handler requires the use of NMI interrupts, it should invoke a dummy interrupt service routine for the purpose of executing an IRET/IRETD instruction. Once an IRET/IRETD instruciton is executed, NMI interrupt requrests are serviced in the same “real mode” manner in which they are handled outside of SMM.

A special case can occur if an SMI handler nests inside an NMI handler and then another NMI occurs. During NMI interrupt handling, NMI interrupts are disabled, so normally NMI interrupts are serviced and completed with an IRET instruction one at a time. When the processor enters SMM while executing an NMI handler, the processor saves the SMRAM state save map but does not save the attribute to keep NMI interrupts disabled. Potentially, an NMI could be latched (while in SMM or upon exit) and serviced upon exit of SMM even though the previous NMI handler has still not completed. One or more NMIs could thus be nested inside the first NMI handler. The NMI interrupt handler should take this possibility into consideration.

Also, for the Pentium® processor, exceptions that invoke a trap or fault handler will enable NMI interrupts from inside of SMM. This behavior is implementation specific for the Pentium® processor and is not part the Intel Architecture.

12.8. SAVING THE FPU STATE WHILE IN SMM

In some instances (for example prior to powering down system memory when entering a 0-volt suspend state), it is necessary to save the state of the FPU while in SMM. Care should be taken when performing this operation to insure that relevant FPU state information is not lost. The

safest way to perform this task is to place the processor in 32-bit protected mode before saving the FPU state. The reason for this is as follows.

The FSAVE instruction saves the FPU context in any of four different formats, depending on which mode the processor is in when FSAVE is executed (refer to Figures 7-13 through 7-16 in the *Intel Architecture Software Developer's Manual, Volume 1*). When in SMM, by default, the 16-bit real-address mode format is used (shown in Figure 7-16). If an SMI interrupt occurs while the processor is in a mode other than 16-bit real-address mode, FSAVE and FRSTOR will be unable to save and restore all the relevant FPU information, and this situation may result in a malfunction when the interrupted program is resumed. To avoid this problem, the processor should be in 32-bit protected mode when executing the FSAVE and FRSTOR instructions.

The following guidelines should be used when going into protected mode from an SMI handler to save and restore the FPU state:

- Use the CPUID instruction to insure that the processor contains an FPU.
- Create a 32-bit code segment in SMRAM space that contains procedures or routines to save and restore the FPU using the FSAVE and FRSTOR instructions, respectively. A GDT with an appropriate code-segment descriptor (D bit is set to 1) for the 32-bit code segment must also be placed in SMRAM.
- Write a procedure or routine that can be called by the SMI handler to save and restore the FPU state. This procedure should do the following:
  - — Place the processor in 32-bit protected mode as describe in Section 8.8.1., "Switching to Protected Mode" in Chapter 8, *Processor Management and Initialization*.
  - — Execute a far JMP to the 32-bit code segment that contains the FPU save and restore procedures.
  - — Place the processor back in 16-bit real-address mode before returning to the SMI handler (refer to Section 8.8.2., "Switching Back to Real-Address Mode" in Chapter 8, *Processor Management and Initialization*).

The SMI handler may continue to execute in protected mode after the FPU state has been saved and return safely to the interrupted program from protected mode. However, it is recommended that the handler execute primarily in 16- or 32-bit real-address mode.

12.9. SMM REVISION IDENTIFIER

The SMM revision identifier field is used to indicate the version of SMM and the SMM extensions that are supported by the processor (refer to Figure 12-2). The SMM revision identifier is written during SMM entry and can be examined in SMRAM space at offset 7EFCH. The lower word of the SMM revision identifier refers to the version of the base SMM architecture.

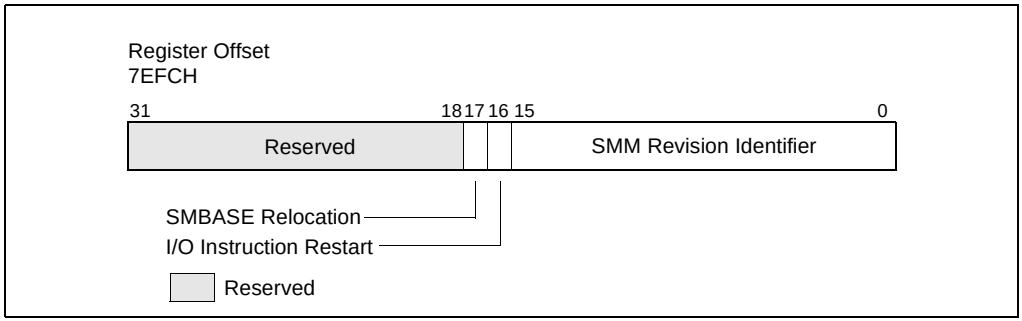


Figure 12-2. SMM Revision Identifier

The upper word of the SMM revision identifier refers to the extensions available. If the I/O instruction restart flag (bit 16) is set, the processor supports the I/O instruction restart (refer to Section 12.12., "I/O Instruction Restart"); if the SMBASE relocation flag (bit 17) is set, SMRAM base address relocation is supported (refer to Section 12.11., "SMBASE Relocation").

12.10. AUTO HALT RESTART

If the processor is in a HALT state (due to the prior execution of a HLT instruction) when it receives an SMI, the processor records the fact in the auto HALT restart flag in the saved processor state (refer to Figure 12-3). (This flag is located at offset 7F02H and bit 0 in the state save area of the SMRAM.)

If the processor sets the auto HALT restart flag upon entering SMM (indicating that the SMI occurred when the processor was in the HALT state), the SMI handler has two options:

- It can leave the auto HALT restart flag set, which instructs the RSM instruction to return program control to the HLT instruction. This option in effect causes the processor to re-enter the HALT state after handling the SMI. (This is the default operation.)
- It can clear the auto HALT restart flag, with instructs the RSM instruction to return program control to the instruction following the HLT instruction.

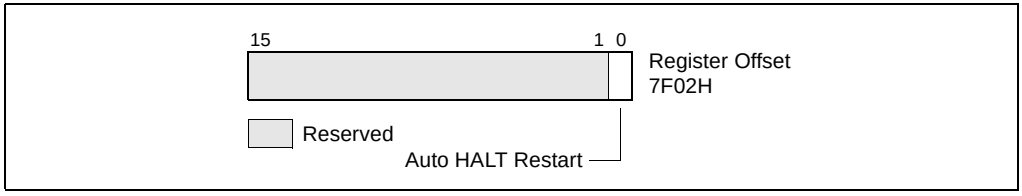


Figure 12-3. Auto HALT Restart Field

These options are summarized in Table 12-3. Note that if the processor was not in a HALT state when the SMI was received (the auto HALT restart flag is cleared), setting the flag to 1 will cause unpredictable behavior when the RSM instruction is executed.

Table 12-3. Auto HALT Restart Flag Values

Value of Flag After Entry to SMM	Value of Flag When Exiting SMM	Action of Processor When Exiting SMM
0	0	Returns to next instruction in interrupted program or task
0	1	Unpredictable
1	0	Returns to next instruction after HLT instruction
1	1	Returns to HALT state

If the HLT instruction is restarted, the processor will generate a memory access to fetch the HLT instruction (if it is not in the internal cache), and execute a HLT bus transaction. This behavior results in multiple HLT bus transactions for the same HLT instruction.

12.10.1. Executing the HLT Instruction in SMM

The HLT instruction should not be executed during SMM, unless interrupts have been enabled by setting the IF flag in the EFLAGS register. If the processor is halted in SMM, the only event that can remove the processor from this state is a maskable hardware interrupt or a hardware reset.

12.11. SMBASE RELOCATION

The default base address for the SMRAM is 30000H. This value is contained in an internal processor register called the SMBASE register. The operating system or executive can relocate the SMRAM by setting the SMBASE field in the saved state map (at offset 7EF8H) to a new value (refer to Figure 12-4). The RSM instruction reloads the internal SMBASE register with the value in the SMBASE field each time it exits SMM. All subsequent SMI requests will use the new SMBASE value to find the starting address for the SMI handler (at SMBASE + 8000H) and the SMRAM state save area (from SMBASE + FE00H to SMBASE + FFFFH). (The processor resets the value in its internal SMBASE register to 30000H on a RESET, but does not change it on an INIT.) In multiple-processor systems, initialization software must adjust the

SMBASE value for each processor so that the SMRAM state save areas for each processor do not overlap. (For Pentium® and Intel486™ processors, the SMBASE values must be aligned on a 32-KByte boundary or the processor will enter shutdown state during the execution of a RSM instruction.)

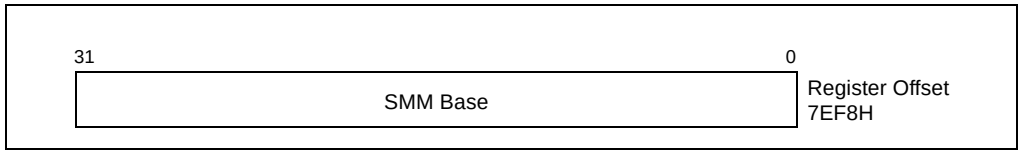


Figure 12-4. SMBASE Relocation Field

If the SMBASE relocation flag in the SMM revision identifier field is set, it indicates the ability to relocate the SMBASE (refer to Section 12.9., “SMM Revision Identifier”).

12.11.1. Relocating SMRAM to an Address Above 1 MByte

In SMM, the segment base registers can only be updated by changing the value in the segment registers. The segment registers contain only 16 bits, which allows only 20 bits to be used for a segment base address (the segment register is shifted left 4 bits to determine the segment base address). If SMRAM is relocated to an address above 1 MByte, software operating in real-address mode can no longer initialize the segment registers to point to the SMRAM base address (SMBASE).

The SMRAM can still be accessed by using 32-bit address-size override prefixes to generate an offset to the correct address. For example, if the SMBASE has been relocated to FFFFFFH (immediately below the 16-MByte boundary) and the DS, ES, FS, and GS registers are still initialized to 0H, data in SMRAM can be accessed by using 32-bit displacement registers, as in the following example:

```
mov   esi,00FFxxxxH; 64K segment immediately below 16M
mov   ax,ds:[esi]
```

A stack located above the 1-MByte boundary can be accessed in the same manner.

12.12. I/O INSTRUCTION RESTART

If the I/O instruction restart flag in the SMM revision identifier field is set (refer to Section 12.9., “SMM Revision Identifier”), the I/O instruction restart mechanism is present on the processor. This mechanism allows an interrupted I/O instruction to be re-executed upon returning from SMM mode. For example, if an I/O instruction is used to access a powered-down I/O device, a chip set supporting this device can intercept the access and respond by asserting SMI#. This action invokes the SMI handler to power-up the device. Upon returning from the SMI handler, the I/O instruction restart mechanism can be used to re-execute the I/O instruction that caused the SMI.

The I/O instruction restart field (at offset 7F00H in the SMM state-save area, refer to Figure 12-5) controls I/O instruction restart. When an RSM instruction is executed, if this field contains the value FFH, then the EIP register is modified to point to the I/O instruction that received the SMI request. The processor will then automatically re-execute the I/O instruction that the SMI trapped. (The processor saves the necessary machine state to insure that re-execution of the instruction is handled coherently.)

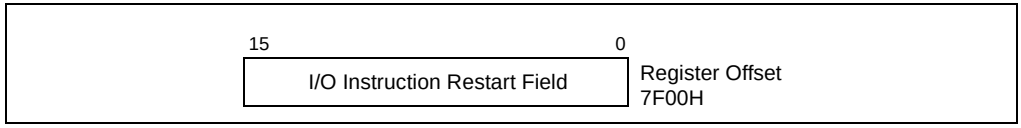


Figure 12-5. I/O Instruction Restart Field

If the I/O instruction restart field contains the value 00H when the RSM instruction is executed, then the processor begins program execution with the instruction following the I/O instruction. (When a repeat prefix is being used, the next instruction may be the next I/O instruction in the repeat loop.) Not re-executing the interrupted I/O instruction is the default behavior; the processor automatically initializes the I/O instruction restart field to 00H upon entering SMM. Table 12-4 summarizes the states of the I/O instruction restart field.

Table 12-4. I/O Instruction Restart Field Values

Value of Flag After Entry to SMM	Value of Flag When Exiting SMM	Action of Processor When Exiting SMM
00H	00H	Does not re-execute trapped I/O instruction.
00H	FFH	Re-executes trapped I/O instruction.

Note that the I/O instruction restart mechanism does not indicate the cause of the SMI. It is the responsibility of the SMI handler to examine the state of the processor to determine the cause of the SMI and to determine if an I/O instruction was interrupted and should be restarted upon exiting SMM. If an SMI interrupt is signaled on a non-I/O instruction boundary, setting the I/O instruction restart field to FFH prior to executing the RSM instruction will likely result in a program error.

12.12.1. Back-to-Back SMI Interrupts When I/O Instruction Restart Is Being Used

If an SMI interrupt is signaled while the processor is servicing an SMI interrupt that occurred on an I/O instruction boundary, the processor will service the new SMI request before restarting the originally interrupted I/O instruction. If the I/O instruction restart field is set to FFH prior to returning from the second SMI handler, the EIP will point to an address different from the originally interrupted I/O instruction, which will likely lead to a program error. To avoid this situation, the SMI handler must be able to recognize the occurrence of back-to-back SMI interrupts

when I/O instruction restart is being used and insure that the handler sets the I/O instruction restart field to 00H prior to returning from the second invocation of the SMI handler.

12.13. SMM MULTIPLE-PROCESSOR CONSIDERATIONS

The following should be noted when designing multiple-processor systems:

- Any processor in a multiprocessor system can respond to an SMM.
- Each processor needs its own SMRAM space. This space can be in system memory or in a separate RAM.
- The SMRAMs for different processors can be overlapped in the same memory space. The only stipulation is that each processor needs its own state save area and its own dynamic data storage area. (Also, for the Pentium® and Intel486™ processors, the SMBASE address must be located on a 32-KByte boundary.) Code and static data can be shared among processors. Overlapping SMRAM spaces can be done more efficiently with the P6 family processors because they do not require that the SMBASE address be on a 32-KByte boundary.
- The SMI handler will need to initialize the SMBASE for each processor.
- Processors can respond to local SMIs through their SMI# pins or to SMIs received through the APIC interface. The APIC interface can distribute SMIs to different processors.
- Two or more processors can be executing in SMM at the same time.
- When operating Pentium® processors in dual processing (DP) mode, the SMIACT# pin is driven only by the MRM processor and should be sampled with ADS#. For additional details, refer to Chapter 14 of the *Pentium® Processor Family User's Manual, Volume 1*.

SMM is not re-entrant, because the SMRAM State Save Map is fixed relative to the SMBASE. If there is a need to support two or more processors in SMM mode at the same time then each processor should have dedicated SMRAM spaces. This can be done by using the SMBASE Relocation feature (refer to Section 12.11., "SMBASE Relocation").

13

Machine-Check Architecture

CHAPTER 13
MACHINE-CHECK ARCHITECTURE

This chapter describes the P6 family's machine-check architecture and machine-check exception mechanism. Refer to Chapter 5, *Interrupt and Exception Handling* for more information on the machine-check exception. A brief description of the Pentium® processor's machine check capability is also given.

13.1. MACHINE-CHECK EXCEPTIONS AND ARCHITECTURE

The P6 family of processors implement a machine-check architecture that provides a mechanism for detecting and reporting hardware (machine) errors, such as system bus errors, ECC errors, parity errors, cache errors, and TLB errors. It consists of a set of model-specific registers (MSRs) that are used to set up machine checking and additional banks of MSRs for recording the errors that are detected. The processor signals the detection of a machine-check error by generating a machine-check exception (#MC). A machine-check exception is generally an abort class exception. The implementation of the machine-check architecture, does not ordinarily permit the processor to be restarted reliably after generating a machine-check exception; however, the machine-check-exception handler can collect information about the machine-check error from the machine-check MSRs.

13.2. COMPATIBILITY WITH PENTIUM® PROCESSOR

The P6 family processors support and extend the machine-check exception mechanism used in the Pentium® processor. The Pentium® processor reports the following machine-check errors:

- Data parity errors during read cycles.
- Unsuccessful completion of a bus cycle.

These errors are reported through the P5_MC_TYPE and P5_MC_ADDR MSRs, which are implementation specific for the Pentium® processor. These MSRs can be read with the RDMSR instruction. Refer to Table B-1 in Appendix B, *Model-Specific Registers* for the register addresses for these MSRs.

The machine-check error reporting mechanism that the Pentium® processors use is similar to that used in the P6 family processors. That is, when an error is detected, it is recorded in the P5_MC_TYPE and P5_MC_ADDR MSRs and then the processor generates a machine-check exception (#MC).

Refer to Section 13.3.3., "Mapping of the Pentium® Processor Machine-Check Errors to the P6 Family Machine-Check Architecture" and Section 13.7.2., "Pentium® Processor Machine-Check Exception Handling" for information on compatibility between machine-check code written to run on the Pentium® processors and code written to run on P6 family processors.

13.3. MACHINE-CHECK MSRS

The machine check MSRs in the P6 family processors consist of a set of global control and status registers and several error-reporting register banks (refer to Figure 13-1). Each error-reporting bank is associated with a specific hardware unit (or group of hardware units) within the processor. The RDMSR and WRMSR instructions are used to read and write these registers.

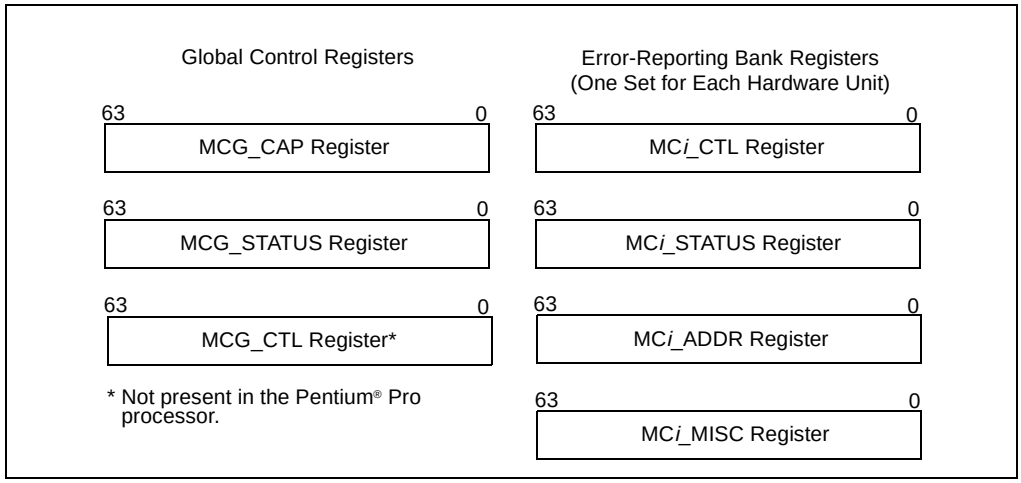


Figure 13-1. Machine-Check MSRs

13.3.1. Machine-Check Global Control MSRs

The machine-check global control registers include the MCG_CAP, MCG_STATUS, and MCG_CTL MSRs. Refer to Appendix B, *Model-Specific Registers* for the addresses of these registers.

13.3.1.1. MCG_CAP MSR

The MCG_CAP MSR is a read-only register that provides information about the machine-check architecture implementation in the processor (refer to Figure 13-2). It contains the following field and flag:

Count field, bits 0 through 7
Indicates the number of hardware unit error-reporting banks available in a particular processor implementation.

MCG_CTL_P (register present) flag, bit 8
Indicates that the MCG_CTL register is present when set, and absent when clear.

Bits 9 through 63 are reserved. The effect of writing to the MCG_CAP register is undefined. Figure 5-1 shows the bit fields of MCG_CAP.

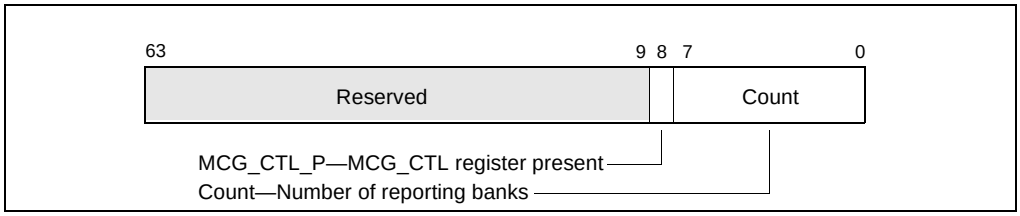


Figure 13-2. MCG_CAP Register

13.3.1.2. MCG_STATUS MSR

The MCG_STATUS MSR describes the current state of the processor after a machine-check exception has occurred (refer to Figure 13-3). This register contains the following flags:

RIPV (restart IP valid) flag, bit 0
Indicates (when set) that program execution can be restarted reliably at the instruction pointed to by the instruction pointer pushed on the stack when the machine-check exception is generated. When clear, the program cannot be reliably restarted at the pushed instruction pointer.

EIPV (error IP valid) flag, bit 1
Indicates (when set) that the instruction pointed to by the instruction pointer pushed onto the stack when the machine-check exception is generated is directly associated with the error. When this flag is cleared, the instruction pointed to may not be associated with the error.

MCIP (machine check in progress) flag, bit 2
Indicates (when set) that a machine-check exception was generated. Software can set or clear this flag. The occurrence of a second Machine-Check Event while MCIP is set will cause the processor to enter a shutdown state.

Bits 3 through 63 in the MCG_STATUS register are reserved.

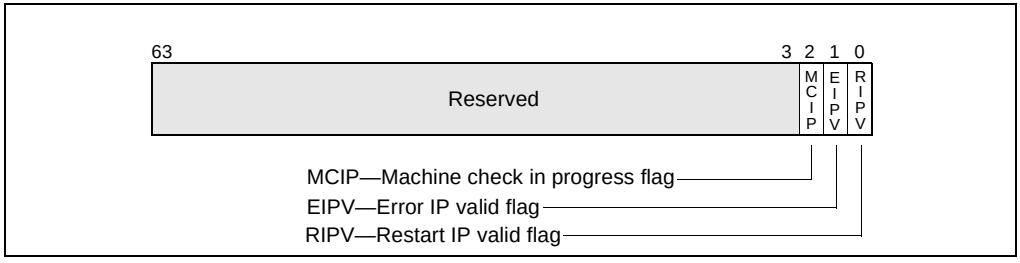


Figure 13-3. MCG_STATUS Register

13.3.1.3. MCG_CTL MSR

The MCG_CTL register is present if the capability flag MCG_CTL_P is set in the MCG_CAP register. The MCG_CTL register controls the reporting of machine-check exceptions. If present (MCG_CTL_P flag in the MCG_CAP register is set), writing all 1s to this register enables all machine-check features and writing all 0s disables all machine-check features. All other values are undefined and/or implementation specific.

13.3.2. Error-Reporting Register Banks

Each error-reporting register bank can contains an MC*i*_CTL, MC*i*_STATUS, MC*i*_ADDR, and MC*i*_MISC MSR. The P6 family processors provide five banks of error-reporting registers. The first error-reporting register (MC0_CTL) always starts at address 400H. Refer to Table B-1 in Appendix B, *Model-Specific Registers* for the addresses of the other error-reporting registers.

13.3.2.1. MC*i*_CTL MSR

The MC*i*_CTL MSR controls error reporting for specific errors produced by a particular hardware unit (or group of hardware units). Each of the 64 flags (EE*j*) represents a potential error. Setting an EE*j* flag enables reporting of the associated error and clearing it disables reporting of the error. Writing the 64-bit value FFFFFFFFFFFFFFFFH to an MC*i*_CTL register enables logging of all errors. The processor does not write changes to bits that are not implemented. Figure 13-4 shows the bit fields of MC*i*_CTL

NOTE

Operating system or executive software must not modify the contents of the MC0_CTL register. The MC0_CTL register is internally aliased to the EBL_CR_POWERON register and as such controls system-specific error handling features. These features are platform specific. System specific firmware (the BIOS) is responsible for the appropriate initialization of MC0_CTL. The P6 family processors only allows the writing of all 1s or all 0s to the MC*i*_CTL registers.

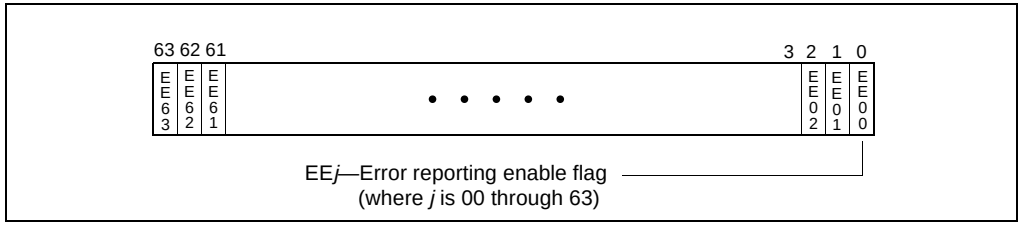


Figure 13-4. MC*i*_CTL Register

13.3.2.2. MC*i*_STATUS MSR

The MC*i*_STATUS MSR contains information related to a machine-check error if its VAL (valid) flag is set (refer to Figure 13-5). Software is responsible for clearing the MC*i*_STATUS register by writing it with all 0s; writing 1s to this register will cause a general-protection exception to be generated. The flags and fields in this register are as follows:

MCA (machine-check architecture) error code field, bits 0 through 15
Specifies the machine-check architecture-defined error code for the machine-check error condition detected. The machine-check architecture-defined error codes are guaranteed to be the same for all Intel Architecture processors that implement the machine-check architecture. Refer to Section 13.6., "Interpreting the MCA Error Codes" for information on machine-check error codes.

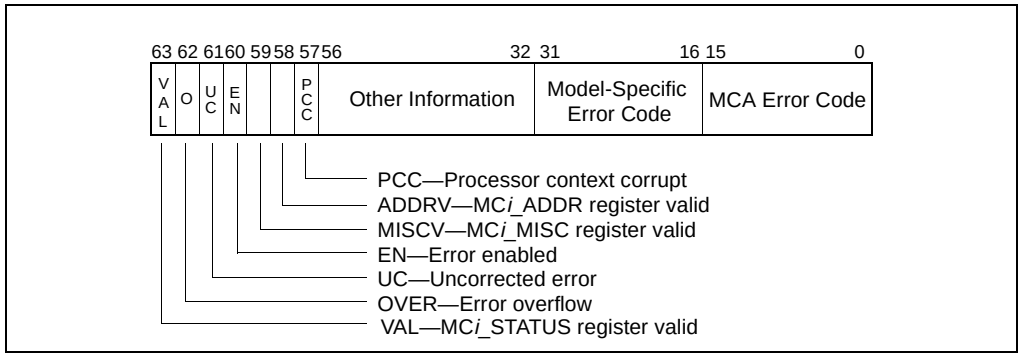


Figure 13-5. MC*i*_STATUS Register

Model-specific error code field, bits 16 through 31
Specifies the model-specific error code that uniquely identifies the machine-check error condition detected. The model-specific error codes may differ among Intel Architecture processors for the same machine-check error condition.

Other information field, bits 32 through 56
The functions of the bits in this field are implementation specific and are not part of the machine-check architecture. Software that is intended to be portable among Intel Architecture processors should not rely on the values in this field.

PCC (processor context corrupt) flag, bit 57
Indicates (when set) that the state of the processor might have been corrupted by the error condition detected and that reliable restarting of the processor may not be possible. When clear, this flag indicates that the error did not affect the processor's state.

ADDRV (MC*i*_ADDR register valid) flag, bit 58
Indicates (when set) that the MC*i*_ADDR register contains the address where the error occurred (refer to Section 13.3.2.3., "MCi_ADDR MSR"). When clear, this flag indicates that the MC*i*_ADDR register does not contain the address where the error occurred. Do not read these registers if they are not implemented in the processor.

MISCV (MC*i*_MISC register valid) flag, bit 59

Indicates (when set) that the MC*i*_MISC register contains additional information regarding the error. When clear, this flag indicates that the MC*i*_MISC register does not contain additional information regarding the error. Do not read these registers if they are not implemented in the processor

EN (error enabled) flag, bit 60

Indicates (when set) that the error was enabled by the associated EEj bit of the MC*i*_CTL register.

UC (error uncorrected) flag, bit 61

Indicates (when set) that the processor did not or was not able to correct the error condition. When clear, this flag indicates that the processor was able to correct the error condition.

OVER (machine check overflow) flag, bit 62

Indicates (when set) that a machine-check error occurred while the results of a previous error were still in the error-reporting register bank (that is, the VAL bit was already set in the MC*i*_STATUS register). The processor sets the OVER flag and software is responsible for clearing it. Enabled errors are written over disabled errors, and uncorrected errors are written over corrected errors. Uncorrected errors are not written over previous valid uncorrected errors.

VAL (MC*i*_STATUS register valid) flag, bit 63

Indicates (when set) that the information within the MC*i*_STATUS register is valid. When this flag is set, the processor follows the rules given for the OVER flag in the MC*i*_STATUS register when overwriting previously valid entries. The processor sets the VAL flag and software is responsible for clearing it.

13.3.2.3. MC*i*_ADDR MSR

The MC*i*_ADDR MSR contains the address of the code or data memory location that produced the machine-check error if the ADDRV flag in the MC*i*_STATUS register is set (refer to Section 13.3.2.2., “MCi_STATUS MSR”). The address returned is either 32-bit offset into a segment, 32-bit linear address, or 36-bit physical address, depending upon the type of error encountered. Bits 36 through 63 of this register are reserved for future address expansion and are always read as zeros.

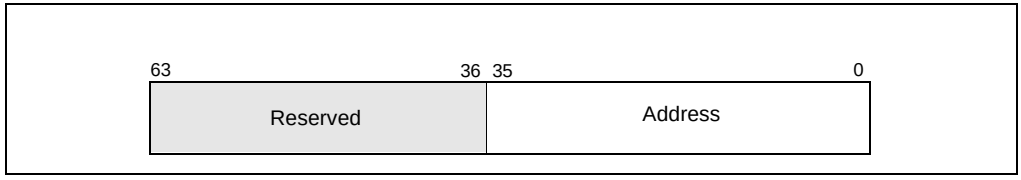


Figure 13-6. Machine-Check Bank Address Register

13.3.2.4. MC*i*_MISC MSR

The MC*i*_MISC MSR contains additional information describing the machine-check error if the MISCV flag in the MC*i*_STATUS register is set. This register is not implemented in any of the error-reporting register banks for the P6 family processors.

13.3.3. Mapping of the Pentium® Processor Machine-Check Errors to the P6 Family Machine-Check Architecture

The Pentium® processor reports machine-check errors using two registers: P5_MC_TYPE and P5_MC_ADDR. The P6 family processors map these registers into the MC*i*_STATUS and MC*i*_ADDR registers of the error-reporting register bank that reports on the type of external bus errors reported in the P5_MC_TYPE and P5_MC_ADDR registers. The information in these registers can then be accessed in either of two ways:

- By reading the MC*i*_STATUS and MC*i*_ADDR registers as part of a generalized machine-check exception handler written for a P6 family processor.
- By reading the P5_MC_TYPE and P5_MC_ADDR registers with the RDMSR instruction.

The second access capability permits a machine-check exception handler written to run on a Pentium® processor to be run on a P6 family processor. There is a limitation in that information returned by the P6 family processor will be encoded differently than it is for the Pentium® processor. To run the Pentium® processor machine-check exception handler on a P6 family processor, it must be rewritten to interpret the P5_MC_TYPE register encodings correctly.

13.4. MACHINE-CHECK AVAILABILITY

The machine-check architecture and machine-check exception (#MC) are model-specific features. Software can execute the CPUID instruction to determine whether a processor implements these features. Following the execution of the CPUID instruction, the settings of the MCA flag (bit 14) and MCE flag (bit 7) in the EDX register indicate whether the processor implements the machine-check architecture and machine-check exception, respectively.

13.5. MACHINE-CHECK INITIALIZATION

To use the processors machine-check architecture, software must initialize the processor to activate the machine-check exception and the error-reporting mechanism. Example 13-1 gives pseudocode for performing this initialization. This pseudocode checks for the existence of the machine-check architecture and exception on the processor, then enables the machine-check exception and the error-reporting register banks. The pseudocode assumes that the machine-check exception (#MC) handler has been installed on the system. This initialization procedure is compatible with the Pentium® and P6 family processors.

Example 13-1. Machine-Check Initialization Pseudocode

```
EXECUTE the CPUID instruction;
READ bits 7 (MCE) and 14 (MCA) of the EDX register;
IF CPU supports MCE
    THEN
        IF CPU supports MCA
            THEN
                IF MCG_CAP.MCG_CTL_P = 1 (* MCG_CTL register is present *)
                    Set MCG_CTL register to all 1s; (* enables all MCA features *)
                FI;
                COUNT ← MCG_CAP.Count;
                (* determine number of error-reporting banks supported *)
                FOR error-reporting banks (1 through COUNT) DO
                    Set MCi_CTL register to all 1s;
                    (* enables logging of all errors except for the MC0_CTL register *)
                OD
                FOR error-reporting banks (0 through COUNT) DO
                    Set MCi_STATUS register to all 0s; (* clears all errors *)
                OD
        FI;
    Set the MCE flag (bit 6) in CR4 register to enable machine-check exceptions;
FI;
```

The processor can write valid information (such as an ECC error) into the MC*i*_STATUS registers while it is being powered up. As part of the initialization of the MCE exception handler, software might examine all the MC*i*_STATUS registers and log the contents of them, then rewrite them all to zeros. This procedure is not included in the initialization pseudocode in Example 13-1.

13.6. INTERPRETING THE MCA ERROR CODES

When the processor detects a machine-check error condition, it writes a 16-bit error code in the MCA Error Code field of one of the MC*i*_STATUS registers and sets the VAL (valid) flag in that register. The processor may also write a 16-bit Model-specific Error Code in the MC*i*_STATUS register depending on the implementation of the machine-check architecture of the processor.

The MCA error codes are architecturally defined for Intel Architecture processors; however, the specific MC*i*_STATUS register that a code is written into is model specific. To determine the cause of a machine-check exception, the machine-check exception handler must read the VAL flag for each MC*i*_STATUS register, and, if the flag is set, then read the MCA error code field of the register. It is the encoding of the MCACOD value that determines the type of error being reported and not the register bank reporting it.

There are two types of MCA error codes: simple error codes and compound error codes.

13.6.1. Simple Error Codes

Table 13-1 shows the simple error codes. These unique codes indicate global error information.

Table 13-1. Simple Error Codes

Error Code	Binary Encoding	Meaning
No Error	0000 0000 0000 0000	No error has been reported to this bank of error-reporting registers.
Unclassified	0000 0000 0000 0001	This error has not been classified into the MCA error classes.
Microcode ROM Parity Error	0000 0000 0000 0010	Parity error in internal microcode ROM
External Error	0000 0000 0000 0011	The BINIT# from another processor caused this processor to enter machine check.
FRC Error	0000 0000 0000 0100	FRC (functional redundancy check) master/slave error
Internal Unclassified	0000 01xx xxxx xxxx	Internal unclassified errors

13.6.2. Compound Error Codes

The compound error codes describe errors related to the TLBs, memory, caches, bus and interconnect logic. A set of sub-fields is common to all of the compound error encodings. These sub-fields describe the type of access, level in the memory hierarchy, and type of request. Table 13-2 shows the general form of the compound error codes. The interpretation column indicates the name of a compound error. The name is constructed by substituting mnemonics from Tables 13-2 through 13-6 for the sub-field names given within curly braces. For example, the error code ICACHEL1_RD_ERR is constructed from the form:

{TT}CACHE{LL}_{RRRR}_ERR

where {TT} is replaced by I, {LL} is replaced by L1, and {RRRR} is replaced by RD.

The 2-bit TT sub-field (refer to Table 13-2) indicates the type of transaction (data, instruction, or generic). It applies to the TLB, cache, and interconnect error conditions. The generic type is reported when the processor cannot determine the transaction type.

Table 13-2. General Forms of Compound Error Codes

Type	Form	Interpretation
TLB Errors	0000 0000 0001 TTLL	{TT}TLB{LL}_ERR
Memory Hierarchy Errors	0000 0001 RRRR TTLL	{TT}CACHE{LL}_{RRRR}_ERR
Bus and Interconnect Errors	0000 1PPT RRRR IILL	BUS{LL}_{PP}_{RRRR}_{II}_{T}_ERR

Table 13-3. Encoding for TT (Transaction Type) Sub-Field

Transaction Type	Mnemonic	Binary Encoding
Instruction	I	00
Data	D	01
Generic	G	10

The 2-bit LL sub-field (refer to Table 13-4) indicates the level in the memory hierarchy where the error occurred (level 0, level 1, level 2, or generic). The LL sub-field also applies to the TLB, cache, and interconnect error conditions. The P6 family processors support two levels in the cache hierarchy and one level in the TLBs. Again, the generic type is reported when the processor cannot determine the hierarchy level.

Table 13-4. Level Encoding for LL (Memory Hierarchy Level) Sub-Field

Hierarchy Level	Mnemonic	Binary Encoding
Level 0	L0	00
Level 1	L1	01
Level 2	L2	10
Generic	LG	11

The 4-bit RRRR sub-field (refer to Table 13-5) indicates the type of action associated with the error. Actions include read and write operations, prefetches, cache evictions, and snoops. Generic error is returned when the type of error cannot be determined. Generic read and generic write are returned when the processor cannot determine the type of instruction or data request that caused the error. Eviction and Snoop requests apply only to the caches. All of the other requests apply to TLBs, caches and interconnects.

Table 13-5. Encoding of Request (RRRR) Sub-Field

Request Type	Mnemonic	Binary Encoding
Generic Error	ERR	0000
Generic Read	RD	0001
Generic Write	WR	0010
Data Read	DRD	0011
Data Write	DWR	0100
Instruction Fetch	IRD	0101
Prefetch	PREFETCH	0110
Eviction	EVICT	0111
Snoop	SNOOP	1000

The bus and interconnect errors are defined with the 2-bit PP (participation), 1-bit T (time-out), and 2-bit II (memory or I/O) sub-fields, in addition to the LL and RRRR sub-fields (refer to Table 13-6). The bus error conditions are implementation dependent and related to the type of bus implemented by the processor. Likewise, the interconnect error conditions are predicated on a specific implementation-dependent interconnect model that describes the connections between the different levels of the storage hierarchy. The type of bus is implementation dependent, and as such is not specified in this document. A bus or interconnect transaction consists of a request involving an address and a response.

Table 13-6. Encodings of PP, T, and II Sub-Fields

Sub-Field	Transaction	Mnemonic	Binary Encoding
PP (Participation)	Local processor originated request	SRC	00
	Local processor responded to request	RES	01
	Local processor observed error as third party	OBS	10
	Generic		11
T (Time-out)	Request timed out	TIMEOUT	1
	Request did not time out	NOTIMEOUT	0
II (Memory or I/O)	Memory Access	M	00
	Reserved		01
	I/O	IO	10
	Other transaction		11

13.6.3. Interpreting the Machine-Check Error Codes for External Bus Errors

Table 13-7 gives additional information for interpreting the MCA error code, model-specific error code, and other information error code fields for machine-check errors that occur on the external bus. This information can be used to design a machine-check exception handler for the processor that offers greater granularity for the external bus errors.

Table 13-7. Encoding of the MC*i*_STATUS Register for External Bus Errors

Bit No.	Bit Function	Bit Description
0-1	MCA Error Code	Undefined.
2-3	MCA Error Code	Bit 2 is set to 1 if the access was a special cycle. Bit 3 is set to 1 if the access was a special cycle OR a I/O cycle.
4-7	MCA Error Code	00WR; W = 1 for writes, R = 1 for reads.

Table 13-7. Encoding of the MC*i*_STATUS Register for External Bus Errors (Contd.)

Bit No.	Bit Function	Bit Description
8-9	MCA Error Code	Undefined.
10	MCA Error Code	Set to 0 for all EBL errors. Set to 1 for internal watch-dog timer time-out. For a watch-dog timer time-out, all the MCACOD bits except this bit are set to 0. A watch-dog timer time-out only occurs if the BINIT driver is enabled.
11	MCA Error Code	Set to 1 for EBL errors. Set to 0 for internal watch-dog timer time-out.
12-15	MCA Error Code	Reserved.
16-18	Model-Specific Error Code	Reserved.
19-24	Model-Specific Error Code	000000 for BQ_DCU_READ_TYPE error. 000010 for BQ_IFU_DEMAND_TYPE error. 000011 for BQ_IFU_DEMAND_NC_TYPE error. 000100 for BQ_DCU_RFO_TYPE error. 000101 for BQ_DCU_RFO_LOCK_TYPE error. 000110 for BQ_DCU_ITOM_TYPE error. 001000 for BQ_DCU_WB_TYPE error. 001010 for BQ_DCU_WCEVICT_TYPE error. 001011 for BQ_DCU_WCLINE_TYPE error. 001100 for BQ_DCU_BTM_TYPE error. 001101 for BQ_DCU_INTACK_TYPE error. 001110 for BQ_DCU_INVALL2_TYPE error. 001111 for BQ_DCU_FLUSHL2_TYPE error. 010000 for BQ_DCU_PART_RD_TYPE error. 010010 for BQ_DCU_PART_WR_TYPE error. 010100 for BQ_DCU_SPEC_CYC_TYPE error. 011000 for BQ_DCU_IO_RD_TYPE error. 011001 for BQ_DCU_IO_WR_TYPE error. 011100 for BQ_DCU_LOCK_RD_TYPE error. 011110 for BQ_DCU_SPLOCK_RD_TYPE error. 011101 for BQ_DCU_LOCK_WR_TYPE error.
27-25	Model-Specific Error Code	000 for BQ_ERR_HARD_TYPE error. 001 for BQ_ERR_DOUBLE_TYPE error. 010 for BQ_ERR_AERR2_TYPE error. 100 for BQ_ERR_SINGLE_TYPE error. 101 for BQ_ERR_AERR1_TYPE error.
28	Model-Specific Error Code	1 if FRC error is active.
29	Model-Specific Error Code	1 if BERR is driven.

Table 13-7. Encoding of the MC*i*_STATUS Register for External Bus Errors (Contd.)

Bit No.	Bit Function	Bit Description
30	Model-Specific Error Code	1 if BINIT is driven for this processor.
31	Model-Specific Error Code	Reserved.
32-34	Other Information	Reserved.
35	Other Information BINIT	1 if BINIT is received from external bus.
36	Other Information RESPONSE PARITY ERROR	This bit is asserted in the MC*i*_STATUS register if this component has received a parity error on the RS[2:0]# pins for a response transaction. The RS signals are checked by the RSP# external pin.
37	Other Information BUS BINIT	This bit is asserted in the MC*i*_STATUS register if this component has received a hard error response on a split transaction (one access that has needed to be split across the 64-bit external bus interface into two accesses).
38	Other Information TIMEOUT BINIT	This bit is asserted in the MC*i*_STATUS register if this component has experienced a ROB time-out, which indicates that no microinstruction has been retired for a predetermined period of time. A ROB time-out occurs when the 15-bit ROB time-out counter carries a 1 out of its high order bit. The timer is cleared when a microinstruction retires, an exception is detected by the core processor, RESET is asserted, or when a ROB BINIT occurs. The ROB time-out counter is prescaled by the 8-bit PIC timer which is a divide by 128 of the bus clock (the bus clock is 1:2, 1:3, 1:4 the core clock). When a carry out of the 8-bit PIC timer occurs, the ROB counter counts up by one. While this bit is asserted, it cannot be overwritten by another error.
39-41	Other Information	Reserved.
42	Other Information HARD ERROR	This bit is asserted in the MC*i*_STATUS register if this component has initiated a bus transactions which has received a hard error response. While this bit is asserted, it cannot be overwritten.
43	Other Information IERR	This bit is asserted in the MC*i*_STATUS register if this component has experienced a failure that causes the IERR pin to be asserted. While this bit is asserted, it cannot be overwritten.
44	Other Information AERR	This bit is asserted in the MC*i*_STATUS register if this component has initiated 2 failing bus transactions which have failed due to Address Parity Errors (AERR asserted). While this bit is asserted, it cannot be overwritten.

Table 13-7. Encoding of the MC*i*_STATUS Register for External Bus Errors (Contd.)

Bit No.	Bit Function	Bit Description
45	Other Information UECC	Uncorrectable ECC error bit is asserted in the MC*i*_STATUS register for uncorrected ECC errors. While this bit is asserted, the ECC syndrome field will not be overwritten.
46	Other Information CECC	The correctable ECC error bit is asserted in the MC*i*_STATUS register for corrected ECC errors.
47-54	Other Information SYNDROME	The ECC syndrome field in the MC*i*_STATUS register contains the 8-bit ECC syndrome only if the error was a correctable/uncorrectable ECC error, and there wasn't a previous valid ECC error syndrome logged in the MC*i*_STATUS register. A previous valid ECC error in MC*i*_STATUS is indicated by MC*i*_STATUS.bit45 (uncorrectable error occurred) being asserted. After processing an ECC error, machine-check handling software should clear MC*i*_STATUS.bit45 so that future ECC error syndromes can be logged.
55-56	Other Information	Reserved.

13.7. GUIDELINES FOR WRITING MACHINE-CHECK SOFTWARE

The machine-check architecture and error logging can be used in two different ways:

- To detect machine errors during normal instruction execution, using the machine-check exception (#MC).
- To periodically check and log machine errors.

To use the machine-check exception, the operating system or executive software must provide a machine-check exception handler. This handler can be designed specifically for P6 family processors or be a portable handler that also handles Pentium® processor machine-check errors.

A special program or utility is required to log machine errors.

Guidelines for writing a machine-check exception handler or a machine-error logging utility are given in the following sections.

13.7.1. Machine-Check Exception Handler

The machine-check exception (#MC) corresponds to vector 18. To service machine-check exceptions, a trap gate must be added to the IDT, and the pointer in the trap gate must point to a machine-check exception handler. Two approaches can be taken to designing the exception handler:

- The handler can merely log all the machine status and error information, then call a debugger or shut down the system.
- The handler can analyze the reported error information and, in some cases, attempt to correct the error and restart the processor.

Virtually all the machine-check conditions detected with the P6 family processors cannot be recovered from (they result in abort-type exceptions). The logging of status and error information is therefore a baseline implementation. Refer to Section 13.7., “Guidelines for Writing Machine-Check Software” for more information on logging errors.

For future P6 family processor implementations, where recovery may be possible, the following things should be considered when writing a machine-check exception handler:

- To determine the nature of the error, the handler must read each of the error-reporting register banks. The count field in the MCG_CAP register gives number of register banks. The first register of register bank 0 is at address 400H.
- The VAL (valid) flag in each MC*i*_STATUS register indicates whether the error information in the register is valid. If this flag is clear, the registers in that bank do not contain valid error information and do not need to be checked.
- To write a portable exception handler, only the MCA error code field in the MC*i*_STATUS register should be checked. Refer to Section 13.6., “Interpreting the MCA Error Codes” for information that can be used to write an algorithm to interpret this field.
- The RIPV, PCC, and OVER flags in each MC*i*_STATUS register indicate whether recovery from the error is possible. If either of these fields is set, recovery is not possible. The OVER field indicates that two or more machine-check error occurred. When recovery is not possible, the handler typically records the error information and signals an abort to the operating system.
- Corrected errors will have been corrected automatically by the processor. The UC flag in each MC*i*_STATUS register indicates whether the processor automatically corrected the error.
- The RIPV flag in the MCG_STATUS register indicates whether the program can be restarted at the instruction pointed to by the instruction pointer pushed on the stack when the exception was generated. If this flag is clear, the processor may still be able to be restarted (for debugging purposes), but not without loss of program continuity.
- For unrecoverable errors, the EIPV flag in the MCG_STATUS register indicates whether the instruction pointed to by the instruction pointer pushed on the stack when the exception was generated is related to the error. If this flag is clear, the pushed instruction may not be related to the error.
- The MCIP flag in the MCG_STATUS register indicates whether a machine-check exception was generated. Before returning from the machine-check exception handler, software should clear this flag so that it can be used reliably by an error logging utility. The MCIP flag also detects recursion. The machine-check architecture does not support recursion. When the processor detects machine-check recursion, it enters the shutdown state.

Example 13-2 gives typical steps carried out by a machine-check exception handler:

Example 13-2. Machine-Check Exception Handler Pseudocode

```
IF CPU supports MCE
    THEN
        IF CPU supports MCA
            THEN
                call errorlogging routine; (* returns restartability *)
        FI;
    ELSE (* Pentium(R) processor compatible *)
        READ P5_MC_ADDR
        READ P5_MC_TYPE;
        report RESTARTABILITY to console;
FI;
IF error is not restartable
    THEN
        report RESTARTABILITY to console;
        abort system;
FI;
CLEAR MCIP flag in MCG_STATUS;
```

13.7.2. Pentium® Processor Machine-Check Exception Handling

To make the machine-check exception handler portable to the Pentium® and P6 family processors, checks can be made (using the CPUID instruction) to determine the processor type. Then based on the processor type, machine-check exceptions can be handled specifically for Pentium® or P6 family processors.

When machine-check exceptions are enabled for the Pentium® processor (MCE flag is set in control register CR0), the machine-check exception handler uses the RDMSR instruction to read the error type from the P5_MC_TYPE register and the machine check address from the P5_MC_ADDR register. The handler then normally reports these register values to the system console before aborting execution (refer to Example 13-2).

13.7.3. Logging Correctable Machine-Check Errors

If a machine-check error is correctable, the processor does not generate a machine-check exception for it. To detect correctable machine-check errors, a utility program must be written that reads each of the machine-check error-reporting register banks and logs the results in an accounting file or data structure. This utility can be implemented in either of the following ways:

- A system daemon that polls the register banks on an infrequent basis, such as hourly or daily.

- A user-initiated application that polls the register banks and records the exceptions. Here, the actual polling service is provided by an operating-system driver or through the system call interface.

Example 13-3 gives pseudocode for an error logging utility.

Example 13-3. Machine-Check Error Logging Pseudocode

```
Assume that execution is restartable;
IF the processor supports MCA
    THEN
    FOR each bank of machine-check registers
        DO
            READ MCi_STATUS;
            IF VAL flag in MCi_STATUS = 1
                THEN
                    IF ADDRV flag in MCi_STATUS = 1
                        THEN READ MCi_ADDR;
                    FI;
                    IF MISCV flag in MCi_STATUS = 1
                        THEN READ MCi_MISC;
                    FI;
                    IF MCIP flag in MCG_STATUS = 1
                        (* Machine-check exception is in progress *)
                        AND PCC flag in MCi_STATUS = 1
                        AND RIPV flag in MCG_STATUS = 0
                        (* execution is not restartable *)
                            THEN
                                RESTARTABILITY = FALSE;
                                return RESTARTABILITY to calling procedure;
                    FI;
                    Save time-stamp counter and processor ID;
                    Set MCi_STATUS to all 0s;
                    Execute serializing instruction (i.e., CPUID);
            FI;
        OD;
FI;
```

If the processor supports the machine-check architecture, the utility reads through the banks of error-reporting registers looking for valid register entries, and then saves the values of the MC*i*_STATUS, MC*i*_ADDR, MC*i*_MISC and MCG_STATUS registers for each bank that is valid. The routine minimizes processing time by recording the raw data into a system data structure or file, reducing the overhead associated with polling. User utilities analyze the collected data in an off-line environment.

When the MCIP flag is set in the MCG_STATUS register, a machine-check exception is in progress and the machine-check exception handler has called the exception logging routine. Once the logging process has been completed the exception-handling routine must determine

whether execution can be restarted, which is usually possible when damage has not occurred (The PCC flag is clear, in the MC*i*_STATUS register) and when the processor can guarantee that execution is restartable (the RIPV flag is set in the MCG_STATUS register). If execution cannot be restarted, the system is not recoverable and the exception-handling routine should signal the console appropriately before returning the error status to the Operating System kernel for subsequent shutdown.

