Embedded Intel486™ Processor Family Developer's Manual

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The Intel486™ processors may contain design defects known as errata which may cause the products to deviate from published specifications. Currently characterized errata are available on request.

Copies of documents which have an ordering number and are referenced in this document, or other Intel literature, may be obtained from:

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Guide to this Manual

Chapter Contents

CHAPTER 1
GUIDE TO THIS MANUAL

This manual describes the embedded Intel486™ processors. It is intended for use by hardware designers familiar with the principles of embedded microprocessors and with the Intel486 processor architecture.

1.1 MANUAL CONTENTS

This manual contains 12 chapters, seven appendices, a glossary, and an index. This section summarizes the contents of the remaining chapters and appendixes. The remainder of this chapter describes notation conventions and special terminology used throughout the manual and provides references to related documentation.

Chapter 2: "Embedded Intel486™ Processor Overview"	This chapter provides an overview of the current embedded Intel486 processor family, including product features, system components, system architecture, and applications. This chapter also lists product frequency, voltage, and package offerings.
Chapter 3: "Architectural Overview"	This chapter describes the Intel486 processor internal architecture, with an overview of the processor's functional units.
Chapter 4: "System Register Organization"	This chapter details the Intel486 processor register set, including the base architecture registers, system-level registers, and debug and test registers.
Chapter 5: "Real Mode Architecture"	When the processor is powered-up, it is initialized in Real Mode, which is an architecture similar to the 8086 processor. This chapter describes Real Mode addressing and interrupt handling.
Chapter 6: "Protected Mode Architecture"	This chapter describes Protected Mode, which is an architecture that allows the Intel486 processor to access up to four Gbytes of address space.
Chapter 7: "On-Chip Cache"	All members of the Intel486 processor family contain an on-chip cache, also known as L1 cache. This chapter describes its functionality.
Chapter 8: "System Management Mode (SMM) Architectures"	This chapter describes the System Management Mode architecture of the Intel486 processors, including System Management Mode interrupt processing and programming.

Chapter 9: "Hardware Interface"	This chapter describes the hardware interface of the current Intel486 processor family, including signal descriptions, interrupt interfaces, write buffers, reset and initialization, and clock control. Use and operation of the Stop Clock, Auto HALT Power Down and other power-saving SL Technology features are described. The IntelDX4 processor speed multiplying options and the Write-Back Enhanced processor signals are also detailed in this chapter.
Chapter 10: "Bus Operation"	This chapter describes the features of the processor bus, including bus cycle handling, interrupt and reset signals, cache control, and floating-point error control.
Chapter 11: "Debugging Support"	This chapter describes the Intel486 processor debugging support, including the breakpoint instruction, single-step trap, and debug registers.
Chapter 12: "Instruction Set Summary"	This chapter describes the Intel486 processor instruction set and the encoding of each field within the instructions.
Appendix A: "Signal Descriptions"	This appendix lists each Intel486 processor signal and describes its function.
Appendix B: "Testability"	This appendix describes the testability of the Intel486 processors, including the built-in self test (BIST), on-chip cache testing, translation lookaside buffer (TLB) testing, three-state output test mode, and boundary scan (JTAG). Processor-specific differences regarding the Write-Back Enhanced Intel486 processors are documented in this chapter. A complete listing of Boundary Scan ID Codes and Boundary Scan Register Bits orders is also included.
Appendix C: "Advanced Features"	This appendix documents the advanced features of the Intel486 processor family not covered in other chapters.
Appendix D: "Feature Determination"	This appendix documents the CPUID function, which is used to determine the Intel486 processor family identification and processor-specific information.
Appendix E: "I/O Buffer Models"	This appendix provides a detailed sample listing of the types of I/O buffer modeling information available for the Intel486 processor family.
Appendix F: "BSDL Listings"	This appendix provides a sample listing of a BSDL file for the Intel486 processor family.
Appendix G: "System Design Notes"	This appendix provides design notes applicable to the use of System Management Mode and SMM routines with the Intel486 processor.

1.2 NOTATION CONVENTIONS

The following notations are used throughout this manual.

The pound symbol (#) appended to a signal name indicates that the signal is active low.

Variables Variables are shown in italics. Variables must be replaced with correct values.

New Terms New terms are shown in italics.

Instructions Instruction mnemonics are shown in upper case. When you are programming, instructions are not case-sensitive. You may use either upper or lower case.

Numbers Hexadecimal numbers are represented by a string of hexadecimal digits followed by the character H. A zero prefix is added to numbers that begin with A through F. (For example, FF is shown as 0FFH.) Decimal and binary numbers are represented by their customary notations. (That is, 255 is a decimal number and 1111 1111 is a binary number. In some cases, the letter B is added for clarity.)

Units of Measure The following abbreviations are used to represent units of measure:

A	amps, amperes
mA	milliamps, milliamperes
µA	microamps, microamperes
Mbyte	megabytes
Kbyte	kilobytes
Gbyte	gigabyte
W	watts
KW	kilowatts
mW	milliwatts
µW	microwatts
MHz	megahertz
ms	milliseconds
ns	nanoseconds
µs	microseconds
µF	microfarads
pF	picofarads
V	volts

Register Bits When the text refers to more that one bit, the range of bits is represented by the highest and lowest numbered bits, separated by a colon (example: A[15:8]). The first bit shown (15 in the example) is the most-significant bit and the second bit shown (8) is the least-significant bit.

Register Names Register names are shown in upper case. If a register name contains a lower case, italic character, it represents more than one register. For example, P*n*CFG represents three registers: P1CFG, P2CFG, and P3CFG.

Signal Names Signal names are shown in upper case. When several signals share a common name, an individual signal is represented by the signal name followed by a number, whereas the group is represented by the signal name followed by a variable (*n*). For example, the lower chip select signals are named CS0#, CS1#, CS2#, and so on; they are collectively called CS*n*#. A pound symbol (#) appended to a signal name identifies an active-low signal. Port pins are represented by the port abbreviation, a period, and the pin number (e.g., P1.0, P1.1).

1.3 SPECIAL TERMINOLOGY

The following terms have special meanings in this manual.

Assert and De-assert — The terms assert and de-assert refer to the act of making a signal active and inactive, respectively. The active polarity (high/low) is defined by the signal name. Active-low signals are designated by the pound symbol (#) suffix; active-high signals have no suffix. To assert RD# is to drive it low; to assert HOLD is to drive it high; to de-assert RD# is to drive it high; to de-assert HOLD is to drive it low.

DOS I/O Address — Peripherals that are compatible with PC/AT system architecture can be mapped into DOS (or PC/AT) addresses 0H–03FFH. In this manual, the terms *DOS address* and *PC/AT address* are synonymous.

Expanded I/O Address — All peripheral registers reside at I/O addresses 0F000H–0FFFFH. PC/AT-compatible integrated peripherals can also be mapped into DOS (or PC/AT) address space (0H–03FFH).

PC/AT Address — Integrated peripherals that are compatible with PC/AT system architecture can be mapped into PC/AT (or DOS) addresses 0H–03FFH. In this manual, the terms *DOS address* and *PC/AT address are synonymous.*

Set and Clear — The terms set and clear refer to the value of a bit or the act of giving it a value. If a bit is set, its value is "1"; setting a bit gives it a "1" value. If a bit is clear, its value is "0"; clearing a bit gives it a "0" value.

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Intel's FaxBack* service provides up-to-date technical information. Intel also offers a variety of information on the World Wide Web. These systems are available 24 hours a day, 7 days a week, providing technical information whenever you need it.

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1-800-525-3019 (US or Canada)

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+886-2-514-0815 (Taiwan)

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+61-2-975-3922 (Australia)

1-503-264-6835 (Worldwide)

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In the U.S. and Canada, technical support representatives are available to answer your questions between 5 a.m. and 5 p.m. PST. You can also fax your questions to us. (Please include your voice telephone number and indicate whether you prefer a response by phone or by fax). Outside the U.S. and Canada, please contact your local distributor.

1-800-628-8686	U.S. and Canada
916-356-7599	U.S. and Canada
916-356-6100 (fax)	U.S. and Canada

1.6 PRODUCT LITERATURE

You can order product literature from the following Intel literature centers.

1-800-548-4725	U.S. and Canada
708-296-9333	U.S. (from overseas)
44(0)1793-431155	Europe (U.K.)
44(0)1793-421333	Germany
44(0)1793-421777	France
81(0)120-47-88-32	Japan (fax only)

1.6.1 Related Documents

The following Intel documents contain additional information on designing systems that incorporate the Intel486 processors.

Intel Document Name	*Intel Order Number*
Datasheets	
Embedded Intel486™ SX Processor datasheet	272769
Embedded IntelDX2™ Processor datasheet	272770
Embedded Ultra-Low Power Intel486™ SX Processor datasheet	272731
Embedded Ultra Low-Power Intel486™ GX Processor datasheet	272755
Embedded Write-Back Enhanced IntelDX4™ Processor datasheet	272771
Manuals	
Embedded Intel486™ Processor Hardware Reference Manual	273025
Intel Architecture Software Developer's Manual, Volumes 1 and 2	243190 243191
Ultra-Low Power Intel486™ SX Processor Evaluation Board Manual	272815
Intel486™ Processor Family Programmer's Reference Manual	240486
Application Notes/Performance Briefs	
AP-505--Picking Up the Pace: Designing the IntelDX4™ Processor into Intel486™ Processor-Based Designs	242034
Intel486™ Microprocessor Performance Brief	241254
IntelDX4™ Processor Performance Brief	242446
MultiProcessor Specification	242016

You can obtain the following resources from the Word Wide Web at the sites listed.

Document Name	***Web Site***
Standard 1149.1—1990, IEEE Standard Test Access Port and Boundary-Scan Architecture and its supplement, *Standard 1149.1a—1993*	Contact the IEEE at http://www.ieee.org.
PCI Local Bus Specification, Revisions 2.0 and 2.1	Contact the PCI Special Interest Group at http://www.pcisig.com

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Embedded Intel486™ Processor Overview

Chapter Contents

CHAPTER 2
EMBEDDED Intel486™ PROCESSOR OVERVIEW

The Intel486™ processor family enables a range of low-cost, high-performance system designs capable of running the entire installed base of DOS*, Windows 95*, Windows NT*, OS/2*, and UNIX*-based applications written for the Intel architecture. The processor family also enables a wide range of high-performance embedded application designs. This family includes the following processors:

- The IntelDX4™ processor is the fastest Intel486 processor (up to 50% faster than the IntelDX2™ processor). The IntelDX4 processor integrates a 16-Kbyte unified cache and floating-point hardware on-chip for improved performance.

  The IntelDX4 processor is also available with a write-back on-chip cache for improved performance.

- The IntelDX2 processor integrates an 8 Kbyte unified cache and floating-point hardware on-chip.

  The IntelDX4 and IntelDX2 processors use Intel's speed-multiplying technology, allowing the processor core to operate at frequencies higher than the external processor bus.

- The Intel486 SX processor offers the features of the IntelDX2 processor without floating-point hardware and clock multiplying.

- The Ultra-Low Power Ultra-Low Power Intel486 SX and Ultra-Low Power Intel486 GX processors provide additional power-saving features for use in battery-operated and hand-held embedded designs. The Ultra-Low Power Intel486 SX, like the other Intel486 processors, supports dynamic data bus sizing for 8-, 16-, or 32-bit bus sizes, whereas the Ultra-Low Power Intel486 GX has a 16-bit external data bus.

The entire Intel486 processor family incorporates energy efficient "SL Technology" for mobile and fixed embedded computing. SL Technology enables system designs that exceed the Environment Protection Agency's (EPA) Energy Star program guidelines without compromising performance. It also increases system design flexibility and improves battery life in all Intel486 processor-based, hand-held applications. SL Technology allows system designers to differentiate their power management schemes with a variety of energy efficient, battery life enhancing features.

Intel486 processors provide power management features that are transparent to application and operating system software. Stop Clock, Auto HALT Power Down, and Auto Idle Power Down allow software-transparent control over processor power management.

Equally important is the capability of the processor to manage system power consumption. Intel486 processor System Management Mode (SMM) incorporates a non-maskable System Management Interrupt (SMI#), a corresponding Resume (RSM) instruction and a new memory space for system management code. Although transparent to any application or operating system, Intel's SMM ensures seamless power control of the processor core, system logic, main memory, and one or more peripheral devices.

Intel486 processors are available in a full range of speeds (25 MHz to 100 MHz), packages (PGA, SQFP, PQFP, TQFP), and voltages (5 V, 3.3 V, 3.0 V and 2.0 V) to meet many system design requirements.

2.1 PROCESSOR FEATURES

All Intel486 processors consist of a 32-bit integer processing unit, an on-chip cache, and a memory management unit. These ensure full binary compatibility with the 8086, 8088, 80186, 80286, Intel386™ SX, and Intel386 DX processors, and with all versions of Intel486 processors. All Intel486 processors offer the following features:

- *32-bit RISC integer core* — The Intel486 processor performs a complete set of arithmetic and logical operations on 8-, 16-, and 32-bit data types using a full-width ALU and eight general purpose registers.
- *Single Cycle Execution* — Many instructions execute in a single clock cycle.
- *Instruction Pipelining* — The fetching, decoding, address translation, and execution of instructions are overlapped within the Intel486 processor.
- *On-Chip Floating-Point Unit* — The IntelDX2 and Intel DX4 processors support the 32-, 64-, and 80-bit formats specified in IEEE standard 754.
- *On-Chip Cache with Cache Consistency Support* — An 8-Kbyte (16-Kbyte on the IntelDX4 processor) internal cache is used for both data and instructions. Cache hits provide zero wait state access times for data within the cache. Bus activity is tracked to detect alterations in the memory represented by the internal cache. The internal cache can be invalidated or flushed so that an external cache controller can maintain cache consistency.
- *External Cache Control* — Write-back and flush controls for an external cache are provided so the processor can maintain cache consistency.
- *On-Chip Memory Management Unit* — Address management and memory space protection mechanisms maintain the integrity of memory in a multi-tasking and virtual memory environment. The memory management unit supports both segmentation and paging.
- *Burst Cycles* — Burst transfers allow a new doubleword to be read from memory on each bus clock cycle. This capability is especially useful for instruction prefetch and for filling the internal cache.
- *Write Buffers* — The processor contains four write buffers to enhance the performance of consecutive writes to memory. The processor can continue internal operations after a write to these buffers, without waiting for the write to be completed on the external bus.
- *Bus Backoff* — If another bus master needs control of the bus during a processor-initiated bus cycle, the Intel486 processor floats its bus signals, then restarts the cycle when the bus becomes available again.
- *Instruction Restart* — Programs can continue execution following an exception that is generated by an unsuccessful attempt to access memory. This feature is important for supporting demand-paged virtual memory applications.

- *Dynamic Bus Sizing* — External controllers can dynamically alter the effective width of the data bus. Bus widths of 8, 16, or 32 bits can be used (the 8-bit and 32-bit bus widths are not available on the Ultra-Low Power Intel486 GX processor).
- *Boundary Scan (JTAG)* — Boundary Scan provides in-circuit testing of components on printed circuit boards. The Intel Boundary Scan implementation conforms with the IEEE Standard Test Access Port and Boundary Scan Architecture.

SL Technology provides the following features:

- *Intel System Management Mode* — A unique Intel architecture operating mode provides a dedicated special purpose interrupt and address space that can be used to implement intelligent power management and other enhanced functions in a manner that is completely transparent to the operating system and applications software.
- *I/O Restart* — An I/O instruction interrupted by a System Management Interrupt (SMI#) can automatically be restarted following the execution of the RSM instruction.
- *Stop Clock* — The Intel486 processor has a stop clock control mechanism that provides two low-power states: a “fast wake-up” Stop Grant state and a “slow wake-up” Stop Clock state with CLK frequency at 0 MHz.
- *Auto HALT Power Down* — After the execution of a HALT instruction, the Intel486 processor issues a normal Halt bus cycle and the clock input to the Intel486 processor core is automatically stopped, causing the processor to enter the Auto HALT Power Down state.
- *Upgrade Power Down Mode* — When an Intel486 processor upgrade is installed, the Upgrade Power Down Mode detects the presence of the upgrade, powers down the core, and three-states all outputs of the original processor, so the Intel486 processor enters a very low current mode.
- *Auto Idle Power Down* — This function allows the processor to reduce the core frequency to the bus frequency when both the core and bus are idle. Auto Idle Power Down is software-transparent and does not affect processor performance. Auto Idle Power Down provides an average power savings of 10% and is only applicable to clock-multiplied processors.

Enhanced Bus Mode Features (for the Write-Back Enhanced IntelDX4 processor only):

- *Write Back Internal Cache* — The Write-Back Enhanced IntelDX4 processor adds write-back support to the unified cache. The on-chip cache is configurable to be write-back or write-through on a line-by-line basis. The internal cache implements a modified MESI protocol, which is most applicable to single processor systems.
- *Enhanced Bus Mode* — The definitions of some signals have been changed to support the new Enhanced Bus Mode (Write-Back Mode).
- *Write Bursting* — Data written from the processor to memory can be burst to provide zero wait state transfers.

The Intel486 processor also has features that facilitate high-performance hardware designs. The 1X bus clock input eases high-frequency board-level designs. The clock multiplier on IntelDX2 and IntelDX4 processors improves execution performance without increasing board design complexity. The clock multiplier enhances all operations operating out of the cache that are not blocked by external bus accesses. The burst bus feature enables fast cache fills.

2.2 Intel486™ PROCESSOR PRODUCT OPTIONS

Table 2-1 shows the Intel486 processors available by clock mode, supply voltage, maximum frequency, and package. An individual product has either a 5 V supply voltage or a 3.3 V supply voltage, but not both. Likewise, an individual product may have 1x, 2x, or 3x clock. Please contact Intel for the latest product availability and specifications.

Table 2-1. Product Options

Intel486™ Processor	V_{CC}†	Processor Frequency (MHz)									168-Pin PGA	208-Lead SQFP	196-Lead PQFP	176-Lead TQFP
		16	20	25	33	40	50	66	75	100				
1x Clock														
Intel486 SX Processor	3.3 V			✓	✓							✓		
Ultra-Low Power Intel486 SX Processor	2.4-3.3			✓										✓
	2.7-3.3				✓									✓
Ultra-Low Power Intel486 GX Processor	2.0-3.3	✓												✓
	V_{CCP}‡ 2.2-3.3		✓											✓
	2.4-3.3			✓										✓
	V_{CCP}‡ 2.7-3.3				✓									✓
2x Clock														
IntelDX2™ Processor	3.3						✓					✓		
3x Clock														
Write-Back Enhanced IntelDX4™ Processor	3.3								✓	✓	✓	✓		

† V_{CC} is the main power to the processor core.

‡ V_{CCP} is used in the ULP486 SX/GX processors as a separate power supply to the peripherals.

2.2.1 Operating Modes and Compatibility

The Intel486 processor can run in modes that give it object-code compatibility with software written for the 8086, 80286, and Intel386 processor families. The operating mode is set in software as one of the following:

- Real Mode: When the processor is powered up or reset, it is initialized in Real Mode. This mode has the same base architecture as the 8086 processor but allows access to the 32-bit register set of the Intel486 processor. The address mechanism, maximum memory size (1 Mbyte), and interrupt handling are identical to the Real Mode of the 80286 processor. Nearly all Intel486 processor instructions are available, but the default operand size is 16 bits; in order to use the 32-bit registers and addressing modes, override instruction prefixes must be used. The primary purpose of Real Mode is to set up the processor for Protected Mode operation.
- Protected Mode (also called Protected Virtual Address Mode): The complete capabilities of the Intel486 processor become available when programs are run in Protected Mode. In addition to segmentation protection, paging can be used in Protected Mode. The linear address space is four gigabytes and virtual memory programs of up to 64 terabytes can be run. All existing 8086, 80286, and Intel386 processor software can be run under the Intel486 processor's hardware-assisted protection mechanism. The addressing mechanism is more sophisticated in Protected Mode than in Real Mode.
- Virtual 8086 Mode, a sub-mode of Protected Mode, allows 8086 programs to be run with the segmentation and paging protection mechanisms of Protected Mode. This mode offers more flexibility than the Real Mode for running 8086 programs. Using this mode, the Intel486 processor can execute 8086 operating systems and applications simultaneously with an Intel486 operating system and both 80286 and Intel486 processor applications.

2.3 SYSTEMS APPLICATIONS

Most Intel486 processor systems can be grouped as one of these types:

- Embedded Personal Computer
- Embedded Controller

Each type of system has distinct design goals and constraints, as described in the following sections. Software running on the processor, even in stand-alone embedded applications, should use a standard operating system such as DOS, Windows 95, Windows NT, OS/2, or UNIX System V/386*, to facilitate debugging, documentation, and transportability.

2.3.1 Embedded Personal Computers

In single-processor embedded systems, the processor interacts directly with I/O devices and DRAM memory. Other bus masters such as a LAN coprocessor typically reside on the system bus; conventional personal computer architecture puts most peripherals on separate plug-in boards. Expansion is typically limited to memory boards and I/O boards. A standard I/O architecture such as MCA or EISA is used. Figure 2-1 shows an example of a personal computer application.

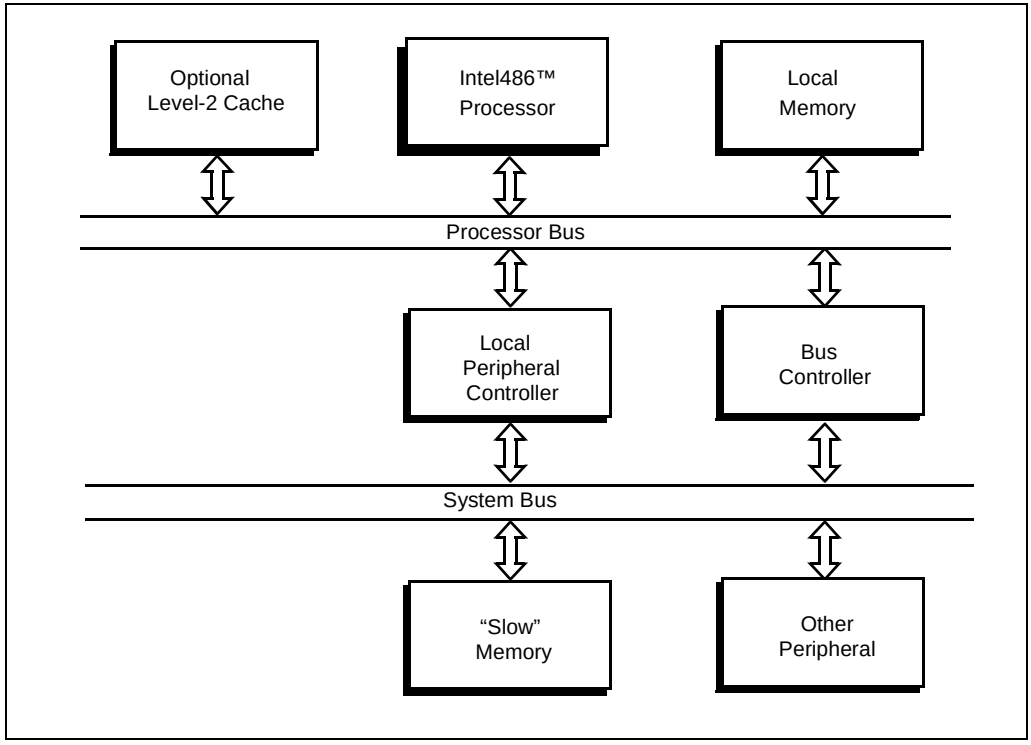


Figure 2-1. Embedded Personal Computer and Embedded Controller Example

External cache is optional in such environments, particularly if system performance is not a critical parameter. Where an external cache is used, memory-access speeds improve only if the cache memory access has zero to one wait states.

2.3.2 Embedded Controllers

Most embedded controllers perform real-time tasks. The performance of the Intel486 processor and its compatibility with the extensive installed base of Intel386 processors are important factors in its choice for embedded designs. Embedded controllers are usually implemented as stand-alone systems, with less expansion capability than other applications because they are tailored specifically to a single environment.

If code must be stored in EPROM, ROM, or Flash for non-volatility, but performance is also a critical issue, then the code should be copied into RAM provided specifically for this purpose. Frequently used routines and variables, such as interrupt handlers and interrupt stacks, can be placed in the processor's internal cache so they are always available quickly.

Embedded controllers usually require less memory than other applications, and control programs are usually tightly written machine-level routines that need optimal performance in a limited variety of tasks. The processor typically interacts directly with I/O devices and DRAM memory. Other peripherals connect to the system bus.

3

Architectural Overview

Chapter Contents

CHAPTER 3
ARCHITECTURAL OVERVIEW

3.1 INTERNAL ARCHITECTURE

3.1.1 Overview

The Intel486™ SX processor and the Ultra-Low Power Intel486 SX have a 32-bit architecture with on-chip memory management and level-1 cache.

The IntelDX2™ and IntelDX4™ processors also have a 32-bit architecture with on-chip memory management and cache, but add clock multiplier and floating point units. The Intel486 SX, Ultra-Low Power Intel486 SX, and Intel486 DX processors support dynamic bus sizing for the external data bus; that is, the bus size can be specified as 8-, 16-, or 32-bits wide.

Internally, the ultra-low power processors are similar to the Intel486 SX, but add a specialized clock control unit. Although the Ultra-Low Power Intel486 SX supports dynamic bus sizing, the Ultra-Low Power Intel486 GX supports only a 16-bit external data bus. The Ultra-Low Power Intel486 GX also has advanced power management features.

Table 3-1 lists the functional units of the embedded Intel486 processors.

Table 3-1. Intel486™ Processor Family Functional Units

Functional Unit	IntelDX2™ and IntelDX4™ Processors	Intel486 SX™ Processor	Ultra-Low Power Intel486 SX and Ultra-Low Power Intel486 GX Processors
Bus Interface	✓	✓	✓
Cache (L1)	✓	✓	✓
Instruction Prefetch	✓	✓	✓
Instruction Decode	✓	✓	✓
Control	✓	✓	✓
Integer and Datapath	✓	✓	✓
Segmentation	✓	✓	✓
Paging	✓	✓	✓
Floating-Point	✓		
Clock Multiplier	✓		
Clock Control			✓

Figure 3-1 is a block diagram of the embedded IntelDX2 and IntelDX4 processors. Note that the cache unit is 8 Kbytes for the IntelDX2 processor and 16 Kbytes for the IntelDX4.

Figure 3-2 is a block diagram of the embedded Intel486 SX processor. Figures 3-3 and 3-4 are block diagrams of the Ultra-Low Power Intel486 SX and GX processors, respectively.

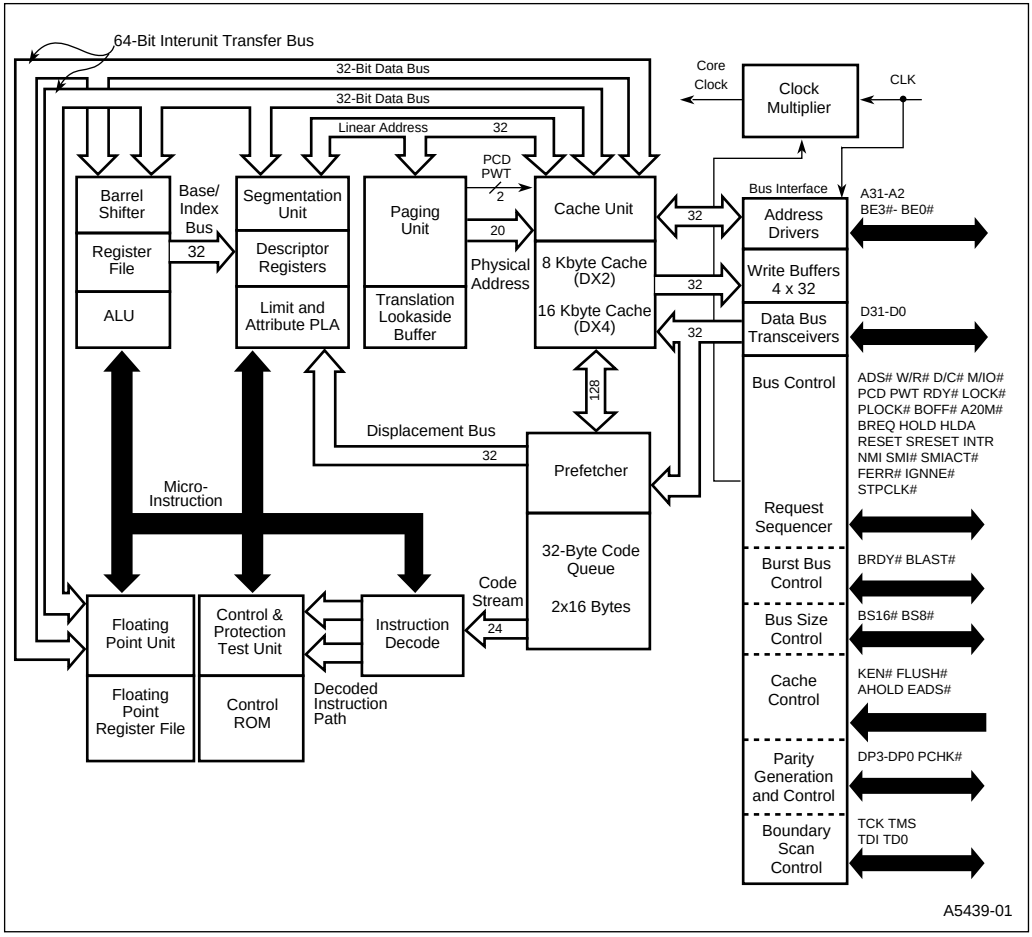


Figure 3-1. IntelDX2™ and IntelDX4™ Processors Block Diagram

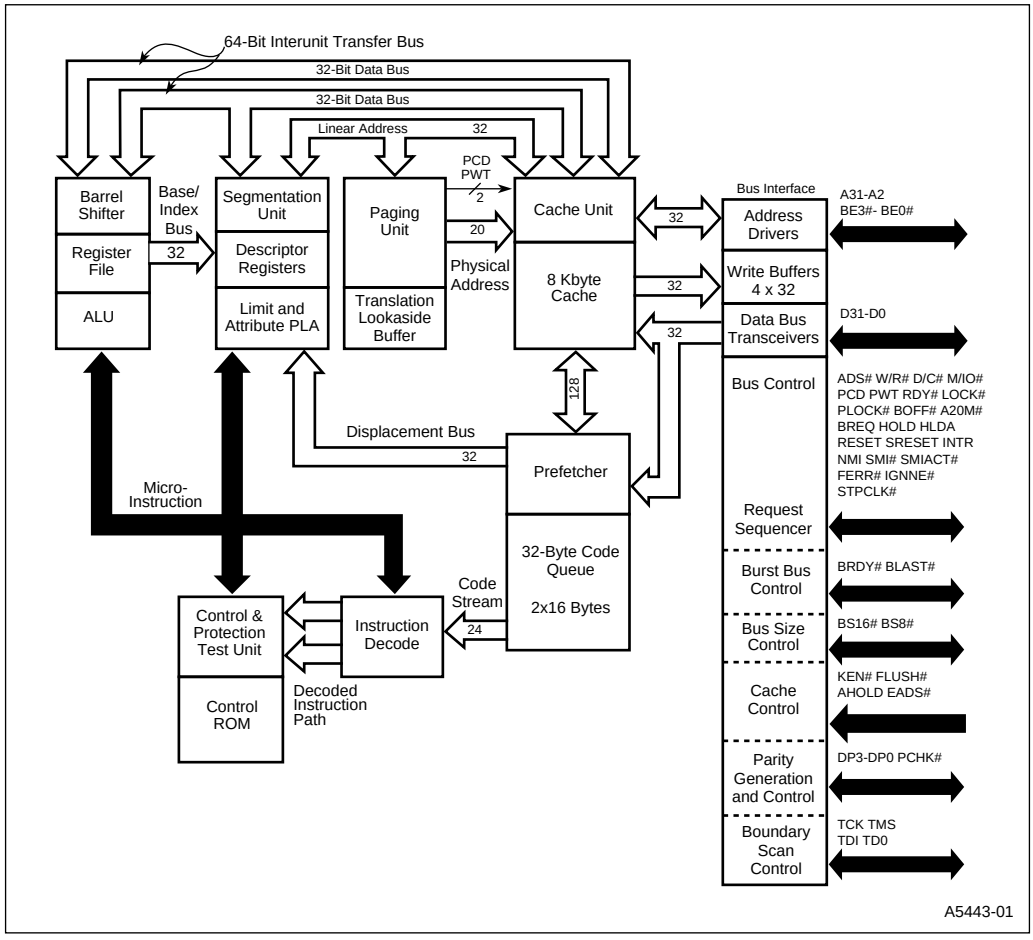


Figure 3-2. Intel486™ SX Processor Block Diagram

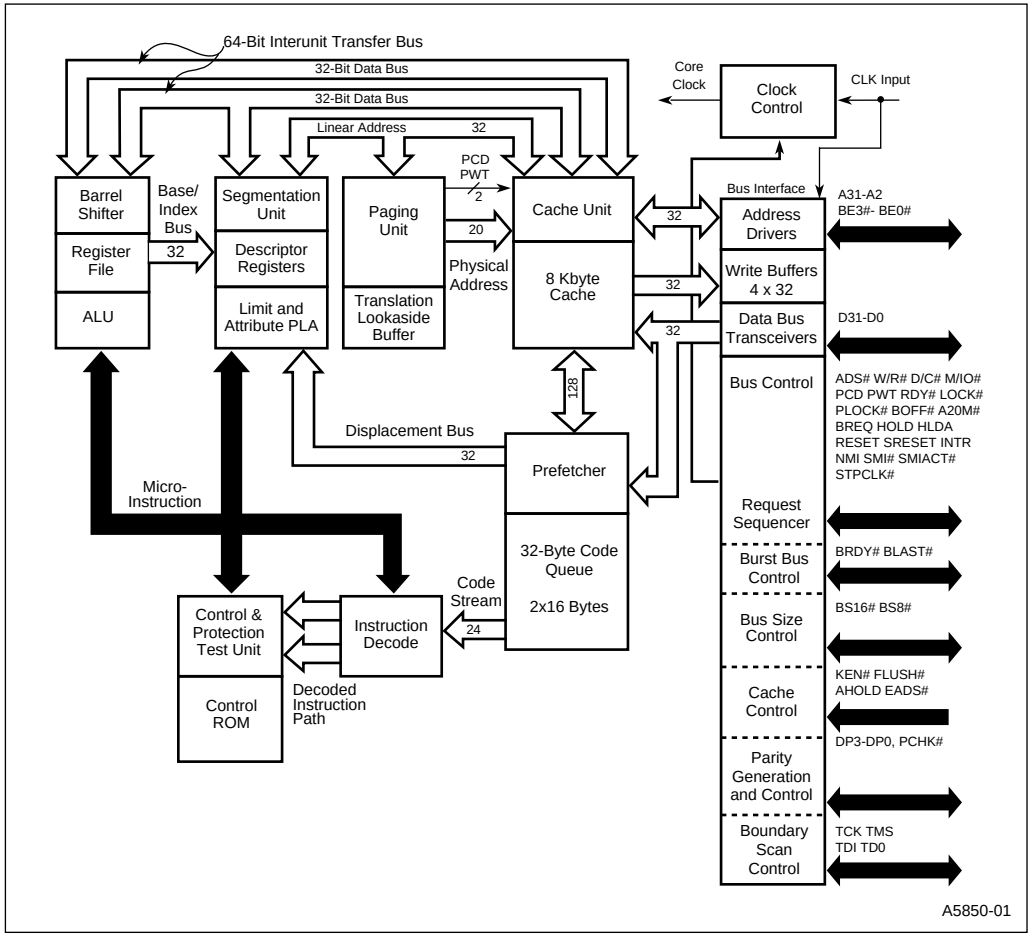


Figure 3-3. Ultra-Low Power Intel486™ SX Processor Block Diagram

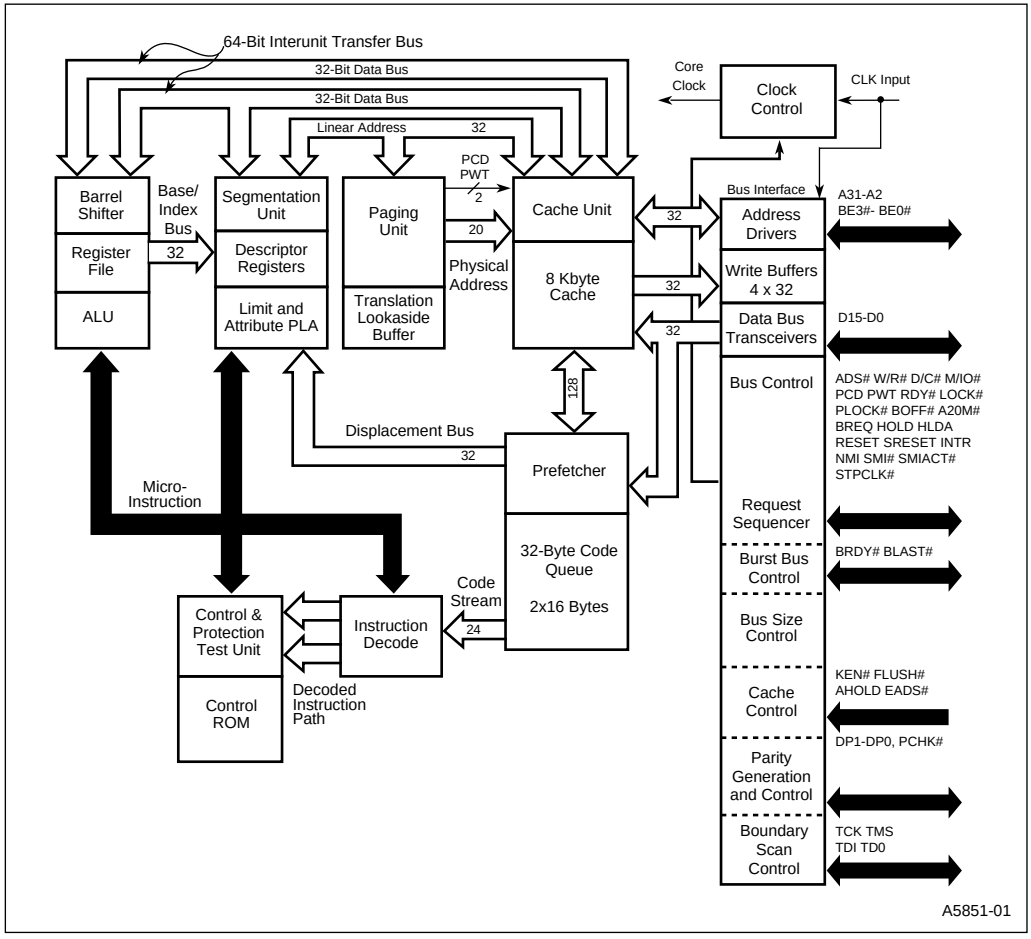


Figure 3-4. Ultra-Low Power Intel486™ GX Processor Block Diagram

The functional units of the Intel486 processor are described in the following sections.

3.1.2 Bus Interface Unit (BIU)

The bus interface unit (BIU) prioritizes and coordinates data transfers, instruction prefetches, and control functions between the processor's internal units and the outside system. Internally, the BIU communicates with the cache and the instruction prefetch units through three 32-bit buses, as shown in Figure 3-1. Externally, the BIU provides the processor bus signals, as described in Chapter 3. Except for cycle definition signals, all external bus cycles, memory reads, instruction prefetches, cache line fills, etc., look like conventional microprocessor cycles to external hardware, with all cycles having the same bus timing.

The BIU contains the following architectural features:

- Address Transceivers and Drivers — The A31–A2 address signals are driven on the processor bus, together with their corresponding byte-enable signals, BE3#–BE0#. The high-order 28 address signals are bidirectional, allowing external logic to drive cache invalidation addresses into the processor.
- Data Bus Transceivers — The D31–D0 data signals are driven onto and received from the processor bus (for the Ultra-Low Power Intel486 GX processor, signals D15–D0 comprise the data bus transceivers).
- Bus Size Control — Three sizes of external data bus can be used: 32, 16, and 8 bits wide. Two inputs (BS16# and BS8#) from external logic specify the width to be used. Bus size can be changed on a cycle-by-cycle basis. The Ultra-Low Power Intel486 GX does not support dynamic bus sizing; its external data bus is 16 bits wide.
- Write Buffering — Up to four write requests can be buffered, allowing many internal operations to continue without waiting for write cycles to be completed on the processor bus.
- Bus Cycles and Bus Control — A large selection of bus cycles and control functions are supported, including burst transfers, non-burst transfers (single- and multiple-cycle), bus arbitration (bus request, bus hold, bus hold acknowledge, bus locking, bus pseudo-locking, and bus backoff), floating-point error signalling, interrupts, and reset. Two software-controlled outputs enable page caching on a cycle-by-cycle basis. One input and one output are provided for controlling burst read transfers.
- Parity Generation and Control — Even parity is generated on writes to the processor and checked on reads. An error signal indicates a read parity error.
- Cache Control — Cache control and consistency operations are supported. Four inputs (KEN#, Flush#, PCD, and PWT) allow the external system to control the consistency of data stored in the internal cache unit. Two special bus cycles allow the processor to control the consistency of external cache.

NOTE

The PWT and PCD bits function differently on the Write-back Enhanced IntelDX4 processor. See Section 7.6.1, Write-Back Enhanced IntelDX4™ Processor and Processor Page Cacheability (pg. 7-11) for more information.

3.1.3 Data Transfers

To support the cache, the BIU reads 16-byte cacheable transfers of operands, instructions, and other data on the processor bus and passes them to the cache unit. When cache contents are updated from an internal source, such as a register, the BIU writes the updated cache information to the external system. Non-cacheable read transfers are passed through the cache to the integer or floating-point units.

During instruction prefetch, the BIU reads instructions on the processor bus and passes them to both the instruction prefetch unit and the cache. The instruction prefetch unit may then obtain its inputs directly from the cache.

3.1.4 Write Buffers

The BIU has temporary storage for buffering up to four 32-bit write transfers to memory. Addresses, data, or control information can be buffered. Single I/O-mapped writes are not buffered, although multiple I/O writes may be buffered. The buffers can accept memory writes as quickly as one per clock. Once a write request is buffered, the internal unit that generated the request is free to continue processing. If no higher-priority request is pending and the bus is free, the transfer is propagated as an immediate write cycle to the processor bus. When all four write buffers are full, any subsequent write transfer stalls inside the processor until a write buffer becomes available.

The BIU can re-order pending reads in front of buffered writes. This is done because pending reads can prevent an internal unit from continuing, whereas buffered writes need not have a detrimental effect on processing speed.

Writes are propagated to the processor bus in the first-in-first-out order in which they are received from the internal unit. However, a subsequently generated read request (data or instruction) may be re-ordered in front of buffered writes. As a protection against reading invalid data, this re-ordering of reads in front of buffered writes occurs only if all buffered writes are cache hits. Because an external read is generated only for a cache miss, and is re-ordered in front of buffered writes only if all such buffered writes are cache hits, any read generated on the external bus with this protection never reads a location that is about to be written by a buffered write. This re-ordering can only happen once for a given set of buffered writes, because the data returned by the read cycle could otherwise replace data about to be written from the write buffers.

To ensure that no more than one such re-ordering is done for a given set of buffered writes, all buffered writes are re-flagged as cache misses when a read request is re-ordered ahead of them. Buffered writes thus marked are propagated to the processor bus before the next read request is acted upon. Invalidation of data in the internal cache also causes all pending writes to be flagged as cache misses. Disabling the cache unit disables the write buffers, which eliminates any possibility of re-ordering bus cycles.

3.1.5 Locked Cycles

The processor can generate signals to lock a contiguous series of bus cycles. These cycles can then be performed without interference from other bus masters, if external logic observes these lock signals. One example of a locked operation is a semaphor read-modify-write update, where a resource control register is updated. No other operations should be allowed on the bus until the entire locked semaphor update is completed.

When a locked read cycle is generated, the internal cache is not read. All pending writes in the buffer are completed first. Only then is the read part of the locked operation performed, the data modified, the result placed in a write buffer, and a write cycle performed on the processor bus. This sequence of operations ensures that all writes are performed in the order in which they were generated.

3.1.6 I/O Transfers

Transfers to and from I/O locations have some restrictions to ensure data integrity:

- Caching — I/O reads are never cached.
- Read Re-ordering — I/O reads are never re-ordered ahead of buffered writes to memory. This ensures that the processor has completed updating all memory locations before reading status from a device.
- Writes — Single I/O writes are never buffered. When processing an OUT instruction, internal execution stops until all buffered writes and the I/O write are completed on the processor bus. This allows time for external logic to drive a cache invalidate cycle or mask interrupts before the processor executes the next instruction. The processor completes updating all memory locations before writing to the I/O location. Repeated OUT instructions may be buffered.

The write buffers and the cache unit determine I/O device recovery time. In the Intel386 processor, back-to-back write recovery time could be guaranteed to exceed a certain value by inserting a jump to the next instruction that writes to the I/O device. This forced an instruction prefetch cycle that could only be performed after the preceding write was completed. This technique is not used in the Intel486 processor because a prefetch can be satisfied internally by the cache and recovery time may be too short. The same effect is achieved in the Intel486 processor by explicitly generating a read to an area of memory that is not cacheable. Because the Intel486 processor does not buffer single I/O writes, such a read is not done until the I/O write is completed.

3.2 CACHE UNIT

The cache unit stores copies of recently read instructions, operands, and other data. When the processor requests information already in the cache, called a cache hit, no processor-bus cycle is required. When the processor requests information not in the cache, called a cache miss, the information is read into the cache in one or more 16-byte cacheable data transfers, called cache line fills. An internal write request to an area currently in the cache causes two distinct actions if the cache is using a write-through policy: the cache is updated, and the write is also passed through the cache to memory. If the cache is using a write-back policy, then the internal write request only causes the cache to be updated and the write is stored for future main memory updating.

The cache transfers data to other units on two 32-bit buses, as shown in Figure 3-1. The cache receives linear addresses on a 32-bit bus and the corresponding physical addresses on a 20-bit bus. The cache and instruction prefetch units are closely coupled. 16-Byte blocks of instructions in the cache can be passed quickly to the instruction prefetch unit. Both units read information in 16-byte blocks.

The cache can be accessed as often as once each clock. The cache acts on physical addresses, which minimizes the number of times the cache must be flushed. When both the cache and the cache write-through functions are disabled, the cache may be used as a high-speed RAM.

3.2.1 Cache Structure

The cache has a four-way set associative organization. There are four possible cache locations to store data from a given area of memory. Four-way association is a compromise between the speed of a direct-mapped cache during cache hits and the high cache-hit ratio of a fully associative cache. As shown in Figure 3-5, the 8-Kbyte data block is divided into four data ways, each containing 128 16-byte sets, or cache lines (the DX4 processor has 256 16-byte sets). Each cache line holds data from 16 successive byte addresses in memory, beginning with an address divisible by 16.