The machine-check architecture allows buffering of exceptions from a given error-reporting bank although the P6 family processors do not implement this feature. The error logging routine should provide compatibility with future processors by reading each hardware error-reporting bank's MC*i*_STATUS register and then writing 0s to clear the OVER and VAL flags in this register. The error logging utility should re-read the MC*i*_STATUS register for the bank ensuring that the valid bit is clear. The processor will write the next error into the register bank and set the VAL flags.

Additional information that should be stored by the exception-logging routine includes the processor's time-stamp counter value, which provides a mechanism to indicate the frequency of exceptions. A multiprocessing operating system stores the identity of the processor node incurring the exception using a unique identifier, such as the processor's APIC ID (refer to Section 7.5.9., "Interrupt Destination and APIC ID").

The basic algorithm given in Example 13-3 can be modified to provide more robust recovery techniques. For example, software has the flexibility to attempt recovery using information unavailable to the hardware. Specifically, the machine-check exception handler can, after logging carefully analyze the error-reporting registers when the error-logging routine reports an error that does not allow execution to be restarted. These recovery techniques can use external bus related model-specific information provided with the error report to localize the source of the error within the system and determine the appropriate recovery strategy.

14

Code Optimization

CHAPTER 14
CODE OPTIMIZATION

This chapter describes the more important code optimization techniques for Intel Architecture processors with and without MMX™ technology, as well as with and without Streaming SIMD Extensions. The chapter begins with general code-optimization guidelines and continues with a brief overview of the more important blended techniques for optimizing integer, MMX™ technology, floating-point, and SIMD floating-point code. A comprehensive discussion of code optimization techniques can be found in the *Intel Architecture Optimization Manual*, Order Number 242816.

14.1. CODE OPTIMIZATION GUIDELINES

This section contains general guidelines for optimizing applications code, as well as specific guidelines for optimizing MMX™, floating-point, and SIMD floating-point code. Developers creating applications that use MMX™ and/or floating-point instructions should apply the first set of guidelines in addition to the MMX™ and/or floating-point code optimization guidelines. Developers creating applications that use SIMD floating-point code should apply the first set of guidelines, as well as the MMX™ and/or floating-point code optimization guidelines, in addition to the SIMD floating-point code optimization guidelines.

14.1.1. General Code Optimization Guidelines

Use the following guidelines to optimize code to run efficiently across several families of Intel Architecture processors:

- Use a current generation compiler that produces optimized code to insure that efficient code is generated from the start of code development.
- Write code that can be optimized by the compiler. For example:
  - — Minimize the use of global variables, pointers, and complex control flow statements.
  - — Do not use the “register” modifier.
  - — Use the “const” modifier.
  - — Do not defeat the typing system.
  - — Do not make indirect calls.
  - — Use minimum sizes for integer and floating-point data types, to enable SIMD parallelism.

- Pay attention to the branch prediction algorithm for the target processor. This optimization is particularly important for P6 family processors. Code that optimizes branch predictability will spend fewer clocks fetching instructions.
- Take advantage of the SIMD capabilities of MMX™ technology and Streaming SIMD Extensions.
- Avoid partial register stalls.
- Align all data.
- Organize code to minimize instruction cache misses and optimize instruction prefetches.
- Schedule code to maximize pairing on Pentium® processors.
- Avoid prefixed opcodes other than 0FH.
- When possible, load and store data to the same area of memory using the same data sizes and address alignments; that is, avoid small loads after large stores to the same area of memory, and avoid large loads after small stores to the same area of memory.
- Use software pipelining.
- Always pair CALL and RET (return) instructions.
- Avoid self-modifying code.
- Do not place data in the code segment.
- Calculate store addresses as soon as possible.
- Avoid instructions that contain 4 or more micro-ops or instructions that are more than 7 bytes long. If possible, use instructions that require 1 micro-op.
- Cleanse partial registers before calling callee-save procedures.

14.1.2. Guidelines for Optimizing MMX™ Code

Use the following guidelines to optimize MMX™ code:

- Do not intermix MMX™ instructions and floating-point instructions.
- Use the *opcode reg, mem* instruction format whenever possible. This format helps to free registers and reduce clocks without generating unnecessary loads.
- Put an EMMS instruction at the end of all MMX™ code sections that you know will transition to floating-point code.
- Optimize data cache bandwidth to MMX™ registers.

14.1.3. Guidelines for Optimizing Floating-Point Code

Use the following guidelines to optimize floating-point code:

- Understand how the compiler handles floating-point code. Look at the assembly dump and see what transforms are already performed on the program. Study the loop nests in the application that dominate the execution time.
- Determine why the compiler is not creating the fastest code. For example, look for dependences that can be resolved by rearranging code
- Look for and correct situations known to cause slow execution of floating-point code, such as:
  - — Large memory bandwidth requirements.
  - — Poor cache locality.
  - — Long-latency floating-point arithmetic operations.
- Do not use more precision than is necessary. Single precision (32-bits) is faster on some operations and consumes only half the memory space as double precision (64-bits) or double extended (80-bits).
- Use a library that provides fast floating-point to integer routines. Many library routines do more work than is necessary.
- Insure whenever possible that computations stay in range. Out of range numbers cause very high overhead.
- Schedule code in assembly language using the FXCH instruction. When possible, unroll loops and pipeline code.
- Perform transformations to improve memory access patterns. Use loop fusion or compression to keep as much of the computation in the cache as possible.
- Break dependency chains.

14.1.4. Guidelines for Optimizing SIMD Floating-point Code

Generally, it is important to understand and balance port utilization to create efficient SIMD floating-point code. Use the following guidelines to optimize SIMD floating-point code:

- Balance the limitations of the architecture.
- Schedule instructions to resolve dependencies.
- Schedule utilization of the triple/quadruple rule (port 0, port 1, port 2, 3, and 4).
- Group instructions that utilize the same registers as closely as possible. Take into consideration the resolution of true dependencies.
- Intermix SIMD-fp operations that utilize port 0 and port 1.
- Do not issue consecutive instructions that utilize the same port.
- Use the reciprocal instructions followed by iteration for increased accuracy. These instructions yield reduced accuracy but execute much faster. If reduced accuracy is acceptable,

use them with no iteration. If near full accuracy is needed, use a Newton-Raphson iteration. If full accuracy is needed, then use divide and square root which provide more accuracy, but slow down performance.

- Exceptions: mask exceptions to achieve higher performance. Unmasked exceptions may cause a reduction in the retirement rate.
- Utilize the flush-to-zero mode for higher performance to avoid the penalty of dealing with denormals and underflows.
- Incorporate the prefetch instruction whenever possible (for details, refer to Chapter 6, “Optimizing Cache Utilization for Pentium® III processors”).
- Try to emulate conditional moves by masked compares and logicals instead of using conditional jumps.
- Utilize MMX™ technology instructions if the computations can be done in SIMD-integer or for shuffling data or copying data that is not used later in SIMD floating-point computations.
- If the algorithm requires extended precision, then conversion to SIMD floating-point code is not advised because the SIMD floating-point instructions are single-precision.

14.2. BRANCH PREDICTION OPTIMIZATION

The P6 family and Pentium® processors provide dynamic branch prediction using the branch target buffers (BTBs) on the processors. Understanding the flow of branches and improving the predictability of branches can increase code execution speed significantly.

14.2.1. Branch Prediction Rules

Three elements of dynamic branch prediction are important to understand:

- If the instruction address is not in the BTB, execution is predicted to continue without branching (fall through).
- Predicted taken branches have a 1 clock delay.
- The BTB stores a four-bit history of branch predictions on Pentium® Pro processors, the Pentium® II processor family, and the Pentium® III processor.
- The Pentium® II and Pentium® III processor’s BTB pattern matches on the direction of the last four branches to dynamically predict whether a branch will be taken.

During the process of instruction prefetch, the instruction address of a conditional instruction is checked with the entries in the BTB. When the address is not in the BTB, execution is predicted to fall through to the next instruction.

On P6 family processors, branches that do not have a history in the BTB are predicted using a static prediction algorithm. The static prediction algorithm does the following:

- Predicts unconditional branches to be taken.
- Predicts backward conditional branches to be taken. This rule is suitable for loops.
- Predicts forward conditional branches to be **not** taken.

14.2.2. Optimizing Branch Predictions in Code

To optimize branch predictions in an application code, apply the following techniques:

- Reduce or eliminate branches (see Section 14.2.3., “Eliminating and Reducing the Number of Branches”).
- Insure that each CALL instruction has a matching RET instruction. The P6 family of processors have a return stack buffer that keeps track of the target address of the next RET instruction. Do not use pops and jumps to return from a CALL instruction; always use the RET instruction.
- Do not intermingle data with instructions in a code segment. Unconditional jumps, when not in the BTB, are predicted to be not taken. If data follows a unconditional branch, the data might be fetched, causing the loss of instruction fetch cycles and valuable instruction-cache space. When data must be stored in the code segment, move it to the end where it will not be in the instruction fetch stream.
- Unroll all very short loops. Loops that execute for less than 2 clocks waste loop overhead.
- Write code to follow the static prediction algorithm. The static prediction algorithm follows the natural flow of program code. Following this algorithm reduces the number of branch mispredictions.

14.2.3. Eliminating and Reducing the Number of Branches

Eliminating branches improves processor performance by:

- Removing the possibility of branch mispredictions.
- Reducing the number of BTB entries required.

Branches can be eliminated by using the SET*cc* instruction, or by using the P6 family processors’ conditional move (CMOV*cc* or FCMOV*cc*) instructions.

The following C code example shows conditions that are dependent upon on of the constants A and B:

```
/* C Code /*
ebx = (A < B) ? C1 : C2;
```

This code conditionally compares the values A and B. If the condition is true, EBX is set to C1; otherwise it is set to C2. The assembly-language equivalent of the C code is shown in the example below:

```
; Assembly Code
```

```
        cmp     A, B                    ; condition
        jge   L30                       ; conditional branch
        mov   ebx, CONST1
        jmp   L31                       ; unconditional branch
L30:
        mov   ebx, CONST2
L31:
```

By replacing the JGE instruction as shown in the previous example with a SET*cc* instruction, the EBX register is set to either C1 or C2. This code can be optimized to eliminate the branches as shown in the following code:

```
        xor     ebx, ebx                ;clear ebx
        cmp   A, B
        setge   bl                      ;When ebx = 0 or 1
                                        ;OR the complement condition
        dec     ebx                     ;ebx=00...00 or 11...11
        and     ebx, (CONST2-CONST1)    ;ebx=0 or(CONST2-CONST1)
        add     ebx, min(CONST1,CONST2) ;ebx=CONST1 or CONST2
```

The optimized code sets register EBX to 0 then compares A and B. If A is greater than or equal to B then EBX is set to 1. EBX is then decremented and ANDed with the difference of the constant values. This sets EBX to either 0 or the difference of the values. By adding the minimum of the two constants the correct value is written to EBX. When CONST1 or CONST2 is equal to zero, the last instruction can be deleted as the correct value already has been written to EBX.

When ABS(CONST1-CONST2) is 1 of {2,3,5,9}, the following example applies:

```
        xor     ebx, ebx
        cmp     A, B
        setge   bl                      ; or the complement condition
        lea     ebx, [ebx*D+ebx+CONST1-CONST2]
```

where D stands for ABS(CONST1 − CONST2) − 1.

A second way to remove branches on P6 family processors is to use the new CMOV*cc* and FCMOV*cc* instructions. The following example shows how to use the CMOV*cc* instruction to eliminate the branch from a test and branch instruction sequence. If the test sets the equal flag then the value in register EBX will be moved to register EAX. This branch is data dependent, and is representative of a unpredictable branch.

```
        test    ecx, ecx
        jne     1h
        mov     eax, ebx
1h:
```

To change the code, the JNE and the MOV instructions are combined into one CMOV*cc* instruction, which checks the equal flag. The optimized code is shown below:

```
        test    ecx, ecx        ; test the flags
        cmoveqeax, ebx          ; if the equal flag is set, move ebx to eax
1h:
```

The label 1h: is no longer needed unless it is the target of another branch instruction. These instructions will generate invalid opcodes when used on previous generation Intel Architecture processors. Therefore, use the CPUID instruction to check feature bit 15 of the EDX register, which when set indicates presence of the CMOV*cc* family of instructions. Do not use the family and model codes returned by CPUID to test for the presence of specific features.

Additional information on branch optimization can be found in the *Intel Architecture Optimization Manual*.

14.3. REDUCING PARTIAL REGISTER STALLS ON P6 FAMILY PROCESSORS

On P6 family processors, when a large (32-bit) general-purpose register is read immediately after a small register (8- or 16-bit) that is contained in the large register has been written, the read is stalled until the write retires (a minimum of 7 clocks). Consider the example below:

```
MOV     AX, 8
ADD     ECX, EAX            ; Partial stall occurs on access of
                            ; the EAX register
```

Here, the first instruction moves the value 8 into the small register AX. The next instruction accesses the large register EAX. This code sequence results in a partial register stall.

Pentium® and Intel486™ processors do not generate this stall.

Table 14-1 lists the groups of small registers and their corresponding large register for which a partial register stall can occur. For example, writing to register BL, BH, or BX and subsequently reading register EBX will result in a stall.

Table 14-1. Small and Large General-Purpose Register Pairs

Small Registers			Large Registers
AL	AH	AX	EAX
BL	BH	BX	EBX
CL	CH	CX	ECX
DL	DH	DX	EDX
		SP	ESP
		BP	EBP
		DI	EDI
		SI	ESI

Because the P6 family processors can execute code out of order, the instructions need not be immediately adjacent for the stall to occur. The following example also contains a partial stall:

```
MOV     AL, 8
MOV     EDX, 0x40
MOV     EDI, new_value
```

```
ADD     EDX, EAX            ; Partial stall occurs on access of
                            ; the EAX register
```

In addition, any micro-ops that follow the stalled micro-op will also wait until the clock cycle after the stalled micro-op continues through the pipe. In general, to avoid stalls, do not read a large register after writing a small register that is contained in the large register.

Special cases of writing and reading corresponding small and large registers have been implemented in the P6 family processors to simplify the blending of code across processor generations. The special cases include the XOR and SUB instructions when using EAX, EBX, ECX, EDX, EBP, ESP, EDI and ESI as shown in the following examples:

```
xor     eax, eax
movb    al, mem8
add     eax, mem32          ; no partial stall

xor     eax, eax
movw    ax, mem16
add     eax, mem32          ; no partial stall

sub     ax, ax
movb    al, mem8
add     ax, mem16           ; no partial stall

sub     eax, eax
movb    al, mem8
or      ax, mem16           ; no partial stall

xor     ah, ah
movb    al, mem8
sub     ax, mem16           ; no partial stall
```

In general, when implementing this sequence, always write all zeros to the large register then write to the lower half of the register.

14.4. ALIGNMENT RULES AND GUIDELINES

The following section gives rules and guidelines for aligning of code and data for optimum code execution speed.

14.4.1. Alignment Penalties

The following are common penalties for accesses to misaligned data or code:

- On a Pentium® processor, a misaligned access costs 3 clocks.
- On a P6 family processor, a misaligned access that crosses a cache line boundary costs 6 to 9 clocks.
- On a P6 family processor, unaligned accesses that cause a data cache split stall the processor. A data cache split is a memory access that crosses a 32-byte cache line boundary.

For best performance, make sure that data structures and arrays greater than 32 bytes, are 32-byte aligned, and that access patterns to data structures and arrays do not break the alignment rules.

14.4.2. Code Alignment

The P6 family and Pentium® processors have a cache line size of 32 bytes. Since the prefetch buffers fetch on 16-byte boundaries, code alignment has a direct impact on prefetch buffer efficiency.

For optimal performance across the Intel Architecture family, it is recommended that:

- A loop entry label should be 16-byte aligned when it is less than 8 bytes away from that boundary.
- A label that follows a conditional branch should not be aligned.
- A label that follows an unconditional branch or function call should be 16-byte aligned when it is less than 8 bytes away from that boundary.

14.4.3. Data Alignment

A misaligned access in the data cache or on the bus costs at least 3 extra clocks on the Pentium® processor. A misaligned access in the data cache, which crosses a cache line boundary, costs 9 to 12 clocks on the P6 family processors. It is recommended that data be aligned on the following boundaries for optimum code execution on all processors:

- Align 8-bit data on any boundary.
- Align 16-bit data to be contained within an aligned 4-byte word.
- Align 32-bit data on any boundary that is a multiple of 4.
- Align 64-bit data on any boundary that is a multiple of 8.

- Align 80-bit data on a 128-bit boundary (that is, any boundary that is a multiple of 16 bytes).
- Align 128-bit SIMD floating-point data on a 128-bit boundary (that is, any boundary that is a multiple of 16 bytes).

14.4.3.1. ALIGNMENT OF DATA STRUCTURES AND ARRAYS GREATER THAN 32 BYTES

A 32-byte or greater data structure or array should be aligned such that the beginning of each structure or array element is aligned on a 32 byte boundary, and such that each structure or array element does not cross a 32-byte cache line boundary.

Does this general discussion adequately cover the differences between 8, 16, and 32 bit alignments?

14.4.3.2. ALIGNMENT OF DATA IN MEMORY AND ON THE STACK

On the Pentium® processor, accessing 64-bit variables that are not 8-byte aligned will cost an extra 3 clocks. On the P6 family processors, accessing a 64-bit variable will cause a data cache split. Some commercial compilers do not align double precision variables on 8-byte boundaries. In such cases, the following techniques can be used to force optimum alignment of data:

- Use static variables instead of dynamic (stack) variables.
- Use in-line assembly code that explicitly aligns data.
- In C code, use “malloc” to explicitly allocate variables.

The following sections describe these techniques.

Static Variables

When a compiler allocates stack space for a dynamic variable, it may not align the variable (see Figure 14-1). However, in most cases, when the compiler allocates space in memory for static variables, the variables are aligned.

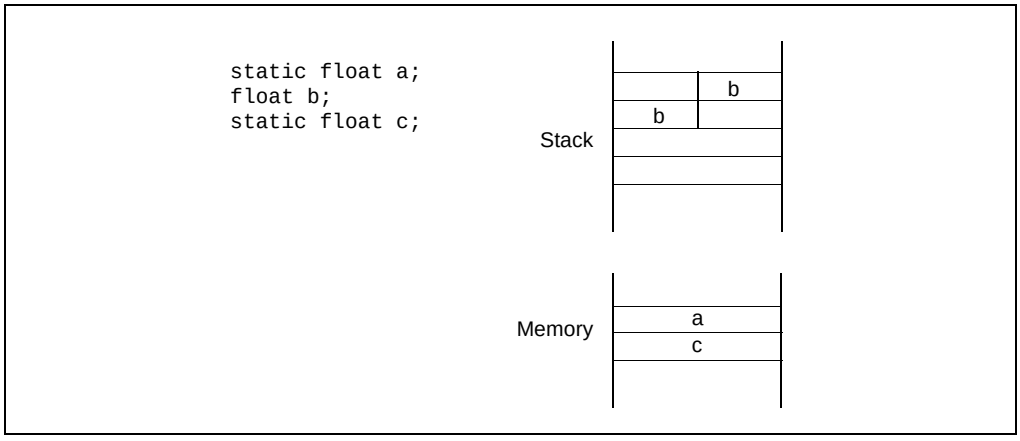


Figure 14-1. Stack and Memory Layout of Static Variables

Alignment Using Assembly Language

Use in-line assembly code to explicitly align variables. The following example aligns the stack to 64-bits.

```
; procedure prologue
push        ebp
mov         esp, ebp
and         ebp, -8
sub         esp, 12

; procedure epilogue
add         esp, 12
pop         ebp
ret
```

Dynamic Allocation Using MALLOC

When using dynamic allocation, check that the compiler aligns doubleword or quadword values on 8-byte boundaries. If the compiler does not implement this alignment, then use the following technique to align doublewords and quadwords for optimum code execution:

1. Allocate memory equal to the size of the array or structure plus 4 bytes.
2. Use “bitwise” and to make sure that the array is aligned, for example:

```
double      a[5];
double      *p, *newp;
p = (double*)malloc ((sizeof(double)*5)+4)
newp = (p+4) & (-7)
```

14.5. INSTRUCTION SCHEDULING OVERVIEW

On all Intel Architecture processors, the **scheduling** of (arrangement of) instructions in the instruction stream can have a significant affect on the execution speed of the processor. For example, when executing code on a Pentium® or later Intel Architecture processor, two 1-clock instructions that do not have register or data dependencies between them can generally be executed in parallel (in a single clock) if they are paired—placed adjacent to one another in the instruction stream. Likewise, a long-latency instruction such as a floating-point instruction can often be executed in parallel with a sequence of 1-clock integer instructions or shorter latency floating-point instructions if the instructions are scheduled appropriately in the instruction stream.

The following sections describe two aspects of scheduling that can provide improved performance in Intel Architecture processors: pairing and pipelining. Pairing is generally used to optimize the execution of integer and MMX™ instructions; pipelining is generally used to optimize the execution of MMX™ and floating-point instructions.

14.5.1. Instruction Pairing Guidelines

The microarchitecture for the Pentium® family of processors (with and without MMX™ technology) contain two instruction execution pipelines: the U-pipe and the V-pipe. These pipelines are capable of executing two Intel Architecture instructions in parallel (during the same clock or clocks) if the two instructions are **pairable**. Pairable instructions are those instructions that when they appear adjacent to one another in the instruction stream will normally be executed in parallel. By ordering a code sequence so that whenever possible pairable instructions occur sequentially, code can be optimized to take advantage of the Pentium® processor's two-pipe microarchitecture.

NOTE

Pairing of instructions improves Pentium® processor performance significantly. It does not slow and sometimes improves the performance of P6 family processors.

The following subsections describe the Pentium® processor pairing rules for integer, MMX™, and, floating-point instructions. The pairing rules are grouped into types, as follows:

- General pairing rules
- Integer instruction pairing rules.
- MMX™ instruction pairing rules.
- Floating-point instruction pairing rules.

14.5.1.1. GENERAL PAIRING RULES

The following are general rules for instruction pairing in code written to run on Pentium® processors:

- Unpairable instructions are always executed in the U-pipe.
- For paired instructions to execute in parallel, the first instruction of the pair must fall on an instruction boundary that forces the instruction to be executed in the U-pipe. The following placements of an instruction in the instruction stream will force an instruction to be executed in the U-pipe:
  - — If the first instruction of a pair of pairable instructions is the first instruction in a block of code, the first instruction will be executed in the U-pipe and the second of the pair will be executed in the V-pipe, resulting in parallel execution of the two instructions.
  - — If the first instruction of a pair of pairable instructions follows an unpairable instruction in the instruction stream, the first of the pairable instructions will be executed in the U-pipe and the second of the pair in the V-pipe, resulting in parallel execution.
  - — After one pair of instructions has been executed in parallel, subsequent pairs will also be executed in parallel until an unpairable instruction is encountered.
- Parallel execution of paired instructions will not occur if:
  - — The next two instructions are not pairable instructions.
  - — The next two instructions have some type of register contention (implicit or explicit). There are some special exceptions (see “Special Pairs”, in Section 14.5.1.2., “Integer Pairing Rules”) to this rule where register contention can occur with pairing.
  - — The instructions are not both in the instruction cache. An exception to this that permits pairing is if the first instruction is a one byte instruction.
  - — The processor is operating in single-step mode.
- Instructions that have data dependencies should be separated by at least one other instruction.
- Pentium® processors without MMX™ technology do not execute a set of paired instructions if either instruction is longer than 7 bytes; Pentium® processors with MMX™ technology do not execute a set of paired instructions if the first instruction is longer than 11 bytes or the second instruction is longer than 7 bytes. Prefixes are not counted.
- On Pentium® processors without MMX™ technology, prefixed instructions are pairable only in the U-pipe. On Pentium® processors with MMX™ technology, instructions with 0FH, 66H or 67H prefixes are also pairable in the V-pipe. For this and the previous rule, stalls at the entrance to the instruction FIFO, on Pentium® processors with MMX™ technology, will prevent pairing.
- Floating-point instructions are not pairable with MMX™ instructions.

14.5.1.2. INTEGER PAIRING RULES

Table 14-2 shows the integer instructions that can be paired. The table is divided into two halves: one for the U-pipe and one for the V-pipe. Any instruction in the U-pipe list can be paired with any instruction in the V-pipe list, and vice versa.

Table 14-2. Pairable Integer Instructions

Integer Instruction Pairable in U-Pipe			Integer Instruction Pairable in V-Pipe		
MOV *reg*, *reg*	*ALU reg*, *imm*	PUSH *reg*	MOV *reg*, *reg*	*ALU reg*, *imm*	PUSH *reg*
MOV *reg*, *mem*	*ALU mem*, *imm*	PUSH *imm*	MOV *reg*, *mem*	*ALU mem*, *imm*	PUSH *imm*
MOV *mem*, *reg*	*ALU* eax, *imm*	POP *reg*	MOV *mem*, *reg*	*ALU* eax, *imm*	POP *reg*
MOV *reg*, *imm*	*ALU mem*, *reg*	NOP	MOV *reg*, *imm*	*ALU mem*, *reg*	JMP near
MOV *mem*, *imm*	*ALU reg*, *mem*	SHIFT/ROT by 1	MOV *mem*, *imm*	*ALU reg*, *mem*	J*cc* near
MOV eax, *mem*	INC/DEC *reg*	SHIFT by *imm*	MOV eax, *mem*	INC./DEC *reg*	0F J*cc*
MOV *mem*, eax	INC/DEC *mem*	TEST *reg*, *r/m*	MOV m, eax	INC/DEC *mem*	CALL near
ALU reg, *reg*	LEA *reg*, *mem*	TEST *acc*, *imm*	*ALU reg*, *reg*	LEA *reg*, *mem*	NOP
				TEST *reg*, *r/m*	TEST *acc*, *imm*

NOTES:

ALU—Arithmetic or logical instruction such as ADD, SUB, or AND. In general, most simple ALU instructions are pairable.

imm—Immediate.

reg—Register.

mem—Memory location.

r/m—Register or memory location.

acc—Accumulator (EAX or AX register).

General Integer-Instruction Pairability Rules

The following are general rules for pairability of integer instructions. These rules summarize the pairing of instructions in Table 14-2.

- NP Instructions—The following integer instructions cannot be paired:
  - — The shift and rotate instructions with a shift count in the CL register.
  - — Long-arithmetic instructions, such as MUL and DIV.
  - — Extended instructions, such as RET, ENTER, PUSHA, MOVS, STOS, and LOOPNZ.
  - — Inter-segment instructions, such as PUSH sreg and CALL far.
- UV Instructions—The following instructions can be paired when issued to the U- or V-pipes:
  - — Most 8/32 bit ALU operations, such as ADD, INC, and XOR.
  - — All 8/32 bit compare instructions, such as CMP and TEST.
  - — All 8/32 bit stack operations using registers, such as PUSH reg and POP reg.
- PU instructions—The following instructions when issued to the U-pipe can be paired with a suitable instruction in the V-Pipe. These instructions never execute in the V-pipe.
  - — Carry and borrow instructions, such as ADC and SBB.

— Prefixed instructions.

— Shift with immediate instructions.

- PV instructions—The following instructions when issued to the V-pipe can be paired with a suitable instruction in the U-Pipe. The simple control transfer instructions, such as the CALL near, JMP near, or J*cc* instructions, can execute in either the U-pipe or the V-pipe, but they can be paired with other instructions only when they are in the V-pipe. Since these instructions change the instruction pointer (EIP), they cannot pair in the U-pipe since the next instruction may not be adjacent. The PV instructions include both J*cc* short and J*cc* near (which have a 0FH prefix) versions of the J*cc* instruction.

Unpairability Due to Register Dependencies

Instruction pairing is also affected by instruction operands. The following instruction pairings will not result in parallel execution because of register contention. Exceptions to these rules are given in “Special Pairs”, in Section 14.5.1.2., “Integer Pairing Rules”.

- Flow Dependence—The first instruction writes to a register that the second one reads from, as in the following example:

```
mov     eax, 8
mov     [ebp], eax
```

- Output Dependence—Both instructions write to the same register, as in the following example.

```
mov     eax, 8
mov     eax, [ebp]
```

This output dependence limitation does not apply to a pair of instructions that write to the EFLAGS register (for example, two ALU operations that change the condition codes). The condition code after the paired instructions execute will have the condition from the V-pipe instruction.

Note that a pair of instructions in which the first reads a register and the second writes to the same register (anti-dependence) may be paired, as in the following example:

```
mov     eax, ebx
mov     ebx, [ebp]
```

For purposes of determining register contention, a reference to a byte or word register is treated as a reference to the containing 32-bit register. Therefore, the following instruction pair does not execute in parallel because of output dependencies on the contents of the EAX register.

```
mov     al, 1
mov     ah, 0
```

Special Pairs

Some integer instructions can be paired in spite of the previously described general integer-instruction rules. These special pairs overcome register dependencies, and most involve implicit reads/writes to the ESP register or implicit writes to the condition codes:

- Stack Pointer.

```
push   reg/imm    ; push reg/imm
push   reg/imm    ; call
pop    reg        ; pop reg
```

- Condition Codes.

```
cmp               ; jcc
add               ; jne
```

Note that the special pairs that consist of PUSH/POP instructions may have only immediate or register operands, not memory operands.

Restrictions On Pair Execution

Some integer-instruction pairs may be issued simultaneously but will not execute in parallel:

- Data-Cache Conflict—If both instructions access the same data-cache memory bank then the second request (V-pipe) must wait for the first request to complete. A bank conflict occurs when bits 2 through 4 of the two physical addresses are the same. A bank conflict results in a 1-clock penalty on the V-pipe instruction.
- Inter-Pipe Concurrency—Parallel execution of integer instruction pairs preserves memory-access ordering. A multiclock instruction in the U-pipe will execute alone until its last memory access.

For example, the following instructions add the contents of the register and the value at the memory location, then put the result in the register. An add with a memory operand takes 2 clocks to execute. The first clock loads the value from the data cache, and the second clock performs the addition. Since there is only one memory access in the U-pipe instruction, the add in the V-pipe can start in the same clock.

```
add      eax, meml
add      ebx, mem2              ; 1
(add)    (add)                  ; 2  2-cycle
```

The following instructions add the contents of the register to the memory location and store the result at the memory location. An add with a memory result takes 3 clocks to execute. The first clock loads the value, the second performs the addition, and the third stores the result. When paired, the last clock of the U-pipe instruction overlaps with the first clock of the V-pipe instruction execution.

```
add       meml, eax             ; 1
(add)                           ; 2
(add)    add  mem2, ebx         ; 3
(add)                    ; 4
(add)                    ; 5
```

No other instructions may begin execution until the instructions already executing have completed.

To expose the opportunities for scheduling and pairing, it is better to issue a sequence of simple instructions rather than a complex instruction that takes the same number of clocks. The simple instruction sequence can take advantage of more issue slots. The load/store style code generation requires more registers and increases code size. This impacts Intel486™ processor performance, although only as a second order effect. To compensate for the extra registers needed, extra effort should be put into register allocation and instruction scheduling so that extra registers are only used when parallelism increases.

14.5.1.3. MMX™ INSTRUCTION PAIRING GUIDELINES

This section specifies guidelines and restrictions for pairing MMX™ instructions with each other and with integer instructions.

Pairing Two MMX™ Instructions

The following restrictions apply when pairing of two MMX™ instructions:

- Two MMX™ instructions that both use the MMX™ shifter unit (pack, unpack, and shift instructions) are not pairable because there is only one MMX™ shifter unit. Shift operations may be issued in either the U-pipe or the V-pipe, but cannot executed in both pipes in the same clock.
- Two MMX™ instructions that both use the MMX™ multiplier unit (PMULL, PMULH, PMADD type instructions) are not pairable because there is only one MMX™ multiplier unit. Multiply operations may be issued in either the U-pipe or the V-pipe, but cannot executed in both pipes in the same clock.
- MMX™ instructions that access either memory or a general-purpose register can be issued in the U-pipe only. Do not schedule these instructions to the V-pipe as they will wait and be issued in the next pair of instructions (and to the U-pipe).
- The MMX™ destination register of the U-pipe instruction should not match the source or destination register of the V-pipe instruction (dependency check).
- The EMMS instruction is not pairable with other instructions.
- If either the TS flag or the EM flag in control register CR0 is set, MMX™ instructions cannot be executed in the V-pipe.

Pairing an Integer Instruction in the U-Pipe With an MMX™ Instruction in the V-Pipe

Use the following guidelines for pairing an integer instruction in the U-pipe and an MMX™ instruction in the V-pipe:

- The MMX™ instruction is not the first MMX™ instruction following a floating-point instruction.
- The V-pipe MMX™ instruction does not access either memory or a general-purpose register.

- The U-pipe integer instruction is a pairable U-pipe integer instruction (see Table 14-2).

Pairing an MMX™ Instruction in the U-Pipe with an Integer Instruction in the V-Pipe

Use the following guidelines for pairing an MMX™ instruction in the U-pipe and an integer instruction in the V-pipe:

- The U-pipe MMX™ instruction does not access either memory or a general-purpose register.
- The V-pipe instruction is a pairable integer V-pipe instruction (see Table 14-2).

14.5.2. Pipelining Guidelines

The term **pipelining** refers to the practice of scheduling instructions in the instruction stream to reduce processor stalls due to register, data, or data-cache dependencies. The effect of pipelining on code execution is highly dependent on the family of Intel Architecture processors the code is intended to run on. Pipelining can greatly increase the performance of code written to run on the Pentium® family of processors. It is less important for code written to run on the P6 family processors, because the dynamic execution model that these processors use does a significant amount of pipelining automatically.

The following subsections describe general pipelining guidelines for MMX™ and floating-point instructions. These guidelines yield significant improvements in execution speed for code running on the Pentium® processors and may yield additional improvements in execution speed on the P6 family processors. Specific pipelining guidelines for the P6 family processors are given in Section 14.5.3., “Scheduling Rules for P6 Family Processors”

14.5.2.1. MMX™ INSTRUCTION PIPELINING GUIDELINES

All MMX™ instructions can be pipelined on P6 family and Pentium® (with MMX™ technology) processors, including the multiply instructions. All MMX™ instructions take a single clock to execute except the MMX™ multiply instructions which take 3 clocks.

Since MMX™ multiply instructions take 3 clocks to execute, the result of a multiply instruction can be used only by other instructions issued 3 clocks later. For this reason, avoid scheduling a dependent instruction in the 2 instruction pairs following the multiply.

The store of a register after writing the register must wait for 2 clocks after the update of the register. Scheduling the store 2 clocks after the update avoids a pipeline stall.

14.5.2.2. FLOATING-POINT PIPELINING GUIDELINES

Many of the floating-point instructions have a latency greater than 1 clock, therefore on Pentium® processors the next floating-point instruction cannot access the result until the first operation has finished execution. To hide this latency, instructions should be inserted between the pair that causes the pipe stall. These instructions can be integer instructions or floating-point instructions that will not cause a new stall themselves. The number of instructions that should be inserted depends on the length of the latency. Because of the out-of-order execution capa-

bility of the P6 family processors, stalls will not necessarily occur on an instruction or micro-op basis. However, if an instruction has a very long latency such as an FDIV, then scheduling can improve the throughput of the overall application. The following sections list considerations for floating-point pipelining on Pentium® processors.

Pairing of Floating-Point Instructions

In a Pentium® processor, pairing floating-point instructions with one another (with one exception) does not result in a performance enhancement because the processor has only one floating-point unit (FPU). However, some floating-point instructions can be paired with integer instructions or the FXCH instruction to improve execution times. The following are some general pairing rules and restrictions for floating-point instructions:

- All floating-point instructions can be executed in the V-pipe and paired with suitable instructions (generally integer instructions) in the U-pipe.
- The only floating-point instruction that can be executed in the U-pipe is the FXCH instruction. The FXCH instruction, if executed in the U-pipe can be paired with another floating-point instruction executing in the V-pipe.
- The floating-point instructions FSCALE, FLDCW, and FST cannot be paired with any instruction (integer instruction or the FXCH instruction).

Using Integer Instructions to Hide Latencies and Schedule Floating-Point Instructions

When a floating-point instruction depends on the result of the immediately preceding instruction, and that instruction is also a floating-point instruction, performance can be improved by placing one or more integer instructions between the two floating-point instructions. This is true even if the integer instructions perform loop control. The following example restructures a loop in this manner:

```
for (i=0; i<Size; i++)
    array1 [i] += array2 [i];

; assume eax=Size-1, esi=array1, edi=array2

PENTIUM(R) PROCESSORCLOCKS

LoopEntryPoint:
    fld         real4 ptr [esi+eax*4]           ; 2 - AGI
    fadd        real4 ptr [edi+eax*4]           ; 1
    fstp        real4 ptr [esi+eax*4]           ; 5 - waits for fadd
    dec         eax                             ; 1
    jnz         LoopEntryPoint

    ; assume eax=Size-1, esi=array1, edi=array2

    jmp         LoopEntryPoint
    Align   16
TopOfLoop:
    fstp    real4 ptr [esi+eax*4+4]             ; 4 - waits for fadd + AGI
LoopEntryPoint:
    fld         real4 ptr [esi+eax*4]           ;1
```

```
fadd        real4 ptr [edi+eax*4]          ;1
dec         eax                            ;1
jnz         TopOfLoop
;
fstp        real4 ptr [esi+eax*4+4]
```

By moving the integer instructions between the FADDS and FSTPS instructions, the integer instructions can be executed while the FADDS instruction is completing in the floating-point unit and before the FSTPS instruction begins execution. Note that this new loop structure requires a separate entry point for the first iteration because the loop needs to begin with the FLDS instruction. Also, there needs to be an additional FSTPS instruction after the conditional jump to finish the final loop iteration.

Hiding the One-Clock Latency of a Floating-Point Store

A floating-point store must wait an extra clock for its floating-point operand. After an FLD, an FST must wait 1 clock, as shown in the following example:

```
fld         meml        ; 1 fld takes 1 clock
                        ; 2 fst waits, schedule something here
fst         mem2        ; 3,4 fst takes 2 clocks
```

After the common arithmetic operations, FMUL and FADD, which normally have a latency of 3 clocks, FST waits an extra clock for a total of 4 (see following example).

```
fadd        meml        ; 1 add takes 3 clocks
                        ; 2 add, schedule something here
                        ; 3 add, schedule something here
                        ; 4 fst waits, schedule something here
fst         mem2        ; 5,2 fst takes 2 clocks
```

Other instructions such as FADDP and FSUBRP also exhibit this type of latency.

In the next example, the store is not dependent on the previous load:

```
fld         meml        ; 1
fld         mem2        ; 2
fxch        st(l)       ; 2
fst         mem3        ; 3 stores values loaded from meml
```

Here, a register may be used immediately after it has been loaded (with FLD):

```
fld         mem1        ; l
fadd        mem2        ; 2,3,4
```

Use of a register by a floating-point operation immediately after it has been written by another FADD, FSUB, or FMUL causes a 2-clock delay. If instructions are inserted between these two, then latency and a potential stall can be hidden.

Additionally, there are multiclock floating-point instructions (FDIV and FSQRT) that execute in the floating-point unit pipe (the U-pipe). While executing these instructions in the floating-point unit pipe, integer instructions can be executed in parallel. Emitting a number of integer instructions after such an instruction will keep the integer execution units busy (the exact number of instructions depends on the floating-point instruction's clock count).

Integer instructions generally overlap with the floating-point operations except when the last floating-point operation was FXCH. In this case there is a 1 clock delay:

```
U-pipe                  V-pipe
fadd                    fxch        ; 1
                                    ; 2 fxch delay
mov eax, 1              inc edx
```

Integer and Floating-Point Multiply

The integer multiply operations, the MUL and IMUL instructions, are executed by the FPU's multiply unit. Therefore, for the Pentium® processor, these instructions cannot be executed in parallel with a floating-point instruction. This restriction does not apply to the P6 family processors, because these processors have two internal FPU execution units.

A floating-point multiply instruction (FMUL) delays for 1 clock if the immediately preceding clock executed an FMUL or an FMUL-FXCH pair. The multiplier can only accept a new pair of operands every other clock.

Floating-Point Operations with Integer Operands

Floating-point operations that take integer operands (the FIADD or FISUB instruction) should be avoided. These instructions should be split into two instructions: the FILD instruction and a floating-point operation. The number of clocks before another instruction can be issued (throughput) for FIADD is 4, while for FILD and simple floating-point operations it is 1, as shown in the example below:

```
Complex Instructions        Better for Potential Overlap
fiadd  [ebp] ; 4            fild   [ebp]  ; 1
                            faddp  st(l)  ; 2
```

Using the FILD and FADDP instructions in place of FIADD yields 2 free clocks for executing other instructions.

FSTSW Instruction

The FSTSW instruction that usually appears after a floating-point comparison instruction (FCOM, FCOMP, FCOMPP) delays for 3 clocks. Other instructions may be inserted after the comparison instruction to hide this latency. On the P6 family processors the FCMOV*cc* instruction can be used instead.

Transcendental Instructions

Transcendental instructions execute in the U-pipe and nothing can be overlapped with them, so an integer instruction following a transcendental instruction will wait until the previous instruction completes.

Transcendental instructions execute on the Pentium® processor (and later Intel Architecture processors) much faster than the software emulations of these instructions found in most math libraries. Therefore, it may be worthwhile in-lining transcendental instructions in place of math library calls to transcendental functions. Software emulations of transcendental instructions will execute faster than the equivalent instructions only if accuracy is sacrificed.

FXCH Guidelines

The FXCH instruction costs no extra clocks on the Pentium® processor when all of the following conditions occur, allowing the instruction to execute in the V-pipe in parallel with another floating-point instruction executing in the U-pipe:

- A floating-point instruction follows the FXCH instruction.
- A floating-point instruction from the following list immediately precedes the FXCH instruction: FADD, FSUB, FMUL, FLD, FCOM, FUCOM, FCHS, FTST, FABS, or FDIV.
- An FXCH instruction has already been executed. This is because the instruction boundaries in the cache are marked the first time the instruction is executed, so pairing only happens the second time this instruction is executed from the cache.

When the above conditions are true, the instruction is almost “free” and can be used to access elements in the deeper levels of the floating-point stack instead of storing them and then loading them again.

14.5.3. Scheduling Rules for P6 Family Processors

The P6 family processors have 3 decoders that translate Intel Architecture macro instructions into micro operations (micro-ops, also called “uops”). The decoder limitations are as follows:

- The first decoder (decoder 0) can decode instructions up to 7 bytes in length and with up to 4 micro-ops in one clock cycle. The second two decoders (decoders 1 and 2) can decode instructions that are 1 micro-op instructions, and these instructions will also be decoded in one clock cycle.
- Three macro instructions in an instruction sequence that fall into this envelope will be decoded in one clock cycle.
- Macro instructions outside this envelope will be decoded through decoder 0 alone. While decoder 0 is decoding a long macro instruction, decoders 1 and 2 (second and third decoders) are quiescent.

Appendix C of the *Intel Architecture Optimization Manual* lists all Intel macro-instructions and the decoders on which they can be decoded.

The macro instructions entering the decoder travel through the pipe in order; therefore, if a macro instruction will not fit in the next available decoder then the instruction must wait until the next clock to be decoded. It is possible to schedule instructions for the decoder such that the instructions in the in-order pipeline are less likely to be stalled.

Consider the following examples:

- If the next available decoder for a multimicro-op instruction is not decoder 0, the multimicro-op instruction will wait for decoder 0 to be available, usually in the next clock, leaving the other decoders empty during the current clock. Hence, the following two instructions will take 2 clocks to decode.

```
add     eax, ecx        ; 1 uop instruction (decoder 0)
add     edx, [ebx]      ; 2 uop instruction (stall 1 cycle wait till
                        ; decoder 0 is available)
```

- During the beginning of the decoding clock, if two consecutive instructions are more than 1 micro-op, decoder 0 will decode one instruction and the next instruction will not be decoded until the next clock.

```
add     eax, [ebx]      ; 2 uop instruction (decoder 0)
mov     ecx, [eax]      ; 2 uop instruction (stall 1 cycle to wait until
                        ; decoder 0 is available)
add     ebx, 8          ; 1 uop instruction (decoder 1)
```

Instructions of the *opcode reg, mem* form produce two micro-ops: the load from memory and the operation micro-op. Scheduling for the decoder template (4-1-1) can improve the decoding throughput of your application.

In general, the *opcode reg, mem* forms of instructions are used to reduce register pressure in code that is not memory bound, and when the data is in the cache. Use simple instructions for improved speed on the Pentium® and P6 family processors.

The following rules should be observed while using the *opcode reg, mem* instruction on Pentium® processors with MMX™ technology:

- Schedule for minimal stalls in the Pentium® processor pipe. Use as many simple instructions as possible. Generally, 32-bit assembly code that is well optimized for the Pentium® processor pipeline will execute well on the P6 family processors.
- When scheduling for Pentium® processors, keep in mind the primary stall conditions and decoder (4-1-1) template on the P6 family processors, as shown in the example below.

```
pmaddw      mm6, [ebx]      ; 2 uops instruction (decoder 0)
paddd       mm7, mm6        ; 1 uop instruction (decoder 1)
ad          ebx, 8          ; 1 uop instruction (decoder 2)
```

14.6. ACCESSING MEMORY

The following subsections describe optimizations that can be obtained when scheduling instructions that access memory.

14.6.1. Using MMX™ Instructions That Access Memory

An MMX™ instruction may have two register operands (*opcode reg*, *reg*) or one register and one memory operand (*opcode reg, mem*), where *opcode* represents the instruction opcode, *reg* represents the register, and *mem* represents memory. The *opcode reg, mem* instructions are useful in some cases to reduce register pressure, increase the number of operations per clock, and reduce code size.

The following discussion assumes that the memory operand is present in the data cache. If it is not, then the resulting penalty is usually large enough to obviate the scheduling effects discussed in this section.

In Pentium® processor with MMX™ technology, the *opcode reg, mem* MMX™ instructions do not have longer latency than the *opcode reg, reg* instructions (assuming a cache hit). They do have more limited pairing opportunities, however. In the Pentium® II and Pentium® III processors, the *opcode reg, mem* MMX™ instructions translate into two micro-ops, as opposed to one micro-op for the *opcode reg, reg* instructions. Thus, they tend to limit decoding bandwidth and occupy more resources than the *opcode reg, reg* instructions.

The recommended usage of the *opcode reg, reg* instructions depends on whether the MMX™ code is memory-bound (that is, execution speed is limited by memory accesses). As a rule of thumb, an MMX™ code sequence is considered to be memory-bound if the following inequality holds:

$$\frac{\text{Instructions}}{2} < \text{MemoryAccesses} + \frac{\text{NonMMXInstructions}}{2}$$

For memory-bound MMX™ code, Intel recommends merging loads whenever the same memory address is used more than once to reduce memory accesses. For example, the following code sequence can be speeded up by using a MOVQ instruction in place of the *opcode reg, mem* forms of the MMX™ instructions:

```
OPCODE    MM0, [address A]
OPCODE    MM1, [address A]
; optimized by use of a MOVQ instruction and opcode reg, mem forms
; of the MMX(TM) instructions

MOVQ      MM2, [address A]
OPCODE    MM0, MM2
OPCODE    MM1, MM2
```

Another alternative is to incorporate the prefetch instruction introduced in the Pentium® III processor. Prefetching the data preloads the cache prior to actually needing the data. Proper use of prefetch can improve performance if the application is not memory bandwidth bound or the

data does not already fit into cache. For more information on proper usage of the prefetch instruction see the *Intel Architecture Optimization Manual order number 245127-001*.

For MMX™ code that is not memory-bound, load merging is recommended only if the same memory address is used more than twice. Where load merging is not possible, usage of the *opcode reg, mem* instructions is recommended to minimize instruction count and code size. For example, the following code sequence can be shortened by removing the MOVQ instruction and using an *opcode reg, mem* form of the MMX™ instruction:

```
MOVQ      mm0, [address A]
OPCODE    mm1, mm0
; optimized by removing the MOVQ instruction and using an
; opcode reg, mem form of the MMX(TM) instructions

OPCODE    mm1, [address A]
```

In many cases, a MOVQ *reg, reg* and *opcode reg, mem* can be replaced by a MOVQ *reg, mem* and the *opcode reg, reg*. This should be done where possible, since it saves one micro-op on the Pentium® II and Pentium® III processors. The following example is one where the *opcode* is a symmetric operation:

```
MOVQ      mm1, mm0          (1 micro-op)
OPCODE    mm1, [address A]  (2 micro-ops)
```

One clock can be saved by rewriting the code as follows:

```
MOVQ      mm1, [address A]  (1 micro-op)
OPCODE    mm1, mm0          (1 micro-op)
```

14.6.2. Partial Memory Accesses With MMX™ Instructions

The MMX™ registers allow large quantities of data to be moved without stalling the processor. Instead of loading single array values that are 8-, 16-, or 32-bits long, the values can be loaded in a single quadword, with the structure or array pointer being incremented accordingly.

Any data that will be manipulated by MMX™ instructions should be loaded using either:

- The MMX™ instruction that loads a 64-bit operand (for example, MOVQ MM0, m64), or
- The register-memory form of any MMX™ instruction that operates on a quadword memory operand (for example, PMADDW MM0, m64).

All data in MMX™ registers should be stored using the MMX™ instruction that stores a 64-bit operand (for example, MOVQ m64, MM0).

The goal of these recommendations is twofold. First, the loading and storing of data in MMX™ registers is more efficient using the larger quadword data block sizes. Second, using quadword data block sizes helps to avoid the mixing of 8-, 16-, or 32-bit load and store operations with 64-bit MMX™ load and store operations on the same data. This, in turn, prevents situations in which small loads follow large stores to the same area of memory, or large loads follow small stores to the same area of memory. The Pentium® II and Pentium® III processors will stall in these situations.

Consider the following examples.

The first example illustrates the effects of a large load after a series of small stores to the same area of memory (beginning at memory address *mem*). The large load will stall the processor:

```
MOV     mem, eax        ; store dword to address "mem"
MOV     mem + 4, ebx    ; store dword to address "mem + 4"
  :
  :
MOVQ    mm0, mem        ; load qword at address "mem", stalls
```

The MOVQ instruction in this example must wait for the stores to write memory before it can access all the data it requires. This stall can also occur with other data types (for example, when bytes or words are stored and then words or doublewords are read from the same area of memory). By changing the code sequence as follows, the processor can access the data without delay:

```
MOVD    mm1, ebx        ; build data into a qword first before storing it to memory
MOVD    mm2, eax
PSLLQ   mm1, 32
POR     mm1, mm2
MOVQ    mem, mm1        ; store SIMD variable to "mem" as a qword
  :
  :
MOVQ    mm0, mem        ; load qword SIMD variable "mem", no stall
```

The second example illustrates the effect of a series of small loads after a large store to the same area of memory (beginning at memory address mem). Here, the small loads will stall the processor:

```
MOVQ    mem, mm0        ; store qword to address "mem"
  :
  :
MOV   bx, mem + 2       ; load word at address "mem + 2" stalls
MOV   cx, mem + 4       ; load word at address "mem + 4" stalls
```

The word loads must wait for the MOVQ instruction to write to memory before they can access the data they require. This stall can also occur with other data types (for example, when double-words or words are stored and then words or bytes are read from the same area of memory). Changing the code sequence as follows allows the processor to access the data without a stall:

```
MOVQ    mem, mm0        ; store qword to address "mem"
  :
  :
MOVQ    mm1, mem        ; load qword at address "mem"
MOVD    eax, mm1        ; transfer "mem + 2" to ax from
                        ; MMX(TM) register not memory
PSRLQ   mm1, 32
SHR     eax, 16
MOVD    ebx, mm1        ; transfer "mem + 4" to bx from
                        ; MMX register, not memory
AND     ebx, 0ffffh
```

These transformations, in general, increase the number the instructions required to perform the desired operation. For the Pentium® II and Pentium® III processors, the performance penalty due to the increased number of instructions is more than offset by the number of clocks saved. For the Pentium® processor with MMX™ technology, however, the increased number of instructions can negatively impact performance. For this reason, careful and efficient coding of these transformations is necessary to minimize any potential negative impact to Pentium® processor performance.

14.6.3. Write Allocation Effects

P6 family processors have a “write allocate by read-for-ownership” cache, whereas the Pentium® processor has a “no-write-allocate; write through on write miss” cache.

On P6 family processors, when a write occurs and the write misses the cache, the entire 32-byte cache line is fetched. On the Pentium® processor, when the same write miss occurs, the write is simply sent out to memory.

Write allocate is generally advantageous, since sequential stores are merged into burst writes, and the data remains in the cache for use by later loads. This is why P6 family processors adopted this write strategy, and why some Pentium® processor system designs implement it for the L2 cache.

Write allocate can be a disadvantage in code where:

- Just one piece of a cache line is written.
- The entire cache line is not read.
- Strides are larger than the 32-byte cache line.
- Writes to a large number of addresses (greater than 8000).

When a large number of writes occur within an application, and both the stride is longer than the 32-byte cache line and the array is large, every store on a P6 family processor will cause an entire cache line to be fetched. In addition, this fetch will probably replace one (sometimes two) dirty cache line(s). The result is that every store causes an additional cache line fetch and slows down the execution of the program. When many writes occur in a program, the performance decrease can be significant.

The following Sieve of Erastothenes example program demonstrates these cache effects. In this example, a large array is stepped through in increasing strides while writing a single value of the array with zero.

NOTE

This is a very simplistic example used only to demonstrate cache effects. Many other optimizations are possible in this code.

```
boolean array[max];
for(i=2;i<max;i++) {
        array = 1;
    }

    for(i=2;i<max;i++) {
        if( array[i] ) {
            for(j=2;j<max;j+=i) {
                array[j] = 0;          /*here we assign memory to 0 causing
                                       the cache line fetch within the j
                                       loop */
            }
        }
}
```

Two optimizations are available for this specific example:

- Optimization 1—In “boolean” in this example there is a “char” array. Here, it may well be better to make the “boolean” array into an array of bits, thereby reducing the size of the array, which in turn reduces the number of cache line fetches. The array is packed so that read-modify-writes are done (since the cache protocol makes every read into a read-modify-write). Unfortunately, in this example, the vast majority of strides are greater than 256 bits (one cache line of bits), so the performance increase is not significant.
- Optimization 2—Another optimization is to check if the value is already zero before writing (as shown in the following example), thereby reducing the number of writes to memory (dirty cache lines)

```
boolean array[max];
for(i=2;i<max;i++) {
        array = 1;
    }

    for(i=2;i<max;i++) {
        if( array[i] ) {
      for(j=2;j<max;j+=i) {
       if( array[j] != 0 ) {                  /* check to see if value is
                                              already 0 */
                array[j] = 0;
                }
            }
        }
}
```

The external bus activity is reduced by half because most of the time in the Sieve program the data is already zero. By checking first, you need only 1 burst bus cycle for the read and you save the burst bus cycle for every line you do not write. The actual write back of the modified line is no longer needed, therefore saving the extra cycles.

NOTE

This operation benefits the P6 family processors, but it may not enhance the performance of Pentium® processors. As such, it should not be considered generic.

14.7. ADDRESSING MODES AND REGISTER USAGE

On the Pentium® processor, when a register is used as the base component, an additional clock is used if that register is the destination of the immediately preceding instruction (assuming all instructions are already in the prefetch queue). For example:

```
add     esi, eax            ; esi is destination register
mov     eax, [esi]          ; esi is base, 1 clock penalty
```

Since the Pentium® processor has two integer pipelines, a register used as the base or index component of an effective address calculation (in either pipe) causes an additional clock if that register is the destination of either instruction from the immediately preceding clock (see Figure 14-2). This effect is known as Address Generation Interlock (AGI). To avoid the AGI, the instructions should be separated by at least 1 clock by placing other instructions between them. The MMX™ registers cannot be used as base or index registers, so the AGI does not apply for MMX™ register destinations.

No penalty occurs in the P6 family processors for the AGI condition.

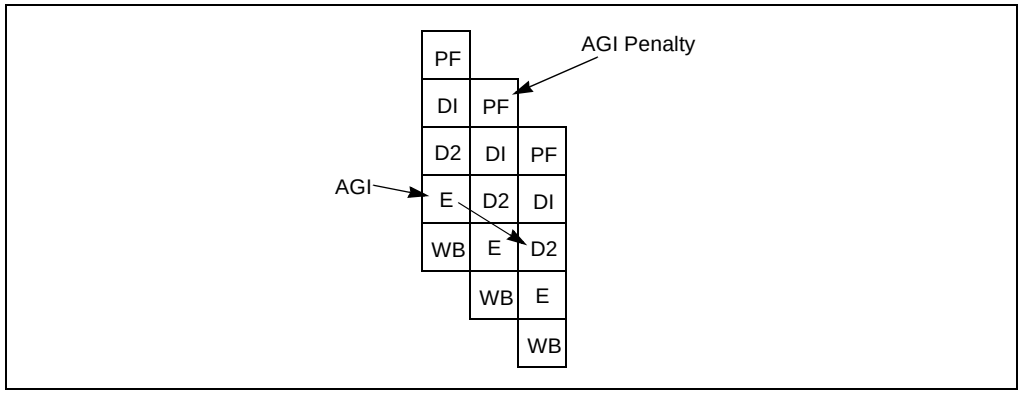


Figure 14-2. Pipeline Example of AGI Stall

Note that some instructions have implicit reads/writes to registers. Instructions that generate addresses implicitly through ESP (such as PUSH, POP, RET, CALL) also suffer from the AGI penalty, as shown in the following example:

```
sub     esp, 24
; 1 clock cycle stall
push    ebx
mov     esp, ebp
; 1 clock cycle stall
pop     ebp
```

The PUSH and POP instructions also implicitly write to the ESP register. These writes, however, do not cause an AGI when the next instruction addresses through the ESP register. Pentium® processors "rename" the ESP register from PUSH and POP instructions to avoid the AGI penalty (see the following example):

```
push    edi                     ; no stall
mov     ebx, [esp]
```

On Pentium® processors, instructions that include both an immediate and a displacement field are pairable in the U-pipe. When it is necessary to use constants, it is usually more efficient to use immediate data instead of loading the constant into a register first. If the same immediate data is used more than once, however, it is faster to load the constant in a register and then use the register multiple times, as illustrated in the following example:

```
mov     result, 555                 ; 555 is immediate, result is
                                    ; displacement
mov     word ptr [esp+4], 1         ; 1 is immediate, 4 is displacement
```

Since MMX™ instructions have 2-byte opcodes (0FH opcode map), any MMX™ instruction that uses base or index addressing with a 4-byte displacement to access memory will have a length of 8 bytes. Instructions over 7 bytes can slow macro instruction decoding and should be avoided where possible. It is often possible to reduce the size of such instructions by adding the immediate value to the value in the base or index register, thus removing the immediate field.

14.8. INSTRUCTION LENGTH

On Pentium® processors, instructions greater than 7 bytes in length cannot be executed in the V-pipe. In addition, two instructions cannot be pushed into the instruction FIFO unless both are 7 bytes or less in length. If only one instruction is pushed into the instruction FIFO, pairing will not occur unless the instruction FIFO already contains at least one instruction. In code where pairing is very high (as is often the case in MMX™ code) or after a mispredicted branch, the instruction FIFO may be empty, leading to a loss of pairing whenever the instruction length is over 7 bytes.

In addition, the P6 family processors can only decode one instruction at a time when an instruction is longer than 7 bytes.

So, for best performance on all Intel processors, use simple instructions that are less than 8 bytes in length.

14.9. PREFIXED OPCODES

On the Pentium® processor, an instruction with a prefix is pairable in the U-pipe (PU) if the instruction (without the prefix) is pairable in both pipes (UV) or in the U-pipe (PU). The prefixes are issued to the U-pipe and get decoded in 1 clock for each prefix and then the instruction is issued to the U-pipe and may be paired.

For the P6 family and Pentium® processors, the prefixes that should be avoided for optimum code execution speeds are:

- Lock.
- Segment override.
- Address size.
- Operand size.
- 2-byte opcode map (0FH) prefix. An exception is the Streaming SIMD Extensions instructions introduced with the Pentium® III processor. The first byte of these instructions is 0FH. It is not used as a prefix.
- 2-byte opcode map (0FH) prefix.

On Pentium® processors with MMX™ technology, a prefix on an instruction can delay the parsing and inhibit pairing of instructions.

The following list highlights the effects of instruction prefixes on the Pentium® processor instruction FIFO:

- There is no penalty on 0FH-prefix instructions.
- An instruction with a 66H or 67H prefix takes 1 clock for prefix detection, another clock for length calculation, and another clock to enter the instruction FIFO (3 clocks total). It must be the first instruction to enter the instruction FIFO, and a second instruction can be pushed with it.
- Instructions with other prefixes (not 0FH, 66H, or 67H) take 1 additional clock to detect each prefix. These instructions are pushed into the instruction FIFO only as the first instruction. An instruction with two prefixes will take 3 clocks to be pushed into the instruction FIFO (2 clocks for the prefixes and 1 clock for the instruction). A second instruction can be pushed with the first into the instruction FIFO in the same clock.

The impact on performance exists only when the instruction FIFO does not hold at least two entries. As long as the decoder (D1 stage) has two instructions to decode there is no penalty. The instruction FIFO will quickly become empty if the instructions are pulled from the instruction FIFO at the rate of two per clock. So, if the instructions just before the prefixed instruction suffer from a performance loss (for example, no pairing, stalls due to cache misses, misalignments, etc.), then the performance penalty of the prefixed instruction may be masked.

On the P6 family processors, instructions longer than 7 bytes in length limit the number of instructions decoded in each clock. Prefixes add 1 to 2 bytes to the length of an instruction, possibly limiting the decoder.

It is recommended that, whenever possible, prefixed instructions not be used or that they be scheduled behind instructions which themselves stall the pipe for some other reason.

14.10. INTEGER INSTRUCTION SELECTION AND OPTIMIZATIONS

This section describes both instruction sequences to avoid and sequences to use when generating optimal assembly code. The information applies to the P6 family processors and the Pentium® processors with and without MMX™ technology.

- LEA Instruction. The LEA instruction can be used in the following situations to optimize code execution:

  — The LEA instruction may be used sometimes as a three/four operand addition instruction (for example, LEA ECX, [EAX+EBX+4+a]).

  — In many cases, an LEA instruction or a sequence of LEA, ADD, SUB and SHIFT instructions may be used to replace constant multiply instructions. For the P6 family processors the constant multiply is faster relative to other instructions than on the Pentium® processor, therefore the trade off between the two options occurs sooner. It is recommended that the integer multiply instruction be used in code designed for P6 family processor execution.

  — The above technique can also be used to avoid copying a register when both operands to an ADD instruction are still needed after the ADD, since the LEA instruction need not overwrite its operands.

  The disadvantage of the LEA instruction is that it increases the possibility of an AGI stall with previous instructions. LEA is useful for shifts of 2, 4, and 8 because on the Pentium® processor, LEA can execute in either the U- or V-pipe, but the shift can only execute in the U-pipe. On the P6 family processors, both the LEA and SHIFT instructions are single micro-op instructions that execute in 1 clock.

- Complex Instructions. For greater execution speed, avoid using complex instructions (for example, LOOP, ENTER, or LEAVE). Use sequences of simple instructions instead to accomplish the function of a complex instruction.

- Zero-Extension of Short Integers. On the Pentium® processor, the MOVZX instruction has a prefix and takes 3 clocks to execute totaling 4 clocks. It is recommended that the following sequence be used instead of the MOVZX instruction:

```
xor     eax, eax
mov     al, mem
```

  If this code occurs within a loop, it may be possible to pull the XOR instruction out of the loop if the only assignment to EAX is the MOV AL, MEM. This has greater importance for the Pentium® processor since the MOVZX is not pairable and the new sequence may be paired with adjacent instructions.

  In order to avoid a partial register stall on the P6 family processors, special hardware has been implemented that allows this code sequence to execute without a stall. Even

so, the MOVZX instruction is a better choice for the P6 family processors than the alternative sequences.

- PUSH *Mem*. The PUSH *mem* instruction takes 4 clocks for the Intel486™ processor. It is recommended that the following sequence be used in place of a PUSH *mem* instruction because it takes only 2 clocks for the Intel486™ processor and increases pairing opportunity for the Pentium® processor.

```
mov     reg, mem
push    reg
```

- Short Opcodes. Use 1 byte long instructions as much as possible. This will reduce code size and help increase instruction density in the instruction cache. The most common example is using the INC and DEC instructions rather than adding or subtracting the constant 1 with an ADD or SUB instruction. Another common example is using the PUSH and POP instructions instead of the equivalent sequence.

- 8/16 Bit Operands. With 8-bit operands, try to use the byte opcodes, rather than using 32-bit operations on sign and zero extended bytes. Prefixes for operand size override apply to 16-bit operands, not to 8-bit operands.

  Sign Extension is usually quite expensive. Often, the semantics can be maintained by zero extending 16-bit operands. Specifically, the C code in the following example does not need sign extension nor does it need prefixes for operand size overrides.

```
static short int a, b;
if (a==b) {
  . . .
}
```

Code for comparing these 16-bit operands might be:

```
U Pipe                  V Pipe
xor   eax, eax          xor   ebx, ebx          ; 1

movw  ax, [a]                                   ; 2 (prefix) + 1

movw  bx, [b]                                   ; 4 (prefix) + 1

                        cmp   eax, ebx          ; 6
```

Of course, this can only be done under certain circumstances, but the circumstances tend to be quite common. This would not work if the compare was for greater than, less than, greater than or equal, and so on, or if the values in EAX or EBX were to be used in another operation where sign extension was required.

The P6 family processors provides special support for the XOR *reg*, *reg* instruction where both operands point to the same register, recognizing that clearing a register does not depend on the old value of the register. Additionally, special support is provided for the above specific code sequence to avoid the partial stall.

The following straight-forward method may be slower on Pentium® processors.

```
movsw     eax, a          ; 1  prefix + 3
movsw     ebx, b          ; 5
cmp       ebx, eax        ; 9
```

However, the P6 family processors have improved the performance of the MOVZX instructions to reduce the prevalence of partial stalls. Code written specifically for the P6 family processors should use the MOVZX instructions.

- Compares. Use the TEST instruction when comparing a value in a register with 0. TEST essentially ANDs the operands together without writing to a destination register. If a value is ANDed with itself and the result sets the zero condition flag, the value was zero. TEST is preferred over an AND instruction because AND writes the result register which may subsequently cause an AGI or an artificial output dependence on the P6 family processors. TEST is better than CMP .., 0 because the instruction size is smaller.

  Use the TEST instruction when comparing the result of a boolean AND with an immediate constant for equality or inequality if the register is EAX (if (avar & 8) { }).

  On the Pentium® processor, the TEST instruction is a 1 clock pairable instruction when the form is TEST EAX, *imm* or TEST *reg*, *reg*. Other forms of TEST take 2 clocks and do not pair.

- Address Calculations. Pull address calculations into load and store instructions. Internally, memory reference instructions can have 4 operands: a relocatable load-time constant, an immediate constant, a base register, and a scaled index register. (In the segmented model, a segment register may constitute an additional operand in the linear address calculation.) In many cases, several integer instructions can be eliminated by fully using the operands of memory references.

- Clearing a Register. The preferred sequence to move zero to a register is XOR *reg*, *reg*. This sequence saves code space but sets the condition codes. In contexts where the condition codes must be preserved, use MOV *reg*, 0.

- Integer Divide. Typically, an integer divide is preceded by a CDQ instruction. (Divide instructions use EDX: EAX as the dividend and CDQ sets up EDX.) It is better to copy EAX into EDX, then right shift EDX 31 places to sign extend. On the Pentium® processor, the copy/shift takes the same number of clocks as CDQ, but the copy/shift scheme allows two other instructions to execute at the same time. If the value is known to be positive, use XOR EDX, EDX.

  On the P6 family processors, the CDQ instruction is faster, because CDQ is a single micro-op instruction as opposed to two instructions for the copy/shift sequence.

- Prolog Sequences. Be careful to avoid AGIs in the procedure and function prolog sequences due to register ESP. Since PUSH can pair with other PUSH instructions, saving callee-saved registers on entry to functions should use these instructions. If possible, load parameters before decrementing ESP.

In routines that do not call other routines (leaf routines), use ESP as the base register to free up EBP. If you are not using the 32-bit flat model, remember that EBP cannot be used as a general purpose base register because it references the stack segment.

- Avoid Compares with Immediate Zero. Often when a value is compared with zero, the operation producing the value sets condition codes that can be tested directly by a J*cc* instruction. The most notable exceptions are the MOV and LEA instructions. In these cases, use the TEST instruction.
- Epilog Sequence. If only 4 bytes were allocated in the stack frame for the current function, instead of incrementing the stack pointer by 4, use POP instructions to prevent AGIs. For the Pentium® processor, use two pops for eight bytes.

15

Debugging and Performance Monitoring

CHAPTER 15
DEBUGGING AND PERFORMANCE MONITORING

The Intel Architecture provides extensive debugging facilities for use in debugging code and monitoring code execution and processor performance. These facilities are valuable for debugging applications software, system software, and multitasking operating systems.

The debugging support is accessed through the debug registers (DB0 through DB7) and two model-specific registers (MSRs). The debug registers of the Intel Architecture processors hold the addresses of memory and I/O locations, called breakpoints. Breakpoints are user-selected locations in a program, a data-storage area in memory, or specific I/O ports where a programmer or system designer wishes to halt execution of a program and examine the state of the processor by invoking debugger software. A debug exception (#DB) is generated when a memory or I/O access is made to one of these breakpoint addresses. A breakpoint is specified for a particular form of memory or I/O access, such as a memory read and/or write operation or an I/O read and/or write operation. The debug registers support both instruction breakpoints and data breakpoints. The MSRs (which were introduced into the Intel Architecture in the P6 family processors) monitor branches, interrupts, and exceptions and record the addresses of the last branch, interrupt or exception taken and the last branch taken before an interrupt or exception.

15.1. OVERVIEW OF THE DEBUGGING SUPPORT FACILITIES

The following processor facilities support debugging and performance monitoring:

- **Debug exception (#DB)—**Transfers program control to a debugger procedure or task when a debug event occurs.
- **Breakpoint exception (#BP)—**Transfers program control to a debugger procedure or task when an INT 3 instruction is executed.
- **Breakpoint-address registers (DB0 through DB3)—**Specifies the addresses of up to 4 breakpoints.
- **Debug status register (DB6)—**Reports the conditions that were in effect when a debug or breakpoint exception was generated.
- **Debug control register (DB7)—**Specifies the forms of memory or I/O access that cause breakpoints to be generated.
- **DebugCtlMSR register**—Enables last branch, interrupt, and exception recording; taken branch traps; the breakpoint reporting pins; and trace messages.
- **LastBranchToIP and LastBranchFromIP MSRs**—Specifies the source and destination addresses of the last branch, interrupt, or exception taken. The address saved is the offset in the code segment of the branch (source) or target (destination) instruction.

- **LastExceptionToIP and LastExceptionFromIP MSRs**—Specifies the source and destination addresses of the last branch that was taken prior to an exception or interrupt being generated. The address saved is the offset in the code segment of the branch (source) or target (destination) instruction.
- **T (trap) flag, TSS—**Generates a debug exception (#DB) when an attempt is made to switch to a task with the T flag set in its TSS.
- **RF (resume) flag, EFLAGS register—** Suppresses multiple exceptions to the same instruction.
- **TF (trap) flag, EFLAGS register—**Generates a debug exception (#DB) after every execution of an instruction.
- **Breakpoint instruction (INT 3)—**Generates a breakpoint exception (#BP), which transfers program control to the debugger procedure or task. This instruction is an alternative way to set code breakpoints. It is especially useful when more than four breakpoints are desired, or when breakpoints are being placed in the source code.

These facilities allow a debugger to be called either as a separate task or as a procedure in the context of the current program or task. The following conditions can be used to invoke the debugger:

- Task switch to a specific task.
- Execution of the breakpoint instruction.
- Execution of any instruction.
- Execution of an instruction at a specified address.
- Read or write of a byte, word, or doubleword at a specified memory address.
- Write to a byte, word, or doubleword at a specified memory address.
- Input of a byte, word, or doubleword at a specified I/O address.
- Output of a byte, word, or doubleword at a specified I/O address.
- Attempt to change the contents of a debug register.

15.2. DEBUG REGISTERS

The eight debug registers (refer to Figure 15-1) control the debug operation of the processor. These registers can be written to and read using the move to or from debug register form of the MOV instruction. A debug register may be the source or destination operand for one of these instructions. The debug registers are privileged resources; a MOV instruction that accesses these registers can only be executed in real-address mode, in SMM, or in protected mode at a CPL of 0. An attempt to read or write the debug registers from any other privilege level generates a general-protection exception (#GP).

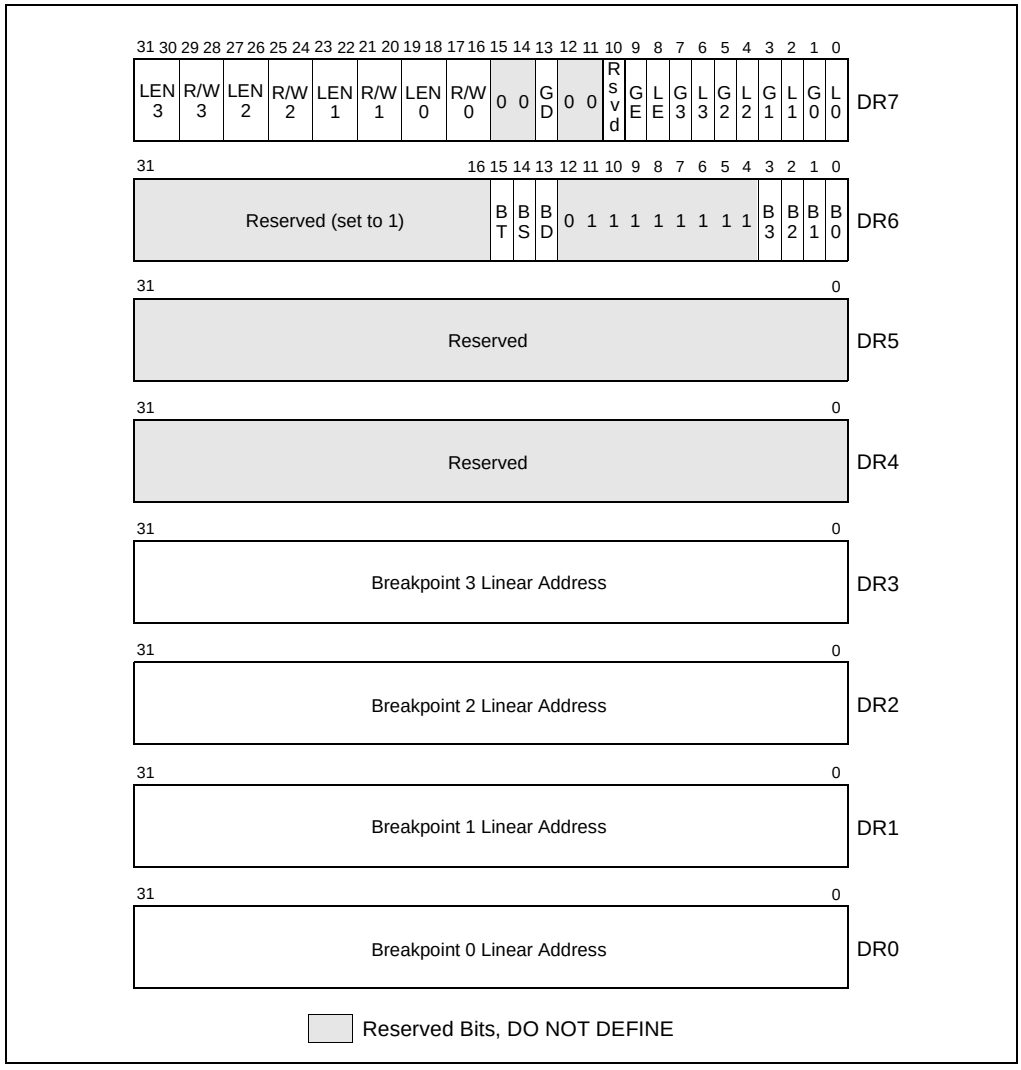


Figure 15-1. Debug Registers

The primary function of the debug registers is to set up and monitor from 1 to 4 breakpoints, numbered 0 though 3. For each breakpoint, the following information can be specified and detected with the debug registers:

- The linear address where the breakpoint is to occur.
- The length of the breakpoint location (1, 2, or 4 bytes).
- The operation that must be performed at the address for a debug exception to be generated.
- Whether the breakpoint is enabled.
- Whether the breakpoint condition was present when the debug exception was generated.

The following paragraphs describe the functions of flags and fields in the debug registers.

15.2.1. Debug Address Registers (DR0-DR3)

Each of the four debug-address registers (DR0 through DR3) holds the 32-bit linear address of a breakpoint (refer to Figure 15-1). Breakpoint comparisons are made before physical address translation occurs. Each breakpoint condition is specified further by the contents of debug register DR7.

15.2.2. Debug Registers DR4 and DR5

Debug registers DR4 and DR5 are reserved when debug extensions are enabled (when the DE flag in control register CR4 is set), and attempts to reference the DR4 and DR5 registers cause an invalid-opcode exception (#UD) to be generated. When debug extensions are not enabled (when the DE flag is clear), these registers are aliased to debug registers DR6 and DR7.

15.2.3. Debug Status Register (DR6)

The debug status register (DR6) reports the debug conditions that were sampled at the time the last debug exception was generated (refer to Figure 15-1). Updates to this register only occur when an exception is generated. The flags in this register show the following information:

B0 through B3 (breakpoint condition detected) flags (bits 0 through 3)
Indicates (when set) that its associated breakpoint condition was met when a debug exception was generated. These flags are set if the condition described for each breakpoint by the LEN*n*, and R/W*n* flags in debug control register DR7 is true. They are set even if the breakpoint is not enabled by the L*n* and G*n* flags in register DR7.

BD (debug register access detected) flag (bit 13)
Indicates that the next instruction in the instruction stream will access one of the debug registers (DR0 through DR7). This flag is enabled when the GD (general detect) flag in debug control register DR7 is set. Refer to Section 15.2.4., “Debug Control Register (DR7)” for further explanation of the purpose of this flag.

BS (single step) flag (bit 14)
Indicates (when set) that the debug exception was triggered by the single-step execution mode (enabled with the TF flag in the EFLAGS register). The single-step mode is the highest-priority debug exception. When the BS flag is set, any of the other debug status bits also may be set.

BT (task switch) flag (bit 15)
Indicates (when set) that the debug exception resulted from a task switch where the T flag (debug trap flag) in the TSS of the target task was set (refer to Section 6.2.1., "Task-State Segment (TSS)", in Section 6, "Task Management", for the format of a TSS). There is no flag in debug control register DR7 to enable or disable this exception; the T flag of the TSS is the only enabling flag.

Note that the contents of the DR6 register are never cleared by the processor. To avoid any confusion in identifying debug exceptions, the debug handler should clear the register before returning to the interrupted program or task.

15.2.4. Debug Control Register (DR7)

The debug control register (DR7) enables or disables breakpoints and sets breakpoint conditions (refer to Figure 15-1). The flags and fields in this register control the following things:

L0 through L3 (local breakpoint enable) flags (bits 0, 2, 4, and 6)
Enable (when set) the breakpoint condition for the associated breakpoint for the current task. When a breakpoint condition is detected and its associated L*n* flag is set, a debug exception is generated. The processor automatically clears these flags on every task switch to avoid unwanted breakpoint conditions in the new task.

G0 through G3 (global breakpoint enable) flags (bits 1, 3, 5, and 7)
Enable (when set) the breakpoint condition for the associated breakpoint for all tasks. When a breakpoint condition is detected and its associated G*n* flag is set, a debug exception is generated. The processor does not clear these flags on a task switch, allowing a breakpoint to be enabled for all tasks.

LE and GE (local and global exact breakpoint enable) flags (bits 8 and 9)
(Not supported in the P6 family processors.) When set, these flags cause the processor to detect the exact instruction that caused a data breakpoint condition. For backward and forward compatibility with other Intel Architecture processors, Intel recommends that the LE and GE flags be set to 1 if exact breakpoints are required.

GD (general detect enable) flag (bit 13)
Enables (when set) debug-register protection, which causes a debug exception to be generated prior to any MOV instruction that accesses a debug register. When such a condition is detected, the BD flag in debug status register DR6 is set prior to generating the exception. This condition is provided to support in-circuit emulators. (When the emulator needs to access the debug registers, emulator software can set the GD flag to prevent interference from the program

currently executing on the processor.) The processor clears the GD flag upon entering to the debug exception handler, to allow the handler access to the debug registers.

R/W0 through R/W3 (read/write) fields (bits 16, 17, 20, 21, 24, 25, 28, and 29)
Specifies the breakpoint condition for the corresponding breakpoint. The DE (debug extensions) flag in control register CR4 determines how the bits in the R/W*n* fields are interpreted. When the DE flag is set, the processor interprets these bits as follows:

00—Break on instruction execution only.
01—Break on data writes only.
10—Break on I/O reads or writes.
11—Break on data reads or writes but not instruction fetches.

When the DE flag is clear, the processor interprets the R/W*n* bits the same as for the Intel386™ and Intel486™ processors, which is as follows:

00—Break on instruction execution only.
01—Break on data writes only.
10—Undefined.
11—Break on data reads or writes but not instruction fetches.

LEN0 through LEN3 (Length) fields (bits 18, 19, 22, 23, 26, 27, 30, and 31)
Specify the size of the memory location at the address specified in the corresponding breakpoint address register (DR0 through DR3). These fields are interpreted as follows:

00—1-byte length
01—2-byte length
10—Undefined
11—4-byte length

If the corresponding RW*n* field in register DR7 is 00 (instruction execution), then the LEN*n* field should also be 00. The effect of using any other length is undefined. Refer to Section 15.2.5., “Breakpoint Field Recognition” for further information on the use of these fields.

15.2.5. Breakpoint Field Recognition

The breakpoint address registers (debug registers DR0 through DR3) and the LEN*n* fields for each breakpoint define a range of sequential byte addresses for a data or I/O breakpoint. The LEN*n* fields permit specification of a 1-, 2-, or 4-byte range beginning at the linear address specified in the corresponding debug register (DR*n*). Two-byte ranges must be aligned on word boundaries and 4-byte ranges must be aligned on doubleword boundaries. I/O breakpoint addresses are zero extended from 16 to 32 bits for purposes of comparison with the breakpoint address in the selected debug register. These requirements are enforced by the processor; it uses the LEN*n* field bits to mask the lower address bits in the debug registers. Unaligned data or I/O breakpoint addresses do not yield the expected results.

A data breakpoint for reading or writing data is triggered if any of the bytes participating in an access is within the range defined by a breakpoint address register and its LEN*n* field. Table 15-1 gives an example setup of the debug registers and the data accesses that would subsequently trap or not trap on the breakpoints.

Table 15-1. Breakpointing Examples

Debug Register Setup			
Debug Register	**R/W*n***	**Breakpoint Address**	**LEN*n***
DR0 DR1 DR2 DR3	R/W0 = 11 (Read/Write) R/W1 = 01 (Write) R/W2 = 11 (Read/Write) R/W3 = 01 (Write)	A0001H A0002H B0002H C0000H	LEN0 = 00 (1 byte) LEN1 = 00 (1 byte) LEN2 = 01) (2 bytes) LEN3 = 11 (4 bytes)
Data Accesses			
Operation		**Address**	**Access Length (In Bytes)**
Data operations that trap - Read or write - Read or write - Write - Write - Read or write - Read or write - Read or write - Write - Write - Write		 A0001H A0001H A0002H A0002H B0001H B0002H B0002H C0000H C0001H C0003H	 1 2 1 2 4 1 2 4 2 1
Data operations that do not trap - Read or write - Read - Read or write - Read or write - Read - Read or write		 A0000H A0002H A0003H B0000H C0000H C0004H	 1 1 4 2 2 4

A data breakpoint for an unaligned operand can be constructed using two breakpoints, where each breakpoint is byte-aligned, and the two breakpoints together cover the operand. These breakpoints generate exceptions only for the operand, not for any neighboring bytes.

Instruction breakpoint addresses must have a length specification of 1 byte (the LEN*n* field is set to 00). The behavior of code breakpoints for other operand sizes is undefined. The processor recognizes an instruction breakpoint address only when it points to the first byte of an instruction. If the instruction has any prefixes, the breakpoint address must point to the first prefix.

15.3. DEBUG EXCEPTIONS

The Intel Architecture processors dedicate two interrupt vectors to handling debug exceptions: vector 1 (debug exception, #DB) and vector 3 (breakpoint exception, #BP). The following

sections describe how these exceptions are generated and typical exception handler operations for handling these exceptions.

15.3.1. Debug Exception (#DB)—Interrupt Vector 1

The debug-exception handler is usually a debugger program or is part of a larger software system. The processor generates a debug exception for any of several conditions. The debugger can check flags in the DR6 and DR7 registers to determine which condition caused the exception and which other conditions might also apply. Table 15-2 shows the states of these flags following the generation of each kind of breakpoint condition.

Table 15-2. Debug Exception Conditions

Debug or Breakpoint Condition	DR6 Flags Tested	DR7 Flags Tested	Exception Class
Single-step trap	BS = 1		Trap
Instruction breakpoint, at addresses defined by DR*n* and LEN*n*	B*n* = 1 and (GE*n* or LE*n* = 1)	R/Wn = 0	Fault
Data write breakpoint, at addresses defined by DR*n* and LEN*n*	B*n* = 1 and (GE*n* or LE*n* = 1)	R/Wn = 1	Trap
I/O read or write breakpoint, at addresses defined by DR*n* and LEN*n*	B*n* = 1 and (GE*n* or LE*n* = 1)	R/Wn = 2	Trap
Data read or write (but not instruction fetches), at addresses defined by DR*n* and LEN*n*	B*n* = 1 and (GE*n* or LE*n* = 1)	R/Wn = 3	Trap
General detect fault, resulting from an attempt to modify debug registers (usually in conjunction with in-circuit emulation)	BD = 1		Fault
Task switch	BT = 1		Trap

Instruction-breakpoint and general-detect conditions (refer to Section 15.3.1.3., “General-Detect Exception Condition”) result in faults; other debug-exception conditions result in traps. The debug exception may report either or both at one time. The following sections describe each class of debug exception. Refer to Section 5.12., “Exception and Interrupt Reference” in Chapter 5, *Interrupt and Exception Handling* for additional information about this exception.

15.3.1.1. INSTRUCTION-BREAKPOINT EXCEPTION CONDITION

The processor reports an instruction breakpoint when it attempts to execute an instruction at an address specified in a breakpoint-address register (DB0 through DR3) that has been set up to detect instruction execution (R/W flag is set to 0). Upon reporting the instruction breakpoint, the processor generates a fault-class, debug exception (#DB) before it executes the target instruction

for the breakpoint. Instruction breakpoints are the highest priority debug exceptions and are guaranteed to be serviced before any other exceptions that may be detected during the decoding or execution of an instruction.

Because the debug exception for an instruction breakpoint is generated before the instruction is executed, if the instruction breakpoint is not removed by the exception handler, the processor will detect the instruction breakpoint again when the instruction is restarted and generate another debug exception. To prevent looping on an instruction breakpoint, the Intel Architecture provides the RF flag (resume flag) in the EFLAGS register (refer to Section 2.3., "System Flags and Fields in the EFLAGS Register" in Chapter 2, *System Architecture Overview*). When the RF flag is set, the processor ignores instruction breakpoints.

All Intel Architecture processors manage the RF flag as follows. The processor sets the RF flag automatically prior to calling an exception handler for any fault-class exception except a debug exception that was generated in response to an instruction breakpoint. For debug exceptions resulting from instruction breakpoints, the processor does not set the RF flag prior to calling the debug exception handler. The debug exception handler then has the option of disabling the instruction breakpoint or setting the RF flag in the EFLAGS image on the stack. If the RF flag in the EFLAGS image is set when the processor returns from the exception handler, it is copied into the RF flag in the EFLAGS register by the IRETD or task switch instruction that causes the return. The processor then ignores instruction breakpoints for the duration of the next instruction. (Note that the POPF, POPFD, and IRET instructions do not transfer the RF image into the EFLAGS register.) Setting the RF flag does not prevent other types of debug-exception conditions (such as, I/O or data breakpoints) from being detected, nor does it prevent nondebug exceptions from being generated. After the instruction is successfully executed, the processor clears the RF flag in the EFLAGS register, except after an IRETD instruction or after a JMP, CALL, or INT *n* instruction that causes a task switch. (Note that the processor also does not set the RF flag when calling exception or interrupt handlers for trap-class exceptions, for hardware interrupts, or for software-generated interrupts.)

For the Pentium® processor, when an instruction breakpoint coincides with another fault-type exception (such as a page fault), the processor may generate one spurious debug exception after the second exception has been handled, even though the debug exception handler set the RF flag in the EFLAGS image. To prevent this spurious exception with Pentium® processors, all fault-class exception handlers should set the RF flag in the EFLAGS image.

15.3.1.2. DATA MEMORY AND I/O BREAKPOINT EXCEPTION CONDITIONS

Data memory and I/O breakpoints are reported when the processor attempts to access a memory or I/O address specified in a breakpoint-address register (DB0 through DR3) that has been set up to detect data or I/O accesses (R/W flag is set to 1, 2, or 3). The processor generates the exception after it executes the instruction that made the access, so these breakpoint condition causes a trap-class exception to be generated.

Because data breakpoints are traps, the original data is overwritten before the trap exception is generated. If a debugger needs to save the contents of a write breakpoint location, it should save the original contents before setting the breakpoint. The handler can report the saved value after the breakpoint is triggered. The address in the debug registers can be used to locate the new value stored by the instruction that triggered the breakpoint.

The Intel486™ and later Intel Architecture processors ignore the GE and LE flags in DR7. In the Intel386™ processor, exact data breakpoint matching does not occur unless it is enabled by setting the LE and/or the GE flags.

The P6 family processors, however, are unable to report data breakpoints exactly for the REP MOVS and REP STOS instructions until the completion of the iteration after the iteration in which the breakpoint occurred.

For repeated INS and OUTS instructions that generate an I/O-breakpoint debug exception, the processor generates the exception after the completion of the first iteration. Repeated INS and OUTS instructions generate an I/O-breakpoint debug exception after the iteration in which the memory address breakpoint location is accessed.

15.3.1.3. GENERAL-DETECT EXCEPTION CONDITION

When the GD flag in DR7 is set, the general-detect debug exception occurs when a program attempts to access any of the debug registers (DR0 through DR7) at the same time they are being used by another application, such as an emulator or debugger. This additional protection feature guarantees full control over the debug registers when required. The debug exception handler can detect this condition by checking the state of the BD flag of the DR6 register. The processor generates the exception before it executes the MOV instruction that accesses a debug register, which causes a fault-class exception to be generated.

15.3.1.4. SINGLE-STEP EXCEPTION CONDITION

The processor generates a single-step debug exception if (while an instruction is being executed) it detects that the TF flag in the EFLAGS register is set. The exception is a trap-class exception, because the exception is generated after the instruction is executed. (Note that the processor does not generate this exception after an instruction that sets the TF flag. For example, if the POPF instruction is used to set the TF flag, a single-step trap does not occur until after the instruction that follows the POPF instruction.)

The processor clears the TF flag before calling the exception handler. If the TF flag was set in a TSS at the time of a task switch, the exception occurs after the first instruction is executed in the new task.

The TF flag normally is not cleared by privilege changes inside a task. The INT *n* and INTO instructions, however, do clear this flag. Therefore, software debuggers that single-step code must recognize and emulate INT *n* or INTO instructions rather than executing them directly. To maintain protection, the operating system should check the CPL after any single-step trap to see if single stepping should continue at the current privilege level.

The interrupt priorities guarantee that, if an external interrupt occurs, single stepping stops. When both an external interrupt and a single-step interrupt occur together, the single-step interrupt is processed first. This operation clears the TF flag. After saving the return address or switching tasks, the external interrupt input is examined before the first instruction of the single-step handler executes. If the external interrupt is still pending, then it is serviced. The external interrupt handler does not run in single-step mode. To single step an interrupt handler, set a break point inside the handler and then set the TF flag.

15.3.1.5. TASK-SWITCH EXCEPTION CONDITION

The processor generates a debug exception after a task switch if the T flag of the new task's TSS is set. This exception is generated after program control has passed to the new task, and after the first instruction of that task is executed. The exception handler can detect this condition by examining the BT flag of the DR6 register.

Note that, if the debug exception handler is a task, the T bit of its TSS should not be set. Failure to observe this rule will put the processor in a loop.

15.3.2. Breakpoint Exception (#BP)—Interrupt Vector 3

The breakpoint exception (interrupt 3) is caused by execution of an INT 3 instruction (refer to Section 5.12., "Exception and Interrupt Reference" in Chapter 5, *Interrupt and Exception Handling*). Debuggers use break exceptions in the same way that they use the breakpoint registers; that is, as a mechanism for suspending program execution to examine registers and memory locations. With earlier Intel Architecture processors, breakpoint exceptions are used extensively for setting instruction breakpoints. With the Intel386™ and later Intel Architecture processors, it is more convenient to set breakpoints with the breakpoint-address registers (DR0 through DR3). However, the breakpoint exception still is useful for breakpointing debuggers, because the breakpoint exception can call a separate exception handler. The breakpoint exception is also useful when it is necessary to set more breakpoints than there are debug registers or when breakpoints are being placed in the source code of a program under development.

15.4. LAST BRANCH, INTERRUPT, AND EXCEPTION RECORDING

The P6 family processors provide five MSRs for recording the last branch, interrupt, or exception taken by the processor: DebugCtlMSR, LastBranchToIP, LastBranchFromIP, LastExceptionToIP, and LastExceptionFromIP. These registers can be used to set breakpoints on branches, interrupts, and exceptions, and to single-step from one branch to the next.

15.4.1. DebugCtlMSR Register

The DebugCtlMSR register enables last branch, interrupt, and exception recording; taken branch breakpoints; the breakpoint reporting pins; and trace messages. This register can be written to using the WRMSR instruction, when operating at privilege level 0 or when in real-address mode. A protected-mode operating system procedure is required to provide user access to this register. Figure 15-2 shows the flags in the DebugCtlMSR register. The functions of these flags are as follows:

LBR (last branch/interrupt/exception) flag (bit 0)

When set, the processor records the source and target addresses for the last branch and the last exception or interrupt taken by the processor prior to a debug exception being generated. The processor clears this flag whenever a debug exception, such as an instruction or data breakpoint or single-step trap occurs.

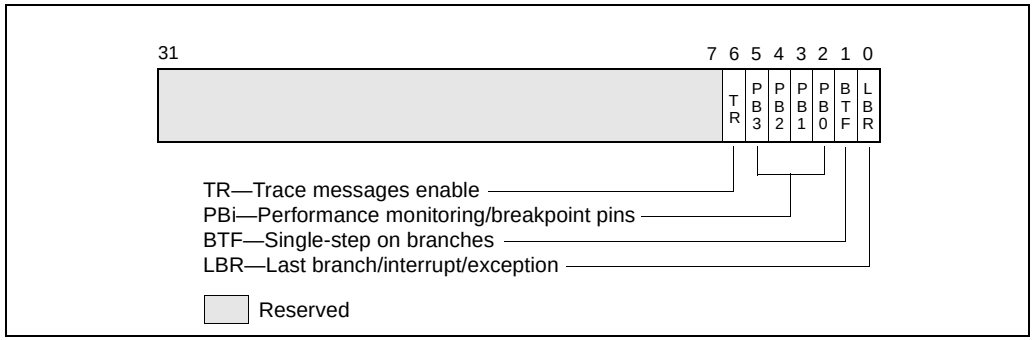


Figure 15-2. DebugCtlMSR Register

BTF (single-step on branches) flag (bit 1)

When set, the processor treats the TF flag in the EFLAGS register as a "single-step on branches" flag rather than a "single-step on instructions" flag. This mechanism allows single-stepping the processor on taken branches. Software must set both the BTF and TF flag to enable debug breakpoints on branches; the processor clears both flags whenever a debug exception occurs.

PB*i* (performance monitoring/breakpoint pins) flags (bits 2 through 5)

When these flags are set, the performance monitoring/breakpoint pins on the processor (BP0#, BP1#, BP2#, and BP3#) report breakpoint matches in the corresponding breakpoint-address registers (DR0 through DR3). The processor asserts then deasserts the corresponding BP*i*# pin when a breakpoint match occurs. When a PB*i* flag is clear, the performance monitoring/breakpoint pins report performance events. Processor execution is not affected by reporting performance events.

TR (trace message enable) flag (bit 6)

When set, trace messages are enabled. Thereafter, when the processor detects a branch, exception, or interrupt, it sends the "to" and "from" addresses out on the system bus as part of a branch trace message. A debugging device that is monitoring the system bus can read these messages and synchronize operations with branch, exception, and interrupt events. Setting this flag greatly reduces the performance of the processor. When trace messages are enabled, the values stored in the LastBranchToIP, LastBranchFromIP, LastExceptionToIP, and LastExceptionFromIP MSRs are undefined.

Note that the "from" addresses sent out on the system bus may differ from those stored in the LastBranchFromIP MSRs or LastExceptionFromIP MSRs. The from address sent out on the bus is always the next instruction in the instruction stream following a successfully completed instruction. For example, if a branch completes successfully, the address stored in the Last-BranchFromIP MSR is the address of the branch instruction, but the address sent out on the bus in the trace message is the address of the instruction

following the branch instruction. If the processor faults on the branch, the address stored in the LastBranchFromIP MSR is again the address of the branch instruction and that same address is sent out on the bus.

15.4.2. Last Branch and Last Exception MSRs

The LastBranchToIP and LastBranchFromIP MSRs are 32-bit registers for recording the instruction pointers for the last branch, interrupt, or exception that the processor took prior to a debug exception being generated (refer to Figure 15-2). When a branch occurs, the processor loads the address of the branch instruction into the LastBranchFromIP MSR and loads the target address for the branch into the LastBranchToIP MSR. When an interrupt or exception occurs (other than a debug exception), the address of the instruction that was interrupted by the exception or interrupt is loaded into the LastBranchFromIP MSR and the address of the exception or interrupt handler that is called is loaded into the LastBranchToIP MSR.

The LastExceptionToIP and LastExceptionFromIP MSRs (also 32-bit registers) record the instruction pointers for the last branch that the processor took prior to an exception or interrupt being generated. When an exception or interrupt occurs, the contents of the LastBranchToIP and LastBranchFromIP MSRs are copied into these registers before the to and from addresses of the exception or interrupt are recorded in the LastBranchToIP and LastBranchFromIP MSRs.

These registers can be read using the RDMSR instruction.

15.4.3. Monitoring Branches, Exceptions, and Interrupts

When the LBR flag in the DebugCtlMSR register is set, the processor automatically begins recording branches that it takes, exceptions that are generated (except for debug exceptions), and interrupts that are serviced. Each time a branch, exception, or interrupt occurs, the processor records the to and from instruction pointers in the LastBranchToIP and LastBranchFromIP MSRs. In addition, for interrupts and exceptions, the processor copies the contents of the LastBranchToIP and LastBranchFromIP MSRs into the LastExceptionToIP and LastExceptionFromIP MSRs prior to recording the to and from addresses of the interrupt or exception.

When the processor generates a debug exception (#DB), it automatically clears the LBR flag before executing the exception handler, but does not touch the last branch and last exception MSRs. The addresses for the last branch, interrupt, or exception taken are thus retained in the LastBranchToIP and LastBranchFromIP MSRs and the addresses of the last branch prior to an interrupt or exception are retained in the LastExceptionToIP, and LastExceptionFromIP MSRs.

The debugger can use the last branch, interrupt, and/or exception addresses in combination with code-segment selectors retrieved from the stack to reset breakpoints in the breakpoint-address registers (DR0 through DR3), allowing a backward trace from the manifestation of a particular bug toward its source. Because the instruction pointers recorded in the LastBranchToIP, LastBranchFromIP, LastExceptionToIP, and LastExceptionFromIP MSRs are offsets into a code segment, software must determine the segment base address of the code segment associated with

the control transfer to calculate the linear address to be placed in the breakpoint-address registers. The segment base address can be determined by reading the segment selector for the code segment from the stack and using it to locate the segment descriptor for the segment in the GDT or LDT. The segment base address can then be read from the segment descriptor.

Before resuming program execution from a debug-exception handler, the handler should set the LBR flag again to re-enable last branch and last exception/interrupt recording.

15.4.4. Single-Stepping on Branches, Exceptions, and Interrupts

When the BTF flag in the DebugCtlMSR register and the TF flag in the EFLAGS register are both set, the processor generates a single-step debug exception the next time it takes a branch, generates an exception, or services an interrupt. This mechanism allows the debugger to single-step on control transfers caused by branches, exceptions, or interrupts. This "control-flow single stepping" helps isolate a bug to a particular block of code before instruction single-stepping further narrows the search. If the BTF flag is set when the processor generates a debug exception, the processor clears the flag along with the TF flag. The debugger must reset the BTF flag before resuming program execution to continue control-flow single stepping.

15.4.5. Initializing Last Branch or Last Exception/Interrupt Recording

The LastBranchToIP, LastBranchFromIP, LastExceptionToIP, and LastException-FromIP MSRs are enabled by setting the LBR flag in the DebugCtlMSR register. Control-flow single stepping is enabled by setting the BTF flag in the DebugCtlMSR register. The processor clears both the LBR and the BTF flags whenever a debug exception is generated. To re-enable these mechanisms, the debug-exception handler must thus explicitly set these flags before returning to the interrupted program.

15.5. TIME-STAMP COUNTER

The Intel Architecture (beginning with the Pentium® processor) defines a time-stamp counter mechanism that can be used to monitor and identify the relative time of occurrence of processor events. The time-stamp counter architecture includes an instruction for reading the time-stamp counter (RDTSC), a feature bit (TCS flag) that can be read with the CPUID instruction, a time-stamp counter disable bit (TSD flag) in control register CR4, and a model-specific time-stamp counter.

Following execution of the CPUID instruction, the TSC flag in register EDX (bit 4) indicates (when set) that the time-stamp counter is present in a particular Intel Architecture processor implementation. (Refer to "CPUID—CPU Identification" in Chapter 3 of the *Intel Architecture Software Developer's Manual, Volume 2*.)

The time-stamp counter (as implemented in the Pentium® and P6 family processors) is a 64-bit counter that is set to 0 following the hardware reset of the processor. Following reset, the counter

is incremented every processor clock cycle, even when the processor is halted by the HLT instruction or the external STPCLK# pin.

The RDTSC instruction reads the time-stamp counter and is guaranteed to return a monotonically increasing unique value whenever executed, except for 64-bit counter wraparound. Intel guarantees, architecturally, that the time-stamp counter frequency and configuration will be such that it will not wraparound within 10 years after being reset to 0. The period for counter wrap is several thousands of years in the Pentium® and P6 family processors.

Normally, the RDTSC instruction can be executed by programs and procedures running at any privilege level and in virtual-8086 mode. The TSD flag in control register CR4 (bit 2) allows use of this instruction to be restricted to only programs and procedures running at privilege level 0. A secure operating system would set the TSD flag during system initialization to disable user access to the time-stamp counter. An operating system that disables user access to the time-stamp counter should emulate the instruction through a user-accessible programming interface.