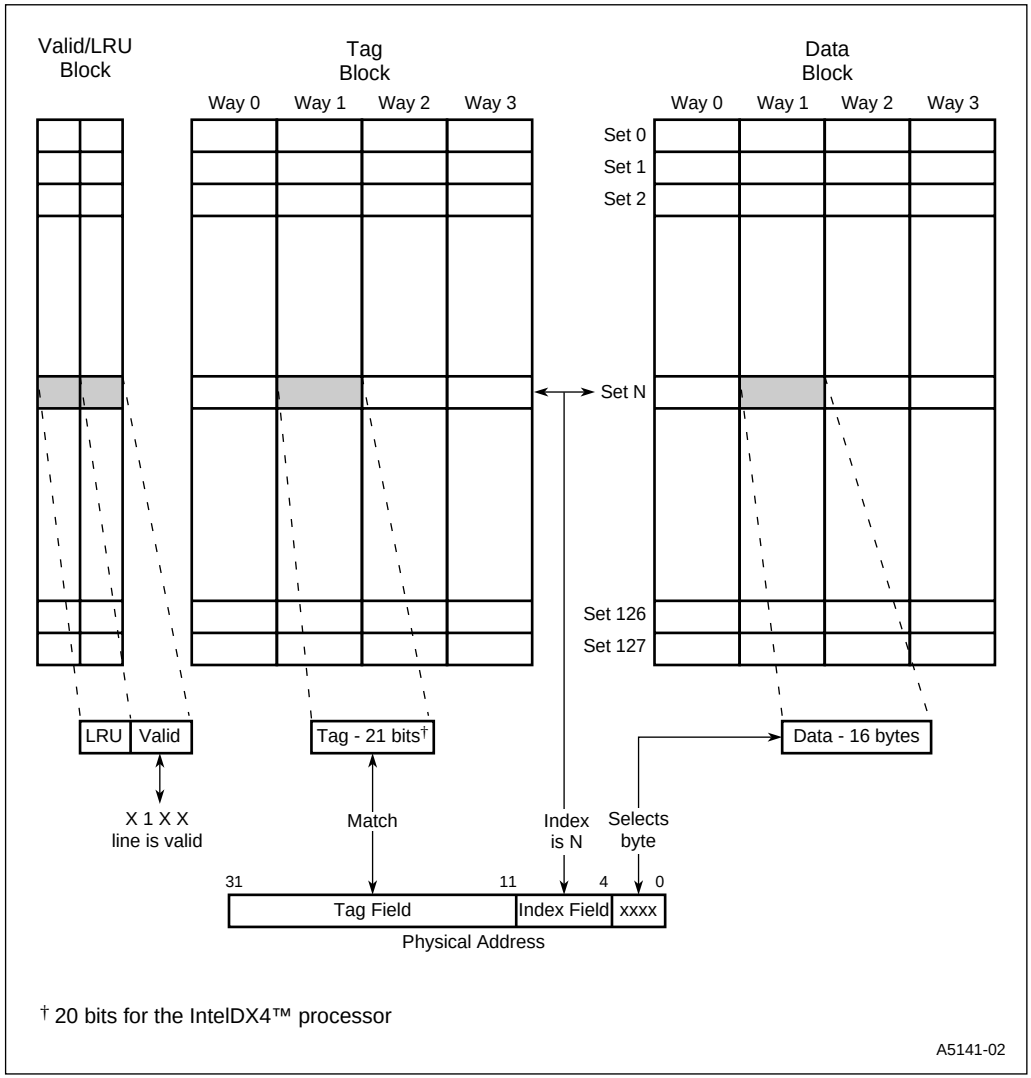


Figure 3-5. Cache Organization

Cache addressing is performed by dividing the high-order 28 bits of the physical address into three parts, as shown in Figure 3-5. The 7 bits of the index field specify the set number, one of 128, within the cache. The high-order 21 bits (20 on the IntelDX4 processor) are the tag field; these bits are compared with tags for each cache line in the indexed set, and they indicate whether a 16-byte cache line is stored for that physical address. The low-order 4 bits of the physical address select the byte within the cache line. Finally, a 4-bit valid field, one for each way within a given set, indicates whether the cached data at that physical address is currently valid.

3.2.2 Cache Updating

When a cache miss occurs on a read, the 16-byte block containing the requested information is written into the cache. Data in the neighborhood of the required data is also read into the cache, but the exact position of data within the cache line depends on its location in memory with respect to addresses divisible by 16.

Any area of memory can be cacheable, but any page of memory can be declared not cacheable by setting a bit in its page table entry. The I/O region of memory is non-cacheable. When a read from memory is initiated on the bus, external logic can indicate whether the data may be placed in cache, as discussed in Chapter 10, “Bus Operation.” If the read is cacheable, the processor attempts to read an entire 16-byte cache line.

The cache unit follows a write-through cache policy. The unit on the IntelDX4 processor can be configured to be a write-through or write-back cache. Cache line fills are performed only for read misses, never for write misses. When the processor is enabled for normal caching and write-through operation, every internal write to the cache (cache hit) not only updates the cache but is also passed along to the BIU and propagated through the processor bus to memory. The only conditions under which data in the cache differs from the corresponding data in memory occur when a processor write cycle to memory is delayed by buffering in the BIU, or when an external bus master alters the memory area mapped to the internal cache. When the IntelDX4 processor is enabled for normal caching and write-back operation, an internal write only causes the cache to be updated. The modified data is stored for the future update of main memory and is not immediately written to memory.

3.2.3 Cache Replacement

Replacement in the cache is handled by a pseudo-LRU (least recently used) mechanism. This mechanism maintains three bits for each set in the valid/LRU block, as shown in Figure 3-5. The LRU bits are updated on each cache hit or cache line fill. Each cache line (four per set) also has an associated valid bit that indicates whether the line contains valid data. When the cache is flushed or the processor is reset, all of the valid bits are cleared. When a cache line is to be filled, a location for the fill is selected by simply finding any cache line that is invalid. If no cache line is invalid, the LRU bits select the line to be overwritten. Valid bits are not set for lines that are only partially valid.

Cache lines can be invalidated individually by a cache line invalidation operation on the processor bus. When such an operation is initiated, the cache unit compares the address to be invalidated with tags for the lines currently in cache and clears the valid bit if a match is found. A cache flush operation is also available. This invalidates the entire contents of the internal cache unit.

3.2.4 Cache Configuration

Configuration of the cache unit is controlled by two bits in the processor’s machine status register (CR0). One of these bits enables caching (cache line fills). The other bit enables memory write-through. Table 3-2 shows the four configuration options. Chapter 10, “Bus Operation,” gives details.

Table 3-2. Cache Configuration Options

Cache Enabled	Write-through Enabled	Operating Mode
no	no	Cache line fills, cache write-throughs, and cache invalidations are disabled. This configuration allows the internal cache to be used as high-speed static RAM.
no	yes	Cache line fills are disabled, and cache write-throughs and cache invalidations are enabled. This configuration allows software to disable the cache for a short time, then re-enable it without flushing the original contents.
yes	no	INVALID
yes	yes	Cache line fills, cache write-throughs, and cache invalidations are enabled. This is the normal operating configuration.

When caching is enabled, memory reads and instruction prefetches are cacheable. These transfers are cached if external logic asserts the cache enable input in that bus cycle, and if the current page table entry allows caching. During cycles in which caching is disabled, cache lines are not filled on cache misses. However, the cache remains active even though it is disabled for further filling. Data already in the cache is used if it is still valid. When all data in the cache is flagged invalid, as happens in a cache flush, all internal read requests are propagated as bus cycles to the external system.

When cache write-through is enabled, all writes, including those that are cache hits, are written through to memory. Invalidation operations remove a line from cache if the invalidate address maps to a cache line. When cache write-throughs are disabled, an internal write request that is a cache hit does not cause a write-through to memory, and cache invalidation operations are disabled. With both caching and cache write-through disabled, the cache can be used as a high-speed static RAM. In this configuration, the only write cycles that are propagated to the processor bus are cache misses, and cache invalidation operations are ignored.

The IntelDX4 processor can also be configured to use a write-back cache policy. For detailed information on the Intel486 processor cache feature, and on the Write-Back Enhanced IntelDX4 processor, refer to Chapter 7, "On-Chip Cache."

3.3 INSTRUCTION PREFETCH UNIT

When the BIU is not performing bus cycles to execute an instruction, the instruction prefetch unit uses the BIU to prefetch instructions. By reading instructions before they are needed, the processor rarely needs to wait for an instruction prefetch cycle on the processor bus.

Instruction prefetch cycles read 16-byte blocks of instructions, starting at addresses numerically greater than the last-fetched instruction. The prefetch unit, which has a direct connection (not shown in Figure 3-1) to the paging unit, generates the starting address. The 16-byte prefetched blocks are read into both the prefetch and cache units simultaneously. The prefetch queue in the prefetch unit stores 32 bytes of instructions. As each instruction is fetched from the queue, the code part is sent to the instruction decode unit and (depending on the instruction) the displacement part is sent to the segmentation unit, where it is used for address calculation. If loops are encountered in the program being executed, the prefetch unit gets copies of previously executed instructions from the cache.

The prefetch unit has the lowest priority for processor bus access. Assuming zero wait-state memory access, prefetch activity never delays execution. However, if there is no pending data transfer, prefetching may use bus cycles that would otherwise be idle. The prefetch unit is flushed whenever the next instruction needed is not in numerical sequence with the previous instruction; for example, during jumps, task switches, exceptions, and interrupts.

The prefetch unit never accesses beyond the end of a code segment and it never accesses a page that is not present. However, prefetching may cause problems for some hardware mechanisms. For example, prefetching may cause an interrupt when program execution nears the end of memory. To keep prefetching from reading past a given address, instructions should come no closer to that address than one byte plus one aligned 16-byte block.

3.4 INSTRUCTION DECODE UNIT

The instruction decode unit receives instructions from the instruction prefetch unit and translates them in a two-stage process into low-level control signals and microcode entry points, as shown in Figure 3-1. Most instructions can be decoded at a rate of one per clock. Stage 1 of the decode, shown in Figure 3-8, initiates a memory access. This allows execution of a two-instruction sequence that loads and operates on data in just two clocks, as described in Section 3.2.

The decode unit simultaneously processes instruction prefix bytes, opcodes, modR/M bytes, and displacements. The outputs include hardwired microinstructions to the segmentation, integer, and floating-point units. The instruction decode unit is flushed whenever the instruction prefetch unit is flushed.

3.5 CONTROL UNIT

The control unit interprets the instruction word and microcode entry points received from the instruction decode unit. The control unit has outputs with which it controls the integer and floating-point processing units. It also controls segmentation because segment selection may be specified by instructions.

The control unit contains the processor's microcode. Many instructions have only one line of microcode, so they can execute in an average of one clock cycle. Figure 3-8 shows how execution fits into the internal pipelining mechanism.

3.6 INTEGER (DATAPATH) UNIT

The integer and datapath unit identifies where data is stored and performs all of the arithmetic and logical operations available in the Intel386 processor's instruction set, plus a few new instructions. It has eight 32-bit general-purpose registers, several specialized registers, an ALU, and a barrel shifter. Single load, store, addition, subtraction, logic, and shift instructions execute in one clock.

Two 32-bit bidirectional buses connect the integer and floating-point units. These buses are used together for transferring 64-bit operands. The same buses also connect the processing units with the cache unit. The contents of the general purpose registers are sent to the segmentation unit on a separate 32-bit bus for generation of effective addresses.

3.7 FLOATING-POINT UNIT

The floating-point unit executes the same instruction set as the 387 math coprocessor. The unit contains a push-down register stack and dedicated hardware for interpreting the 32-, 64-, and 80-bit formats as specified in IEEE Standard 754. An output signal passed through to the processor bus indicates floating-point errors to the external system, which in turn can assert an input to the processor indicating that the processor should ignore these errors and continue normal operations.

3.7.1 IntelDX2™ and IntelDX4™ Processor On-Chip Floating-Point Unit

The IntelDX2 and IntelDX4 processors incorporate the basic Intel486 processor 32-bit architecture, with on-chip memory management and cache memory units. They also have an on-chip floating-point unit (FPU) that operates in parallel with the arithmetic and logic unit. The FPU provides arithmetic instructions for a variety of numeric data types and executes numerous built-in transcendental functions (e.g., tangent, sine, cosine, and log functions). The floating-point unit fully conforms to the ANSI/IEEE standard 754-1985 for floating-point arithmetic.

All software written for the Intel386 processor, Intel387 math coprocessor and previous members of the 86/87 architectural family runs on these processors without modifications.

3.8 SEGMENTATION UNIT

A segment is a protected, independent address space. Segmentation is used to enforce isolation among application programs, to invoke recovery procedures, and to isolate the effects of programming errors.

The segmentation unit translates a segmented address issued by a program, called a logical address, into an unsegmented address, called a linear address. The locations of segments in the linear address space are stored in data structures called segment descriptors. The segmentation unit performs its address calculations using segment descriptors and displacements (offsets) extracted from instructions. Linear addresses are sent to the paging and cache units. When a segment is accessed for the first time, its segment descriptor is copied into a processor register. A program can have as many as 16,383 segments. Up to six segment descriptors can be held in processor registers at a time. Figure 3-6 shows the relationships between logical, linear, and physical addresses.

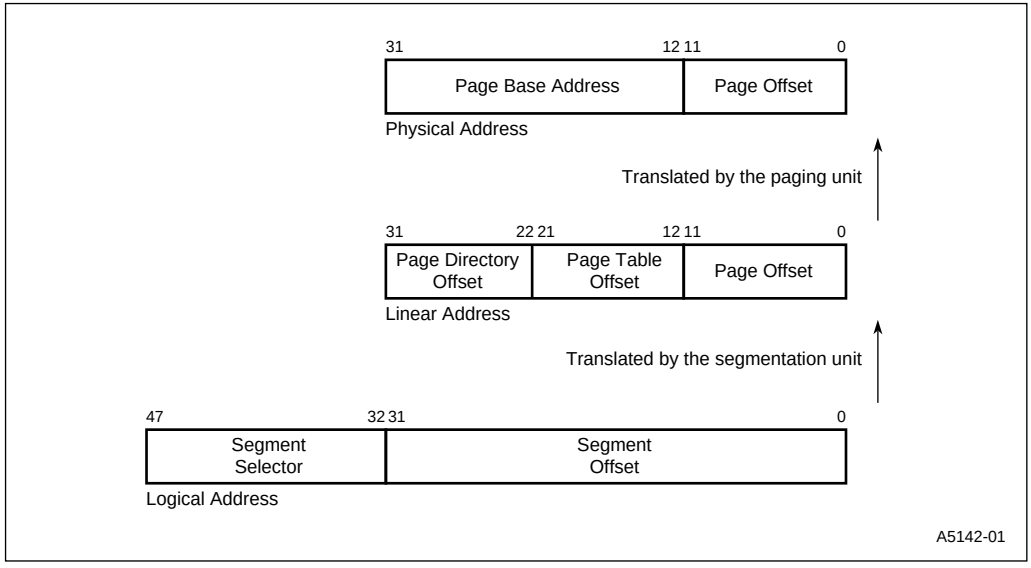


Figure 3-6. Segmentation and Paging Address Formats

3.9 PAGING UNIT

The paging unit allows access to data structures larger than the available memory space by keeping them partly in memory and partly on disk. Paging divides the linear address space into 4-Kbyte blocks called pages. Paging uses data structures in memory called page tables for mapping a linear address to a physical address. The cache uses physical addresses and puts them on the processor bus. The paging unit also identifies problems, such as accesses to a page that is not resident in memory, and raises exceptions called page faults. When a page fault occurs, the operating system has a chance to bring the required page into memory from disk. If necessary, it can free space in memory by sending another page out to disk. If paging is not enabled, the physical address is identical to the linear address.

The paging unit includes a translation lookaside buffer (TLB) that stores the 32 most recently used page table entries. Figure 3-7 shows the TLB data structures. The paging unit looks up linear addresses in the TLB. If the paging unit does not find a linear address in the TLB, the unit generates requests to fill the TLB with the correct physical address contained in a page table in memory. Only when the correct page table entry is in the TLB does the bus cycle take place. When the paging unit maps a page in the linear address space to a page in physical memory, it maps only the upper 20 bits of the linear address. The lowest 12 bits of the physical address come unchanged from the linear address.

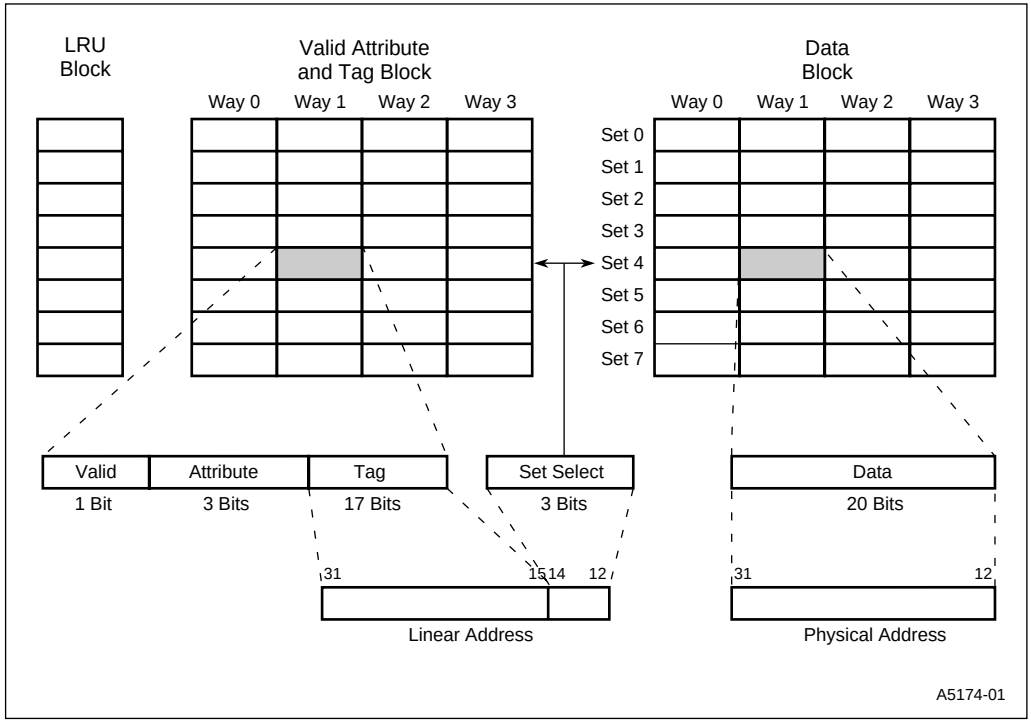


Figure 3-7. Translation Lookaside Buffer

Most programs access only a small number of pages during any short span of time. When this is true, the pages stay in memory and the address translation information stays in the TLB. In typical systems, the TLB satisfies 99% of the requests to access the page tables. The TLB uses a pseudo-LRU algorithm, similar to the cache, as a content-replacement strategy.

The TLB is flushed whenever the page directory base register (CR3) is loaded. Page faults can occur during either a page directory read or a page table read. The cache can be used to supply data for the TLB, although this may not be desirable when external logic monitors TLB updates.

Unlike segmentation, paging is invisible to application programs and does not provide the same kind of protection against programs altering data outside a restricted part of memory. Paging is visible to the operating system, which uses it to satisfy application program memory requirements. For more information on paging and segmentation, see the *Intel486™ Processor Family Programmer's Reference Manual*.

3.9.1 Instruction Pipelining

Not every instruction involves all internal units. When an instruction needs the participation of several units, each unit operates in parallel with others on instructions at different stages of execution. Although each instruction is processed sequentially, several instructions are at varying stages of execution in the processor at any given time. This is called *instruction pipelining*. Instruction prefetch, instruction decode, microcode execution, integer operations, floating-point operations, segmentation, paging, cache management, and bus interface operations are all performed simultaneously. Figure 3-8 shows some of this parallelism for a single instruction: the instruction fetch, two-stage decode, execution, and register write-back of the execution result. Each stage in this pipeline can occur in one clock cycle.

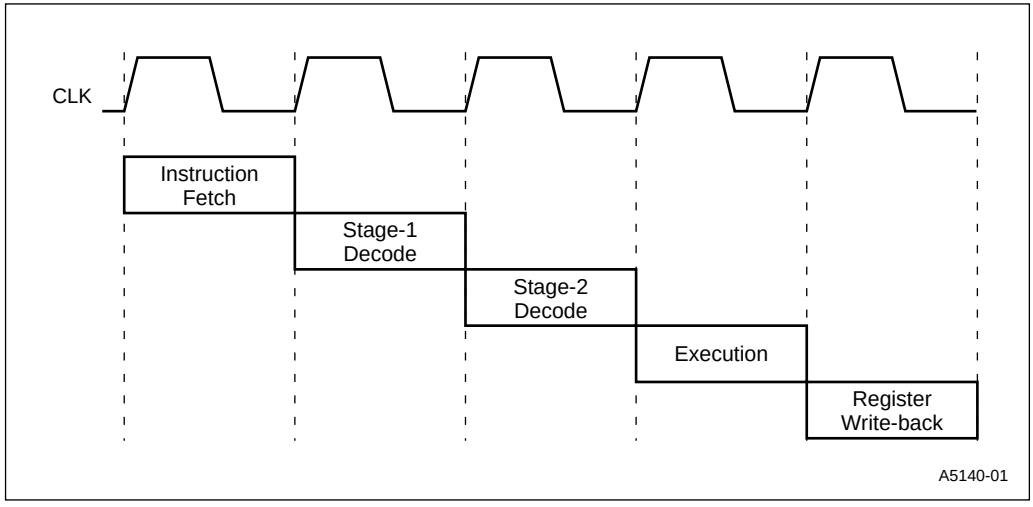


Figure 3-8. Internal Pipelining

The internal pipelining on the Intel486 processor offers an important performance advantage over many single-clock RISC processors: in the Intel486 processor, data can be loaded from the cache with one instruction and used by the next instruction in the next clock. This performance advantage results from the stage-1 decode step, which initiates memory accesses before the execution cycle. Because most compilers and application programs follow load instructions with instructions that operate on the loaded data, this method optimizes the execution of existing binary code.

The method has a performance trade-off: an instruction sequence that changes register contents and then uses that register in the next instruction to access memory takes three clocks rather than two. This trade-off is only a minor disadvantage, however, since most instructions that access memory use the stable contents of the stack pointer or frame pointer, and the additional clock is not used very often. Compilers often place an unrelated instruction between one that changes an addressing register and one that uses the register. Such code is compatible with the Intel386 processor, and the Intel486 processor provides special stack increment/decrement hardware and an extra register port to execute back-to-back stack push/pop instructions in a single clock.

3.10 SYSTEM ARCHITECTURE

The Intel486 processor can be the foundation for single-processor or multi-processor embedded systems. A single-processor system might be an embedded personal computer designed to use the Intel486 processor. A system design of this type offers higher performance through the integration of floating-point processing, memory management, and caching. More complex embedded systems may use multiple processors that provide, at chip-level, the equivalent of board-level functions. Designs of this type are typically used in multi-user machines, scientific workstations, and engineering workstations.

A typical Intel486 design is shown in Figure 3-9. This example uses a single Intel486 processor with external cache. Other examples of system design are illustrated in the figures that follow.

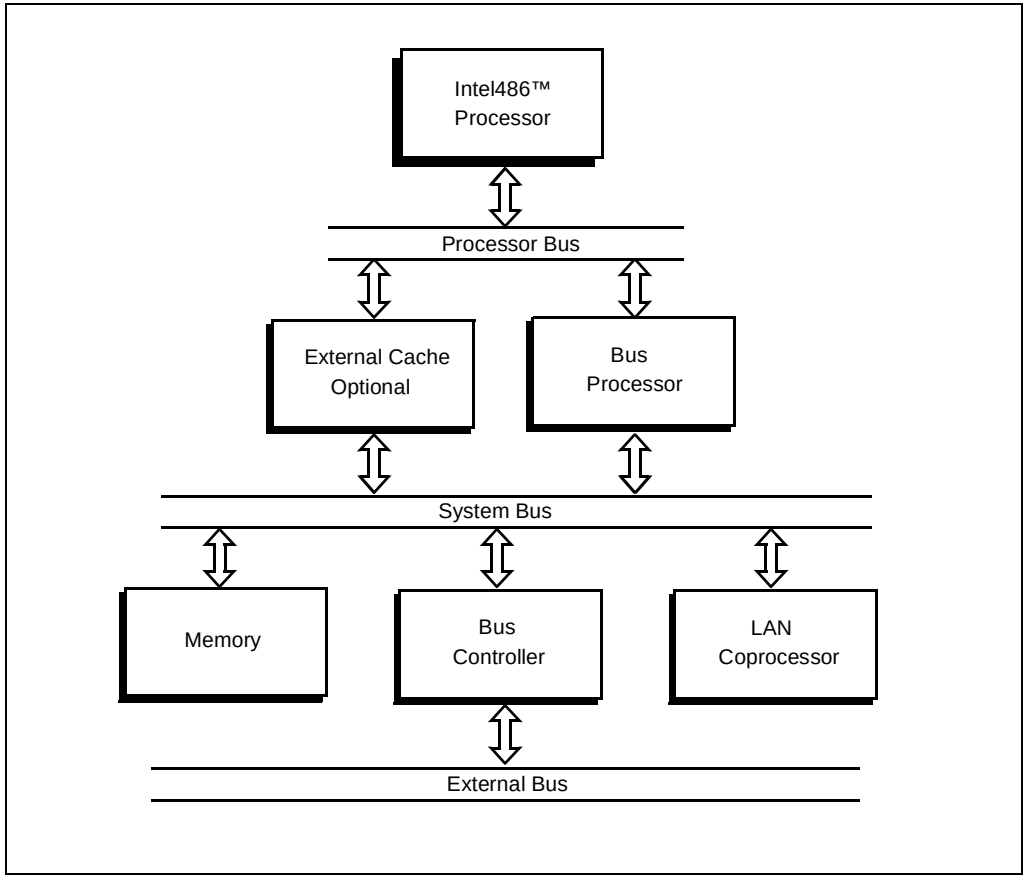


Figure 3-9. A Typical Intel486™ Processor System

3.10.1 Single Processor System

In single-processor systems, the processor handles all peripheral resources and intelligent devices, and executes all software. The Intel486 processor does this in a more efficient way and for a wider range of task complexity than earlier processors. Single-processor systems offer small size and low cost in exchange for flexibility in upgrading or expanding the system. Typical applications include personal computers, small desktop workstations, and embedded controllers. Such applications are implemented as a single board, usually called a motherboard; the processor bus does not extend beyond the board occupied by the Intel486 processor.

Figure 3-10 shows an example of such a system. In a single-processor system, devices that share the processor bus must be selected carefully. All components must interact directly with the processor bus or have interface logic that allows them to do so. The total bus bandwidth requirements of other components should be no more than 50% of the available processor-bus bandwidth. Traffic above 50% degrades performance of the processor.

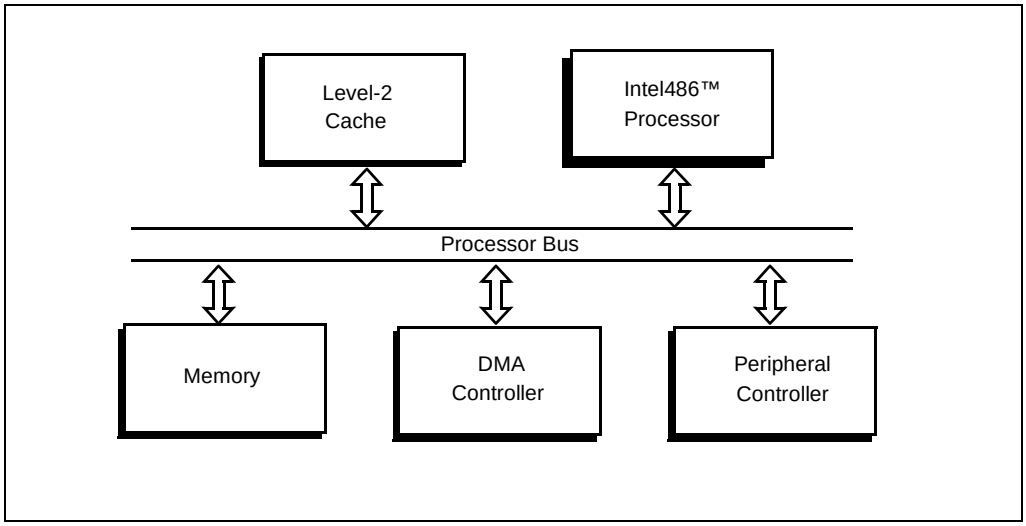


Figure 3-10. Single-Processor System

Two basic design approaches are used to elaborate the single-processor system into a more complex system. The first approach is to add more devices to the processor bus. This can be done up to the limit mentioned above: no more than 50% of the processor-bus bandwidth should be used by devices other than the Intel486 processor. The second design approach is to add more buses to the system. By adding buses, greater bus bandwidth is created in the system as a whole, which in turn allows more devices to be added to the system. The two approaches go hand-in-hand to expand the capabilities of a system. The sections below give only a few examples of the great variety of designs that are possible with Intel486 processor-compatible devices.

3.10.2 Loosely Coupled Multi-Processor System

Loosely coupled multi-processor systems include board-level products that communicate with one another through a standard system bus. In this architecture, each board contains a processor and associated logic. There is typically only one processor per board. Components within each board communicate on either a processor bus or on the buffered system bus. The system bus usually provides extra bandwidth beyond the processor bus.

A typical system is shown in Figure 3-11. Such system-bus boards typically occur in higher-end personal computers and embedded systems that allow for modular expansion. A typical design would include a coprocessor or LAN interface board in a personal computer, or a network-interface board in a file server or gateway. Systems built from these boards can contain a mix of processor types. Devices attached to the processor bus on a given board make demands that may affect system performance. For example, a typical system may use up to 3% of the bus bandwidth to handle 10-Mbit/second Ethernet traffic.

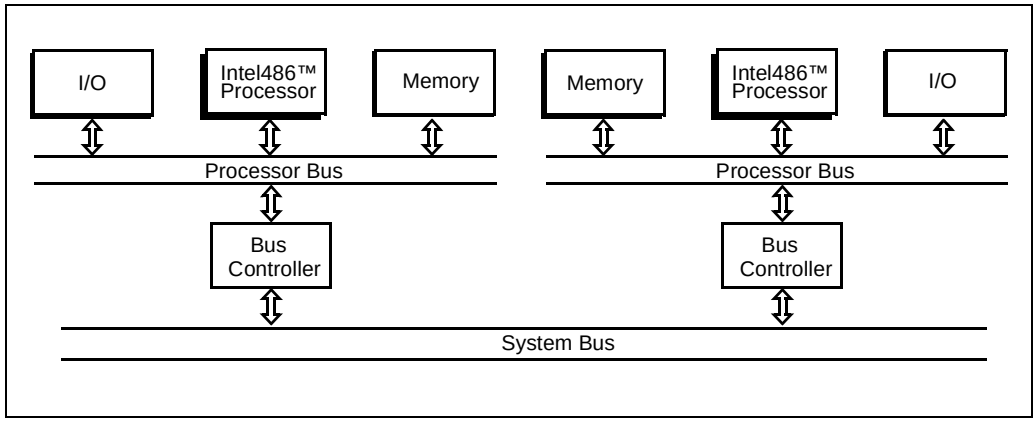


Figure 3-11. Loosely Coupled Multi-processor System

3.10.3 System Components

Intel offers several chips that are highly compatible with the Intel486 processor. These components can be used to design high-performance embedded systems with a minimum of effort and cost. For components not directly connectable to the Intel486 processor bus, industry-standard interfaces can be used.

The Intel486 processor provides all integer and floating-point CPU functions plus many of the peripheral functions required in a typical computer system. It executes the complete instruction set of the Intel386 processor and Intel387 DX numerics coprocessor, with some extensions. The processor eliminates the need for an external memory management unit, and the on-chip cache minimizes the need for external cache and associated control logic.

The remaining chapters of this manual detail the Intel486 processor's architecture, hardware functions, and interfacing. For more information on the architecture and software interface, see the *Intel486™ Processor Programmer's Reference Manual.*

3.10.4 External Cache

External cache allows a system to achieve maximum performance. This cache is essential in tightly coupled multi-processor embedded systems. The external cache consists of cache memory (usually fast SRAM) and cache control logic.

External cache systems typically provide access to the cache from both the processor and the system buses. This is shown in Figure 3-12. These caches typically monitor processor memory accesses, processor access time, and consistency between cache and memory. The cache controller is responsible for maintaining an optimal mix of data and instructions in cache.

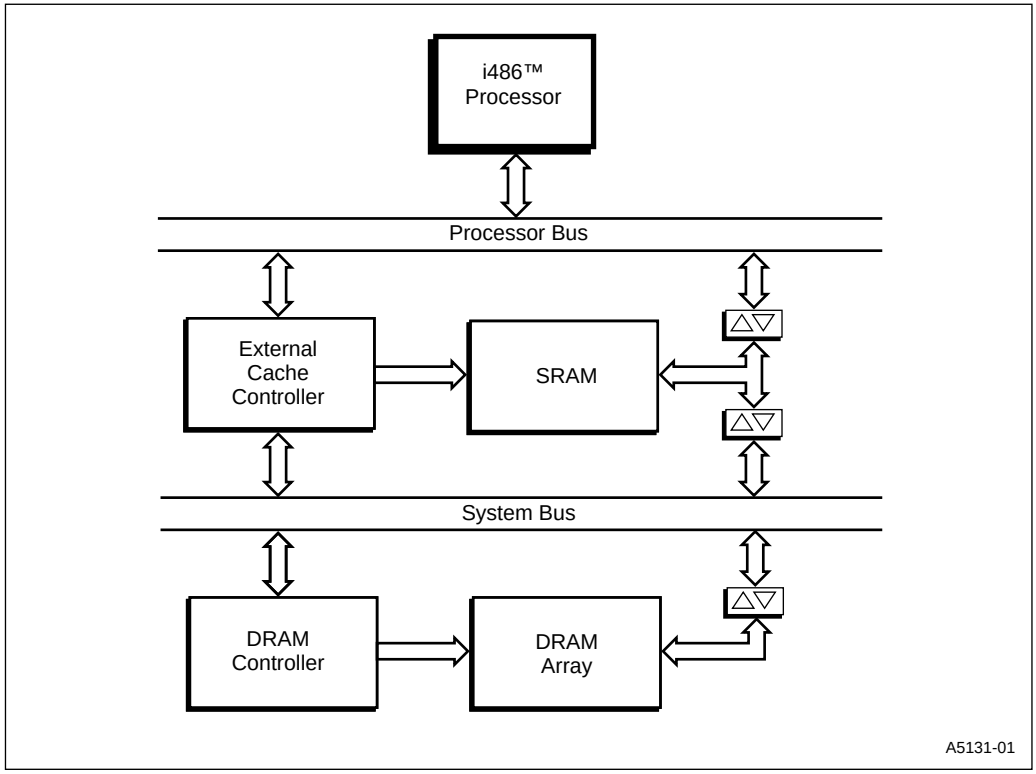


Figure 3-12. External Cache

3.11 MEMORY ORGANIZATION

Memory on the Intel486 processor is divided up into 8-bit quantities (bytes), 16-bit quantities (words), and 32-bit quantities (dwords). Words are stored in two consecutive bytes in memory with the low-order byte at the lowest address, the high order byte at the high address. Dwords are stored in four consecutive bytes in memory with the low-order byte at the lowest address, the high-order byte at the highest address. The address of a word or dword is the byte address of the low-order byte.

In addition to these basic data types, the Intel486 processor supports two larger units of memory: pages and segments. Memory can be divided up into one or more variable-length segments, which can be swapped to disk or shared between programs. Memory can also be organized into one or more 4-Kbyte pages. Both segmentation and paging can be combined, gaining the advantages of both systems. The Intel486 processor supports both pages and segments in order to provide maximum flexibility to the system designer. Segmentation and paging are complementary. Segmentation is useful for organizing memory in logical modules, and as such is a tool for the application programmer, while pages are useful for the system programmer for managing the physical memory of a system.

3.11.1 Address Spaces

The Intel486 processor has three distinct address spaces: logical, linear, and physical. A logical address (also known as a virtual address) consists of a selector and an offset. A selector is the contents of a segment register. An offset is formed by summing all of the addressing components (BASE, INDEX, DISPLACEMENT) discussed in Section 3.13.3, “32-BIT MEMORY ADDRESSING MODES,” into an effective address. Because each task on the Intel486 processor has a maximum of 16 K (2^{14} - 1) selectors, and offsets can be 4 Gbytes (2^{32} bits), this gives a total of 2^{46} bits or 64 terabytes of logical address space per task. The programmer sees this virtual address space.

The segmentation unit translates the logical address space into a 32-bit linear address space. If the paging unit is not enabled then the 32-bit linear address corresponds to the physical address. The paging unit translates the linear address space into the physical address space. The physical address is what appears on the address pins.

The primary difference between Real Mode and Protected Mode is how the segmentation unit performs the translation of the logical address into the linear address. In Real Mode, the segmentation unit shifts the selector left four bits and adds the result to the offset to form the linear address. While in Protected Mode every selector has a linear base address associated with it. The linear base address is stored in one of two operating system tables (i.e., the Local Descriptor Table or Global Descriptor Table). The selector's linear base address is added to the offset to form the final linear address.

Figure 3-13 shows the relationship between the various address spaces.

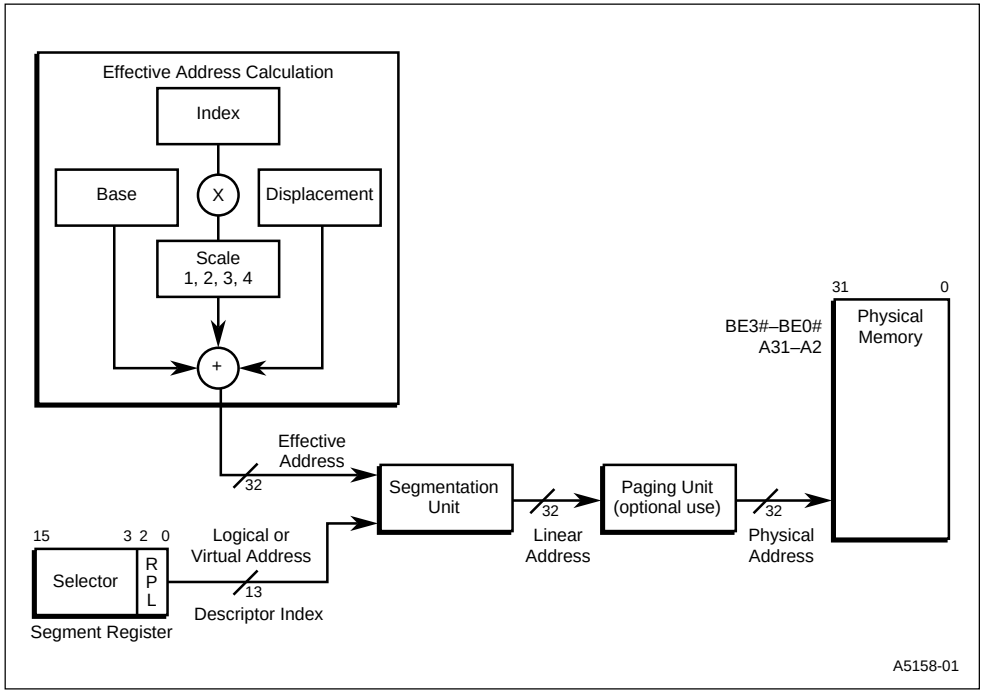


Figure 3-13. Address Translation

3.11.2 Segment Register Usage

The main data structure used to organize memory is the segment. On the Intel486 processor, segments are variable sized blocks of linear addresses which have certain attributes associated with them. There are two main types of segments: code and data. The segments are of variable size and can be as small as 1 byte or as large as 4 Gbytes (2^{32} bytes).

In order to provide compact instruction encoding, and increase Intel486 processor performance, instructions do not need to explicitly specify which segment register is used. A default segment register is automatically chosen according to the rules of Table 3-3. In general, data references use the selector contained in the DS register; stack references use the SS register and Instruction fetches use the CS register. The contents of the Instruction Pointer provide the offset. Special segment override prefixes allow the explicit use of a given segment register, and override the implicit rules listed in Table 3-3. The override prefixes also allow the use of the ES, FS and GS segment registers.

There are no restrictions regarding the overlapping of the base addresses of any segments. Thus, all 6 segments could have the base address set to zero and create a system with a 4-Gbyte linear address space. This creates a system where the virtual address space is the same as the linear address space. Further details of segmentation are discussed in Chapter 6, "Protected Mode Architecture."

3.12 I/O SPACE

The Intel486 processor has two distinct physical address spaces: Memory and I/O. Generally, peripherals are placed in I/O space, although the Intel486 processor also supports memory-mapped peripherals. The I/O space consists of 64 Kbytes. It can be divided into 64 K 8-bit ports, 32 K 16-bit ports, or 16 K 32-bit ports, or any combination of ports that add up to less than 64 Kbytes. The 64 K I/O address space refers to physical memory rather than linear address, because I/O instructions do not go through the segmentation or paging hardware. The M/IO# pin acts as an additional address line, thus allowing the system designer to easily determine which address space the processor is accessing.

Table 3-3. Segment Register Selection Rules

Type of Memory Reference	Implied (Default) Segment Use	Segment Override Prefixes Possible
Code Fetch	CS	None
Destination of PUSH, PUSHF, INT, CALL, PUSHA Instructions	SS	None
Source of POP, POPA, POPF, IRET, RET instructions	SS	None
Destination of STOS, MOVS, REP STOS, REP MOVS Instructions (DI is Base Register)	ES	None
Other Data References, with Effective Address using Base Register of:		
[EAX]	DS	
[EBX]	DS	
[ECX]	DS	
[EDX]	DS	All
[ESI]	DS	
[EDI]	DS	
[EBP]	SS	
[ESP]	SS	

The I/O ports are accessed via the IN and OUT I/O instructions, with the port address supplied as an immediate 8-bit constant in the instruction or in the DX register. All 8- and 16-bit port addresses are zero extended on the upper address lines. The I/O instructions cause the M/IO# pin to be driven low.

I/O port addresses 00F8H through 00FFH are reserved for use by Intel.

I/O instruction code is cacheable.

I/O data is not cacheable.

I/O transfers (data or code) can be bursted.

3.13 ADDRESSING MODES

3.13.1 Addressing Modes Overview

The Intel486 processor provides a total of 11 addressing modes for instructions to specify operands. The addressing modes are optimized to allow the efficient execution of high-level languages such as C and FORTRAN, and they cover the vast majority of data references needed by high-level languages.

3.13.2 Register and Immediate Modes

The following two addressing modes provide for instructions that operate on register or immediate operands:

- Register Operand Mode: The operand is located in one of the 8-, 16- or 32-bit general registers.
- Immediate Operand Mode: The operand is included in the instruction as part of the opcode.

3.13.3 32-Bit Memory Addressing Modes

The remaining modes provide a mechanism for specifying the effective address of an operand. The linear address consists of two components: the segment base address and an effective address. The effective address is calculated by using combinations of the following four address elements:

- DISPLACEMENT: An 8-, or 32-bit immediate value, following the instruction.
- BASE: The contents of any general purpose register. The base registers are generally used by compilers to point to the start of the local variable area.
- INDEX: The contents of any general purpose register except for ESP. The index registers are used to access the elements of an array, or a string of characters.
- SCALE: The index register's value can be multiplied by a scale factor, either 1, 2, 4 or 8. Scaled index mode is especially useful for accessing arrays or structures.

Combinations of these 4 components make up the 9 additional addressing modes. There is no performance penalty for using any of these addressing combinations, because the effective address calculation is pipelined with the execution of other instructions. The one exception is the simultaneous use of Base and Index components, which requires one additional clock.

As shown in Figure 3-14, the effective address (EA) of an operand is calculated according to the following formula:

EA = Base Reg + (Index Reg * Scaling) + Displacement

Direct Mode: The operand's offset is contained as part of the instruction as an 8-, 16- or 32-bit displacement.

Example: INC Word PTR [500]

Register Indirect Mode: A BASE register contains the address of the operand.

Example: MOV [ECX], EDX

Based Mode: A BASE register's contents is added to a DISPLACEMENT to form the operand's offset.

Example: MOV ECX, [EAX+24]

Index Mode: An INDEX register's contents is added to a DISPLACEMENT to form the operand's offset.

Example: ADD EAX, TABLE[ESI]

Scaled Index Mode: An INDEX register's contents is multiplied by a scaling factor which is added to a DISPLACEMENT to form the operand's offset.

Example: IMUL EBX, TABLE[ESI*4],7

Based Index Mode: The contents of a BASE register is added to the contents of an INDEX register to form the effective address of an operand.

Example: MOV EAX, [ESI] [EBX]

Based Scaled Index Mode: The contents of an INDEX register is multiplied by a SCALING factor and the result is added to the contents of a BASE register to obtain the operand's offset.

Example: MOV ECX, [EDX*8] [EAX]

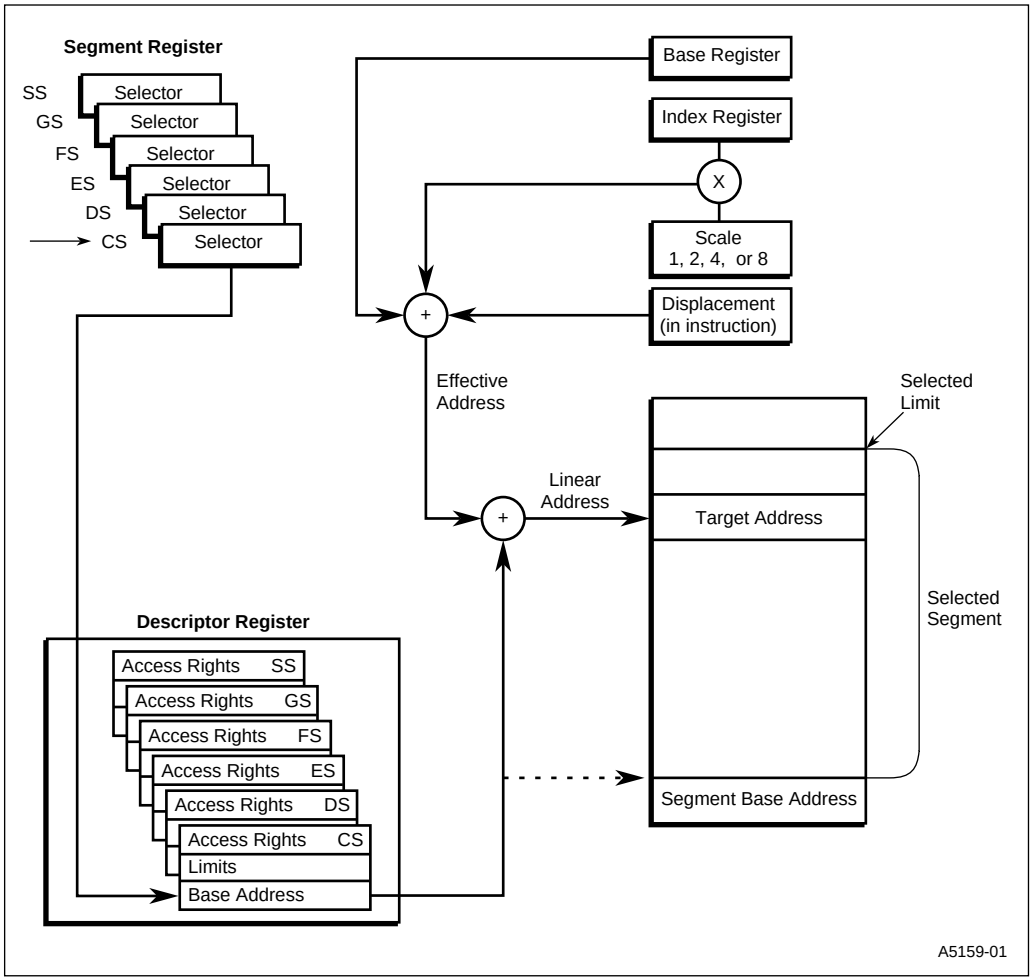


Figure 3-14. Addressing Mode Calculations

Based Index Mode with Displacement: The contents of an INDEX Register and a BASE register's contents and a DISPLACEMENT are all summed together to form the operand offset.

Example: ADD EDX, [ESI] [EBP+00FFFFF0H]

Based Scaled Index Mode with Displacement: The contents of an INDEX register are multiplied by a SCALING factor, the result is added to the contents of a BASE register and a DISPLACEMENT to form the operand's offset.

Example: MOV EAX, LOCALTABLE[EDI*4] [EBP+80]

3.13.4 Differences Between 16- and 32-Bit Addresses

In order to provide software compatibility with 80286 and 8086 processors, the Intel486 processor can execute 16-bit instructions in Real and Protected Modes. The processor determines the size of the instructions it is executing by examining the D bit in the CS segment Descriptor. If the D bit is 0 then all operand lengths and effective addresses are assumed to be 16 bits long. If the D bit is 1 then the default length for operands and addresses is 32 bits. In Real Mode the default size for operands and addresses is 16-bits.

Regardless of the default precision of the operands or addresses, the Intel486 processor is able to execute either 16- or 32-bit instructions. This is specified via the use of override prefixes. Two prefixes, the Operand Size Prefix and the Address Length Prefix, override the value of the D bit on an individual instruction basis. These prefixes are automatically added by Intel assemblers.

Example: The Intel486 processor is executing in Real Mode and the programmer needs to access the EAX registers. The assembler code for this might be MOV EAX, 32-bit MEMORY OP. The ASM486 Macro Assembler automatically determines that an Operand Size Prefix is needed and generates it.

Example: The D bit is 0, and the programmer wishes to use Scaled Index addressing mode to access an array. The Address Length Prefix allows the use of MOV DX, TABLE[ESI*2]. The assembler uses an Address Length Prefix because, with D=0, the default addressing mode is 16-bits.

Example: The D bit is 1, and the program wants to store a 16-bit quantity. The Operand Length Prefix is used to specify only a 16-bit value; MOV MEM16, DX.

The OPERAND LENGTH and Address Length Prefixes can be applied separately or in combination to any instruction. The Address Length Prefix does not allow addresses over 64 Kbytes to be accessed in Real Mode. A memory address which exceeds FFFFH will result in a General Protection Fault. An Address Length Prefix only allows the use of the additional Intel486 processor addressing modes.