The RDTSC instruction is not serializing or ordered with other instructions. Thus, it does not necessarily wait until all previous instructions have been executed before reading the counter. Similarly, subsequent instructions may begin execution before the RDTSC instruction operation is performed.

The RDMSR and WRMSR instructions can read and write the time-stamp counter, respectively, as a model-specific register (TSC). The ability to read and write the time-stamp counter with the RDMSR and WRMSR instructions is not an architectural feature, and may not be supported by future Intel Architecture processors. Writing to the time-stamp counter with the WRMSR instruction resets the count. Only the low order 32-bits of the time-stamp counter can be written to; the high-order 32 bits are 0 extended (cleared to all 0s).

15.6. PERFORMANCE-MONITORING COUNTERS

The Pentium® processor introduced model-specific performance-monitoring counters to the Intel Architecture. These counters permit processor performance parameters to be monitored and measured. The information obtained from these counters can then be used for tuning system and compiler performance.

In the Intel P6 family of processors, the performance-monitoring counter mechanism was modified and enhanced to permit a wider variety of events to be monitored and to allow greater control over the selection of the events to be monitored.

The following sections describe the performance-monitoring counter mechanism in the Pentium® and P6 family processors.

15.6.1. P6 Family Processor Performance-Monitoring Counters

The P6 family processors provide two 40-bit performance counters, allowing two types of events to be monitored simultaneously. These counters can either count events or measure duration. When counting events, a counter is incremented each time a specified event takes place or a specified number of events takes place. When measuring duration, a counter counts the

number of processor clocks that occur while a specified condition is true. The counters can count events or measure durations that occur at any privilege level. Table A-1 in Appendix A, *Performance-Monitoring Events* lists the events that can be counted with the P6 family performance monitoring counters.

The performance-monitoring counters are supported by four MSRs: the performance event select MSRs (PerfEvtSel0 and PerfEvtSel1) and the performance counter MSRs (PerfCtr0 and PerfCtr1). These registers can be read from and written to using the RDMSR and WRMSR instructions, respectively. They can be accessed using these instructions only when operating at privilege level 0. The PerfCtr0 and PerfCtr1 MSRs can be read from any privilege level using the RDPMC (read performance-monitoring counters) instruction.

NOTE

The PerfEvtSel0, PerfEvtSel1, PerfCtr0, and PerfCtr1 MSRs and the events listed in Table A-1 in Appendix A, *Performance-Monitoring Events* are model-specific for P6 family processors. They are not guaranteed to be available in future Intel Architecture processors.

15.6.1.1. PERFEVTSEL0 AND PERFEVTSEL1 MSRS

The PerfEvtSel0 and PerfEvtSel1 MSRs control the operation of the performance-monitoring counters, with one register used to set up each counter. They specify the events to be counted, how they should be counted, and the privilege levels at which counting should take place. Figure 15-3 shows the flags and fields in these MSRs.

The functions of the flags and fields in the PerfEvtSel0 and PerfEvtSel1 MSRs are as follows:

Event select field (bits 0 through 7)
Selects the event to be monitored (refer to Table A-1 in Appendix A, *Performance-Monitoring Events* for a list of events and their 8-bit codes).

Unit mask field (bits 8 through 15)
Further qualifies the event selected in the event select field. For example, for some cache events, the mask is used as a MESI-protocol qualifier of cache states (refer to Table A-1 in Appendix A, *Performance-Monitoring Events*).

USR (user mode) flag (bit 16)
Specifies that events are counted only when the processor is operating at privilege levels 1, 2 or 3. This flag can be used in conjunction with the OS flag.

OS (operating system mode) flag (bit 17)
Specifies that events are counted only when the processor is operating at privilege level 0. This flag can be used in conjunction with the USR flag.

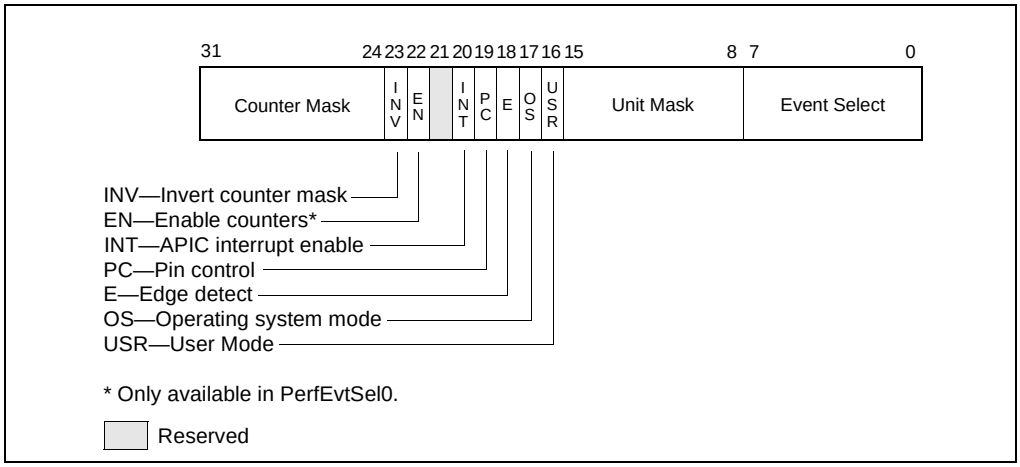


Figure 15-3. PerfEvtSel0 and PerfEvtSel1 MSRs

E (edge detect) flag (bit 18)

Enables (when set) edge detection of events. The processor counts the number of deasserted to asserted transitions of any condition that can be expressed by the other fields. The mechanism is limited in that it does not permit back-to-back assertions to be distinguished. This mechanism allows software to measure not only the fraction of time spent in a particular state, but also the average length of time spent in such a state (for example, the time spent waiting for an interrupt to be serviced).

PC (pin control) flag (bit 19)

When set, the processor toggles the PM*i* pins and increments the counter when performance-monitoring events occur; when clear, the processor toggles the PM*i* pins when the counter overflows. The toggling of a pin is defined as assertion of the pin for a single bus clock followed by deassertion

INT (APIC interrupt enable) flag (bit 20)

When set, the processor generates an exception through its local APIC on counter overflow.

EN (Enable Counters) Flag (bit 22)

This flag is only present in the PerfEvtSel0 MSR. When set, performance counting is enabled in both performance-monitoring counters; when clear, both counters are disabled.

INV (invert) flag (bit 23)

Inverts the result of the counter-mask comparison when set, so that both greater than and less than comparisons can be made.

Counter mask field (bits 24 through 31)

When nonzero, the processor compares this mask to the number of events

counted during a single cycle. If the event count is greater than or equal to this mask, the counter is incremented by one. Otherwise the counter is not incremented. This mask can be used to count events only if multiple occurrences happen per clock (for example, two or more instructions retired per clock). If the counter-mask field is 0, then the counter is incremented each cycle by the number of events that occurred that cycle.

15.6.1.2. PERFCTR0 AND PERFCTR1 MSRS

The performance-counter MSRs (PerfCtr0 and PerfCtr1) contain the event or duration counts for the selected events being counted. The RDPMC instruction can be used by programs or procedures running at any privilege level and in virtual-8086 mode to read these counters. The PCE flag in control register CR4 (bit 8) allows the use of this instruction to be restricted to only programs and procedures running at privilege level 0.

The RDPMC instruction is not serializing or ordered with other instructions. Thus, it does not necessarily wait until all previous instructions have been executed before reading the counter. Similarly, subsequent instructions may begin execution before the RDPMC instruction operation is performed.

Only the operating system, executing at privilege level 0, can directly manipulate the performance counters, using the RDMSR and WRMSR instructions. A secure operating system would set the TSD flag during system initialization to disable direct user access to the performance-monitoring counters, but provide a user-accessible programming interface that emulates the RDPMC instruction.

The WRMSR instruction cannot arbitrarily write to the performance-monitoring counter MSRs (PerfCtr0 and PerfCtr1). Instead, the lower-order 32 bits of each MSR may be written with any value, and the high-order 8 bits are sign-extended according to the value of bit 31. This operation allows writing both positive and negative values to the performance counters.

15.6.1.3. STARTING AND STOPPING THE PERFORMANCE-MONITORING COUNTERS

The performance-monitoring counters are started by writing valid setup information in the PerfEvtSel0 and/or PerfEvtSel1 MSRs and setting the enable counters flag in the PerfEvtSel0 MSR. If the setup is valid, the counters begin counting following the execution of a WRMSR instruction that sets the enable counter flag. The counters can be stopped by clearing the enable counters flag or by clearing all the bits in the PerfEvtSel0 and PerfEvtSel1 MSRs. Counter 1 alone can be stopped by clearing the PerfEvtSel1 MSR.

15.6.1.4. EVENT AND TIME-STAMP MONITORING SOFTWARE

To use the performance-monitoring counters and time-stamp counter, the operating system needs to provide an event-monitoring device driver. This driver should include procedures for handling the following operations:

- Feature checking.
- Initialize and start counters.

- Stop counters.
- Read the event counters.
- Read the time-stamp counter.

The event monitor feature determination procedure must determine whether the current processor supports the performance-monitoring counters and time-stamp counter. This procedure compares the family and model of the processor returned by the CPUID instruction with those of processors known to support performance monitoring. (The Pentium® and P6 family processors support performance counters.) The procedure also checks the MSR and TSC flags returned to register EDX by the CPUID instruction to determine if the MSRs and the RDTSC instruction are supported.

The initialize and start counters procedure sets the PerfEvtSel0 and/or PerfEvtSel1 MSRs for the events to be counted and the method used to count them and initializes the counter MSRs (PerfCtr0 and PerfCtr1) to starting counts. The stop counters procedure stops the performance counters. (Refer to Section 15.6.1.3., “Starting and Stopping the Performance-Monitoring Counters” for more information about starting and stopping the counters.)

The read counters procedure reads the values in the PerfCtr0 and PerfCtr1 MSRs, and a read time-stamp counter procedure reads the time-stamp counter. These procedures would be provided in lieu of enabling the RDTSC and RDPMC instructions that allow application code to read the counters.

15.6.2. Monitoring Counter Overflow

The P6 family processors provide the option of generating a local APIC interrupt when a performance-monitoring counter overflows. This mechanism is enabled by setting the interrupt enable flag in either the PerfEvtSel0 or the PerfEvtSel1 MSR. The primary use of this option is for statistical performance sampling.

To use this option, the operating system should do the following things on the processor for which performance events are required to be monitored:

- Provide an interrupt vector for handling the counter-overflow interrupt.
- Initialize the APIC PERF local vector entry to enable handling of performance-monitor counter overflow events.
- Provide an entry in the IDT that points to a stub exception handler that returns without executing any instructions.
- Provide an event monitor driver that provides the actual interrupt handler and modifies the reserved IDT entry to point to its interrupt routine.

When interrupted by a counter overflow, the interrupt handler needs to perform the following actions:

- Save the instruction pointer (EIP register), code-segment selector, TSS segment selector, counter values and other relevant information at the time of the interrupt.

- Reset the counter to its initial setting and return from the interrupt.

An event monitor application utility or another application program can read the information collected for analysis of the performance of the profiled application.

15.6.3. Pentium® Processor Performance-Monitoring Counters

The Pentium® processor provides two 40-bit performance counters, which can be used either to count events or measure duration. The performance-monitoring counters are supported by three MSRs: the control and event select MSR (CESR) and the performance counter MSRs (CTR0 and CTR1). These registers can be read from and written to using the RDMSR and WRMSR instructions, respectively. They can be accessed using these instructions only when operating at privilege level 0. Each counter has an associated external pin (PM0/BP0 and PM1/BP1), which can be used to indicate the state of the counter to external hardware.

NOTE

The CESR, CTR0, and CTR1 MSRs and the events listed in Table A-1 in Appendix A, *Performance-Monitoring Events* are model-specific for the Pentium® processor.

15.6.3.1. CONTROL AND EVENT SELECT REGISTER (CESR)

The 32-bit control and event select MSR (CESR) is used to control the operation of performance-monitoring counters CTR0 and CTR1 and their associated pins (refer to Figure 15-3). To control each counter, the CESR register contains a 6-bit event select field (ES0 and ES1), a pin control flag (PC0 and PC1), and a 3-bit counter control field (CC0 and CC1). The functions of these fields are as follows:

ES0 and ES1 (event select) fields (bits 0 through 5, bits 16 through 21)
Selects (by entering an event code in the field) up to two events to be monitored. Refer to Table A-1 in Appendix A, *Performance-Monitoring Events* for a list of available event codes

CC0 and CC1 (counter control) fields (bits 6 through 8, bits 22 through 24)
Controls the operation of the counter. The possible control codes are as follows:

CC*n*	**Meaning**
000	Count nothing (counter disabled)
001	Count the selected event while CPL is 0, 1, or 2
010	Count the selected event while CPL is 3
011	Count the selected event regardless of CPL
100	Count nothing (counter disabled)
101	Count clocks (duration) while CPL is 0, 1, or 2
110	Count clocks (duration) while CPL is 3
111	Count clocks (duration) regardless of CPL

Note that the highest order bit selects between counting events and counting clocks (duration); the middle bit enables counting when the CPL is 3; and the low-order bit enables counting when the CPL is 0, 1, or 2.

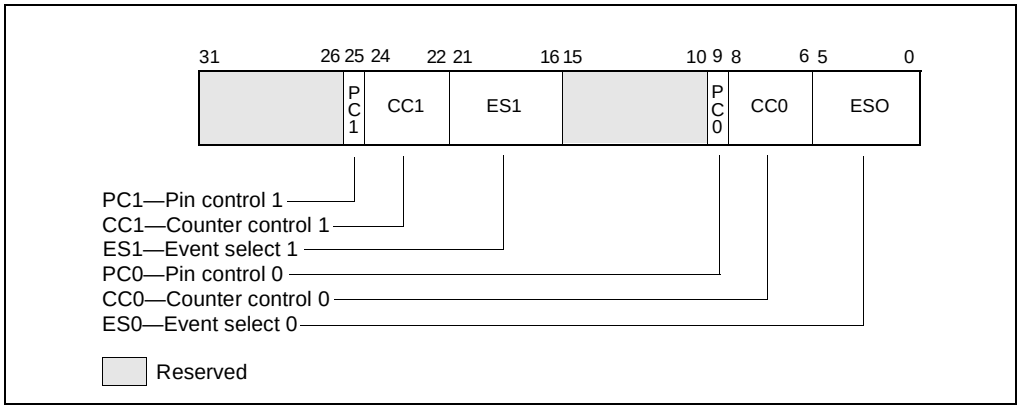


Figure 15-4. CESR MSR (Pentium® Processor Only)

PC0 and PC1 (pin control) flags (bit 9, bits 25)

Selects the function of the external performance-monitoring counter pin (PM0/BP0 and PM1/BP1). Setting one of these flags to 1 causes the processor to assert its associated pin when the counter has overflowed; setting the flag to 0 causes the pin to be asserted when the counter has been incremented. These flags permit the pins to be individually programmed to indicate the overflow or incremented condition. Note that the external signaling of the event on the pins will lag the internal event by a few clocks as the signals are latched and buffered.

While a counter need not be stopped to sample its contents, it must be stopped and cleared or preset before switching to a new event. It is not possible to set one counter separately. If only one event needs to be changed, the CESR register must be read, the appropriate bits modified, and all bits must then be written back to CESR. At reset, all bits in the CESR register are cleared.

15.6.3.2. USE OF THE PERFORMANCE-MONITORING PINS

When the performance-monitor pins PM0/BP0 and/or PM1/BP1 are configured to indicate when the performance-monitor counter has incremented and an “occurrence event” is being counted, the associated pin is asserted (high) each time the event occurs. When a “duration event” is being counted the associated PM pin is asserted for the entire duration of the event. When the performance-monitor pins are configured to indicate when the counter has overflowed, the associated PM pin is not asserted until the counter has overflowed.

When the PM0/BP0 and/or PM1/BP1 pins are configured to signal that a counter has incremented, it should be noted that although the counters may increment by 1 or 2 in a single clock,

the pins can only indicate that the event occurred. Moreover, since the internal clock frequency may be higher than the external clock frequency, a single external clock may correspond to multiple internal clocks.

A “count up to” function may be provided when the event pin is programmed to signal an overflow of the counter. Because the counters are 40 bits, a carry out of bit 39 indicates an overflow. A counter may be preset to a specific value less then $2^{40} - 1$. After the counter has been enabled and the prescribed number of events has transpired, the counter will overflow. Approximately 5 clocks later, the overflow is indicated externally and appropriate action, such as signaling an interrupt, may then be taken.

The PM0/BP0 and PM1/BP1 pins also serve to indicate breakpoint matches during in-circuit emulation, during which time the counter increment or overflow function of these pins is not available. After RESET, the PM0/BP0 and PM1/BP1 pins are configured for performance monitoring, however a hardware debugger may reconfigure these pins to indicate breakpoint matches.

15.6.3.3. EVENTS COUNTED

The events that the performance-monitoring counters can set to count and record in the CTR0 and CTR1 MSRs are divided into two categories: occurrences and duration. Occurrences events are counted each time the event takes place. If the PM0/BP0 or PM1/BP1 pins are configured to indicate when a counter increments, they ar asserted each clock the counter increments. Note that if an event can happen twice in one clock, the counter increments by 2, however, the pins are asserted only once.

For duration events, the counter counts the total number of clocks that the condition is true. When configured to indicate when a counter increments, the PM0/BP0 and/or PM1/BP1 pins are asserted for the duration of the event.

Table A-2 in Appendix A, *Performance-Monitoring Events* lists the events that can be counted with the Pentium® processor performance-monitoring counters.

intel®

16

8086 Emulation

CHAPTER 16
8086 EMULATION

Intel Architecture processors (beginning with the Intel386™ processor) provide two ways to execute new or legacy programs that are assembled and/or compiled to run on an Intel 8086 processor:

- Real-address mode.
- Virtual-8086 mode.

Figure 2-2 in Chapter 2, *System Architecture Overview* shows the relationship of these operating modes to protected mode and system management mode (SMM).

When the processor is powered up or reset, it is placed in the real-address mode. This operating mode almost exactly duplicates the execution environment of the Intel 8086 processor, with some extensions. Virtually any program assembled and/or compiled to run on an Intel 8086 processor will run on an Intel Architecture processor in this mode.

When running in protected mode, the processor can be switched to virtual-8086 mode to run 8086 programs. This mode also duplicates the execution environment of the Intel 8086 processor, with extensions. In virtual-8086 mode, an 8086 program runs as a separate protected-mode task. Legacy 8086 programs are thus able to run under an operating system (such as Microsoft Windows*) that takes advantage of protected mode and to use protected-mode facilities, such as the protected-mode interrupt- and exception-handling facilities. Protected-mode multitasking permits multiple virtual-8086 mode tasks (with each task running a separate 8086 program) to be run on the processor along with other nonvirtual-8086 mode tasks.

This section describes both the basic real-address mode execution environment and the virtual-8086-mode execution environment, available on the Intel Architecture processors beginning with the Intel386™ processor.

16.1. REAL-ADDRESS MODE

The Intel Architecture's real-address mode runs programs written for the Intel 8086, Intel 8088, Intel 80186, and Intel 80188 processors, or for the real-address mode of the Intel 286, Intel386™, Intel486™, Pentium®, Pentium® Pro, Pentium® II, and P6-family processors.

The execution environment of the processor in real-address mode is designed to duplicate the execution environment of the Intel 8086 processor. To an 8086 program, a processor operating in real-address mode behaves like a high-speed 8086 processor. The principal features of this architecture are defined in Chapter 3, *Basic Execution Environment*, of the *Intel Architecture Software Developer's Manual, Volume 1*. The following is a summary of the core features of the real-address mode execution environment as would be seen by a program written for the 8086:

- The processor supports a nominal 1-MByte physical address space (refer to Section 16.1.1., “Address Translation in Real-Address Mode” for specific details). This address space is divided into segments, each of which can be up to 64 KBytes in length. The base of a segment is specified with a 16-bit segment selector, which is zero extended to form a 20-bit offset from address 0 in the address space. An operand within a segment is addressed with a 16-bit offset from the base of the segment. A physical address is thus formed by adding the offset to the 20-bit segment base (refer to Section 16.1.1., “Address Translation in Real-Address Mode”).
- All operands in “native 8086 code” are 8-bit or 16-bit values. (Operand size override prefixes can be used to access 32-bit operands.)
- Eight 16-bit general-purpose registers are provided: AX, BX, CX, DX, SP, BP, SI, and DI. The extended 32 bit registers (EAX, EBX, ECX, EDX, ESP, EBP, ESI, and EDI) are accessible to programs that explicitly perform a size override operation.
- Four segment registers are provided: CS, DS, SS, and ES. (The FS and GS registers are accessible to programs that explicitly access them.) The CS register contains the segment selector for the code segment; the DS and ES registers contain segment selectors for data segments; and the SS register contains the segment selector for the stack segment.
- The 8086 16-bit instruction pointer (IP) is mapped to the lower 16-bits of the EIP register. Note this register is a 32-bit register and unintentional address wrapping may occur.
- The 16-bit FLAGS register contains status and control flags. (This register is mapped to the 16 least significant bits of the 32-bit EFLAGS register.)
- All of the Intel 8086 instructions are supported (refer to Section 16.1.3., “Instructions Supported in Real-Address Mode”).
- A single, 16-bit-wide stack is provided for handling procedure calls and invocations of interrupt and exception handlers. This stack is contained in the stack segment identified with the SS register. The SP (stack pointer) register contains an offset into the stack segment. The stack grows down (toward lower segment offsets) from the stack pointer. The BP (base pointer) register also contains an offset into the stack segment that can be used as a pointer to a parameter list. When a CALL instruction is executed, the processor pushes the current instruction pointer (the 16 least-significant bits of the EIP register and, on far calls, the current value of the CS register) onto the stack. On a return, initiated with a RET instruction, the processor pops the saved instruction pointer from the stack into the EIP register (and CS register on far returns). When an implicit call to an interrupt or exception handler is executed, the processor pushes the EIP, CS, and EFLAGS (low-order 16-bits only) registers onto the stack. On a return from an interrupt or exception handler, initiated with an IRET instruction, the processor pops the saved instruction pointer and EFLAGS image from the stack into the EIP, CS, and EFLAGS registers.
- A single interrupt table, called the “interrupt vector table” or “interrupt table,” is provided for handling interrupts and exceptions (refer to Figure 16-2). The interrupt table (which has 4-byte entries) takes the place of the interrupt descriptor table (IDT, with 8-byte entries) used when handling protected-mode interrupts and exceptions. Interrupt and exception vector numbers provide an index to entries in the interrupt table. Each entry provides a pointer (called a “vector”) to an interrupt- or exception-handling procedure. Refer to

Section 16.1.4., “Interrupt and Exception Handling” for more details. It is possible for software to relocate the IDT by means of the LIDT instruction on Intel Architecture processors beginning with the Intel386™ processor.

- The floating-point unit (FPU) is active and available to execute FPU instructions in real-address mode. Programs written to run on the Intel 8087 and Intel 287 math coprocessors can be run in real-address mode without modification.

The following extensions to the Intel 8086 execution environment are available in the Intel Architecture’s real-address mode. If backwards compatibility to Intel 286 and Intel 8086 processors is required, these features should not be used in new programs written to run in real-address mode.

- Two additional segment registers (FS and GS) are available.
- Many of the integer and system instructions that have been added to P6-family processors can be executed in real-address mode (refer to Section 16.1.3., “Instructions Supported in Real-Address Mode”).
- The 32-bit operand prefix can be used in real-address mode programs to execute the 32-bit forms of instructions. This prefix also allows real-address mode programs to use the processor’s 32-bit general-purpose registers.
- The 32-bit address prefix can be used in real-address mode programs, allowing 32-bit offsets.

The following sections describe address formation, registers, available instructions, and interrupt and exception handling in real-address mode. For information on I/O in real-address mode, refer to Chapter 9, *Input/Output*, in the *Intel Architecture Software Developer’s Manual, Volume 1*.

16.1.1. Address Translation in Real-Address Mode

In real-address mode, the processor does not interpret segment selectors as indexes into a descriptor table; instead, it uses them directly to form linear addresses as the 8086 processor does. It shifts the segment selector left by 4 bits to form a 20-bit base address (refer to Figure 16-1). The offset into a segment is added to the base address to create a linear address that maps directly to the physical address space.

When using 8086-style address translation, it is possible to specify addresses larger than 1 MByte. For example, with a segment selector value of FFFFH and an offset of FFFFH, the linear (and physical) address would be 10FFEFH (1 megabyte plus 64 KBytes). The 8086 processor, which can form addresses only up to 20 bits long, truncates the high-order bit, thereby “wrapping” this address to FFEFH. When operating in real-address mode, however, the processor does not truncate such an address and uses it as a physical address. (Note, however, that for Intel Architecture processors beginning with the Intel486™ processor, the A20M# signal can be used in real-address mode to mask address line A20, thereby mimicking the 20-bit wrap-around behavior of the 8086 processor.) Care should be take to ensure that A20M# based address wrapping is handled correctly in multiprocessor based system.

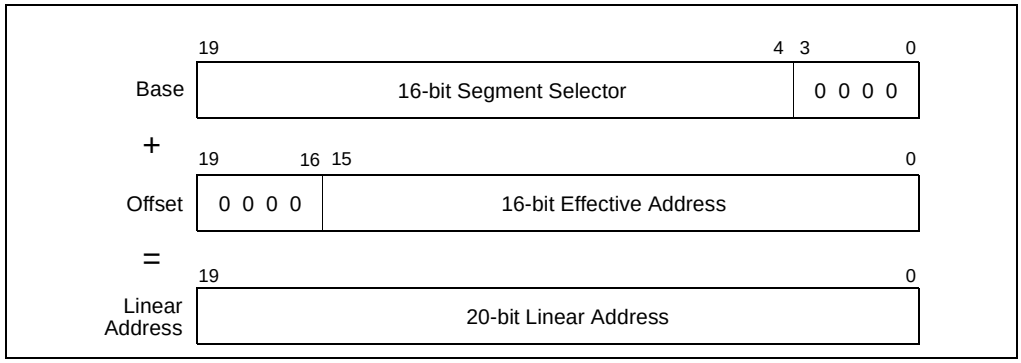


Figure 16-1. Real-Address Mode Address Translation

The Intel Architecture processors beginning with the Intel386™ processor can generate 32-bit offsets using an address override prefix; however, in real-address mode, the value of a 32-bit offset may not exceed FFFFH without causing an exception.

For full compatibility with Intel 286 real-address mode, pseudo-protection faults (interrupt 12 or 13) occur if a 32-bit offset is generated outside the range 0 through FFFFH.

16.1.2. Registers Supported in Real-Address Mode

The register set available in real-address mode includes all the registers defined for the 8086 processor plus the new registers introduced inP6-family processors, such as the FS and GS segment registers, the debug registers, the control registers, and the floating-point unit registers. The 32-bit operand prefix allows a real-address mode program to use the 32-bit general-purpose registers (EAX, EBX, ECX, EDX, ESP, EBP, ESI, and EDI).

16.1.3. Instructions Supported in Real-Address Mode

The following instructions make up the core instruction set for the 8086 processor. If backwards compatibility to the Intel 286 and Intel 8086 processors is required, only these instructions should be used in a new program written to run in real-address mode.

- Move (MOV) instructions that move operands between general-purpose registers, segment registers, and between memory and general-purpose registers,
- The exchange (XCHG) instruction.
- Load segment register instructions LDS and LES.
- Arithmetic instructions ADD, ADC, SUB, SBB, MUL, IMUL, DIV, IDIV, INC, DEC, CMP, and NEG.
- Logical instructions AND, OR, XOR, and NOT.

- Decimal instructions DAA, DAS, AAA, AAS, AAM, and AAD.
- Stack instructions PUSH and POP (to general-purpose registers and segment registers).
- Type conversion instructions CWD, CDQ, CBW, and CWDE.
- Shift and rotate instructions SAL, SHL, SHR, SAR, ROL, ROR, RCL, and RCR.
- TEST instruction.
- Control instructions JMP, J*cc*, CALL, RET, LOOP, LOOPE, and LOOPNE.
- Interrupt instructions INT *n*, INTO, and IRET.
- EFLAGS control instructions STC, CLC, CMC, CLD, STD, LAHF, SAHF, PUSHF, and POPF.
- I/O instructions IN, INS, OUT, and OUTS.
- Load effective address (LEA) instruction, and translate (XLATB) instruction.
- LOCK prefix.
- Repeat prefixes REP, REPE, REPZ, REPNE, and REPNZ.
- Processor halt (HLT) instruction.
- No operation (NOP) instruction.

The following instructions, added to P6-family processors (some in the Intel 286 processor and the remainder in the Intel386™ processor), can be executed in real-address mode, if backwards compatibility to the Intel 8086 processor is not required.

- Move (MOV) instructions that operate on the control and debug registers.
- Load segment register instructions LSS, LFS, and LGS.
- Generalized multiply instructions and multiply immediate data.
- Shift and rotate by immediate counts.
- Stack instructions PUSHA, PUSHAD, POPA and POPAD, and PUSH immediate data.
- Move with sign extension instructions MOVSX and MOVZX.
- Long-displacement J*cc* instructions.
- Exchange instructions CMPXCHG, CMPXCHG8B, and XADD.
- String instructions MOVS, CMPS, SCAS, LODS, and STOS.
- Bit test and bit scan instructions BT, BTS, BTR, BTC, BSF, and BSR; the byte-set-on condition instruction SET*cc*; and the byte swap (BSWAP) instruction.
- Double shift instructions SHLD and SHRD.
- EFLAGS control instructions PUSHF and POPF.
- ENTER and LEAVE control instructions.

- BOUND instruction.
- CPU identification (CPUID) instruction.
- System instructions CLTS, INVD, WINVD, INVLPG, LGDT, SGDT, LIDT, SIDT, LMSW, SMSW, RDMSR, WRMSR, RDTSC, and RDPMC.

Execution of any of the other Intel Architecture instructions (not given in the previous two lists) in real-address mode result in an invalid-opcode exception (#UD) being generated.

16.1.4. Interrupt and Exception Handling

When operating in real-address mode, software must provide interrupt and exception-handling facilities that are separate from those provided in protected mode. Even during the early stages of processor initialization when the processor is still in real-address mode, elementary real-address mode interrupt and exception-handling facilities must be provided to insure reliable operation of the processor, or the initialization code must insure that no interrupts or exceptions will occur.

The Intel Architecture processors handle interrupts and exceptions in real-address mode similar to the way they handle them in protected mode. When a processor receives an interrupt or generates an exception, it uses the vector number of the interrupt or exception as an index into the interrupt table. (In protected mode, the interrupt table is called the **interrupt descriptor table (IDT)**, but in real-address mode, the table is usually called the **interrupt vector table**, or simply the **interrupt table**.) The entry in the interrupt vector table provides a pointer to an interrupt- or exception-handler procedure. (The pointer consists of a segment selector for a code segment and a 16-bit offset into the segment.) The processor performs the following actions to make an implicit call to the selected handler:

1. Pushes the current values of the CS and EIP registers onto the stack. (Only the 16 least-significant bits of the EIP register are pushed.)
2. Pushes the low-order 16 bits of the EFLAGS register onto the stack.
3. Clears the IF flag in the EFLAGS register to disable interrupts.
4. Clears the TF, RC, and AC flags, in the EFLAGS register.
5. Transfers program control to the location specified in the interrupt vector table.

An IRET instruction at the end of the handler procedure reverses these steps to return program control to the interrupted program. Exceptions do not return error codes in real-address mode.

The interrupt vector table is an array of 4-byte entries (refer to Figure 16-2). Each entry consists of a far pointer to a handler procedure, made up of a segment selector and an offset. The processor scales the interrupt or exception vector by 4 to obtain an offset into the interrupt table. Following reset, the base of the interrupt vector table is located at physical address 0 and its limit is set to 3FFH. In the Intel 8086 processor, the base address and limit of the interrupt vector table cannot be changed. In the P6-family processors, the base address and limit of the interrupt vector table are contained in the IDTR register and can be changed using the LIDT instruction. (For

backward compatibility to Intel 8086 processors, the default base address and limit of the interrupt vector table should not be changed.)

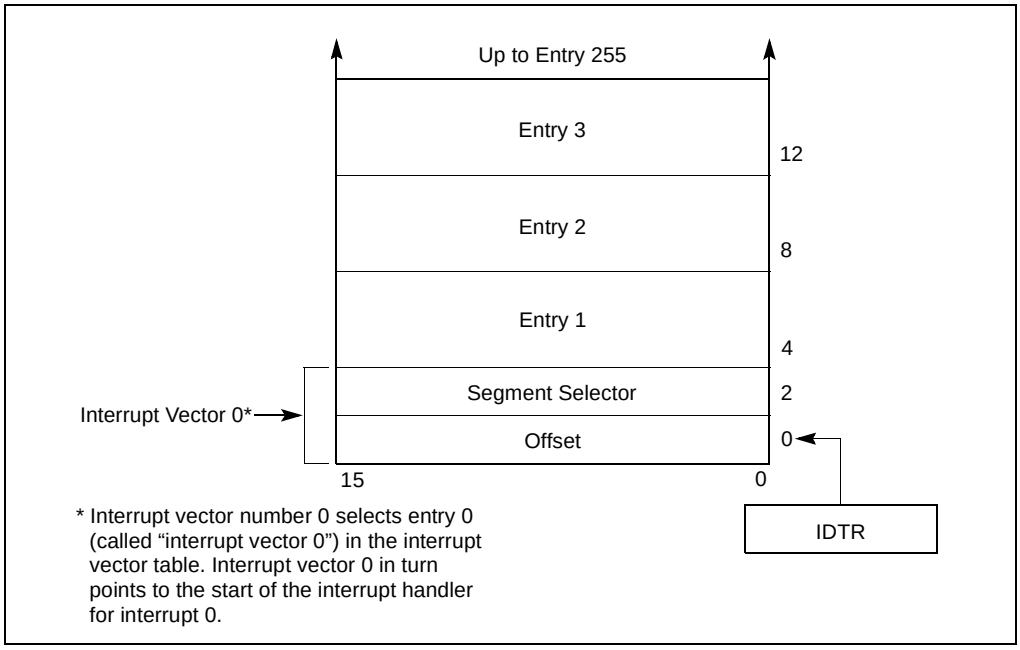


Figure 16-2. Interrupt Vector Table in Real-Address Mode

Table 16-1 shows the interrupt and exception vectors that can be generated in real-address mode and virtual-8086 mode, and in the Intel 8086 processor. Refer to Chapter 5, *Interrupt and Exception Handling* for a description of the exception conditions.

Table 16-1. Real-Address Mode Exceptions and Interrupts

Vector No.	Description	Real-Address Mode	Virtual-8086 Mode	Intel 8086 Processor
0	Divide Error (#DE)	Yes	Yes	Yes
1	Debug Exception (#DB)	Yes	Yes	No
2	NMI Interrupt	Yes	Yes	Yes
3	Breakpoint (#BP)	Yes	Yes	Yes
4	Overflow (#OF)	Yes	Yes	Yes
5	BOUND Range Exceeded (#BR)	Yes	Yes	Reserved
6	Invalid Opcode (#UD)	Yes	Yes	Reserved
7	Device Not Available (#NM)	Yes	Yes	Reserved
8	Double Fault (#DF)	Yes	Yes	Reserved
9	(Intel reserved. Do not use.)	Reserved	Reserved	Reserved
10	Invalid TSS (#TS)	Reserved	Yes	Reserved
11	Segment Not Present (#NP)	Reserved	Yes	Reserved
12	Stack Fault (#SS)	Yes	Yes	Reserved
13	General Protection (#GP)*	Yes	Yes	Reserved
14	Page Fault (#PF)	Reserved	Yes	Reserved
15	(Intel reserved. Do not use.)	Reserved	Reserved	Reserved
16	Floating-Point Error (#MF)	Yes	Yes	Reserved
17	Alignment Check (#AC)	Reserved	Yes	Reserved
18	Machine Check (#MC)	Yes	Yes	Reserved
19	SIMD Floating-Point Numeric Error (#XF)	Yes	Yes	Reserved
20-31	(Intel reserved. Do not use.)	Reserved	Reserved	Reserved
32-255	User Defined Interrupts	Yes	Yes	Yes

NOTE:

* In the real-address mode, vector 13 is the segment overrun exception. In protected and virtual-8086 modes, this exception covers all general-protection error conditions, including traps to the virtual-8086 monitor from virtual-8086 mode.

16.2. VIRTUAL-8086 MODE

Virtual-8086 mode is actually a special type of a task that runs in protected mode. When the operating-system or executive switches to a virtual-8086-mode task, the processor emulates an Intel 8086 processor. The execution environment of the processor while in the 8086-emulation state is the same as is described in Section 16.1., “Real-Address Mode” for real-address mode, including the extensions. The major difference between the two modes is that in virtual-8086 mode the 8086 emulator uses some protected-mode services (such as the protected-mode interrupt and exception-handling and paging facilities).

As in real-address mode, any new or legacy program that has been assembled and/or compiled to run on an Intel 8086 processor will run in a virtual-8086-mode task. And several 8086 programs can be run as virtual-8086-mode tasks concurrently with normal protected-mode tasks, using the processor’s multitasking facilities.

16.2.1. Enabling Virtual-8086 Mode

The processor runs in virtual-8086 mode when the VM (virtual machine) flag in the EFLAGS register is set. This flag can only be set when the processor switches to a new protected-mode task or resumes virtual-8086 mode via an IRET instruction.

System software cannot change the state of the VM flag directly in the EFLAGS register (for example, by using the POPFD instruction). Instead it changes the flag in the image of the EFLAGS register stored in the TSS or on the stack following a call to an interrupt- or exception-handler procedure. For example, software sets the VM flag in the EFLAGS image in the TSS when first creating a virtual-8086 task.

The processor tests the VM flag under three general conditions:

- When loading segment registers, to determine whether to use 8086-style address translation.
- When decoding instructions, to determine which instructions are not supported in virtual-8086 mode and which instructions are sensitive to IOPL.
- When checking privileged instructions, on page accesses, or when performing other permission checks. (Virtual-8086 mode always executes at CPL 3.)

16.2.2. Structure of a Virtual-8086 Task

A virtual-8086-mode task consists of the following items:

- A 32-bit TSS for the task.
- The 8086 program.
- A virtual-8086 monitor.
- 8086 operating-system services.

The TSS of the new task must be a 32-bit TSS, not a 16-bit TSS, because the 16-bit TSS does not load the most-significant word of the EFLAGS register, which contains the VM flag. All TSS's, stacks, data, and code used to handle exceptions when in virtual-8086 mode must also be 32-bit segments.

The processor enters virtual-8086 mode to run the 8086 program and returns to protected mode to run the virtual-8086 monitor.

The virtual-8086 monitor is a 32-bit protected-mode code module that runs at a CPL of 0. The monitor consists of initialization, interrupt- and exception-handling, and I/O emulation procedures that emulate a personal computer or other 8086-based platform. Typically, the monitor is either part of or closely associated with the protected-mode general-protection (#GP) exception handler, which also runs at a CPL of 0. As with any protected-mode code module, code-segment descriptors for the virtual-8086 monitor must exist in the GDT or in the task's LDT. The virtual-8086 monitor also may need data-segment descriptors so it can examine the IDT or other parts of the 8086 program in the first 1 MByte of the address space. The linear addresses above 10FFEFH are available for the monitor, the operating system, and other system software.

The 8086 operating-system services consists of a kernel and/or operating-system procedures that the 8086 program makes calls to. These services can be implemented in either of the following two ways:

- They can be included in the 8086 program. This approach is desirable for either of the following reasons:
  - — The 8086 program code modifies the 8086 operating-system services.
  - — There is not sufficient development time to merge the 8086 operating-system services into main operating system or executive.
- They can be implemented or emulated in the virtual-8086 monitor. This approach is desirable for any of the following reasons:
  - — The 8086 operating-system procedures can be more easily coordinated among several virtual-8086 tasks.
  - — Memory can be saved by not duplicating 8086 operating-system procedure code for several virtual-8086 tasks.
  - — The 8086 operating-system procedures can be easily emulated by calls to the main operating system or executive.

The approach chosen for implementing the 8086 operating-system services may result in different virtual-8086-mode tasks using different 8086 operating-system services.

16.2.3. Paging of Virtual-8086 Tasks

Even though a program running in virtual-8086 mode can use only 20-bit linear addresses, the processor converts these addresses into 32-bit linear addresses before mapping them to the physical address space. If paging is being used, the 8086 address space for a program running in virtual-8086 mode can be paged and located in a set of pages in physical address space. If paging

is used, it is transparent to the program running in virtual-8086 mode just as it is for any task running on the processor.

Paging is not necessary for a single virtual-8086-mode task, but paging is useful or necessary in the following situations:

- When running multiple virtual-8086-mode tasks. Here, paging allows the lower 1 MByte of the linear address space for each virtual-8086-mode task to be mapped to a different physical address location.
- When emulating the 8086 address-wraparound that occurs at 1 MByte. When using 8086-style address translation, it is possible to specify addresses larger than 1 MByte. These addresses automatically wraparound in the Intel 8086 processor (refer to Section 16.1.1., "Address Translation in Real-Address Mode"). If any 8086 programs depend on address wraparound, the same effect can be achieved in a virtual-8086-mode task by mapping the linear addresses between 100000H and 110000H and linear addresses between 0 and 10000H to the same physical addresses.
- When sharing the 8086 operating-system services or ROM code that is common to several 8086 programs running as different 8086-mode tasks.
- When redirecting or trapping references to memory-mapped I/O devices.

16.2.4. Protection within a Virtual-8086 Task

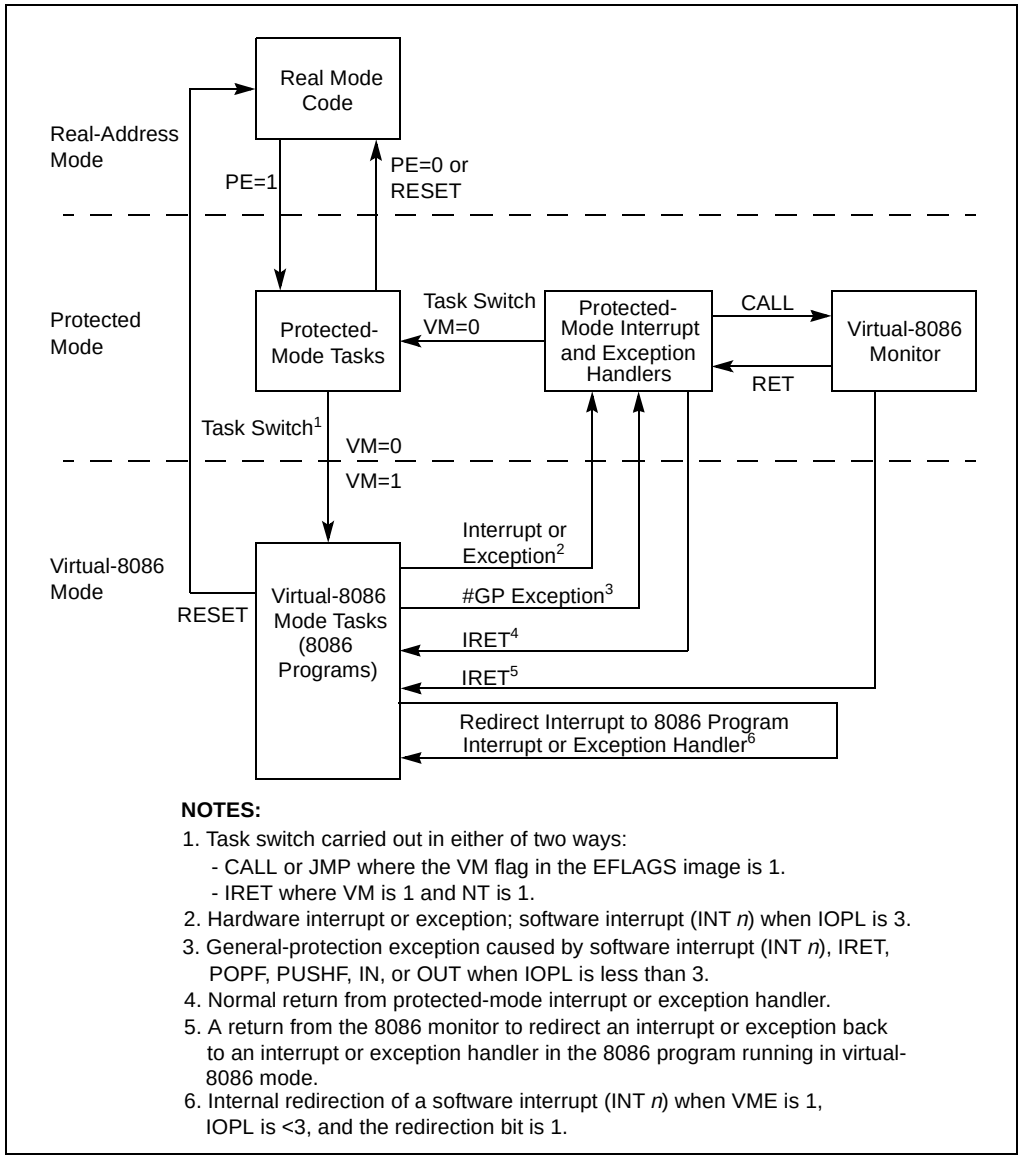
Protection is not enforced between the segments of an 8086 program. Either of the following techniques can be used to protect the system software running in a virtual-8086-mode task from the 8086 program:

- Reserve the first 1 MByte plus 64 KBytes of each task's linear address space for the 8086 program. An 8086 processor task cannot generate addresses outside this range.
- Use the U/S flag of page-table entries to protect the virtual-8086 monitor and other system software in the virtual-8086 mode task space. When the processor is in virtual-8086 mode, the CPL is 3. Therefore, an 8086 processor program has only user privileges. If the pages of the virtual-8086 monitor have supervisor privilege, they cannot be accessed by the 8086 program.

16.2.5. Entering Virtual-8086 Mode

Figure 16-3 summarizes the methods of entering and leaving virtual-8086 mode. The processor switches to virtual-8086 mode in either of the following situations:

- Task switch when the VM flag is set to 1 in the EFLAGS register image stored in the TSS for the task. Here the task switch can be initiated in either of two ways:
  - — A CALL or JMP instruction.
  - — An IRET instruction, where the NT flag in the EFLAGS image is set to 1.
- Return from a protected-mode interrupt or exception handler when the VM flag is set to 1 in the EFLAGS register image on the stack.



NOTES:

1. Task switch carried out in either of two ways:
   - CALL or JMP where the VM flag in the EFLAGS image is 1.
   - IRET where VM is 1 and NT is 1.
2. Hardware interrupt or exception; software interrupt (INT *n*) when IOPL is 3.
3. General-protection exception caused by software interrupt (INT *n*), IRET, POPF, PUSHF, IN, or OUT when IOPL is less than 3.
4. Normal return from protected-mode interrupt or exception handler.
5. A return from the 8086 monitor to redirect an interrupt or exception back to an interrupt or exception handler in the 8086 program running in virtual-8086 mode.
6. Internal redirection of a software interrupt (INT *n*) when VME is 1, IOPL is <3, and the redirection bit is 1.

Figure 16-3. Entering and Leaving Virtual-8086 Mode

When a task switch is used to enter virtual-8086 mode, the TSS for the virtual-8086-mode task must be a 32-bit TSS. (If the new TSS is a 16-bit TSS, the upper word of the EFLAGS register is not in the TSS, causing the processor to clear the VM flag when it loads the EFLAGS register.) The processor updates the VM flag prior to loading the segment registers from their images in the new TSS. The new setting of the VM flag determines whether the processor interprets the

contents of the segment registers as 8086-style segment selectors or protected-mode segment selectors. When the VM flag is set, the segment registers are loaded from the TSS, using 8086-style address translation to form base addresses.

Refer to Section 16.3., “Interrupt and Exception Handling in Virtual-8086 Mode” for information on entering virtual-8086 mode on a return from an interrupt or exception handler.

16.2.6. Leaving Virtual-8086 Mode

The processor can leave the virtual-8086 mode only through an interrupt or exception. The following are situations where an interrupt or exeception will lead to the processor leaving virtual-8086 mode (refer to Figure 16-3):

- The processor services a hardware interrupt generated to signal the suspension of execution of the virtual-8086 application. This hardware interrupt may be generated by a timer or other external mechanism. Upon receiving the hardware interrupt, the processor enters protected mode and switches to a protected-mode (or another virtual-8086 mode) task either through a task gate in the protected-mode IDT or through a trap or interrupt gate that points to a handler that initiates a task switch. A task switch from a virtual-8086 task to another task loads the EFLAGS register from the TSS of the new task. The value of the VM flag in the new EFLAGS determines if the new task executes in virtual-8086 mode or not.
- The processor services an exception caused by code executing the virtual-8086 task or services a hardware interrupt that “belongs to” the virtual-8086 task. Here, the processor enters protected mode and services the exception or hardware interrupt through the protected-mode IDT (normally through an interrupt or trap gate) and the protected-mode exception- and interrupt-handlers. The processor may handle the exception or interrupt within the context of the virtual 8086 task and return to virtual-8086 mode on a return from the handler procedure. The processor may also execute a task switch and handle the exception or interrupt in the context of another task.
- The processor services a software interrupt generated by code executing in the virtual-8086 task (such as a software interrupt to call a MS-DOS* operating system routine). The processor provides several methods of handling these software interrupts, which are discussed in detail in Section 16.3.3., “Class 3—Software Interrupt Handling in Virtual-8086 Mode” Most of them involve the processor entering protected mode, often by means of a general-protection (#GP) exception. In protected mode, the processor can send the interrupt to the virtual-8086 monitor for handling and/or redirect the interrupt back to the application program running in virtual-8086 mode task for handling.

  Intel Architecture processors that incorporate the virtual mode extension (enabled with the VME flag in control register CR4) are capable of redirecting software-generated interrupts back to the program’s interrupt handlers without leaving virtual-8086 mode. Refer to Section 16.3.3.4., “Method 5: Software Interrupt Handling” for more information on this mechanism.

- A hardware reset initiated by asserting the RESET or INIT pin is a special kind of interrupt. When a RESET or INIT is signaled while the processor is in virtual-8086 mode, the processor leaves virtual-8086 mode and enters real-address mode.
- Execution of the HLT instruction in virtual-8086 mode will cause a general-protection (GP#) fault, which the protected-mode handler generally sends to the virtual-8086 monitor. The virtual-8086 monitor then determines the correct execution sequence after verifying that it was entered as a result of a HLT execution.

Refer to Section 16.3., “Interrupt and Exception Handling in Virtual-8086 Mode” for information on leaving virtual-8086 mode to handle an interrupt or exception generated in virtual-8086 mode.

16.2.7. Sensitive Instructions

When an Intel Architecture processor is running in virtual-8086 mode, the CLI, STI, PUSHF, POPF, INT *n*, and IRET instructions are sensitive to IOPL. The IN, INS, OUT, and OUTS instructions, which are sensitive to IOPL in protected mode, are not sensitive in virtual-8086 mode.

The CPL is always 3 while running in virtual-8086 mode; if the IOPL is less than 3, an attempt to use the IOPL-sensitive instructions listed above triggers a general-protection exception (#GP). These instructions are sensitive to IOPL to give the virtual-8086 monitor a chance to emulate the facilities they affect.

16.2.8. Virtual-8086 Mode I/O

Many 8086 programs written for nonmultitasking systems directly access I/O ports. This practice may cause problems in a multitasking environment. If more than one program accesses the same port, they may interfere with each other. Most multitasking systems require application programs to access I/O ports through the operating system. This results in simplified, centralized control.

The processor provides I/O protection for creating I/O that is compatible with the environment and transparent to 8086 programs. Designers may take any of several possible approaches to protecting I/O ports:

- Protect the I/O address space and generate exceptions for all attempts to perform I/O directly.
- Let the 8086 program perform I/O directly.
- Generate exceptions on attempts to access specific I/O ports.
- Generate exceptions on attempts to access specific memory-mapped I/O ports.

The method of controlling access to I/O ports depends upon whether they are I/O-port mapped or memory mapped.

16.2.8.1. I/O-PORT-MAPPED I/O

The I/O permission bit map in the TSS can be used to generate exceptions on attempts to access specific I/O port addresses. The I/O permission bit map of each virtual-8086-mode task determines which I/O addresses generate exceptions for that task. Because each task may have a different I/O permission bit map, the addresses that generate exceptions for one task may be different from the addresses for another task. This differs from protected mode in which, if the CPL is less than or equal to the IOPL, I/O access is allowed without checking the I/O permission bit map. Refer to Chapter 9, *Input/Output*, in the *Intel Architecture Software Developer's Manual, Volume 1*, for more information about the I/O permission bit map.

16.2.8.2. MEMORY-MAPPED I/O

In systems which use memory-mapped I/O, the paging facilities of the processor can be used to generate exceptions for attempts to access I/O ports. The virtual-8086 monitor may use paging to control memory-mapped I/O in these ways:

- Map part of the linear address space of each task that needs to perform I/O to the physical address space where I/O ports are placed. By putting the I/O ports at different addresses (in different pages), the paging mechanism can enforce isolation between tasks.
- Map part of the linear address space to pages that are not-present. This generates an exception whenever a task attempts to perform I/O to those pages. System software then can interpret the I/O operation being attempted.

Software emulation of the I/O space may require too much operating system intervention under some conditions. In these cases, it may be possible to generate an exception for only the first attempt to access I/O. The system software then may determine whether a program can be given exclusive control of I/O temporarily, the protection of the I/O space may be lifted, and the program allowed to run at full speed.

16.2.8.3. SPECIAL I/O BUFFERS

Buffers of intelligent controllers (for example, a bit-mapped frame buffer) also can be emulated using page mapping. The linear space for the buffer can be mapped to a different physical space for each virtual-8086-mode task. The virtual-8086 monitor then can control which virtual buffer to copy onto the real buffer in the physical address space.

16.3. INTERRUPT AND EXCEPTION HANDLING IN VIRTUAL-8086 MODE

When the processor receives an interrupt or detects an exception condition while in virtual-8086 mode, it invokes an interrupt or exception handler, just as it does in protected or real-address mode. The interrupt or exception handler that is invoked and the mechanism used to invoke it depends on the class of interrupt or exception that has been detected or generated and the state of various system flags and fields.

In virtual-8086 mode, the interrupts and exceptions are divided into three classes for the purposes of handling:

- Class 1—All processor-generated exceptions and all hardware interrupts, including the NMI interrupt and the hardware interrupts sent to the processor's external interrupt delivery pins. All class 1 exceptions and interrupts are handled by the protected-mode exception and interrupt handlers.
- Class 2—Special case for maskable hardware interrupts (Section 5.1.1.2., "Maskable Hardware Interrupts", in Chapter 5, *Interrupt and Exception Handling*) when the virtual mode extensions are enabled.
- Class 3—All software-generated interrupts, that is interrupts generated with the INT *n* instruction[1].

The method the processor uses to handle class 2 and 3 interrupts depends on the setting of the following flags and fields:

- IOPL field (bits 12 and 13 in the EFLAGS register)—Controls how class 3 software interrupts are handled when the processor is in virtual-8086 mode (refer to Section 2.3., "System Flags and Fields in the EFLAGS Register", in Chapter 2, *System Architecture Overview*). This field also controls the enabling of the VIF and VIP flags in the EFLAGS register when the VME flag is set. The VIF and VIP flags are provided to assist in the handling of class 2 maskable hardware interrupts.
- VME flag (bit 0 in control register CR4)—Enables the virtual mode extension for the processor when set (refer to Section 2.5., "Control Registers", in Chapter 2, *System Architecture Overview*).
- Software interrupt redirection bit map (32 bytes in the TSS, refer to Figure 16-5)—Contains 256 flags that indicates how class 3 software interrupts should be handled when they occur in virtual-8086 mode. A software interrupt can be directed either to the interrupt and exception handlers in the currently running 8086 program or to the protected-mode interrupt and exception handlers.
- The virtual interrupt flag (VIF) and virtual interrupt pending flag (VIP) in the EFLAGS register—Provides **virtual interrupt support** for the handling of class 2 maskable hardware interrupts (refer to Section 16.3.2., "Class 2—Maskable Hardware Interrupt Handling in Virtual-8086 Mode Using the Virtual Interrupt Mechanism").

NOTE

The VME flag, software interrupt redirection bit map, and VIF and VIP flags are only available in Intel Architecture processors that support the virtual mode extensions. These extensions were introduced in the Intel Architecture with the Pentium® processor.

The following sections describe the actions that processor takes and the possible actions of interrupt and exception handlers for the two classes of interrupts described in the previous paragraphs. These sections describe three possible types of interrupt and exception handlers:

1. The INT 3 instruction is a special case (refer to the description of the INT *n* instruction in Chapter 3, *Instruction Set Reference*, of the *Intel Architecture Software Developer's Manual, Volume 2*).

- Protected-mode interrupt and exceptions handlers—These are the handlers that the processor calls through the protected-mode IDT.
- Virtual-8086 monitor interrupt and exception handlers—These handlers are resident in the virtual-8086 monitor, and they are commonly accessed through a general-protection exception (#GP, interrupt 13) that is directed to the protected-mode general-protection exception handler.
- 8086 program interrupt and exception handlers—These handlers are part of the 8086 program that is running in virtual-8086 mode.

The following sections describe how these handlers are used, depending on the selected class and method of interrupt and exception handling.

16.3.1. Class 1—Hardware Interrupt and Exception Handling in Virtual-8086 Mode

In virtual-8086 mode, the Pentium® and P6 family processors handle hardware interrupts and exceptions in the same manner as they are handled by the Intel486™ and Intel386™ processors. They invoke the protected-mode interrupt or exception handler that the interrupt or exception vector points to in the IDT. Here, the IDT entry must contain either a 32-bit trap or interrupt gate or a task gate. The following sections describe various ways that a virtual-8086 mode interrupt or exception can be handled after the protected-mode handler has been invoked.

Refer to Section 16.3.2., “Class 2—Maskable Hardware Interrupt Handling in Virtual-8086 Mode Using the Virtual Interrupt Mechanism” for a description of the virtual interrupt mechanism that is available for handling maskable hardware interrupts while in virtual-8086 mode. When this mechanism is either not available or not enabled, maskable hardware interrupts are handled in the same manner as exceptions, as described in the following sections.

16.3.1.1. HANDLING AN INTERRUPT OR EXCEPTION THROUGH A PROTECTED-MODE TRAP OR INTERRUPT GATE

When an interrupt or exception vector points to a 32-bit trap or interrupt gate in the IDT, the gate must in turn point to a nonconforming, privilege-level 0, code segment. When accessing this code segment, the processor performs the following steps.

1. Switches to 32-bit protected mode and privilege level 0.
2. Saves the state of the processor on the privilege-level 0 stack. The states of the EIP, CS, EFLAGS, ESP, SS, ES, DS, FS, and GS registers are saved (refer to Figure 16-4).
3. Clears the segment registers. Saving the DS, ES, FS, and GS registers on the stack and then clearing the registers lets the interrupt or exception handler safely save and restore these registers regardless of the type segment selectors they contain (protected-mode or 8086-style). The interrupt and exception handlers, which may be called in the context of either a protected-mode task or a virtual-8086-mode task, can use the same code sequences for saving and restoring the registers for any task. Clearing these registers before execution of the IRET instruction does not cause a trap in the interrupt handler. Interrupt procedures that

expect values in the segment registers or that return values in the segment registers must use the register images saved on the stack for privilege level 0.

4. Clears the VM flag in the EFLAGS register.
5. Begins executing the selected interrupt or exception handler.

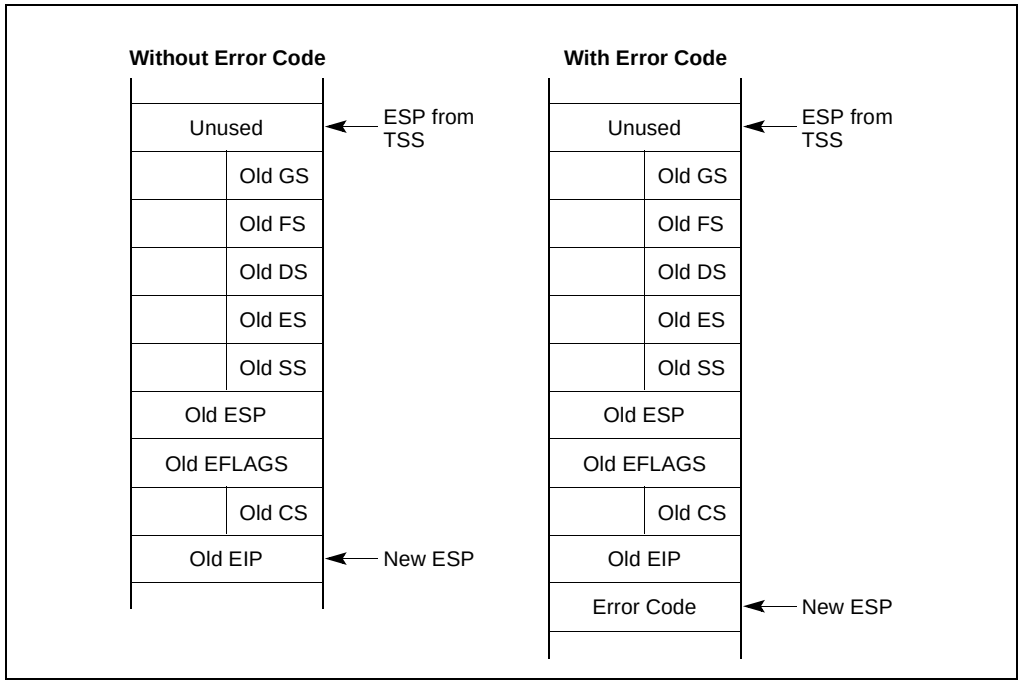


Figure 16-4. Privilege Level 0 Stack After Interrupt or Exception in Virtual-8086 Mode

If the trap or interrupt gate references a procedure in a conforming segment or in a segment at a privilege level other than 0, the processor generates a general-protection exception (#GP). Here, the error code is the segment selector of the code segment to which a call was attempted.

Interrupt and exception handlers can examine the VM flag on the stack to determine if the interrupted procedure was running in virtual-8086 mode. If so, the interrupt or exception can be handled in one of three ways:

- The protected-mode interrupt or exception handler that was called can handle the interrupt or exception.
- The protected-mode interrupt or exception handler can call the virtual-8086 monitor to handle the interrupt or exception.
- The virtual-8086 monitor (if called) can in turn pass control back to the 8086 program's interrupt and exception handler.

If the interrupt or exception is handled with a protected-mode handler, the handler can return to the interrupted program in virtual-8086 mode by executing an IRET instruction. This instruction loads the EFLAGS and segment registers from the images saved in the privilege level 0 stack (refer to Figure 16-4). A set VM flag in the EFLAGS image causes the processor to switch back to virtual-8086 mode. The CPL at the time the IRET instruction is executed must be 0, otherwise the processor does not change the state of the VM flag.

The virtual-8086 monitor runs at privilege level 0, like the protected-mode interrupt and exception handlers. It is commonly closely tied to the protected-mode general-protection exception (#GP, vector 13) handler. If the protected-mode interrupt or exception handler calls the virtual-8086 monitor to handle the interrupt or exception, the return from the virtual-8086 monitor to the interrupted virtual-8086 mode program requires two return instructions: a RET instruction to return to the protected-mode handler and an IRET instruction to return to the interrupted program.

The virtual-8086 monitor has the option of directing the interrupt and exception back to an interrupt or exception handler that is part of the interrupted 8086 program, as described in Section 16.3.1.2., “Handling an Interrupt or Exception With an 8086 Program Interrupt or Exception Handler”.

16.3.1.2. HANDLING AN INTERRUPT OR EXCEPTION WITH AN 8086 PROGRAM INTERRUPT OR EXCEPTION HANDLER

Because it was designed to run on an 8086 processor, an 8086 program running in a virtual-8086-mode task contains an 8086-style interrupt vector table, which starts at linear address 0. If the virtual-8086 monitor correctly directs an interrupt or exception vector back to the virtual-8086-mode task it came from, the handlers in the 8086 program can handle the interrupt or exception. The virtual-8086 monitor must carry out the following steps to send an interrupt or exception back to the 8086 program:

1. Use the 8086 interrupt vector to locate the appropriate handler procedure in the 8086 program interrupt table.
2. Store the EFLAGS (low-order 16 bits only), CS and EIP values of the 8086 program on the privilege-level 3 stack. This is the stack that the virtual-8086-mode task is using. (The 8086 handler may use or modify this information.)
3. Change the return link on the privilege-level 0 stack to point to the privilege-level 3 handler procedure.
4. Execute an IRET instruction to pass control to the 8086 program handler.
5. When the IRET instruction from the privilege-level 3 handler triggers a general-protection exception (#GP) and thus effectively again calls the virtual-8086 monitor, restore the return link on the privilege-level 0 stack to point to the original, interrupted, privilege-level 3 procedure.
6. Copy the low order 16 bits of the EFLAGS image from the privilege-level 3 stack to the privilege-level 0 stack (because some 8086 handlers modify these flags to return information to the code that caused the interrupt).

7. Execute an IRET instruction to pass control back to the interrupted 8086 program.

Note that if an operating system intends to support all 8086 MS-DOS-based programs, it is necessary to use the actual 8086 interrupt and exception handlers supplied with the program. The reason for this is that some programs modify their own interrupt vector table to substitute (or hook in series) their own specialized interrupt and exception handlers.

16.3.1.3. HANDLING AN INTERRUPT OR EXCEPTION THROUGH A TASK GATE

When an interrupt or exception vector points to a task gate in the IDT, the processor performs a task switch to the selected interrupt- or exception-handling task. The following actions are carried out as part of this task switch:

1. The EFLAGS register with the VM flag set is saved in the current TSS.
2. The link field in the TSS of the called task is loaded with the segment selector of the TSS for the interrupted virtual-8086-mode task.
3. The EFLAGS register is loaded from the image in the new TSS, which clears the VM flag and causes the processor to switch to protected mode.
4. The NT flag in the EFLAGS register is set.
5. The processor begins executing the selected interrupt- or exception-handler task.

When an IRET instruction is executed in the handler task and the NT flag in the EFLAGS register is set, the processors switches from a protected-mode interrupt- or exception-handler task back to a virtual-8086-mode task. Here, the EFLAGS and segment registers are loaded from images saved in the TSS for the virtual-8086-mode task. If the VM flag is set in the EFLAGS image, the processor switches back to virtual-8086 mode on the task switch. The CPL at the time the IRET instruction is executed must be 0, otherwise the processor does not change the state of the VM flag.

16.3.2. Class 2—Maskable Hardware Interrupt Handling in Virtual-8086 Mode Using the Virtual Interrupt Mechanism

Maskable hardware interrupts are those interrupts that are delivered through the INTR# pin or through an interrupt request to the local APIC (refer to Section 5.1.1.2., “Maskable Hardware Interrupts”, in Chapter 5, *Interrupt and Exception Handling*). These interrupts can be inhibited (masked) from interrupting an executing program or task by clearing the IF flag in the EFLAGS register.

When the VME flag in control register CR4 is set and the IOPL field in the EFLAGS register is less than 3, two additional flags are activated in the EFLAGS register:

- VIF (virtual interrupt) flag, bit 19 of the EFLAGS register.
- VIP (virtual interrupt pending) flag, bit 20 of the EFLAGS register.

These flags provide the virtual-8086 monitor with more efficient control over handling maskable hardware interrupts that occur during virtual-8086 mode tasks. They also reduce interrupt-handling overhead, by eliminating the need for all IF related operations (such as PUSHF, POPF, CLI, and STI instructions) to trap to the virtual-8086 monitor. The purpose and use of these flags are as follows.

NOTE

The VIF and VIP flags are only available in Intel Architecture processors that support the virtual mode extensions. These extensions were introduced in the Intel Architecture with the Pentium® processor. When this mechanism is either not available or not enabled, maskable hardware interrupts are handled as class 1 interrupts. Here, if VIF and VIP flags are needed, the virtual-8086 monitor can implement them in software.

Existing 8086 programs commonly set and clear the IF flag in the EFLAGS register to enable and disable maskable hardware interrupts, respectively; for example, to disable interrupts while handling another interrupt or an exception. This practice works well in single task environments, but can cause problems in multitasking and multiple-processor environments, where it is often desirable to prevent an application program from having direct control over the handling of hardware interrupts. When using earlier Intel Architecture processors, this problem was often solved by creating a virtual IF flag in software. The Intel Architecture processors (beginning with the Pentium® processor) provide hardware support for this virtual IF flag through the VIF and VIP flags.

The VIF flag is a virtualized version of the IF flag, which an application program running from within a virtual-8086 task can used to control the handling of maskable hardware interrupts. When the VIF flag is enabled, the CLI and STI instructions operate on the VIF flag instead of the IF flag. When an 8086 program executes the CLI instruction, the processor clears the VIF flag to request that the virtual-8086 monitor inhibit maskable hardware interrupts from interrupting program execution; when it executes the STI instruction, the processor sets the VIF flag requesting that the virtual-8086 monitor enable maskable hardware interrupts for the 8086 program. But actually the IF flag, managed by the operating system, always controls whether maskable hardware interrupts are enabled. Also, if under these circumstances an 8086 program tries to read or change the IF flag using the PUSHF or POPF instructions, the processor will change the VIF flag instead, leaving IF unchanged.

The VIP flag provides software a means of recording the existence of a deferred (or pending) maskable hardware interrupt. This flag is read by the processor but never explicitly written by the processor; it can only be written by software.

If the IF flag is set and the VIF and VIP flags are enabled, and the processor receives a maskable hardware interrupt (interrupt vector 0 through 255), the processor performs and the interrupt handler software should perform the following operations:

1. The processor invokes the protected-mode interrupt handler for the interrupt received, as described in the following steps. These steps are almost identical to those described for

method 1 interrupt and exception handling in Section 16.3.1.1., “Handling an Interrupt or Exception Through a Protected-Mode Trap or Interrupt Gate”:

a. Switches to 32-bit protected mode and privilege level 0.

b. Saves the state of the processor on the privilege-level 0 stack. The states of the EIP, CS, EFLAGS, ESP, SS, ES, DS, FS, and GS registers are saved (refer to Figure 16-4). In the EFLAGS image on the stack, the IOPL field is set to 3 and the VIF flag is copied to the IF flag.

c. Clears the segment registers.

d. Clears the VM flag in the EFLAGS register.

e. Begins executing the selected protected-mode interrupt handler.

2. The recommended action of the protected-mode interrupt handler is to read the VM flag from the EFLAGS image on the stack. If this flag is set, the handler makes a call to the virtual-8086 monitor.

3. The virtual-8086 monitor should read the VIF flag in the EFLAGS register.

   — If the VIF flag is clear, the virtual-8086 monitor sets the VIP flag in the EFLAGS image on the stack to indicate that there is a deferred interrupt pending and returns to the protected-mode handler.

   — If the VIF flag is set, the virtual-8086 monitor can handle the interrupt if it “belongs” to the 8086 program running in the interrupted virtual-8086 task; otherwise, it can call the protected-mode interrupt handler to handle the interrupt.

4. The protected-mode handler executes a return to the program executing in virtual-8086 mode.

5. Upon returning to virtual-8086 mode, the processor continues execution of the 8086 program.

When the 8086 program is ready to receive maskable hardware interrupts, it executes the STI instruction to set the VIF flag (enabling maskable hardware interrupts). Prior to setting the VIF flag, the processor automatically checks the VIP flag and does one of the following, depending on the state of the flag:

- If the VIP flag is clear (indicating no pending interrupts), the processor sets the VIF flag.
- If the VIP flag is set (indicating a pending interrupt), the processor generates a general-protection exception (#GP).

The recommended action of the protected-mode general-protection exception handler is to then call the virtual-8086 monitor and let it handle the pending interrupt. After handling the pending interrupt, the typical action of the virtual-8086 monitor is to clear the VIP flag and set the VIF flag in the EFLAGS image on the stack, and then execute a return to the virtual-8086 mode. The next time the processor receives a maskable hardware interrupt, it will then handle it as described in steps 1 through 5 earlier in this section.

If the processor finds that both the VIF and VIP flags are set at the beginning of an instruction, it generates a general-protection exception. This action allows the virtual-8086 monitor to

handle the pending interrupt for the virtual-8086 mode task for which the VIF flag is enabled. Note that this situation can only occur immediately following execution of a POPF or IRET instruction or upon entering a virtual-8086 mode task through a task switch.

Note that the states of the VIF and VIP flags are not modified in real-address mode or during transitions between real-address and protected modes.

NOTE

The virtual interrupt mechanism described in this section is also available for use in protected mode, refer to Section 16.4., “Protected-Mode Virtual Interrupts”.

16.3.3. Class 3—Software Interrupt Handling in Virtual-8086 Mode

When the processor receives a software interrupt (an interrupt generated with the INT *n* instruction) while in virtual-8086 mode, it can use any of six different methods to handle the interrupt. The method selected depends on the settings of the VME flag in control register CR4, the IOPL field in the EFLAGS register, and the software interrupt redirection bit map in the TSS. Table 16-2 lists the six methods of handling software interrupts in virtual-8086 mode and the respective settings of the VME flag, IOPL field, and the bits in the interrupt redirection bit map for each method. The table also summarizes the various actions the processor takes for each method.

The VME flag enables the virtual mode extensions for the Pentium® and P6-family processors. When this flag is clear, the processor responds to interrupts and exceptions in virtual-8086 mode in the same manner as an Intel386™ or Intel486™ processor does. When this flag is set, the virtual mode extension provides the following enhancements to virtual-8086 mode:

- Speeds up the handling of software-generated interrupts in virtual-8086 mode by allowing the processor to bypass the virtual-8086 monitor and redirect software interrupts back to the interrupt handlers that are part of the currently running 8086 program.
- Supports virtual interrupts for software written to run on the 8086 processor.

The IOPL value interacts with the VME flag and the bits in the interrupt redirection bit map to determine how specific software interrupts should be handled.

The software interrupt redirection bit map (refer to Figure 16-5) is a 32-byte field in the TSS. This map is located directly below the I/O permission bit map in the TSS. Each bit in the interrupt redirection bit map is mapped to an interrupt vector. Bit 0 in the interrupt redirection bit map (which maps to vector zero in the interrupt table) is located at the I/O base map address in the TSS minus 32 bytes. When a bit in this bit map is set, it indicates that the associated software interrupt (interrupt generated with an INT *n* instruction) should be handled through the protected-mode IDT and interrupt and exception handlers. When a bit in this bit map is clear, the processor redirects the associated software interrupt back to the interrupt table in the 8086 program (located at linear address 0 in the program’s address space).

NOTE

The software interrupt redirection bit map does not affect hardware generated interrupts and exceptions. Hardware generated interrupts and exceptions are always handled by the protected-mode interrupt and exception handlers.

Table 16-2. Software Interrupt Handling Methods While in Virtual-8086 Mode

Method	VME	IOPL	Bit in Redir. Bitmap*	Processor Action
1	0	3	X	**Interrupt directed to a protected-mode interrupt handler:** - Clears VM and TF flags - If serviced through interrupt gate, clears IF flag - Switches to privilege-level 0 stack - Pushes GS, FS, DS and ES onto privilege-level 0 stack - Clears GS, FS, DS and ES to 0 - Pushes SS, ESP, EFLAGS, CS and EIP of interrupted task onto privilege-level 0 stack - Sets CS and EIP from interrupt gate
2	0	< 3	X	**Interrupt directed to protected-mode general-protection exception (#GP) handler.**
3	1	< 3	1	**Interrupt directed to a protected-mode general-protection exception (#GP) handler; VIF and VIP flag support for handling class 2 maskable hardware interrupts.**
4	1	3	1	**Interrupt directed to protected-mode interrupt handler:** (refer to method 1 processor action).
5	1	3	0	**Interrupt redirected to 8086 program interrupt handler:** - Pushes EFLAGS with NT cleared and IOPL set to 0 - Pushes CS and EIP (lower 16 bits only) - Clears IF flag - Clears TF flag - Loads CS and EIP (lower 16 bits only) from selected entry in the interrupt vector table of the current virtual-8086 task
6	1	< 3	0	**Interrupt redirected to 8086 program interrupt handler; VIF and VIP flag support for handling class 2 maskable hardware interrupts:** - Pushes EFLAGS with IOPL set to 3 and VIF copied to IF - Pushes CS and EIP (lower 16 bits only) - Clears the VIF flag - Clears TF flag - Loads CS and EIP (lower 16 bits only) from selected entry in the interrupt vector table of the current virtual-8086 task

NOTE:

* When set to 0, software interrupt is redirected back to the 8086 program interrupt handler; when set to 1, interrupt is directed to protected-mode handler.

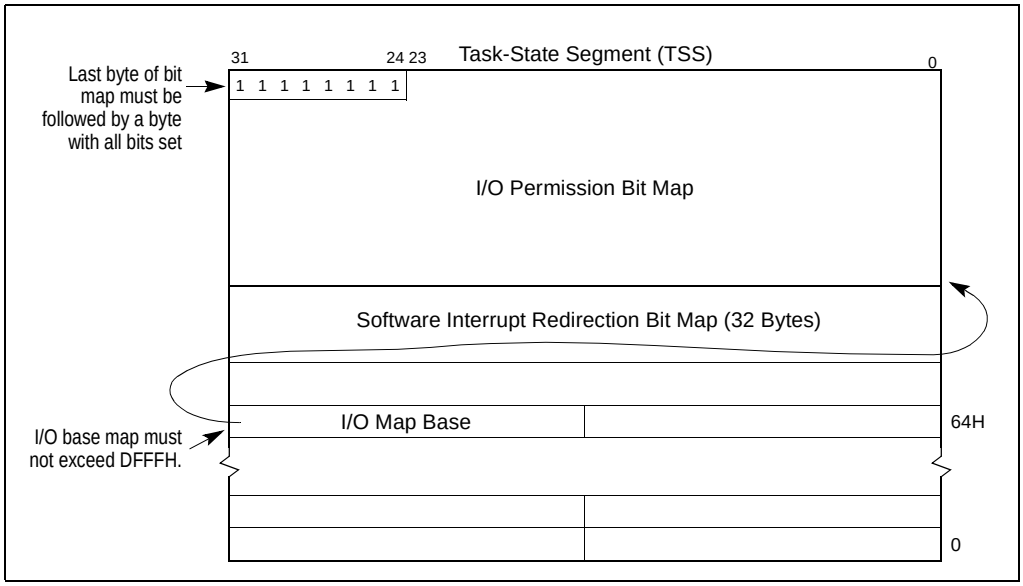


Figure 16-5. Software Interrupt Redirection Bit Map in TSS

Redirecting software interrupts back to the 8086 program potentially speeds up interrupt handling because a switch back and forth between virtual-8086 mode and protected mode is not required. This latter interrupt-handling technique is particularly useful for 8086 operating systems (such as MS-DOS) that use the INT *n* instruction to call operating system procedures.

The CPUID instruction can be used to verify that the virtual mode extension is implemented on the processor. Bit 1 of the feature flags register (EDX) indicates the availability of the virtual mode extension (refer to "CPUID—CPU Identification" in Chapter 3 of the *Intel Architecture Software Developer's Manual, Volume 2*).

The following sections describe the six methods (or mechanisms) for handling software interrupts in virtual-8086 mode. Refer to Section 16.3.2., "Class 2—Maskable Hardware Interrupt Handling in Virtual-8086 Mode Using the Virtual Interrupt Mechanism" for a description of the use of the VIF and VIP flags in the EFLAGS register for handling maskable hardware interrupts.

16.3.3.1. METHOD 1: SOFTWARE INTERRUPT HANDLING

When the VME flag in control register CR4 is clear and the IOPL field is 3, a Pentium®, or P6-family processor handles software interrupts in the same manner as they are handled by an Intel386™ or Intel486™ processor. It executes an implicit call to the interrupt handler in the protected-mode IDT pointed to by the interrupt vector. Refer to Section 16.3.1., "Class 1—Hardware Interrupt and Exception Handling in Virtual-8086 Mode" for a complete description of this mechanism and its possible uses.

16.3.3.2. METHODS 2 AND 3: SOFTWARE INTERRUPT HANDLING

When a software interrupt occurs in virtual-8086 mode and the method 2 or 3 conditions are present, the processor generates a general-protection exception (#GP). Method 2 is enabled when the VME flag is set to 0 and the IOPL value is less than 3. Here the IOPL value is used to bypass the protected-mode interrupt handlers and cause any software interrupt that occurs in virtual-8086 mode to be treated as a protected-mode general-protection exception (#GP). The general-protection exception handler calls the virtual-8086 monitor, which can then emulate an 8086-program interrupt handler or pass control back to the 8086 program's handler, as described in Section 16.3.1.2., "Handling an Interrupt or Exception With an 8086 Program Interrupt or Exception Handler".

Method 3 is enabled when the VME flag is set to 1, the IOPL value is less than 3, and the corresponding bit for the software interrupt in the software interrupt redirection bit map is set to 1. Here, the processor performs the same operation as it does for method 2 software interrupt handling. If the corresponding bit for the software interrupt in the software interrupt redirection bit map is set to 0, the interrupt is handled using method 6 (refer to Section 16.3.3.5., "Method 6: Software Interrupt Handling").

16.3.3.3. METHOD 4: SOFTWARE INTERRUPT HANDLING

Method 4 handling is enabled when the VME flag is set to 1, the IOPL value is 3, and the bit for the interrupt vector in the redirection bit map is set to 1. Method 4 software interrupt handling allows method 1 style handling when the virtual mode extension is enabled; that is, the interrupt is directed to a protected-mode handler (refer to Section 16.3.3.1., "Method 1: Software Interrupt Handling").

16.3.3.4. METHOD 5: SOFTWARE INTERRUPT HANDLING

Method 5 software interrupt handling provides a streamlined method of redirecting software interrupts (invoked with the INT *n* instruction) that occur in virtual 8086 mode back to the 8086 program's interrupt vector table and its interrupt handlers. Method 5 handling is enabled when the VME flag is set to 1, the IOPL value is 3, and the bit for the interrupt vector in the redirection bit map is set to 0. The processor performs the following actions to make an implicit call to the selected 8086 program interrupt handler:

1. Pushes the low-order 16 bits of the EFLAGS register onto the stack with the NT and IOPL bits cleared.
2. Pushes the current values of the CS and EIP registers onto the current stack. (Only the 16 least-significant bits of the EIP register are pushed and no stack switch occurs.)
3. Clears the IF flag in the EFLAGS register to disable interrupts.
4. Clears the TF flag, in the EFLAGS register.
5. Locates the 8086 program interrupt vector table at linear address 0 for the 8086-mode task.
6. Loads the CS and EIP registers with values from the interrupt vector table entry pointed to by the interrupt vector number. Only the 16 low-order bits of the EIP are loaded and the 16

high-order bits are set to 0. The interrupt vector table is assumed to be at linear address 0 of the current virtual-8986 task.

7. Begins executing the selected interrupt handler.

An IRET instruction at the end of the handler procedure reverses these steps to return program control to the interrupted 8086 program.

Note that with method 5 handling, a mode switch from virtual-8086 mode to protected mode does not occur. The processor remains in virtual-8086 mode throughout the interrupt-handling operation.

The method 5 handling actions are virtually identical to the actions the processor takes when handling software interrupts in real-address mode. The benefit of using method 5 handling to access the 8086 program handlers is that it avoids the overhead of methods 2 and 3 handling, which requires first going to the virtual-8086 monitor, then to the 8086 program handler, then back again to the virtual-8086 monitor, before returning to the interrupted 8086 program (refer to Section 16.3.1.2., “Handling an Interrupt or Exception With an 8086 Program Interrupt or Exception Handler”).

NOTE

Methods 1 and 4 handling can handle a software interrupt in a virtual-8086 task with a regular protected-mode handler, but this approach requires all virtual-8086 tasks to use the same software interrupt handlers, which generally does not give sufficient latitude to the programs running in the virtual-8086 tasks, particularly MS-DOS programs.

16.3.3.5. METHOD 6: SOFTWARE INTERRUPT HANDLING

Method 6 handling is enabled when the VME flag is set to 1, the IOPL value is less than 3, and the bit for the interrupt or exception vector in the redirection bit map is set to 0. With method 6 interrupt handling, software interrupts are handled in the same manner as was described for method 5 handling (refer to Section 16.3.3.4., “Method 5: Software Interrupt Handling”).

Method 6 differs from method 5 in that with the IOPL value set to less than 3, the VIF and VIP flags in the EFLAGS register are enabled, providing virtual interrupt support for handling class 2 maskable hardware interrupts (refer to Section 16.3.2., “Class 2—Maskable Hardware Interrupt Handling in Virtual-8086 Mode Using the Virtual Interrupt Mechanism”). These flags provide the virtual-8086 monitor with an efficient means of handling maskable hardware interrupts that occur during a virtual-8086 mode task. Also, because the IOPL value is less than 3 and the VIF flag is enabled, the information pushed on the stack by the processor when invoking the interrupt handler is slightly different between methods 5 and 6 (refer to Table 16-2).

16.4. PROTECTED-MODE VIRTUAL INTERRUPTS

The Intel Architecture processors (beginning with the Pentium® processor) also support the VIF and VIP flags in the EFLAGS register in protected mode by setting the PVI (protected-mode

virtual interrupt) flag in the CR4 register. Setting the PVI flag allows applications running at privilege level 3 to execute the CLI and STI instructions without causing a general-protection exception (#GP) or affecting hardware interrupts.

When the PVI flag is set to 1, the CPL is 3, and the IOPL is less than 3, the STI and CLI instructions set and clear the VIF flag in the EFLAGS register, leaving IF unaffected. In this mode of operation, an application running in protected mode and at a CPL of 3 can inhibit interrupts in the same manner as is described in Section 16.3.2., “Class 2—Maskable Hardware Interrupt Handling in Virtual-8086 Mode Using the Virtual Interrupt Mechanism” for a virtual-8086 mode task. When the application executes the CLI instruction, the processor clears the VIF flag. If the processor receives a maskable hardware interrupt when the VIF flag is clear, the processor invokes the protected-mode interrupt handler. This handler checks the state of the VIF flag in the EFLAGS register. If the VIF flag is clear (indicating that the active task does not want to have interrupts handled now), the handler sets the VIP flag in the EFLAGS image on the stack and returns to the privilege-level 3 application, which continues program execution. When the application executes a STI instruction to set the VIF flag, the processor automatically invokes the general-protection exception handler, which can then handle the pending interrupt. After handing the pending interrupt, the handler typically sets the VIF flag and clears the VIP flag in the EFLAGS image on the stack and executes a return to the application program. The next time the processor receives a maskable hardware interrupt, the processor will handle it in the normal manner for interrupts received while the processor is operating at a CPL of 3.

As with the virtual mode extension (enabled with the VME flag in the CR4 register), the protected-mode virtual interrupt extension only affects maskable hardware interrupts (interrupt vectors 32 through 255). NMI interrupts and exceptions are handled in the normal manner.

When protected-mode virtual interrupts are disabled (that is, when the PVI flag in control register CR4 is set to 0, the CPL is less than 3, or the IOPL value is 3), then the CLI and STI instructions execute in a manner compatible with the Intel486™ processor. That is, if the CPL is greater (less privileged) than the I/O privilege level (IOPL), a general-protection exception occurs. If the IOPL value is 3, CLI and STI clear or set the IF flag, respectively.

PUSHF, POPF, and IRET are executed like in the Intel486™ processor, regardless of whether protected-mode virtual interrupts are enabled.

It is only possible to enter virtual-8086 mode through a task switch or the execution of an IRET instruction, and it is only possible to leave virtual-8086 mode by faulting to a protected-mode interrupt handler (typically the general-protection exception handler, which in turn calls the virtual 8086-mode monitor). In both cases, the EFLAGS register is saved and restored. This is not true, however, in protected mode when the PVI flag is set and the processor is not in virtual-8086 mode. Here, it is possible to call a procedure at a different privilege level, in which case the EFLAGS register is not saved or modified. However, the states of VIF and VIP flags are never examined by the processor when the CPL is not 3.

17

Mixing 16-Bit and 32-Bit Code

CHAPTER 17
MIXING 16-BIT AND 32-BIT CODE

Program modules written to run on Intel Architecture processors can be either 16-bit modules or 32-bit modules. Table 17-1 shows the characteristic of 16-bit and 32-bit modules.

Table 17-1. Characteristics of 16-Bit and 32-Bit Program Modules

Characteristic	16-Bit Program Modules	32-Bit Program Modules
Segment Size	0 to 64 KBytes	0 to 4 GBytes
Operand Sizes	8 bits and 16 bits	8 bits and 32 bits
Pointer Offset Size (Address Size)	16 bits	32 bits
Stack Pointer Size	16 Bits	32 Bits
Control Transfers Allowed to Code Segments of This Size	16 Bits	32 Bits

The Intel Architecture processors function most efficiently when executing 32-bit program modules. They can, however, also execute 16-bit program modules, in any of the following ways:

- In real-address mode.
- In virtual-8086 mode.
- System management mode (SMM).
- As a protected-mode task, when the code, data, and stack segments for the task are all configured as a 16-bit segments.
- By integrating 16-bit and 32-bit segments into a single protected-mode task.
- By integrating 16-bit operations into 32-bit code segments.

Real-address mode, virtual-8086 mode, and SMM are native 16-bit modes. A legacy program assembled and/or compiled to run on an Intel 8086 or Intel 286 processor should run in real-address mode or virtual-8086 mode without modification. Sixteen-bit program modules can also be written to run in real-address mode for handling system initialization or to run in SMM for handling system management functions. Refer to Chapter 16, *8086 Emulation* for detailed information on real-address mode and virtual-8086 mode; refer to Chapter 12, *System Management Mode (SMM)* for information on SMM.

This chapter describes how to integrate 16-bit program modules with 32-bit program modules when operating in protected mode and how to mix 16-bit and 32-bit code within 32-bit code segments.

17.1. DEFINING 16-BIT AND 32-BIT PROGRAM MODULES

The following Intel Architecture mechanisms are used to distinguish between and support 16-bit and 32-bit segments and operations:

- The D (default operand and address size) flag in code-segment descriptors.
- The B (default stack size) flag in stack-segment descriptors.
- 16-bit and 32-bit call gates, interrupt gates, and trap gates.
- Operand-size and address-size instruction prefixes.
- 16-bit and 32-bit general-purpose registers.

The D flag in a code-segment descriptor determines the default operand-size and address-size for the instructions of a code segment. (In real-address mode and virtual-8086 mode, which do not use segment descriptors, the default is 16 bits.) A code segment with its D flag set is a 32-bit segment; a code segment with its D flag clear is a 16-bit segment.

The B flag in the stack-segment descriptor specifies the size of stack pointer (the 32-bit ESP register or the 16-bit SP register) used by the processor for implicit stack references. The B flag for all data descriptors also controls upper address range for expand down segments.

When transferring program control to another code segment through a call gate, interrupt gate, or trap gate, the operand size used during the transfer is determined by the type of gate used (16-bit or 32-bit), (not by the D-flag or prefix of the transfer instruction). The gate type determines how return information is saved on the stack (or stacks).

For most efficient and trouble-free operation of the processor, 32-bit programs or tasks should have the D flag in the code-segment descriptor and the B flag in the stack-segment descriptor set, and 16-bit programs or tasks should have these flags clear. Program control transfers from 16-bit segments to 32-bit segments (and vice versa) are handled most efficiently through call, interrupt, or trap gates.

Instruction prefixes can be used to override the default operand size and address size of a code segment. These prefixes can be used in real-address mode as well as in protected mode and virtual-8086 mode. An operand-size or address-size prefix only changes the size for the duration of the instruction.

17.2. MIXING 16-BIT AND 32-BIT OPERATIONS WITHIN A CODE SEGMENT

The following two instruction prefixes allow mixing of 32-bit and 16-bit operations within one segment:

- The operand-size prefix (66H)
- The address-size prefix (67H)

These prefixes reverse the default size selected by the D flag in the code-segment descriptor. For example, the processor can interpret the (MOV *mem*, *reg*) instruction in any of four ways:

- In a 32-bit code segment:
  - — Moves 32 bits from a 32-bit register to memory using a 32-bit effective address.
  - — If preceded by an operand-size prefix, moves 16 bits from a 16-bit register to memory using a 32-bit effective address.
  - — If preceded by an address-size prefix, moves 32 bits from a 32-bit register to memory using a 16-bit effective address.
  - — If preceded by both an address-size prefix and an operand-size prefix, moves 16 bits from a 16-bit register to memory using a 16-bit effective address.
- In a 16-bit code segment:
  - — Moves 16 bits from a 16-bit register to memory using a 16-bit effective address.
  - — If preceded by an operand-size prefix, moves 32 bits from a 32-bit register to memory using a 16-bit effective address.
  - — If preceded by an address-size prefix, moves 16 bits from a 16-bit register to memory using a 32-bit effective address.
  - — If preceded by both an address-size prefix and an operand-size prefix, moves 32 bits from a 32-bit register to memory using a 32-bit effective address.

The previous examples show that any instruction can generate any combination of operand size and address size regardless of whether the instruction is in a 16- or 32-bit segment. The choice of the 16- or 32-bit default for a code segment is normally based on the following criteria:

- **Performance**—Always use 32-bit code segments when possible. They run much faster than 16-bit code segments on P6 family processors, and somewhat faster on earlier Intel Architecture processors.
- **The operating system the code segment will be running on**—If the operating system is a 16-bit operating system, it may not support 32-bit program modules.
- **Mode of operation**—If the code segment is being designed to run in real-address mode, virtual-8086 mode, or SMM, it must be a 16-bit code segment.
- **Backward compatibility to earlier Intel Architecture processors**—If a code segment must be able to run on an Intel 8086 or Intel 286 processor, it must be a 16-bit code segment.

17.3. SHARING DATA AMONG MIXED-SIZE CODE SEGMENTS

Data segments can be accessed from both 16-bit and 32-bit code segments. When a data segment that is larger than 64 KBytes is to be shared among 16- and 32-bit code segments, the data that is to be accessed from the 16-bit code segments must be located within the first 64 KBytes of the data segment. The reason for this is that 16-bit pointers by definition can only point to the first 64 KBytes of a segment.

A stack that spans less than 64 KBytes can be shared by both 16- and 32-bit code segments. This class of stacks includes:

- Stacks in expand-up segments with the G (granularity) and B (big) flags in the stack-segment descriptor clear.
- Stacks in expand-down segments with the G and B flags clear.
- Stacks in expand-up segments with the G flag set and the B flag clear and where the stack is contained completely within the lower 64 KBytes. (Offsets greater than FFFFH can be used for data, other than the stack, which is not shared.)

Refer to Section 3.4.3., “Segment Descriptors” in Chapter 3, *Protected-Mode Memory Management* for a description of the G and B flags and the expand-down stack type.

The B flag cannot, in general, be used to change the size of stack used by a 16-bit code segment. This flag controls the size of the stack pointer only for implicit stack references such as those caused by interrupts, exceptions, and the PUSH, POP, CALL, and RET instructions. It does not control explicit stack references, such as accesses to parameters or local variables. A 16-bit code segment can use a 32-bit stack only if the code is modified so that all explicit references to the stack are preceded by the 32-bit address-size prefix, causing those references to use 32-bit addressing and explicit writes to the stack pointer are preceded by a 32-bit operand-size prefix.

In 32-bit, expand-down segments, all offsets may be greater than 64 KBytes; therefore, 16-bit code cannot use this kind of stack segment unless the code segment is modified to use 32-bit addressing.

17.4. TRANSFERRING CONTROL AMONG MIXED-SIZE CODE SEGMENTS

There are three ways for a procedure in a 16-bit code segment to safely make a call to a 32-bit code segment:

- Make the call through a 32-bit call gate.
- Make a 16-bit call to a 32-bit interface procedure. The interface procedure then makes a 32-bit call to the intended destination.
- Modify the 16-bit procedure, inserting an operand-size prefix before the call, to change it to a 32-bit call.

Likewise, there are three ways for procedure in a 32-bit code segment to safely make a call to a 16-bit code segment:

- Make the call through a 16-bit call gate. Here, the EIP value at the CALL instruction cannot exceed FFFFH.
- Make a 32-bit call to a 16-bit interface procedure. The interface procedure then makes a 16-bit call to the intended destination.
- Modify the 32-bit procedure, inserting an operand-size prefix before the call, changing it to a 16-bit call. Be certain that the return offset does not exceed FFFFH.

These methods of transferring program control overcome the following architectural limitations imposed on calls between 16-bit and 32-bit code segments:

- Pointers from 16-bit code segments (which by default can only be 16-bits) cannot be used to address data or code located beyond FFFFH in a 32-bit segment.
- The operand-size attributes for a CALL and its companion RETURN instruction must be the same to maintain stack coherency. This is also true for implicit calls to interrupt and exception handlers and their companion IRET instructions.
- A 32-bit parameters (particularly a pointer parameter) greater than FFFFH cannot be squeezed into a 16-bit parameter location on a stack.
- The size of the stack pointer (SP or ESP) changes when switching between 16-bit and 32-bit code segments.

These limitations are discussed in greater detail in the following sections.

17.4.1. Code-Segment Pointer Size

For control-transfer instructions that use a pointer to identify the next instruction (that is, those that do not use gates), the operand-size attribute determines the size of the offset portion of the pointer. The implications of this rule are as follows:

- A JMP, CALL, or RET instruction from a 32-bit segment to a 16-bit segment is always possible using a 32-bit operand size, providing the 32-bit pointer does not exceed FFFFH.
- A JMP, CALL, or RET instruction from a 16-bit segment to a 32-bit segment cannot address a destination greater than FFFFH, unless the instruction is given an operand-size prefix.

Refer to Section 17.4.5., “Writing Interface Procedures” for an interface procedure that can transfer program control from 16-bit segments to destinations in 32-bit segments beyond FFFFH.

17.4.2. Stack Management for Control Transfer

Because the stack is managed differently for 16-bit procedure calls than for 32-bit calls, the operand-size attribute of the RET instruction must match that of the CALL instruction (refer to Figure 17-1). On a 16-bit call, the processor pushes the contents of the 16-bit IP register and (for calls between privilege levels) the 16-bit SP register. The matching RET instruction must also use a 16-bit operand size to pop these 16-bit values from the stack into the 16-bit registers.

A 32-bit CALL instruction pushes the contents of the 32-bit EIP register and (for inter-privilege-level calls) the 32-bit ESP register. Here, the matching RET instruction must use a 32-bit operand size to pop these 32-bit values from the stack into the 32-bit registers. If the two parts of a CALL/RET instruction pair do not have matching operand sizes, the stack will not be managed correctly and the values of the instruction pointer and stack pointer will not be restored to correct values.

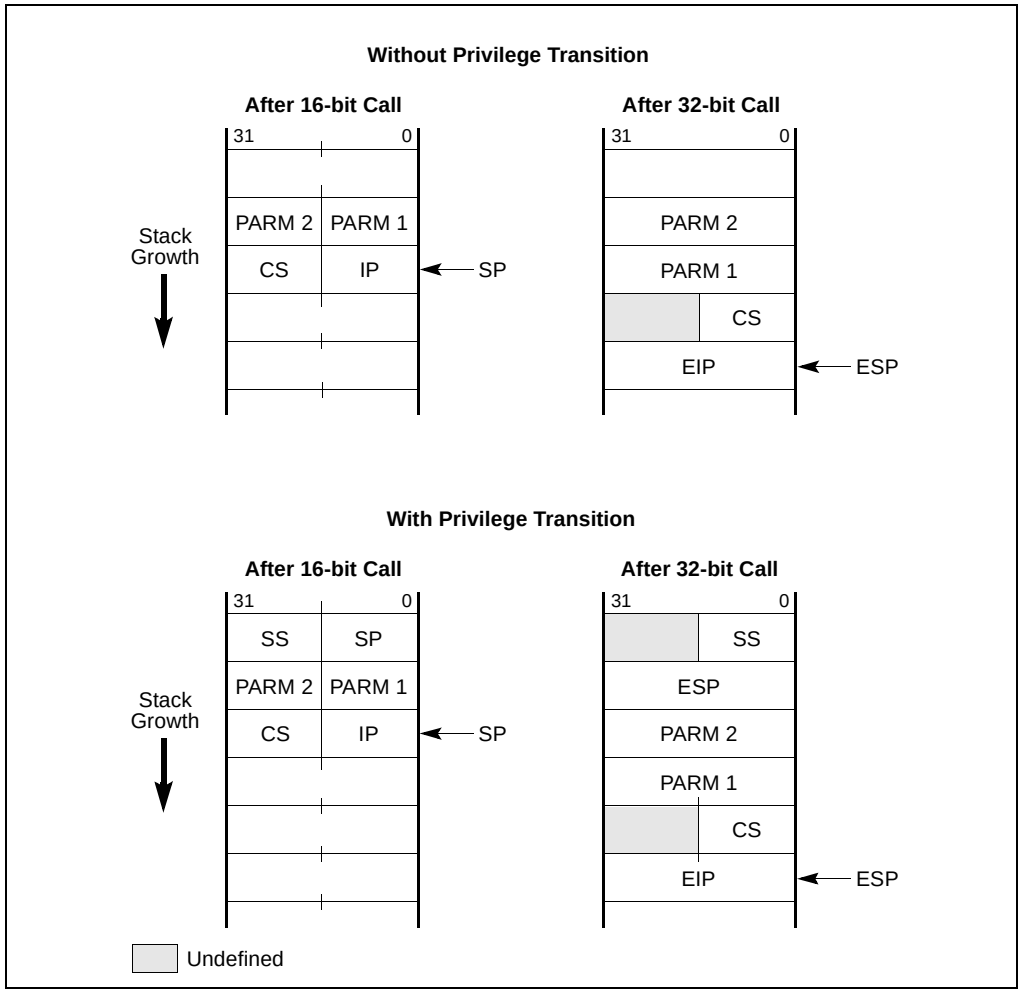


Figure 17-1. Stack after Far 16- and 32-Bit Calls

While executing 32-bit code, if a call is made to a 16-bit code segment which is at the same or a more privileged level (that is, the DPL of the called code segment is less than or equal to the CPL of the calling code segment) through a 16-bit call gate, then the upper 16-bits of the ESP register may be unreliable upon returning to the 32-bit code segment (that is, after executing a RET in the 16-bit code segment).

When the CALL instruction and its matching RET instruction are in code segments that have D flags with the same values (that is, both are 32-bit code segments or both are 16-bit code segments), the default settings may be used. When the CALL instruction and its matching RET instruction are in segments which have different D-flag settings, an operand-size prefix must be used.

17.4.2.1. CONTROLLING THE OPERAND-SIZE ATTRIBUTE FOR A CALL

Three things can determine the operand-size of a call:

- The D flag in the segment descriptor for the calling code segment.
- An operand-size instruction prefix.
- The type of call gate (16-bit or 32-bit), if a call is made through a call gate.

When a call is made with a pointer (rather than a call gate), the D flag for the calling code segment determines the operand-size for the CALL instruction. This operand-size attribute can be overridden by prepending an operand-size prefix to the CALL instruction. So, for example, if the D flag for a code segment is set for 16 bits and the operand-size prefix is used with a CALL instruction, the processor will cause the information stored on the stack to be stored in 32-bit format. If the call is to a 32-bit code segment, the instructions in that code segment will be able to read the stack coherently. Also, a RET instruction from the 32-bit code segment without an operand-size prefix will maintain stack coherency with the 16-bit code segment being returned to.