When executing 32-bit code, the Intel486 processor uses either 8-, or 32-bit displacements, and any register can be used as base or index registers. When executing 16-bit code, the displacements are either 8, or 16 bits, and the base and index register conform to the 80286 processor model. Table 3-4 illustrates the differences.

Table 3-4. BASE and INDEX Registers for 16- and 32-Bit Addresses

	16-Bit Addressing	32-Bit Addressing
BASE REGISTER	BX,BP	Any 32-bit GP Register
INDEX REGISTER	SI,DI	Any 32-bit GP Register Except ESP
SCALE FACTOR	none	1, 2, 4, 8
DISPLACEMENT	0, 8, 16 bits	0, 8, 32 bits

3.14 Data Formats

3.14.1 Data Types

The Intel486 processor can support a wide-variety of data types. In the following descriptions, the processor consists of the base architecture registers.

3.14.1.1 Unsigned Data Types

Byte: Unsigned 8-bit quantity

Word: Unsigned 16-bit quantity

Dword: Unsigned 32-bit quantity

The least significant bit (LSB) in a byte is bit 0, and the most significant bit is 7.

3.14.1.2 Signed Data Types

All signed data types assume 2's complement notation. The signed data types contain two fields, a sign bit and a magnitude. The sign bit is the most significant bit (MSB). The number is negative if the sign bit is 1. If the sign bit is 0, the number is positive. The magnitude field consists of the remaining bits in the number. (Refer to Figure 3-15.)

8-bit Integer: Signed 8-bit quantity

16-bit Integer: Signed 16-bit quantity

32-bit Integer: Signed 32-bit quantity

64-bit Integer: Signed 64-bit quantity

The integer core of the Intel486 processors only support 8-, 16- and 32-bit integers. (See Section 3.14.1.4, "Floating-Point Data Types")

3.14.1.3 BCD Data Types

The Intel486 processor supports packed and unpacked binary coded decimal (BCD) data types. A packed BCD data type contains two digits per byte, the lower digit is in bits 3:0 and the upper digit in bits 7:4. An unpacked BCD data type contains 1 digit per byte stored in bits 3:0.

The Intel486 processor supports 8-bit packed and unpacked BCD data types. (Refer to Figure 3-15.)

3.14.1.4 Floating-Point Data Types

In addition to the base registers, the IntelDX2™ and IntelDX4™ processors' on-chip floating-point unit consists of the floating-point registers. The floating-point unit data type contain three fields: sign, significand, and exponent. The sign field is one bit and is the MSB of the floating-point number. The number is negative if the sign bit is 1. If the sign bit is 0, the number is positive. The significand gives the significant bits of the number. The exponent field contains the power of 2 needed to scale the significand. (Refer to Figure 3-15.)

Only the FPU supports floating-point data types.

Single Precision Real:	23-bit significand and 8-bit exponent. 32 bits total.
Double Precision Real:	52-bit significand and 11-bit exponent. 64 bits total.
Extended Precision Real:	64-bit significand and 15-bit exponent. 80 bits total.

Floating-Point Unsigned Data Types

The on-chip FPU does not support unsigned data types. (Refer to Figure 3-15.)

Floating-Point Signed Data Types

The on-chip FPU only supports 16-, 32- and 64-bit integers.

Floating-Point BCD Data Types

The on-chip FPU only supports 80-bit packed BCD data types.

3.14.1.5 String Data Types

A string data type is a contiguous sequence of bits, bytes, words or dwords. A string may contain between 1 byte and 4 Gbytes. (Refer to Figure 3-16.)

String data types are only supported by the CPU section of the Intel486 processor.

Byte String:	Contiguous sequence of bytes.
Word String:	Contiguous sequence of words.
Dword String:	Contiguous sequence of dwords.
Bit String:	A set of contiguous bits. In the Intel486 processor bit strings can be up to 4-gigabits long.

3.14.1.6 ASCII Data Types

The Intel486 processor supports ASCII (American Standard Code for Information Interchange) strings and can perform arithmetic operations (such as addition and division) on ASCII data. The Intel486 processor can only operate on ASCII data. (Refer to Figure 3-16.)

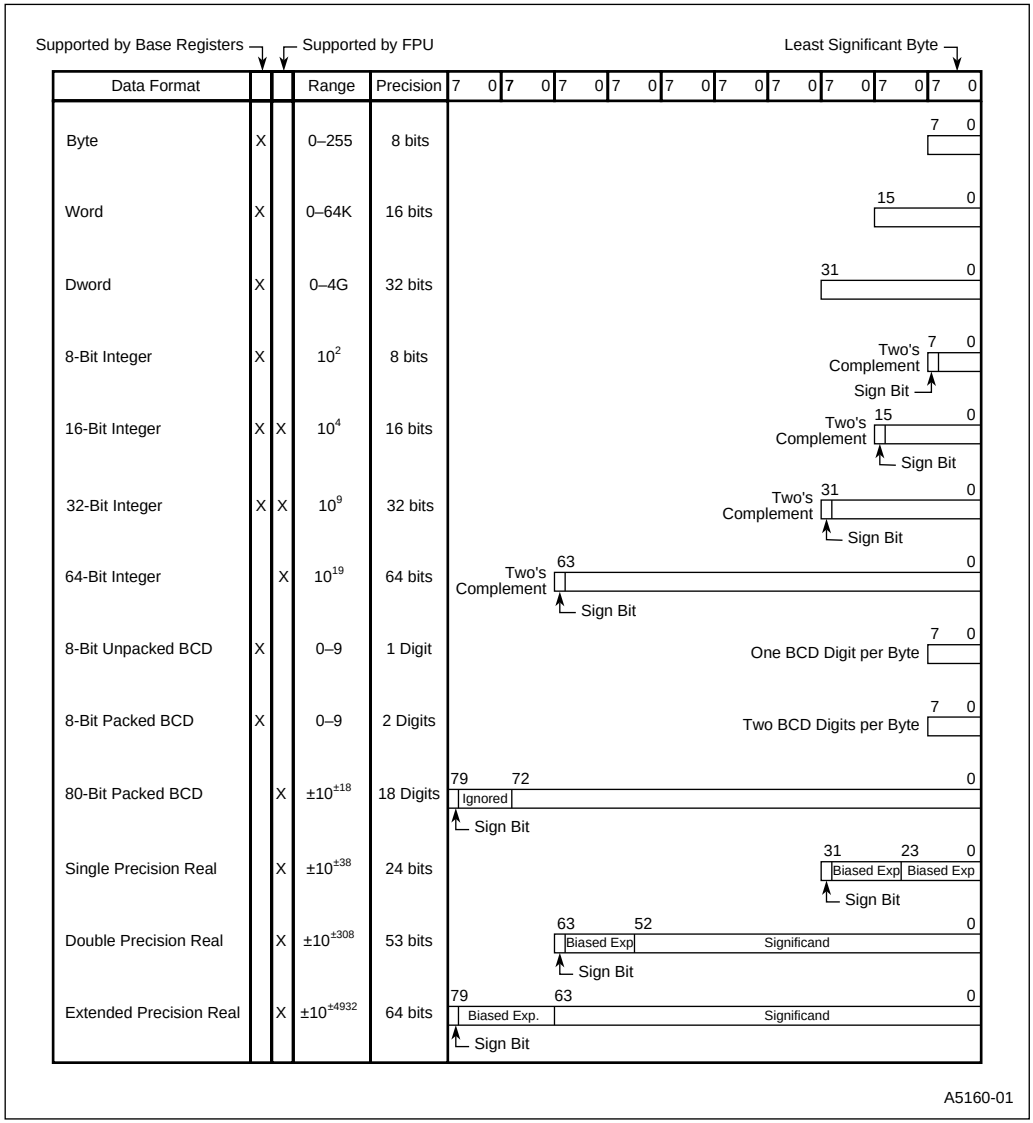


Figure 3-15. Intel486™ Processor Data Types

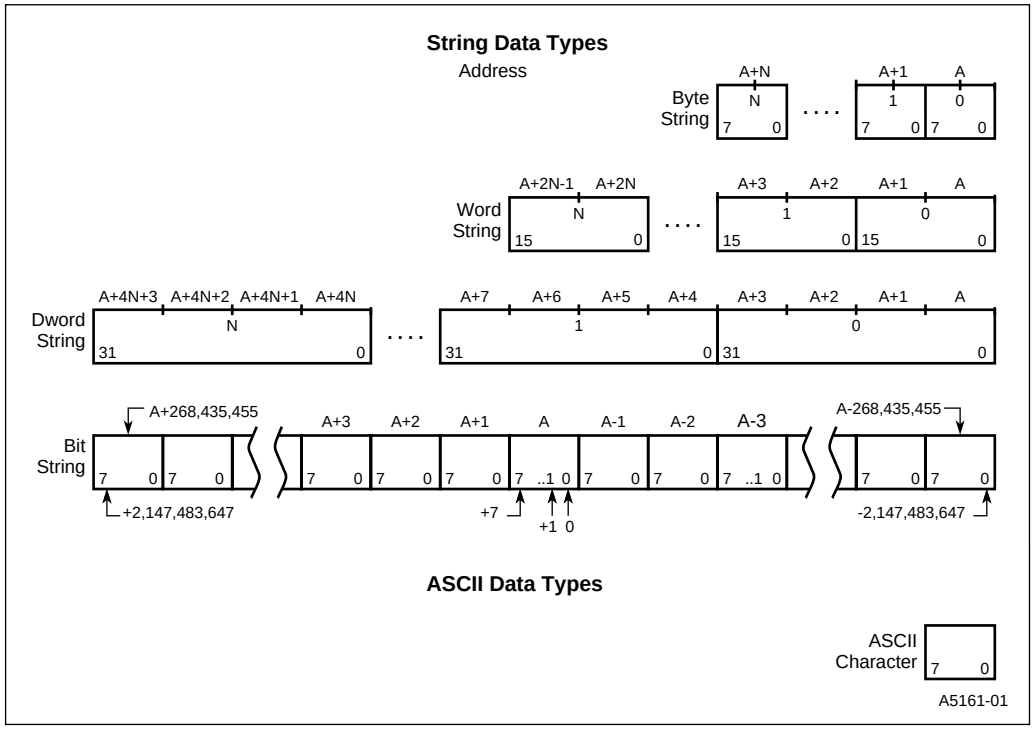


Figure 3-16. String and ASCII Data Types

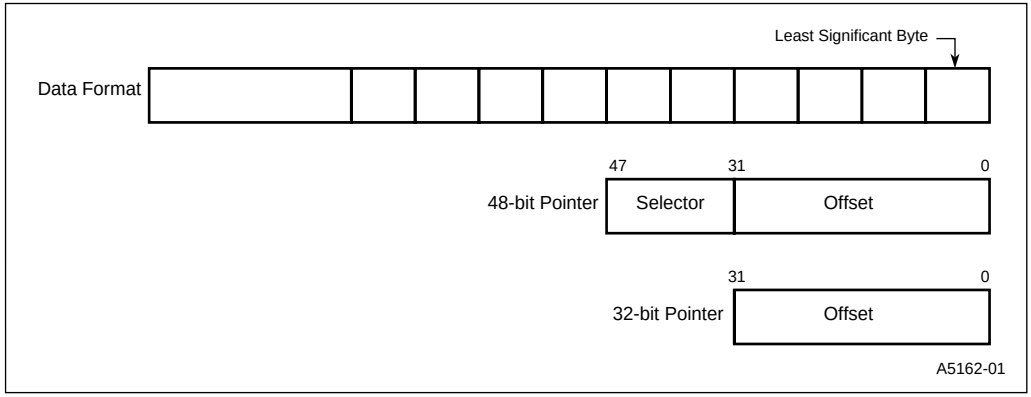


Figure 3-17. Pointer Data Types

3.14.1.7 Pointer Data Types

A pointer data type contains a value that gives the address of a piece of data. Intel486 processors support the following two types of pointers (see Figure 3-17):

- 48-bit Pointer: 16-bit selector and 32-bit offset
- 32-bit Pointer: 32-bit offset

3.14.2 Little Endian vs. Big Endian Data Formats

The Intel486 processors, as well as all other members of the Intel architecture, use the "little-endian" method for storing data types that are larger than one byte. Words are stored in two consecutive bytes in memory with the low-order byte at the lowest address and the high order byte at the high address. Dwords are stored in four consecutive bytes in memory with the low-order byte at the lowest address and the high order byte at the highest address. The address of a word or dword data item is the byte address of the low-order byte.

Figure 3-18 illustrates the differences between the big-endian and little-endian formats for dwords. The 32 bits of data are shown with the low order bit numbered bit 0 and the high order bit numbered 32. Big-endian data is stored with the high-order bits at the lowest addressed byte. Little-endian data is stored with the high-order bits in the highest addressed byte.

The Intel486 processor has the following two instructions that can convert 16- or 32-bit data between the two byte orderings:

- BSWAP (byte swap) handles 4-byte values
- XCHG (exchange) handles 2-byte values

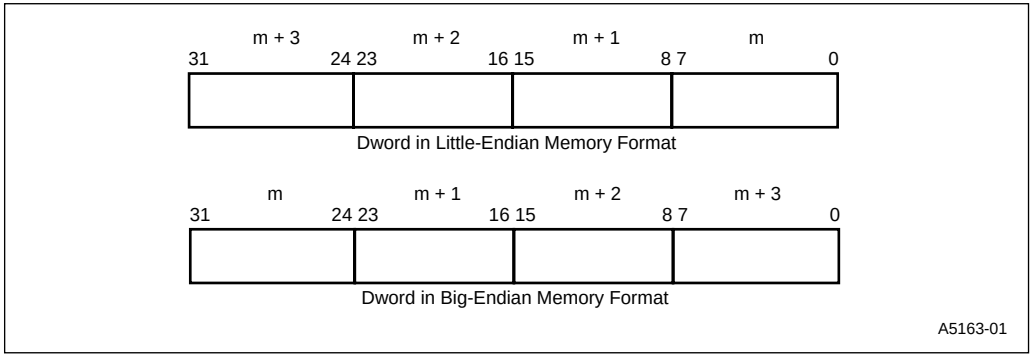


Figure 3-18. Big vs. Little Endian Memory Format

3.15 INTERRUPTS

3.15.1 Interrupts and Exceptions

Interrupts and exceptions alter the normal program flow, in order to handle external events, to report errors or exceptional conditions. The difference between interrupts and exceptions is that interrupts are used to handle asynchronous external events while exceptions handle instruction faults. Although a program can generate a software interrupt via an INT N instruction, the Intel486 processors treat software interrupts as exceptions.

Hardware interrupts occur as the result of an external event and are classified into two types: maskable or non-maskable. Interrupts are serviced after the execution of the current instruction. After the interrupt handler is finished servicing the interrupt, execution proceeds with the instruction immediately **after** the interrupted instruction. Section 3.15.3, “Maskable Interrupt” and Section 3.15.4, “Non-Maskable Interrupt” discuss the differences between Maskable and Non-Maskable interrupts.

Exceptions are classified as faults, traps, or aborts, depending on the way they are reported, and whether or not restart of the instruction causing the exception is supported. **Faults** are exceptions that are detected and serviced **before** the execution of the faulting instruction. A fault would occur in a virtual memory system when the processor referenced a page or a segment that was not present. The operating system would fetch the page or segment from disk, and then the Intel486 processor would restart the instruction. **Traps** are exceptions that are reported immediately **after** the execution of the instruction that caused the problem. User defined interrupts are examples of traps. **Aborts** are exceptions that do not permit the precise location of the instruction causing the exception to be determined. Aborts are used to report severe errors, such as a hardware error or illegal values in system tables.

Thus, when an interrupt service routine has been completed, execution proceeds from the instruction immediately following the interrupted instruction. On the other hand, the return address from an exception fault routine will always point at the instruction causing the exception and include any leading instruction prefixes. Tables 3-5 and 3-6 summarize the possible interrupts for Intel486 processors and shows where the return address points.

Intel486 processors can handle up to 256 different interrupts and/or exceptions. In order to service the interrupts, a table with up to 256 interrupt vectors must be defined. The interrupt vectors are simply pointers to the appropriate interrupt service routine. In Real Mode (see Chapter 5, “Real Mode Architecture”), the vectors are 4-byte quantities, a Code Segment plus a 16-bit offset; in Protected Mode, the interrupt vectors are 8-byte quantities, which are put in an Interrupt Descriptor Table (see Section 6.2.3.4, “Interrupt Descriptor Table”). Of the 256 possible interrupts, 32 are reserved for use by Intel, the remaining 224 are free to be used by the system designer.

3.15.2 Interrupt Processing

When an interrupt occurs, the following actions happen. First, the current program address and the Flags are saved on the stack to allow resumption of the interrupted program. Next, an 8-bit vector is supplied to the Intel486 processor which identifies the appropriate entry in the interrupt table. The table contains the starting address of the interrupt service routine. Then, the user supplied interrupt service routine is executed. Finally, when an IRET instruction is executed the old Intel486 processor state is restored and program execution resumes at the appropriate instruction.

The 8-bit interrupt vector is supplied to the Intel486 processor in several different ways: exceptions supply the interrupt vector internally; software INT instructions contain or imply the vector; maskable hardware interrupts supply the 8-bit vector via the interrupt acknowledge bus sequence. Non-maskable hardware interrupts are assigned to interrupt vector 2.

3.15.3 Maskable Interrupt

Maskable interrupts are the most common way used by the Intel486 processor to respond to asynchronous external hardware events. A hardware interrupt occurs when the INTR is pulled high and the Interrupt Flag bit (IF) is enabled. The Intel486 processor only responds to interrupts between instructions, (REPeat String instructions, have an "interrupt window," between memory moves, which allows interrupts during long string moves). When an interrupt occurs, the Intel486 processor reads an 8-bit vector supplied by the hardware which identifies the source of the interrupt, (one of 224 user defined interrupts). The exact nature of the interrupt sequence is discussed in Section 10.3.10, "Interrupt Acknowledge."

The IF bit in the EFLAG registers is reset when an interrupt is being serviced. This effectively disables servicing additional interrupts during an interrupt service routine. However, the IF may be set explicitly by the interrupt handler, to allow the nesting of interrupts. When an IRET instruction is executed, the original state of the IF is restored.

Table 3-5. Interrupt Vector Assignments

Function	Interrupt Number	Instruction that Can Cause Exception	Return Address Points to Faulting Instruction	Type
Divide Error	0	DIV, IDIV	YES	FAULT
Debug Exception	1	Any instruction	YES	TRAP†
NMI Interrupt	2	INT 2 or NMI	NO	NMI
One Byte Interrupt	3	INT	NO	TRAP
Interrupt on Overflow	4	INTO	NO	TRAP
Array Bounds Check	5	BOUND	YES	FAULT
Invalid OP-Code	6	Any illegal instruction	YES	FAULT
Device Not Available	7	ESC, WAIT	YES	FAULT
Double Fault	8	Any instruction that can generate an exception		ABORT
Intel Reserved	9			
Invalid TSS	10	JMP, CALL, IRET, INT	YES	FAULT
Segment Not Present	1	Segment Register Instructions	YES	FAULT
Stack Fault	12	Stack References	YES	FAULT
General Protection Fault	13	Any Memory Reference	YES	FAULT
Page Fault	14	Any Memory Access or Code Fetch	YES	FAULT
Intel Reserved	15			
Alignment Check Interrupt	17	Unaligned Memory Access	YES	FAULT
Intel Reserved	18–31			
Two Byte Interrupt	0–255	INT n	NO	TRAP

†Some debug exceptions may report both traps on the previous instruction, and faults on the next instruction.

Table 3-6. FPU Interrupt Vector Assignments

Function	Interrupt Number	Instruction Which Can Cause Exception	Return Address Points to Faulting Instruction	Type
Floating-Point Error	16	Floating-point, WAIT	YES	FAULT

3.15.4 Non-Maskable Interrupt

Non-maskable interrupts provide a method of servicing very high priority interrupts. A common example of the use of a non-maskable interrupt (NMI) would be to activate a power failure routine or SMI# to activate a power saving mode. When the NMI input is pulled high, it causes an interrupt with an internally supplied vector value of 2. Unlike a normal hardware interrupt, no interrupt acknowledgment sequence is performed for an NMI.

While executing the NMI servicing procedure, the Intel486 processor will not service further NMI requests until an interrupt return (IRET) instruction is executed or the processor is reset (RSM in the case of SMI#). If NMI occurs while currently servicing an NMI, its presence will be saved for servicing after executing the first IRET instruction. The IF bit is cleared at the beginning of an NMI interrupt to inhibit further INTR interrupts.

3.15.5 Software Interrupts

A third type of interrupt/exception for the Intel486 processor is the software interrupt. An INT n instruction causes the processor to execute the interrupt service routine pointed to by the *n*th vector in the interrupt table.

A special case of the two byte software interrupt INT n is the one byte INT 3, or breakpoint interrupt. By inserting this one byte instruction in a program, the user can set breakpoints in his program as a debugging tool.

A final type of software interrupt is the single step interrupt. It is discussed in Section 11.2, "Single-Step Trap."

3.15.6 Interrupt and Exception Priorities

Interrupts are externally-generated events. Maskable Interrupts (on the INTR input) and Non-Maskable Interrupts (on the NMI input or SMI# input) are recognized at instruction boundaries. When more than one interrupt or external event are both recognized at the same instruction boundary, the Intel486 processor invokes the highest priority routine first. (See list below.) If, after the NMI service routine has been invoked, maskable interrupts are still enabled, then the Intel486 processor will invoke the appropriate interrupt service routine.

Priority for Servicing External Events for All Intel486 processors Except the Write-Back Enhanced IntelDX4 processor:

1. RESET/SRESET
2. FLUSH#
3. SMI#
4. NMI
5. INTR
6. STPCLK#

NOTE

STPCLK# will be recognized while in an interrupt service routine or an SMM handler.

For the Write-Back Enhanced IntelDX4 processor, the priority of servicing external events is modified from the standard Intel486 processor. The list below shows the priority for write-back enhanced mode

Priority for Servicing External Events for the Write-Back Enhanced IntelDX4 processor:

1. RESET
2. FLUSH#
3. SRESET
4. SMI#
5. NMI
6. INTR
7. STPCLK#

Exceptions are internally-generated events. Exceptions are detected by the Intel486 processor if, in the course of executing an instruction, the Intel486 processor detects a problematic condition. The IntelDX4 processor then immediately invokes the appropriate exception service routine. The state of the Intel486 processor is such that the instruction causing the exception can be restarted. If the exception service routine has taken care of the problematic condition, the instruction will execute without causing the same exception.

It is possible for a single instruction to generate several exceptions (for example, transferring a single operand could generate two page faults if the operand location spans two “not present” pages). However, only one exception is generated upon each attempt to execute the instruction. Each exception service routine should correct its corresponding exception, and restart the instruction. In this manner, exceptions are serviced until the instruction executes successfully.

As the Intel486 processor executes instructions, it follows a consistent cycle in checking for exceptions. Consider the case of the Intel486 processor having just completed an instruction. It then performs the checks listed in Table 3-7 before reaching the point where the next instruction is completed. This cycle is repeated as each instruction is executed, and occurs in parallel with instruction decoding and execution. Checking for EM, TS, or FPU error status only occurs for processors with on-chip Floating-Point Units.

Table 3-7. Sequence of Exception Checking

Sequence	Description
1	Check for Exception 1 Traps from the instruction just completed (single-step via Trap Flag, or Data Breakpoints set in the Debug Registers).
2	Check for Exception 1 Faults in the next instruction (Instruction Execution Breakpoint set in the Debug Registers for the next instruction).
3	Check for external NMI and INTR.
4	Check for Segmentation Faults that prevented fetching the entire next instruction (exceptions 11 or 13).
5	Check for Page Faults that prevented fetching the entire next instruction (exception 14).
6	Check for Faults decoding the next instruction (exception 6 if illegal opcode; exception 6 if in Real Mode or in Virtual 8086 Mode and attempting to execute an instruction for Protected Mode only (see Section 6.5.4, "Protection and I/O Permission Bitmap"); or exception 13 if instruction is longer than 15 bytes, or privilege violation in Protected Mode (i.e., not at IOPL or at CPL=0).
7	If WAIT opcode, check if TS=1 and MP=1 (exception 7 if both are 1).
8	If opcode for Floating-Point Unit, check if EM=1 or TS=1 (exception 7 if either are 1).
9	If opcode for Floating-Point Unit (FPU), check FPU error status (exception 16 if error status is asserted).
10	Check in the following order for each memory reference required by the instruction: a. Check for Segmentation Faults that prevent transferring the entire memory quantity (exceptions 11, 12, 13). b. Check for Page Faults that prevent transferring the entire memory quantity (exception 14).

NOTE: The order stated supports the concept of the paging mechanism being "underneath" the segmentation mechanism. Therefore, for any given code or data reference in memory, segmentation exceptions are generated before paging exceptions are generated.

3.15.7 Instruction Restart

The Intel486 processor fully supports restarting all instructions after faults. If an exception is detected in the instruction to be executed (exception categories 4 through 10 in Table 3-8), the Intel486 processor invokes the appropriate exception service routine.

The Intel486 processor is in a state that permits restart of the instruction, for all cases except the following. An instruction causes a task switch to a task whose Task State Segment is partially "not present." (An entirely "not present" TSS is restartable.) Partially present TSSs can be avoided either by keeping the TSSs of such tasks present in memory, or by aligning TSS segments to reside entirely within a single 4 K page (for TSS segments of 4 Kbytes or less).

NOTE

Partially present task state segments can be easily avoided by proper design of the operating system.

3.15.8 Double Fault

A Double Fault (exception 8) results when the Intel486 processor attempts to invoke an exception service routine for the segment exceptions (10, 11, 12 or 13), but in the process of doing so, detects an exception other than a Page Fault (exception 14).

A Double Fault (exception 8) will also be generated when the Intel486 processor attempts to invoke the Page Fault (exception 14) service routine, and detects an exception other than a second Page Fault. In any functional system, the entire Page Fault service routine must remain “present” in memory.

When a Double Fault occurs, the Intel486 processor invokes the exception service routine for exception 8.

3.15.9 Floating-Point Interrupt Vectors

Several interrupt vectors of the IntelDX2 and IntelDX4 processors are used to report exceptional conditions while executing numeric programs in either real or protected mode. Table 4-19 shows these interrupts and their causes.

Table 3-8. Interrupt Vectors Used by FPU

Interrupt Number	Cause of Interrupt
7	A Floating-Point instruction was encountered when EM or TS of the IntelDX2™ and IntelDX4™ processor control register zero (CR0) was set. EM = 1 indicates that software emulation of the instruction is required. When TS is set, either a Floating-Point or WAIT instruction causes interrupt 7. This indicates that the current FPU context may not belong to the current task.
13	The first word or doubleword of a numeric operand is not entirely within the limit of its segment. The return address pushed onto the stack of the exception handler points at the Floating-Point instruction that caused the exception, including any prefixes. The FPU has not executed this instruction; the instruction pointer and data pointer register refer to a previous, correctly executed instruction.
16	The previous numerics instruction caused an unmasked exception. The address of the faulty instruction and the address of its operand are stored in the instruction pointer and data pointer registers. Only Floating-Point and WAIT instructions can cause this interrupt. The IntelDX2 and IntelDX4 processors return address pushed onto the stack of the exception handler points to a WAIT or Floating-Point instruction (including prefixes). This instruction can be restarted after clearing the exception condition in the FPU. The FNINIT, FNCLEX, FNSTSW, FNSTENV, and FNSAVE instructions can not cause this interrupt.

4

System Register Organization

Chapter Contents

CHAPTER 4
SYSTEM REGISTER ORGANIZATION

4.1 REGISTER SET OVERVIEW

The Intel486™ processor register set can be split into the following categories:

- Base Architecture Registers
  - — General Purpose Registers
  - — Instruction Pointer
  - — Flags Register
  - — Segment Registers
- System-Level Registers
  - — Control Registers
  - — System Address Registers
- Debug and Test Registers

The base architecture and floating-point registers (see below) are accessible by the applications program. The system-level registers can only be accessed at privilege level 0 and can only be used by system-level programs. The debug and test registers also can only be accessed at privilege level 0.

4.2 FLOATING-POINT REGISTERS

In addition to the registers listed above, the IntelDX2™ and IntelDX4™ processors have the following:

- Floating-Point Registers
- Data Registers
- Tag Word
- Status Word
- Instruction and Data Pointers
- Control Word

4.3 BASE ARCHITECTURE REGISTERS

Figure 4-1 shows the Intel486 processor base architecture registers. The contents of these registers are task-specific and are automatically loaded with a new context upon a task switch operation.

The base architecture includes six directly accessible descriptors, each specifying a segment up to 4 Gbytes in size. The descriptors are indicated by the selector values placed in the Intel486 processor segment registers. Various selector values can be loaded as a program executes.

NOTE

In register descriptions, "set" means "set to 1," and "reset" means "set to 0."

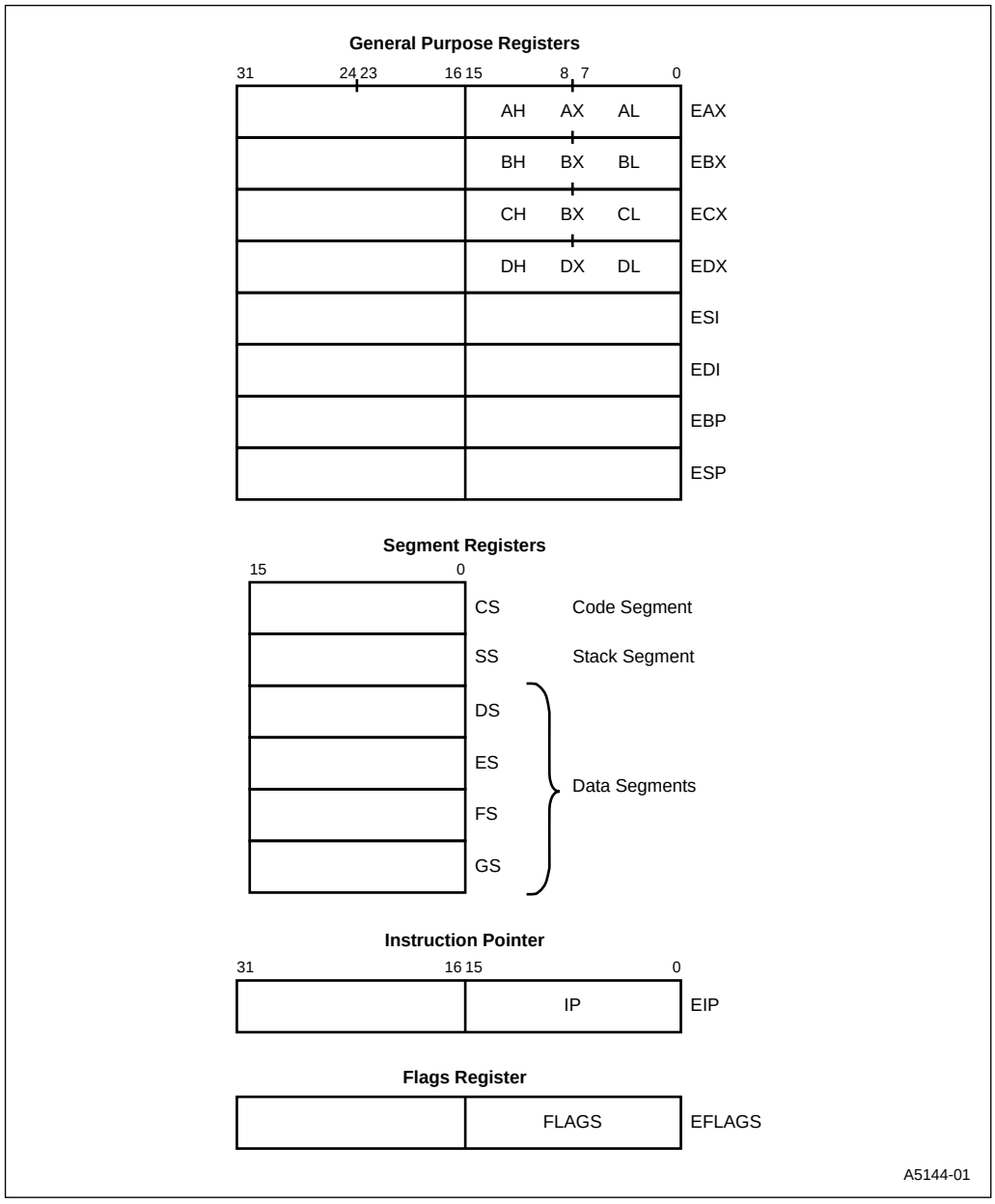


Figure 4-1. Base Architecture Registers

4.3.1 General Purpose Registers

Figure 4-1 on page 4-3 shows the eight 32-bit general purpose registers. These registers hold data or address quantities. The general purpose registers can support data operands of 1, 8, 16 and 32 bits, and bit fields of 1 to 32 bits. Address operands of 16 and 32 bits are supported. The 32-bit registers are named EAX, EBX, ECX, EDX, ESI, EDI, EBP and ESP.

The least significant 16 bits of the general purpose registers can be accessed separately using the 16-bit names of the registers AX, BX, CX, DX, SI, DI, BP and SP. The upper 16 bits of the register are not changed when the lower 16 bits are accessed separately.

Finally, 8-bit operations can individually access the lower byte (bits 7:0) and the highest byte (bits 15:8) of the general purpose registers AX, BX, CX and DX. The lowest bytes are named AL, BL, CL and DL, respectively. The higher bytes are named AH, BH, CH and DH, respectively. The individual byte accessibility offers additional flexibility for data operations, but is not used for effective address calculation.

4.3.2 Instruction Pointer

The instruction pointer shown in Figure 4-1 is a 32-bit register named EIP. EIP holds the offset of the next instruction to be executed. The offset is always relative to the base of the code segment (CS). The lower 16 bits (bits 15:0) of the EIP contain the 16-bit instruction pointer named IP, which is used for 16-bit addressing.

4.3.3 Flags Register

The flags register is a 32-bit register named EFLAGS. The defined bits and bit fields within EFLAGS control certain operations and indicate the status of the Intel486 processor. The lower 16 bits (bit 15:0) of EFLAGS contain the 16-bit register named FLAGS, which is most useful when executing 8086 and 80286 processor code. Figure 4-2 shows the EFLAGS register.

EFLAGS bits 1, 3, 5, 15, and 22 to 31 are defined as "Intel Reserved." When these bits are stored during interrupt processing or with a PUSHF instruction (push flags onto stack), a "1" is stored in bit 1 and zeros are stored in bits 3, 5, 15, and 22 to 31.

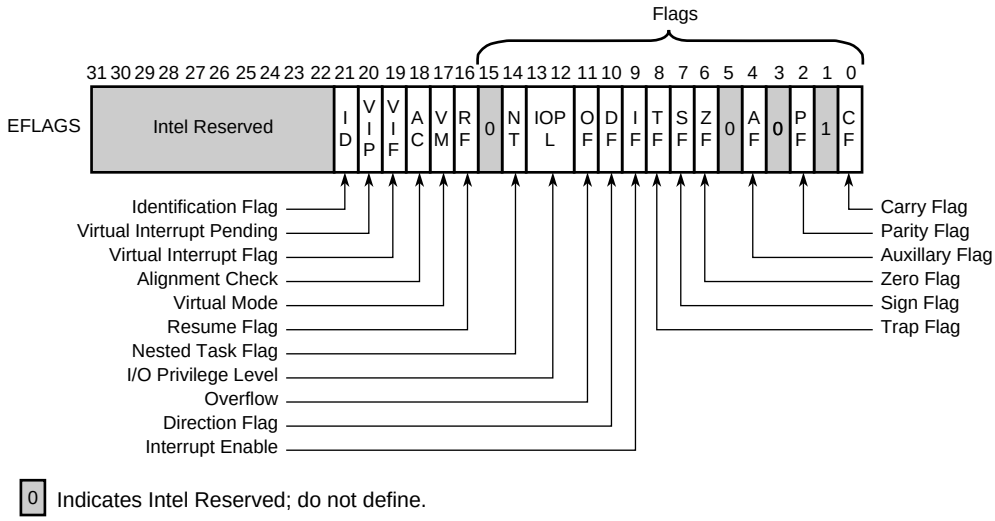


Figure 4-2. Flag Registers

ID (Identification Flag, bit 21)

The ability of a program to set and clear the ID flag indicates that the processor supports the CPUID instruction. (Refer to Chapter 12, “Instruction Set Summary” and Appendix D, “Feature Determination.”)

VIP (Virtual Interrupt Pending Flag, bit 20)

The VIP flag together with the VIF enable each applications program in a multi-tasking environment to have virtualized versions of the system's IF flag. For more on the use of this flag in Virtual-8086 Mode and in Protected Mode, refer to Appendix C, “Advanced Features.”

VIF (Virtual Interrupt Flag, bit 19)

The VIF is a virtual image of the IF (interrupt flag) used with VIP. For more on the use of this flag in Virtual-86 Mode and in Protected Mode refer to Appendix C, “Advanced Features.”

AC (Alignment Check, bit 18)

The AC bit is defined in the upper 16 bits of the register. It enables the generation of faults when a memory reference is to a misaligned address. Alignment faults are enabled when AC is set to 1. A misaligned address is a word access to an odd address, a dword access to an address that is not on a dword boundary, or an 8-byte reference to an address that is not on a 64-bit word boundary. (See Section 10.1.5, "Operand Alignment")

Alignment faults are only generated by programs running at privilege level 3. The AC bit setting is ignored at privilege levels 0, 1, and 2. Note that references to the descriptor tables (for selector loads), or the task state segment (TSS), are implicitly level 0 references even when the instructions causing the references are executed at level 3. Alignment faults are reported through interrupt 17, with an error code of 0. Table 4-1 gives the alignment required for the Intel486 processor data types.

Table 4-1. Data Type Alignment Requirements

Memory Access	Alignment (Byte Boundary)
Word	2
Dword	4
Single Precision Real	4
Double Precision Real	8
Extended Precision Real	8
Selector	2
48-bit Segmented Pointer	4
32-bit Flat Pointer	4
32-bit Segmented Pointer	2
48-bit "Pseudo-Descriptor"	4
FSTENV/FLDENV Save Area	4/2 (On Operand Size)
FSAVE/FRSTOR Save Area	4/2 (On Operand Size)
Bit String	4

NOTE

Several instructions on the Intel486 processor generate misaligned references, even when their memory address is aligned. For example, on the Intel486 processor, the SGDT/SIDT (store global/interrupt descriptor table) instruction reads/writes two bytes, and then reads/writes four bytes from a "pseudo-descriptor" at the given address. The Intel486 processor generates misaligned references unless the address is on a 2 mod 4 boundary. The FSAVE and FRSTOR instructions (floating-point save and restore state) generate misaligned references for one-half of the register save/restore cycles. The Intel486 processor does not cause any AC faults when the effective address given in the instruction has the proper alignment.

VM (Virtual 8086 Mode, bit 17)

The VM bit provides Virtual 8086 Mode within Protected Mode. When the VM bit is set while the Intel486 processor is in Protected Mode, the Intel486 processor switches to Virtual 8086 operation, handling segment loads as the 8086 processor does, but generating exception 13 faults on privileged opcodes. The VM bit can be set only in Protected Mode by the IRET instruction (when current privilege level = 0) and by task switches at any privilege level. The VM bit is unaffected by POPF. PUSHF always pushes a 0 in this bit, even when executing in Virtual 8086 Mode. The EFLAGS image pushed during interrupt processing or saved during task switches contains a 1 in this bit if the interrupted code was executing as a Virtual 8086 Task.

RF (Resume Flag, bit 16)

The RF flag is used in conjunction with the debug register breakpoints. It is checked at instruction boundaries before breakpoint processing. When RF is set, it causes any debug fault to be ignored on the next instruction. RF is then automatically reset at the successful completion of every instruction (no faults are signaled) except the IRET instruction, the POPF instruction, (and JMP, CALL, and INT instructions causing a task switch). These instructions set RF to the value specified by the memory image. For example, at the end of the breakpoint service routine, the IRET instruction can pop an EFLAG image having the RF bit set and resume the program's execution at the breakpoint address without generating another breakpoint fault on the same location.

NT (Nested Task, bit 14)

The flag applies to Protected Mode. NT is set to indicate that the execution of this task is within another task. When set, it indicates that the current nested task's Task State Segment (TSS) has a valid back link to the previous task's TSS. This bit is set or reset by control transfers to other tasks. The value of NT in EFLAGS is tested by the IRET instruction to determine whether to do an inter-task return or an intra-task return. A POPF or an IRET instruction affects the setting of this bit according to the image popped, at any privilege level.

IOPL (Input/Output Privilege Level, bits 12-13)

This two-bit field applies to Protected Mode. IOPL indicates the numerically maximum CPL (current privilege level) value permitted to execute I/O instructions without generating an exception 13 fault or consulting the I/O Permission Bitmap. It also indicates the maximum CPL value allowing alteration of the IF (INTR Enable Flag) bit when new values are popped into the EFLAG register. POPF and IRET instruction can alter the IOPL field when executed at CPL = 0. Task switches can always alter the IOPL field, when the new flag image is loaded from the incoming task's TSS.

OF (Overflow Flag, bit 11)

The OF bit is set when the operation results in a signed overflow. Signed overflow occurs when the operation resulted in carry/borrow into the sign bit (high-order bit) of the result but did not result in a carry/borrow out of the high-order bit, or vice-versa. For 8-, 16-, 32-bit operations, OF is set according to overflow at bit 7, 15, and 31, respectively.

DF (Direction Flag, bit 10)

DF defines whether ESI and/or EDI registers post decrement or post increment during the string instructions. Post increment occurs when DF is reset. Post decrement occurs when DF is set.

IF (INTR Enable Flag, bit 9)

The IF flag, when set, allows recognition of external interrupts signaled on the INTR pin. When IF is reset, external interrupts signaled on the INTR are not recognized. IOPL indicates the maximum CPL value allowing alteration of the IF bit when new values are popped into EFLAGS or FLAGS.

TF (Trap Enable Flag, bit 8)

TF controls the generation of the exception 1 trap when the processor is single-stepping through code. When TF is set, the Intel486 processor generates an exception 1 trap after the next instruction is executed. When TF is reset, exception 1 traps occur only as a function of the breakpoint addresses loaded into debug registers DR[3:0].

SF (Sign Flag, bit 7)

SF is set if the high-order bit of the result is set; otherwise, it is reset. For 8-, 16-, 32-bit operations, SF reflects the state of bits 7, 15, and 31 respectively.

ZF (Zero Flag, bit 6)

ZF is set if all bits of the result are 0; otherwise, it is reset.

AF (Auxiliary Carry Flag, bit 4)

The Auxiliary Flag is used to simplify the addition and subtraction of packed BCD quantities. AF is set if the operation resulted in a carry out of bit 3 (addition) or a borrow into bit 3 (subtraction). Otherwise, AF is reset. AF is affected by carry out of, or borrow into bit 3 only, regardless of overall operand length: 8, 16 or 32 bits.

PF (Parity Flags, bit 2)

PF is set if the low-order eight bits of the operation contain an even number of "1's" (even parity). PF is reset if the low-order eight bits have odd parity. PF is a function of only the low-order eight bits, regardless of operand size.

CF (Carry Flag, bit 0)

CF is set if the operation resulted in a carry out of (addition), or a borrow into (subtraction) the high-order bit. Otherwise, CF is reset. For 8-, 16-, or 32-bit operations, CF is set according to carry/borrow at bit 7, 15, or 31, respectively.

4.3.4 Segment Registers

Six 16-bit segment registers hold segment selector values identifying the currently addressable memory segments. In Protected Mode, each segment may range in size from one byte up to the entire linear and physical address space of the machine, 4 Gbytes (2^{32} bytes). In Real Mode, the maximum segment size is fixed at 64 Kbytes (2^{16} bytes).

The six addressable segments are defined by the segment registers CS, SS, DS, ES, FS and GS. The selector in CS indicates the current code segment; the selector in SS indicates the current stack segment; the selectors in DS, ES, FS, and GS indicate the current data segments.

4.3.5 Segment Descriptor Cache Registers

The segment descriptor cache registers are not programmer-visible, but it is useful to understand their content. A programmer-invisible descriptor cache register is associated with each programmer-visible segment register, as shown in Figure 4-3. Each descriptor cache register holds a 32-bit base address, a 32-bit segment limit, and the other necessary segment attributes.

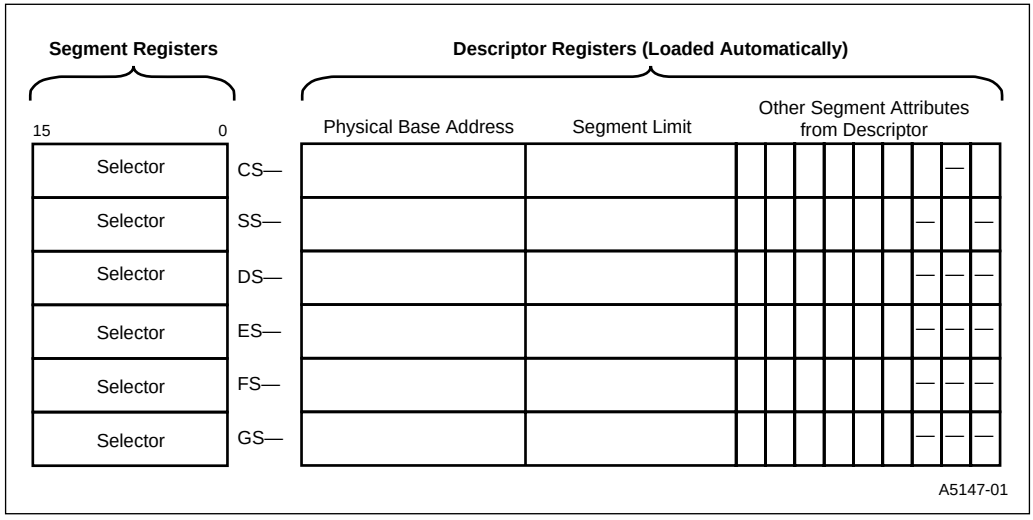


Figure 4-3. Intel486™ Processor Segment Registers and Associated Descriptor Cache Registers

When a selector value is loaded into a segment register, the associated descriptor cache register is automatically updated with the correct information. In Real Mode, only the base address is updated directly (by shifting the selector value four bits to the left), because the segment maximum limit and attributes are fixed in Real Mode. In Protected Mode, the base address, the limit, and the attributes are all updated with the contents of the segment descriptor indexed by the selector.

When a memory reference occurs, the segment descriptor cache register associated with the segment being used is automatically involved with the memory reference. The 32-bit segment base address becomes a component of the linear address calculation, the 32-bit limit is used for the limit-check operation, and the attributes are checked against the type of memory reference requested.

4.4 SYSTEM-LEVEL REGISTERS

Figure 4-4 illustrates the system-level registers, which are the control operation of the on-chip cache, the on-chip floating-point unit (on the IntelDX2 and IntelDX4 processors) and the segmentation and paging mechanisms. These registers are only accessible to programs running at privilege level 0, the highest privilege level.

The system-level registers include three control registers and four segmentation base registers. The three control registers are CR0, CR2 and CR3. CR1 is reserved for future Intel processors. The four segmentation base registers are the Global Descriptor Table Register (GDTR), the Interrupt Descriptor Table Register (IDTR), the Local Descriptor Table Register (LDTR) and the Task State Segment Register (TR).