When a CALL instruction references a call-gate descriptor, the type of call is determined by the type of call gate (16-bit or 32-bit). The offset to the destination in the code segment being called is taken from the gate descriptor; therefore, if a 32-bit call gate is used, a procedure in a 16-bit code segment can call a procedure located more than 64 Kbytes from the base of a 32-bit code segment, because a 32-bit call gate uses a 32-bit offset.

Note that regardless of the operand size of the call and how it is determined, the size of the stack pointer used (SP or ESP) is always controlled by the B flag in the stack-segment descriptor currently in use (that is, when B is clear, SP is used, and when B is set, ESP is used).

An unmodified 16-bit code segment that has run successfully on an 8086 processor or in real-mode on a P6-family processor will have its D flag clear and will not use operand-size override prefixes. As a result, all CALL instructions in this code segment will use the 16-bit operand-size attribute. Procedures in these code segments can be modified to safely call procedures to 32-bit code segments in either of two ways:

- Relink the CALL instruction to point to 32-bit call gates (refer to Section 17.4.2.2., “Passing Parameters With a Gate”).
- Add a 32-bit operand-size prefix to each CALL instruction.

17.4.2.2. PASSING PARAMETERS WITH A GATE

When referencing 32-bit gates with 16-bit procedures, it is important to consider the number of parameters passed in each procedure call. The count field of the gate descriptor specifies the size of the parameter string to copy from the current stack to the stack of a more privileged (numerically lower privilege level) procedure. The count field of a 16-bit gate specifies the number of 16-bit words to be copied, whereas the count field of a 32-bit gate specifies the number of 32-bit doublewords to be copied. The count field for a 32-bit gate must thus be half the size of the number of words being placed on the stack by a 16-bit procedure. Also, the 16-bit procedure must use an even number of words as parameters.

17.4.3. Interrupt Control Transfers

A program-control transfer caused by an exception or interrupt is always carried out through an interrupt or trap gate (located in the IDT). Here, the type of the gate (16-bit or 32-bit) determines the operand-size attribute used in the implicit call to the exception or interrupt handler procedure in another code segment.

A 32-bit interrupt or trap gate provides a safe interface to a 32-bit exception or interrupt handler when the exception or interrupt occurs in either a 32-bit or a 16-bit code segment. It is sometimes impractical, however, to place exception or interrupt handlers in 16-bit code segments, because only 16-bit return addresses are saved on the stack. If an exception or interrupt occurs in a 32-bit code segment when the EIP was greater than FFFFH, the 16-bit handler procedure cannot provide the correct return address.

17.4.4. Parameter Translation

When segment offsets or pointers (which contain segment offsets) are passed as parameters between 16-bit and 32-bit procedures, some translation is required. If a 32-bit procedure passes a pointer to data located beyond 64 KBytes to a 16-bit procedure, the 16-bit procedure cannot use it. Except for this limitation, interface code can perform any format conversion between 32-bit and 16-bit pointers that may be needed.

Parameters passed by value between 32-bit and 16-bit code also may require translation between 32-bit and 16-bit formats. The form of the translation is application-dependent.

17.4.5. Writing Interface Procedures

Placing interface code between 32-bit and 16-bit procedures can be the solution to the following interface problems:

- Allowing procedures in 16-bit code segments to call procedures with offsets greater than FFFFH in 32-bit code segments.
- Matching operand-size attributes between companion CALL and RET instructions.
- Translating parameters (data), including managing parameter strings with a variable count or an odd number of 16-bit words.
- The possible invalidation of the upper bits of the ESP register.

The interface procedure is simplified where these rules are followed.

1. The interface procedure must reside in a 32-bit code segment (the D flag for the code-segment descriptor is set).
2. All procedures that may be called by 16-bit procedures must have offsets not greater than FFFFH.
3. All return addresses saved by 16-bit procedures must have offsets not greater than FFFFH.

The interface procedure becomes more complex if any of these rules are violated. For example, if a 16-bit procedure calls a 32-bit procedure with an entry point beyond FFFFH, the interface procedure will need to provide the offset to the entry point. The mapping between 16- and 32-bit addresses is only performed automatically when a call gate is used, because the gate descriptor for a call gate contains a 32-bit address. When a call gate is not used, the interface code must provide the 32-bit address.

The structure of the interface procedure depends on the types of calls it is going to support, as follows:

- **Calls from 16-bit procedures to 32-bit procedures.** Calls to the interface procedure from a 16-bit code segment are made with 16-bit CALL instructions (by default, because the D flag for the calling code-segment descriptor is clear), and 16-bit operand-size prefixes are used with RET instructions to return from the interface procedure to the calling procedure. Calls from the interface procedure to 32-bit procedures are performed with 32-bit CALL instructions (by default, because the D flag for the interface procedure's code segment is set), and returns from the called procedures to the interface procedure are performed with 32-bit RET instructions (also by default).
- **Calls from 32-bit procedures to 16-bit procedures.** Calls to the interface procedure from a 32-bit code segment are made with 32-bit CALL instructions (by default), and returns to the calling procedure from the interface procedure are made with 32-bit RET instructions (also by default). Calls from the interface procedure to 16-bit procedures require the CALL instructions to have the operand-size prefixes, and returns from the called procedures to the interface procedure are performed with 16-bit RET instructions (by default).

18

Intel Architecture Compatibility

CHAPTER 18
INTEL ARCHITECTURE COMPATIBILITY

All Intel Architecture processors are binary compatible. Compatibility means that, within certain limited constraints, programs that execute on previous generations of Intel Architecture processors will produce identical results when executed on later Intel Architecture processors. The compatibility constraints and any implementation differences between the Intel Architecture processors are described in this chapter.

Each new Intel Architecture processor has enhanced the software visible architecture from that found in earlier Intel Architecture processors. Those enhancements have been defined with consideration for compatibility with previous and future processors. This chapter also summarizes the compatibility considerations for those extensions.

18.1. INTEL ARCHITECTURE FAMILIES AND CATEGORIES

Intel Architecture processors are referred to in several different ways in this chapter, depending on the type of compatibility information being related, as described in the following:

- **Intel Architecture Processors**—All the Intel processors based on the Intel Architecture, which include the 8086/88, Intel 286, Intel386™, Intel486™, Pentium®, and P6 family processors.
- **32-bit Processors**—All the Intel Architecture processors that use a 32-bit architecture, which include the Intel386™, Intel486™, Pentium®, and P6 family processors.
- **16-bit Processors**—All the Intel Architecture processors that use a 16-bit architecture, which include the 8086/88 and Intel 286 processors.
- **P6 Family Processors**—All the Intel Architecture processors that are based on the P6 family micro-architecture, which include the Pentium® Pro, Pentium® II, Pentium® III and future P6 family processors.

18.2. RESERVED BITS

Throughout this manual, certain bits are marked as reserved in many register and memory layout descriptions. When bits are marked as undefined or reserved, it is essential for compatibility with future processors that software treat these bits as having a future, though unknown effect. Software should follow these guidelines in dealing with reserved bits:

- Do not depend on the states of any reserved bits when testing the values of registers or memory locations that contain such bits. Mask out the reserved bits before testing.
- Do not depend on the states of any reserved bits when storing them to memory or to a register.

- Do not depend on the ability to retain information written into any reserved bits.
- When loading a register, always load the reserved bits with the values indicated in the documentation, if any, or reload them with values previously read from the same register.

Software written for existing Intel Architecture processor that handles reserved bits correctly will port to future Intel Architecture processors without generating protection exceptions.

18.3. ENABLING NEW FUNCTIONS AND MODES

Most of the new control functions defined for the P6 family and Pentium® processors are enabled by new mode flags in the control registers (primarily register CR4). This register is undefined for Intel Architecture processors earlier than the Pentium® processor. Attempting to access this register with an Intel486™ or earlier Intel Architecture processor results in an invalid-opcode exception (#UD). Consequently, programs that execute correctly on the Intel486™ or earlier Intel Architecture processor cannot erroneously enable these functions. Attempting to set a reserved bit in register CR4 to a value other than its original value results in a general-protection exception (#GP). So, programs that execute on the P6 family and Pentium® processors cannot erroneously enable functions that may be implemented in future Intel Architecture processors.

The P6 family and Pentium® processors do not check for attempts to set reserved bits in model-specific registers. It is the obligation of the software writer to enforce this discipline. These reserved bits may be used in future Intel processors.

18.4. DETECTING THE PRESENCE OF NEW FEATURES THROUGH SOFTWARE

Software can check for the presence of new architectural features and extensions in either of two ways:

- Test for the presence of the feature or extension — Software can test for the presence of new flags in the EFLAGS register and control registers. If these flags are reserved (meaning not present in the processor executing the test), an exception is generated. Likewise, software can attempt to execute a new instruction, which results in an invalid-opcode exception (#UD) being generated if it is not supported.
- Execute the CPUID instruction — The CPUID instruction (added to the Intel Architecture in the Pentium® processor) indicates the presence of new features directly.

Refer to Chapter 10, *Processor Identification and Feature Determination*, in the *Intel Architecture Software Developer's Manual, Volume 1*, for detailed information on detecting new processor features and extensions.

18.5. MMX™ TECHNOLOGY

The Pentium® processor with MMX™ technology introduced the MMX™ technology and a set of MMX™ instructions to the Intel Architecture. The MMX™ instructions are summarized in Chapter 6, *Instruction Set Summary*, in the *Intel Architecture Software Developer's Manual, Volume 1* and are described in detail in Chapter 3 in the *Intel Architecture Software Developer's Manual, Volume 2*. The MMX™ technology and MMX™ instructions are also included in the Pentium® II and Pentium® III processors.

18.6. STREAMING SIMD EXTENSIONS

The Pentium® III processor introduced the Streaming SIMD Extensions. This is a set of new instructions added to enhance perfomance of several classes of applications. The Streaming SIMD Extensions are summarized in Chapter 6, *Instruction Set Summary*, in the *Intel Architecture Software Developer's Manual, Volume 1* and are described in detail in Chapter 3 in the *Intel Architecture Software Developer's Manual, Volume 2*. Several of these new instructions operate in the same register space as the MMX™ instructions. When using these instructions, the rules that apply to MMX™ technology programming apply to this subset of the new instructions as well.

18.7. NEW INSTRUCTIONS IN THE PENTIUM® AND LATER INTEL ARCHITECTURE PROCESSORS

Table 18-1 identifies the instructions introduced into the Intel Architecture in the Pentium® and later Intel Architecture processors.

Table 18-1. New Instructions in the Pentium® and Later Intel Architecture Processors

Instruction	CPUID Identification Bits	Introduced In
Streaming SIMD Extensions	EDX, Bit 25	Pentium® III processor
SYSENTER/SYSEXIT(fast system call)	EDX, Bit 11	Pentium® II processor
FXSAVE/FXRSTOR(fast save/restore)	EDX, Bit 24	Pentium® II processor
CMOV*cc* (conditional move)	EDX, Bit 15	Pentium® Pro processor
FCMOV*cc* (floating-point conditional move)	EDX, Bits 0 and 15	
FCOMI (floating-point compare and set EFLAGS)	EDX, Bits 0 and 15	
RDPMC (read performance monitoring counters)	EAX, Bits 8-11, set to 6H; refer to Note 1	
UD2 (undefined)	EAX, Bits 8-11, set to 6H	

Table 18-1. New Instructions in the Pentium® and Later Intel Architecture Processors

Instruction	CPUID Identification Bits	Introduced In
CMPXCHG8B (compare and exchange 8 bytes)	EDX, Bit 8	Pentium® processor
CPUID (CPU identification)	None; refer to Note 2	
RDTSC (read time-stamp counter)	EDX, Bit 4	
RDMSR (read model-specific register)	EDX, Bit 5	
WRMSR (write model-specific register)	EDX, Bit 5	
MMX™ Instructions	EDX, Bit 23	

NOTES:

1. The RDPMC instruction was introduced in the P6 family of processors and added to later model Pentium® processors. This instruction is model specific in nature and not architectural.
2. The CPUID instruction is available in all Pentium® and P6 family processors and in later models of the Intel486™ processors. The ability to set and clear the ID flag (bit 21) in the EFLAGS register indicates the availability of the CPUID instruction.

18.7.1. Instructions Added Prior to the Pentium® Processor

The following instructions were added in the Intel486™ processor:

- BSWAP (byte swap) instruction.
- XADD (exchange and add) instruction.
- CMPXCHG (compare and exchange) instruction.
- INVD (invalidate cache) instruction.
- WBINVD (write-back and invalidate cache) instruction.
- INVLPG (invalidate TLB entry) instruction.

The following instructions were added in the Intel386™ processor:

- LSS, LFS, and LGS (load SS, FS, and GS registers).
- Long-displacement conditional jumps.
- Single-bit instructions.
- Bit scan instructions.
- Double-shift instructions.
- Byte set on condition instruction.
- Move with sign/zero extension.
- Generalized multiply instruction.
- MOV to and from control registers.
- MOV to and from test registers (now obsolete).
- MOV to and from debug registers.
- RSM (resume from SMM). This instruction was introduced in the Intel386™ SL and Intel486™ SL processors.

The following instructions were added in the Intel 387 math coprocessor:

- FPREM1.
- FUCOM, FUCOMP, and FUCOMPP.

18.8. OBSOLETE INSTRUCTIONS

The MOV to and from test registers instructions were removed from the Pentium® and future Intel Architecture processors. Execution of these instructions generates an invalid-opcode exception (#UD).

18.9. UNDEFINED OPCODES

All new instructions defined for Intel Architecture processors use binary encodings that were reserved on earlier-generation processors. Attempting to execute a reserved opcode always results in an invalid-opcode (#UD) exception being generated. Consequently, programs that execute correctly on earlier-generation processors cannot erroneously execute these instructions and thereby produce unexpected results when executed on later Intel Architecture processors.

18.10.NEW FLAGS IN THE EFLAGS REGISTER

The section titled "EFLAGS Register" in Chapter 3 of the *Intel Architecture Software Developer's Manual, Volume 1*, shows the configuration of flags in the EFLAGS register for the P6 family processors. No new flags have been added to this register in the P6 family processors. The flags added to this register in the Pentium® and Intel486™ processors are described in the following sections.

The following flags were added to the EFLAGS register in the Pentium® processor:

- VIF (virtual interrupt flag), bit 19.
- VIP (virtual interrupt pending), bit 20.
- ID (identification flag), bit 21.

The AC flag (bit 18) was added to the EFLAGS register in the Intel486™ processor.

18.10.1. Using EFLAGS Flags to Distinguish Between 32-Bit Intel Architecture Processors

The following bits in the EFLAGS register that can be used to differentiate between the 32-bit Intel Architecture processors:

- Bit 18 (the AC flag) can be used to distinguish an Intel386™ processor from the P6 family, Pentium®, and Intel486™ processors. Since it is not implemented on the Intel386™ processor, it will always be clear.
- Bit 21 (the ID flag) indicates whether an application can execute the CPUID instruction. The ability to set and clear this bit indicates that the processor is a P6 family or Pentium® processor. The CPUID instruction can then be used to determine which processor.
- Bits 19 (the VIF flag) and 20 (the VIP flag) will always be zero on processors that do not support virtual mode extensions, which includes all 32-bit processors prior to the Pentium® processor.

Refer to Chapter 10, *Processor Identification and Feature Determination*, in the *Intel Architecture Software Developer's Manual, Volume 1*, for more information on identifying processors.

18.11.STACK OPERATIONS

This section identifies the differences in stack implementation between the various Intel Architecture processors.

18.11.1. PUSH SP

The P6 family, Pentium®, Intel486™, Intel386™, and Intel 286 processors push a different value on the stack for a PUSH SP instruction than the 8086 processor. The 32-bit processors push the value of the SP register before it is decremented as part of the push operation; the 8086 processor pushes the value of the SP register after it is decremented. If the value pushed is important, replace PUSH SP instructions with the following three instructions:

```
PUSH BP
MOV  BP, SP
XCHG BP, [BP]
```

This code functions as the 8086 processor PUSH SP instruction on the P6 family, Pentium®, Intel486™, Intel386™, and Intel 286 processors.

18.11.2. EFLAGS Pushed on the Stack

The setting of the stored values of bits 12 through 15 (which includes the IOPL field and the NT flag) in the EFLAGS register by the PUSHF instruction, by interrupts, and by exceptions is different with the 32-bit Intel Architecture processors than with the 8086 and Intel 286 processors. The differences are as follows:

- 8086 processor—bits 12 through 15 are always set.
- Intel 286 processor—bits 12 through 15 are always cleared in real-address mode.
- 32-bit processors in real-address mode—bit 15 (reserved) is always cleared, and bits 12 through 14 have the last value loaded into them.

18.12.FPU

This section addresses the issues that must be faced when porting floating-point software designed to run on earlier Intel Architecture processors and math coprocessors to a Pentium® or P6 family processor with integrated FPU. To software, a P6 family processor looks very much like a Pentium® processor. Floating-point software which runs on a Pentium® or Intel486™ DX processor, or on an Intel486™ SX processor/Intel 487 SX math coprocessor system or an Intel386™ processor/Intel 387 math coprocessor system, will run with at most minor modifications on a P6 family processor. To port code directly from an Intel 286 processor/Intel 287 math coprocessor system or an Intel 8086 processor/8087 math coprocessor system to the Pentium® and P6 family processors, certain additional issues must be addressed.

In the following sections, the term “32-bit Intel Architecture FPUs” refers to the P6 family, Pentium®, and Intel486™ DX processors, and to the Intel 487 SX and Intel 387 math coprocessors; the term “16-bit Intel Architecture math coprocessors” refers to the Intel 287 and 8087 math coprocessors.

18.12.1. Control Register CR0 Flags

The ET, NE, and MP flags in control register CR0 control the interface between the integer unit of an Intel Architecture processor and either its internal FPU or an external math coprocessor. The effect of these flags in the various Intel Architecture processors are described in the following paragraphs.

The ET (extension type) flag (bit 4 of the CR0 register) is used in the Intel386™ processor to indicate whether the math coprocessor in the system is an Intel 287 math coprocessor (flag is clear) or an Intel 387 DX math coprocessor (flag is set). This bit is hardwired to 1 in the P6 family, Pentium®, and Intel486™ processors.

The NE (Numeric Exception) flag (bit 5 of the CR0 register) is used in the P6 family, Pentium®, and Intel486™ processors to determine whether unmasked floating-point exceptions are reported internally through interrupt vector 16 (flag is set) or externally through an external interrupt (flag is clear). On a hardware reset, the NE flag is initialized to 0, so software using the automatic internal error-reporting mechanism must set this flag to 1. This flag is nonexistent on the Intel386™ processor.

As on the Intel 286 and Intel386™ processors, the MP (monitor coprocessor) flag (bit 1 of register CR0) determines whether the WAIT/FWAIT instructions or waiting-type floating-point instructions trap when the context of the FPU is different from that of the currently-executing task. If the MP and TS flag are set, then a WAIT/FWAIT instruction and waiting instructions will cause a device-not-available exception (interrupt vector 7). The MP flag is used on the Intel 286 and Intel386™ processors to support the use of a WAIT/FWAIT instruction to wait on a device other than a math coprocessor. The device reports its status through the BUSY# pin. Since the P6 family, Pentium®, and Intel486™ processors do not have such a pin, the MP flag has no relevant use and should be set to 1 for normal operation.

18.12.2. FPU Status Word

This section identifies differences to the FPU status word for the different Intel Architecture processors and math coprocessors, the reason for the differences, and their impact on software.

18.12.2.1. CONDITION CODE FLAGS (C0 THROUGH C3)

The following information pertains to differences in the use of the condition code flags (C0 through C3) located in bits 8, 9, 10, and 14 of the FPU status word.

After execution of an FINIT instruction or a hardware reset on a 32-bit Intel Architecture FPU, the condition code flags are set to 0. The same operations on a 16-bit Intel Architecture math

coprocessor leave these flags intact (they contain their prior value). This difference in operation has no impact on software and provides a consistent state after reset.

Transcendental instruction results in the core range of the P6 family and Pentium® processors may differ from the Intel486™ DX processor and Intel 487 SX math coprocessor by 2 to 3 units in the last place (ulps)—(refer to "Transcendental Instruction Accuracy" in Chapter 7 of the *Intel Architecture Software Developer's Manual, Volume 1*). As a result, the value saved in the C1 flag may also differ.

After an incomplete FPREM/FPREM1 instruction, the C0, C1, and C3 flags are set to 0 on the 32-bit Intel Architecture FPUs. After the same operation on a 16-bit Intel Architecture math coprocessor, these flags are left intact.

On the 32-bit Intel Architecture FPUs, the C2 flag serves as an incomplete flag for the FTAN instruction. On the 16-bit Intel Architecture math coprocessors, the C2 flag is undefined for the FPTAN instruction. This difference has no impact on software, because Intel 287 or 8087 programs do not check C2 after an FPTAN instruction. The use of this flag on later processors allows fast checking of operand range.

18.12.2.2. STACK FAULT FLAG

When unmasked stack overflow or underflow occurs on a 32-bit Intel Architecture FPU, the IE flag (bit 0) and the SF flag (bit 6) of the FPU status word are set to indicate a stack fault and condition code flag C1 is set or cleared to indicate overflow or underflow, respectively. When unmasked stack overflow or underflow occurs on a 16-bit Intel Architecture math coprocessor, only the IE flag is set. Bit 6 is reserved on these processors. The addition of the SF flag on a 32-bit Intel Architecture FPU has no impact on software. Existing exception handlers need not change, but may be upgraded to take advantage of the additional information.

18.12.3. FPU Control Word

Only affine closure is supported for infinity control on a 32-bit Intel Architecture FPU. The infinity control flag (bit 12 of the FPU control word) remains programmable on these processors, but has no effect. This change was made to conform to IEEE Standard 754. On a 16-bit Intel Architecture math coprocessor, both affine and projective closures are supported, as determined by the setting of bit 12. After a hardware reset, the default value of bit 12 is projective. Software that requires projective infinity arithmetic may give different results.

18.12.4. FPU Tag Word

When loading the tag word of a 32-bit Intel Architecture FPU, using an FLDENV, FRSTOR, or FXRSTOR (Pentium® III processor only) instruction, the processor examines the incoming tag and classifies the location only as empty or nonempty. Thus, tag values of 00, 01, and 10 are interpreted by the processor to indicate a nonempty location. The tag value of 11 is interpreted by the processor to indicate an empty location. Subsequent operations on a nonempty register always examine the value in the register, not the value in its tag. The FSTENV, FSAVE, and

FXSAVE (Pentium® III processor only) instructions examine the nonempty registers and put the correct values in the tags before storing the tag word.

The corresponding tag for a 16-bit Intel Architecture math coprocessor is checked before each register access to determine the class of operand in the register; the tag is updated after every change to a register so that the tag always reflects the most recent status of the register. Software can load a tag with a value that disagrees with the contents of a register (for example, the register contains a valid value, but the tag says special). Here, the 16-bit Intel Architecture math coprocessors honor the tag and do not examine the register.

Software written to run on a 16-bit Intel Architecture math coprocessor may not operate correctly on a 16-bit Intel Architecture FPU, if it uses FLDENV, FRSTOR, or FXRSTOR (Pentium® III processor only) to change tags to values (other than to empty) that are different from actual register contents.

The encoding in the tag word for the 32-bit Intel Architecture FPUs for unsupported data formats (including pseudo-zero and unnormal) is special (10B), to comply with the IEEE Standard 754. The encoding in the 16-bit Intel Architecture math coprocessors for pseudo-zero and unnormal is valid (00B) and the encoding for other unsupported data formats is special (10B). Code that recognizes the pseudo-zero or unnormal format as valid must therefore be changed if it is ported to a 32-bit Intel Architecture FPU.

18.12.5. Data Types

This section discusses the differences of data types for the various Intel Architecture FPUs and math coprocessors.

18.12.5.1. NaNs

The 32-bit Intel Architecture FPUs distinguish between signaling NaNs (SNaNs) and quiet NaNs (QNaNs). These FPUs only generate QNaNs and normally do not generate an exception upon encountering a QNaN. An invalid operation exception (#I) is generated only upon encountering a SNaN, except for the FCOM, FIST, and FBSTP instructions, which also generates an invalid operation exceptions for a QNaNs. This behavior matches the IEEE Standard 754.

The 16-bit Intel Architecture math coprocessors only generate one kind of NaN (the equivalent of a QNaN), but the raise an invalid operation exception upon encountering any kind of NaN.

When porting software written to run on a 16-bit Intel Architecture math coprocessor to a 32-bit Intel Architecture FPU, uninitialized memory locations that contain QNaNs should be changed to SNaNs to cause the FPU or math coprocessor to fault when uninitialized memory locations are referenced.

18.12.5.2. PSEUDO-ZERO, PSEUDO-NaN, PSEUDO-INFINITY, AND UNNORMAL FORMATS

The 32-bit Intel Architecture FPUs neither generate nor support the pseudo-zero, pseudo-NaN, pseudo-infinity, and unnormal formats. Whenever they encounter them in an arithmetic opera-

tion, they raise an invalid operation exception. The 16-bit Intel Architecture math coprocessors define and support special handling for these formats. Support for these formats was dropped to conform with the IEEE Standard 754.

This change should not impact software ported from 16-bit Intel Architecture math coprocessors to 32-bit Intel Architecture FPUs. The 32-bit Intel Architecture FPUs do not generate these formats, and therefore will not encounter them unless software explicitly loads them in the data registers. The only affect may be in how software handles the tags in the tag word (refer to Section 18.12.4., “FPU Tag Word”).

18.12.6. Floating-Point Exceptions

This section identifies the implementation differences in exception handling for floating-point instructions in the various Intel Architecture FPUs and math coprocessors.

18.12.6.1. DENORMAL OPERAND EXCEPTION (#D)

When the denormal operand exception is masked, the 32-bit Intel Architecture FPUs automatically normalize denormalized numbers when possible; whereas, the 16-bit Intel Architecture math coprocessors return a denormal result. A program written to run on a 16-bit Intel Architecture math coprocessor that uses the denormal exception solely to normalize denormalized operands is redundant when run on the 32-bit Intel Architecture FPUs. If such a program is run on 32-bit Intel Architecture FPUs, performance can be improved by masking the denormal exception. Floating-point programs run faster when the FPU performs normalization of denormalized operands.

The denormal operand exception is not raised for transcendental instructions and the FXTRACT instruction on the 16-bit Intel Architecture math coprocessors. This exception is raised for these instructions on the 32-bit Intel Architecture FPUs. The exception handlers ported to these latter processors need to be changed only if the handlers gives special treatment to different opcodes.

18.12.6.2. NUMERIC OVERFLOW EXCEPTION (#O)

On the 32-bit Intel Architecture FPUs, when the numeric overflow exception is masked and the rounding mode is set to chop (toward 0), the result is the largest positive or smallest negative number. The 16-bit Intel Architecture math coprocessors do not signal the overflow exception when the masked response is not ∞; that is, they signal overflow only when the rounding control is not set to round to 0. If rounding is set to chop (toward 0), the result is positive or negative ∞. Under the most common rounding modes, this difference has no impact on existing software.

If rounding is toward 0 (chop), a program on a 32-bit Intel Architecture FPU produces, under overflow conditions, a result that is different in the least significant bit of the significand, compared to the result on a 16-bit Intel Architecture math coprocessor. The reason for this difference is IEEE Standard 754 compatibility.

When the overflow exception is not masked, the precision exception is flagged on the 32-bit Intel Architecture FPUs. When the result is stored in the stack, the significand is rounded according to the precision control (PC) field of the FPU control word or according to the opcode.

On the 16-bit Intel Architecture math coprocessors, the precision exception is not flagged and the significand is not rounded. The impact on existing software is that if the result is stored on the stack, a program running on a 32-bit Intel Architecture FPU produces a different result under overflow conditions than on a 16-bit Intel Architecture math coprocessor. The difference is apparent only to the exception handler. This difference is for IEEE Standard 754 compatibility.

18.12.6.3. NUMERIC UNDERFLOW EXCEPTION (#U)

When the underflow exception is masked on the 32-bit Intel Architecture FPUs, the underflow exception is signaled when both the result is tiny and denormalization results in a loss of accuracy. When the underflow exception is unmasked and the instruction is supposed to store the result on the stack, the significand is rounded to the appropriate precision (according to the PC flag in the FPU control word, for those instructions controlled by PC, otherwise to extended precision), after adjusting the exponent.

When the underflow exception is masked on the 16-bit Intel Architecture math coprocessors and rounding is toward 0, the underflow exception flag is raised on a tiny result, regardless of loss of accuracy. When the underflow exception is not masked and the destination is the stack, the significand is not rounded, but instead is left as is.

When the underflow exception is masked, this difference has no impact on existing software. The underflow exception occurs less often when rounding is toward 0.

When the underflow exception not masked. A program running on a 32-bit Intel Architecture FPU produces a different result during underflow conditions than on a 16-bit Intel Architecture math coprocessor if the result is stored on the stack. The difference is only in the least significant bit of the significand and is apparent only to the exception handler.

18.12.6.4. EXCEPTION PRECEDENCE

There is no difference in the precedence of the denormal operand exception on the 32-bit Intel Architecture FPUs, whether it be masked or not. When the denormal operand exception is not masked on the 16-bit Intel Architecture math coprocessors, it takes precedence over all other exceptions. This difference causes no impact on existing software, but some unneeded normalization of denormalized operands is prevented on the Intel486™ processor and Intel 387 math coprocessor.

18.12.6.5. CS AND EIP FOR FPU EXCEPTIONS

On the Intel 32-bit Intel Architecture FPUs, the values from the CS and EIP registers saved for floating-point exceptions point to any prefixes that come before the floating-point instruction. On the 8087 math coprocessor, the saved CS and IP registers points to the floating-point instruction.

18.12.6.6. FPU ERROR SIGNALS

The floating-point error signals to the P6 family, Pentium®, and Intel486™ processors do not pass through an interrupt controller; an INT# signal from an Intel 387, Intel 287 or 8087 math

coprocessors does. If an 8086 processor uses another exception for the 8087 interrupt, both exception vectors should call the floating-point-error exception handler. Some instructions in a floating-point-error exception handler may need to be deleted if they use the interrupt controller. The P6 family, Pentium®, and Intel486™ processors have signals that, with the addition of external logic, support reporting for emulation of the interrupt mechanism used in many personal computers.

On the P6 family, Pentium®, and Intel486™ processors, an undefined floating-point opcode will cause an invalid-opcode exception (#UD, interrupt vector 6). Undefined floating-point opcodes, like legal floating-point opcodes, cause a device not available exception (#NM, interrupt vector 7) when either the TS or EM flag in control register CR0 is set. The P6 family, Pentium®, and Intel486™ processors do not check for floating-point error conditions on encountering an undefined floating-point opcode.

18.12.6.7. ASSERTION OF THE FERR# PIN

When using the MS-DOS compatibility mode for handing floating-point exceptions, the FERR# pin must be connected to an input to an external interrupt controller. An external interrupt is then generated when the FERR# output drives the input to the interrupt controller and the interrupt controller in turn drives the INTR pin on the processor. For the P6 family and Intel386™ processors, an unmasked floating-point exception always causes the FERR# pin to be asserted upon completion of the instruction that caused the exception. For the Pentium® and Intel486™ processors, an unmasked floating-point exception may cause the FERR# pin to be asserted either at the end of the instruction causing the exception or immediately before execution of the next floating-point instruction. (Note that the next floating-point instruction would not be executed until the pending unmasked exception has been handled.) Refer to Appendix D in the *Intel Architecture Software Developer's Manual, Volume 1*, for a complete description of the required mechanism for handling floating-point exceptions using the MS-DOS compatibility mode.

18.12.6.8. INVALID OPERATION EXCEPTION ON DENORMALS

An invalid operation exception is not generated on the 32-bit Intel Architecture FPUs upon encountering a denormal value when executing a FSQRT, FDIV, or FPREM instruction or upon conversion to BCD or to integer. The operation proceeds by first normalizing the value. On the 16-bit Intel Architecture math coprocessors, upon encountering this situation, the invalid operation exception is generated. This difference has no impact on existing software. Software running on the 32-bit Intel Architecture FPUs continues to execute in cases where the 16-bit Intel Architecture math coprocessors trap. The reason for this change was to eliminate an exception from being raised.

18.12.6.9. ALIGNMENT CHECK EXCEPTIONS (#AC)

If alignment checking is enabled, a misaligned data operand on the P6 family, Pentium®, and Intel486™ processors causes an alignment check exception (#AC) when a program or procedure is running at privilege-level 3, except for the stack portion of the FSAVE/FNSAVE/FXSAVE and FRSTOR/FXRSTOR instructions.

18.12.6.10. SEGMENT NOT PRESENT EXCEPTION DURING FLDENV

On the Intel486™ processor, when a segment not present exception (#NP) occurs in the middle of an FLDENV instruction, it can happen that part of the environment is loaded and part not. In such cases, the FPU control word is left with a value of 007FH. The P6 family and Pentium® processors ensure the internal state is correct at all times by attempting to read the first and last bytes of the environment before updating the internal state.

18.12.6.11. DEVICE NOT AVAILABLE EXCEPTION (#NM)

The device-not-available exception (#NM, interrupt 7) will occur in the P6 family, Pentium®, and Intel486™ processors as described in Section 2.5., "Control Registers" in Chapter 2, *System Architecture Overview*, and Section 5.12., "Exception and Interrupt Reference" in Chapter 5, *Interrupt and Exception Handling*.

18.12.6.12. COPROCESSOR SEGMENT OVERRUN EXCEPTION

The coprocessor segment overrun exception (interrupt 9) does not occur in the P6 family, Pentium®, and Intel486™ processors. In situations where the Intel 387 math coprocessor would cause an interrupt 9, the P6 family, Pentium®, and Intel486™ processors simply abort the instruction. To avoid undetected segment overruns, it is recommended that the floating-point save area be placed in the same page as the TSS. This placement will prevent the FPU environment from being lost if a page fault occurs during the execution of an FLDENV, FRSTOR, or FXRSTOR instructions while the operating system is performing a task switch.

18.12.6.13. GENERAL PROTECTION EXCEPTION (#GP)

A general-protection exception (#GP, interrupt 13) occurs if the starting address of a floating-point operand falls outside a segment's size. An exception handler should be included to report these programming errors.

18.12.6.14. FLOATING-POINT ERROR EXCEPTION (#MF)

In real mode and protected mode (not including virtual-8086 mode), interrupt vector 16 must point to the floating-point exception handler. In virtual 8086 mode, the virtual-8086 monitor can be programmed to accommodate a different location of the interrupt vector for floating-point exceptions.

18.12.7. Changes to Floating-Point Instructions

This section identifies the differences in floating-point instructions for the various Intel FPU and math coprocessor architectures, the reason for the differences, and their impact on software.

18.12.7.1. FDIV, FPREM, AND FSQRT INSTRUCTIONS

The 32-bit Intel Architecture FPUs support operations on denormalized operands and, when detected, an underflow exception can occur, for compatibility with the IEEE Standard 754. The 16-bit Intel Architecture math coprocessors do not operate on denormalized operands or return underflow results. Instead, they generate an invalid operation exception when they detect an underflow condition. An existing underflow exception handler will require change only if it gives different treatment to different opcodes. Also, it is possible that fewer invalid operation exceptions will occur.

18.12.7.2. FSCALE INSTRUCTION

With the 32-bit Intel Architecture FPUs, the range of the scaling operand is not restricted. If (0 < | ST(1) < 1), the scaling factor is 0; therefore, ST(0) remains unchanged. If the rounded result is not exact or if there was a loss of accuracy (masked underflow), the precision exception is signaled. With the 16-bit Intel Architecture math coprocessors, the range of the scaling operand is restricted. If (0 < | ST(1) | < 1), the result is undefined and no exception is signaled. The impact of this difference on exiting software is that different results are delivered on the 32-bit and 16-bit FPUs and math coprocessors when (0 < | ST(1) | < 1).

18.12.7.3. FPREM1 INSTRUCTION

The 32-bit Intel Architecture FPUs compute a partial remainder according to the IEEE Standard 754. This instruction does not exist on the 16-bit Intel Architecture math coprocessors. The availability of the FPREM1 instruction has is no impact on existing software.

18.12.7.4. FPREM INSTRUCTION

On the 32-bit Intel Architecture FPUs, the condition code flags C0, C3, C1 in the status word correctly reflect the three low-order bits of the quotient following execution of the FPREM instruction. On the 16-bit Intel Architecture math coprocessors, the quotient bits are incorrect when performing a reduction of $(64^N + M)$ when $(N \geq 1)$ and M is 1 or 2. This difference does not affect existing software; software that works around the bug should not be affected.

18.12.7.5. FUCOM, FUCOMP, AND FUCOMPP INSTRUCTIONS

When executing the FUCOM, FUCOMP, and FUCOMPP instructions, the 32-bit Intel Architecture FPUs perform unordered compare according to IEEE Standard 754. These instructions do not exist on the 16-bit Intel Architecture math coprocessors. The availability of these new instructions has no impact on existing software.

18.12.7.6. FPTAN INSTRUCTION

On the 32-bit Intel Architecture FPUs, the range of the operand for the FPTAN instruction is much less restricted ($| ST(0) | < 2^{63}$) than on earlier math coprocessors. The instruction reduces the operand internally using an internal $\pi/4$ constant that is more accurate. The range of the

operand is restricted to (| ST(0) | < π/4) on the 16-bit Intel Architecture math coprocessors; the operand must be reduced to this range using FPREM. This change has no impact on existing software.

18.12.7.7. STACK OVERFLOW

On the 32-bit Intel Architecture FPUs, if an FPU stack overflow occurs when the invalid operation exception is masked, the FPU returns the real, integer, or BCD-integer indefinite value to the destination operand, depending on the instruction being executed. On the 16-bit Intel Architecture math coprocessors, the original operand remains unchanged following a stack overflow, but it is loaded into register ST(1). This difference has no impact on existing software.

18.12.7.8. FSIN, FCOS, AND FSINCOS INSTRUCTIONS

On the 32-bit Intel Architecture FPUs, these instructions perform three common trigonometric functions. These instructions do not exist on the 16-bit Intel Architecture math coprocessors. The availability of these instructions has no impact on existing software, but using them provides a performance upgrade.

18.12.7.9. FPATAN INSTRUCTION

On the 32-bit Intel Architecture FPUs, the range of operands for the FPATAN instruction is unrestricted. On the 16-bit Intel Architecture math coprocessors, the absolute value of the operand in register ST(0) must be smaller than the absolute value of the operand in register ST(1). This difference has impact on existing software.

18.12.7.10. F2XM1 INSTRUCTION

The 32-bit Intel Architecture FPUs support a wider range of operands ($-1 < ST(0) < +1$) for the F2XM1 instruction. The supported operand range for the 16-bit Intel Architecture math coprocessors is ($0 \leq ST(0) \leq 0.5$). This difference has no impact on existing software.

18.12.7.11. FLD INSTRUCTION

On the 32-bit Intel Architecture FPUs, when using the FLD instruction to load an extended-real value, a denormal operand exception is not generated because the instruction is not arithmetic. The 16-bit Intel Architecture math coprocessors do report a denormal operand exception in this situation. This difference does not affect existing software.

On the 32-bit Intel Architecture FPUs, loading a denormal value that is in single- or double-real format causes the value to be converted to extended-real format. Loading a denormal value on the 16-bit Intel Architecture math coprocessors causes the value to be converted to an unnormal. If the next instruction is FXTRACT or FXAM, the 32-bit Intel Architecture FPUs will give a different result than the 16-bit Intel Architecture math coprocessors. This change was made for IEEE Standard 754 compatibility.

On the 32-bit Intel Architecture FPUs, loading an SNaN that is in single- or double-real format causes the FPU to generate an invalid operation exception. The 16-bit Intel Architecture math coprocessors do not raise an exception when loading a signaling NaN. The invalid operation exception handler for 16-bit math coprocessor software needs to be updated to handle this condition when porting software to 32-bit FPUs. This change was made for IEEE Standard 754 compatibility.

18.12.7.12. FXTRACT INSTRUCTION

On the 32-bit Intel Architecture FPUs, if the operand is 0 for the FXTRACT instruction, the divide-by-zero exception is reported and –∞ is delivered to register ST(1). If the operand is +∞, no exception is reported. If the operand is 0 on the 16-bit Intel Architecture math coprocessors, 0 is delivered to register ST(1) and no exception is reported. If the operand is +∞, the invalid operation exception is reported. These differences have no impact on existing software. Software usually bypasses 0 and ∞. This change is due to the IEEE 754 recommendation to fully support the “logb” function.

18.12.7.13. LOAD CONSTANT INSTRUCTIONS

On 32-bit Intel Architecture FPUs, rounding control is in effect for the load constant instructions. Rounding control is not in effect for the 16-bit Intel Architecture math coprocessors. Results for the FLDPI, FLDLN2, FLDLG2, and FLDL2E instructions are the same as for the 16-bit Intel Architecture math coprocessors when rounding control is set to round to nearest or round to +∞. They are the same for the FLDL2T instruction when rounding control is set to round to nearest, round to –∞, or round to zero. Results are different from the 16-bit Intel Architecture math coprocessors in the least significant bit of the mantissa if rounding control is set to round to –∞ or round to 0 for the FLDPI, FLDLN2, FLDLG2, and FLDL2E instructions; they are different for the FLDL2T instruction if round to +∞ is specified. These changes were implemented for compatibility with IEEE 754 recommendations.

18.12.7.14. FSETPM INSTRUCTION

With the 32-bit Intel Architecture FPUs, the FSETPM instruction is treated as NOP (no operation). This instruction informs the Intel 287 math coprocessor that the processor is in protected mode. This change has no impact on existing software. The 32-bit Intel Architecture FPUs handle all addressing and exception-pointer information, whether in protected mode or not.

18.12.7.15. FXAM INSTRUCTION

With the 32-bit Intel Architecture FPUs, if the FPU encounters an empty register when executing the FXAM instruction, it will generate combinations of C0 through C3 equal to 1101 or 1111. The 16-bit Intel Architecture math coprocessors may generate these combinations, among others. This difference has no impact on existing software; it provides a performance upgrade to provide repeatable results.

18.12.7.16. FSAVE AND FSTENV INSTRUCTIONS

With the 32-bit Intel Architecture FPUs, the address of a memory operand pointer stored by FSAVE or FSTENV is undefined if the previous floating-point instruction did not refer to memory

18.12.8. Transcendental Instructions

The floating-point results of the P6 family and Pentium® processors for transcendental instructions in the core range may differ from the Intel486™ processors by about 2 or 3 ulps (refer to "Transcendental Instruction Accuracy" in Chapter 7 of the *Intel Architecture Software Developer's Manual, Volume 1*). Condition code flag C1 of the status word may differ as a result. The exact threshold for underflow and overflow will vary by a few ulps. The P6 family and Pentium® processors' results will have a worst case error of less than 1 ulp when rounding to the nearest-even and less than 1.5 ulps when rounding in other modes. The transcendental instructions are guaranteed to be monotonic, with respect to the input operands, throughout the domain supported by the instruction.

Transcendental instructions may generate different results in the round-up flag (C1) on the 32-bit Intel Architecture FPUs. The round-up flag is undefined for these instructions on the 16-bit Intel Architecture math coprocessors. This difference has no impact on existing software.

18.12.9. Obsolete Instructions

The 8087 math coprocessor instructions FENI and FDISI and the Intel 287 math coprocessor instruction FSETPM are treated as integer NOP instructions in the 32-bit Intel Architecture FPUs. If these opcodes are detected in the instruction stream, no specific operation is performed and no internal states are affected.

18.12.10.WAIT/FWAIT Prefix Differences

On the Intel486™ processor, when a WAIT/FWAIT instruction precedes a floating-point instruction (one which itself automatically synchronizes with the previous floating-point instruction), the WAIT/FWAIT instruction is treated as a no-op. Pending floating-point exceptions from a previous floating-point instruction are processed not on the WAIT/FWAIT instruction but on the floating-point instruction following the WAIT/FWAIT instruction. In such a case, the report of a floating-point exception may appear one instruction later on the Intel486™ processor than on a P6 family or Pentium® FPU, or on Intel 387 math coprocessor.

18.12.11.Operands Split Across Segments and/or Pages

On the P6 family, Pentium®, and Intel486™ processor FPUs, when the first half of an operand to be written is inside a page or segment and the second half is outside, a memory fault can cause the first half to be stored but not the second half. In this situation, the Intel 387 math coprocessor stores nothing.

18.12.12.FPU Instruction Synchronization

On the 32-bit Intel Architecture FPUs, all floating-point instructions are automatically synchronized; that is, the processor automatically waits until the previous floating-point instruction has completed before completing the next floating-point instruction. No explicit WAIT/FWAIT instructions are required to assure this synchronization. For the 8087 math coprocessors, explicit waits are required before each floating-point instruction to ensure synchronization. Although 8087 programs having explicit WAIT instructions execute perfectly on the 32-bit Intel Architecture processors without reassembly, these WAIT instructions are unnecessary.

18.13. SERIALIZING INSTRUCTIONS

Certain instructions have been defined to serialize instruction execution to ensure that modifications to flags, registers and memory are completed before the next instruction is executed (or in P6 family processor terminology “committed to machine state”). Because the P6 family processors use branch-prediction and out-of-order execution techniques to improve performance, instruction execution is not generally serialized until the results of an executed instruction are committed to machine state (refer to Chapter 2, *Introduction to the Intel Architecture*, in the *Intel Architecture Software Developer's Manual, Volume 1*). As a result, at places in a program or task where it is critical to have execution completed for all previous instructions before executing the next instruction (for example, at a branch, at the end of a procedure, or in multiprocessor dependent code), it is useful to add a serializing instruction. Refer to Section 7.4., “Serializing Instructions” in Chapter 7, *Multiple-Processor Management* for more information on serializing instructions.

18.14. FPU AND MATH COPROCESSOR INITIALIZATION

Table 8-1 in Chapter 8, *Processor Management and Initialization* shows the states of the FPUs in the P6 family, Pentium®, Intel486™ processors and of the Intel 387 math coprocessor and Intel 287 coprocessor following a power-up, reset, or INIT, or following the execution of an FINIT/FNINIT instruction. The following is some additional compatibility information concerning the initialization of Intel Architecture FPUs and math coprocessors.

18.14.1. Intel 387 and Intel 287 Math Coprocessor Initialization

Following an Intel386™ processor reset, the processor identifies its coprocessor type (Intel 287 or Intel 387 DX math coprocessor) by sampling its ERROR# input some time after the falling edge of RESET# signal and before execution of the first floating-point instruction. The Intel 287 coprocessor keeps its ERROR# output in inactive state after hardware reset; the Intel 387 coprocessor keeps its ERROR# output in active state after hardware reset.

Upon hardware reset or execution of the FINIT/FNINIT instruction, the Intel 387 math coprocessor signals an error condition. The P6 family, Pentium®, and Intel486™ processors, like the Intel 287 coprocessor, do not.

18.14.2. Intel486™ SX Processor and Intel 487 SX Math Coprocessor Initialization

When initializing an Intel486™ SX processor and an Intel 487 SX math coprocessor, the initialization routine should check the presence of the math coprocessor and should set the FPU related flags (EM, MP, and NE) in control register CR0 accordingly (refer to Section 2.5., "Control Registers" in Chapter 2, *System Architecture Overview* for a complete description of these flags). Table 18-1 gives the recommended settings for these flags when the math coprocessor is present. The FSTCW instruction will give a value of FFFFH for the Intel486™ SX microprocessor and 037FH for the Intel 487 SX math coprocessor.

Table 18-1. Recommended Values of the FP Related Bits for Intel486™ SX Microprocessor/Intel 487 SX Math Coprocessor System

CR0 Flags	Intel486™ SX Processor Only	Intel 487 SX Math Coprocessor Present
EM	1	0
MP	0	1
NE	1	0, for MS-DOS* systems 1, for user-defined exception handler

The EM and MP flags in register CR0 are interpreted as shown in Table 18-2.

Table 18-2. EM and MP Flag Interpretation

EM	MP	Interpretation
0	0	Floating-point instructions are passed to FPU; WAIT/FWAIT and other waiting-type instructions ignore TS.
0	1	Floating-point instructions are passed to FPU; WAIT/FWAIT and other waiting-type instructions test TS.
1	0	Floating-point instructions trap to emulator; WAIT/FWAIT and other waiting-type instructions ignore TS.
1	1	Floating-point instructions trap to emulator; WAIT/FWAIT and other waiting-type instructions test TS.

Following is an example code sequence to initialize the system and check for the presence of Intel486™ SX processor/Intel 487 SX math coprocessor.

```
fninit
fstcw mem_loc
mov ax, mem_loc
cmp ax, 037fh
jz Intel487_SX_Math_CoProcessor_present;ax=037fh
jmp Intel486_SX_microprocessor_present;ax=ffffh
```

If the Intel 487 SX math coprocessor is not present, the following code can be run to set the CR0 register for the Intel486™ SX processor.

```
mov eax, cr0
and eax, fffffffdh ;make MP=0
or eax, 0024h      ;make EM=1, NE=1
mov cr0, eax
```

This initialization will cause any floating-point instruction to generate a device not available exception (#NH), interrupt 7. The software emulation will then take control to execute these instructions. This code is not required if an Intel 487 SX math coprocessor is present in the system. In that case, the typical initialization routine for the Intel486™ SX microprocessor will be adequate.

Also, when designing an Intel486™ SX processor based system with an Intel 487 SX math coprocessor, timing loops should be independent of clock speed and clocks per instruction. One way to attain this is to implement these loops in hardware and not in software (for example, BIOS).

18.15. CONTROL REGISTERS

The following sections identify the new control registers and control register flags and fields that were introduced to the 32-bit Intel Architecture in various processor families. Refer to Figure 2-5 in Chapter 2, *System Architecture Overview* for the location of these flags and fields in the control registers.

The Pentium® III processor introduced one new control flag in control register CR4:

- OSXMMEXCPT (bit 10)—The OS will set this bit if it supports unmasked SIMD floating-point exceptions.

The Pentium® II processor introduced one new control flag in control register CR4:

- OSFXSR (bit 9)—The OS supports saving and restoring the Pentium® III processor state during context switches.

The Pentium® Pro processor introduced three new control flags in control register CR4:

- PAE (bit 5)—Physical address extension. Enables paging mechanism to reference 36-bit physical addresses when set; restricts physical addresses to 32 bits when clear (refer to Section 18.16.1.1., “Physical Memory Addressing Extension” in Chapter 18, *Intel Architecture Compatibility*).
- PGE (bit 7)—Page global enable. Inhibits flushing of frequently-used or shared pages on task switches (refer to Section 18.16.1.2., “Global Pages” in Chapter 18, *Intel Architecture Compatibility*).
- PCE (bit 8)—Performance-monitoring counter enable. Enables execution of the RDPMC instruction at any protection level.

The content of CR4 is 0H following a hardware reset.

Control register CR4 was introduced in the Pentium® processor. This register contains flags that enable certain new extensions provided in the Pentium® processor:

- VME—Virtual-8086 mode extensions. Enables support for a virtual interrupt flag in virtual-8086 mode (refer to Section 16.3., "Interrupt and Exception Handling in Virtual-8086 Mode" in Chapter 16, *8086 Emulation*).
- PVI—Protected-mode virtual interrupts. Enables support for a virtual interrupt flag in protected mode (refer to Section 16.4., "Protected-Mode Virtual Interrupts" in Chapter 16, *8086 Emulation*).
- TSD—Time-stamp disable. Restricts the execution of the RDTSC instruction to procedures running at privileged level 0.
- DE—Debugging extensions. Causes an undefined opcode (#UD) exception to be generated when debug registers DR4 and DR5 are references for improved performance (refer to Section 15.2.2., "Debug Registers DR4 and DR5" in Chapter 15, *Debugging and Performance Monitoring*).
- PSE—Page size extensions. Enables 4-MByte pages when set (refer to Section 3.6.1., "Paging Options" in Chapter 3, *Protected-Mode Memory Management*).
- MCE—Machine-check enable. Enables the machine-check exception, allowing exception handling for certain hardware error conditions (refer to Chapter 13, *Machine-Check Architecture*).