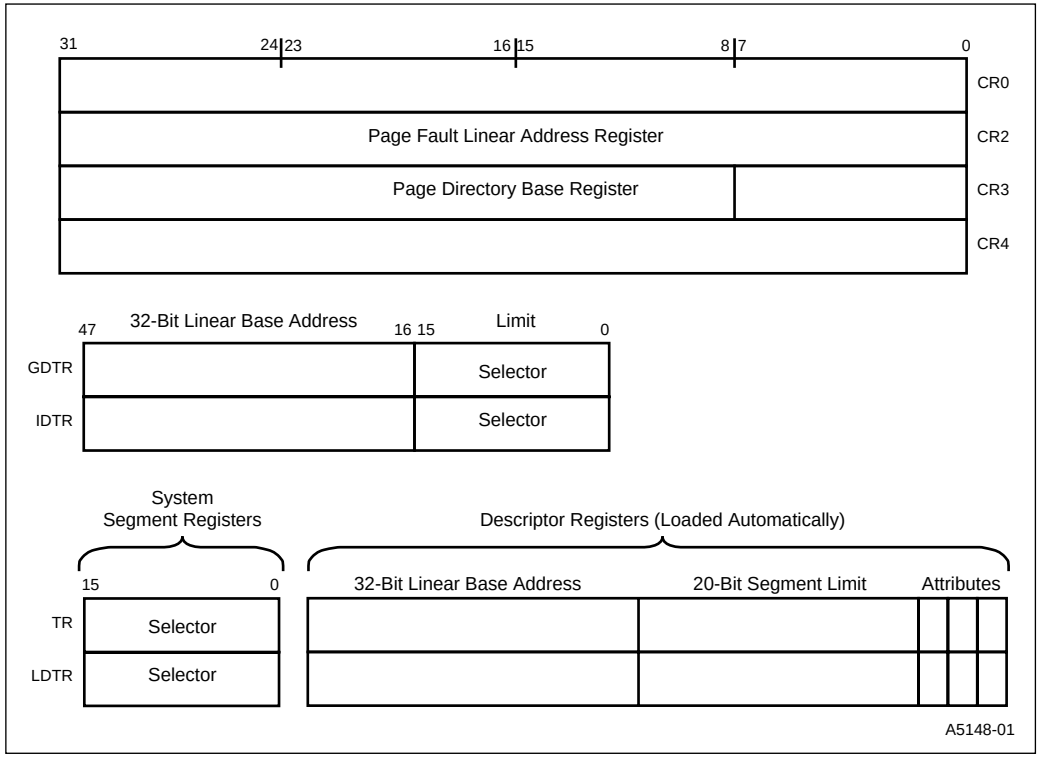
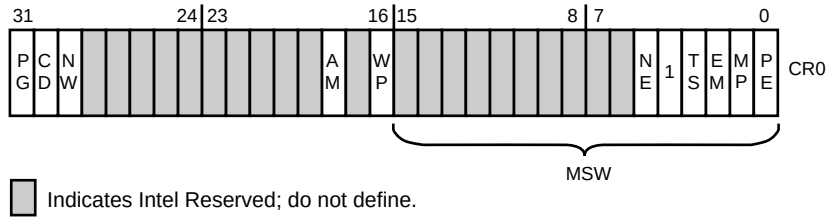


Figure 4-4. System-Level Registers



Note:
See section 4.2.7 "Compatibility."

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Figure 4-5. Control Register 0

4.4.1 Control Registers

Control Register 0 (CR0)

CR0, shown in Figure 4-5, contains 10 bits for control and status purposes. The function of the bits in CR0 can be categorized as follows:

- Intel486 Processor Operating Modes: PG, PE (Table 4-2)
- On-Chip Cache Control Modes: CD, NW (Table 4-3)
- On-Chip Floating-Point Unit: NE, TS, EM, TS (Tables 4-4, 4-5, and 4-6). (Also applies for the Intel486 SX processor.)
- Alignment Check Control: AM
- Supervisor Write Protect: WP

Table 4-2. Intel486™ Processor Operating Modes

PG	PE	Mode
0	0	Real Mode. Exact 8086 processor semantics, with 32-bit extensions available with prefixes.
0	1	Protected Mode. Exact 80286 processor semantics, plus 32-bit extensions through both prefixes and “default” prefix setting associated with code segment descriptors. Also, a sub-mode is defined to support a virtual 8086 processor within the context of the extended 80286 processor protection model.
1	0	Undefined. Loading CR0 with this combination of PG and PE bits causes a GP fault with error code 0.
1	1	Paged Protected Mode. All the facilities of Protected Mode, with paging enabled underneath segmentation.

Table 4-3. On-Chip Cache Control Modes

CD	NW	Operating Mode
1	1	Cache fills disabled, write-through and invalidates disabled.
1	0	Cache fills disabled, write-through and invalidates enabled.
0	1	INVALID. If CR0 is loaded with this configuration of bits, a GP fault with error code results.
0	0	Cache fills enabled, write-through and invalidates enabled.

The low-order 16 bits of CR0 are also known as the Machine Status Word (MSW), for compatibility with the 80286 processor Protected Mode. LMSW and SMSW (load and store MSW) instructions are taken as special aliases of the load and store CR0 operations, where only the low-order 16 bits of CR0 are involved. The LMSW and SMSW instructions in the Intel486 processor work in an identical fashion to the LMSW and SMSW instructions in the 80286 processor (i.e., they operate only on the low-order 16 bits of CR0 and ignore the new bits). New Intel486 processor operating systems should use the MOV CR0, Reg instruction.

NOTE

All Intel386 and Intel486 processor CR0 bits, except for ET and NE, are upwardly compatible with the 80286 processor, because they are in register bits not defined in the 80286 processor. For strict compatibility with the 80286 processor, the load machine status word (LMSW) instruction is defined to not change the ET or NE bits.

The defined CR0 bits are described as follows.

The PG (Paging Enable, bit 31)

PG bit is used to indicate whether paging is enabled (PG=1) or disabled (PG=0). (See Table 4-2.)

CD (Cache Disable, bit 30)

The CD bit is used to enable the on-chip cache. When CD=1, the cache is not filled on cache misses. When CD=0, cache fills may be performed on misses. (See Table 4-3.)

The state of the CD bit, the cache enable input pin (KEN#), and the relevant page cache disable (PCD) bit determine whether a line read in response to a cache miss will be installed in the cache. A line is installed in the cache only when CD=0 and KEN# and PCD are both zero. The relevant PCD bit comes from either the page table entry, page directory entry or control register 3. (Refer to Section 6.4.4, "Page Cacheability (PWT and PCD Bits)")

CD is set to "1" after RESET.

NW (Not Write-Through, bit 29)

The NW bit enables on-chip cache write-throughs and write-invalidate cycles (NW=0).

When NW=0, all writes, including cache hits, are sent out to the pins. Invalidate cycles are enabled when NW=0. During an invalidate cycle, a line is removed from the cache if the invalidate address hits in the cache. (See Table 4-3.)

When NW=1, write-throughs and write-invalidate cycles are disabled. A write is not sent to the pins if the write hits in the cache. With NW=1 the only write cycles that reach the external bus are cache misses. Write hits with NW=1 never update main memory. Invalidate cycles are ignored when NW=1.

AM (Alignment Mask, bit 18)

The AM bit controls whether the alignment check (AC) bit in the flag register (EFLAGS) can allow an alignment fault. AM=0 disables the AC bit. AM=1 enables the AC bit. AM=0 is the Intel386 processor compatible mode.

Intel386 processor software may load incorrect data into the AC bit in the EFLAGS register. Setting AM=0 prevents AC faults from occurring before the Intel486 processor has created the AC interrupt service routine.

WP (Write Protect, bit 16)

WP protects read-only pages from supervisor write access. The Intel386 processor allows a read-only page to be written from privilege levels 0 to 2. The Intel486 processor are compatible with the Intel386 processor when WP = 0. WP = 1 forces a fault on a write to a read-only page from any privilege level. Operating systems with Copy-on-Write features can be supported with the WP bit. (Refer to Section 6.4.3, "Page Level Protection (R/W, U/S Bits)")

NOTE

Refer to Tables 4-4, 4-5, and 4-6 for values and interpolation of NE, EM, TS, and MP bits, in addition to the sections below.

NE (Numerics Exception, bit 5)

- Intel486 SX Processor NE bit:

  For the Intel486 SX processor, interrupt 7 is generated upon encountering any floating-point instruction regardless of the value of the NE bit. It is recommended that NE=1 for normal operation of the processor.

- IntelDX2 and IntelDX4 Processor NE bit:

  For IntelDX2 and IntelDX4 processors, the NE bit controls whether unmasked floating-point exceptions (UFPE) are handled through interrupt vector 16 (NE=1) or through an external interrupt (NE=0). NE=0 (default at reset) supports the DOS operating system error reporting scheme from the 8087, Intel287 and Intel387 math coprocessors. In DOS systems, math coprocessor errors are reported via external interrupt vector 13. DOS uses interrupt vector 16 for an operating system call. (Refer to Section 9.2.15, "Numeric Error Reporting (FERR#, IGNNE#)" and Section 10.3.14, "Floating-Point Error Handling for the IntelDX2™ and IntelDX4™ Processors")

  For any UFPE, the floating-point error output pin (FERR#) is driven active.

  For NE=0, the IntelDX2 and IntelDX4 processors work in conjunction with the ignore numeric error input (IGNNE#) and the FERR# output pins. When a UFPE occurs and the IGNNE# input is inactive, the IntelDX2 and IntelDX4 processors freeze immediately before executing the next floating-point instruction. An external interrupt controller supplies an interrupt vector when FERR# is driven active. The UFPE is ignored if IGNNE# is active and floating-point execution continues.

NOTE

The freeze does not take place when the next instruction is one of the control instructions FNCLEX, FNINIT, FNSAVE, FNSTENV, FNSTCW, FNSTSW, FNSTSW AX, FNENI, FNDISI and FNSETPM. The freeze does occur when the next instruction is WAIT.

For NE=1, any UFPE results in a software interrupt 16, immediately before executing the next non-control floating-point or WAIT instruction. The ignore numeric error input (IGNNE#) signal is ignored.

TS (Task Switch, bit 3)

- Intel486 SX Processor TS bit:

  For the Intel486 SX processor, the TS bit is set whenever a task switch operation is performed. Execution of floating-point instructions with TS=1 causes a Device Not Available (DNA) fault (trap vector 7). With MP=0, the value of TS bit is a don't care for the WAIT instructions; i.e., these instructions do not generate trap 7.

- IntelDX2 and IntelDX4 Processor TS bit:

  For IntelDX2 and IntelDX4 processors, the TS bit is set whenever a task switch operation is performed. Execution of floating-point instructions with TS=1 causes a Device Not Available (DNA) fault (trap vector 7). If TS=1 and MP=1 (monitor coprocessor in CR0), a WAIT instruction causes a DNA fault.

EM (Emulate Coprocessor, bit 2)

- Intel486 SX Processor EM bit:

  For the Intel486 SX processor, the EM bit should be set to one. This causes the Intel486 SX processor to trap via interrupt vector 7 (Device Not Available) to a software exception handler whenever it encounters a floating-point instruction. If EM bit is 0 for the Intel486 SX processors, the system hangs. (See Tables 4-4 and 4-5.)

- IntelDX2 and IntelDX4 Processor EM bit:

  For the IntelDX2, and IntelDX4 processors, the EM bit determines whether floating-point instructions are trapped (EM=1) or executed. If EM=1, all floating-point instructions cause fault 7.

  If EM=0, the on-chip floating-point is used.

NOTE

WAIT instructions are not affected by the state of EM.
(See Tables 4-4 and 4-6.)

MP (Monitor Coprocessor, bit 1)

- Intel486 SX Processor MP bit:

  For the Intel486 SX processor, the MP bit must be set to zero (MP=0). The MP bit is used in conjunction with the TS bit to determine whether WAIT instructions should trap. For MP=0, the value of TS is a don't care for these type of instructions. (See Tables 4-4 and 4-5.)

- IntelDX2 and IntelDX4 Processor MP bit:

  For the IntelDX2 and IntelDX4 processors, the MP is used in conjunction with the TS bit to determine whether WAIT instructions cause fault 7. (See Table 4-6.) The TS bit is set to 1 on task switches by the IntelDX2 and IntelDX4 processors. Floating-point instructions are not affected by the state of the MP bit. It is recommended that the MP bit be set to one for normal processor operation.

PE (Protection Enable, bit 0)

The PE bit enables the segment based protection mechanism when PE=1 protection is enabled. When PE=0 the Intel486 processor operates in Real Mode, with segment based protection disabled and addresses formed as in an 8086 processor. (Refer to Table 4-2.)

Table 4-4. Recommended Values of NE, EM, TS, and MP Bits in CR0 Register for the Intel486™ SX Processor

CR0 Bit				Instruction Type	
NE	EM	TS	MP	FP	WAIT
1	1	0	0	Trap7	Execute
1	1	1	0	Trap7	Execute

Table 4-5. Recommended Values of the Floating-Point Related Bits for Intel486™ Processors

CR0 Bit	Intel486™ SX Processor	IntelDX2™, and IntelDX4™ Processors
EM	1	0
MP	0	1
NE	1	0 for DOS Systems 1 for User-Defined Exception Handler

Table 4-6. Interpretation of Different Combinations of the EM, TS and MP Bits for All Intel486™ Processors

CR0 Bit			Instruction Type	
EM	TS	MP	Floating-Point	Wait
0	0	0	Execute	Execute
0	0	1	Execute	Execute
0	1	0	Exception 7	Execute
0	1	1	Exception 7	Exception 7
1	0	0	Exception 7	Execute
1	0	1	Exception 7	Execute
1	1	0	Exception 7	Execute
1	1	1	Exception 7	Exception 7

NOTE: For IntelDX2™ and IntelDX4™ processors, when MP=1 and TS=1, the processor generates a trap 7 so that the system software can save the floating-point status of the old task.

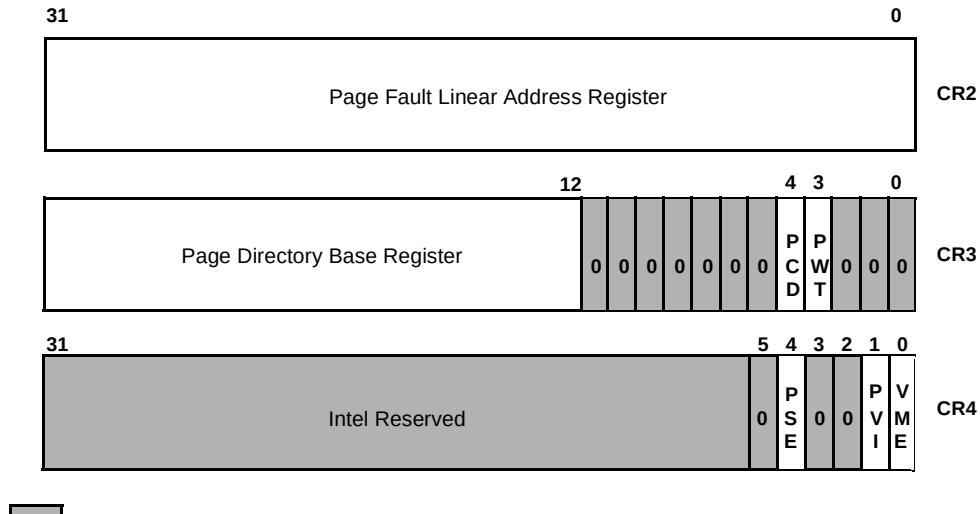


Figure 4-6. Control Registers 2, 3, and 4

Control Register 1 (CR1)

CR1 is reserved for use in future Intel processors.

Control Register 2 (CR2)

CR2, shown in Figure 4-6, holds the 32-bit linear address that caused the last page fault detected. The error code pushed onto the page fault handler's stack when it is invoked provides additional status information on this page fault.

Control Register 3 (CR3)

CR3, shown in Figure 4-6, contains the physical base address of the page directory table. The page directory is always page aligned (4 Kbyte-aligned). This alignment is enforced by only storing bits 12-31 in CR3.

In the Intel486 processor, CR3 contains two bits, page write-through (PWT) (bit 3) and page cache disable (PCD) (bit 4). The page table entry (PTE) and page directory entry (PDE) also contain PWT and PCD bits. PWT and PCD control page cacheability. When a page is accessed in external memory, the states of PWT and PCD are driven out on the PWT and PCD pins. The source of PWT and PCD can be CR3, the PTE or the PDE. PWT and PCD are sourced from CR3 when the PDE is being updated. When paging is disabled (PG = 0 in CR0), PCD and PWT are assumed to be 0, regardless of their state in CR3.

A task switch through a task state segment (TSS) which changes the values in CR3, or an explicit load into CR3 with any value, invalidates all cached page table entries in the translation lookaside buffer (TLB).

The page directory base address in CR3 is a physical address. The page directory can be paged out while its associated task is suspended, but the operating system must ensure that the page directory is resident in physical memory before the task is dispatched. The entry in the TSS for CR3 has a physical address, with no provision for a present bit. This means that the page directory for a task must be resident in physical memory. The CR3 image in a TSS must point to this area, before the task can be dispatched through its TSS.

Control Register 4 (CR4)

CR4, shown in Figure 4-6, contains bits that enable Virtual-86 Mode extensions and Protected Mode virtual interrupts.

VME (Virtual-8086 Mode Extensions, bit 0 of CR4)

Setting this bit to 1 enables support for a virtual interrupt flag in Virtual-86 Mode. This feature can improve the performance of Virtual-86 Mode applications by eliminating the overhead of faulting to a Virtual-86 Mode monitor for emulation of certain operations. (Refer to Appendix A, "Advanced Features.")

PVI (Protected-Mode Virtual Interrupts, bit 1 of CR4)

Setting this bit to 1 enables support for a virtual interrupt flag in Protected Mode. This feature can enable some programs designed for execution at privilege level 0 to execute at privilege level 3. (Refer to Appendix A, "Advanced Features.")

PSE (Page Size Extensions, bit 4 of CR4)

Setting this bit to 1 enables 4-Mbyte pages. (Refer to Appendix A, "Advanced Features.")

NOTE

Features described in CR4 (VME, PVI, and PSE) in the CPUID Feature Flag should be qualified with the CPUID instruction. The CPUID instruction and CPUID Feature Flag are specific to particular models in the Intel486 processor family. (Refer to Appendix B, "Feature Determination.")

4.4.2 System Address Registers

Four special registers are defined to reference the tables or segments supported by the 80286, Intel386, and Intel486 processors' protection model. These tables or segments are: GDT (Global Descriptor Table), IDT (Interrupt Descriptor Table), LDT (Local Descriptor Table), TSS (Task State Segment).

The addresses of these tables and segments are stored in special registers: the System Address and System Segment Registers, illustrated in Figure 4-4. These registers are named GDTR, IDTR, LDTR, and TR respectively. Chapter 6, "Protected Mode Architecture" describes how to use these registers.

System Address Registers: GDTR and IDTR

The GDTR and IDTR hold the 32-bit linear-base address and 16-bit limit of the GDT and IDT, respectively.

Because the GDT and IDT segments are global to all tasks in the system, the GDT and IDT are defined by 32-bit linear addresses (subject to page translation when paging is enabled) and 16-bit limit values.

System Segment Registers: LDTR and TR

The LDTR and TR hold the 16-bit selector for the LDT descriptor and the TSS descriptor, respectively.

Because the LDT and TSS segments are task-specific segments, the LDT and TSS are defined by selector values stored in the system segment registers.

NOTE

A programmer-invisible segment descriptor register is associated with each system segment register.

4.5 FLOATING-POINT REGISTERS

Figure 4-7 shows the floating-point register set. The on-chip FPU contains eight data registers, a tag word, a control register, a status register, an instruction pointer and a data pointer.

The operation of the IntelDX2 and IntelDX4 processor on-chip floating-point unit is exactly the same as the Intel387 math coprocessor. Software written for the Intel387 math coprocessor runs on the on-chip floating-point unit (FPU) without modifications.

4.5.1 Floating-Point Data Registers

Floating-point computations use the IntelDX2 and IntelDX4 processor FPU data registers. These eight 80-bit registers provide the equivalent capacity of twenty 32-bit registers. Each of the eight data registers is divided into "fields" corresponding to the FPU's extended-precision data type.

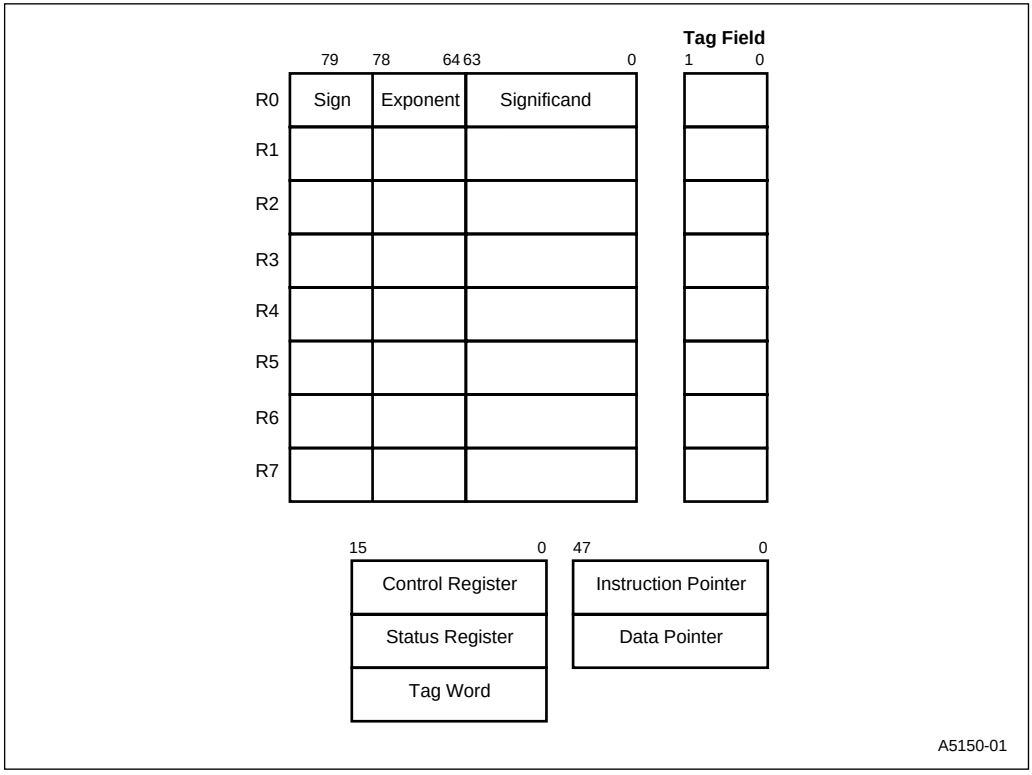


Figure 4-7. Floating-Point Registers

The FPU's register set can be accessed either as a stack, with instructions operating on the top one or two stack elements, or as a fixed register set, with instructions operating on explicitly designated registers. The TOP field in the status word identifies the current top-of-stack register. A "push" operation decrements TOP by one and loads a value into the new top register. A "pop" operation stores the value from the current top register and then increments TOP by one. Like other IntelDX2 and IntelDX4 processor stacks in memory, the FPU register stack grows "down" toward lower-addressed registers.

Instructions may address the data registers either implicitly or explicitly. Many instructions operate on the register at the TOP of the stack. These instructions implicitly address the register at which TOP points. Other instructions allow the programmer to explicitly specify which register to use. This explicit register addressing is also relative to TOP.

4.5.2 Floating-Point Tag Word

The tag word marks the content of each numeric data register, as shown in Figure 4-8. Each two-bit tag represents one of the eight data registers. The principal function of the tag word is to optimize the FPU's performance and stack handling by making it possible to distinguish between empty and non-empty register locations. It also enables exception handlers to check the contents of a stack location without the need to perform complex decoding of the actual data.

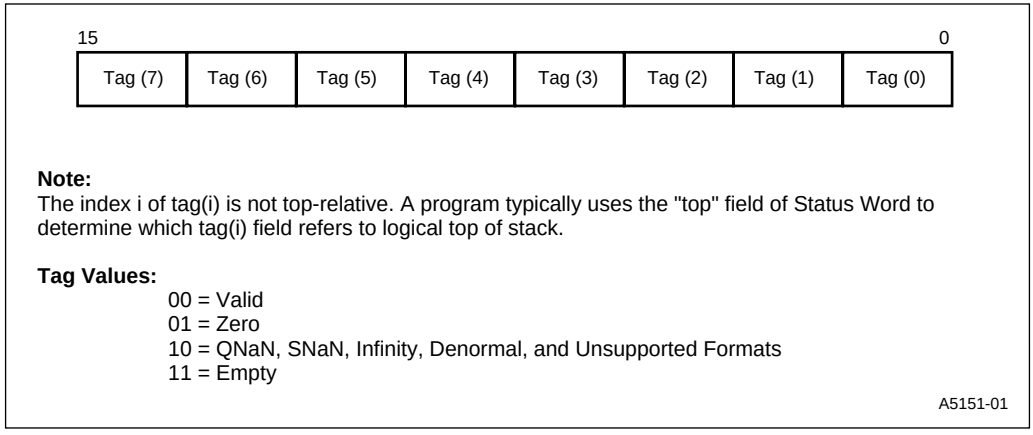
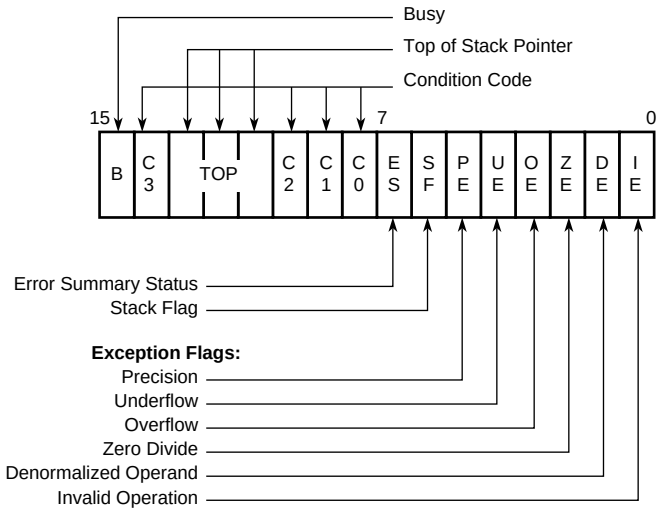


Figure 4-8. Floating-Point Tag Word

4.5.3 Floating-Point Status Word

The 16-bit status word reflects the overall state of the FPU. The status word is shown in Figure 4-9 and is located in the status register.



ES is set if any unmasked exception bit is set; cleared otherwise.
See Table 4-7 for interpretation of condition code.
Top Values:

000 = Register 0 is Top of Stack
001 = Register 1 is Top of Stack
*
*
*
111 = Register 7 is Top of Stack

For definitions of exceptions, refer to the section entitled, "Exception Handling".

Note:
The B-bit (Busy, bit 15) is included for 8087 compatibility. The B-bit reflects the contents of the ES bit (bit 7 of the status word).
Bits 13-11 (TOP) point to the FPU register that is the current top-of-stack.
The four numeric condition code bits, C0-C3, are similar to the flags in EFLAGS. Instructions that perform arithmetic operations update C0-C3 to reflect the outcome. The effects of these instructions on the condition codes are summarized in Table 4-7 through Table 4-10.

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Figure 4-9. Floating-Point Status Word

Table 4-7. Floating-Point Condition Code Interpretation

Instruction	C0 (S)	C3 (Z)	C1 (A)	C2 (C)
FPREM, FPREM1	Three least significant bits of quotient (See Table 4-8.)			Reduction 0 = complete
	Q2	Q0	Q1 or O/U#	1 = incomplete
FCOM, FCOMP, FCOMPP, FTST, FUCOM, FUCOMP, FUCOMPP, FICOM, FICOMP	Result of comparison (see Table 4-9)		Zero or O/U#	Operand is not comparable
FXAM	Operand class (see Table 4-10)		Sign or O/U#	Operand class
FCHS, FABS, FXCH, FINCTOP, FDECTOP, Constant loads, FXTRACT, FLD, FILD, FBLD, FSTP (ext real)	UNDEFINED		Zero or O/U#	UNDEFINED
FIST, FBSTP, FRNDINT, FST, FSTP, FADD, FMUL, FDIV, FDIVR, FSUB, FSUBR, FSCALE, FSQRT, FPATAN, F2XM1, FYL2X, FYL2XP1	UNDEFINED		Roundup or O/U#	UNDEFINED
FPTAN, FSIN, FCOS, FSINCOS	UNDEFINED		Roundup or O/U#, if C2 = 1	Reduction 0 = complete 1 = incomplete
FLDENV, FRSTOR	Each bit loaded from memory			
FINIT	Clears these bits			
FLDCW, FSTENV, FSTCW, FSTSW, FCLEX, FSAVE	UNDEFINED			

NOTES:

1. When both IE and SF bits of status word are set, indicating a stack exception, this bit distinguishes between stack overflow (C1 = 1) and underflow (C1 = 0).
2. Reduction: If FPREM or FPREM1 produces a remainder that is less than the modulus, reduction is complete. When reduction is incomplete, the value at the top of the stack is a partial remainder, which can be used as input to further reduction. For FPTAN, FSIN, FCOS, and FSINCOS, the reduction bit is set if the operand at the top of the stack is too large. In this case, the original operand remains at the top of the stack.
3. Roundup: When the PE bit of the status word is set, this bit indicates whether the last rounding in the instruction was upward.
4. UNDEFINED: Do not rely on finding any specific value in these bits. See Section 4.8, Compatibility with Future Processors (pg. 4-34).

Table 4-8. Condition Code Interpretation after FPREM and FPREM1 Instructions

Condition Code				Interpretation after FPREM and FPREM1	
C2	C3	C1	C0		
1	X	X	X	Incomplete Reduction: further interaction required for complete reduction	
	Q1	Q0	Q2	Q MOD8	Complete Reduction: C0, C3, and C1 contain the three least-significant bits of the quotient
	0	0	0	0	
	0	1	0	1	
0	1	0	0	2	
	1	1	0	3	
	0	0	1	4	
	0	1	1	5	
	1	0	1	6	
	1	1	1	7	

Table 4-9. Condition Code Resulting from Comparison

Order	C3	C2	C0
TOP > Operand	0	0	0
TOP < Operand	0	0	1
TOP = Operand	1	0	0
Unordered	1	1	1

Table 4-10. Condition Code Defining Operand Class

C3	C2	C1	C0	Value at TOP
0	0	0	0	+ Unsupported
0	0	0	1	+ NaN
0	0	1	0	- Unsupported
0	0	1	1	- NaN
0	1	0	0	+ Normal
0	1	0	1	+ Infinity
0	1	1	0	- Normal
0	1	1	1	- Infinity
1	0	0	0	+ 0
1	0	0	1	+ Empty
1	0	1	0	- 0
1	0	1	1	- Empty
1	1	0	0	+ Denormal
1	1	1	0	- Denormal

Bit 7 is the error summary (ES) status bit. The ES bit is set if any unmasked exception bit (bits 5:0 in the status word) is set; ES is clear otherwise. The FERR# (floating-point error) signal is asserted when ES is set.

Bit 6 is the stack flag (SF). This bit is used to distinguish invalid operations due to stack overflow or underflow. When SF is set, bit 9 (C1) distinguishes between stack overflow (C1=1) and underflow (C1=0).

Table 4-11 shows the six exception flags in bits 5:0 of the status word. Bits 5:0 are set to indicate that the FPU has detected an exception while executing an instruction.

The six exception flags in the status word can be individually masked by mask bits in the FPU control word. Table 4-11 lists the exception conditions, and their causes in order of precedence. Table 4-11 also shows the action taken by the FPU if the corresponding exception flag is masked.

An exception that is not masked by the control word causes three things to happen: the corresponding exception flag in the status word is set, the ES bit in the status word is set, and the FERR# output signal is asserted. When the IntelDX2 or IntelDX4 processor attempts to execute another floating-point or WAIT instruction, exception 16 occurs or an external interrupt happens if the NE=1 in control register 0. The exception condition must be resolved via an interrupt service routine. The FPU saves the address of the floating-point instruction that caused the exception and the address of any memory operand required by that instruction in the instruction and data pointers. (See Section 4.5.4, “Instruction and Data Pointers.”)

Note that when a new value is loaded into the status word by the FLDENV (load environment) or FRSTOR (restore state) instruction, the value of ES (bit 7) and its reflection in the B bit (bit 15) are not derived from the values loaded from memory. The values of ES and B are dependent upon the values of the exception flags in the status word and their corresponding masks in the control word. If ES is set in such a case, the FERR# output of the IntelDX2 or IntelDX4 processor is activated immediately.

Table 4-11. FPU Exceptions

Exception	Cause	Default Action (if exception is masked)
Invalid Operation	Operation on a signaling NaN, unsupported format, indeterminate form (0*∞, 0/0, (+∞) + (-∞), etc.), or stack overflow/underflow (SF is also set).	Result is a quiet NaN, integer indefinite, or BCD indefinite
Denormalized Operand	At least one of the operands is denormalized; i.e., it has the smallest exponent but a non-zero significand.	Normal processing continues
Zero Divisor	The divisor is zero while the dividend is a non-infinite, non-zero number.	Result is ∞
Overflow	The result is too large in magnitude to fit in the specified format.	Result is largest finite value or ∞
Underflow	The true result is non-zero but too small to be represented in the specified format, and, when underflow exception is masked, denormalization causes loss of accuracy.	Result is denormalized or zero
Inexact Result (Precision)	The true result is not exactly representable in the specified format (e.g., 1/3); the result is rounded according to the rounding mode.	Normal processing continues

4.5.4 Instruction and Data Pointers

Because the FPU operates in parallel with the ALU (in the IntelDX2 and IntelDX4 processors the arithmetic and logic unit (ALU) consists of the base architecture registers), any errors detected by the FPU may be reported after the ALU has executed the floating-point instruction that caused it. To allow identification of the failing numeric instruction, the IntelDX2 and IntelDX4 processors contain two pointer registers that supply the address of the failing numeric instruction and the address of its numeric memory operand (if appropriate).

The instruction and data pointers are provided for user-written error handlers. These registers are accessed by the FLDENV (load environment), FSTENV (store environment), FSAVE (save state) and FRSTOR (restore state) instructions. Whenever the IntelDX2 and IntelDX4 processors decode a new floating-point instruction, it saves the instruction (including any prefixes that may be present), the address of the operand (if present) and the opcode.

The instruction and data pointers appear in one of four formats depending on the operating mode of the IntelDX2 and IntelDX4 processors (Protected Mode or Real Mode) and depending on the operand-size attribute in effect (32-bit operand or 16-bit operand). When the IntelDX2 or IntelDX4 processor is in the Virtual-86 Mode, the Real Mode formats are used. Figures 4-10 through Figure 4-13 show the four formats. The floating-point instructions FLDENV, FSTENV, FSAVE and FRSTOR are used to transfer these values to and from memory. Note that the value of the data pointer is undefined if the prior floating-point instruction did not have a memory operand.

NOTE

The operand size attribute is the D bit in a segment descriptor.

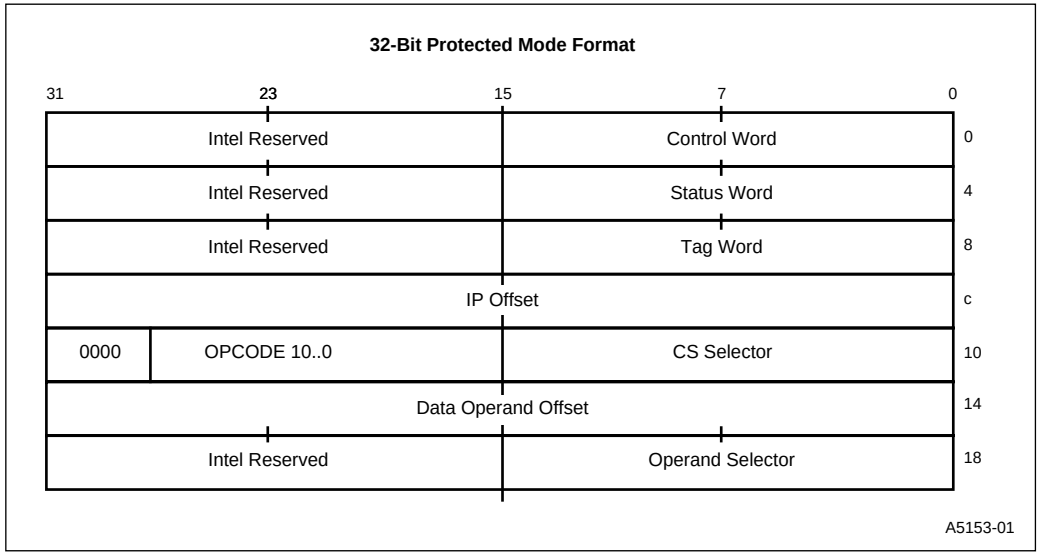

Figure 4-10. Protected Mode FPU Instructions and Data Pointer Image in Memory—32-Bit Format

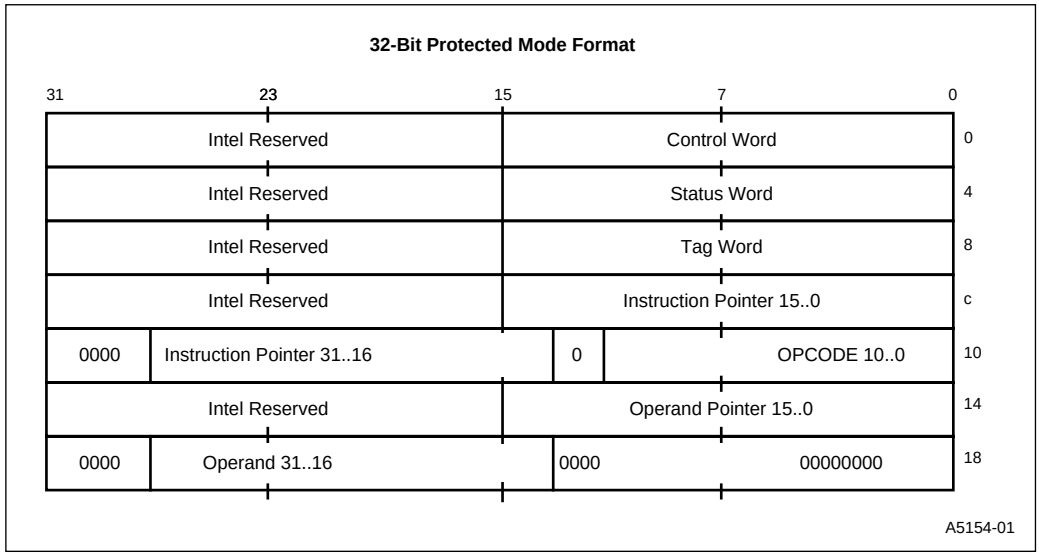

Figure 4-11. Real Mode FPU Instruction and Data Pointer Image in Memory—32-Bit Format

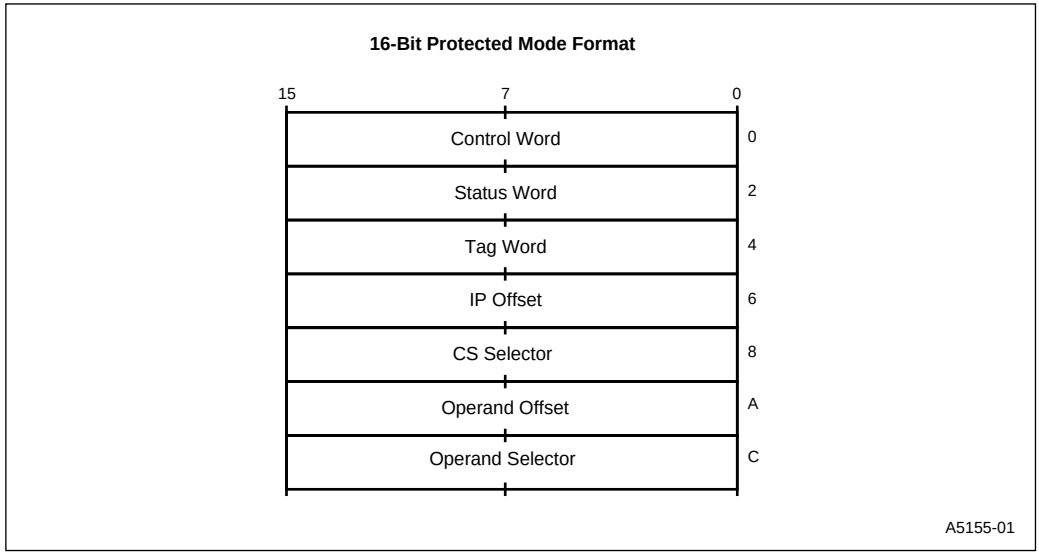

Figure 4-12. Protected Mode FPU Instruction and Data Pointer Image in Memory—16-Bit Format

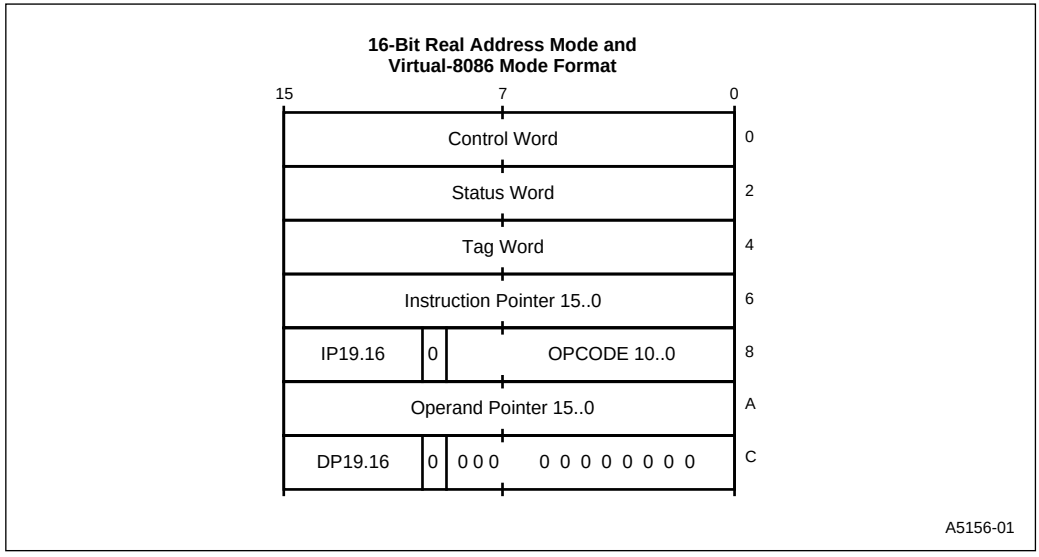

Figure 4-13. Real Mode FPU Instruction and Data Pointer Image in Memory—16-Bit Format

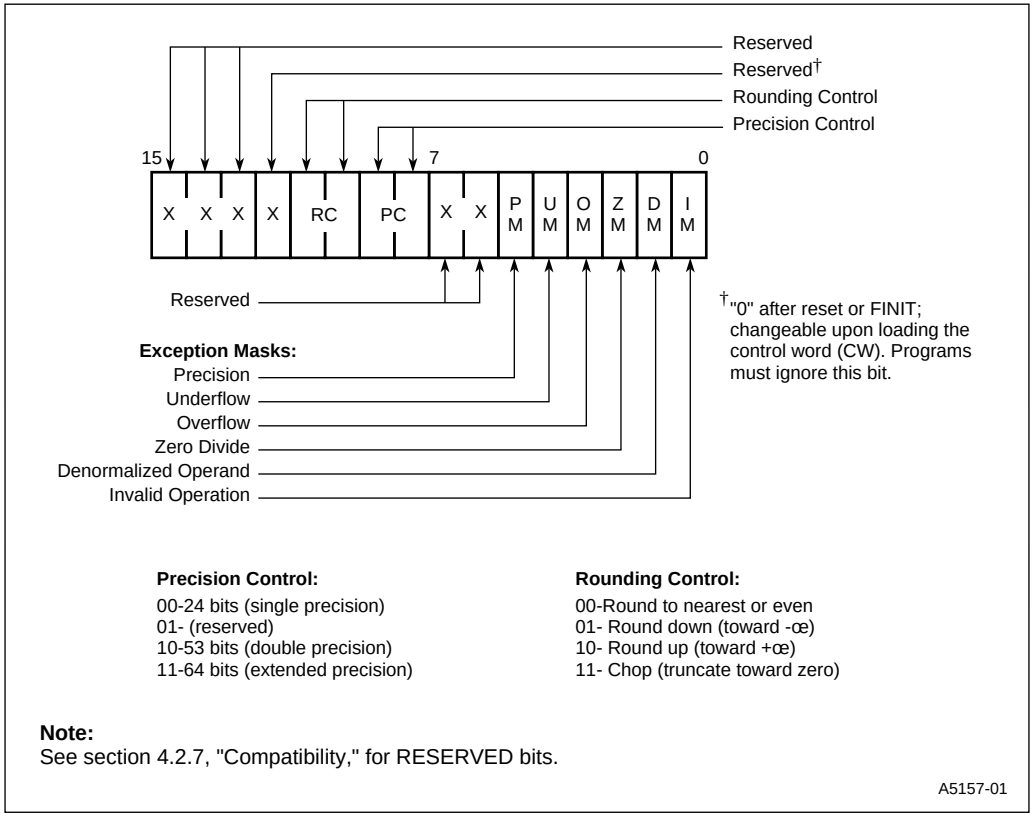

Figure 4-14. FPU Control Word

4.5.5 FPU Control Word

The FPU provides several processing options that are selected by loading a control word from memory into the control register. Figure 4-14 shows the format and encoding of fields in the control word.

The low-order byte of the FPU control word configures the FPU error and exception masking. Bits 5:0 of the control word contain individual masks for each of the six exceptions that the FPU recognizes.

The high-order byte of the control word configures the FPU operating mode, including precision and rounding.

RC (Rounding Control, bits 11:10)

RC bits provide for directed rounding and true chop, as well as the unbiased round to nearest even mode specified in the IEEE standard. Rounding control affects only those instructions that perform rounding at the end of the operation (and thus can generate a precision exception); namely, FST, FSTP, FIST, all arithmetic instructions (except FPREM, FPREM1, FXTRACT, FABS and FCHS), and all transcendental instructions.

PC (Precision Control, bits 9:8)

PC bits can be used to set the FPU internal operating precision of the significand at less than the default of 64 bits (extended precision). This can be useful in providing compatibility with early generation arithmetic processors of smaller precision. PC affects only the instructions ADD, SUB, DIV, MUL, and SQRT. For all other instructions, either the precision is determined by the opcode or extended precision is used.

4.6 DEBUG AND TEST REGISTERS

4.6.1 Debug Registers

The six programmer accessible debug registers (Figure 4-15) provide on-chip support for debugging. Debug registers DR[3:0] specify the four linear breakpoints. The Debug control register DR7, is used to set the breakpoints and the Debug Status Register, DR6, displays the current state of the breakpoints. The use of the Debug registers is described in Chapter 11, “Debugging Support.”

Debug Registers	
Linear Breakpoint Address 0	DR0
Linear Breakpoint Address 1	DR1
Linear Breakpoint Address 2	DR2
Linear Breakpoint Address 3	DR3
Intel Reserved, Do Not Define	DR4
Intel Reserved, Do Not Define	DR5
Breakpoint Status	DR6
Breakpoint Control	DR7
Test Registers	
Cache Test Data	TR3
Cache Test Status	TR4
Cache Test Control	TR5
TLB Test Control	TR6
TLB Test Status	TR7
TLB - Translation Lookaside Buffer	

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Figure 4-15. Debug and Test Registers

4.6.2 Test Registers

The Intel486 processor contains five test registers. Figure 4-15 show the test registers. TR6 and TR7 are used to control the testing of the translation lookaside buffer. TR3, TR4 and TR5 are used for testing the on-chip cache. The use of the test registers is discussed in Appendix B, "Testability."

4.7 REGISTER ACCESSIBILITY

There are a few differences regarding the accessibility of the registers in Real and Protected Mode. Table 4-12 summarizes these differences. (See Chapter 6, "Protected Mode Architecture.")

4.7.1 FPU Register Usage

In addition to the differences listed in Table 4-12, Table 4-13 summarizes the differences for the on-chip FPU.

Table 4-12. Register Usage

Register	Use in Real Mode		Use in Protected Mode		Use in Virtual 8086 Mode	
	Load	Store	Load	Store	Load	Store
General Registers	Yes	Yes	Yes	Yes	Yes	Yes
Segment Register	Yes	Yes	Yes	Yes	Yes	Yes
Flag Register	Yes	Yes	Yes	Yes	IOPL(1)	IOPL
Control Registers	Yes	Yes	PL = 0(2)	PL = 0	No	Yes
GDTR	Yes	Yes	PL = 0	Yes	No	Yes
IDTR	Yes	Yes	PL = 0	Yes	No	Yes
LDTR	No	No	PL = 0	Yes	No	No
TR	No	No	PL = 0	Yes	No	No
Debug Registers	Yes	Yes	PL = 0	PL = 0	No	No
Test Registers	Yes	Yes	PL = 0	PL = 0	No	No

NOTES:
1. IOPL: The PUSHF and POPF instructions are made I/O Privilege Level sensitive in Virtual 8086 Mode.
2. PL = 0: The registers can be accessed only when the current privilege level is zero.

Table 4-13. FPU Register Usage Differences

Register	Use in Real Mode		Use in Protected Mode		Use in Virtual 8086 Mode	
	Load	Store	Load	Store	Load	Store
FPU Data Registers	Yes	Yes	Yes	Yes	Yes	Yes
FPU Control Registers	Yes	Yes	Yes	Yes	Yes	Yes
FPU Status Registers	Yes	Yes	Yes	Yes	Yes	Yes
FPU Instruction Pointer	Yes	Yes	Yes	Yes	Yes	Yes
FPU Data Pointer	Yes	Yes	Yes	Yes	Yes	Yes

4.8 COMPATIBILITY WITH FUTURE PROCESSORS

In the preceding register descriptions, note certain Intel486 processor register bits are Intel reserved. When reserved bits are called out, treat them as fully undefined. This is essential for your software compatibility with future processors. Follow the guidelines below:

1. Do not depend on the states of any undefined bits when testing the values of defined register bits. Mask them out when testing.
2. Do not depend on the states of any undefined bits when storing them to memory or another register.
3. Do not depend on the ability to retain information written into any undefined bits.
4. When loading registers, always load the undefined bits as zeros.
5. However, registers that have been previously stored may be reloaded without masking.

Depending upon the values of undefined register bits makes your software dependent upon the unspecified Intel486 processor handling of these bits. Depending on undefined values risks making your software incompatible with future processors that define usages for the Intel486 processor-undefined bits.

NOTE

Avoid any software dependence on the state of undefined Intel486 Processor Register Bits.

5

Real Mode Architecture

Chapter Contents

CHAPTER 5
REAL MODE ARCHITECTURE

5.1 INTRODUCTION

When the Intel486™ processor is powered up or reset, it is initialized in Real Mode. Real Mode has the same base architecture as the 8086 processor, except that it allows access to the 32-bit register set of the Intel486 processor. The Intel486 processor addressing mechanism, memory size, and interrupt handling are identical to those of Real Mode on the 80286 processor.

All of the Intel486 processor instructions are available in Real Mode (except those instructions listed in Section 6.5.4, "Protection and I/O Permission Bitmap"). The default operand size in Real Mode is 16 bits, as in the 8086 processor. In order to use the 32-bit registers and addressing modes, override prefixes must be used. Also, the segment size on the Intel486 processor in Real Mode is 64 Kbytes, forcing 32-bit effective addresses to have a value less than 0000FFFFH. The primary purpose of Real Mode is to enable Protected Mode operation.

The LOCK prefix on the Intel486 processor, even in Real Mode, is more restrictive than on the 80286 processor. This is due to the addition of paging on the Intel486 processor in Protected Mode and Virtual 8086 Mode. Paging makes it impossible to guarantee that repeated string instructions can be LOCKed. The Intel486 processor cannot require that all pages holding the string be physically present in memory. Hence, a Page Fault (exception 14) might have to be taken during the repeated string instruction. Therefore, the LOCK prefix can not be supported during repeated string instructions.

Table 5-1 lists the only instruction forms in which the LOCK prefix is legal on the Intel486 processor.

An exception 6 is generated if a LOCK prefix is placed before any instruction form or opcode not listed Table 5-1. The LOCK prefix allows indivisible read/modify/write operations on memory operands using the instructions Table 5-1. For example, even the ADD Reg, Mem instruction is not LOCKable, because the Mem operand is not the destination (and therefore no memory read/modify/operation is being performed).

On the Intel486 processor, repeated string instructions are not LOCKable; therefore, it is not possible to LOCK the bus for a long period of time. Therefore, the LOCK prefix is not IOPL-sensitive on the Intel486 processor. The LOCK prefix can be used at any privilege level, but only on the instruction forms listed in Table 5-1.

Table 5-1. Instruction Forms in which LOCK Prefix Is Legal

Opcode	Operands (Dest, Source)
BIT Test and SET/RESET/COMPLEMENT	Mem, Reg/immed.
XCHG	Reg, Mem
CHG	Mem, Reg
ADD, OR, ADC, SBB, AND, SUB, XOR	Mem, Reg/immed.
NOT, NEG, INC, DEC	Mem
CMPXCHG, XADD	Mem, Reg

5.2 MEMORY ADDRESSING

In Real Mode, the maximum memory size is limited to 1 Mbyte. (See Figure 5-1.) Thus, only address lines A[19:2] are active with this exception: after RESET address lines A[31:20] are high during CS-relative memory cycles until an intersegment jump or call is executed. See Section 9.5, "Reset and Initialization."

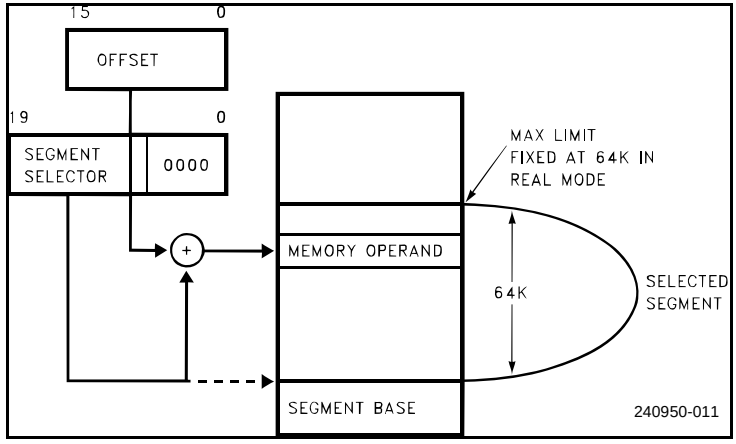


Figure 5-1. Real Address Mode Addressing

Because paging is not allowed in Real Mode, the linear addresses are the same as the physical addresses. Physical addresses are formed in Real Mode by adding the contents of the appropriate segment register, which is shifted left by four bits to create an effective address. This addition results in a physical address from 00000000H to 0010FFEFH. This is compatible with 80286 Real Mode. Because segment registers are shifted left by 4 bits, Real Mode segments always start on 16-byte boundaries.

All segments in Real Mode are exactly 64-Kbytes long, and may be read, written, or executed. The Intel486 processor generates an exception 13 if a data operand or instruction fetch occurs past the end of a segment (i.e., if an operand has an offset greater than FFFFH, as when a word has a low byte at FFFFH and the high byte at 0000H).

Segments may be overlapped in Real Mode. If a segment does not use all 64 Kbytes, another segment can be overlaid on top of the unused portion of the previous segment. This allows the programmer to minimize the amount of physical memory needed for a program.

5.3 RESERVED LOCATIONS

There are two fixed areas in memory that are reserved in Real Address Mode: the system initialization area and the interrupt table area. Locations 00000H through 003FFH are reserved for interrupt vectors. Each one of the 256 possible interrupts has a 4-byte jump vector reserved for it. Locations FFFFFFF0H through FFFFFFFFH are reserved for system initialization.

5.4 INTERRUPTS

Many of the exceptions discussed in Section 3.15.3, “Maskable Interrupt,” are not applicable to Real Mode operation, in particular exceptions 10, 11, 14, and 17, which do not occur in Real Mode. Other exceptions have slightly different meanings in Real Mode; Table 5-2 identifies these exceptions.

5.5 SHUTDOWN AND HALT

The HALT instruction stops program execution and prevents the Intel486 processor from using the local bus until restarted via the RESUME instruction. The Intel486 processor is forced out of halt by NMI, INTR with interrupts enabled (IF=1), or by RESET. If interrupted, the saved CS:IP points to the next instruction after the HLT.

As in the case of Protected Mode, the shutdown occurs when a severe error is detected that prevents further processing. In Real Mode, shutdown can occur under the following two conditions:

- An interrupt or an exception occurs (exceptions 8 or 13) and the interrupt vector is larger than the Interrupt Descriptor Table (i.e., there is not an interrupt handler for the interrupt).
- A CALL, INT or PUSH instruction attempts to wrap around the stack segment when SP is not even (i.e., pushing a value on the stack when SP = 0001, resulting in a stack segment greater than FFFFH).

An NMI input can bring the processor out of shutdown if the Interrupt Descriptor Table limit is large enough to contain the NMI interrupt vector (at least 0017H) and the stack has enough room to contain the vector and flag information (i.e., SP is greater than 0005H). If these conditions are not met, the Intel486 processor is unable to execute the NMI and executes another shutdown cycle. In this case, the Intel486 processor remains in the shutdown and can only exit via the RESET input.

Table 5-2. Exceptions with Different Meanings in Real Mode (see Table 5-1)

Function	Interrupt Number	Related Instructions	Return Address Location
Interrupt table limit too small	8	INT Vector is not within table limit	Before Instruction
CS, DS, ES, FS, GS Segment overrun exception	13	Word memory reference beyond offset = FFFFH. An attempt to execute past the end of CS segment.	Before Instruction
SS Segment overrun exception	12	Stack Reference beyond offset = FFFFH	Before Instruction

6

Protected Mode Architecture

Chapter Contents

CHAPTER 6
PROTECTED MODE ARCHITECTURE

The full capabilities of the Intel486™ processor are available when it operates in Protected Virtual Address Mode (Protected Mode). Protected Mode vastly increases the linear address space to four Gbytes (2^{32} bytes) and allows the processor to run virtual memory programs of almost unlimited size (64 terabytes or 2^{46} bytes). In addition Protected Mode allows the Intel486 processor to run all of the existing 8086, 80286 and Intel386™ processor software, while providing a sophisticated memory management and a hardware-assisted protection mechanism. Protected Mode allows the use of additional instructions that support multi-tasking operating systems. The base architecture of the Intel486 processor remains the same and the registers, instructions, and addressing modes described in the previous chapters are retained. The main difference between Protected Mode and Real Mode from a programmer's view is the increased address space and a different addressing mechanism.

6.1 ADDRESSING MECHANISM

Like Real Mode, Protected Mode uses two components to form the logical address: a 16-bit selector is used to determine the linear base address of a segment, then the base address is added to a 32-bit effective address to form a 32-bit linear address. The linear address is either used as the 32-bit physical address, or if paging is enabled, the paging mechanism maps the 32-bit linear address into a 32-bit physical address.

The difference between the two modes lies in calculating the base address. In Protected Mode the selector is used to specify an index into an operating system defined table (see Figure 6-1). The table contains the 32-bit base address of a given segment. The physical address is formed by adding the base address obtained from the table to the offset.

Paging provides an additional memory management mechanism that operates only in Protected Mode. Paging provides a means of managing the very large segments of the Intel486 processor. As such, paging operates beneath segmentation. The paging mechanism translates the protected linear address that comes from the segmentation unit into a physical address. Figure 6-2 shows the complete Intel486 processor addressing mechanism with paging enabled.

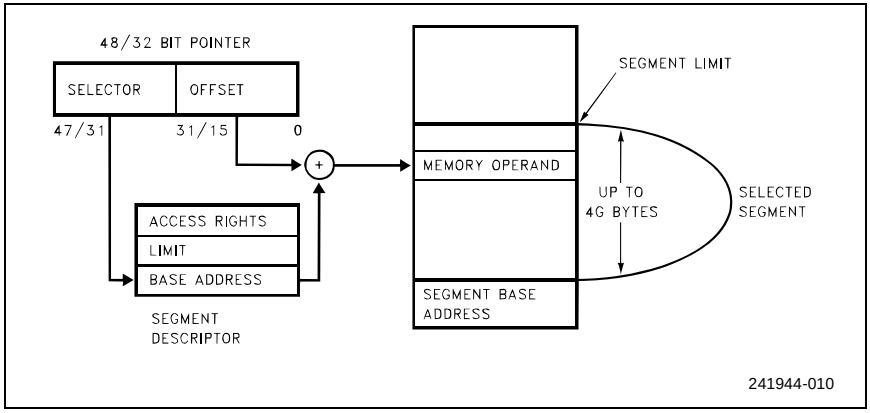


Figure 6-1. Protected Mode Addressing

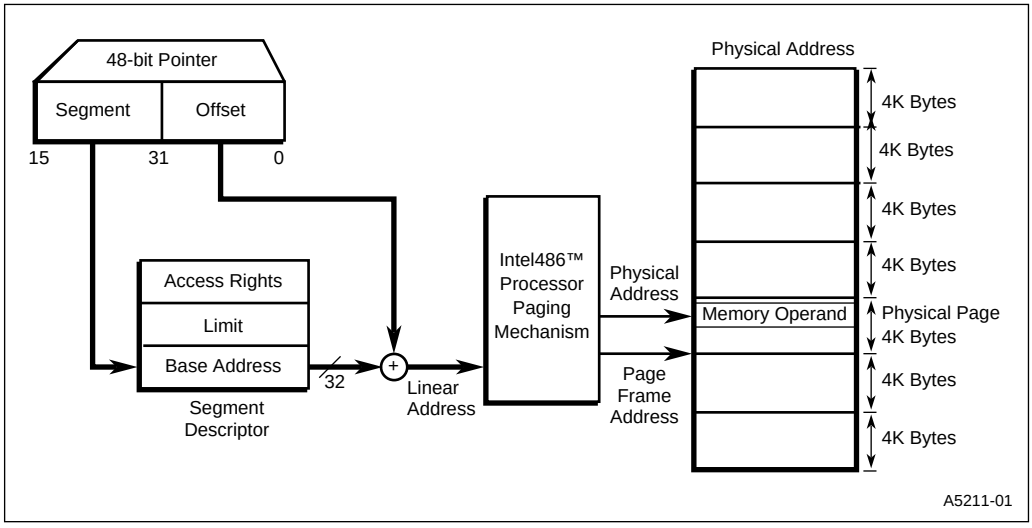


Figure 6-2. Paging and Segmentation

6.2 SEGMENTATION

6.2.1 Segmentation Introduction

Segmentation is one method of memory management. Segmentation provides the basis for protection. Segments are used to encapsulate regions of memory that have common attributes. For example, all of the code of a given program could be contained in a segment, or an operating system table may reside in a segment. All information about a segment is stored in an 8-byte data structure called a descriptor. All of the descriptors in a system are contained in tables recognized by hardware.

6.2.2 Terminology

The following terms are used throughout the discussion of descriptors, privilege levels and protection:

PL: Privilege Level	One of the four hierarchical privilege levels. Level 0 is the most privileged level and level 3 is the least privileged. Higher privilege levels are numerically smaller than lower privilege levels.
RPL: Requester Privilege Level	The privilege level of the original supplier of the selector. RPL is determined by the least two significant bits of a selector.
DPL: Descriptor Privilege Level	The least privileged level at which a task may access that descriptor (and the segment associated with that descriptor). Descriptor Privilege Level is determined by bits 6:5 in the Access Right Byte of a descriptor.
CPL: Current Privilege Level	The privilege level at which a task is currently executing, which equals the privilege level of the code segment being executed. CPL can also be determined by examining the lowest 2 bits of the CS register, except for conforming code segments.
EPL: Effective Privilege Level	The effective privilege level is the least privileged of the RPL and DPL. Because smaller privilege level values indicate greater privilege, EPL is the numerical maximum of RPL and DPL.
Task	One instance of the execution of a program. Tasks are also referred to as processes.

6.2.3 Descriptor Tables

6.2.3.1 Descriptor Tables Introduction

The descriptor tables define all of the segments that are used in an Intel486 processor system (see Figure 6-3). There are three types of tables on the Intel486 processor that hold descriptors: the Global Descriptor Table, Local Descriptor Table, and the Interrupt Descriptor Table. All of the tables are variable length memory arrays. They range in size between 8 bytes and 64 Kbytes. Each table can hold up to 8192 8-byte descriptors. The upper 13 bits of a selector are used as an index into the descriptor table. The tables have registers associated with them that hold the 32-bit linear base address, and the 16-bit limit of each table.

Each table has a different register associated with it: the GDTR, LDTR, and the IDTR (see Figure 6-3). The LGDT, LLDT, and LIDT instructions load the base and limit of the Global, Local, and Interrupt Descriptor Tables, respectively, into the appropriate register. The SGDT, SLDT, and SIDT store the base and limit values. These tables are manipulated by the operating system. Therefore, the load descriptor table instructions are privileged instructions.

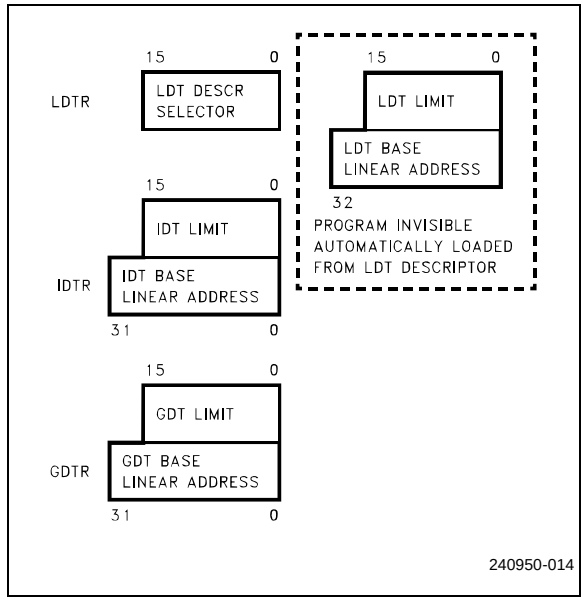


Figure 6-3. Descriptor Table Registers

6.2.3.2 Global Descriptor Table

The Global Descriptor Table (GDT) contains descriptors that are possibly available to all of the tasks in a system. The GDT can contain any type of segment descriptor except for descriptors that are used for servicing interrupts (i.e., interrupt and trap descriptors). Every Intel486 processor system contains a GDT. Generally the GDT contains code and data segments used by the operating systems and task state segments, and descriptors for the LDTs in a system.

The first slot of the Global Descriptor Table corresponds to the null selector and is not used. The null selector defines a null pointer value.

6.2.3.3 Local Descriptor Table

LDTs contain descriptors that are associated with a given task. Generally, operating systems are designed so that each task has a separate LDT. The LDT may contain only code, data, stack, task gate, and call gate descriptors. LDTs provide a mechanism for isolating a given task's code and data segments from the rest of the operating system, while the GDT contains descriptors for segments that are common to all tasks. A segment cannot be accessed by a task if its segment descriptor does not exist in either the current LDT or the GDT. This provides both isolation and protection for a task's segments, while still allowing global data to be shared among tasks.

Unlike the 6-byte GDT or IDT registers which contain a base address and limit, the visible portion of the LDT register contains only a 16-bit selector. This selector refers to a Local Descriptor Table descriptor in the GDT.

6.2.3.4 Interrupt Descriptor Table

The third table needed for Intel486 processor systems is the Interrupt Descriptor Table (see Figure 6-4). The IDT contains the descriptors that point to the location of up to 256 interrupt service routines. The IDT may contain only task gates, interrupt gates, and trap gates. The IDT should be at least 256 bytes in order to hold the descriptors for the 32 Intel Reserved Interrupts. Every interrupt used by a system must have an entry in the IDT. The IDT entries are referenced via INT instructions, external interrupt vectors, and exceptions (see Section 3.15, "Interrupts,").

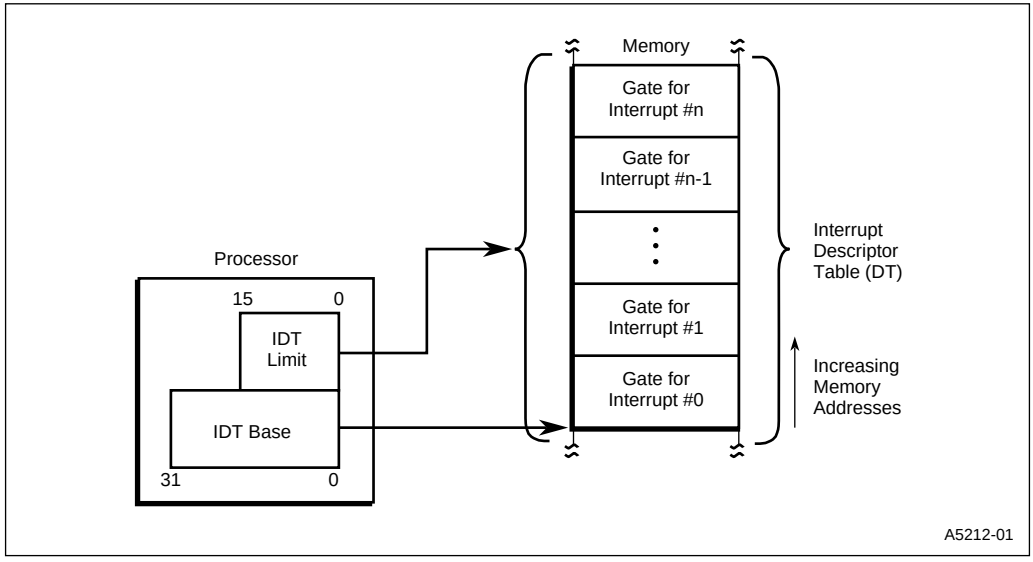


Figure 6-4. Interrupt Descriptor Table Register Use

6.2.4 Descriptors

6.2.4.1 Descriptor Attribute Bits

The object to which the segment selector points to is called a descriptor. Descriptors are eight-byte quantities that contain attributes about a given region of linear address space (i.e., a segment). These attributes include the 32-bit base linear address of the segment; the 20-bit length and granularity of the segment; the protection level; read, write or execute privileges; the default size of the operands (16-bit or 32-bit); and the type of segment. All attribute information about a segment is contained in 12 bits in the segment descriptor. All segments on the Intel486 processor have three attribute fields in common: the Present (P) bit, the Descriptor Privilege Level (DPL) bit, and the Segment (S) bit. The P bit is 1 if the segment is loaded in physical memory. If P=0, any attempt to access this segment causes a not present exception (exception 11). The DPL is a two-bit field that specifies the protection level 0–3 associated with a segment.

The Intel486 processor has two main categories of segments: system segments and non-system segments (for code and data). The S bit in the segment descriptor determines if a given segment is a system segment or a code or data segment. If the S bit is 1, the segment is either a code or data segment. If it is 0, the segment is a system segment.

6.2.4.2 Intel486™ Processor Code, Data Descriptors (S=1)

Figure 6-5 shows the general format of a code and data descriptor and Table 6-1 illustrates how the bits in the Access Rights Byte are interpreted. The Access Rights Bytes are bits 31:24 associated with the segment limit.

Code and data segments have several descriptor fields in common. The accessed (A) bit is set whenever the processor accesses a descriptor. The A bit is used by operating systems to keep usage statistics on a given segment. The G bit, or granularity bit, specifies if a segment length is byte-granular or page-granular. Intel486 processor segments can be one Mbyte long with byte granularity (G=0) or four Gbytes with page granularity (G=1), (i.e., 2^{20} pages, each page 4 Kbytes long). The granularity is unrelated to paging. An Intel486 processor system can consist of segments with byte granularity and page granularity, whether or not paging is enabled.

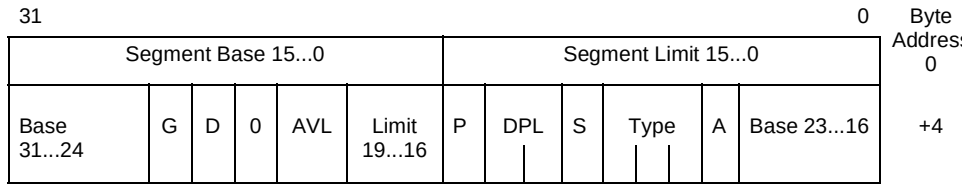
The executable (E) bit tells if a segment is a code or data segment. A code segment (E=1, S=1) may be execute-only or execute/read as determined by the Read (R) bit. Code segments are execute-only if R=0, and execute/read if R=1. Code segments may never be written to.

NOTE

Code segments can be modified via aliases. Aliases are writeable data segments that occupy the same range of linear address space as the code segment.

The D bit indicates the default length for operands and effective addresses. If D=1, 32-bit operands and 32-bit addressing modes are assumed. When D=0, 16-bit operands and 16-bit addressing modes are assumed. All existing 80286 code segments execute on the Intel486 processor when the D bit is set 0.

Another attribute of code segments is determined by the conforming (C) bit. Conforming segments, indicated when C=1, can be executed and shared by programs at different privilege levels (see Section 6.3, “Protection”).



BASE	Base Address of the segment
LIMIT	The length of the segment
P	Present Bit 1=Present, 0=Not Present
DPL	Descriptor Privilege Level 0–3
S	Segment Descriptor 0=System Descriptor, 1=Code or Data Segment Descriptor
TYPE	Type of Segment
A	Accessed Bit
G	Granularity Bit 1=Segment length is page granular, 0=Segment length is byte granular
D	Default Operation Size (recognized in code segment descriptors only)
	1=32-bit segment, 0=16-bit segment
0	Bit must be zero (0) for compatibility with future processors
AVL	Available field for user or OS

NOTE:

In a maximum-size segment (i.e., a segment with G=1 and segment limit 19...0=FFFFFH), the lowest 12 bits of the segment base should be zero (i.e., segment base 11...000=000H).

Figure 6-5. Segment Descriptors

Table 6-1. Access Rights Byte Definition for Code and Data Descriptions

Bit Position	Name	Function	
7	Present (P)	P = 1 P = 0	Segment is mapped into physical memory. No mapping to physical memory exits, base and limit are not used.
6–5	Descriptor Privilege Level (DPL)		Segment privilege attribute used in privilege tests.
4	Segment Descriptor (S)	S = 1 S = 0	Code or Data (includes stacks) segment descriptor. System Segment Descriptor or Gate Descriptor.
If Data Segment (S = 1, E = 0)			
3	Executable (E)	E = 0	Descriptor type is data segment
2	Expansion Direction (ED)	ED = 0 ED = 1	Expand up segment, offsets must be ≤ limit. Expand down segment, offsets must be > limit.
1	Writeable (W)	W = 0 W = 1	Data segment may not be written to. Data segment may be written to.
If Code Segment (S = 1, E = 1)			
3	Executable (E)	E = 1	Descriptor type is code segment
2	Conforming (C)	C = 1	Code segment may only be executed when CPL ≥ DPL and CPL remains unchanged.
1	Readable (R)	R = 0 R = 1	Code segment may not be read. Code segment may be read.
0	Accessed (A)	A = 0 A = 1	Segment has not been accessed. Segment selector has been loaded into segment register or used by selector test instructions.

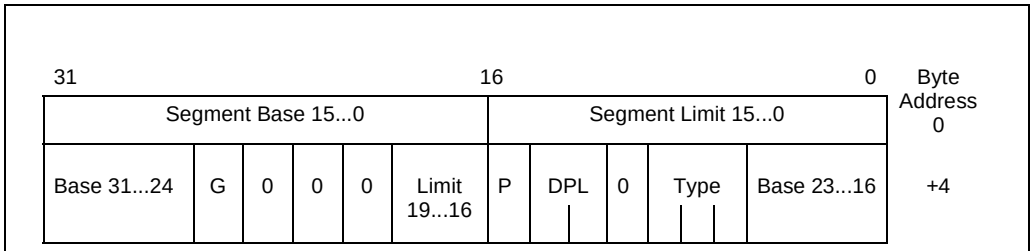
Segments identified as data segments (E=0, S=1) are used for two types of Intel486 processor segments: stack and data segments. The expansion direction (ED) bit specifies if a segment expands downward (stack) or upward (data). If a segment is a stack segment, all offsets must be greater than the segment limit. On a data segment, all offsets must be less than or equal to the limit. In other words, stack segments start at the base linear address plus the maximum segment limit and grow down to the base linear address plus the limit. On the other hand, data segments start at the base linear address and expand to the base linear address plus limit.

The write W bit controls the ability to write into a segment. Data segments are read-only if W=0. The stack segment must have W=1.

The B bit controls the size of the stack pointer register. If B=1, then PUSHes, POPs, and CALLs all use the 32-bit ESP register for stack references and assume an upper limit of FFFFFFFFH. If B=0, stack instructions all use the 16-bit SP register and assume an upper limit of FFFFH.

6.2.4.3 System Descriptor Formats

System segments describe information about operating system tables, tasks, and gates. Figure 6-6 shows the general format of system segment descriptors, and the various types of system segments. Intel486 processor system descriptors contain a 32-bit base linear address and a 20-bit segment limit. 80286 system descriptors have a 24-bit base address and a 16-bit segment limit. 80286 system descriptors are identified by the upper 16 bits being all zero.



Type	Defines	Type	Defines
0	Invalid	8	Invalid
1	Available 80286 TSS	9	Available Intel486 processor TSS
2	LDT	A	Undefined (Intel Reserved)
3	Busy 80286 TSS	B	Busy Intel486 processor TSS
4	80286 call gate	C	Intel486 processor call gate
5	Task Gate (for 80286, Intel486™ processor task)	D	Undefined (Intel Reserved)
6	80286 interrupt gate	E	Intel486 processor
7	80286 trap gate	F	Intel486 processor

Figure 6-6. System Segment Descriptors

6.2.4.4 LDT Descriptors (S=0, TYPE=2)

LDT descriptors (S=0, TYPE=2) contain information about Local Descriptor Tables. LDTs contain a table of segment descriptors, unique to a particular task. Because the instruction to load the LDTR is only available at privilege level 0, the DPL field is ignored. LDT descriptors are only allowed in the Global Descriptor Table (GDT).

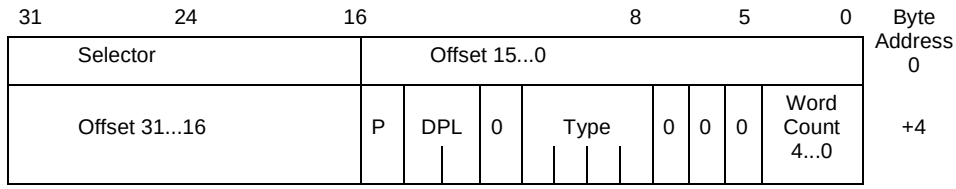
6.2.4.5 TSS Descriptors (S=0, TYPE=1, 3, 9, B)

A Task State Segment (TSS) descriptor contains information about the location, size, and privilege level of a Task State Segment (TSS). A TSS in turn is a special fixed format segment that contains all the state information for a task and a linkage field to permit nesting tasks. The TYPE field is used to indicate whether the task is currently busy (i.e., on a chain of active tasks) or the TSS is available. The TYPE field also indicates if the segment contains an 80286 processor TSS or an Intel486 processor TSS. The Task Register (TR) contains the selector that points to the current Task State Segment.

6.2.4.6 Gate Descriptors (S=0, TYPE=4–7, C, F)

Gates are used to control access to entry points within the target code segment. The various types of gate descriptors are call gates, task gates, interrupt gates, and trap gates. Gates provide a level of indirection between the source and destination of the control transfer. This indirection allows the processor to automatically perform protection checks. It also allows system designers to control entry points to the operating system. Call gates are used to change privilege levels (see Section 6.3, "Protection"), task gates are used to perform a task switch, and interrupt and trap gates are used to specify interrupt service routines.

Figure 6-7 shows the format of the four types of gate descriptors. Call gates are primarily used to transfer program control to a more privileged level. The call gate descriptor consists of three fields: the access byte, a long pointer (selector and offset) that points to the start of a routine, and a word count that specifies how many parameters are to be copied from the caller's stack to the stack of the called routine. The word count field is only used by call gates when there is a change in the privilege level; other types of gates ignore the word count field.



Gate Descriptor Fields

Name	Value	Description
Type	4	80286 call gate
	5	Task gate (for 80286 or Intel486 processor task)
	6	80286 interrupt gate
	7	80286 trap gate
	C	Intel486 processor call gate
	E	Intel486 processor interrupt gate
	F	Intel486 processor trap gate
P	0	Descriptor contents are not valid
	1	Descriptor contents are valid

DPL—least privileged level at which a task may access the gate. WORD COUNT 0–31—the number of parameters to copy from caller's stack to the called procedure's stack. The parameters are 32-bit quantities for Intel486 processor gates, and 16-bit quantities for 80286 gates.

DESTINATION SELECTOR	16-bit selector	Selector to the target code segment or Selector to the target task state segment for task gate
DESTINATION OFFSET	offset 16-bit 80286 32-bit Intel486 processor	Entry point within the target code segment

Figure 6-7. Gate Descriptor Formats

Interrupt and trap gates use the destination selector and destination offset fields of the gate descriptor as a pointer to the start of the interrupt or trap handler routines. The difference between interrupt gates and trap gates is that the interrupt gate disables interrupts (resets the IF bit), whereas the trap gate does not.

Task gates are used to switch tasks. Task gates may only refer to a task state segment (see Section 6.3.6, “Task Switching”). Therefore, only the destination selector portion of a task gate descriptor is used, and the destination offset is ignored.

Exception 13 is generated when a destination selector does not refer to a correct descriptor type, i.e., a code segment for an interrupt, trap or call gate, or a TSS for a task gate.

The access byte format is the same for all gate descriptors. P=1 indicates that the gate contents are valid. P=0 indicates the contents are not valid and causes exception 11 when referenced. DPL is the descriptor privilege level and specifies when this descriptor may be used by a task (see Section 6.3, “Protection”). The S field, bit 4 of the access rights byte, must be 0 to indicate a system control descriptor. The type field specifies the descriptor type as indicated in Figure 6-7.

6.2.4.7 Differences Between Intel486™ Processor and 80286 Descriptors

In order to provide operating system compatibility between 80286 and Intel486 processors, the Intel486 processor supports all of the 80286 segment descriptors. Figure 6-8 shows the general format of an 80286 system segment descriptor. The only differences between 80286 and Intel486 processor descriptor formats are that the values of the type fields, and the limit and base address fields have been expanded for the Intel486 processor. The 80286 system segment descriptors contain a 24-bit base address and 16-bit limit, while the Intel486 processor system segment descriptors have a 32-bit base address, a 20-bit limit field, and a granularity bit.

By supporting 80286 system segments, the Intel486 processor is able to execute 80286 application programs on an Intel486 processor operating system. This is possible because the Intel486 processor automatically understands which descriptors are 80286-style descriptors and which are Intel486 processor-style descriptors. In particular, if the upper word of a descriptor is zero, then that descriptor is an 80286-style descriptor.

The only other differences between 80286-style descriptors and Intel486 processor descriptors are the interpretation of the word count field of call gates and the B bit. The word count field specifies the number of 16-bit quantities to copy for 80286 call gates and 32-bit quantities for Intel486 processor call gates. The B bit controls the size of PUSHes when using a call gate; if B=0 PUSHes are 16 bits, if B=1 PUSHes are 32 bits.

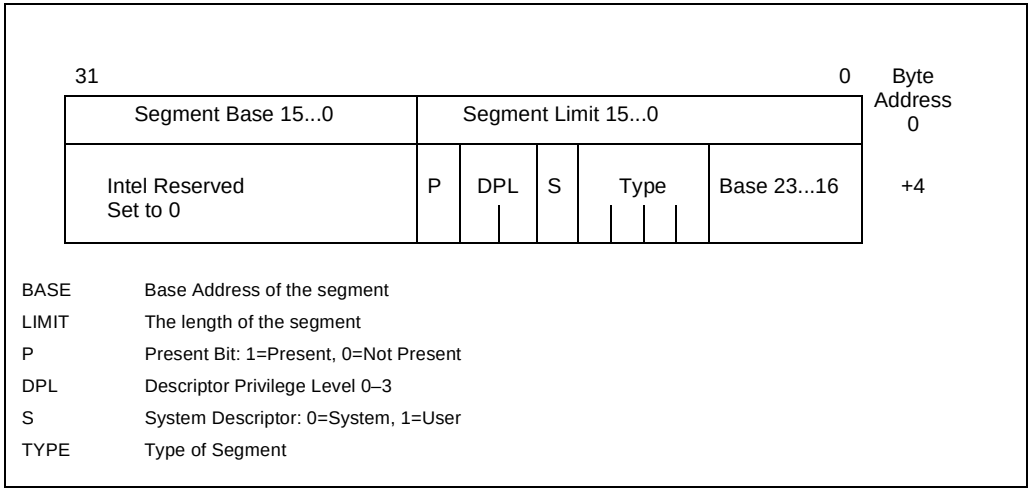


Figure 6-8. 80286 Code and Data Segment Descriptors

6.2.4.8 Selector Fields

A selector in Protected Mode has three fields: Local or Global Descriptor Table Indicator (TI), Descriptor Entry Index (Index), and Requester (the selector's) Privilege Level (RPL) as shown in Figure 6-9. The TI bits select one of two memory-based tables of descriptors (the Global Descriptor Table or the Local Descriptor Table). The Index selects one of 8 K descriptors in the appropriate descriptor table. The RPL bits allow high speed testing of the selector's privilege attributes.

6.2.4.9 Segment Descriptor Cache

In addition to the selector value, every segment register has a segment descriptor cache register associated with it. Whenever a segment register's contents are changed, the 8-byte descriptor associated with that selector is automatically loaded (cached) on the chip. Once loaded, all references to that segment use the cached descriptor information instead of re-accessing the descriptor. The contents of the descriptor cache are not visible to the programmer. Because descriptor caches only change when a segment register is changed, programs that modify the descriptor tables must reload the appropriate segment registers after changing a descriptor's value.

6.2.4.10 Segment Descriptor Register Settings

The contents of the segment descriptor cache vary depending on the mode in which the Intel486 processor is operating. When operating in Real Address Mode, the segment base, limit, and other attributes within the segment cache registers are defined as shown in Figure 6-10. For compatibility with the 8086 architecture, the base is set to 16 times the current selector value, the limit is fixed at 0000FFFFH, and the attributes are fixed to indicate that the segment is present and fully usable. In Real Address Mode, the internal "privilege level" is always fixed to the highest level, level 0, so I/O and other privileged opcodes may be executed.

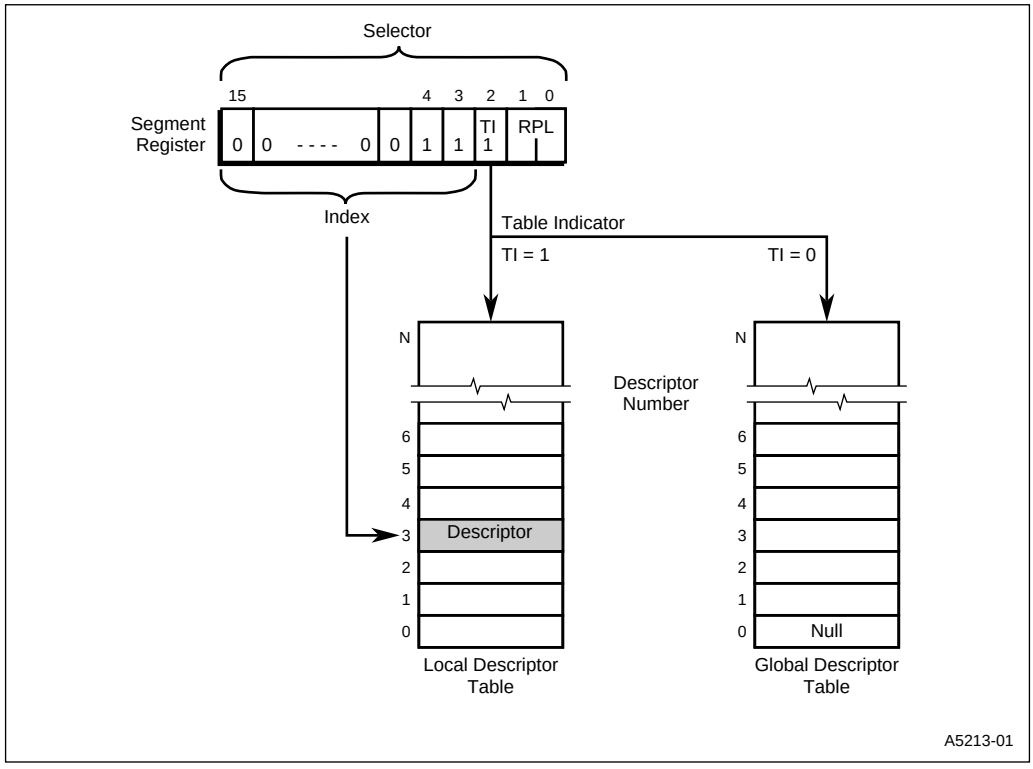
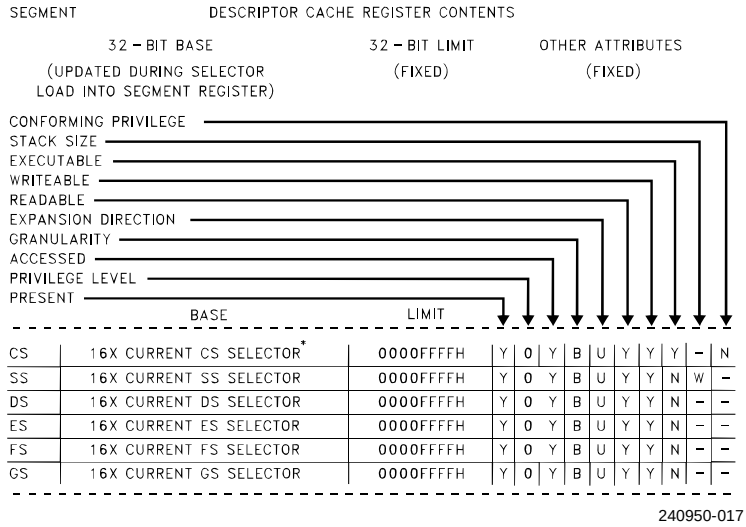


Figure 6-9. Example Descriptor Selection



240950-017

Key:

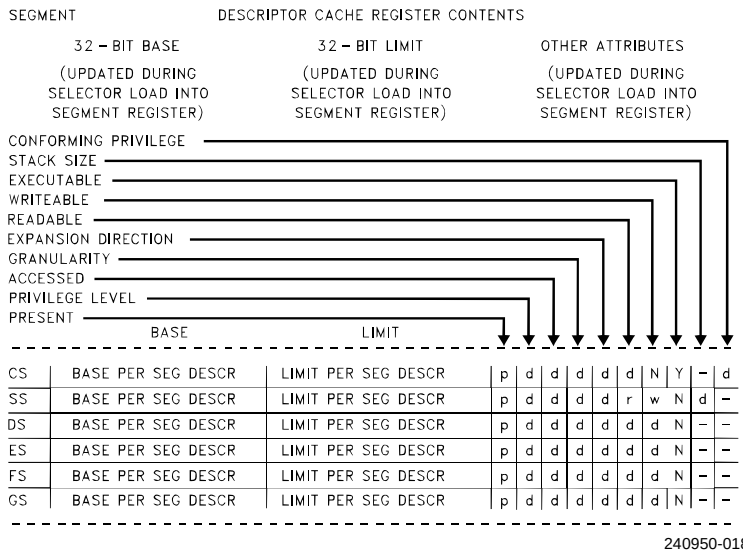
Y	= yes	D	= expand down
N	= no	B	= byte granularity
0	= privilege level 0	P	= page granularity
1	= privilege level 1	W	= push/pop 16-bit words
2	= privilege level 2	F	= push/pop 32-bit dwords
3	= privilege level 3	–	= does not apply to that segment cache register
U	= expand up		

†Except the 32-bit CS base is initialized to FFFFF000H after reset until first intersegment control transfer (i.e., intersegment CALL, or intersegment JMP, or INT). (See Figure 6-12 for an example.)

Figure 6-10. Segment Descriptor Caches for Real Address Mode (Segment Limit and Attributes Are Fixed)

When operating in Protected Mode, the segment base, limit, and other attributes within the segment cache registers are defined as shown in Figure 6-11. In Protected Mode, each of these fields are defined according to the contents of the segment descriptor indexed by the selector value loaded into the segment register.

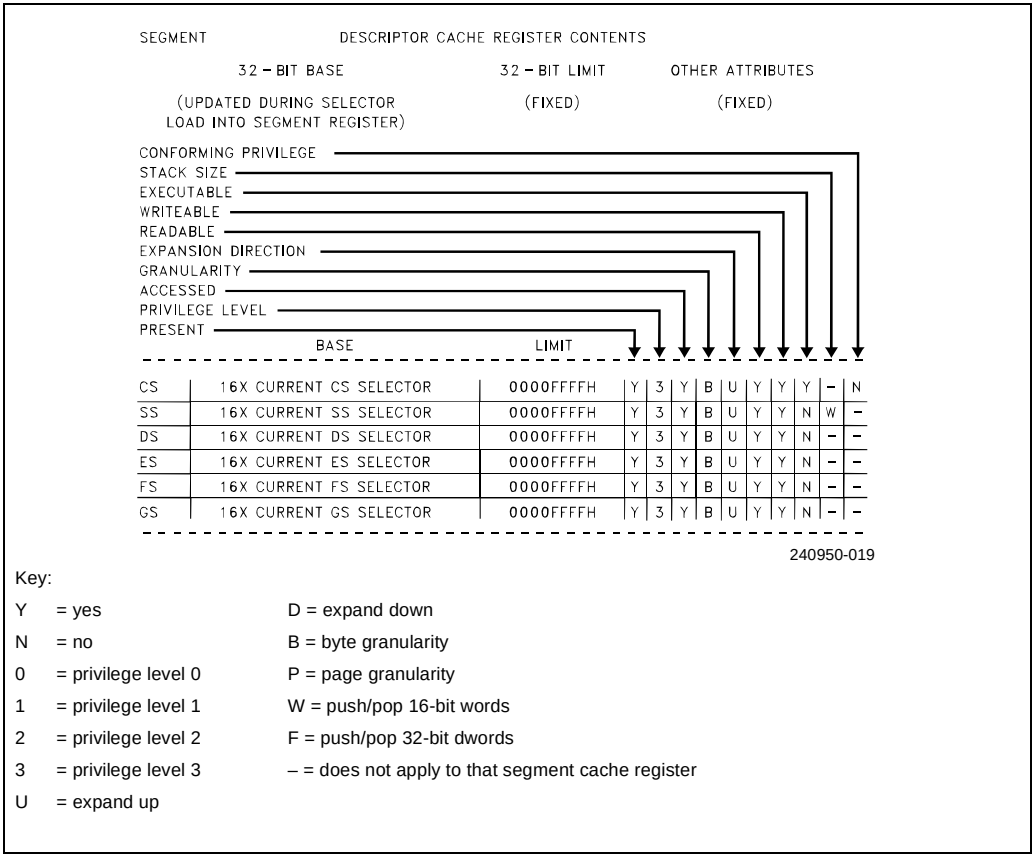
When operating in a Virtual 8086 Mode within the Protected Mode, the segment base, limit, and other attributes within the segment cache registers are defined as shown in Figure 6-12. For compatibility with the 8086 architecture, the base is set to sixteen times the current selector value, the limit is fixed at 0000FFFFH, and the attributes are fixed so as to indicate the segment is present and fully usable. The virtual program executes at lowest privilege level, level 3, to allow trapping of all IOPL-sensitive instructions and level-0-only instructions.



Key:

Y	=	fixed yes
N	=	fixed no
d	=	per segment descriptor
p	=	per segment descriptor; descriptor must indicate “present” to avoid exception 11 (exception 12 in case of SS)
r	=	per segment descriptor, but descriptor must indicate “readable” to avoid exception 13 (special case for SS)
w	=	per segment descriptor, but descriptor must indicate “writeable” to avoid exception 13 (special case for SS)
–	=	does not apply to that segment cache register

Figure 6-11. Segment Descriptor Caches for Protected Mode (Loaded per Descriptor)



Key:

Y	= yes	D	= expand down
N	= no	B	= byte granularity
0	= privilege level 0	P	= page granularity
1	= privilege level 1	W	= push/pop 16-bit words
2	= privilege level 2	F	= push/pop 32-bit dwords
3	= privilege level 3	–	= does not apply to that segment cache register
U	= expand up		

Figure 6-12. Segment Descriptor Caches for Virtual 8086 Mode within Protected Mode (Segment Limit and Attributes are Fixed)

6.3 PROTECTION

6.3.1 Protection Concepts

The Intel486 processor has four levels of protection that support multi-tasking by isolating and protecting user programs from each other and the operating system. The privilege levels control the use of privileged instructions, I/O instructions, and access to segments and segment descriptors. Unlike traditional processor-based systems, in which this protection is achieved only through the use of complex external hardware and software, the Intel486 processor provides the protection as part of its integrated Memory Management Unit. The Intel486 processor offers an additional type of protection on a page basis, when paging is enabled. See Section 6.4.3, "Page Level Protection (R/W, U/S Bits)."

The four-level hierarchical privilege system is illustrated in Figure 6-13. It is an extension of the user/supervisor privilege mode commonly used by minicomputers. The user/supervisor mode is fully supported by the Intel486 processor paging mechanism. The privilege levels (PLs) are numbered 0 through 3. Level 0 is the most privileged or trusted level.

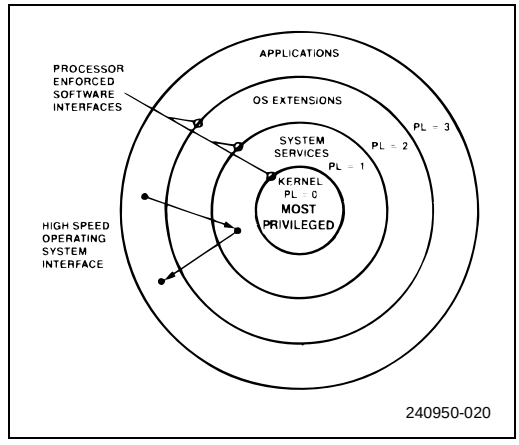


Figure 6-13. Four-Level Hierarchical Protection

6.3.2 Rules of Privilege

The Intel486 processor controls access to both data and procedures between levels of a task, according to the following rules.