The Intel486™ processor introduced five new flags in control register CR0:

- NE—Numeric error. Enables the normal mechanism for reporting floating-point numeric errors.
- WP—Write protect. Write-protects user-level pages against supervisor-mode accesses.
- AM—Alignment mask. Controls whether alignment checking is performed. Operates in conjunction with the AC (Alignment Check) flag.
- NW—Not write-through. Enables write-throughs and cache invalidation cycles when clear and disables invalidation cycles and write-throughs that hit in the cache when set.
- CD—Cache disable. Enables the internal cache when clear and disables the cache when set.

The Intel486™ processor introduced two new flags in control register CR3:

- PCD—Page-level cache disable. The state of this flag is driven on the PCD# pin during bus cycles that are not paged, such as interrupt acknowledge cycles, when paging is enabled. The PCD# pin is used to control caching in an external cache on a cycle-by-cycle basis.
- PWT—Page-level write-through. The state of this flag is driven on the PWT# pin during bus cycles that are not paged, such as interrupt acknowledge cycles, when paging is enabled. The PWT# pin is used to control write through in an external cache on a cycle-by-cycle basis.

18.16. MEMORY MANAGEMENT FACILITIES

The following sections describe the new memory management facilities available in the various Intel Architecture processors and some compatibility differences.

18.16.1. New Memory Management Control Flags

The Pentium® Pro processor introduced three new memory management features: physical memory addressing extension, the global bit in page-table entries, and general support for larger page sizes. These features are only available when operating in protected mode.

18.16.1.1. PHYSICAL MEMORY ADDRESSING EXTENSION

The new PAE (physical address extension) flag in control register CR4, bit 5, enables 4 additional address lines on the processor, allowing 36-bit physical addresses. This option can only be used when paging is enabled, using a new page-table mechanism provided to support the larger physical address range (refer to Section 3.8., "Physical Address Extension" in Chapter 3, *Protected-Mode Memory Management*).

18.16.1.2. GLOBAL PAGES

The new PGE (page global enable) flag in control register CR4, bit 7, provides a mechanism for preventing frequently used pages from being flushed from the translation lookaside buffer (TLB). When this flag is set, frequently used pages (such as pages containing kernel procedures or common data tables) can be marked global by setting the global flag in a page-directory or page-table entry. On a task switch or a write to control register CR3 (which normally causes the TLBs to be flushed), the entries in the TLB marked global are not flushed. Marking pages global in this manner prevents unnecessary reloading of the TLB due to TLB misses on frequently used pages. Refer to Section 3.7., "Translation Lookaside Buffers (TLBs)" in Chapter 3, *Protected-Mode Memory Management* for a detailed description of this mechanism.

18.16.1.3. LARGER PAGE SIZES

The P6 family processors support large page sizes. This facility is enabled with the PSE (page size extension) flag in control register CR4, bit 4. When this flag is set, the processor supports either 4-KByte or 4-MByte page sizes when normal paging is used and 4-KByte and 2-MByte page sizes when the physical address extension is used. Refer to Section 3.6.1., "Paging Options" in Chapter 3, *Protected-Mode Memory Management* for more information about large page sizes.

18.16.2. CD and NW Cache Control Flags

The CD and NW flags in control register CR0 were introduced in the Intel486™ processor. In the P6 family and Pentium® processors, these flags are used to implement a writeback strategy for the data cache; in the Intel486™ processor, they implement a write-through strategy. Refer

to Table 9-4, in Chapter 9, *Memory Cache Control* for a comparison of these bits on the P6 family, Pentium®, and Intel486™ processors. For complete information on caching, refer to Chapter 9, *Memory Cache Control*.

18.16.3. Descriptor Types and Contents

Operating-system code that manages space in descriptor tables often contains an invalid value in the access-rights field of descriptor-table entries to identify unused entries. Access rights values of 80H and 00H remain invalid for the P6 family, Pentium®, Intel486™, Intel386™, and Intel 286 processors. Other values that were invalid on the Intel 286 processor may be valid on the 32-bit processors because uses for these bits have been defined.

18.16.4. Changes in Segment Descriptor Loads

On the Intel386™ processor, loading a segment descriptor always causes a locked read and write to set the accessed bit of the descriptor. On the P6 family, Pentium®, and Intel486™ processors, the locked read and write occur only if the bit is not already set.

18.17. DEBUG FACILITIES

The P6 family and Pentium® processors include extensions to the Intel486™ processor debugging support for breakpoints. To use the new breakpoint features, it is necessary to set the DE flag in control register CR4.

18.17.1. Differences in Debug Register DR6

It is not possible to write a 1 to reserved bit 12 in debug status register DR6 on the P6 family and Pentium® processors; however, it is possible to write a 1 in this bit on the Intel486™ processor. Refer to Table 8-1 in Chapter 8, *Processor Management and Initialization* for the different setting of this register following a power-up or hardware reset.

18.17.2. Differences in Debug Register DR7

The P6 family and Pentium® processors determines the type of breakpoint access by the R/W0 through R/W3 fields in debug control register DR7 as follows:

00 Break on instruction execution only.

01 Break on data writes only.

10 Undefined if the DE flag in control register CR4 is cleared; break on I/O reads or writes but not instruction fetches if the DE flag in control register CR4 is set.

11 Break on data reads or writes but not instruction fetches.

On the P6 family and Pentium® processors, reserved bits 11, 12, 14 and 15 are hard-wired to 0. On the Intel486™ processor, however, bit 12 can be set. Refer to Table 8-1 in Chapter 8, *Processor Management and Initialization* for the different settings of this register following a power-up or hardware reset.

18.17.3. Debug Registers DR4 and DR5

Although the DR4 and DR5 registers are documented as reserved, previous generations of processors aliased references to these registers to debug registers DR6 and DR7, respectively. When debug extensions are not enabled (the DE flag in control register CR4 is cleared), the P6 family and Pentium® processors remain compatible with existing software by allowing these aliased references. When debug extensions are enabled (the DE flag is set), attempts to reference registers DR4 or DR5 will result in an invalid-opcode exception (#UD).

18.17.4. Recognition of Breakpoints

For the Pentium® processor, it is recommended that debuggers execute the LGDT instruction before returning to the program being debugged to ensure that breakpoints are detected. This operation does not need to be performed on the P6 family, Intel486™, or Intel386™ processors.

18.18. TEST REGISTERS

The implementation of test registers on the Intel486™ processor used for testing the cache and TLB has been redesigned using MSRs on the P6 family and Pentium® processors. (Note that MSRs used for this function are different on the P6 family and Pentium® processors.) The MOV to and from test register instructions generate invalid-opcode exceptions (#UD) on the P6 family processors.

18.19. Exceptions and/or Exception Conditions

This section describes the new exceptions and exception conditions added to the 32-bit Intel Architecture processors and implementation differences in existing exception handling. Refer to Chapter 5, *Interrupt and Exception Handling* for a detailed description of the Intel Architecture exceptions.

The Pentium® III processor introduced new state with the SIMD floating-point registers. Computations involving data in these registers can produce exceptions. A new control/status register is used to determine which exception or exceptions have occurred. When an exception associated with the SIMD floating-point registers occurs, an interrupt is generated.

- Streaming SIMD Extensions exception (#XF, interrupt 19)—New exceptions associated with the SIMD floating-point registers and resulting computations.

No new exceptions were added to the Pentium® II and Pentium® Pro processors. The set of available exceptions is the same as for the Pentium® processor. However, the following exception condition was added to the Intel Architecture with the Pentium® Pro processor:

- Machine-check exception (#MC, interrupt 18)—New exception conditions. Many exception conditions have been added to the machine-check exception and a new architecture has been added for handling and reporting on hardware errors. Refer to Chapter 13, *Machine-Check Architecture* for a detailed description of the new conditions.

The following exceptions and/or exception conditions were added to the Intel Architecture with the Pentium® processor:

- Machine-check exception (#MC, interrupt 18)—New exception. This exception reports parity and other hardware errors. It is a model-specific exception and may not be implemented or implemented differently in future processors. The MCE flag in control register CR4 enables the machine-check exception. When this bit is clear (which it is at reset), the processor inhibits generation of the machine-check exception.
- General-protection exception (#GP, interrupt 13)—New exception condition added. An attempt to write a 1 to a reserved bit position of a special register causes a general-protection exception to be generated.
- Page-fault exception (#PF, interrupt 14)—New exception condition added. When a 1 is detected in any of the reserved bit positions of a page-table entry, page-directory entry, or page-directory pointer during address translation, a page-fault exception is generated.

The following exception was added to the Intel486™ processor:

- Alignment-check exception (#AC, interrupt 17)—New exception. Reports unaligned memory references when alignment checking is being performed.

The following exceptions and/or exception conditions were added to the Intel386™ processor:

- Divide-error exception (#DE, interrupt 0)
  - — Change in exception handling. Divide-error exceptions on the Intel386™ processors always leave the saved CS:IP value pointing to the instruction that failed. On the 8086 processor, the CS:IP value points to the next instruction.
  - — Change in exception handling. The Intel386™ processors can generate the largest negative number as a quotient for the IDIV instruction (80H and 8000H). The 8086 processor generates a divide-error exception instead.
- Invalid-opcode exception (#UD, interrupt 6)—New exception condition added. Improper use of the LOCK instruction prefix can generate an invalid-opcode exception.
- Page-fault exception (#PF, interrupt 14)—New exception condition added. If paging is enabled in a 16-bit program, a page-fault exception can be generated as follows. Paging can be used in a system with 16-bit tasks if all tasks use the same page directory. Because there is no place in a 16-bit TSS to store the PDBR register, switching to a 16-bit task does not change the value of the PDBR register. Tasks ported from the Intel 286 processor should be given 32-bit TSSs so they can make full use of paging.

- General-protection exception (#GP, interrupt 13)—New exception condition added. The Intel386™ processor sets a limit of 15 bytes on instruction length. The only way to violate this limit is by putting redundant prefixes before an instruction. A general-protection exception is generated if the limit on instruction length is violated. The 8086 processor has no instruction length limit.

18.19.1. Machine-Check Architecture

The Pentium® Pro processor introduced a new architecture to the Intel Architecture for handling and reporting on machine-check exceptions. This machine-check architecture (described in detail in Chapter 13, *Machine-Check Architecture*) greatly expands the ability of the processor to report on internal hardware errors.

18.19.2. Priority OF Exceptions

The priority of exceptions are broken down into several major categories:

1. Traps on the previous instruction
2. External interrupts
3. Faults on fetching the next instruction
4. Faults in decoding the next instruction
5. Faults on executing an instruction

There are no changes in the priority of these major categories between the different processors, however, exceptions within these categories are implementation dependent and may change from processor to processor.

18.20. INTERRUPTS

The following differences in handling interrupts are found among the Intel Architecture processors.

18.20.1. Interrupt Propagation Delay

External hardware interrupts may be recognized on different instruction boundaries on the P6 family, Pentium®, Intel486™, and Intel386™ processors, due to the superscaler designs of the P6 family and Pentium® processors. Therefore, the EIP pushed onto the stack when servicing an interrupt may be different for the P6 family, Pentium®, Intel486™, and Intel386™ processors.

18.20.2. NMI Interrupts

After an NMI interrupt is recognized by the P6 family, Pentium®, Intel486™, Intel386™, and Intel 286 processors, the NMI interrupt is masked until the first IRET instruction is executed, unlike the 8086 processor.

18.20.3. IDT Limit

The LIDT instruction can be used to set a limit on the size of the IDT. A double-fault exception (#DF) is generated if an interrupt or exception attempts to read a vector beyond the limit. Shut-down then occurs on the 32-bit Intel Architecture processors if the double-fault handler vector is beyond the limit. (The 8086 processor does not have a shutdown mode nor a limit.)

18.21. TASK SWITCHING AND TSS

This section identifies the implementation differences of task switching, additions to the TSS and the handling of TSSs and TSS segment selectors.

18.21.1. P6 Family and Pentium® Processor TSS

When the virtual mode extensions are enabled (by setting the VME flag in control register CR4), the TSS in the P6 family and Pentium® processors contain an interrupt redirection bit map, which is used in virtual-8086 mode to redirect interrupts back to an 8086 program.

18.21.2. TSS Selector Writes

During task state saves, the Intel486™ processor writes 2-byte segment selectors into a 32-bit TSS, leaving the upper 16 bits undefined. For performance reasons, the P6 family and Pentium® processors write 4-byte segment selectors into the TSS, with the upper 2 bytes being 0. For compatibility reasons, code should not depend on the value of the upper 16 bits of the selector in the TSS.

18.21.3. Order of Reads/Writes to the TSS

The order of reads and writes into the TSS is processor dependent. The P6 family and Pentium® processors may generate different page-fault addresses in control register CR2 in the same TSS area than the Intel486™ and Intel386™ processors, if a TSS crosses a page boundary (which is not recommended).

18.21.4. Using A 16-Bit TSS with 32-Bit Constructs

Task switches using 16-bit TSSs should be used only for pure 16-bit code. Any new code written using 32-bit constructs (operands, addressing, or the upper word of the EFLAGS register) should use only 32-bit TSSs. This is due to the fact that the 32-bit processors do not save the upper 16 bits of EFLAGS to a 16-bit TSS. A task switch back to a 16-bit task that was executing in virtual mode will never re-enable the virtual mode, as this flag was not saved in the upper half of the EFLAGS value in the TSS. Therefore, it is strongly recommended that any code using 32-bit constructs use a 32-bit TSS to ensure correct behavior in a multitasking environment.

18.21.5. Differences in I/O Map Base Addresses

The Intel486™ processor considers the TSS segment to be a 16-bit segment and wraps around the 64K boundary. Any I/O accesses check for permission to access this I/O address at the I/O base address plus the I/O offset. If the I/O map base address exceeds the specified limit of 0DFFFH, an I/O access will wrap around and obtain the permission for the I/O address at an incorrect location within the TSS. A TSS limit violation does not occur in this situation on the Intel486™ processor. However, the P6 family and Pentium® processors consider the TSS to be a 32-bit segment and a limit violation occurs when the I/O base address plus the I/O offset is greater than the TSS limit. By following the recommended specification for the I/O base address to be less than 0DFFFH, the Intel486™ processor will not wrap around and access incorrect locations within the TSS for I/O port validation and the P6 family and Pentium® processors will not experience general-protection exceptions (#GP). Figure 18-1 demonstrates the different areas accessed by the Intel486™ and the P6 family and Pentium® processors.

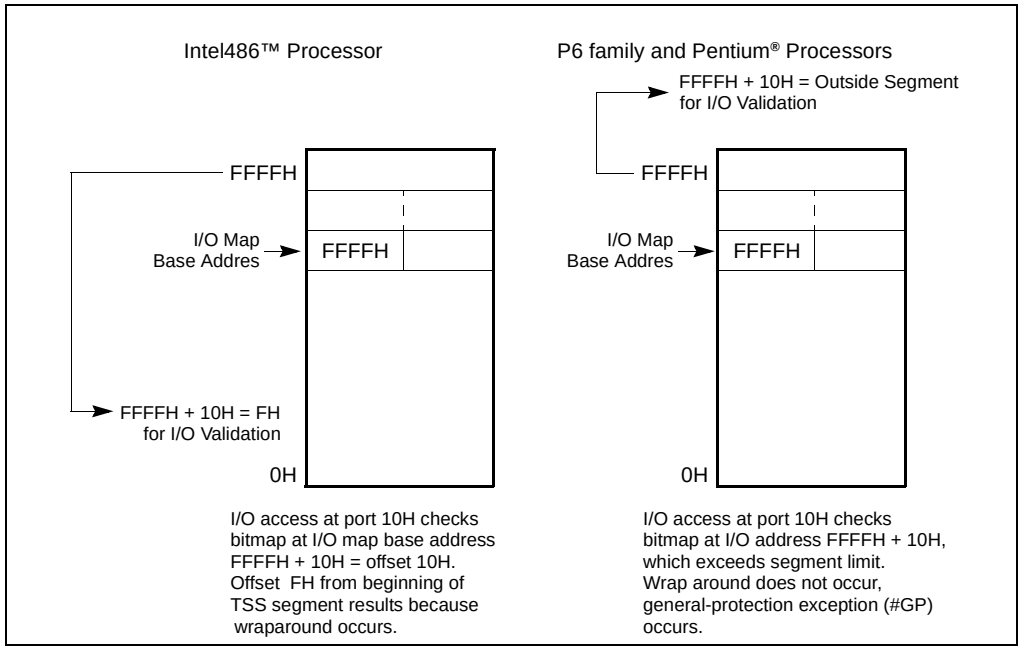


Figure 18-1. I/O Map Base Address Differences

18.22. CACHE MANAGEMENT

The P6 family processors include two levels of internal caches: L1 (level 1) and L2 (level 2). The L1 cache is divided into an instruction cache and a data cache; the L2 cache is a general-purpose cache. Refer to Section 9.1., “Internal Caches, TLBs, and Buffers”, in Chapter 9, *Memory Cache Control*, for a description of these caches. (Note that although the Pentium® II processor L2 cache is physically located on a separate chip in the cassette, it is considered an internal cache.)

The Pentium® processor includes separate level 1 instruction and data caches. The data cache supports a writeback (or alternatively write-through, on a line by line basis) policy for memory updates. Refer to the *Pentium® Processor Data Book* for more information about the organization and operation of the Pentium® processor caches.

The Intel486™ processor includes a single level 1 cache for both instructions and data.

The meaning of the CD and NW flags in control register CR0 have been redefined for the P6 family and Pentium® processors. For these processors, the recommended value (00B) enables writeback for the data cache of the Pentium® processor and for the L1 data cache and L2 cache of the P6 family processors. In the Intel486™ processor, setting these flags to (00B) enables write-through for the cache.

External system hardware can force the Pentium® processor to disable caching or to use the write-through cache policy should that be required. Refer to the *Pentium® Processor Data Book*

for more information about hardware control of the Pentium® processor caches. In the P6 family processors, the MTRRs can be used to override the CD and NW flags (refer to Table 9-6, in Chapter 9, *Memory Cache Control*).

The P6 family and Pentium® processors support page-level cache management in the same manner as the Intel486™ processor by using the PCD and PWT flags in control register CR3, the page-directory entries, and the page-table entries. The Intel486™ processor, however, is not affected by the state of the PWT flag since the internal cache of the Intel486™ processor is a write-through cache.

18.22.1. Self-Modifying Code with Cache Enabled

On the Intel486™ processor, a write to an instruction in the cache will modify it in both the cache and memory. If the instruction was prefetched before the write, however, the old version of the instruction could be the one executed. To prevent this problem, it is necessary to flush the instruction prefetch unit of the Intel486™ processor by coding a jump instruction immediately after any write that modifies an instruction. The P6 family and Pentium® processors, however, check whether a write may modify an instruction that has been prefetched for execution. This check is based on the linear address of the instruction. If the linear address of an instruction is found to be present in the prefetch queue, the P6 family and Pentium® processors flush the prefetch queue, eliminating the need to code a jump instruction after any writes that modify an instruction.

Because the linear address of the write is checked against the linear address of the instructions that have been prefetched, special care must be taken for self-modifying code to work correctly when the physical addresses of the instruction and the written data are the same, but the linear addresses differ. In such cases, it is necessary to execute a serializing operation to flush the prefetch queue after the write and before executing the modified instruction. Refer to Section 7.4., “Serializing Instructions” in Chapter 7, *Multiple-Processor Management* for more information on serializing instructions.

NOTE

The check on linear addresses described above is not in practice a concern for compatibility. Applications that include self-modifying code use the same linear address for modifying and fetching the instruction. System software, such as a debugger, that might possibly modify an instruction using a different linear address than that used to fetch the instruction must execute a serializing operation, such as IRET, before the modified instruction is executed.

18.23. PAGING

This section identifies enhancements made to the paging mechanism and implementation differences in the paging mechanism for various Intel Architecture processors.

18.23.1. Large Pages

The Pentium® processor extended the memory management/paging facilities of the Intel Architecture to allow large (4Mbytes) pages sizes (refer to Section 3.6.1., "Paging Options" in Chapter 3, *Protected-Mode Memory Management*). The initial P6 family processor (the Pentium® Pro processor) added a 2MByte page size to the Intel Architecture in conjunction with the physical address extension (PAE) feature (refer to Section 3.8., "Physical Address Extension" in Chapter 3, *Protected-Mode Memory Management*).

The availability of large pages on any Intel Architecture processor can be determined via feature bit 3 (PSE) of register EDX after the CPUID instruction has been execution with an argument of 1. Intel processors that do not support the CPUID instruction do not support page size enhancements. (Refer to "CPUID—CPU Identification" in Chapter 3, *Instruction Set Reference*, of the *Intel Architecture Software Developer's Manual, Volume 2*, and AP-485, *Intel Processor Identification and the CPUID Instruction*, for more information on the CPUID instruction.)

18.23.2. PCD and PWT Flags

The PCD and PWT flags were introduced to the Intel Architecture in the Intel486™ processor to control the caching of pages:

- PCD (page-level cache disable) flag—Controls caching on a page-by-page basis.
- PWT (page-level write-through) flag—Controls the write-through/writeback caching policy on a page-by-page basis. Since the internal cache of the Intel486™ processor is a write-through cache, it is not affected by the state of the PWT flag.

18.23.3. Enabling and Disabling Paging

Paging is enabled and disabled by loading a value into control register CR0 that modifies the PG flag. For backward and forward compatibility with all Intel Architecture processors, Intel recommends that the following operations be performed when enabling or disabling paging:

1. Execute a MOV CR0, REG instruction to either set (enable paging) or clear (disable paging) the PG flag.
2. Execute a near JMP instruction.

The sequence bounded by the MOV and JMP instructions should be identity mapped (that is, the instructions should reside on a page whose linear and physical addresses are identical).

For the P6 family processors, the MOV CR0, REG instruction is serializing, so the jump operation is not required. However, for backwards compatibility, the JMP instruction should still be included.

18.24. STACK OPERATIONS

This section identifies the differences in the stack mechanism for the various Intel Architecture processors.

18.24.1. Selector Pushes and Pops

When pushing a segment selector onto the stack, the Intel486™ processor writes 2 bytes onto 4-byte stacks and decrements ESP by 4. The P6 family and Pentium® processors write 4 bytes, with the upper 2 bytes being zeros.

When popping a segment selector from the stack, the Intel486™ processor reads only 2 bytes. The P6 family and Pentium® processors read 4 bytes and discard the upper 2 bytes. This operation may have an effect if the ESP is close to the stack-segment limit. On the P6 family and Pentium® processors, stack location at ESP plus 4 may be above the stack limit, in which case a stack fault exception (#SS) will be generated. On the Intel486™ processor, stack location at ESP plus 2 may be less than the stack limit and no exception is generated.

For a POP-to-memory instruction that meets the following conditions:

- The stack segment size is 16-bit
- Any 32-bit addressing form with the SIB byte specifying ESP as the base register
- The initial stack pointer is FFFCh (32-bit operand) or FFFEh (16-bit operand) and will wrap around to 0h as a result of the POP operation

the result of the memory write is specific to the processor-family. For example, in Pentium® II and Pentium® Pro processors, the result of the memory write is SS:0h plus any scaled index and displacement. In Pentium® and Pentium® Pro processors, the result of the memory write may be either a stack fault (real mode or protected mode with stack segment size of 64Kbyte), or write to SS:10000h plus any scaled index and displacement (protected mode and stack segment size exceeds 64Kbyte).

18.24.2. Error Code Pushes

The Intel486™ processor implements the error code pushed on the stack as a 16-bit value. When pushed onto a 32-bit stack, the Intel486™ processor only pushes 2 bytes and updates ESP by 4. The P6 family and Pentium® processors' error code is a full 32 bits with the upper 16 bits set to zero. The P6 family and Pentium® processors, therefore, push 4 bytes and update ESP by 4. Any code that relies on the state of the upper 16 bits may produce inconsistent results.

18.24.3. Fault Handling Effects on the Stack

During the handling of certain instructions, such as CALL and PUSHA, faults may occur in different sequences for the different processors. For example, during far calls, the Intel486™ processor pushes the old CS and EIP before a possible branch fault is resolved. A branch fault

is a fault from a branch instruction occurring from a segment limit or access rights violation. If a branch fault is taken, the Intel486™ and P6 family processors will have corrupted memory below the stack pointer. However, the ESP register is backed up to make the instruction restartable. The P6 family processors issue the branch before the pushes. Therefore, if a branch fault does occur, these processors do not corrupt memory below the stack pointer. This implementation difference, however, does not constitute a compatibility problem, as only values at or above the stack pointer are considered to be valid.

18.24.4. Interlevel RET/IRET From a 16-Bit Interrupt or Call Gate

If a call or interrupt is made from a 32-bit stack environment through a 16-bit gate, only 16 bits of the old ESP can be pushed onto the stack. On the subsequent RET/IRET, the 16-bit ESP is popped but the full 32-bit ESP is updated since control is being resumed in a 32-bit stack environment. The Intel486™ processor writes the SS selector into the upper 16 bits of ESP. The P6 family and Pentium® processors write zeros into the upper 16 bits.

18.25. MIXING 16- AND 32-BIT SEGMENTS

The features of the 16-bit Intel 286 processor are an object-code compatible subset of those of the 32-bit Intel Architecture processors. The D (default operation size) flag in segment descriptors indicates whether the processor treats a code or data segment as a 16-bit or 32-bit segment; the B(default stack size) flag in segment descriptors indicates whether the processor treats a stack segment as a 16-bit or 32-bit segment.

The segment descriptors used by the Intel 286 processor are supported by the 32-bit Intel Architecture processors if the Intel-reserved word (highest word) of the descriptor is clear. On the 32-bit Intel Architecture processors, this word includes the upper bits of the base address and the segment limit.

The segment descriptors for data segments, code segments, local descriptor tables (there are no descriptors for global descriptor tables), and task gates are the same for the 16- and 32-bit processors. Other 16-bit descriptors (TSS segment, call gate, interrupt gate, and trap gate) are supported by the 32-bit processors. The 32-bit processors also have descriptors for TSS segments, call gates, interrupt gates, and trap gates that support the 32-bit architecture. Both kinds of descriptors can be used in the same system.

For those segment descriptors common to both 16- and 32-bit processors, clear bits in the reserved word cause the 32-bit processors to interpret these descriptors exactly as an Intel 286 processor does, that is:

- Base Address—The upper 8 bits of the 32-bit base address are clear, which limits base addresses to 24 bits.
- Limit—The upper 4 bits of the limit field are clear, restricting the value of the limit field to 64 Kbytes.
- Granularity bit—The G (granularity) flag is clear, indicating the value of the 16-bit limit is interpreted in units of 1 byte.

- Big bit—In a data-segment descriptor, the B flag is clear in the segment descriptor used by the 32-bit processors, indicating the segment is no larger than 64 Kbytes.
- Default bit—In a code-segment descriptor, the D flag is clear, indicating 16-bit addressing and operands are the default. In a stack-segment descriptor, the D flag is clear, indicating use of the SP register (instead of the ESP register) and a 64-Kbyte maximum segment limit.

For information on mixing 16- and 32-bit code in applications, refer to Chapter 17, *Mixing 16-Bit and 32-Bit Code*.

18.26. SEGMENT AND ADDRESS WRAPAROUND

This section discusses differences in segment and address wraparound between the P6 family, Pentium®, Intel486™, Intel386™, Intel 286, and 8086 processors.

18.26.1. Segment Wraparound

On the 8086 processor, an attempt to access a memory operand that crosses offset 65,535 or 0FFFFH or offset 0 (for example, moving a word to offset 65,535 or pushing a word when the stack pointer is set to 1) causes the offset to wrap around modulo 65,536 or 010000H. With the Intel 286 processor, any base and offset combination that addresses beyond 16 MBytes wraps around to the 1 MByte of the address space. The P6 family, Pentium®, Intel486™, and Intel386™ processors in real-address mode generate an exception in these cases:

- A general-protection exception (#GP) if the segment is a data segment (that is, if the CS, DS, ES, FS, or GS register is being used to address the segment).
- A stack-fault exception (#SS) if the segment is a stack segment (that is, if the SS register is being used).

An exception to this behavior occurs when a stack access is data aligned, and the stack pointer is pointing to the last aligned piece of data that size at the top of the stack (ESP is FFFFFFFCH). When this data is popped, no segment limit violation occurs and the stack pointer will wrap around to 0.

The address space of the P6 family, Pentium®, and Intel486™ processors may wraparound at 1 MByte in real-address mode. An external A20M# pin forces wraparound if enabled. On Intel 8086 processors, it is possible to specify addresses greater than 1 MByte. For example, with a selector value FFFFH and an offset of FFFFH, the effective address would be 10FFEFH (1 MByte plus 65519 bytes). The 8086 processor, which can form addresses up to 20 bits long, truncates the uppermost bit, which “wraps” this address to FFEFH. However, the P6 family, Pentium®, and Intel486™ processors do not truncate this bit if A20M# is not enabled.

If a stack operation wraps around the address limit, shutdown occurs. (The 8086 processor does not have a shutdown mode nor a limit.)

18.27. WRITE BUFFERS AND MEMORY ORDERING

The Pentium® Pro and Pentium® II processors provide a write buffer for temporary storage of writes (stores) to memory (refer to Section 9.11., “Write Buffer”, in Chapter 9, *Memory Cache Control*). The Pentium® III processor has 4 write buffers. Writes stored in the write buffer(s) are always written to memory in program order, with the exception of “fast string” store operations (refer to Section 7.2.3., “Out of Order Stores From String Operations in P6 Family Processors” in Chapter 7, *Multiple-Processor Management*).

The Pentium® processor has two write buffers, one corresponding to each of the pipelines. Writes in these buffers are always written to memory in the order they were generated by the processor core.

It should be noted that only memory writes are buffered and I/O writes are not. The P6 family, Pentium®, and Intel486™ processors do not synchronize the completion of memory writes on the bus and instruction execution after a write. An I/O, locked, or serializing instruction needs to be executed to synchronize writes with the next instruction (refer to Section 7.4., “Serializing Instructions” in Chapter 7, *Multiple-Processor Management*).

The P6 family processors use processor ordering to maintain consistency in the order that data is read (loaded) and written (stored) in a program and the order the processor actually carries out the reads and writes. With this type of ordering, reads can be carried out speculatively and in any order, reads can pass buffered writes, and writes to memory are always carried out in program order. (Refer to Section 7.2., “Memory Ordering” in Chapter 7, *Multiple-Processor Management* for more information about processor ordering.) The Pentium® III processor introduced a new instruction to serialize writes and make them globally visible. Memory ordering issues can arise between a producer and a consumer of data. The SFENCE instruction provides a performance-efficient way of ensuring ordering between routines that produce weakly-ordered results and routines that consume this data.

No re-ordering of reads occurs on the Pentium® processor, except under the condition noted in Section 7.2.1., “Memory Ordering in the Pentium® and Intel486™ Processors” in Chapter 7, *Multiple-Processor Management*, and in the following paragraph describing the Intel486™ processor. Specifically, the write buffers are flushed before the IN instruction is executed. No reads (as a result of cache miss) are reordered around previously generated writes sitting in the write buffers. The implication of this is that the write buffers will be flushed or emptied before a subsequent bus cycle is run on the external bus.

On both the Intel486™ and Pentium® processors, under certain conditions, a memory read will go onto the external bus before the pending memory writes in the buffer even though the writes occurred earlier in the program execution. A memory read will only be reordered in front of all writes pending in the buffers if all writes pending in the buffers are cache hits and the read is a cache miss. Under these conditions, the Intel486™ and Pentium® processors will not read from an external memory location that needs to be updated by one of the pending writes.

During a locked bus cycle, the Intel486™ processor will always access external memory, it will never look for the location in the on-chip cache. All data pending in the Intel486™ processor's write buffers will be written to memory before a locked cycle is allowed to proceed to the external bus. Thus, the locked bus cycle can be used for eliminating the possibility of reordering read cycles on the Intel486™ processor. The Pentium® processor does check its cache on a read-

modify-write access and, if the cache line has been modified, writes the contents back to memory before locking the bus. The P6 family processors write to their cache on a read-modify-write operation (if the access does not split across a cache line) and does not write back to system memory. If the access does split across a cache line, it locks the bus and accesses system memory.

I/O reads are never reordered in front of buffered memory writes on an Intel Architecture processor. This ensures an update of all memory locations before reading the status from an I/O device.

18.28. BUS LOCKING

The Intel 286 processor performs the bus locking differently than the Intel P6 family, Pentium®, Intel486™, and Intel386™ processors. Programs that use forms of memory locking specific to the Intel 286 processor may not run properly when run on later processors.

A locked instruction is guaranteed to lock only the area of memory defined by the destination operand, but may lock a larger memory area. For example, typical 8086 and Intel 286 configurations lock the entire physical memory space. Programmers should not depend on this.

On the Intel 286 processor, the LOCK prefix is sensitive to IOPL. If the CPL is greater than the IOPL, a general-protection exception (#GP) is generated. On the Intel386™ DX, Intel486™, and Pentium®, and P6 family processors, no check against IOPL is performed.

The Pentium® processor automatically asserts the LOCK# signal when acknowledging external interrupts. After signaling an interrupt request, an external interrupt controller may use the data bus to send the interrupt vector to the processor. After receiving the interrupt request signal, the processor asserts LOCK# to insure that no other data appears on the data bus until the interrupt vector is received. This bus locking does not occur on the P6 family processors.

18.29. BUS HOLD

Unlike the 8086 and Intel 286 processors, but like the Intel386™ and Intel486™ processors, the P6 family and Pentium® processors respond to requests for control of the bus from other potential bus masters, such as DMA controllers, between transfers of parts of an unaligned operand, such as two words which form a doubleword. Unlike the Intel386™ processor, the P6 family, Pentium® and Intel486™ processors respond to bus hold during reset initialization.

18.30. TWO WAYS TO RUN INTEL 286 PROCESSOR TASKS

When porting 16-bit programs to run on 32-bit Intel Architecture processors, there are two approaches to consider:

- Porting an entire 16-bit software system to a 32-bit processor, complete with the old operating system, loader, and system builder. Here, all tasks will have 16-bit TSSs. The 32-bit processor is being used as if it were a faster version of the 16-bit processor.

- Porting selected 16-bit applications to run in a 32-bit processor environment with a 32-bit operating system, loader, and system builder. Here, the TSSs used to represent 286 tasks should be changed to 32-bit TSSs. It is possible to mix 16 and 32-bit TSSs, but the benefits are small and the problems are great. All tasks in a 32-bit software system should have 32-bit TSSs. It is not necessary to change the 16-bit object modules themselves; TSSs are usually constructed by the operating system, by the loader, or by the system builder. Refer to Chapter 17, *Mixing 16-Bit and 32-Bit Code* for more detailed information about mixing 16-bit and 32-bit code.

Because the 32-bit processors use the contents of the reserved word of 16-bit segment descriptors, 16-bit programs that place values in this word may not run correctly on the 32-bit processors.

18.31. MODEL-SPECIFIC EXTENSIONS TO THE INTEL ARCHITECTURE

Certain extensions to the Intel Architecture are specific to a processor or family of Intel Architecture processors and may not be implemented or implemented in the same way in future processors. The following sections describe these model-specific extensions. The CPUID instruction indicates the availability of some of the model-specific features.

18.31.1. Model-Specific Registers

The Pentium® processor introduced a set of model-specific registers (MSRs) for use in controlling hardware functions and performance monitoring. To access these MSRs, two new instructions were added to the Intel Architecture: read MSR (RDMSR) and write MSR (WRMSR). The MSRs in the Pentium® processor are not guaranteed to be duplicated or provided in the next generation Intel Architecture processors.

The P6 family processors greatly increased the number of MSRs available to software. Refer to Appendix B, *Model-Specific Registers* for a complete list of the available MSRs. The new registers control the debug extensions, the performance counters, the machine-check exception capability, the machine-check architecture, and the MTRRs. These registers are accessible using the RDMSR and WRMSR instructions. Specific information on some of these new MSRs is provided in the following sections. As with the Pentium® processor MSR, the P6 family processor MSRs are not guaranteed to be duplicated or provided in the next generation Intel Architecture processors.

18.31.2. RDMSR and WRMSR Instructions

The RDMSR (read model-specific register) and WRMSR (write model-specific register) instructions recognize a much larger number of model-specific registers in the P6 family processors. (Refer to “RDMSR—Read from Model Specific Register” and “WRMSR—Write to Model Specific Register” in Chapter 3 of the *Intel Architecture Software Developer’s Manual, Volume 2*, for more information about these instructions.)

18.31.3. Memory Type Range Registers

Memory type range registers (MTRRs) are a new feature introduced into the Intel Architecture in the Pentium® Pro processor. MTRRs allow the processor to optimize memory operations for different types of memory, such as RAM, ROM, frame buffer memory, and memory-mapped I/O.

MTRRs are MSRs that contain an internal map of how physical address ranges are mapped to various types of memory. The processor uses this internal memory map to determine the cacheability of various physical memory locations and the optimal method of accessing memory locations. For example, if a memory location is specified in an MTRR as write-through memory, the processor handles accesses to this location as follows. It reads data from that location in lines and caches the read data or maps all writes to that location to the bus and updates the cache to maintain cache coherency. In mapping the physical address space with MTRRs, the processor recognizes five types of memory: uncacheable (UC), uncacheable, speculatable, write-combining (USWC), write-through (WT), write-protected (WP), and writeback (WB).

Earlier Intel Architecture processors (such as the Intel486™ and Pentium® processors) used the KEN# (cache enable) pin and external logic to maintain an external memory map and signal cacheable accesses to the processor. The MTRR mechanism simplifies hardware designs by eliminating the KEN# pin and the external logic required to drive it.

Refer to Chapter 8, *Processor Management and Initialization* and Appendix B, *Model-Specific Registers* for more information on the MTRRs.

18.31.4. Machine-Check Exception and Architecture

The Pentium® processor introduced a new exception called the machine-check exception (#MC, interrupt 18). This exception is used to detect hardware-related errors, such as a parity error on a read cycle.

The P6 family processors extend the types of errors that can be detected and that generate a machine-check exception. It also provides a new machine-check architecture for recording information about a machine-check error and provides extended recovery capability.

The machine-check architecture provides several banks of reporting registers for recording machine-check errors. Each bank of registers is associated with a specific hardware unit in the processor. The primary focus of the machine checks is on bus and interconnect operations; however, checks are also made of translation lookaside buffer (TLB) and cache operations.

The machine-check architecture can correct some errors automatically and allow for reliable restart of instruction execution. It also collects sufficient information for software to use in correcting other machine errors not corrected by hardware.

Refer to Chapter 13, *Machine-Check Architecture* for more information on the machine-check exception and the machine-check architecture.

18.31.5. Performance-Monitoring Counters

The P6 family and Pentium® processors provide two performance-monitoring counters for use in monitoring internal hardware operations. These counters are event counters that can be programmed to count a variety of different types of events, such as the number of instructions decoded, number of interrupts received, or number of cache loads. Appendix A, *Performance-Monitoring Events* lists all the events that can be counted (Table A-1 for the P6 family processors and Table A-2 for the Pentium® processors). The counters are set up, started, and stopped using two MSRs and the RDMSR and WRMSR instructions. For the P6 family processors, the current count for a particular counter can be read using the new RDPMC instruction.

The performance-monitoring counters are useful for debugging programs, optimizing code, diagnosing system failures, or refining hardware designs. Refer to Chapter 15, *Debugging and Performance Monitoring* for more information on these counters.

A

Performance-Monitoring Events

APPENDIX A
PERFORMANCE-MONITORING EVENTS

This appendix contains list of the performance-monitoring events that can be monitored with the Intel Architecture processors. In the Intel Architecture processors, the ability to monitor performance events and the events that can be monitored are model specific. Section A.1., “P6 Family Processor Performance-Monitoring Events” lists and describes the events that can be monitored with the P6 family of processors. Section A.2., “Pentium® Processor Performance-Monitoring Events” lists and describes the events that can be monitored with Pentium® processors.

A.1. P6 FAMILY PROCESSOR PERFORMANCE-MONITORING EVENTS

Table A-1 lists the events that can be counted with the performance-monitoring counters and read with the RDPMC instruction for the P6 family of processors. The unit column gives the microarchitecture or bus unit that produces the event; the event number column gives the hexadecimal number identifying the event; the mnemonic event name column gives the name of the event; the unit mask column gives the unit mask required (if any); the description column describes the event; and the comments column gives additional information about the event.

These performance-monitoring events are intended to be used as guides for performance tuning. The counter values reported are not guaranteed to be absolutely accurate and should be used as a relative guide for tuning. Known discrepancies are documented where applicable.

Some performance events are model specific. Those added in later generations of the P6 family processors are listed in this table. Performance events are not architecturally guaranteed in future versions of the P6 family processors. All performance event encodings not listed in Table A-1 are reserved and their use will result in undefined counter results.

Refer to the end of the table for notes related to certain entries in the table.

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
Data Cache Unit (DCU)	43H	DATA_MEM_REFS	00H	All loads from any memory type. All stores to any memory type. Each part of a split is counted separately. The internal logic counts not only memory loads and stores, but also internal retries. Note: 80-bit floating-point accesses are double counted, since they are decomposed into a 16-bit exponent load and a 64-bit mantissa load. Memory accesses are only counted when they are actually performed (such as a load that gets squashed because a previous cache miss is outstanding to the same address, and which finally gets performed, is only counted once). Does not include I/O accesses, or other nonmemory accesses.	
	45H	DCU_LINES_IN	00H	Total lines allocated in the DCU.	
	46H	DCU_M_LINES_IN	00H	Number of M state lines allocated in the DCU.	
	47H	DCU_M_LINES_OUT	00H	Number of M state lines evicted from the DCU. This includes evictions via snoop HITM, intervention or replacement.	
	48H	DCU_MISS_OUTSTANDING	00H	Weighted number of cycles while a DCU miss is outstanding, incremented by the number of outstanding cache misses at any particular time. Cacheable read requests only are considered. Uncacheable requests are excluded. Read-for-ownerships are counted, as well as line fills, invalidates, and stores.	An access that also misses the L2 is short-changed by 2 cycles (i.e., if counts N cycles, should be N+2 cycles). Subsequent loads to the same cache line will not result in any additional counts. Count value not precise, but still useful.
Instruction Fetch Unit (IFU)	80H	IFU_IFETCH	00H	Number of instruction fetches, both cacheable and noncacheable, including UC fetches.	
	81H	IFU_IFETCH_MISS	00H	Number of instruction fetch misses. All instruction fetches that do not hit the IFU (i.e., that produce memory requests). Includes UC accesses.	
	85H	ITLB_MISS	00H	Number of ITLB misses.	

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
	86H	IFU_MEM_STALL	00H	Number of cycles instruction fetch is stalled, for any reason. Includes IFU cache misses, ITLB misses, ITLB faults, and other minor stalls.	
	87H	ILD_STALL	00H	Number of cycles that the instruction length decoder is stalled.	
L2 Cache[1]	28H	L2_IFETCH	MESI 0FH	Number of L2 instruction fetches. This event indicates that a normal instruction fetch was received by the L2. The count includes only L2 cacheable instruction fetches; it does not include UC instruction fetches. It does not include ITLB miss accesses.	
	29H	L2_LD	MESI 0FH	Number of L2 data loads. This event indicates that a normal, unlocked, load memory access was received by the L2. It includes only L2 cacheable memory accesses; it does not include I/O accesses, other nonmemory accesses, or memory accesses such as UC/WT memory accesses. It does include L2 cacheable TLB miss memory accesses.	
	2AH	L2_ST	MESI 0FH	Number of L2 data stores. This event indicates that a normal, unlocked, store memory access was received by the L2. Specifically, it indicates that the DCU sent a read-for-ownership request to the L2. It also includes Invalid to Modified requests sent by the DCU to the L2. It includes only L2 cacheable memory accesses; it does not include I/O accesses, other nonmemory accesses, or memory accesses such as UC/WT memory accesses. It includes TLB miss memory accesses.	
	24H	L2_LINES_IN	00H	Number of lines allocated in the L2.	

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
	26H	L2_LINES_OUT	00H	Number of lines removed from the L2 for any reason.	
	25H	L2_M_LINES_INM	00H	Number of modified lines allocated in the L2.	
	27H	L2_M_LINES_OUTM	00H	Number of modified lines removed from the L2 for any reason.	
	2EH	L2_RQSTS	MESI 0FH	Total number of L2 requests.	
	21H	L2_ADS	00H	Number of L2 address strobes.	
	22H	L2_DBUS_BUSY	00H	Number of cycles during which the L2 cache data bus was busy.	
	23H	L2_DBUS_BUSY_RD	00H	Number of cycles during which the data bus was busy transferring read data from L2 to the processor.	
External Bus Logic (EBL)[2]	62H	BUS_DRDY_ CLOCKS	00H (Self) 20H (Any)	Number of clocks during which DRDY# is asserted. Utilization of the external system data bus during data transfers.	Unit Mask = 00H counts bus clocks when the processor is driving DRDY#. Unit Mask = 20H counts in processor clocks when any agent is driving DRDY#.
	63H	BUS_LOCK_ CLOCKS	00H (Self) 20H (Any)	Number of clocks during which LOCK# is asserted on the external system bus.[3]	Always counts in processor clocks.
	60H	BUS_REQ_ OUTSTANDING	00H (Self)	Number of bus requests outstanding. This counter is incremented by the number of cacheable read bus requests outstanding in any given cycle.	Counts only DCU full-line cacheable reads, not RFOs, writes, instruction fetches, or anything else. Counts “waiting for bus to complete” (last data chunk received).
	65H	BUS_TRAN_BRD	00H (Self) 20H (Any)	Number of burst read transactions.	
	66H	BUS_TRAN_RFO	00H (Self) 20H (Any)	Number of completed read for ownership transactions.	
	67H	BUS_TRANS_WB	00H (Self) 20H (Any)	Number of completed write back transactions.	
	68H	BUS_TRAN_ IFETCH	00H (Self) 20H (Any)	Number of completed instruction fetch transactions.	

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
	69H	BUS_TRAN_INVAL	00H (Self) 20H (Any)	Number of completed invalidate transactions.	
	6AH	BUS_TRAN_PWR	00H (Self) 20H (Any)	Number of completed partial write transactions.	
	6BH	BUS_TRANS_P	00H (Self) 20H (Any)	Number of completed partial transactions.	
	6CH	BUS_TRANS_IO	00H (Self) 20H (Any)	Number of completed I/O transactions.	
	6DH	BUS_TRAN_DEF	00H (Self) 20H (Any)	Number of completed deferred transactions.	
	6EH	BUS_TRAN_BURST	00H (Self) 20H (Any)	Number of completed burst transactions.	
	70H	BUS_TRAN_ANY	00H (Self) 20H (Any)	Number of all completed bus transactions. Address bus utilization can be calculated knowing the minimum address bus occupancy. Includes special cycles, etc.	
	6FH	BUS_TRAN_MEM	00H (Self) 20H (Any)	Number of completed memory transactions.	
	64H	BUS_DATA_RCV	00H (Self)	Number of bus clock cycles during which this processor is receiving data.	
	61H	BUS_BNR_DRV	00H (Self)	Number of bus clock cycles during which this processor is driving the BNR# pin.	

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
	7AH	BUS_HIT_DRV	00H (Self)	Number of bus clock cycles during which this processor is driving the HIT# pin.	Includes cycles due to snoop stalls. The event counts correctly, but the BPM*i* pins function as follows based on the setting of the PC bits (bit 19 in the PerfEvtSel0 and PerfEvtSel1 registers): If the core-clock-to- bus-clock ratio is 2:1 or 3:1, and a PC bit is set, the BPM*i*pins will be asserted for a single clock when the counters overflow. If the PC bit is clear, the processor toggles the BPM*i*pins when the counter overflows. If the clock ratio is not 2:1 or 3:1, the BPM*i* pins will not function for these performance-monitoring counter events.
	7BH	BUS_HITM_DRV	00H (Self)	Number of bus clock cycles during which this processor is driving the HITM# pin.	Includes cycles due to snoop stalls. The event counts correctly, but the BPM*i* pins function as follows based on the setting of the PC bits (bit 19 in the PerfEvtSel0 and PerfEvtSel1 registers): If the core-clock-to- bus-clock ratio is 2:1 or 3:1, and a PC bit is set, the BPM*i*pins will be asserted for a single clock when the counters overflow. If the PC bit is clear, the processor toggles the BPM*i*pins when the counter overflows. If the clock ratio is not 2:1 or 3:1, the BPM*i* pins will not function for these performance-monitoring counter events.
	7EH	BUS_SNOOP_STALL	00H (Self)	Number of clock cycles during which the bus is snoop stalled.	

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
Floating-Point Unit	C1H	FLOPS	00H	Number of computational floating-point operations retired. Excludes floating-point computational operations that cause traps or assists. Includes floating-point computational operations executed by the assist handler. Includes internal sub-operations for complex floating-point instructions like transcendentals. Excludes floating-point loads and stores.	Counter 0 only.
	10H	FP_COMP_OPS_EXE	00H	Number of computational floating-point operations executed. The number of FADD, FSUB, FCOM, FMULs, integer MULs and IMULs, FDIVs, FPREMs, FSQRTS, integer DIVs, and IDIVs. Note not the number of cycles, but the number of operations. This event does not distinguish an FADD used in the middle of a transcendental flow from a separate FADD instruction.	Counter 0 only.
	11H	FP_ASSIST	00H	Number of floating-point exception cases handled by microcode.	Counter 1 only. This event includes counts due to speculative execution.
	12H	MUL	00H	Number of multiplies. Note: Includes integer as well as FP multiplies and is speculative.	Counter 1 only.
	13H	DIV	00H	Number of divides. Note: Includes integer as well as FP divides and is speculative.	Counter 1 only.
	14H	CYCLES_DIV_BUSY	00H	Number of cycles during which the divider is busy, and cannot accept new divides. Note: Includes integer and FP divides, FPREM, FPSQRT, etc., and is speculative.	Counter 0 only.

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
Memory Ordering	03H	LD_BLOCKS	00H	Number of store buffer blocks. Includes counts caused by preceding stores whose addresses are unknown, preceding stores whose addresses are known but whose data is unknown, and preceding stores that conflicts with the load but which incompletely overlap the load.	
	04H	SB_DRAINS	00H	Number of store buffer drain cycles. Incremented every cycle the store buffer is draining. Draining is caused by serializing operations like CPUID, synchronizing operations like XCHG, interrupt acknowledgment, as well as other conditions (such as cache flushing).	
	05H	MISALIGN_ MEM_REF	00H	Number of misaligned data memory references. Incremented by 1 every cycle, during which either the proc load or store pipeline dispatches a misaligned uop. Counting is performed if it is the first or second half, or if it is blocked, squashed, or missed. Note: In this context, misaligned means crossing a 64-bit boundary.	It should be noted that MISALIGN_MEM_REF is only an approximation to the true number of misaligned memory references. The value returned is roughly proportional to the number of misaligned memory accesses, i.e., the size of the problem.
	07H	EMON_KNI_PREF_ DISPATCHED	00H 01H 02H 03H	Number of Streaming SIMD extensions prefetch/weakly-ordered instructions dispatched (speculative prefetches are included in counting) 0: prefetch NTA 1: prefetch T1 2: prefetch T2 3: weakly ordered stores	Counters 0 and 1. Pentium® III processor only.
	4BH	EMON_KNI_PREF_ MISS	00H 01H 02H 03H	Number of prefetch/weakly-ordered instructions that miss all caches. 0: prefetch NTA 1: prefetch T1 2: prefetch T2 3: weakly ordered stores	Counters 0 and 1. Pentium® III processor only.