- Data stored in a segment with privilege level p can be accessed only by code executing at a privilege level at least as privileged as p.
- A code segment/procedure with privilege level p can only be called by a task executing at the same or a lesser privilege level than p.

6.3.3 Privilege Levels

6.3.3.1 Task Privilege

At any point in time, a task on the Intel486 processor always executes at one of the four privilege levels. The current privilege level (CPL) specifies the task's privilege level. A task's CPL may be changed only by control transfers through gate descriptors to a code segment with a different privilege level (see Section 6.3.4, "Privilege Level Transfers"). Thus, an application program running at PL = 3 may call an operating system routine at PL = 1 (via a gate), which would cause the task's CPL to be set to 1 until the operating system routine finishes.

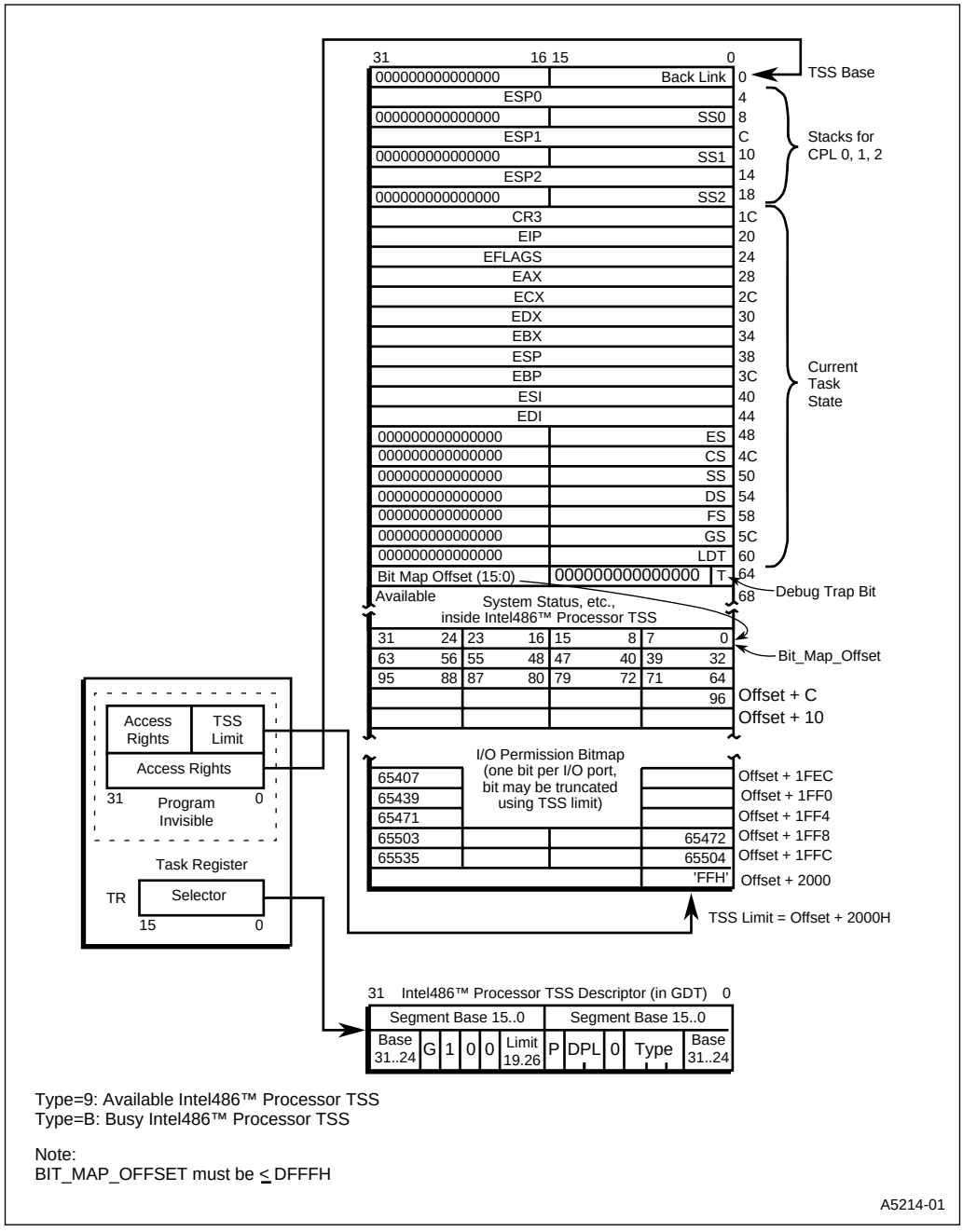
6.3.3.2 Selector Privilege (RPL)

The privilege level of a selector is specified by the RPL field. The RPL is the two least significant bits of the selector. The selector's RPL is used only to establish a less trusted privilege level than the current privilege level for the use of a segment. This level is called the task's effective privilege level (EPL). The EPL is defined as the least privileged (i.e., numerically larger) level of a task's CPL and a selector's RPL. Thus, if selector's RPL = 0 then the CPL always specifies the privilege level for making an access using the selector. On the other hand, if RPL = 3, a selector can only access segments at level 3 regardless of the task's CPL. The RPL is most commonly used to verify that pointers passed to an operating system procedure do not access data that is of higher privilege than the procedure that originated the pointer. Because the originator of a selector can specify any RPL value, the Adjust RPL (ARPL) instruction is provided to force the RPL bits to the originator's CPL.

6.3.3.3 I/O Privilege and I/O Permission Bitmap

The I/O privilege level (IOPL, a 2-bit field in the EFLAG register) defines the least privileged level at which I/O instructions can be unconditionally performed. I/O instructions can be unconditionally performed when CPL ≥ IOPL. (The I/O instructions are IN, OUT, INS, OUTS, REP INS, and REP OUTS.) When CPL > IOPL and the current task is associated with a 286 TSS, attempted I/O instructions cause an exception 13 fault. When CPL > IOPL and the current task is associated with an Intel486 processor TSS, the I/O permission bitmap (part of an Intel486 processor TSS) is consulted on whether I/O to the port is allowed; otherwise an exception 13 fault is generated. For diagrams of the I/O Permission Bitmap, refer to Figures 6-14 and 6-15. For further information on how the I/O Permission Bitmap is used in Protected Mode or in Virtual 8086 Mode, refer to Section 6.5.4, "Protection and I/O Permission Bitmap."

The I/O privilege level (IOPL) also affects whether several other instructions can be executed or whether an exception 13 fault should be generated. These instructions, called "IOPL-sensitive" instructions, are CLI and STI. (Note that the LOCK prefix is not IOPL-sensitive on the Intel486 processor.)



Type=9: Available Intel486™ Processor TSS
Type=B: Busy Intel486™ Processor TSS

Note:
BIT_MAP_OFFSET must be ≤ DFFFH

A5214-01

Figure 6-14. Intel486™ Processor TSS and TSS Registers

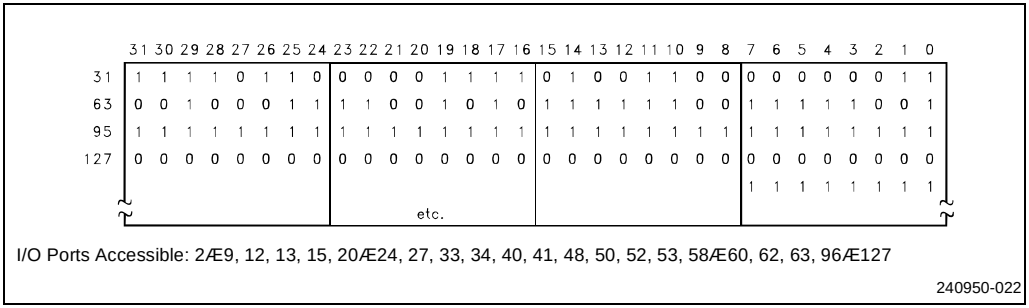


Figure 6-15. Sample I/O Permission Bit Map

The IOPL also affects whether the IF (interrupts enable flag) bit can be changed by loading a value into the EFLAGS register. When CPL ≥ IOPL, the IF bit can be changed by loading a new value into the EFLAGS register. When CPL > IOPL, the IF bit cannot be changed by a new value POPed into (or otherwise loaded into) the EFLAGS register; the IF bit remains unchanged and no exception is generated.

6.3.3.4 Privilege Validation

The Intel486 processor provides several instructions to speed pointer testing and help maintain system integrity by verifying that the selector value refers to an appropriate segment. Table 6-2 summarizes the selector validation procedures available for the Intel486 processor.

Table 6-2. Pointer Test Instructions

Instruction	Operands	Function
ARPL	Selector, Register	Adjust Requested Privilege Level: adjusts the RPL of the selector to the numeric maximum of current selector RPL value and the RPL value in the register. Set zero flag if selector RPL was changed.
VERR	Selector	VERify for Read: sets the zero flag if the segment referred to by the selector can be read.
VERW	Selector	VERify for Write: sets the zero flag if the segment referred to by the selector can be written.
LSL	Register, Selector	Load Segment Limit: reads the segment limit into the register if privilege rules and descriptor type allow. Set zero flag if successful.
LAR	Register, Selector	Load Access Rights: reads the descriptor access rights byte into the register if privilege rules allow. Set zero flag if successful.

This pointer verification prevents this common problem: An application at PL = 3 calls an operating systems routine at PL = 0, and then passes the operating system routine a "bad" pointer that corrupts a data structure belonging to the operating system. This problem can be avoided if the operating system routine uses the ARPL instruction to ensure that the RPL of the selector has no greater privilege than that of the caller.

6.3.3.5 Descriptor Access

There are two types of segment accesses: those involving code segments such as control transfers, and those involving data accesses. Determining the ability of a task to access a segment requires determining the type of segment to be accessed, the instruction used, the type of descriptor used, and CPL, RPL, and DPL, as described above.

Any time an instruction loads data segment registers (DS, ES, FS, GS) the Intel486 processor makes protection validation checks. Selectors loaded in the DS, ES, FS, GS registers must refer only to data segments or readable code segments. (The data access rules are specified in Section 6.3.2, “Rules of Privilege.” The only exception to those rules is readable conforming code segments, that can be accessed at any privilege level.) Finally, the privilege validation checks are performed. The CPL is compared to the EPL, and if the EPL is more privileged than the CPL, an exception 13 (general protection fault) is generated.

The rules for the stack segment are slightly different than those for data segments. Instructions that load selectors into the SS must refer to data segment descriptors for writeable data segments. The DPL and RPL must equal the CPL. All other descriptor types and privilege level violations cause exception 13. A stack not present fault causes exception 12. Note that an exception 11 is used for a not-present code or data segment.

6.3.4 Privilege Level Transfers

Inter-segment control transfers occur when a selector is loaded in the CS register. In a typical system, most of these transfers are the result of a call or a jump to another routine. There are five types of control transfers, which are summarized in Table 6-3. Many of these transfers result in a privilege level transfer. Changing privilege levels is done only via control transfers, by using gates, task switches, and interrupt or trap gates.

Control transfers can only occur if the operation that loaded the selector references the correct descriptor type. Any violation of these descriptor usage rules causes an exception 13 (e.g., JMP through a call gate, or IRET from a normal subroutine call).

To provide further system security, all control transfers are also subject to the privilege rules.

Table 6-3. Descriptor Types Used for Control Transfer

Control Transfer Types	Operation Types	Descriptor Referenced	Descriptor Table
Intersegment within the same privilege level	JMP, CALL, RET, IRET	Code Segment	GDT/LDT
Intersegment to the same or higher privilege level	CALL	Call Gate	GDT/LDT
Interrupt within task may change CPL	Interrupt Instruction, Exception, External Interrupt	Trap or Interrupt Gate	IDT
Intersegment to a lower privilege level (changes task CPL)	RET, IRET(1)	Code Segment	GDT/LDT
	CALL, JMP	Task State Segment	GDT
Task Switch	CALL, JMP	Task Gate	GDT/LDT
	IRET(2) Interrupt Instruction, Exception, External Interrupt	Task Gate	IDT

NOTES:
1. NT (Nested Task bit of flag register) = 0
2. NT (Nested Task bit of flag register) = 1

The privilege rules require that:

- Privilege level transitions can only occur via gates.
- JMPs can be made to a non-conforming code segment with the same privilege or to a conforming code segment with greater or equal privilege.
- CALLs can be made to a non-conforming code segment with the same privilege or via a gate to a more privileged level.
- Interrupts handled within the task obey the same privilege rules as CALLs.
- Conforming code segments are accessible by privilege levels that are the same or less privileged than the conforming-code segment's DPL.
- Both the requested privilege level (RPL) in the selector pointing to the gate and the task's CPL must be of equal or greater privilege than the gate's DPL.
- The code segment selected in the gate must be the same or more privileged than the task's CPL.
- Return instructions that do not switch tasks can only return control to a code segment with the same or less privilege.
- Task switches can be performed by a CALL, JMP, or INT that references either a task gate or task state segment who's DPL is less privileged or the same privilege as the old task's CPL.

Any control transfer that changes CPL within a task causes a change of stacks as a result of the privilege level change. The initial values of SS:ESP for privilege levels 0, 1, and 2 are retained in the task state segment (see Section 6.3.6, “Task Switching”). During a JMP or CALL control transfer, the new stack pointer is loaded into the SS and ESP registers and the previous stack pointer is pushed onto the new stack.

When returning to the original privilege level, use of the lower-privileged stack is restored as part of the RET or IRET instruction operation. For subroutine calls that pass parameters on the stack and cross privilege levels, a fixed number of words (as specified in the gate's word count field) are copied from the previous stack to the current stack. The inter-segment RET instruction with a stack adjustment value correctly restores the previous stack pointer upon return.

6.3.5 Call Gates

Gates provide protected, indirect CALLs. One of the major uses of gates is to provide a secure method of privilege transfers within a task. Because the operating system defines all of the gates in a system, it can ensure that all gates allow entry into a few trusted procedures only (such as those that allocate memory or perform I/O).

Gate descriptors follow the data access rules of privilege; that is, gates can be accessed by a task if the EPL is equal to or more privileged than the gate descriptor's DPL. Gates follow the control transfer rules of privilege and therefore may only transfer control to a more privileged level.

Call Gates are accessed via a CALL instruction and are syntactically identical to calling a normal subroutine. When an inter-level Intel486 processor call gate is activated, the following actions occur.

1. Load CS:EIP from gate check for validity.
2. SS is pushed zero-extended to 32 bits.
3. ESP is pushed.
4. Copy Word Count 32-bit parameters from the old stack to the new stack.
5. Push Return address on stack.

The procedure is identical for 80286 Call gates, except that 16-bit parameters are copied and 16-bit registers are pushed.

Interrupt gates and trap gates work in a similar fashion as the call gates, except there is no copying of parameters. The only difference between trap and interrupt gates is that control transfers through an interrupt gate disable further interrupts (i.e., the IF bit is set to 0), and trap gates leave the interrupt status unchanged.

6.3.6 Task Switching

An important attribute of any multi-tasking/multi-user operating system is its ability to switch between tasks or processes rapidly. The Intel486 processor directly supports this operation by providing a task switch instruction in hardware. The Intel486 processor task switch operation saves the entire state of the machine (all of the registers, address space, and a link to the previous task), loads a new execution state, performs protection checks, and commences execution in the new task, in about 10 microseconds. Like transfer of control via gates, the task switch operation is invoked by executing an inter-segment JMP or CALL instruction that refers to a Task State Segment (TSS) or a task gate descriptor in the GDT or LDT. An INT n instruction, exception, trap, or external interrupt may also invoke the task switch operation if there is a task gate descriptor in the associated IDT descriptor slot.

The TSS descriptor points to a segment (see Figure 6-14) containing the entire Intel486 processor execution state whereas a task gate descriptor contains a TSS selector. The Intel486 processor supports both 80286 and Intel486 processor-style TSSs. Figure 6-16 shows an 80286 TSS. The limit of an Intel486 processor TSS must be greater than 0064H (002BH for an 80286 TSS), and can be as large as 4 Gbytes. In the additional TSS space, the operating system is free to store additional information, such as the reason the task is inactive, the time the task has spent running, and the open files belonging to the task.

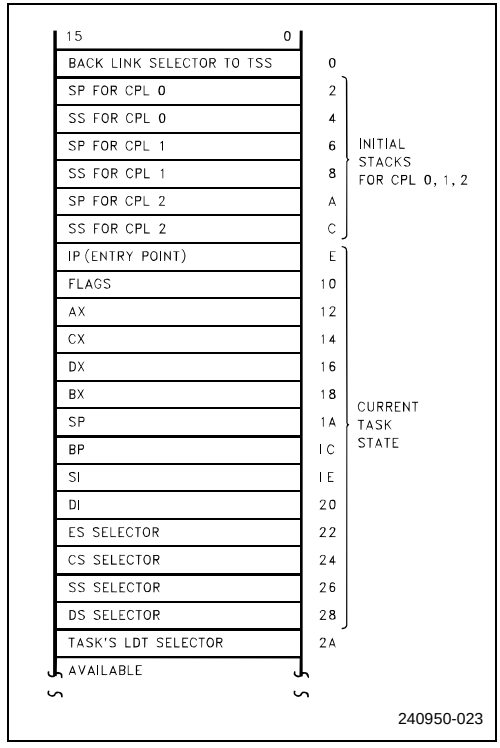


Figure 6-16. 80286 TSS

Each task must have a TSS associated with it. The current TSS is identified by a special register in the Intel486 processor called the Task State Segment Register (TR). This register contains a selector referring to the task state segment descriptor that defines the current TSS. A hidden base register and limit register associated with TR are loaded whenever TR is loaded with a new selector. Returning from a task is accomplished by the IRET instruction. When IRET is executed, control is returned to the task that was interrupted. The currently executing task's state is saved in the TSS and the old task state is restored from its TSS.

Several bits in the flag register and machine status word (CR0) give information about the state of a task that is useful to the operating system. The Nested Task (NT) (bit 14 in EFLAGS) controls the function of the IRET instruction. If NT = 0, the IRET instruction performs the regular return; when NT = 1, IRET performs a task switch operation back to the previous task. The NT bit is set or reset in the following fashion:

When a CALL or INT instruction initiates a task switch, the new TSS is marked busy and the back link field of the new TSS set to the old TSS is selector. The NT bit of the new task is set by CALL or INT initiated task switches. An interrupt that does not cause a task switch clears NT. (The NT bit is restored after execution of the interrupt handler.) NT may also be set or cleared by POPF or IRET instructions.

The Intel486 processor task state segment is marked busy by changing the descriptor type field from TYPE 9H to TYPE BH. An 80286 TSS is marked busy by changing the descriptor type field from TYPE 1 to TYPE 3. Use of a selector that references a busy task state segment causes an exception 13.

The Virtual Mode (VM) bit 17 is used to indicate if a task is a virtual 8086 task. If VM = 1, the tasks use the Real Mode addressing mechanism. The virtual 8086 environment is entered and exited only via a task switch (see Section 6.5, "Virtual 8086 Environment").

The T bit in the Intel486 processor TSS indicates that the processor should generate a debug exception when switching to a task. If T = 1, a debug exception 1 is generated upon entry to a new task

6.3.6.1 Floating-Point Task Switching

The FPU's state is not automatically saved when a task switch occurs, because the incoming task may not use the FPU. The Task Switched (TS) Bit (bit 3 in the CR0) helps identify the FPU's state in a multi-tasking environment. Whenever the Intel OverDrive processors switch tasks, they set the TS bit. The Intel OverDrive processors detect the first use of a processor extension instruction after a task switch and causes the processor extension not available exception 7. The exception handler for exception 7 may then decide whether to save the state of the FPU. A processor extension not present exception (7) occurs when attempting to execute a Floating-Point or WAIT instruction if the Task Switched and Monitor coprocessor extension bits are both set (i.e., TS = 1 and MP = 1).

6.3.7 Initialization and Transition to Protected Mode

Because the Intel486 processor begins executing in Real Mode immediately after RESET, it is necessary to initialize the system tables and registers with the appropriate values.

The GDT and IDT registers must refer to a valid GDT and IDT. The IDT should be at least 256-bytes long, and GDT must contain descriptors for the initial code and data segments. Figure 6-17 shows the tables and Figure 6-18 shows the descriptors needed for a simple Protected Mode Intel486 processor system. It has a single code and single data/stack segment, each four-Gbytes long, and a single privilege level, PL = 0.

The actual method of enabling Protected Mode is to load CR0 with the PE bit set via the MOV CR0, R/M instruction.

After enabling Protected Mode, the next instruction should execute an intersegment JMP to load the CS register and flush the instruction decode queue. The final step is to load all of the data segment registers with the initial selector values.

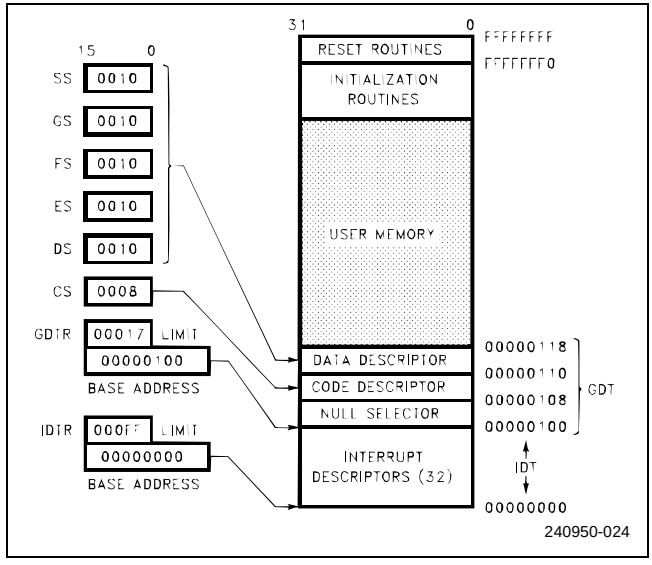


Figure 6-17. Simple Protected System

An alternate approach to entering Protected Mode that is especially appropriate for multi-tasking operating systems is to use the built-in task-switch to load all the registers. In this case, the GDT contains two TSS descriptors in addition to the code and data descriptors needed for the first task. The first JMP instruction in Protected Mode jumps to the TSS, causing a task switch and loading all of the registers with the values stored in the TSS. Because a task switch saves the state of the current task in a task state segment, the Task State Segment register should be initialized to point to a valid TSS descriptor.

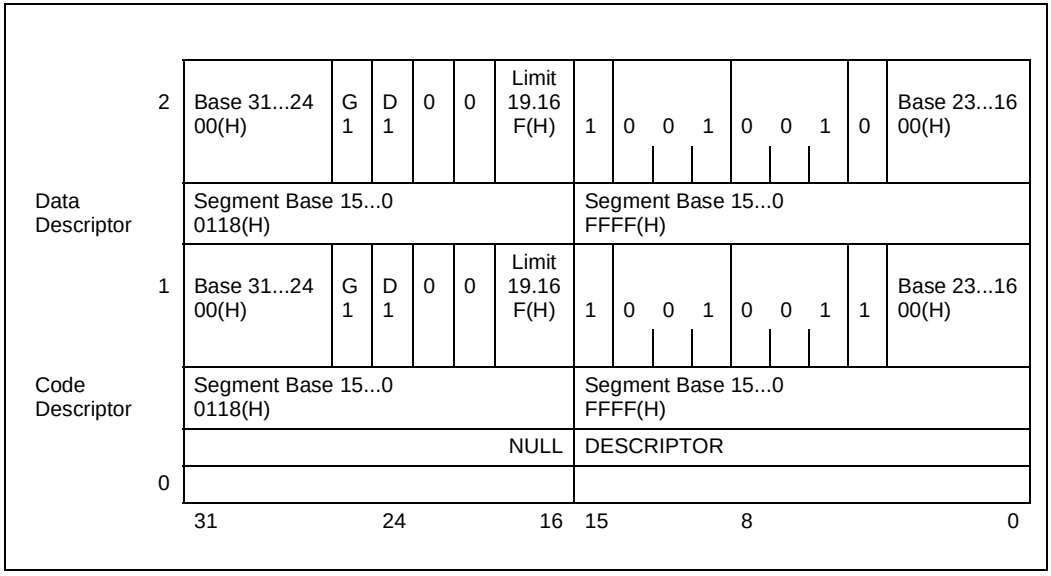


Figure 6-18. GDT Descriptors for Simple System

6.4 PAGING

6.4.1 Paging Concepts

Paging is another type of memory management useful for virtual memory multi-tasking operating systems. Unlike segmentation, which modularizes programs and data into variable length segments, paging divides programs into multiple uniform size pages. Pages bear no direct relation to the logical structure of a program. Whereas segment selectors can be considered the logical "name" of a program module or data structure, a page most likely corresponds to only a portion of a module or data structure.

By taking advantage of the locality of reference displayed by most programs, only a small number of pages from each active task need be in memory at any moment.

6.4.2 Paging Organization

6.4.2.1 Page Mechanism

The Intel486 processor uses two levels of tables to translate the linear address (from the segmentation unit) to a physical address. There are three components to the paging mechanism of the Intel486 processor: the page directory, the page tables, and the page itself (page frame). All memory-resident elements of the Intel486 processor paging mechanism are 4 Kbytes. A uniform size for all of the elements simplifies memory allocation and reallocation schemes by eliminating problems with memory fragmentation. Figure 6-19 shows how the paging mechanism works.

6.4.2.2 Page Descriptor Base Register

CR2 is the Page Fault Linear Address register. It holds the 32-bit linear address that caused the last page fault detected.

CR3 is the Page Directory Physical Base Address register. It contains the physical starting address of the page directory. The lower 12 bits of CR3 are always zero to ensure that the page directory is always page aligned. Loading it via a MOV CR3 reg instruction causes the page table entry cache to be flushed, as does a task switch through a TSS that changes the value of CR0 (see Section 6.4.5, "Translation Lookaside Buffer").

6.4.2.3 Page Directory

The Page Directory is 4 Kbytes long and allows up to 1024 page directory entries. Each page directory entry contains the address of the next level of tables, the Page Tables and information about the page table. The contents of a page directory entry are shown in Figure 6-20. The upper 10 bits of the linear address (A[31:22]) are used as an index to select the correct page directory entry.

6.4.2.4 Page Tables

Each Page Table is 4 Kbytes and holds up to 1024 page table entries. Page table entries contain the starting address of the page frame and statistical information about the page (see Figure 6-21). Address bits A[21:12] are used as an index to select one of the 1024 page table entries. The 20 upper-bit page frame address is concatenated with the lower 12 bits of the linear address to form the physical address. Page tables can be shared between tasks and swapped to disks.

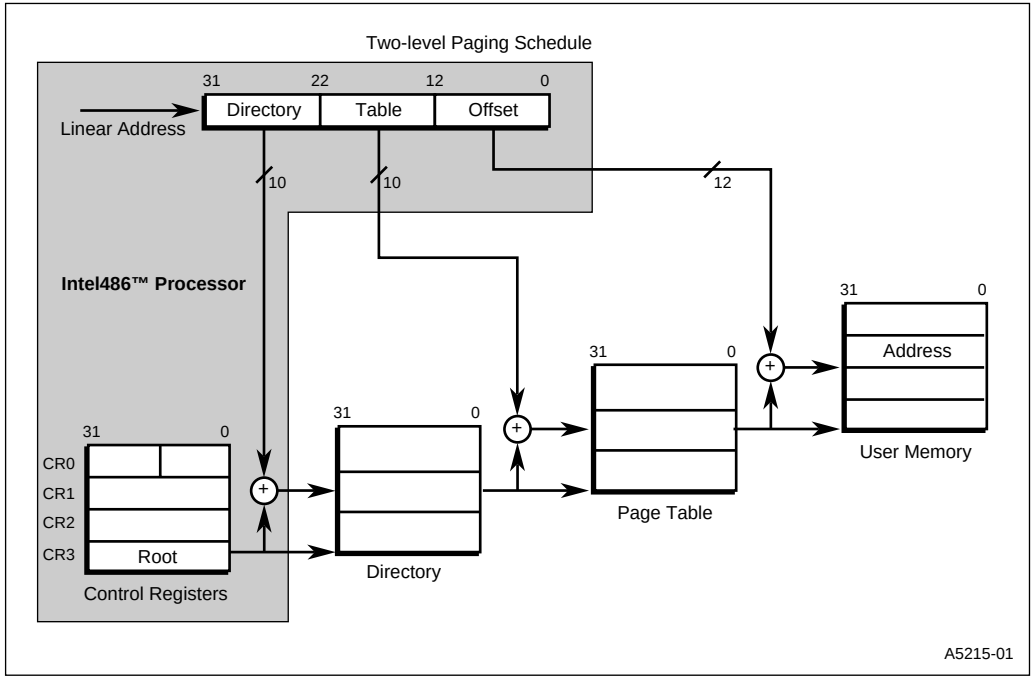


Figure 6-19. Paging Mechanism

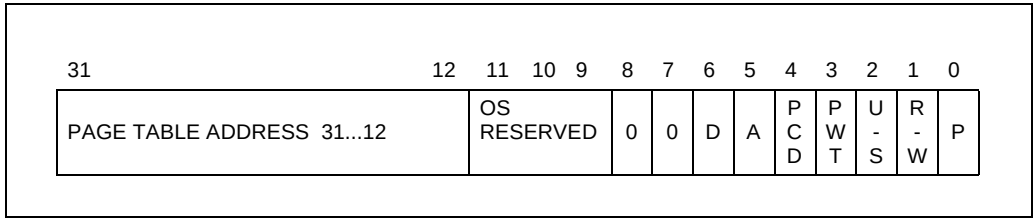


Figure 6-20. Page Directory Entry (Points to Page Table)

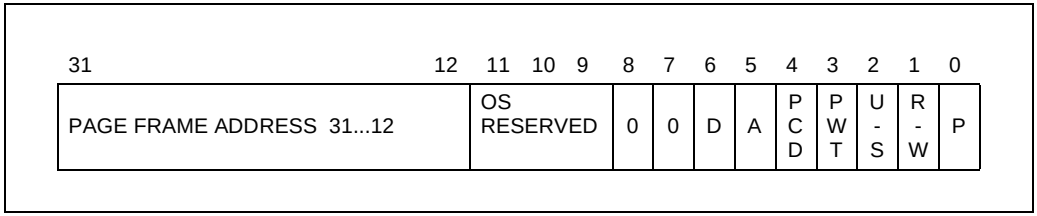


Figure 6-21. Page Table Entry (Points to Page)

6.4.2.5 Page Directory/Table Entries

The lower 12 bits of the page table entries and page directory entries contain statistical information about pages and page tables, respectively. The P (Present) bit 0 indicates whether a page directory or page table entry can be used in address translation. If P = 1 the entry can be used for address translation. If P = 0 the entry cannot be used for translation, and all other bits are available for use by the software. For example the remaining 31 bits could be used to indicate where on the disk the page is stored.

Bit 5, the Accessed (A) bit, is set by the Intel486 processor for both types of entries before a read or write access occurs to an address covered by the entry. Bit 6, the D (Dirty) bit, is set to 1 before a write to an address covered by that page table entry occurs. The D bit is undefined for page directory entries. When the P, A and D bits are updated by the Intel486 processor, a read-modify-write cycle is generated that locks the bus and prevents conflicts with other processors or peripherals. Software that modifies these bits should use the LOCK prefix to ensure the integrity of the page tables in multi-master systems.

The three bits marked OS Reserved in Figures 6-20 and 6-21 (bits 11:9) are software-definable. OSs are free to use these bits for any purpose. An example of the use of the OS Reserved bits is storing information about page aging. By keeping track of how long a page has been in memory since being accessed, an operating system can implement a page replacement algorithm such as least recently used.

Bit 2, the User/Supervisor (U/S) bit, and bit 1, the Read/Write (R/W) bit, are used to provide protection attributes for individual pages.

6.4.3 Page Level Protection (R/W, U/S Bits)

The Intel486 processor provides a set of protection attributes for paging systems. The paging mechanism distinguishes between two levels of protection: user, which corresponds to level 3 of the segmentation based protection; and supervisor, which encompasses all of the other protection levels (0, 1, 2).

The R/W and U/S bits are used in conjunction with the WP bit in the flags register (EFLAGS). The Intel386 processor does not contain the WP bit. The WP bit has been added to the Intel486 processor to protect read-only pages from supervisor write accesses. The Intel386 processor allows a read-only page to be written from protection levels 0, 1, or 2. WP=0 is the Intel386 processor compatible mode. When WP=0, the supervisor can write to a read-only page as defined by the U/S and R/W bits. When WP=1, supervisor access to a read-only page (R/W=0) causes a page fault (exception 14).

Table 6-4 shows the affect of the WP, U/S and R/W bits on accessing memory. When WP=0, the supervisor can write to pages regardless of the state of the R/W bit. When WP=1 and R/W=0, the supervisor cannot write to a read-only page. A user attempt to access a supervisor-only page (U/S=0) or to write to a read-only page causes a page fault (exception 14).

Table 6-4. Page Level Protection Attributes

U/S	R/W	WP	User Access	Supervisor Access
0	0	0	None	Read/Write/Execute
0	1	0	None	Read/Write/Execute
1	0	0	Read/Execute	Read/Write/Execute
1	1	0	Read/Write/Execute	Read/Write/Execute
0	0	1	None	Read/Execute
0	1	1	None	Read/Write/Execute
1	0	1	Read/Execute	Read/Execute
1	1	1	Read/Write/Execute	Read/Write/Execute

The R/W and U/S bits provide protection from user access on a page-by-page basis because the bits are contained in the page table entry and the page directory table. The U/S and R/W bits in the first-level page directory table apply to all entries in the page table pointed to by that directory entry. The U/S and R/W bits in the second-level page table entry apply only to the page described by that entry. The most restrictive U/S and R/W bits from the page directory table and the page table entry are used to address a page.

Example: If the U/S and R/W bits for the page directory entry were 10 (user read/execute) and the U/S and R/W bits for the page table entry were 01 (no user access at all), the access rights for the page would be 01, the numerically smaller of the two.

NOTE

Note that a given segment can be easily made read-only for level 0, 1, or 2 via use of segmented protection mechanisms.

6.4.4 Page Cacheability (PWT and PCD Bits)

See Section 7.6, "Page Cacheability," for a detailed description of page cacheability and the PWT and PCD bits.

6.4.5 Translation Lookaside Buffer

The Intel486 processor paging hardware is designed to support demand paged virtual memory systems. However, performance would degrade substantially if the Intel486 processor were required to access two levels of tables for every memory reference. To solve this problem, the Intel486 processor keeps a cache of the most recently accessed pages. This cache is called the Translation Lookaside Buffer (TLB). The TLB is a four-way set associative 32-entry page table cache. It automatically keeps the most commonly used page table entries in the Intel486 processor. The 32-entry TLB coupled with a 4 Kbyte page size, results in coverage of 128 Kbytes of memory addresses. For many common multi-tasking systems, the TLB has a hit rate of about 98%. This means that the Intel486 processor must access the two-level page structure only on 2% of all memory references. Figure 6-22 illustrates how the TLB complements the Intel486 processor's paging mechanism.

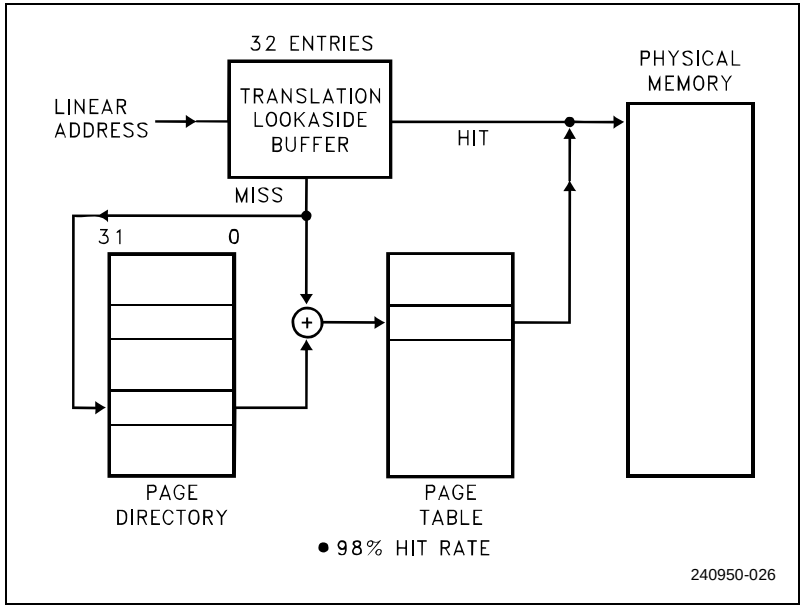


Figure 6-22. Translation Lookaside Buffer

Reading a new entry into the TLB (TLB refresh) is a two step process handled by the Intel486 processor hardware. The sequence of data cycles to perform a TLB refresh is as follows:

1. Read the correct page directory entry, as pointed to by the page base register and the upper 10 bits of the linear address. The page base register is in Control Register 3.

   Optionally, perform a locked read/write to set the accessed bit in the directory entry. The directory entry is read twice if the Intel486 processor needs to set any of the bits in the entry. If the page directory entry changes between the first and second reads, the data returned for the second read is used.

2. Read the correct entry in the Page Table and place the entry in the TLB.

   Optionally, perform a locked read/write to set the accessed and/or dirty bit in the page table entry. Again, note that the page table entry actually is read twice if the Intel486 processor needs to set any of the bits in the entry. Like the directory entry, if the data changes between the first and second read, the data returned for the second read is used.

Note that the directory entry must always be read into the Intel486 processor, because directory entries are never placed in the paging TLB. Page faults can be signaled from either the page directory read or the page table read. Page directory and page table entries can be placed in the Intel486 processor on-chip cache like normal data.

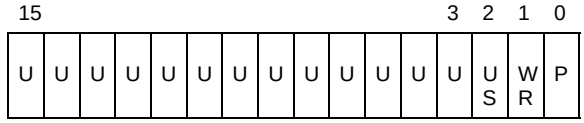
6.4.6 Paging Operation

The paging hardware operates in the following fashion. The paging unit hardware receives a 32-bit linear address from the segmentation unit. The upper 20 linear address bits are compared with all 32 entries in the TLB to determine if there is a match. If there is a match (i.e., a TLB hit), then the 32-bit physical address is calculated and is placed on the address bus.

If the page table entry is not in the TLB, the Intel486 processor reads the appropriate page directory entry. When P = 1 on the page directory entry, indicating that the page table is in memory, then the Intel486 processor reads the appropriate page table entry and sets the Access bit. When P = 1 on the page table entry, indicating that the page is in memory, the Intel486 processor updates the Access and Dirty bits as needed and fetches the operand. The upper 20 bits of the linear address, read from the page table, are stored in the TLB for future accesses. However, if P = 0 for either the page directory entry or the page table entry, the Intel486 processor generates a page fault, exception 14.

The Intel486 processor also generates an exception 14 page fault if the memory reference violated the page protection attributes such as U/S or R/W (for example, when trying to write to a read-only page). CR2 holds the linear address that caused the page fault. If a second page fault occurs while the Intel486 processor is attempting to enter the service routine for the first, the Intel486 processor invokes the page fault handler a second time, rather than the double fault (exception 8) handler. Because exception 14 is classified as a fault, CS: EIP points to the instruction causing the page fault. The 16-bit error code pushed as part of the page fault handler contains status bits that indicate the cause of the page fault.

The 16-bit error code is used by the operating system to determine how to handle the page fault. The upper portion of Figure 6-23 shows the format of the page-fault error code and the interpretation of the bits.



U/S	W/R	Access Type
0	0	Supervisor† Read
0	1	Supervisor Write
1	0	User Read
1	1	User Write

† Descriptor table access faults with U/S = 0, even if the program is executing at level 3.

Key

- U: UNDEFINED
- U/S: The U/S bit indicates whether the access causing the fault occurred when the Intel486 processor was executing in User Mode (U/S = 1) or in Supervisor mode (U/S = 0).
- W/R: The W/R bit indicates whether the access causing the fault was a Read (W/R = 0) or a Write (W/R = 1).
- P: The P bit indicates whether a page fault was caused by a not-present page (P = 0), or by a page level protection violation (P = 1).

Figure 6-23. Page Fault System Information

NOTE

Even though the bits in the error code (U/S, W/R, and P) have similar names as the bits in the Page Directory/Table Entries, the interpretation of the error code bits is different. Figure 6-23 indicates what type of access caused the page fault.

6.4.7 Operating System Responsibilities

The Intel486 processor takes care of the page address translation process, relieving the burden from an operating system in a demand-paged system. The operating system is responsible for setting up the initial page tables, and handling any page faults. The operating system also is required to invalidate (i.e., flush) the TLB when any changes are made to any of the page table entries. The operating system must reload CR3 to cause the TLB to be flushed.

Setting up the tables requires loading CR3 with the address of the page directory, and allocating space for the page directory and the page tables. The primary responsibilities of the operating system are to implement a swapping policy and handle all of the page faults.

The operating system must ensure that the TLB cache matches the information in the paging tables. In particular, when the operating system sets the P bit of page table entry to zero, the TLB must be flushed. Operating systems may want to take advantage of the fact that CR3 is stored as part of a TSS, to give every task or group of tasks its own set of page tables.

6.5 VIRTUAL 8086 ENVIRONMENT

6.5.1 Executing 8086 Programs

The Intel486 processor allows the execution of 8086 application programs in both Real Mode and in the Virtual 8086 Mode (Virtual Mode). Of the two methods, Virtual 8086 Mode offers the system designer the most flexibility. The Virtual 8086 Mode allows the execution of 8086 applications while still allowing the system designer to take full advantage of the Intel486 processor protection mechanism. In particular, the Intel486 processor allows the simultaneous execution of an 8086 operating system (and its applications) and an Intel486 processor operating system running both 80286 and Intel486 processor applications. Thus, on a multi-user Intel486 processor computer, one person could be running an MS-DOS* spreadsheet, another person using MS-DOS, and a third person could be running multiple UNIX utilities and applications. Each person in this scenario would believe that he had sole use of the computer. Figure 6-24 illustrates this concept.

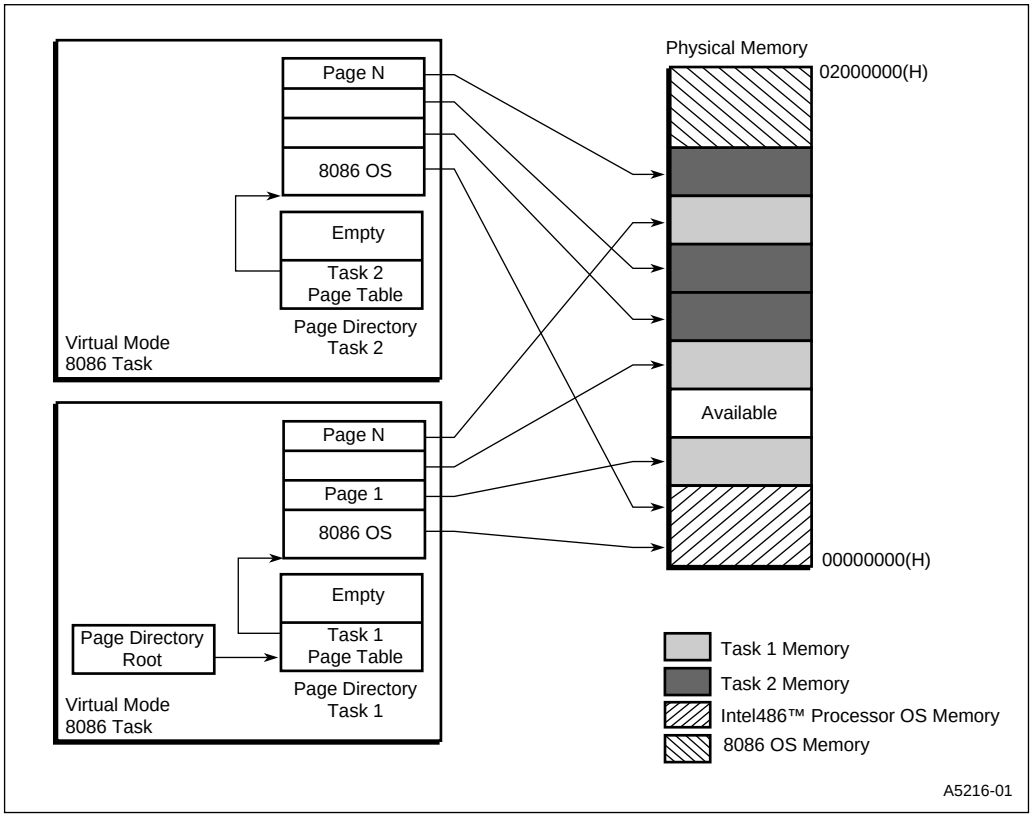


Figure 6-24. Virtual 8086 Environment Memory Management

6.5.2 Virtual 8086 Mode Addressing Mechanism

One of the major differences between Intel486 processor Real and Protected Modes is how the segment selectors are interpreted. When the Intel486 processor is executing in Virtual 8086 Mode, the segment registers are used in an identical fashion to Real Mode. The contents of the segment register are shifted left four bits and added to the offset to form the segment base linear address.

The Intel486 processor allows the operating system to specify which programs use the 8086 style address mechanism, and which programs use Protected Mode addressing. Through the use of paging, the one megabyte address space of the Virtual Mode task can be mapped to anywhere in the 4-Gbyte linear address space of the Intel486 processor. Like Real Mode, Virtual Mode effective addresses (i.e., segment offsets) that exceed 64 Kbyte cause an exception 13. However, these restrictions should not prove to be important, because most tasks running in Virtual 8086 Mode are existing 8086 application programs.

6.5.3 Paging in Virtual Mode

The paging hardware allows the concurrent running of multiple Virtual Mode tasks, and provides protection and operating system isolation. Although it is not strictly necessary to have the paging hardware enabled to run Virtual Mode tasks, it is needed in order to run multiple Virtual Mode tasks or to relocate the address space of a Virtual Mode task to physical address space greater than one Mbyte.

The paging hardware allows the 20-bit linear address produced by a Virtual Mode program to be divided into up to 256 pages. Each one of the pages can be located anywhere within the maximum 4-Gbyte physical address space of the Intel486 processor. In addition, because CR3 (the Page Directory Base Register) is loaded by a task switch, each Virtual Mode task can use a different mapping scheme to map pages to different physical locations. Finally, the paging hardware allows the sharing of the 8086 operating system code between multiple 8086 applications. Figure 6-24 shows how the Intel486 processor paging hardware enables multiple 8086 programs to run under a virtual memory demand paged system.

6.5.4 Protection and I/O Permission Bitmap

All Virtual 8086 Mode programs execute at privilege level 3, the level of least privilege. As such, Virtual 8086 Mode programs are subject to all of the protection checks defined in Protected Mode. (This is different from Real Mode, which implicitly is executing at privilege level 0, the level of greatest privilege.) Thus, an attempt to execute a privileged instruction when in Virtual 8086 Mode causes an exception 13 fault.

The following are privileged instructions that can be executed only at Privilege Level 0. Therefore, attempting to execute these instructions in Virtual 8086 Mode (or anytime CPL > 0) causes an exception 13 fault:

```
LIDT; MOV DRn,reg; MOV reg,DRn;
LGDT; MOV TRn,reg; MOV reg,TRn;
LMSW; MOV CRn,reg; MOV reg,CRn.
CLTS;
HLT;
```

Several instructions, particularly those applying to the multi-tasking model and protection model, are available only in Protected Mode. Therefore, attempting to execute the following instructions in Real Mode or in Virtual 8086 Mode generates an exception 6 fault:

```
LTR;  STR;
LLDT; SLDT;
LAR;  VERR;
LSL;  VERW;
ARPL.
```

The instructions that are IOPL-sensitive in Protected Mode are:

```
IN;    STI;
OUT;   CLI
INS;
OUTS;
REP INS;
REP OUTS;
```

In Virtual 8086 Mode, a slightly different set of instructions are made IOPL-sensitive. The following instructions are IOPL-sensitive in Virtual 8086 Mode:

```
INT n; STI;
PUSHF; CLI;
POPF;  IRET
```

The PUSHF, POPF, and IRET instructions are IOPL-sensitive in Virtual 8086 Mode only. This provision allows the IF flag (interrupt enable flag) to be virtualized to the Virtual 8086 Mode program. The INT n software interrupt instruction is also IOPL-sensitive in Virtual 8086 Mode. Note, however, that the INT 3 (opcode 0CCH), INTO, and BOUND instructions are not IOPL-sensitive in Virtual 8086 Mode (they are not IOPL sensitive in Protected Mode either).

Note that the I/O instructions (IN, OUT, INS, OUTS, REP INS, and REP OUTS) are not IOPL-sensitive in Virtual 8086 Mode. Rather, the I/O instructions become automatically sensitive to the I/O permission bitmap contained in the Intel486 processor Task State Segment. The I/O permission bitmap, automatically used by the Intel486 processor in Virtual 8086 Mode, is illustrated by Figures 6-14 and 6-15.

The I/O Permission Bitmap can be viewed as a 0–64 Kbit string, which begins in memory at offset Bit_Map_Offset in the current TSS. Bit_Map_Offset must be ≤ DFFFH so the entire bit map and the byte FFH that follows the bit map are all at offsets ≤ FFFFH from the TSS base. The 16-bit pointer Bit_Map_Offset (15:0) is found in the word beginning at offset 66H (102 decimal) from the TSS base, as shown in Figure 6-14.

Each bit in the I/O permission bitmap corresponds to a single byte-wide I/O port, as illustrated in Figure 6-14. If a bit is 0, I/O to the corresponding byte-wide port can occur without generating an exception. Otherwise the I/O instruction causes an exception 13 fault. Because every byte-wide I/O port must be protectable, all bits corresponding to a word-wide or dword-wide port must be 0 for the word-wide or dword-wide I/O to be permitted. If all the referenced bits are 0, the I/O is allowed. If any referenced bits are 1, the attempted I/O causes an exception 13 fault.

Due to the use of a pointer to the base of the I/O permission bitmap, the bitmap may be located anywhere within the TSS, or may be ignored completely by pointing the Bit_Map_Offset (15:0) beyond the limit of the TSS segment. In the same manner, by adjusting the TSS limit to truncate the bitmap, only a small portion of the 64 Kbyte I/O space need have an associated map bit. This eliminates the commitment of 8 Kbyte of memory when a complete bitmap is not required.

Example of Bitmap for I/O Ports 0–255: Setting the TSS limit to {bit_Map_Offset + 31 + 1} (see note below) allows a 32-byte bitmap for the I/O ports 0–255, plus a terminator byte of all ones (see note below). This allows the I/O bitmap to control I/O permission to I/O port 0–255, but causes an exception 13 fault on attempted I/O to any I/O port 80256 through 65,565.

NOTE

Beyond the last byte of I/O mapping information in the I/O permission bitmap, there must be a byte containing all ones. The byte of all ones must be within the limit of the Intel486 processor TSS segment (see Figure 6-14).

6.5.5 Interrupt Handling

In order to fully support the emulation of an 8086 machine, interrupts in Virtual 8086 Mode are handled in a unique way. When running in Virtual Mode, all interrupts and exceptions involve a privilege change back to the host Intel486 processor operating system. The Intel486 processor operating system determines if the interrupt comes from a protected mode application or from a Virtual Mode program by examining the VM bit in the EFLAGS image stored on the stack.

When a Virtual Mode program is interrupted and execution passes to the interrupt routine at level 0, the VM bit is cleared. However, the VM bit is still set in the EFLAG image on the stack.

The Intel486 processor operating system in turn handles the exception or interrupt and then returns control to the 8086 program. The Intel486 processor operating system may choose to let the 8086 operating system handle the interrupt or it may emulate the function of the interrupt handler. For example, many 8086 operating system calls are accessed by PUSHing parameters on the stack, and then executing an INT n instruction. If the IOPL is set to 0, then all INT n instructions are intercepted by the Intel486 processor operating system. The Intel486 processor operating system could emulate the 8086 operating system's call. Figure 6-25 shows how the Intel486 processor operating system could intercept an 8086 operating system's call to “Open a File.”

An Intel486 processor operating system can provide a Virtual 8086 environment that is totally transparent to the application software by intercepting and then emulating 8086 operating system's calls, and intercepting IN and OUT instructions.

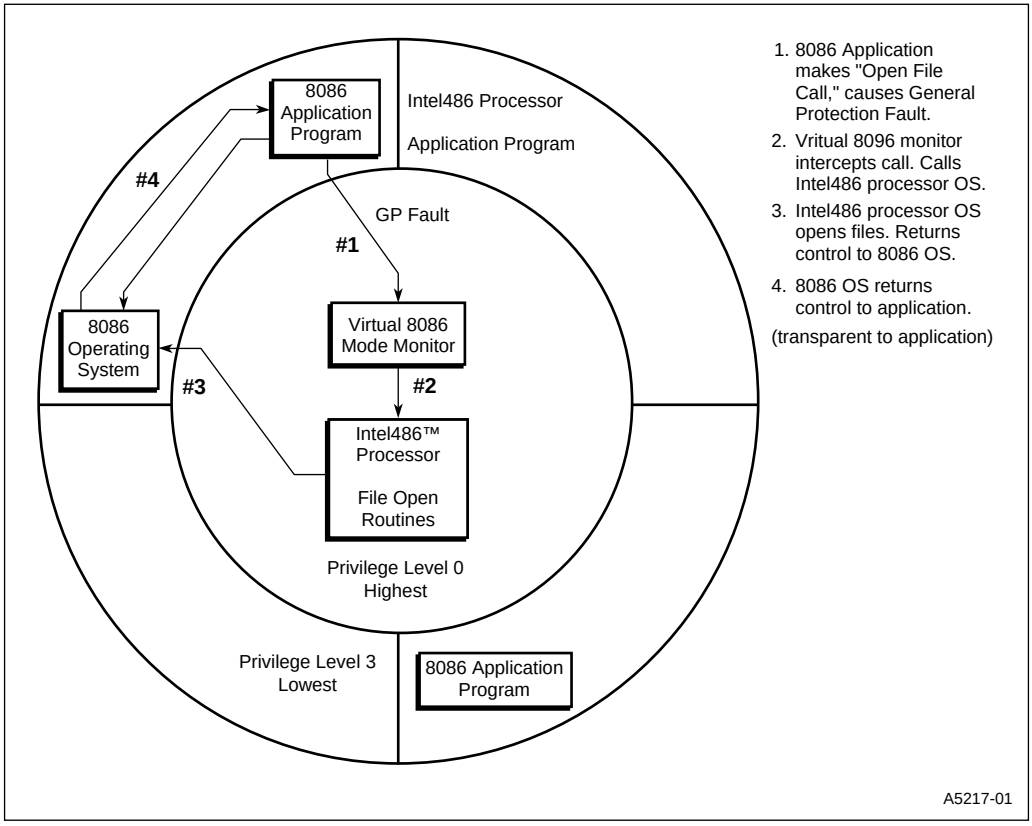


Figure 6-25. Virtual 8086 Environment Interrupt and Call Handling

6.5.6 Entering and Leaving Virtual 8086 Mode

An Intel486 processor is executing in Protected Mode can be switched to Virtual 8086 Mode by executing an IRET instruction (at CPL=0), or task switch (at any CPL) to an Intel486 processor task whose TSS has a FLAGS image containing a 1 in the VM bit position. That is, one way to enter Virtual 8086 Mode is to switch to a task with an Intel486 processor TSS that has a 1 in the VM bit in the EFLAGS image. The other way is to execute a 32-bit IRET instruction at privilege level 0, where the stack has a 1 in the VM bit in the EFLAGS image. POPF does not affect the VM bit, even if the Intel486 processor is in Protected Mode or level 0, and so cannot be used to enter Virtual 8086 Mode. PUSHF always pushes a 0 in the VM bit, even if the Intel486 processor is in Virtual 8086 Mode, so that a program cannot tell whether it is executing in Real Mode or in Virtual 8086 Mode.

The VM bit can be set by executing an IRET instruction only at privilege level 0, or by any instruction or interrupt that causes a task switch in Protected Mode (with VM=1 in the new FLAGS image). The UM bit can be cleared only by an interrupt or exception in Virtual 8086 Mode. IRET and POPF instructions executed in Real Mode or Virtual 8086 Mode do not change the value in the VM bit.

The transition out of Virtual 8086 Mode to Protected Mode occurs only on receipt of an interrupt or exception (such as due to a sensitive instruction). In Virtual 8086 Mode, all interrupts and exceptions vector through the Protected Mode IDT, and enter an interrupt handler in protected Intel486 processor mode. That is, as part of interrupt processing, the VM bit is cleared.

Because the matching IRET must occur from level 0, if an interrupt or trap gate is used to field an interrupt or exception out of Virtual 8086 Mode, the Gate must perform an inter-level interrupt only to level 0. Interrupt or trap gates through conforming segments, or through segments with DPL>0, raise a GP fault with the CS selector as the error code.

6.5.6.1 Task Switches to and from Virtual 8086 Mode

Tasks that can execute in Virtual 8086 Mode must be described by a TSS with the new Intel486 processor format (TYPE 9 or 11 descriptor).

A task switch out of Virtual 8086 Mode operates exactly the same as any other task switch out of a task with an Intel486 processor TSS. The programmer visible state, including the FLAGS register with the VM bit set to 1, is stored in the TSS.

The segment registers in the TSS contain 8086 segment base values rather than selectors.

A task switch into a task described by an Intel486 processor TSS has an additional check to determine if the incoming task should be resumed in Virtual 8086 Mode. Tasks described by 80286 format TSSs cannot be resumed in Virtual 8086 Mode, so no check is required (the FLAGS image in 80286 format TSS has only the low order 16 FLAGS bits). Before loading the segment register images from an Intel486 processor TSS, the FLAGS image is loaded, so that the segment registers are loaded from the TSS image as 8086 segment base values. The task is now ready to resume in Virtual 8086 Mode.

6.5.6.2 Transitions Through Trap and Interrupt Gates, and IRET

A task switch is one way to enter or exit Virtual 8086 Mode. The other method is to exit through a trap or interrupt gate as part of handling an interrupt, and to enter as part of executing an IRET instruction. The transition out must use an Intel486 processor trap gate (Type 14) or Intel486 processor interrupt gate (Type 15), which must point to a non-conforming level 0 segment (DPL=0) in order to permit the trap handler to IRET back to the Virtual 8086 program. The gate must point to a non-conforming level 0 segment to perform a level switch to level 0 so the matching IRET can change the VM bit. Intel486 processor gates must be used, because 80286 gates save only the low 16 bits of the FLAGS register, so that the VM bit is not saved on transitions through the 80286 gates. Also, the 16-bit IRET (presumably) used to terminate the 80286 interrupt handler pops only the lower 16 bits from FLAGS, and does not affect the VM bit. The action taken for an Intel486 processor trap or interrupt gate if an interrupt occurs while the task is executing in Virtual 8086 Mode is given by the following sequence:

1. Save the FLAGS register in a temp to push later. Turn off the VM and TF bits and, if the interrupt is serviced by an Interrupt Gate, turn off the IF bit also.
2. Interrupt and trap gates must perform a level switch from level 3 (where the VM86 program executes) to level 0 (so IRET can return). This process involves a stack switch to the stack given in the TSS for privilege level 0. Save the Virtual 8086 Mode SS and ESP registers to push in a later step. The segment register load of SS is done as a Protected Mode segment load, because the VM bit was turned off in step 1.
3. Push the 8086 segment register values onto the new stack, in the order: GS, FS, DS, ES. These are pushed as 32-bit quantities, with undefined values in the upper 16 bits. Then, load these four registers with null selectors (0).
4. Push the old 8086 stack pointer onto the new stack by pushing the SS register (as 32-bits, high bits undefined), then pushing the 32-bit ESP register saved above.
5. Push the 32-bit FLAGS register saved in step 1.
6. Push the old 8086 instruction pointer onto the new stack by pushing the CS register (as 32-bits, high bits undefined), then pushing the 32-bit EIP register.
7. Load the new CS:EIP value from the interrupt gate, and begin execution of the interrupt routine in Protected Mode.

The transition out of Virtual 8086 Mode performs a level change and stack switch, in addition to changing back to Protected Mode. In addition, all of the 8086 segment register images are stored on the stack (behind the SS:ESP image), and then loaded with null (0) selectors before entering the interrupt handler. This permits the handler to safely save and restore the DS, ES, FS, and GS registers as 80286 selectors. This is needed so that interrupt handlers that do not care about the mode of the interrupted program can use the same prolog and epilog code for state saving (i.e., push all registers in prolog, pop all in epilog), regardless of whether or not a "native" mode or Virtual 8086 Mode program was interrupted. Restoring null selectors to these registers before executing the IRET instruction does not cause a trap in the interrupt handler. Interrupt routines that obtain values from the segment registers or return values to segment registers have to obtain/return them from the 8086 register images pushed onto the new stack. They need to know the mode of the interrupted program in order to know where to find/return segment registers, and also to know how to interpret segment register values.

The IRET instruction performs the inverse of the above sequence. Only the extended Intel486 processor IRET instruction (operand size=32) can be used, and must be executed at level 0 to change the VM bit to 1.

1. If the NT bit in the FLAGs register is on, an inter-task return is performed. The current state is stored in the current TSS, and the link field in the current TSS is used to locate the TSS for the interrupted task that is to be resumed. Otherwise, continue with the following sequence.
2. Read the FLAGS image from SS:8[ESP] into the FLAGS register. This sets VM to the value active in the interrupted routine.
3. Pop off the instruction pointer CS:EIP. EIP is popped first, then a 32-bit word is popped that contains the CS value in the lower 16 bits. If VM=0, this CS load is done as a Protected Mode segment load; if VM=1, this is done as an 8086 segment load.
4. Increment the ESP register by four to bypass the FLAGS image that was “popped” in step 1.
5. If VM=1, load segment registers ES, DS, FS, and GS from memory locations SS:[ESP+8], SS:[ESP+12], SS:[ESP+16], and SS:[ESP+20], respectively, where the new value of ESP stored in step 4 is used. When VM=1, these are done as 8086 segment register loads; when VM=0, check that the selectors in ES, DS, FS, and GS are valid in the interrupted routine. Null out invalid selectors to trap if an attempt is made to access through them.
6. If RPL(CS) > CPL, pop the stack pointer SS:ESP from the stack. The ESP register is popped first, followed by 32-bits containing SS in the lower 16 bits. If VM=0, SS is loaded as a Protected Mode segment register load. If VM=1, an 8086 segment register load is used.
7. Resume execution of the interrupted routine. The VM bit in the FLAGS register (restored from the interrupt routine's stack image in step 1) determines whether the Intel486 processor resumes the interrupted routine in Protected Mode or Virtual 8086 Mode.

7

On-Chip Cache

Chapter Contents

CHAPTER 7
ON-CHIP CACHE

All members of the Intel486™ processor family, except the IntelDX4™ processor, contain an on-chip 8-Kbyte cache. The IntelDX4 processor has a 16-Kbyte cache, as discussed in Section 7.1.1. The cache is software-transparent to maintain binary compatibility with previous generations of the Intel Architecture.

The on-chip cache is designed for maximum flexibility and performance. The cache has several operating modes, offering flexibility during program execution and debugging. Memory areas can be defined as non-cacheable by software and external hardware. Protocols for cache line invalidations and cache replacement are implemented in hardware, easing system design.

7.1 CACHE ORGANIZATION

The on-chip cache is a unified code and data cache; that is, the cache is used for both instruction and data accesses and acts on physical addresses.

The cache organization is 4-way set associative and each line is 16 bytes wide. The 8 Kbytes of cache memory are logically organized as 128 sets, each containing four lines.

The cache memory is physically split into four 2-Kbyte blocks, each containing 128 lines (see Figure 7-1). There are 128 21-bit tags associated with each 2-Kbyte block. There is a valid bit for each line in the cache. Each line in the cache is either valid or not valid; there are no provisions for partially valid lines.

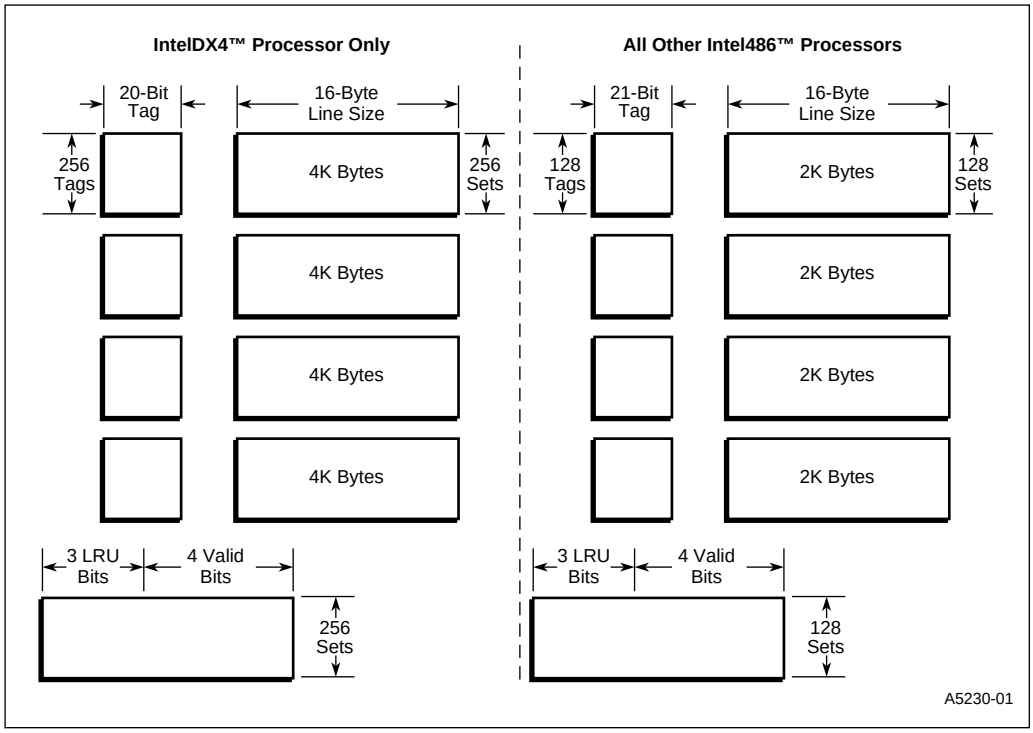


Figure 7-1. On-Chip Cache Physical Organization

For all Intel486 processors except the Write-Back Enhanced IntelDX4 processor, the on-chip cache is write-through only. All writes drive an external write bus cycle in addition to writing the information to the internal cache when the write is a cache hit. A write to an address not contained in the internal cache is written to external memory only. Cache allocations are not made on write misses.

The Write-Back Enhanced IntelDX4 processor supports two modes of operation with respect to internal cache configurations: Standard Bus Mode (write-through cache) and Enhanced Bus Mode (write-back cache). Standard Bus Mode operation for the Write-Back Enhanced IntelDX4 processor is the same as the write-through cache for other Intel486 processors (see Section 7.1.2, "Write-Back Enhanced IntelDX4™ Processor Cache" and other write-back enhanced sections below for write-back cache information).

7.1.1 IntelDX4™ Processor On-Chip Cache

The IntelDX4 processor contains a 16-Kbyte write-through cache. The 16 Kbytes of cache memory are logically organized as 256 sets, each containing four lines.

The cache memory is physically split into four 4-Kbyte blocks, each containing 256 lines (see Figure 7-1). There are 256 20-bit tags associated with each 2-Kbyte block.

All other details listed in Section 7.1 for the 8-Kbyte on-chip cache also apply to the IntelDX4 on-chip cache.

7.1.2 Write-Back Enhanced IntelDX4™ Processor Cache

The Write-Back Enhanced IntelDX4 processor implements a unified cache, with a total cache size of 16 Kbytes. The processor's on-chip cache supports a modified MESI (modified / exclusive / shared / invalid) write-back cache consistency protocol.

The Write-Back Enhanced IntelDX4 processor's internal cache is configurable as write-back or write-through on a line-by-line basis, provided the cache is enabled for write-back operation. The cache is enabled for write-back operation by driving the WB/WT# pin to a high state for at least two clocks before and two clocks after the falling edge of RESET. Cache write-back and invalidations can be initiated by hardware or software. Protocols for cache consistency and line replacement are implemented in hardware to ease system design.

Once the cache configuration is selected, the Write-Back Enhanced IntelDX4 processor continues to operate in the selected configuration and can be changed to a different configuration only by starting the RESET process again. Asserting SRESET does not change the operating mode of the processor. WB/WT# has an internal pull down; when WB/WT# is unconnected, the processor is in Standard Bus Mode, i.e., the on-chip cache is write-through. Table 7-1 lists the two modes of operation and the differences between the two modes.

Unless specifically noted, the following sections apply to the Write-Back Enhanced IntelDX4 processor in Standard Bus Mode (write-through cache) and all other Intel486 processors.

Table 7-1. Write-Back Enhanced IntelDX4™ Processor WB/WT# Initialization

State of WB/WT# at Falling Edge of RESET	Effect on Write-Back Enhanced IntelDX4 Processor Operation
WB/WT# = LOW	Processor is in Standard Bus Mode (write-through cache) 1. When **FLUSH#** is asserted, the internal cache is invalidated in one system **CLK**. 2. No Special **FLUSH#** acknowledge cycles appear on the bus after the assertion of **FLUSH#**. 3. All write-back specific inputs are ignored (**INV, WB/WT#**). 4. SRESET does not clear the SMBASE register. It behaves much like a RESET (invalidating the on-chip cache and resetting the CR0 register, for example). SRESET is not an interrupt.
WB/WT# = HIGH	Processor is in Enhanced Bus Mode (Write-Back Cache) 1. Write backs are performed when a cache flush is requested (via the **FLUSH#** pin or the WBINVD instruction). The system must watch for the **FLUSH#** special cycles to determine the end of the flush. 2. The special **FLUSH#** acknowledge cycles appear on the bus after the assertion of the **FLUSH#** and after all the cache write backs (if any) are completed on the bus. 3. **WB/WT#** is sampled on a line-by-line basis to determine the state of a line to be allocated in the cache (as a write through (S state) or as write back (E state)). 4. The **WB/WT#** and **INV** inputs are no longer ignored. **HITM#** and **CACHE#** are driven during appropriate bus cycles. 5. **PLOCK#** is always driven inactive. 6. **SRESET** is an interrupt. SRESET does not reset the SMBASE register or flush the on-chip cache. The CR0 register gets the same values as after RESET, with the exception of the **CD and NW bits**. These two bits retain their previous status. See Section 9.2.18.4, "Soft Reset (SRESET)" and Table 7-7 for details on SRESET for enhanced bus (write-back) mode.

Table 7-2. Cache Operating Modes

CD	NW	Operating Mode
1	1	Cache fills disabled, write-through and invalidates disabled.
1	0	Cache fills disabled, write-through and invalidates enabled.
0	1	INVALID. When CR0 is loaded with this configuration of bits, a GP fault with error code of 0 is raised.
0	0	Cache fills enabled, write-through and invalidates enabled.

7.2 CACHE CONTROL

Control of the cache is provided by the CD and NW bits in CR0. CD enables and disables the cache. NW controls memory write-throughs and invalidates.

The CD and NW bits define four operating modes of the on-chip cache, as given in Table 7-2. These modes provide flexibility in how the on-chip cache is used.

CD=1, NW=1

The cache is completely disabled by setting CD=1 and NW=1 and then flushing the cache. This mode may be useful for debugging programs in which it is important to see all memory cycles at the pins. Writes that hit in the cache do not appear on the external bus.

It is possible to use the on-chip cache as fast static RAM by "pre-loading" certain memory areas into the cache and then setting CD=1 and NW=1. Pre-loading can be done by careful choice of memory references with the cache turned on or by using of the testability functions (see Section B.2, "On-Chip Cache Testing"). When the cache is turned off, the memory mapped by the cache is "frozen" into the cache because fills and invalidates are disabled.

CD=1, NW=0

Cache fills are disabled but write-throughs and invalidates are enabled. This mode is the same as if the KEN# pin was strapped high, disabling cache fills. Write-throughs and invalidates still may occur to keep the cache valid. This mode is useful when the software must disable the cache for a short period of time, and then re-enable it without flushing the original contents.

CD=0, NW=1

Invalid. When CR0 is loaded with this bit configuration, a General Protection fault with an error code of 0 occurs.

CD=0, NW=0

This is the normal operating mode.

Completely disabling the cache is a two-step process. First, CD and NW must be set to 1, and then the cache must be flushed. When the cache is not flushed, cache hits on reads still occur and data is read from the cache.

7.2.1 Write-Back Enhanced IntelDX4™ Processor Cache Control and Operating Modes

The Write-Back Enhanced IntelDX4 processor retains the use of CR0.CD and CR0.NW when the 1,1 state forces a cache-off condition after RESET and the 0,0 state is the normal run state. Table 7-3 defines these control bits when the cache is enabled for write-back operation. The values in Table 7-3 are also valid when the cache is in write-back mode and some lines are in a write-through state.

CD=1, NW=1

The 1,1 state is best used when no lines are allocated, which occurs naturally after RESET (but not SRESET), but must be forced (e.g., by the WBINVD instruction) when entered during normal operation. In these cases, the Write-Back Enhanced IntelDX4 processor operates as if it had no cache at all.

When the 1,1 state is exited, lines that are allocated as write-back are written back upon a snoop hit or replacement cycle. Lines that were allocated as write-through (and later modified while in the 1,1 state) never appear on the bus.

CD=1, NW=0

The only difference between this state and the normal 0,0 "run" state is that new line fills (and the line replacements that result from capacity limitations) do not occur. This causes the contents of the cache to be locked in, unless lines are invalidated using snoops.

7.3 CACHE LINE FILLS

Any area of memory can be cached in the Intel486 processor. Non-cacheable portions of memory can be defined by the external system or by software. The external system can inform the Intel486 processor that a memory address is non-cacheable by returning the KEN# pin inactive during a memory access. (Refer to Section 10.3.3, "Cacheable Cycles.") Software can prevent certain pages from being cached by setting the PCD bit in the page table entry.

A read request can be generated from program operation or by an instruction pre-fetch. The data is supplied from the on-chip cache when a cache hit occurs on the read address. When the address is not in the cache, a read request for the data is generated on the external bus.

When the read request is to a cacheable portion of memory, the Intel486 processor initiates a cache line fill. During a line fill a 16-byte line is read into the Intel486 processor. Cache line fills are generated only for read misses. Write misses never cause a line in the internal cache to be allocated. When a cache hit occurs on a write, the line is updated. Cache line fills can be performed over 8- and 16-bit buses using the dynamic bus sizing feature. Refer to Section 10.1.2, "Dynamic Data Bus Sizing," for a description of dynamic bus sizing and Section 10.3.3, "Cacheable Cycles," for further information on cacheable cycles.

Table 7-3. Write-Back Enhanced IntelDX4™ Processor Write-Back Cache Operating Modes

CR0, CD, NW	Read Hit	Read Miss	WRITE HIT(1)	Write Mess	Snoops
1,1 (state after reset)	read cache	read bus (no fill)	write cache (no write-through)	write bus	not accepted
1,0	read cache	read bus (no fill)	write cache, write bus if S	write bus	normal operation
0,1	This is a fault-protected disallowed state. A GP(0) occurs when an attempt is made to load CR0 with this state.				
0,0 (state **DURING** normal operation)	read cache	read bus, line fill	write cache, write bus if S	write bus	normal operation

NOTE: Normal MESI state transitions occur on write hits in all legal states.

7.4 CACHE LINE INVALIDATIONS

The Intel486 processors contain both a hardware and software mechanism for invalidating internal cache lines. Cache line invalidations are needed to keep the cache contents consistent with external memory.

Refer to Section 10.3.8, “Invalidate Cycles,” for further information on cache line invalidations.

7.4.1 Write-Back Enhanced IntelDX4™ Processor Snoop Cycles and Write-Back Mode Invalidation

In Enhanced Bus Mode, the Write-Back Enhanced IntelDX4 processor performs invalidations differently than other Intel486 processors. Snoop cycles are initiated by the system to determine whether a line is present in the cache, and what the state is. Snoop cycles may be classified further as Inquire cycles or Invalidate cycles. When another bus master initiates a memory read cycle inquire cycles are driven to the Write-Back Enhanced IntelDX4 processor to determine whether the processor cache contains the latest data. When the snooped line is in the Write-Back Enhanced IntelDX4 processor’s cache and the line contains the most recent information, the processor must schedule a write back of the data. Inquire cycles are driven with INV = ‘0’. Invalidate cycles are driven to the Write-Back Enhanced IntelDX4 processor when the other bus master initiates a memory write cycle to determine whether the Write-Back Enhanced IntelDX4 processor cache contains the snooped line. The invalidate cycles are driven with INV = ‘1’, so that when the snooped line is in the on-chip cache, the line is invalidated. Snoop cycles are described in detail in Section 10.3, “Bus Functional Description.”

The Write-Back Enhanced IntelDX4 processor has control mechanisms (including snooping) for writing back the modified lines and invalidating the cache. There are special bus cycles associated with write-backs and with invalidation. All of the Write-Back Enhanced IntelDX4 processor’s special cycles require acknowledgment by RDY# or BRDY#. During the special cycles, the addresses shown in the Table 7-4 are driven onto the address bus and the data bus is left undefined.

7.5 CACHE REPLACEMENT

Before a line is placed in its internal cache, the Intel486 processor checks whether there is a non-valid line in the set; that line is replaced first. When all four lines in the set are valid, a pseudo least-recently-used mechanism is used to determine which line should be replaced.

A valid bit is associated with each line in the cache. Before a line is placed in a set, the four valid bits are checked to see whether there is a non-valid line that can be replaced. When a non-valid line is found, that line is marked for replacement.

The four lines in the set are labeled l0, l1, l2, and l3. The order in which the valid bits are checked during an invalidation is l0, l1, l2 and l3. All valid bits are cleared when the processor is reset or when the cache is flushed.

Table 7-4. Encoding of the Special Cycles for Write-Back Cache

Cycle Name	M/IO#	D/C#	W/R#	BE[3:0]#	A[4:2]
Write-Back†	0	0	1	0111	000
First Flush Ack Cycle†	0	0	1	0111	001
Flush†	0	0	1	1101	000
Second Flush Ack Cycle†	0	0	1	1101	001
Shutdown	0	0	1	1110	000
HALT	0	0	1	1011	000
Stop Grant Ack Cycle	0	0	1	1011	100

†Write-Back Enhanced IntelDX4™ processor only. FLUSH is present on all Intel486™ processor, but differs for Standard Mode.

Replacement in the cache is handled by a pseudo least recently used (LRU) mechanism when all four lines in a set are valid. Three bits, B0, B1 and B2, are defined for each of the 128 sets in the cache. These bits are called the LRU bits. The LRU bits are updated for every hit or replacement in the cache.

If the most recent access to the set was to l0 or l1, B0 is set to 1. If the most recent access was to l2 or l3, B0 is set to 0. If the most recent access to 11:10 was to l0, B1 is set to 1; otherwise, B1 is set to 0. If the most recent access to 13:12 was to l2, B2 is set to 1; otherwise, B2 is set to 0.

The pseudo LRU mechanism works in the following manner: When a line must be replaced, the cache first selects which of lines 11:10 and 13:12 was least recently used. Then the cache determines which of the two lines was least recently used and mark it for replacement. This decision tree is shown in Figure 7-2.

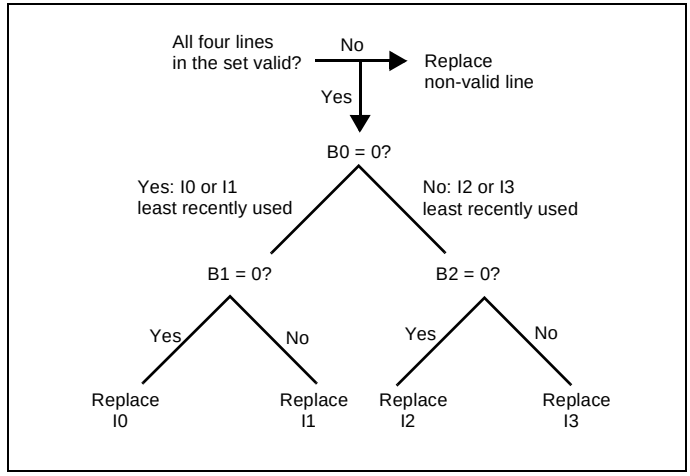


Figure 7-2. On-Chip Cache Replacement Strategy

7.6 PAGE CACHEABILITY

Two bits for cache control, PWT and PCD, are defined in the page table and page directory entries. The states of these bits are driven out on the PWT and PCD pins during memory access cycles.

The PWT bit controls the write policy for second-level caches used with the Intel486 processor. Setting PWT=1 defines a write-through policy for the current page while PWT=0 defines the possibility of write-back. The state of PWT is ignored internally by the Intel486 processor for on-chip cache in write through mode.

The PCD bit controls cacheability on a page-by-page basis. The PCD bit is internally AND'ed with the KEN# signal to control cacheability on a cycle-by-cycle basis (see Figure 7-3). PCD=0 enables caching while PCD=1 forbids it. Note that cache fills are enabled when PCD=0 AND KEN#=0. This logical AND is implemented physically with a NOR gate.

The state of the PCD bit in the page table entry is driven on the PCD pin when a page in external memory is accessed. The state of the PCD pin informs the external system of the cacheability of the requested information. The external system then returns KEN#, telling the Intel486 processor whether the area is cacheable. The Intel486 processor initiates a cache line fill when PCD and KEN# indicate that the requested information is cacheable.

The PCD bit is OR'ed with the CD (cache disable) bit in control register 0 to determine the state of the PCD pin. When CD=1, the Intel486 processor forces the PCD pin HIGH. When CD=0, the PCD pin is driven with the value for the page table entry/directory (see Figure 7-3).

The PWT and PCD bits for a bus cycle are obtained from CR3, the page directory or page table entry. These bits are assumed to be zero during Real Mode, whenever paging is disabled, or for cycles that bypass paging (I/O references, interrupt acknowledge cycles, and HALT cycles).

When paging is enabled, the bits from the page table entry are cached in the TLB, and are driven when the page mapped by the TLB entry is referenced. For normal memory cycles, PWT and PCD are taken from the page table entry. During TLB refresh cycles in which the page table and directory entries are read, the PWT and PCD bits must be obtained elsewhere. During page table updates the bits are obtained from the page directory. When the page directory is updated, these bits are obtained from CR3. PCD and PWT bits are initialized to zero at reset, but can be modified by level 0 software.

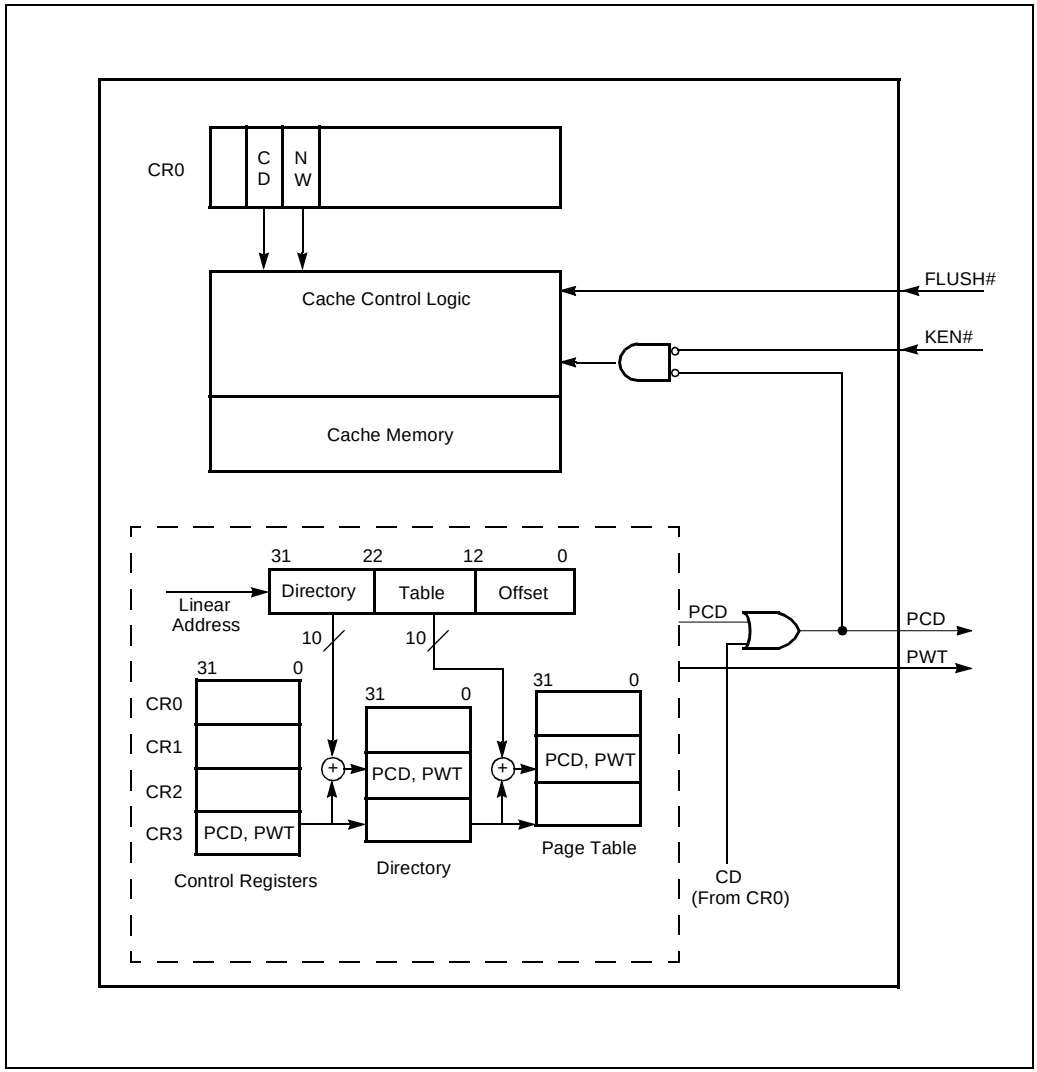


Figure 7-3. Page Cacheability

7.6.1 Write-Back Enhanced IntelDX4™ Processor and Processor Page Cacheability

In Write-Back Enhanced IntelDX4 processor-based systems, both the processor and the system hardware must determine the cacheability and the configuration (write-back or write-through) on a line-by-line basis. The system hardware's cacheability is determined by KEN# and the configuration by WB/WT#. The processor's indication of cacheability is determined by PCD and the configuration by PWT. The PWT bit controls the write policy for the second-level caches used with the Write-Back Enhanced IntelDX4 processor. Setting PWT to 1 defines a write-through policy for the current page, while clearing PWT to 0 defines a write-back policy for the current page.

7.7 CACHE FLUSHING

The on-chip cache can be flushed by external hardware or by software instructions. Flushing the cache clears all valid bits for all lines in the cache. The cache is flushed when external hardware asserts the FLUSH# pin.

The FLUSH# pin must to be asserted for one clock when driven synchronously or for two clocks when driven asynchronously. FLUSH# is asynchronous, but setup and hold times must be met for recognition in a particular cycle. FLUSH# should be deasserted before the cache flush is complete. Failure to deassert the pin causes execution to stop as the processor repeatedly flushes the cache. When external hardware activates FLUSH# in response to an I/O write, FLUSH# must be asserted for at least two clocks prior to ready being returned for the I/O write. This ensures that the flush completes before the processor begins execution of the instruction following the OUT instruction.

The instructions INVD and WBINVD cause the on-chip cache to be flushed. External caches connected to the Intel486 processor are signaled to flush their contents when these instructions are executed.

WBINVD also cause an external write-back cache to write back dirty lines before flushing its contents. The external cache is signaled using the bus cycle definition pins and the byte enables. Refer to Section 9.2.6, "Bus Cycle Definition," for the bus cycle definition pins and Section 10.3.11, "Special Bus Cycles," for special bus cycles. Refer to the *Intel486™ Processor Programmers Reference Manual* for detailed instruction definitions.

The results of the INVD and WBINVD instructions are identical for the operation of the non-write-back enhanced IntelDX4 processor on-chip cache because the cache is write-through.

7.7.1 Write-Back Enhanced IntelDX4™ Processor Cache Flushing

The on-chip cache can be flushed by external hardware or by software instructions.

Flushing the cache through hardware is accomplished by asserting the FLUSH# pin. This causes the cache to write back all modified lines in the cache and mark the state bits invalid. The first flush acknowledge cycle is driven by the Write-Back Enhanced IntelDX4 processor, followed by the second flush acknowledge cycle after all write-backs and invalidations are complete. The two special cycles are issued even when there are no dirty lines to write back.

The INVD and WBINVD instructions cause the on-chip cache to be invalidated. WBINVD causes the modified lines in the internal cache to be written back, and all lines to be marked invalid. After execution of the WBINVD instruction, the write-back and flush special cycles are driven to indicate to external cache that it should write back and invalidate its contents. These two special cycles are issued even when there are no dirty lines to be written back. INVD causes all lines in the cache to be invalidated, so modified lines in the cache are not written back. The Flush special cycle is driven after the INVD instruction is executed to indicate to any external cache that it should invalidate its contents. Care should be taken when using the INVD instruction to avoid creating cache consistency problems.

NOTE

It is recommended to use the WBINVD instruction instead of the INVD instruction when the on-chip cache is configured in write-back mode.

The assertion of RESET invalidates the entire cache without writing back the modified lines. No special cycles are issued after the invalidation is complete.

Snoop cycles with invalidation (INV=1) cause the Write-Back Enhanced IntelDX4 processor to invalidate an individual cache line. When the snooped line is a modified line, then the processor schedules a write-back cycle. Inquire cycles with no-invalidation cause the Write-Back Enhanced IntelDX4 processor only to write-back the line, when the inquired line is in M-state, and not invalidate the line.

SRESET, STPCLK#, INTR, NMI and SMI# are recognized and latched, but not serviced during the full-cache, modified-line write-backs, caused either by the WBINVD instruction or by FLUSH#. However, BOFF#, AHOLD and HOLD are recognized during the full-cache, modified-line write-backs.

7.8 WRITE-BACK ENHANCED IntelDX4™ PROCESSOR WRITE-BACK CACHE ARCHITECTURE

This section describes additional features pertaining to the write-back mode of the Write-Back Enhanced IntelDX4 processor.

7.8.1 Write-Back Cache Coherency Protocol

The Write-Back Enhanced IntelDX4 processor cache protocol supports a cache line in one of the following four states:

- The line is valid and defined as write-back during allocation (E-state)
- The line is valid and defined as write-through during allocation (S-state)
- The line has been modified (M-state)
- The line it is invalid (I-state)

These four states are the M (Modified line), E (write-back line), S (write-through line) and I (Invalid line) states, and the protocol is referred to as the “Modified MESI protocol.” A definition of the states is given below:

M - Modified: An M-state line is modified (different from main memory) and can be accessed (read/written to) without sending a cycle out on the bus.

E - Exclusive: An E-state line is a ‘write-back’ line, but the line is not modified (i.e., it is consistent with main memory). An E-state line can be accessed (read/written to) without generating a bus cycle and a write to an E-state line causes the line to become modified.

S - Shared: An S-state line is a ‘write-through’ line, and is consistent with main memory. A read hit to an S-state line does not generate bus activity, but a write hit to an S-state line generates a write-through cycle on the bus. A write to an S-state line updates the cache and the main memory.

I - Invalid: This state indicates that the line is not in the cache. A read to this line is a miss and may cause the Write-Back Enhanced IntelDX4 processor to execute a line fill (i.e., fetch the whole line into the cache from main memory). A write to an invalid line causes the Write-Back Enhanced IntelDX4 processor to execute a write-through cycle on the bus.

Every line in the Write-Back Enhanced IntelDX4 processor cache is assigned a state that depends on both Write-Back Enhanced IntelDX4 processor-generated activities and activities generated by the system hardware. As the Write-Back Enhanced IntelDX4 processor is targeted for uniprocessor systems, a subset of MESI protocol, namely MEI, is used to maintain cache coherency.

With the modified MESI protocol it is assumed that in a uniprocessor system, lines are defined as write-back or write-through at allocation time. This property associated with a line is never altered. The lines allocated as write-through go to S-state and remain in S-state. A cache line that is allocated as write-back never enters the S-state. The WB/WT# pin is sampled during line allocation and is used strictly to characterize a line as write-back or write-through.

State Transition Tables

State transitions are caused by processor-generated transactions (memory reads/writes) and by a set of external input signals and internally-generated variables. The Write-Back Enhanced IntelDX4 processor also drives certain pins as a consequence of the cache consistency protocol.

Read Cycles

Table 7-5 shows the state transitions for lines in the cache during unlocked read cycles.

Write Cycles

The state transitions of cache lines during Write-Back Enhanced IntelDX4 processor-generated write cycles are described in Table 7-6.

Table 7-5. Cache State Transitions for Write-Back Enhanced IntelDX4™ Processor-Initiated Unlocked Read Cycles

Present State	Pin Activity	Next State	Description
M	n/a	M	Read hit; data is provided to processor core by cache. No bus cycle is generated.
E	n/a	E	Read hit; data is provided to processor core by cache. No bus cycle is generated.
S	n/a	S	Read hit; Data is provided to the processor by the cache. No bus cycle is generated.
I	CACHE# low AND KEN# low AND WB/WT# high AND PWT low	E	Data item does not exist in cache (MISS).
I	CACHE# low AND KEN# low AND (WB/WT# low OR PWT high)	S	Same as previous read miss case except that WB/WT# is sampled low with first BRDY# or PWT is high.
I	CACHE# high OR KEN# high	I	KEN# pin inactive; the line is not intended to be cached in the Write-Back Enhanced IntelDX4 processor.

NOTES:
1. Locked accesses to the cache cause the accessed line to transition to the Invalid state.
2. PCD can also be used by the processor to determine the cacheability, but using the CACHE# pin is recommended. The transition from I to E or S states (based on WB/WT#) occurs only when KEN# is sampled low one clock prior to the first BRDY# and then one clock prior to the last BRDY#, and the cycle is transformed into a line fill cycle. When KEN# is sampled high, the line is not cached and remains in the I state.

Table 7-6. Cache State Transitions for Write-Back Enhanced IntelDX4™ Processor-Initiated Write Cycles

Present State	Pin Activity	Next State	Description
M	n/a	M	Write hit; update cache. No bus cycle generated to update memory.
E	n/a	M	Write hit; update cache only. No bus cycle generated; line is now modified.
S	n/a	S	Write hit; cache updated with write data item. A write-through cycle is generated on the bus to update memory. Subsequent writes to E-state or M-state lines are held up until this write through cycle is completed.
I	n/a	I	Write miss; a write-through cycle is generated on the bus to update external memory. No allocation is done. Subsequent writes to the E or M lines are blocked until the write miss is completed.

Note that even though memory writes are buffered while I/O writes are not, these writes appear at the pins in the same order as they were generated by the processor. Write-back cycles caused by the replacement of M-state lines are buffered, while write backs due to snoop hit to M-state lines are not buffered.

Cache Consistency Cycles (Snoop Cycles)

The purpose of snoop cycles is to check whether the address being presented by another bus master is contained within the cache of the Write-Back Enhanced IntelDX4 processor. Snoop cycles may be initiated with or without an invalidation request (INV = 1 or 0). When a snoop cycle is initiated with INV = 0 (usually during memory read cycles by another master), it is referred to as an inquire cycle. When a snoop cycle is initiated with INV = 1 (usually during memory write cycles), it is referred to as an invalidate cycle. When the address hits a modified line in the cache, HITM# is asserted and the modified line is written back to the bus. Table 7-7 describes state transitions for snoop cycles.

Table 7-7. Cache State Transitions During Snoop Cycles

Present State	Next State INV=1	Next State INV=0	Description
M	I	E	Snoop hit to a modified line indicated by HITM# low. The state of the line changes to E provided INV = 0 and changes to I when INV = 1.
E	I	E	Snoop hit, no bus cycle generated. State remains unaltered when INV = 0, and changes to I when INV = 1. There is no external indication of this snoop hit.
S	I	S	Snoop hit, no bus cycle generated. State remains unaltered when INV = 0, and changes to I when INV = 1. There is no external indication of this snoop hit.
I	I	I	Address not in cache.

7.8.2 Detecting On-Chip Write-Back Cache of the Write-Back Enhanced IntelDX4™ Processor

The Write-Back Enhanced IntelDX4 processor write-back policy for the on-chip cache can be detected by software or hardware. The software mechanism uses the CPUID instruction. (See Appendix B, “Feature Determination,” for use of the CPUID instruction.) The hardware mechanism uses a write-back related output signal from the processor.

A software mechanism to determine whether a processor has write-back support for the on-chip cache should drive the WB/WT# pin to ‘1’ during RESET. This pin is sampled by the processor during the falling edge of RESET. Execute the CPUID instruction, which returns the model number in the EAX register, EAX[7:4]. When the model number returned is 7 (identifying the presence of a Write-Back Enhanced IntelDX4 processor) and the family number is 4, the on-chip cache supports the write-back policy. When the model number returned is in the range 0 through 6 or 8, the on-chip cache supports the write-through policy only.

The following pseudo code/steps give an example of the initialization BIOS that can detect the presence of the write-back on-chip cache:

- Boot address cold start
- Load segment registers and null IDTR
- Execute CPUID instruction and determine the family ID and model ID.
- Compare the family ID to 4 and the Model ID to the values listed in Table D-2 (pg. D-3).