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
Instruction Decoding and Retirement	C0H	INST_RETIRED	OOH	Number of instructions retired.	A hardware interrupt received during/after the last iteration of the REP STOS flow causes the counter to undercount by 1 instruction.
	C2H	UOPS_RETIRED	00H	Number of UOPs retired.	
	D0H	INST_DECODED	00H	Number of instructions decoded.	
	D8H	EMON_KNI_INST_RETIRED	00H 01H	Number of Streaming SIMD extensions retired 0: packed & scalar 1: scalar	Counters 0 and 1. Pentium® III processor only.
	D9H	EMON_KNI_COMP_INST_RET	00H 01H	Number of Streaming SIMD extensions computation instructions retired. 0: packed and scalar 1: scalar	Counters 0 and 1. Pentium® III processor only.
Interrupts	C8H	HW_INT_RX	00H	Number of hardware interrupts received.	
	C6H	CYCLES_INT_MASKED	00H	Number of processor cycles for which interrupts are disabled.	
	C7H	CYCLES_INT_PENDING_AND_MASKED	00H	Number of processor cycles for which interrupts are disabled and interrupts are pending.	
Branches	C4H	BR_INST_RETIRED	00H	Number of branch instructions retired.	
	C5H	BR_MISS_PRED_RETIRED	00H	Number of mispredicted branches retired.	
	C9H	BR_TAKEN_RETIRED	00H	Number of taken branches retired.	
	CAH	BR_MISS_PRED_TAKEN_RET	00H	Number of taken mispredictions branches retired.	
	E0H	BR_INST_DECODED	00H	Number of branch instructions decoded.	
	E2H	BTB_MISSES	00H	Number of branches for which the BTB did not produce a prediction.	
	E4H	BR_BOGUS	00H	Number of bogus branches.	
	E6H	BACLEARS	00H	Number of times BACLEAR is asserted. This is the number of times that a static branch prediction was made, in which the branch decoder decided to make a branch prediction because the BTB did not.	

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
Stalls	A2H	RESOURCE_STALLS	00H	Incremented by 1 during every cycle for which there is a resource related stall. Includes register renaming buffer entries, memory buffer entries. Does not include stalls due to bus queue full, too many cache misses, etc. In addition to resource related stalls, this event counts some other events. Includes stalls arising during branch misprediction recovery, such as if retirement of the mispredicted branch is delayed and stalls arising while store buffer is draining from synchronizing operations.	
	D2H	PARTIAL_RAT_ STALLS	00H	Number of cycles or events for partial stalls. Note: Includes flag partial stalls.	
Segment Register Loads	06H	SEGMENT_REG_ LOADS	00H	Number of segment register loads.	
Clocks	79H	CPU_CLK_ UNHALTED	00H	Number of cycles during which the processor is not halted.	
MMX™ Unit	B0H	MMX_INSTR_EXEC	00H	Number of MMX™ Instructions Executed.	Available in Intel® Celeron™, Pentium® II and Pentium® II Xeon™ processors only. Does not account for MOVQ and MOVD stores from register to memory.
	B1H	MMX_SAT_ INSTR_EXEC	00H	Number of MMX™ Saturating Instructions Executed.	Available in Pentium® II & Pentium® III processors only.
	B2H	MMX_UOPS_EXEC	0FH	Number of MMX™ UOPS Executed.	Available in Pentium® II & Pentium® III processors only.
	B3H	MMX_INSTR_ TYPE_EXEC	01H 02H 04H 08H 10H 20H	MMX™ packed multiply instructions executed. MMX™ packed shift instructions executed. MMX™ pack operation instructions executed. MMX™ unpack operation instructions executed. MMX™ packed logical instructions executed. MMX™ packed arithmetic instructions executed.	Available in Pentium® II & Pentium® III processors only.

Table A-1. Events That Can Be Counted with the P6 Family Performance-Monitoring Counters (Contd.)

Unit	Event Num.	Mnemonic Event Name	Unit Mask	Description	Comments
	CCH	FP_MMX_TRANS	00H 01H	Transitions from MMX™ instruction to floating-point instructions. Transitions from floating-point instructions to MMX™ instructions.	Available in Pentium® II & Pentium® III processors only.
	CDH	MMX_ASSIST	00H	Number of MMX™ Assists (that is, the number of EMMS instructions executed).	Available in Pentium® II & Pentium® III processors only.
	CEH	MMX_INSTR_RET	00H	Number of MMX™ Instructions Retired.	Available in Pentium® II processor only.
Segment Register Renaming	D4H	SEG_RENAME_ STALLS	 01H 02H 04H 08H 0FH	Number of Segment Register Renaming Stalls: Segment register ES Segment register DS Segment register FS Segment register FS Segment registers ES + DS + FS + GS	Available in Pentium® II & Pentium® III processors only.
	D5H	SEG_REG_ RENAMES	 01H 02H 04H 08H 0FH	Number of Segment Register Renames: Segment register ES Segment register DS Segment register FS Segment register FS Segment registers ES + DS + FS + GS	Available in Pentium® II & Pentium® III processors only.
	D6H	RET_SEG_ RENAMES	00H	Number of segment register rename events retired.	Available in Pentium® II & Pentium® III processors only.

NOTES:

1. Several L2 cache events, where noted, can be further qualified using the Unit Mask (UMSK) field in the PerfEvtSel0 and PerfEvtSel1 registers. The lower 4 bits of the Unit Mask field are used in conjunction with L2 events to indicate the cache state or cache states involved. The P6 family processors identify cache states using the “MESI” protocol and consequently each bit in the Unit Mask field represents one of the four states: UMSK[3] = M (8H) state, UMSK[2] = E (4H) state, UMSK[1] = S (2H) state, and UMSK[0] = I (1H) state. UMSK[3:0] = MESI” (FH) should be used to collect data for all states; UMSK = 0H, for the applicable events, will result in nothing being counted.
2. All of the external bus logic (EBL) events, except where noted, can be further qualified using the Unit Mask (UMSK) field in the PerfEvtSel0 and PerfEvtSel1 registers. Bit 5 of the UMSK field is used in conjunction with the EBL events to indicate whether the processor should count transactions that are self-generated (UMSK[5] = 0) or transactions that result from any processor on the bus (UMSK[5] = 1).
3. L2 cache locks, so it is possible to have a zero count.

A.2. PENTIUM® PROCESSOR PERFORMANCE-MONITORING EVENTS

Table A-2 lists the events that can be counted with the performance-monitoring counters for the Pentium® processor. The Event Number column gives the hexadecimal code that identifies the event and that is entered in the ES0 or ES1 (event select) fields of the CESR MSR. The Mnemonic Event Name column gives the name of the event, and the Description and Comments columns give detailed descriptions of the events. Most events can be counted with either counter 0 or counter 1; however, some events can only be counted with only counter 0 or only counter 1 (as noted).

NOTE

The events in the table that are shaded are implemented only in the Pentium® processor with MMX™ technology.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters

Event Num.	Mnemonic Event Name	Description	Comments
00H	DATA_READ	Number of memory data reads (internal data cache hit and miss combined).	Split cycle reads are counted individually. Data Memory Reads that are part of TLB miss processing are not included. These events may occur at a maximum of two per clock. I/O is not included.
01H	DATA_WRITE	Number of memory data writes (internal data cache hit and miss combined), I/O is not included.	Split cycle writes are counted individually. These events may occur at a maximum of two per clock. I/O is not included.
0H2	DATA_TLB_MISS	Number of misses to the data cache translation look-aside buffer.	
03H	DATA_READ_MISS	Number of memory read accesses that miss the internal data cache whether or not the access is cacheable or noncacheable.	Additional reads to the same cache line after the first BRDY# of the burst line fill is returned but before the final (fourth) BRDY# has been returned, will not cause the counter to be incremented additional times. Data accesses that are part of TLB miss processing are not included. Accesses directed to I/O space are not included.
04H	DATA WRITE MISS	Number of memory write accesses that miss the internal data cache whether or not the access is cacheable or noncacheable.	Data accesses that are part of TLB miss processing are not included. Accesses directed to I/O space are not included.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
05H	WRITE_HIT_TO_ M-_OR_E-STATE_LINES	Number of write hits to exclusive or modified lines in the data cache.	These are the writes that may be held up if EWBE# is inactive. These events may occur a maximum of two per clock.
06H	DATA_CACHE_ LINES_ WRITTEN_BACK	Number of dirty lines (all) that are written back, regardless of the cause.	Replacements and internal and external snoops can all cause writeback and are counted.
07H	EXTERNAL_ SNOOPS	Number of accepted external snoops whether they hit in the code cache or data cache or neither.	Assertions of EADS# outside of the sampling interval are not counted, and no internal snoops are counted.
08H	EXTERNAL_DATA_ CACHE_SNOOP_ HITS	Number of external snoops to the data cache.	Snoop hits to a valid line in either the data cache, the data line fill buffer, or one of the write back buffers are all counted as hits.
09H	MEMORY ACCESSES IN BOTH PIPES	Number of data memory reads or writes that are paired in both pipes of the pipeline.	These accesses are not necessarily run in parallel due to cache misses, bank conflicts, etc.
0AH	BANK CONFLICTS	Number of actual bank conflicts.	
0BH	MISALIGNED DATA MEMORY OR I/O REFERENCES	Number of memory or I/O reads or writes that are misaligned.	A 2- or 4-byte access is misaligned when it crosses a 4-byte boundary; an 8-byte access is misaligned when it crosses an 8-byte boundary. Ten byte accesses are treated as two separate accesses of 8 and 2 bytes each.
0CH	CODE READ	Number of instruction reads whether the read is cacheable or noncacheable.	Individual 8-byte noncacheable instruction reads are counted.
0DH	CODE TLB MISS	Number of instruction reads that miss the code TLB whether the read is cacheable or noncacheable.	Individual 8-byte noncacheable instruction reads are counted.
0EH	CODE CACHE MISS	Number of instruction reads that miss the internal code cache whether the read is cacheable or noncacheable.	Individual 8-byte noncacheable instruction reads are counted.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
0FH	ANY SEGMENT REGISTER LOADED	Number of writes into any segment register in real or protected mode including the LDTR, GDTR, IDTR, and TR.	Segment loads are caused by explicit segment register load instructions, far control transfers, and task switches. Far control transfers and task switches causing a privilege level change will signal this event twice. Note that interrupts and exceptions may initiate a far control transfer.
10H	Reserved		
11H	Reserved		
12H	Branches	Number of taken and not taken branches, including conditional branches, jumps, calls, returns, software interrupts, and interrupt returns.	Also counted as taken branches are serializing instructions, VERR and VERW instructions, some segment descriptor loads, hardware interrupts (including FLUSH#), and programmatic exceptions that invoke a trap or fault handler. The pipe is not necessarily flushed. The number of branches actually executed is measured, not the number of predicted branches.
13H	BTB_HITS	Number of BTB hits that occur.	Hits are counted only for those instructions that are actually executed.
14H	TAKEN_BRANCH_ OR_BTB_HIT	Number of taken branches or BTB hits that occur.	This event type is a logical OR of taken branches and BTB hits. It represents an event that may cause a hit in the BTB. Specifically, it is either a candidate for a space in the BTB or it is already in the BTB.
15H	PIPELINE FLUSHES	Number of pipeline flushes that occur. Pipeline flushes are caused by BTB misses on taken branches, mispredictions, exceptions, interrupts, and some segment descriptor loads.	The counter will not be incremented for serializing instructions (serializing instructions cause the prefetch queue to be flushed but will not trigger the Pipeline Flushed event counter) and software interrupts (software interrupts do not flush the pipeline).

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
16H	INSTRUCTIONS_ EXECUTED	Number of instructions executed (up to two per clock).	Invocations of a fault handler are considered instructions. All hardware and software interrupts and exceptions will also cause the count to be incremented. Repeat prefixed string instructions will only increment this counter once despite the fact that the repeat loop executes the same instruction multiple times until the loop criteria is satisfied. This applies to all the Repeat string instruction prefixes (i.e., REP, REPE, REPZ, REPNE, and REPNZ). This counter will also only increment once per each HLT instruction executed regardless of how many cycles the processor remains in the HALT state.
17H	INSTRUCTIONS_ EXECUTED_ V PIPE	Number of instructions executed in the V_pipe. It indicates the number of instructions that were paired.	This event is the same as the 16H event except it only counts the number of instructions actually executed in the V-pipe.
18H	BUS_CYCLE_ DURATION	Number of clocks while a bus cycle is in progress. This event measures bus use.	The count includes HLDA, AHOLD, and BOFF# clocks.
19H	WRITE_BUFFER_ FULL_STALL_ DURATION	Number of clocks while the pipeline is stalled due to full write buffers.	Full write buffers stall data memory read misses, data memory write misses, and data memory write hits to S-state lines. Stalls on I/O accesses are not included.
1AH	WAITING_FOR_ DATA_MEMORY_ READ_STALL_ DURATION	Number of clocks while the pipeline is stalled while waiting for data memory reads.	Data TLB Miss processing is also included in the count. The pipeline stalls while a data memory read is in progress including attempts to read that are not bypassed while a line is being filled.
1BH	STALL ON WRITE TO AN E- OR M-STATE LINE	Number of stalls on writes to E- or M-state lines	
1CH	LOCKED BUS CYCLE	Number of locked bus cycles that occur as the result of the LOCK prefix or LOCK instruction, page-table updates, and descriptor table updates.	Only the read portion of the locked read-modify-write is counted. Split locked cycles (SCYC active) count as two separate accesses. Cycles restarted due to BOFF# are not re-counted.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
1DH	I/O READ OR WRITE CYCLE	Number of bus cycles directed to I/O space.	Misaligned I/O accesses will generate two bus cycles. Bus cycles restarted due to BOFF# are not re-counted.
1EH	NONCACHEABLE_ MEMORY_READS	Number of noncacheable instruction or data memory read bus cycles. Count includes read cycles caused by TLB misses, but does not include read cycles to I/O space.	Cycles restarted due to BOFF# are not re-counted.
1FH	PIPELINE_AGI_ STALLS	Number of address generation interlock (AGI) stalls. An AGI occurring in both the U- and V-pipelines in the same clock signals this event twice.	An AGI occurs when the instruction in the execute stage of either of U- or V-pipelines is writing to either the index or base address register of an instruction in the D2 (address generation) stage of either the U- or V- pipelines.
20H	Reserved		
21H	Reserved		
22H	FLOPS	Number of floating-point operations that occur.	Number of floating-point adds, subtracts, multiplies, divides, remainders, and square roots are counted. The transcendental instructions consist of multiple adds and multiplies and will signal this event multiple times. Instructions generating the divide-by-zero, negative square root, special operand, or stack exceptions will not be counted. Instructions generating all other floating-point exceptions will be counted. The integer multiply instructions and other instructions which use the FPU will be counted.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
23H	BREAKPOINT MATCH ON DR0 REGISTER	Number of matches on register DR0 breakpoint.	The counters is incremented regardless if the breakpoints are enabled or not. However, if breakpoints are not enabled, code breakpoint matches will not be checked for instructions executed in the V-pipe and will not cause this counter to be incremented. (They are checked on instruction executed in the U-pipe only when breakpoints are not enabled.) These events correspond to the signals driven on the BP[3:0] pins. Refer to Chapter 15, *Debugging and Performance Monitoring*, for more information.
24H	BREAKPOINT MATCH ON DR1 REGISTER	Number of matches on register DR1 breakpoint.	Refer to comment for 23H event.
25H	BREAKPOINT MATCH ON DR2 REGISTER	Number of matches on register DR2 breakpoint.	Refer to comment for 23H event.
26H	BREAKPOINT MATCH ON DR3 REGISTER	Number of matches on register DR3 breakpoint.	Refer to comment for 23H event.
27H	HARDWARE INTERRUPTS	Number of taken INTR and NMI interrupts.	
28H	DATA_READ_OR_ WRITE	Number of memory data reads and/or writes (internal data cache hit and miss combined).	Split cycle reads and writes are counted individually. Data Memory Reads that are part of TLB miss processing are not included. These events may occur at a maximum of two per clock. I/O is not included.
29H	DATA_READ_MISS OR_WRITE MISS	Number of memory read and/or write accesses that miss the internal data cache whether or not the access is cacheable or noncacheable.	Additional reads to the same cache line after the first BRDY# of the burst line fill is returned but before the final (fourth) BRDY# has been returned, will not cause the counter to be incremented additional times. Data accesses that are part of TLB miss processing are not included. Accesses directed to I/O space are not included.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
2AH	BUS_OWNERSHIP_ LATENCY (Counter 0)	The time from LRM bus ownership request to bus ownership granted (that is, the time from the earlier of a PBREQ (0), PHITM# or HITM# assertion to a PBGNT assertion).	The ratio of the 2AH events counted on counter 0 and counter 1 is the average stall time due to bus ownership conflict.
2AH	BUS OWNERSHIP TRANSFERS (Counter 1)	The number of buss ownership transfers (that is, the number of PBREQ (0) assertions.	The ratio of the 2AH events counted on counter 0 and counter 1 is the average stall time due to bus ownership conflict.
2BH	MMX_ INSTRUCTIONS_ EXECUTED_ U-PIPE (Counter 0)	Number of MMX™ instructions executed in the U-pipe.	
2BH	MMX_ INSTRUCTIONS_ EXECUTED_ V-PIPE (Counter 1)	Number of MMX™ instructions executed in the V-pipe.	
2CH	CACHE_M-STATE_LINE_ SHARING (Counter 0)	Number of times a processor identified a hit to a modified line due to a memory access in the other processor (PHITM (O)).	If the average memory latencies of the system are known, this event enables the user to count the Write Backs on PHITM(O) penalty and the Latency on Hit Modified(I) penalty.
2CH	CACHE_LINE_ SHARING (Counter 1)	Number of shared data lines in the L1 cache (PHIT (O)).	
2DH	EMMS_ INSTRUCTIONS_ EXECUTED (Counter 0)	Number of EMMS instructions executed.	
2DH	TRANSITIONS_ BETWEEN_MMX_ AND_FP_ INSTRUCTIONS (Counter 1)	Number of transitions between MMX™ and floating-point instructions or vice versa. An even count indicates the processor is in MMX™ state. an odd count indicates it is in FP state.	This event counts the first floating-point instruction following an MMX™ instruction or first MMX™ instruction following a floating-point instruction. The count may be used to estimate the penalty in transitions between floating-point state and MMX™ state.
2DH	BUS_UTILIZATION_ DUE_TO_ PROCESSOR_ ACTIVITY (Counter 0)	Number of clocks the bus is busy due to the processor's own activity, i.e., the bus activity that is caused by the processor.	

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
2EH	WRITES_TO_ NONCACHEABLE_ MEMORY (Counter 1)	Number of write accesses to noncacheable memory.	The count includes write cycles caused by TLB misses and I/O write cycles. Cycles restarted due to BOFF# are not re-counted.
2FH	SATURATING_ MMX_ INSTRUCTIONS_ EXECUTED (Counter 0)	Number of saturating MMX™ instructions executed, independently of whether they actually saturated.	
2FH	SATURATIONS_ PERFORMED (Counter 1)	Number of MMX™ instructions that used saturating arithmetic and that at least one of its results actually saturated.	If an MMX™ instruction operating on 4 doublewords saturated in three out of the four results, the counter will be incremented by one only.
30H	NUMBER_OF_ CYCLES_NOT_IN_ HALT_STATE (Counter 0)	Number of cycles the processor is not idle due to HLT instruction.	This event will enable the user to calculate “net CPI”. Note that during the time that the processor is executing the HLT instruction, the Time-Stamp Counter is not disabled. Since this event is controlled by the Counter Controls CC0, CC1 it can be used to calculate the CPI at CPL=3, which the TSC cannot provide.
30H	DATA_CACHE_ TLB_MISS_ STALL_DURATION (Counter 1)	Number of clocks the pipeline is stalled due to a data cache translation look-aside buffer (TLB) miss.	
31H	MMX_ INSTRUCTION_ DATA_READS (Counter 0)	Number of MMX™ instruction data reads.	
31H	MMX_ INSTRUCTION_ DATA_READ_ MISSES (Counter 1)	Number of MMX™ instruction data read misses.	
32H	FLOATING_POINT_ STALLS_DURATION (Counter 0)	Number of clocks while pipe is stalled due to a floating-point freeze.	
32H	TAKEN_BRANCHES (Counter 1)	Number of taken branches.	
33H	D1_STARVATION_ AND_FIFO_IS_ EMPTY (Counter 0)	Number of times D1 stage cannot issue ANY instructions since the FIFO buffer is empty.	The D1 stage can issue 0, 1, or 2 instructions per clock if those are available in an instructions FIFO buffer.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
33H	D1_STARVATION_ AND_ONLY_ONE_ INSTRUCTION_IN_ FIFO (Counter 1)	Number of times the D1 stage issues just a single instruction since the FIFO buffer had just one instruction ready.	The D1 stage can issue 0, 1, or 2 instructions per clock if those are available in an instructions FIFO buffer. When combined with the previously defined events, Instruction Executed (16H) and Instruction Executed in the V-pipe (17H), this event enables the user to calculate the numbers of time pairing rules prevented issuing of two instructions.
34H	MMX_ INSTRUCTION_ DATA_WRITES (Counter 0)	Number of data writes caused by MMX™ instructions.	
34H	MMX_ INSTRUCTION_ DATA_WRITE_ MISSES (Counter 1)	Number of data write misses caused by MMX™ instructions.	
35H	PIPELINE_ FLUSHES_DUE_ TO_WRONG_ BRANCH_ PREDICTIONS (Counter 0)	Number of pipeline flushes due to wrong branch predictions resolved in either the E-stage or the WB-stage.	The count includes any pipeline flush due to a branch that the pipeline did not follow correctly. It includes cases where a branch was not in the BTB, cases where a branch was in the BTB but was mispredicted, and cases where a branch was correctly predicted but to the wrong address. Branches are resolved in either the Execute stage (E-stage) or the Writeback stage (WB-stage). In the later case, the misprediction penalty is larger by one clock. The difference between the 35H event count in counter 0 and counter 1 is the number of E-stage resolved branches.
35H	PIPELINE_ FLUSHES_DUE_ TO_WRONG_ BRANCH_ PREDICTIONS_ RESOLVED_IN_ WB-STAGE (Counter 1)	Number of pipeline flushes due to wrong branch predictions resolved in the WB-stage.	Refer to note for event 35H (Counter 0).
36H	MISALIGNED_ DATA_MEMORY_ REFERENCE_ON_ MMX_ INSTRUCTIONS (Counter 0)	Number of misaligned data memory references when executing MMX™ instructions.	

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
36H	PIPELINE_ ISTALL_FOR_MMX_ INSTRUCTION_ DATA_MEMORY_ READS (Counter 1)	Number clocks during pipeline stalls caused by waits form MMX™ instruction data memory reads.	
37H	MISPREDICTED_ OR_ UNPREDICTED_ RETURNS (Counter 1)	Number of returns predicted incorrectly or not predicted at all.	The count is the difference between the total number of executed returns and the number of returns that were correctly predicted. Only RET instructions are counted (for example, IRET instructions are not counted).
37H	PREDICTED_ RETURNS (Counter 1)	Number of predicted returns (whether they are predicted correctly and incorrectly.	Only RET instructions are counted (for example, IRET instructions are not counted).
38H	MMX_MULTIPLY_ UNIT_INTERLOCK (Counter 0)	Number of clocks the pipe is stalled since the destination of previous MMX™ multiply instruction is not ready yet.	The counter will not be incremented if there is another cause for a stall. For each occurrence of a multiply interlock this event will be counted twice (if the stalled instruction comes on the next clock after the multiply) or by one (if the stalled instruction comes two clocks after the multiply).
38H	MOVD/MOVQ_ STORE_STALL_ DUE_TO_ PREVIOUS_MMX_ OPERATION (Counter 1)	Number of clocks a MOVD/MOVQ instruction store is stalled in D2 stage due to a previous MMX™ operation with a destination to be used in the store instruction.	
39H	RETURNS (Counter 0)	Number or returns executed.	Only RET instructions are counted; IRET instructions are not counted. Any exception taken on a RET instruction and any interrupt recognized by the processor on the instruction boundary prior to the execution of the RET instruction will also cause this counter to be incremented.
39H	Reserved		
3AH	BTB_FALSE_ ENTRIES (Counter 0)	Number of false entries in the Branch Target Buffer.	False entries are causes for misprediction other than a wrong prediction.

Table A-2. Events That Can Be Counted with the Pentium® Processor Performance-Monitoring Counters (Contd.)

Event Num.	Mnemonic Event Name	Description	Comments
3AH	BTB_MISS_ PREDICTION_ON_ NOT-TAKEN_ BRANCH (Counter 1)	Number of times the BTB predicted a not-taken branch as taken.	
3BH	FULL_WRITE_ BUFFER_STALL_ DURATION_ WHILE_ EXECUTING_MMX_ INSTRUCTIONS (Counter 0)	Number of clocks while the pipeline is stalled due to full write buffers while executing MMX™ instructions.	
3BH	STALL_ON_MMX_ INSTRUCTION_ WRITE_TO E-_OR_ M-STATE_LINE (Counter 1)	Number of clocks during stalls on MMX™ instructions writing to E- or M-state lines.	

B

Model-Specific Registers

APPENDIX B
MODEL-SPECIFIC REGISTERS

Table B-1 lists the model-specific registers (MSRs) that can be read with the RDMSR and written with the WRMSR instructions. Register addresses are given in both hexadecimal and decimal; the register name is the mnemonic register name; the bit description describes individual bits in registers.

NOTE

The registers with addresses 0H, 1H, 10H, 11H, 12H, and 13H in Table B-1 are available only in the Pentium® processor. Code code that accesses registers 0H, 1H, and 10H will run on a P6 family processor without generating exceptions; however, code that accesses registers 11H, 12H, and 13H will generate exceptions on a P6 family processor. The MSRs in this table that are shaded are available only in the Pentium® II and later processors in the P6 family.

Table B-1. Model-Specific Registers (MSRs)

Register Address		Register Name	Bit Description
Hex	Dec		
0H	0	P5_MC_ADDR (Pentium® Processor Only)	
1H	1	P5_MC_TYPE (Pentium® Processor Only)	
10H	16	TSC	
11H	17	CESR (Pentium® Processor Only)	
12H	18	CTR0 (Pentium® Processor Only)	
13H	19	CTR1 (Pentium® Processor Only)	
1BH	27	APICBASE	
		7:0	Reserved
		8	Boot Strap Processor indicator Bit. BSP= 1
		10:9	Reserved
		11	APIC Global Enable Bit - Permanent til reset Enabled = 1, Disabled = 0
		31:12	APIC Base Address

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address		Register Name	Bit Description
Hex	Dec		
		63:32	Reserved
2AH	42	EBL_CR_POWERON	
		0	Reserved[1]
		1	Data Error Checking Enable 1 = Enabled 0 = Disabled Read/Write
		2	Response Error Checking Enable FRCERR Observation Enable 1 = Enabled 0 = Disabled Read/Write
		3	AERR# Drive Enable 1 = Enabled 0 = Disabled Read/Write
		4	BERR# Enable for initiator bus requests 1 = Enabled 0 = Disabled Read/Write
		5	Reserved
		6	BERR# Driver Enable for initiator internal errors 1 = Enabled 0 = Disabled Read/Write
		7	BINIT# Driver Enable 1 = Enabled 0 = Disabled Read/Write
		8	Output Tri-state Enabled 1 = Enabled 0 = Disabled Read
		9	Execute BIST 1 = Enabled 0 = Disabled Read
		10	AERR# Observation Enabled 1 = Enabled 0 = Disabled Read
		11	Reserved

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address		Register Name	Bit Description
Hex	Dec		
		12	BINIT# Observation Enabled 1 = Enabled 0 = Disabled Read
		13	In Order Queue Depth 1 = 1 0 = 8 Read
		14	1Mbyte Power on Reset Vector 1 = 1Mbyte 0 = 4Gbytes Read Only
		15	FRC Mode Enable 1 = Enabled 0 = Disabled Read Only
		17:16	APIC Cluster ID Read
		19:18	Reserved
		21: 20	Symmetric Arbitration ID Read
		24:22	Clock Frequency Ratio Read
		25	Reserved
		26	Low Power Mode Enable Read/Write
		63:27	Reserved[1]
33H	51	TEST_CTL	Test Control Register
		29:0	Reserved
		30	Streaming Buffer Disable
		31	Disable LOCK# assertion for split locked access
79H	121	BIOS_UPDT_TRIG	BIOS Update Trigger Register
88	136	BBL_CR_D0[63:0]	Chunk 0 data register D[63:0]: used to write to and read from the L2
89	137	BBL_CR_D1[63:0]	Chunk 1 data register D[63:0]: used to write to and read from the L2
8A	138	BBL_CR_D2[63:0]	Chunk 2 data register D[63:0]: used to write to and read from the L2

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address			
Hex	**Dec**	**Register Name**	**Bit Description**
8BH	139	BIOS_SIGN/BBL_CR_D3[63:0]	BIOS Update Signature Register or Chunk 3 data register D[63:0]: used to write to and read from the L2 depending on the usage model
C1H	193	PERFCTR0	
C2H	194	PERFCTR1	
FEH	254	MTRRcap	
116	278	BBL_CR_ADDR [63:0] BBL_CR_ADDR [63:32] BBL_CR_ADDR [31:3] BBL_CR_ADDR [2:0]	Address register: used to send specified address (A31-A3) to L2 during cache initialization accesses. Reserved, Address bits [35:3] Reserved Set to 0.
118	280	BBL_CR_DECC[63:0]	Data ECC register D[7:0]: used to write ECC and read ECC to/from L2
119	281	BBL_CR_CTL BL_CR_CTL[63:22] BBL_CR_CTL[21] BBL_CR_CTL[20:19] BBL_CR_CTL[18] BBL_CR_CTL[17] BBL_CR_CTL[16] BBL_CR_CTL[15:14] BBL_CR_CTL[13:12] BBL_CR_CTL[11:10] BBL_CR_CTL[9:8] BBL_CR_CTL[7] BBL_CR_CTL[6:5] BBL_CR_CTL[4:0] 01100 01110 01111 00010 00011 010 + MESI encode 111 + MESI encode 100 + MESI encode	Control register: used to program L2 commands to be issued via cache configuration accesses mechanism. Also receives L2 lookup response Reserved Processor number[2] Disable = 1 Enable = 0 Reserved User supplied ECC Reserved L2 Hit Reserved State from L2 Modified - 11,Exclusive - 10, Shared - 01, Invalid - 00 Way from L2 Way 0 - 00, Way 1 - 01, Way 2 - 10, Way 3 - 11 Way to L2 Reserved State to L2 L2 Command Data Read w/ LRU update (RLU) Tag Read w/ Data Read (TRR) Tag Inquire (TI) L2 Control Register Read (CR) L2 Control Register Write (CW) Tag Write w/ Data Read (TWR) Tag Write w/ Data Write (TWW) Tag Write (TW)
11A	282	BBL_CR_TRIG	Trigger register: used to initiate a cache configuration accesses access, Write only with Data=0.
11B	283	BBL_CR_BUSY	Busy register: indicates when a cache configuration accesses L2 command is in progress. D[0] = 1 = BUSY

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address			
Hex	**Dec**	**Register Name**	**Bit Description**
11E	286	BBL_CR_CTL3	Control register 3: used to configure the L2 Cache
		BBL_CR_CTL3[63:26]	Reserved
		BBL_CR_CTL3[25]	Cache bus fraction (read only)
		BBL_CR_CTL3[24]	Reserved
		BBL_CR_CTL3[23]	L2 Hardware Disable (read only)
		BBL_CR_CTL3[22:20]	L2 Physical Address Range support
		111	64Gbytes
		110	32Gbytes
		101	16Gbytes
		100	8Gbytes
		011	4Gbytes
		010	2Gbytes
		001	1Gbytes
		000	512Mbytes
		BBL_CR_CTL3[19]	Reserved
		BBL_CR_CTL3[18]	Cache State error checking enable (read/write)
		BBL_CR_CTL3[17:13	Cache size per bank (read/write)
		00001	256Kbytes
		00010	512Kbytes
		00100	1Mbyte
		01000	2Mbyte
		10000	4Mbytes
		BBL_CR_CTL3[12:11]	Number of L2 banks (read only)
		BBL_CR_CTL3[10:9]	L2 Associativity (read only)
		00	Direct Mapped
		01	2 Way
		10	4 Way
		11	Reserved
		BBL_CR_CTL3[8]	L2 Enabled (read/write)
		BBL_CR_CTL3[7]	CRTN Parity Check Enable (read/write)
		BBL_CR_CTL3[6]	Address Parity Check Enable (read/write)
		BBL_CR_CTL3[5]	ECC Check Enable (read/write)
		BBL_CR_CTL3[4:1]	L2 Cache Latency (read/write)
		BBL_CR_CTL3[0]	L2 Configured (read/write)
179H	377	MCG_CAP	
17AH	378	MCG_STATUS	
17BH	379	MCG_CTL	
186H	390	EVNTSEL0	
		7:0	Event Select (Refer to Performance Counter section for a list of event encodings)
		15:8	UMASK: Unit Mask Register Set to 0 to enable all count options
		16	USER: Controls the counting of events at Privilege levels of 1, 2, and 3

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address		Register Name	Bit Description
Hex	Dec		
		17	OS: Controls the counting of events at Privilege level of 0
		18	E: Occurrence/Duration Mode Select 1 = Occurrence 0 = Duration
		19	PC: Enabled the signaling of performance counter overflow via BP0 pin
		20	INT: Enables the signaling of counter overflow via input to APIC 1 = Enable 0 = Disable
		22	ENABLE: Enables the counting of performance events in both counters 1 = Enable 0 = Disable
		23	INV: Inverts the result of the CMASK condition 1 = Inverted 0 = Non-Inverted
		31:24	CMASK: Counter Mask
187H	391	EVNTSEL1	
		7:0	Event Select (Refer to Performance Counter section for a list of event encodings)
		15:8	UMASK: Unit Mask Register Set to Zero to enable all count options
		16	USER: Controls the counting of events at Privilege levels of 1, 2, and 3
		17	OS: Controls the counting of events at Privilege level of 0
		18	E: Occurrence/Duration Mode Select 1 = Occurrence 0 = Duration
		19	PC: Enabled the signaling of performance counter overflow via BP0 pin.

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address		Register Name	Bit Description
Hex	Dec		
		20	INT: Enables the signaling of counter overflow via input to APIC 1 = Enable 0 = Disable
		23	INV: Inverts the result of the CMASK condition 1 = Inverted 0 = Non-Inverted
		31:24	CMASK: Counter Mask
1D9H	473	DEBUGCTLMSR	
		0	Enable/Disable Last Branch Records
		1	Branch Trap Flag
		2	Performance Monitoring/Break Point Pins
		3	Performance Monitoring/Break Point Pins
		4	Performance Monitoring/Break Point Pins
		5	Performance Monitoring/Break Point Pins
		6	Enable/Disable Execution Trace Messages
		13:7	Reserved
		14	Enable/Disable Execution Trace Messages
		15	Enable/Disable Execution Trace Messages
1DBH	475	LASTBRANCHFROMIP	
1DCH	476	LASTBRANCHTOIP	
1DDH	477	LASTINTFROMIP	
1DEH	478	LASTINTTOIP	
1E0H	480	ROB_CR_BKUPTMPDR6	
		1:0	Reserved
		2	Fast String Enable bit. Default is enabled
200H	512	MTRRphysBase0	
201H	513	MTRRphysMask0	
202H	514	MTRRphysBase1	
203H	515	MTRRphysMask1	
204H	516	MTRRphysBase2	
205H	517	MTRRphysMask2	

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address		Register Name	Bit Description
Hex	Dec		
206H	518	MTRRphysBase3	
207H	519	MTRRphysMask3	
208H	520	MTRRphysBase4	
209H	521	MTRRphysMask4	
20AH	522	MTRRphysBase5	
20BH	523	MTRRphysMask5	
20CH	524	MTRRphysBase6	
20DH	525	MTRRphysMask6	
20EH	526	MTRRphysBase7	
20FH	527	MTRRphysMask7	
250H	592	MTRRfix64K_00000	
258H	600	MTRRfix16K_80000	
259H	601	MTRRfix16K_A0000	
268H	616	MTRRfix4K_C0000	
269H	617	MTRRfix4K_C8000	
26AH	618	MTRRfix4K_D0000	
26BH	619	MTRRfix4K_D8000	
26CH	620	MTRRfix4K_E0000	
26DH	621	MTRRfix4K_E8000	
26EH	622	MTRRfix4K_F0000	
26FH	623	MTRRfix4K_F8000	
2FFH	767	MTRRdefType	
		2:0	Default memory type
		10	Fixed MTRR enable
		11	MTRR Enable
400H	1024	MC0_CTL	
401H	1025	MC0_STATUS	
		63	MC_STATUS_V
		62	MC_STATUS_O
		61	MC_STATUS_UC
		60	MC_STATUS_EN
		59	MC_STATUS_MISCV

Table B-1. Model-Specific Registers (MSRs) (Contd.)

Register Address		Register Name	Bit Description
Hex	Dec		
		58	MC_STATUS_ADDRV
		57	MC_STATUS_DAM
		31:16	MC_STATUS_MCACOD
		15:0	MC_STATUS_MSCOD
402H	1026	MC0_ADDR	
403H	1027	MC0_MISC	Defined in MCA architecture but not implemented in the P6 family processors
404H	1028	MC1_CTL	
405H	1029	MC1_STATUS	Bit definitions same as MC0_STATUS
406H	1030	MC1_ADDR	
407H	1031	MC1_MISC	Defined in MCA architecture but not implemented in the P6 family processors
408H	1032	MC2_CTL	
409H	1033	MC2_STATUS	Bit definitions same as MC0_STATUS
40AH	1034	MC2_ADDR	
40BH	1035	MC2_MISC	Defined in MCA architecture but not implemented in the P6 family processors
40CH	1036	MC4_CTL	
40DH	1037	MC4_STATUS	Bit definitions same as MC0_STATUS
40EH	1038	MC4_ADDR	Defined in MCA architecture but not implemented in P6 Family processors
40FH	1039	MC4_MISC	Defined in MCA architecture but not implemented in the P6 family processors
410H	1040	MC3_CTL	
411H	1041	MC3_STATUS	Bit definitions same as MC0_STATUS
412H	1042	MC3_ADDR	
413H	1043	MC3_MISC	Defined in MCA architecture but not implemented in the P6 family processors

NOTES:

1. Bit 0 of this register has been redefined several times, and is no longer used in Pentium® Pro processors.
2. The processor number feature may be disabled by setting bit 21 of the BBL_CR_CTL MSR (model-specific register address 119h) to “1”. Once set, bit 21 of the BBL_CR_CTL may not be cleared. This bit is write-once. The processor number feature will be disabled until the processor is reset.
3. The Pentium® III processor will prevent FSB frequency overclocking with a new shutdown mechanism. If the FSB frequency selected is greater than the internal FSB frequency the processor will shutdown. If the FSB selected is less than the internal FSB frequency the BIOS may choose to use bit 11 to implement its own shutdown policy.

C

Dual-Processor Bootup Sequence Example

(Specific to Pentium® Processors)

APPENDIX C
DUAL-PROCESSOR (DP) BOOTUP SEQUENCE EXAMPLE (SPECIFIC TO PENTIUM® PROCESSORS)

The following example shows the DP protocol for booting two Pentium® processors (a primary processor and a secondary processor) in a DP system and initializing their APICs. For dual-processor systems based on Pentium® processors, the APIC ID of the primary processor is always 0.

The following constants and data definitions are used in the accompanying code examples. They are based on the addresses of the APIC registers as defined in Table 7-1 in Chapter 7.

```
ICR_LOW          EQU 0FEE00300H
ICR_HI           EQU 0FEE00310H
SVR              EQU 0FEE000F0H
APIC_ID          EQU 0FEE00020H
LVT3             EQU 0FEE00370H
APIC_ENABLED     EQU 100H
BOOT_ID          DW  ?
UPGRD_ID         DW  ?
```

C.1. PRIMARY PROCESSOR'S SEQUENCE OF EVENTS

1. The primary processor boots at the Intel Architecture address and executes until it is ready to activate the secondary processor.
2. Initialization software should execute the CPUID instruction to determine if the primary processor is a "GenuineIntel." The values of EAX and EDX should be saved into a configuration RAM space for use later.

   If the type field (in the EAX register following CPUID instruction execution) is 01B in bits 13 and 14, respectively, the processor is a future Pentium® OverDrive® processor and the Pentium® processor (735/90, 815/100, 1000,120, 1110/133) has been put to sleep. This means the system is a uniprocessor system and normal AT system configuration can continue. Go to step 14 to configure the APIC.

   If the type field is 00B, the processor is the primary processor and detection of the secondary processor is required. Continue with steps 3 through 13.

3. The following operation can be used to detect the secondary processor:

   Set a timer before sending the start-up IPI to the secondary processor. In the secondary processor's initialization routine, it should write a value into memory indicating its presence. The primary processor can then use the timer expiration to check if something has been written into memory. If the timer expires and nothing has been written into memory, the secondary processor is not present or some error has occurred.

4. Load start-up code for the secondary processor to execute into a 4-KByte page in the lower 1 MByte of memory.

5. Switch to protected mode (to access APIC address space above 1 MByte).

6. Determine the Pentium® processor's APIC ID from the local APIC ID register (default is 0):

```
MOV ESI, APIC_ID; address of local APIC ID register
MOV EAX, [ESI]
AND EAX, 0F000000H; zero out all other bits except APIC ID
MOV BOOT_ID, EAX; save in memory
```

   Save the ID in the configuration RAM (optional).

7. Determine APIC ID of the secondary processor and save it in the configuration RAM (optional).

```
MOV EAX, BOOT_ID
XOR EAX, 100000H; toggle lower bit of ID field (bit 24)
MOV SECOND_ID, EAX
```

8. Convert the base address of the 4-KByte page for the secondary processor's bootup code into 8-bit vector. The 8-bit vector defines the address of a 4-KByte page in the real-address mode address space (1-MByte space). For example, a vector of 0BDH specifies a start-up memory address of 000BD000H.

   Use steps 9 and 10 to use the LVT APIC error handling entry to deal with unsuccessful delivery of the start-up IPI.

9. Enable the local APIC by writing to spurious vector register (SVR). This is required to do APIC error handling via the local vector table.

```
MOV ESI, SVR    ; address of SVR
MOV EAX, [ESI]
OR  EAX, APIC_ENABLED; set bit 8 to enable (0 on reset)
MOV [ESI], EAX
```

10. Program LVT3 (APIC error interrupt vector) of the local vector table with an 8-bit vector for handling APIC errors.

```
MOV ESI, LVT3
MOV EAX, [ESI]
AND EAX, FFFFFF00H; clear out previous vector
OR EAX, 000000xxH; xx is the 8-bit vector for APIC error
                ; handling.
MOV [ESI], EAX
```

11. Write APIC ICRH with address of the secondary processor's APIC.

```
MOV ESI, ICR_HI ; address of ICR high dword
MOV EAX, [ESI]  ; get high word of ICR
AND EAX, 0F0FFFFFFH; zero out ID Bits
OR  EAX, SECOND_ID; write ID into appropriate bits - don't
                ; affect reserved bits
MOV [ESI], SECOND_ID; write upgrade ID to destination field
```

12. Set the timer with an appropriate value (~100 milliseconds).

13. Write APIC ICRL to send a start-up IPI message to the secondary processor via the APIC.

```
MOV ESI, ICR_LOW; write address of ICR low dword
MOV EAX, [ESI]  ; get low dword of ICR
AND EAX, 0FFF0F800H; zero out delivery mode and vector fields
OR  EAX, 000006xxH; 6 selects delivery mode 110 (StartUp IPI)
                ; xx should be vector of 4kb page as
                ; computed in Step 8.
MOV [ESI], EAX
```

14. Configure the APIC as appropriate.

C.2. SECONDARY PROCESSOR'S SEQUENCE OF EVENTS FOLLOWING RECEIPT OF START-UP IPI

If the secondary processor's APIC is to be used for symmetric multiprocessing, the secondary processor must undertake the following steps:

1. Switch to protected mode to access the APIC addresses.
2. Initialize its local APIC by writing to bit 8 of the SVR register and programming its LVT3 for error handling.
3. Configure the APIC as appropriate.
4. Enable interrupts.
5. (Optional.) Execute the CPUID instruction and write the results into the configuration RAM.
6. Do either of the following:
   - — Execute a HALT instruction and wait for an IPI from the operating system.
   - — Continue execution.

D

Multiple-Processor (MP) Bootup Sequence Example

(Specific to P6 Family Processors)

APPENDIX D
MULTIPLE-PROCESSOR (MP) BOOTUP SEQUENCE EXAMPLE (SPECIFIC TO P6 FAMILY PROCESSORS)

The following example illustrates the use of the MP protocol to boot two P6 family processors in a multiple-processor (MP) system and initialize their APICs. The primary processor (the processor that won the "race for the flag") is called the boot strap processor (BSP) and the secondary processor is called the application processor (AP).

The following constants and data definitions are used in the accompanying code examples. They are based on the addresses of the APIC registers as defined in Table 7-1 in Chapter 7.

```
ICR_LOW          EQU 0FEE00300H
ICR_HI           EQU 0FEE00310H
SVR              EQU 0FEE000F0H
APIC_ID          EQU 0FEE00020H
LVT3             EQU 0FEE00370H
APIC_ENABLED     EQU 100H
BOOT_ID          DW  ?
SECOND_ID        DW  ?
```

D.1. BSP'S SEQUENCE OF EVENTS

1. The BSP boots at the Intel Architecture address and executes until it is ready to activate the AP.
2. Initialization software should execute the CPUID instruction to determine if the BSP is a "GenuineIntel." The values of EAX and EDX should be saved into a configuration RAM space for use later.
3. The following operation can be used to detect the AP:

   Set a timer before sending the start-up IPI to the AP. In the AP's initialization routine, it should write a value into memory indicating its presence. The BSP can then use the timer expiration to check if something has been written into memory. If the timer expires and nothing has been written into memory, the AP is not present or some error has occurred.
4. Load start-up code for the AP to execute into a 4-KByte page in the lower 1 MByte of memory.

5. Switch to protected mode (to access APIC address space above 1 MByte) or change the APIC base to less than 1 MByte and insure it is mapped to an uncached (UC) memory type.
6. Determine the BSP's APIC ID from the local APIC ID register (default is 0):

```
MOV ESI, APIC_ID; address of local APIC ID register
MOV EAX, [ESI]
AND EAX, 0F000000H; zero out all other bits except APIC ID
MOV BOOT_ID, EAX; save in memory
```

   Save the ID in the configuration RAM (optional).

7. Determine APIC ID of the AP and save it in the configuration RAM (optional).

```
MOV EAX, BOOT_ID
XOR EAX, 100000H; toggle lower bit of ID field (bit 24)
MOV SECOND_ID, EAX
```

8. Convert the base address of the 4-KByte page for the AP's bootup code into 8-bit vector. The 8-bit vector defines the address of a 4-KByte page in the real-address mode address space (1-MByte space). For example, a vector of 0BDH specifies a start-up memory address of 000BD000H.

   Use steps 9 and 10 to use the LVT APIC error handling entry to deal with unsuccessful delivery of the start-up IPI.

9. Enable the local APIC by writing to spurious vector register (SVR). This is required to do APIC error handling via the local vector table.

```
MOV ESI, SVR    ; address of SVR
MOV EAX, [ESI]
OR  EAX, APIC_ENABLED; set bit 8 to enable (0 on reset)
MOV [ESI], EAX
```

10. Program LVT3 (APIC error interrupt vector) of the local vector table with an 8-bit vector for handling APIC errors.

```
MOV ESI, LVT3
MOV EAX, [ESI]
AND EAX, FFFFFF00H; clear out previous vector
OR EAX, 000000xxH; xx is the 8-bit vector for APIC error
                ; handling.
MOV [ESI], EAX
```

11. Write APIC ICRH with address of the AP's APIC.

```
MOV ESI, ICR_HI ; address of ICR high dword
MOV EAX, [ESI]  ; get high word of ICR
AND EAX, 0F0FFFFFH; zero out ID Bits
OR  EAX, SECOND_ID; write ID into appropriate bits - don't
                ; affect reserved bits
MOV [ESI], SECOND_ID; write upgrade ID to destination field
```

12. Initialize the memory location into which the AP will write to signal it's presence.
13. Set the timer with an appropriate value (~100 milliseconds).
14. Write APIC ICRL to send a start-up IPI message to the AP via the APIC.

```
MOV ESI, ICR_LOW; write address of ICR low dword
MOV EAX, [ESI]  ; get low dword of ICR
AND EAX, 0FFF0F800H; zero out delivery mode and vector fields
OR  EAX, 000006xxH; 6 selects delivery mode 110 (StartUp IPI)
                ; xx should be vector of 4kb page as
                ; computed in Step 8.
MOV [ESI], EAX
```

15. Wait for the timer interrupt or an AP signal appearing in memory.
16. If necessary, reconfigure the APIC and continue with the remaining system diagnostics as appropriate.

D.2. AP'S SEQUENCE OF EVENTS FOLLOWING RECEIPT OF START-UP IPI

If the AP's APIC is to be used for symmetric multiprocessing, the AP must undertake the following steps:

1. Switch to protected mode to access the APIC addresses.
2. Initialize its local APIC by writing to bit 8 of the SVR register and programming its LVT3 for error handling.
3. Configure the APIC as appropriate.
4. Enable interrupts.
5. (Optional) Execute the CPUID instruction and write the results into the configuration RAM.
6. Write into the memory location that is being used to signal to the BSP that the AP is executing.
7. Do either of the following:
   - — Continue execution (that is, self-configuration, MP Specification Configuration table completion).
   - — Execute a HLT instruction and wait for an IPI from the operating system.

E

Programming the LINT0 and LINT1 Inputs

APPENDIX E
PROGRAMMING THE LINT0 AND LINT1 INPUTS

The following procedure describes how to program the LINT0 and LINT1 local APIC pins on a processor after multiple processors have been booted and initialized (as described in Appendix C and Appendix D). In this example, LINT0 is programmed to be the ExtINT pin and LINT1 is programmed to be the NMI pin.

E.1. CONSTANTS

The following constants are defined:

```
LVT1        EQU 0FEE00350H
LVT2        EQU 0FEE00360H
LVT3        EQU 0FEE00370H
SVR         EQU 0FEE000F0H
```

E.2. LINT[0:1] PINS PROGRAMMING PROCEDURE

Use the following to program the LINT[1:0] pins:

1. Mask 8259 interrupts.
2. Enable APIC via SVR (spurious vector register) if not already enabled.

```
MOV ESI, SVR    ; address of SVR
MOV EAX, [ESI]
OR  EAX, APIC_ENABLED; set bit 8 to enable (0 on reset)
MOV [ESI], EAX
```

3. Program LVT1 as an ExtINT which delivers the signal to the INTR signal of all processors cores listed in the destination as an interrupt that originated in an externally connected interrupt controller.

```
MOV ESI, LVT1
MOV EAX, [ESI]
AND EAX, 0FFFE58FFH; mask off bits 8-10, 12, 14 and 16
OR  EAX, 700H   ; Bit 16=0 for not masked, Bit 15=0 for edge
                ; triggered, Bit 13=0 for high active input
                ; polarity, Bits 8-10 are 111b for ExtINT
MOV [ESI], EAX  ; Write to LVT1
```

4. Program LVT2 as NMI, which delivers the signal on the NMI signal of all processor cores listed in the destination.

```
MOV ESI, LVT2
MOV EAX, [ESI]
AND EAX, 0FFFE58FFH; mask off bits 8-10 and 15
OR  EAX, 000000400H; Bit 16=0 for not masked, Bit 15=0 edge
                ; triggered, Bit 13=0 for high active input
                ; polarity, Bits 8-10 are 100b for NMI
MOV [ESI], EAX  ; Write to LVT2
;Unmask 8259 interrupts and allow NMI.
```

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