The hardware mechanism for detecting the presence of write-back cache uses the HITM# signal. For the Write-Back Enhanced IntelDX4 processor, this signal is driven inactive (high) during RESET. The chipset can sample this output on the falling edge of RESET. When HITM# is sampled high on the falling edge of RESET, the processor supports on-chip write-back cache configuration. For those processors that do not support internal write-back caching, this signal is an INC, and this output is not driven.

8

System Management Mode (SMM) Architectures

Chapter Contents

CHAPTER 8
SYSTEM MANAGEMENT MODE (SMM) ARCHITECTURES

8.1 SMM OVERVIEW

The Intel486™ processor supports four modes: Real, Virtual-86, Protected, and System Management Mode (SMM). As an operating mode, SMM has a distinct processor environment, interface and hardware/software features.

SMM provides system designers with a means of adding new software-controlled features to computer products that operate transparently to the operating system and software applications. SMM is intended for use only by system firmware, not by applications software or general purpose systems software.

The SMM architectural extension consists of the following elements:

1. System Management Interrupt (SMI#) hardware interface.
2. Dedicated and secure memory space (SMRAM) for SMI# handler code and processor state (context) data with a status signal (SMIACT#) for to decoding access to that memory space. (The SMBASE address is relocatable and can also be relocated to non-cacheable address space.)
3. Resume (RSM) instruction, for exiting the System Management Mode.
4. Special Features such as I/O-Restart, for transparent power management of I/O peripherals, and Auto HALT Restart.

8.2 TERMINOLOGY

The following terms are used throughout the discussion of System Management Mode.

SMM	System Management Mode. This is the operating environment that the processor (system) enters when the System Management Interrupt is being serviced.
SMI#	System Management Interrupt. This is part of the SMM interface. When SMI# is asserted (low) it causes the processor to invoke SMM. The SMI# pin is the only means of entering SMM.
SMM Handler	System Management Mode handler. This is the code that is executed when the processor is in SMM. An example application that this code might implement is a power management control or a system control function.

RSM	Resume instruction. This instruction is used by the SMM handler to exit SMM and return to the operating system or application process that was interrupted.
SMRAM	Physical memory dedicated to SMM. The SMM handler code and related data reside in this memory. This memory is also used by the processor to store its context before executing the SMM handler. The operating system and applications do not have access to this memory space.
SMBASE	Control register that contains the address of the SMRAM space.
Context	The processor state just before the processor invokes SMM. The context normally consists of the processor registers that fully represent the processor state.
Context Switch	The process of either saving or restoring the context. The SMM discussion refers to the context switch as the process of saving/restoring the context while invoking/exiting SMM, respectively.

8.3 SYSTEM MANAGEMENT INTERRUPT PROCESSING

The system interrupts the normal program execution and invokes SMM by generating a System Management Interrupt (SMI#) to the processor. The processor services the SMI# by executing the following sequence (see Figure 8-1):

1. The processor asserts SMIACT#, indicating to the system that it should enable the SMRAM.
2. The processor saves its state (context) to SMRAM, starting at default address location 3FFFFH, proceeding downward in a stack-like fashion.
3. The processor switches to the System Management Mode processor environment (a pseudo-real mode).

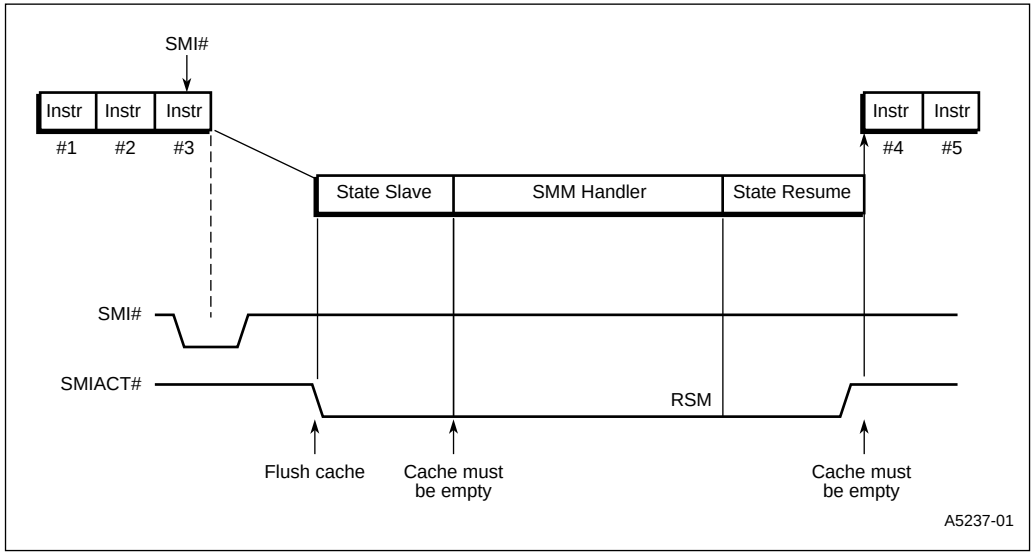


Figure 8-1. Basic SMI# Interrupt Service

4. The processor then jumps to the default absolute address of 38000H in SMRAM to execute the SMI# handler. This SMI# handler performs the system management activities.
5. The SMI# handler then executes the RSM instruction (which restores the processors context from SMRAM), de-asserts the SMIACT# signal, and then returns control to the previously interrupted program execution.

NOTE

The above sequence is valid for the default SMBASE value only. See the following sections for a description of the SMBASE register and SMBASE relocation.

The System Management Interrupt hardware interface consists of the SMI# interrupt request input and the SMIACT# output the system uses to decode the SMRAM.

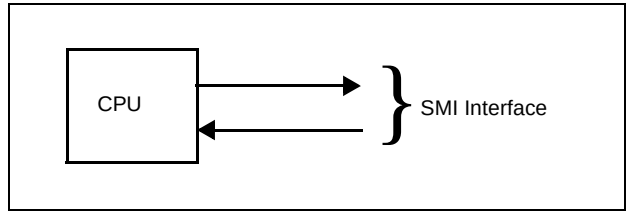


Figure 8-2. Basic SMI# Hardware Interface

8.3.1 System Management Interrupt (SMI#)

SMI# is a falling-edge triggered, non-maskable interrupt request signal. SMI# is an asynchronous signal, but setup and hold times t_{20} and t_{21} must be met in order to guarantee recognition on a specific clock. The SMI# input need not remain active until the interrupt is actually serviced. The SMI# input must remain active for a single clock if the required setup and hold times are met. SMI# also works correctly if it is held active for an arbitrary number of clocks.

The SMI# input must be held inactive for at least four external clocks after it is asserted to reset the edge triggered logic. A subsequent SMI# might not be recognized if the SMI# input is not held inactive for at least four clocks after being asserted.

SMI#, like NMI, is not affected by the IF bit in the EFLAGS register and is recognized on an instruction boundary. An SMI# does not break locked bus cycles. The SMI# has a higher priority than NMI and is not masked during an NMI. In order for SMI# to be recognized with respect to SRESET, SMI# should not be asserted until two (2) clocks after SRESET becomes inactive.

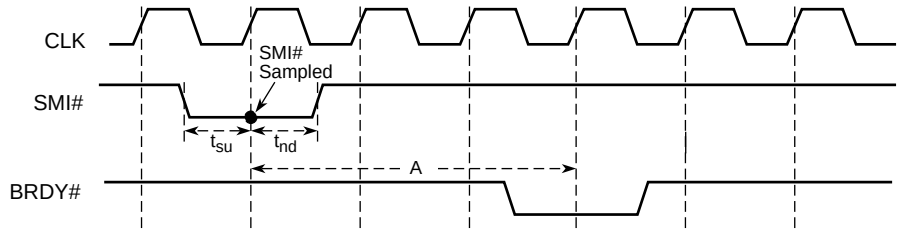
After the SMI# interrupt is recognized, the SMI# signal is masked internally until the RSM instruction is executed and the interrupt service routine is complete. Masking the SMI# prevents recursive SMI# calls. SMI# must be deasserted for at least four clocks to reset the edge triggered logic. If another SMI# occurs while the SMI# is masked, the pending SMI# is recognized and executed on the next instruction boundary after the current SMI# completes. This instruction boundary occurs before execution of the next instruction in the interrupted application code, resulting in back-to-back SMM handlers. Only one SMI# can be pending while SMI# is masked.

The SMI# signal is synchronized internally and must be asserted at least three CLK periods prior to asserting the RDY# signal in order to guarantee recognition on a specific instruction boundary. This is important for servicing an I/O trap with an SMI# handler (see Figure 8-3).

8.3.2 SMI# Active (SMIACT#)

SMIACT# indicates that the processor is operating in System Management Mode. The processor asserts SMIACT# in response to an SMI# interrupt request on the SMI# pin. SMIACT# is driven active after the processor has completed all pending write cycles (including emptying the write buffers), and before the first access to SMRAM, when the processor saves (writes) its state (or context) to SMRAM. SMIACT# remains active until the last access to SMRAM when the processor restores (reads) its state from SMRAM. SMIACT# does not float in response to HOLD. SMIACT# is used by the system logic to decode SMRAM (See Figure 8-2).

The number of CLKs required to complete the SMM state save and restore is dependent on-system memory performance. The values listed in Table 8-1 assume zero wait-state memory writes (two CLK cycles), 2-1-1-1 burst read cycles, and zero wait-state non-burst reads (2 CLK cycles). Additionally, it is assumed that the data read during the SMM state restore sequence is not cacheable.



Note: Setup time (A) for recognition on I/O instruction boundary.

A5232-01

Figure 8-3. SMI# Timing for Servicing an I/O Trap

Figure 8-4 and Table 8-1 can be used for latency calculations. As shown, the minimum time required to enter an SMI# handler routine for the IntelDX4 processor (3x clock) from the completion of the interrupted instruction is given by:

Latency to beginning of SMI# handler =
A + B + C = 153 CLKs

and the minimum time required to return to the interrupted application (following the final SMM instruction before RSM) is given by:

Latency to continue interrupted application =
E + F + G = 243 CLKs

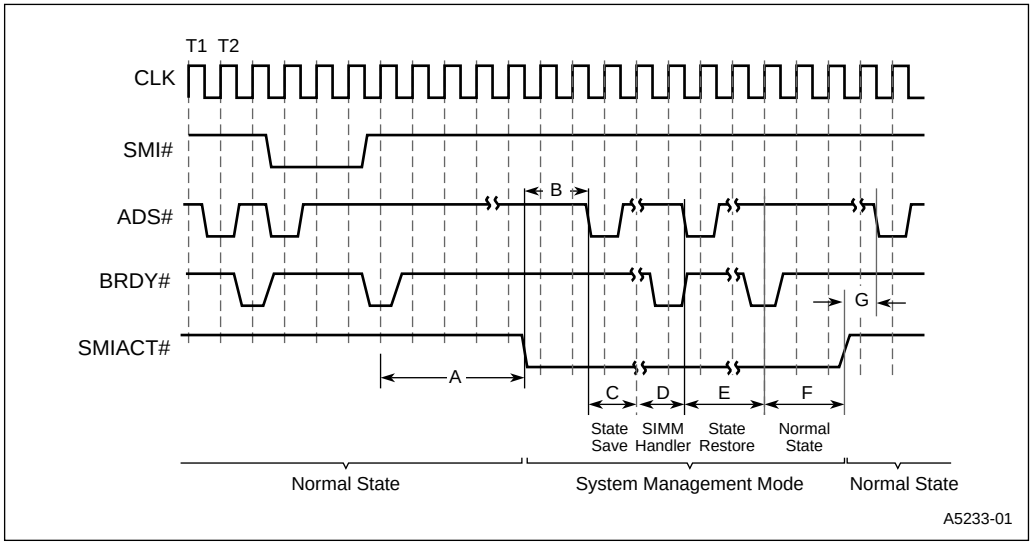


Figure 8-4. Intel486™ Processor SMIACT# Timing

Table 8-1. Intel486™ Processor SMIACT# Timing

	Intel486™ SX Processor	IntelDX2™ Processor	IntelDX4™ Processor 3X	IntelDX4 Processor 2X
A: Last RDY# from non-SMM transfer to SMIACT# assertion	2 CLK minimum	1 CLK minimum	1 CLK minimum	1 CLK minimum
B: SMIACT# assertion to first ADS# for SMM state save	40 CLK minimum	20 CLK minimum	13 CLK minimum	20 CLK minimum
C:SMM state save (dependent on memory performance)	Approx. 139 CLKs	Approx. 139 CLKs	Approx. 139 CLKs	Approx. 139 CLKs
D:SMM handler	User determined	User determined	User determined	User determined
E: SMM state restore (dependent on memory performance)	Approx. 236 CLKs	Approx. 236 CLKs	Approx. 236 CLKs	Approx. 236 CLKs
F: Last RDY# from SMM transfer to de-assertion of SMIACT#	4 CLK minimum	2 CLK minimum	1 CLK minimum	1 CLK minimum
G: SMIACT# de-assertion to first non-SMM ADS#	20 CLK minimum	10 CLK minimum	6 CLK minimum	10 CLK minimum

8.3.3 SMRAM

The Intel486 processor uses the SMRAM space for state save and state restore operations during an SMI# and RSM. The SMI# handler, which also resides in SMRAM, uses the SMRAM space to store code, data and stacks. In addition, the SMI# handler can use the SMRAM for system management information such as the system configuration, configuration of a powered-down device, and system design-specific information.

The processor asserts the SMIACT# output to indicate to the memory controller that it is operating in System Management Mode. The system logic should ensure that only the processor has access to this area. Alternate bus masters or DMA devices that try to access the SMRAM space when SMIACT# is active should be directed to system RAM in the respective area.

The system logic is minimally required to decode the physical memory address range from 38000H-3FFFFH as SMRAM area. The processor saves its state to the state save area from 3FFFFH downward to 3FE00H. After saving its state the processor jumps to the address location 38000H to begin executing the SMI# handler. The system logic can choose to decode a larger area of SMRAM as needed. The size of this SMRAM can be between 32 Kbytes and 4 Gbytes.

The system logic should provide a manual method for switching the SMRAM into system memory space when the processor is not in SMM. This enables initialization of the SMRAM space (i.e., loading SMI# handler) before executing the SMI# handler during SMM (see Figure 8-5).

8.3.3.1 SMRAM State Save Map

When the SMI# is recognized on an instruction boundary, the processor core first sets SMIACT# low, indicating to the system logic that accesses are now being made to the system-defined SMRAM areas. The processor then writes its state to the state save area in the SMRAM. The state save area starts at CS Base + [8000H + 7FFFH]. The default CS Base is 30000H; therefore the default state save area is at 3FFFFH. In this case, the CS Base can also be referred to as the SMBASE.

If SMBASE relocation is enabled, then the SMRAM addresses can change. The following formula is used to determine the relocated addresses where the context is saved. The context resides at CS Base + [8000H + Register Offset], where the default initial CS Base is 30000H and the Register Offset is listed in the SMRAM state save map (Table 8-2). Reserved spaces are used to accommodate new registers in future processors. The state save area starts at 7FFFH and continues downward in a stack-like fashion.

Some of the registers in the SMRAM state save area 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 results in unpredictable behavior). The values stored in reserved areas may change in future processors. An SMM handler should not rely on any values stored in a reserved area.

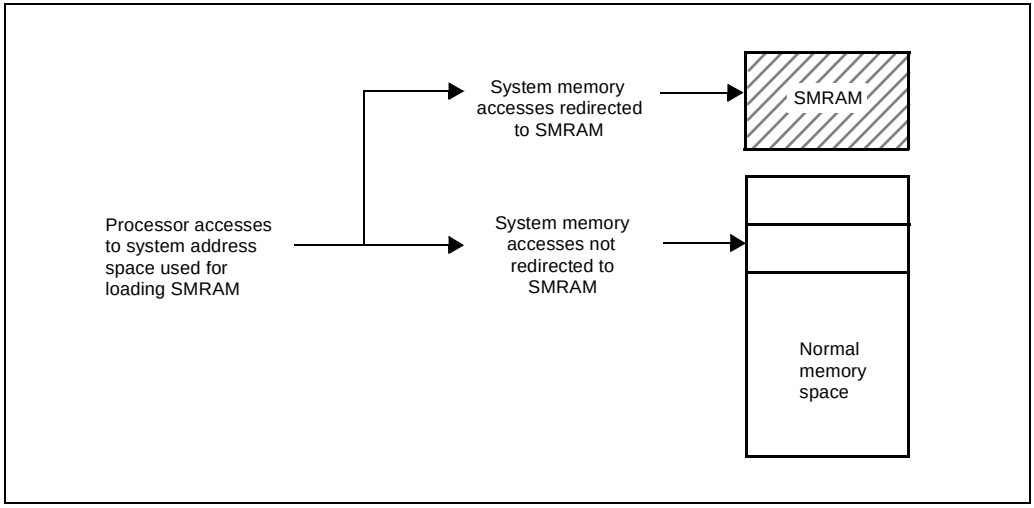


Figure 8-5. Redirecting System Memory Addresses to SMRAM

Table 8-2. SMRAM State Save Map (Sheet 1 of 2)

Register Offset	Register	Writeable?[2]
7FFC	CR0	NO
7FF8	CR3	NO
7FF4	EFLAGS	YES
7FF0	EIP	YES
7FEC	EDI	YES
7FE8	ESI	YES
7FE4	EBP	YES
7FE0	ESP	YES
7FDC	EBX	YES
7FD8	EDX	YES
7FD4	ECX	YES
7FD0	EAX	YES

NOTES:
1. Upper two bytes are reserved.
2. Modifying a value that is marked as not writeable results in unpredictable behavior.
3. Words are stored in two consecutive bytes in memory with the low-order byte at the lowest address and the high-order byte at the high address.

Table 8-2. SMRAM State Save Map (Sheet 2 of 2)

Register Offset	Register	Writeable?[2]
7FCC	DR6	NO
7FC8	DR7	NO
7FC4	TR[1]	NO
7FC0	LDTR[1]	NO
7FBC	GS[1]	NO
7FB8	FS[1]	NO
7FB4	DS[1]	NO
7FB0	SS[1]	NO
7FAC	CS[1]	NO
7FA8	ES[1]	NO
7FA7–7F98	Reserved	NO
7F94	IDT Base	NO
7F93–7F8C	Reserved	NO
7F88	GDT Base	NO
7F87-7F04	Reserved	NO
7F02	Auto HALT Restart Slot (Word)[3]	YES
7F00	I/O Trap Restart Slot (Word)[3]	YES
7EFC	SMM Revision Identifier	NO
	(Dword)3	
7EF8	SMBASE Slot (Dword)[3]	YES
7EF7–7E00	Reserved	NO

NOTES:
1. Upper two bytes are reserved.
2. Modifying a value that is marked as not writeable results in unpredictable behavior.
3. Words are stored in two consecutive bytes in memory with the low-order byte at the lowest address and the high-order byte at the high address.

The following registers are saved and restored (in reserved areas of the state save), but are not visible to the system software programmer: CR1, CR2, and CR4, hidden descriptor registers for 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 non-volatile memory.

The following registers are not automatically saved and restored by SMI# and RSM: DR5:0, TR7:3, and the FPU registers STn, FCS, FSW, tag word, FP instruction pointer, FP opcode, and operand pointer.

For all SMI# requests except for suspend/resume, these registers do not have to be saved because their contents do not change. However, during a power down suspend/resume, a resume reset clears these registers to their default values. In this case, the suspend SMI# handler should read these registers directly to save them and restore them during the power up resume. Anytime the SMI# handler changes these registers in the processor, it must also save and restore them.

8.3.4 Exit From SMM

The RSM instruction is only available to the SMI# handler. The opcode of the instruction is 0FAAH. Execution of this instruction while the processor is executing outside of SMM causes an invalid opcode error. The last instruction of the SMI# handler is the RSM instruction.

The RSM instruction restores the state save image from SMRAM back to the processor, then returns control back to the interrupted program execution. There are three SMM features that can be enabled by writing to control "slots" in the SMRAM state save area.

Auto HALT Restart. It is possible for the SMI# request to interrupt the HALT state. The SMI# handler can tell the RSM instruction to return control to the HALT instruction or to return control to the instruction following the HALT instruction by appropriately setting the Auto HALT Restart slot. The default operation is to restart the HALT instruction.

I/O Trap Restart. If the SMI# interrupt was generated on an I/O access to a powered-down device, the SMI# handler can tell the RSM instruction to re-execute that I/O instruction by setting the I/O Trap Restart slot.

SMBASE Relocation. The system can relocate the SMRAM by setting the SMBASE Relocation slot in the state save area. The RSM instruction sets the SMBASE in the processor based on the value in the SMBASE Relocation slot. The SMBASE must be 32-Kbyte aligned.

For further details on these SMM features, see Section 8.5 "SMM Features."

If the processor detects invalid state information, it enters the shutdown state. This happens only in the following situations:

- The value stored in the SMBASE slot is not a 32-Kbyte aligned address.
- A reserved bit of CR4 is set to 1.
- A combination of bits in CR0 is illegal; namely, (PG=1 and PE=0) or (NW=1 and CD=0).

In shutdown mode, the processor stops executing instructions until an NMI interrupt is received or reset initialization is invoked. The processor generates a special bus cycle to indicate it has entered shutdown mode.

NOTE

INTR and SMI# also brings the processor out of a shutdown that is encountered due to invalid state information from SMM execution. Make sure that INTR and SMI# are not asserted if SMM routines are written such that a shutdown occurs.

8.4 SYSTEM MANAGEMENT MODE PROGRAMMING MODEL

8.4.1 Entering System Management Mode

SMM is one of the major operating modes, on a level with Protected Mode, Real Mode or Virtual-86 Mode. Figure 8-6 shows how the processor can enter SMM from any of the three modes and then return.

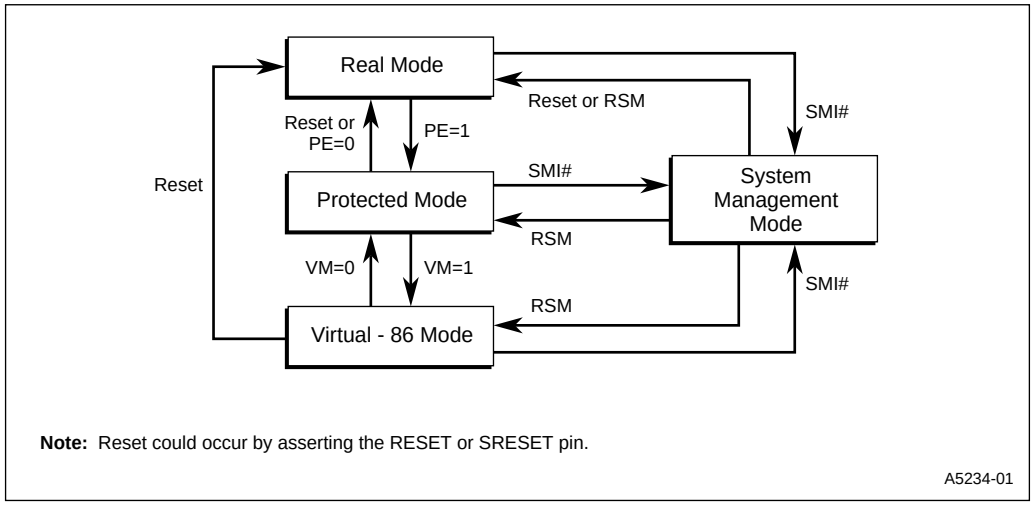


Figure 8-6. Transition to and from System Management Mode

The external signal SMI# causes the processor to switch to SMM. The RSM instruction exits SMM. SMM is transparent to applications programs and operating systems because of the following:

- The only way to enter SMM is via a type of non-maskable interrupt triggered by an external signal.
- The processor begins executing SMM code from a separate address space, called system management RAM (SMRAM).
- Upon entry into SMM, the processor saves the register state of the interrupted program in a part of SMRAM called the SMM context save space.
- All interrupts normally handled by the operating system or by applications are disabled upon entry into SMM.
- A special instruction, RSM, restores processor registers from the SMM context save space and returns control to the interrupted program.

SMM is similar to Real Mode in that there are no privilege levels or address mapping. An SMM program can execute all I/O and other system instructions and can address up to 4 Gbytes of memory.

8.4.2 Processor Environment

When an SMI# signal is recognized on an instruction execution boundary, the processor waits for all stores to complete, including emptying of the write buffers. The final write cycle is complete when the system returns RDY# or BRDY#. The processor then drives SMIACT# active, saves its register state to SMRAM space, and begins to execute the SMM handler.

SMI# has greater priority than debug exceptions and external interrupts. This means that if more than one of these conditions occur at an instruction boundary, only the SMI# processing occurs, not a debug exception or external interrupt. 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 is latched and serviced when the processor exits SMM with the RSM instruction. The processor latches only one SMI# while it is in SMM.

When the processor invokes SMM, the processor core registers are initialized as shown in Table 8-3.

Table 8-3. SMM Initial Processor Core Register Settings

Register	Contents
General Purpose Registers	Unpredictable
EFLAGS	00000002H
EIP	00008000H
CS Selector	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	Bits 0,2,3 & 31 cleared (PE, EM, TS & PG); others are unmodified
DR6	Unpredictable
DR7	00000000H

The following is a summary of the key features in the SMM environment:

1. Real Mode style address calculation.
2. 4-Gbyte limit checking.
3. IF flag is cleared.
4. NMI is disabled.
5. TF flag in EFLAGS is cleared; single step traps are disabled.
6. DR7 is cleared, except for bits 12 and 13; debug traps are disabled.
7. The RSM instruction no longer generates an invalid opcode error.
8. Default 16-bit opcode, register and stack use.

All bus arbitration (HOLD, AHOLD, BOFF#) inputs and bus sizing (BS8#, BS16#) inputs operate normally while the processor is in SMM.

8.4.2.1 Write-Back Enhanced IntelDX4™ Processor Environment

When the Write-Back Enhanced Intel486 processor is in Enhanced Bus Mode, SMI# has greater priority than debug exceptions and external interrupts, except for FLUSH# and SRESET (see Section 3.15.6 “Interrupt and Exception Priorities”).

8.4.3 Executing System Management Mode Handler

The processor begins execution of the SMM handler at offset 8000H in the CS segment. The CS Base is initially 30000H. However, the CS Base can be changed by using the SMM Base relocation feature.

When the SMM handler is invoked, the processors PE and PG bits in CR0 are reset to 0. The processor is in an environment similar to Real mode, but without the 64-Kbyte limit checking. However, the default operand size and the default address size are set to 16 bits.

The EM bit is cleared so that no exceptions are generated. (If the SMM was entered from Protected Mode, the Real Mode interrupt and exception support is not available.) The SMI# handler should not use floating-point unit instructions until the FPU is properly detected (within the SMI# handler) and the exception support is initialized.

Because the segment bases (other than CS) are cleared to 0 and the segment limits are set to 4 Gbytes, the address space may be treated as a single flat 4-Gbyte linear space that is unsegmented. The processor is still in Real Mode and when a segment selector is loaded with a 16-bit value, that value is then shifted left by 4 bits and loaded into the segment base cache. The limits and attributes are not modified.

In SMM, the processor can access or jump anywhere within the 4-Gbyte logical address space. The processor can also indirectly access or perform a near jump anywhere within the 4-Gbyte logical address space.

8.4.3.1 Exceptions and Interrupts within System Management Mode

When the processor enters SMM, it disables INTR interrupts, debug and single-step traps by clearing the EFLAGS, DR6 and DR7 registers. This prevents a debug application from accidentally breaking into an SMM handler. This is necessary because the SMM handler operates from a distinct address space (SMRAM), and hence, the debug trap does not represent the normal system memory space.

If an SMM handler wishes to use the debug trap feature of the processor to debug SMM handler code, it must first ensure that an SMM-compliant debug handler is available. The SMM handler must also ensure DR3:0 is saved to be restored later. The debug registers DR3:0 and DR7 must then be initialized with the appropriate values.

If the processor wishes to use the single step feature of the processor, it must ensure that an SMM compliant single step handler is available and then set the trap flag in the EFLAGS register.

If the system design requires the processor to respond to hardware INTR requests while in SMM, it must ensure that an SMM compliant interrupt handler is available and then set the interrupt flag in the EFLAGS register (using the STI instruction). Software interrupts are not blocked upon entry to SMM, and the system software designer must provide an SMM compliant interrupt handler before attempting to execute any software interrupt instructions. Note that in SMM mode, the interrupt vector table has the same properties and location as the Real Mode vector table.

NMI interrupts are blocked upon entry to the SMM handler. If an NMI request occurs during the SMM handler, it is latched and serviced after the processor exits SMM. Only one NMI request is latched during the SMM 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 processor enters SMM, they may be enabled through software by executing an IRET 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 instruction. Once an IRET instruction is executed, NMI interrupt requests are serviced in the same "Real Mode" manner in which they are handled outside of SMM.

8.5 SMM FEATURES

8.5.1 SMM Revision Identifier

The SMM revision identifier is used to indicate the version of SMM and the SMM extensions supported by the processor. The SMM revision identifier is written during SMM entry and can be examined in SMRAM space at register offset 7EFCH. The lower word of the SMM revision identifier refers to the version of the base SMM architecture. The upper word of the SMM revision identifier refers to the extensions available (see Figure 8-7).

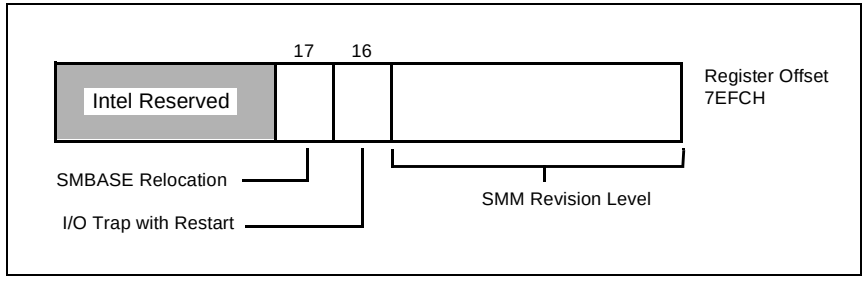


Figure 8-7. SMM Revision Identifier

Table 8-4. Bit Values for SMM Revision Identifier

Bits	Value	Comments
16	0	Processor does not support I/O trap restart
16	1	Processor supports I/O trap restart
17	0	Processor does not support SMBASE relocation
17	1	Processor supports SMBASE relocation

Bit 16 of the SMM revision identifier is used to indicate to the SMM handler that this processor supports the SMM I/O trap extension. If this bit is high, then the processor supports the SMM I/O trap extension. If this bit is low, then this processor does not support I/O trapping using the I/O trap slot mechanism (see Table 8-4).

Bit 17 of this slot indicates whether the processor supports relocation of the SMM jump vector and the SMRAM base address (see Table 8-4).

The Intel486 processor supports both the I/O trap restart and the SMBASE relocation features.

8.5.2 Auto Halt Restart

The Auto HALT restart slot at register offset (word location) 7F02H in SMRAM indicates to the SMM handler that the SMI# interrupted the processor during a HALT state (bit 0 of slot 7F02H is set to 1 if the previous instruction was a HALT). If the SMI# does not interrupt the processor in a HALT state, then the SMI# microcode sets bit 0 of the Auto HALT Restart slot to a value of 0. If the previous instruction was a HALT, the SMM handler can choose to either set or reset bit 0. If this bit is set to 1, the RSM microcode execution forces the processor to re-enter the HALT state. If this bit is set to 0 when the RSM instruction is executed, the processor continues execution starting with the instruction just after the interrupted HALT instruction. Note that if the interrupted instruction was not a HALT instruction (bit 0 is set to 0 in the Auto HALT restart slot upon SMM entry), setting bit 0 to 1 causes unpredictable behavior when the RSM instruction is executed (see Figure 8-8 and Table 8-5).

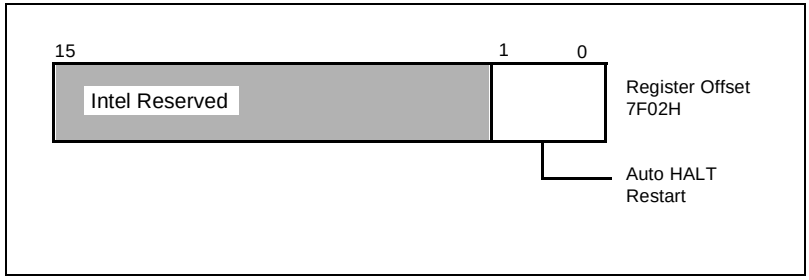


Figure 8-8. Auto HALT Restart

Table 8-5. Bit Values for Auto HALT Restart

Value of Bit 0 at Entry	Value of Bit 0 at Exit	Comments
0	0	Returns to next instruction in interrupted program.
0	1	Unpredictable.
1	0	Returns to next instruction after HALT.
1	1	Returns to HALT state.

If the HALT instruction is restarted, the processor generates a memory access to fetch the HALT instruction (if it is not in the internal cache) and executes a HALT bus cycle.

8.5.3 I/O Instruction Restart

The I/O instruction restart slot (register offset 7F00H in SMRAM) gives the SMM handler the option of causing the RSM instruction to automatically re-execute the interrupted I/O instruction. When the RSM instruction is executed, if the I/O instruction restart slot contains the value 0FFH, then the processor automatically re-executes the I/O instruction that the SMI# trapped. If the I/O instruction restart slot contains the value 00H when the RSM instruction is executed, then the processor does not re-execute the I/O instruction. The processor automatically initializes the I/O instruction restart slot to 00H during SMM entry. The I/O instruction restart slot should be written only when the processor has generated an SMI# on an I/O instruction boundary. Processor operation is unpredictable when the I/O instruction restart slot is set when the processor is servicing an SMI# that originated on a non-I/O instruction boundary (see Figure 8-9 and Table 8-6).

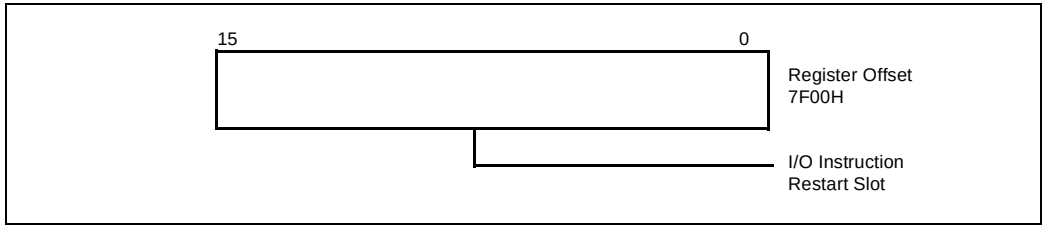


Figure 8-9. I/O Instruction Restart

Table 8-6. I/O Instruction Restart Value

Value at Entry	Value at Exit	Comments
00H	00H	Do not restart trapped I/O instruction
00H	0FFH	Restart trapped I/O instruction

If the system executes back-to-back SMI# requests, the second SMM handler must not set the I/O instruction restart slot (see Section 8.6.6 “Nested SMI#s and I/O Restart”).

8.5.4 SMM Base Relocation

The Intel486 processor provides a control register, SMBASE. The address space used as SMRAM can be modified by changing the SMBASE register before exiting an SMI# handler routine. SMBASE can be changed to any 32-Kbyte aligned value (values that are not 32-Kbyte aligned cause the processor to enter the shutdown state when executing the RSM instruction). SMBASE is set to the default value of 30000H on RESET, but is not changed on SRESET. If the SMBASE register is changed during an SMM handler, all subsequent SMI# requests initiate a state save at the new SMBASE (see Figure 8-10).

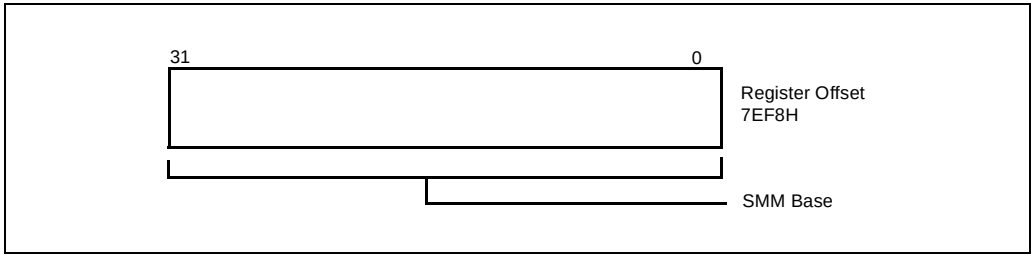


Figure 8-10. SMM Base Location

The SMBASE slot in the SMM state save area is used to indicate and change the SMI# jump vector location and the SMRAM save area. When bit 17 of the SMM revision identifier is set, then this feature exists and the SMRAM base and jump vector are as indicated by the SMM base slot. During the execution of the RSM instruction, the processor reads this slot and initializes the processor to use the new SMBASE during the next SMI#. During an SMI#, the processor performs a context save to the new SMRAM area pointed to by the SMBASE, stores the current SMBASE in the SMM Base slot (offset 7EF8H), and then start execution of the new jump vector based on the current SMBASE.

The SMBASE must be a 32-Kbyte aligned, 32-bit integer that indicates a base address for the SMRAM context save area and the SMI# jump vector. For example when the processor first powers up, the minimum SMRAM area is from 38000H-3FFFFH. The default SMBASE is 30000H. Hence the starting address of the jump vector is calculated by:

SMBASE + 8000H

While the starting address for the SMRAM state save area is calculated by:

SMM Base + [8000H + 7FFFH]

Hence, when this feature is enabled, the SMRAM register map is addressed according to the above formulas (see Figure 8-11).

To change the SMRAM base address and SMM jump vector location, the SMM handler should modify the SMBASE slot. Upon executing an RSM instruction, the processor reads the SMBASE slot and stores it internally. Upon recognition of the next SMI# request, the processor uses the new SMBASE slot for the SMRAM dump and SMI# jump vector.

If the modified SMBASE slot does not contain a 32-Kbyte aligned value, the RSM microcode causes the processor to enter the shutdown state.

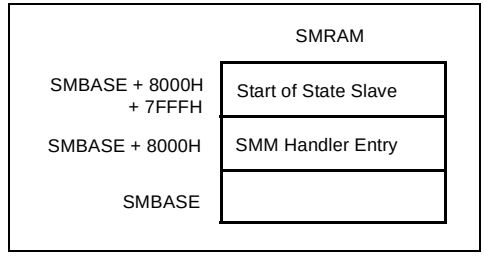


Figure 8-11. SMRAM Usage

8.6 SMM SYSTEM DESIGN CONSIDERATIONS

8.6.1 SMRAM Interface

The hardware designed to control the SMRAM space must follow these guidelines:

1. A provision should be made to allow for initialization of SMRAM space during system boot up. This initialization of SMRAM space must happen before the first occurrence of an SMI# interrupt. Initializing the SMRAM space must include installation of an SMM handler, and may include installation of related data structures necessary for particular SMM applications. The memory controller providing the interface to the SMRAM should provide a means for the initialization code to manually open the SMRAM space.
2. A minimum initial SMRAM address space of 38000H-3FFFFH should be decoded by the memory controller.
3. Alternate bus masters (such as DMA controllers) should not be allowed to access SMRAM space. Only the processor, either through SMI# or during initialization, should be allowed access to SMRAM.
4. In order to implement a zero-volt suspend function, the system must have access to all of normal system memory from within an SMM handler routine. If the SMRAM is going to overlay normal system memory, there must be a method of accessing any system memory located underneath SMRAM.

There are two potential schemes for locating the SMRAM: either overlaid to an address space on top of normal system memory, or placed in a distinct address space (see Figure 8-12). When SMRAM is overlaid on top of normal system memory, the processor output signal SMIACT# must be used to distinguish SMRAM from main system memory. Additionally, if the overlaid normal memory is cacheable, both the processor internal cache and any second-level caches must be empty before the first read of an SMM handler routine. If the SMM memory is cacheable, the caches must be empty before the first read of normal memory following an SMM handler routine. This is done by flushing the caches, and is required to maintain cache coherency. When the default SMRAM location is used, SMRAM is overlaid on top of system main memory (at 38000H through 3FFFFH).

If SMRAM is located in its own distinct memory space, that can be completely decoded using only the processor address signals, it is said to be non-overlaid. In this case, there are no new requirements for maintaining cache coherency.

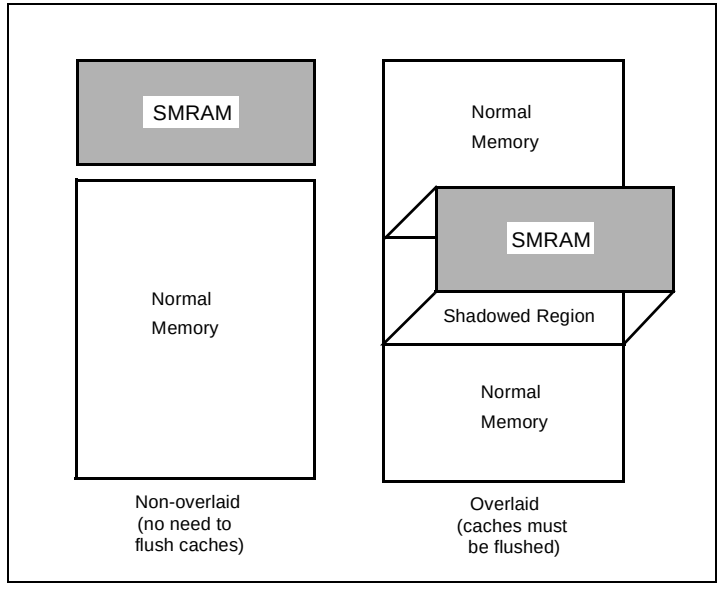


Figure 8-12. SMRAM Location

8.6.2 Cache Flushes

The processor does not unconditionally flush its cache before entering SMM (this option is left to the system designer). If SMRAM is shadowed in a cacheable memory area that is visible to the application or operating system, it is necessary for the system to empty both the processor cache and any second-level cache before entering SMM. That is, if SMRAM is in the same physical address location as the normal cacheable memory space, then an SMM read may hit the cache, which would contain normal memory space code/data. If the SMM memory is cacheable, the normal read cycles after SMM may hit the cache, which may contain SMM code/data. In this case the cache should be empty before the first memory read cycle during SMM and before the first normal cycle after exiting SMM (see Figure 8-13).

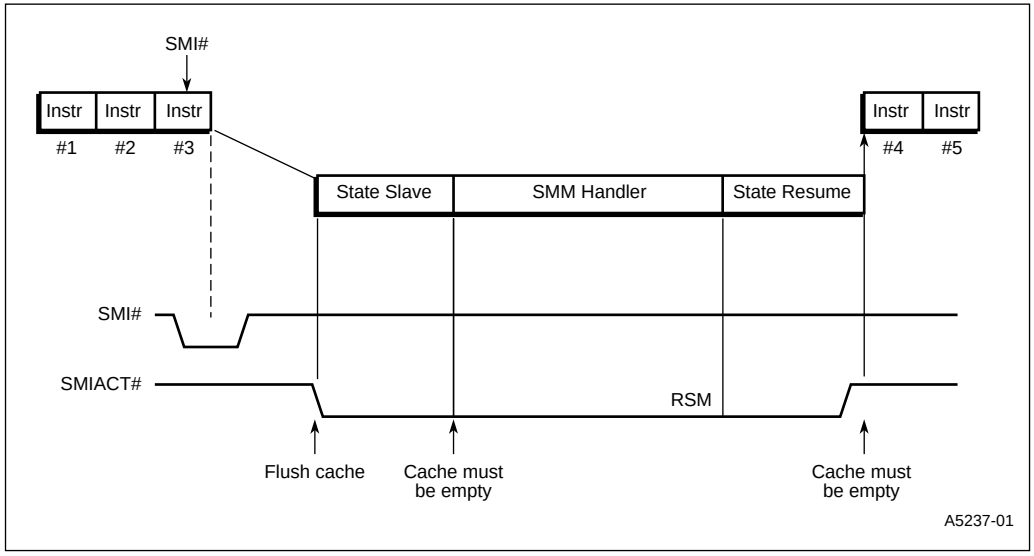


Figure 8-13. FLUSH# Mechanism during SMM

The FLUSH# and KEN# signals can be used to ensure cache coherency when switching between normal and SMM modes. Cache flushing during SMM entry is accomplished by asserting the FLUSH# pin when SMI# is driven active. Cache flushing during SMM exit is accomplished by asserting the FLUSH# pin after the SMIACT# pin is deasserted (within one CLK). To guarantee this behavior, the constraints on setup and hold timings on the interaction of FLUSH# and SMIACT# as specified for a processor should be followed.

If the SMRAM area is overlaid over normal memory and if the system designer does not want to flush the caches upon leaving SMM, then references to the SMRAM area should not be cached. It is the obligation of the system designer to ensure that the KEN# pin is sampled inactive during all references to the SMRAM area. Figures 8-14 and 8-15 illustrate a cached and non-cached SMM using FLUSH# and KEN#.

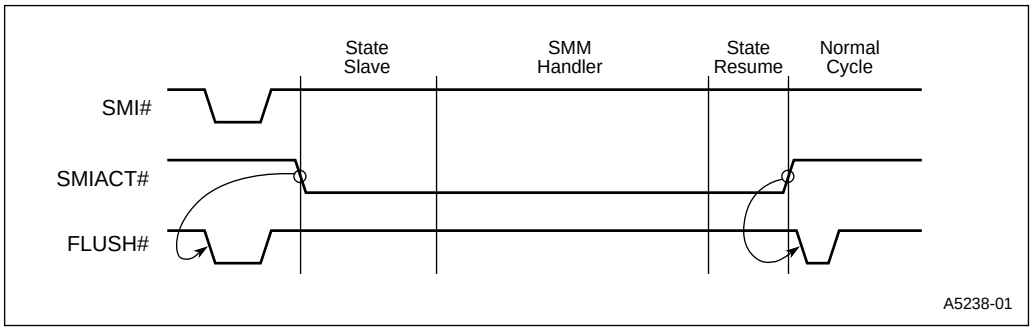


Figure 8-14. Cached SMM

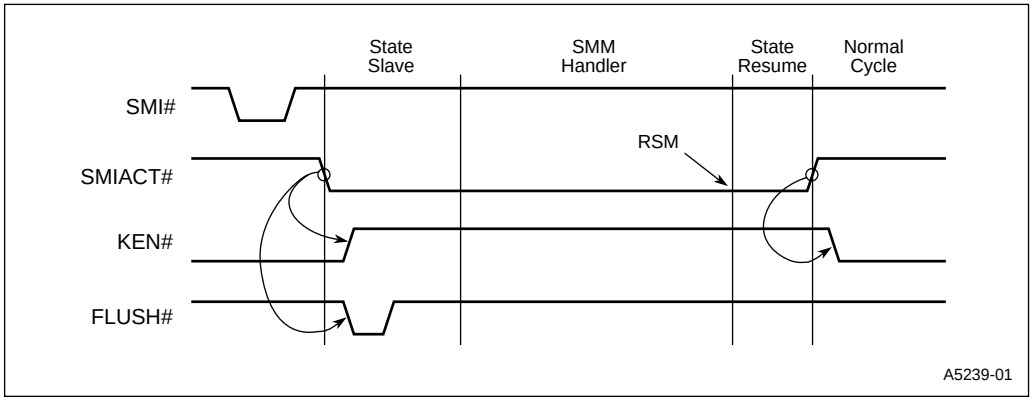


Figure 8-15. Non-Cached SMM

8.6.2.1 Write-Back Enhanced IntelDX4™ Processor System Management Mode and Cache Flushing

Regardless of the on-chip cache mode (i.e., write-through or write-back) it is recommended that SMRAM be non-overlaid. This provides the greatest freedom for caching both SMRAM and normal memory, provides a simplified memory controller design, and eliminates the performance penalty of flushing.

In general, cache flushing is not required when the SMRAM and normal memory are not overlaid. Table 8-7 gives the cache flushing requirements for entering and exiting SMM, when the SMRAM is not overlaid with normal memory space.

SMRAM can not be cached as write-back lines. If SMRAM is cached, it should be cached only as write-through lines. This is because dirty lines can not be written back to SMRAM upon exit from SMM. The de-assertion of SMIACT# signals that the processor is exiting SMM, and is used to assert FLUSH#. By the time the write back of dirty lines occurs, SMIACT# would already be inactive, so the SMRAM could no longer be decoded. When the SMRAM is cached as write-through, this problem does not occur.

Table 8-7. Cache Flushing (Non-Overlaid SMRAM)

Normal Memory Cacheable	SMRAM Cacheable	FLUSH Entering SMM
No	No	No
No	WT	No
WT	No	No
WB	No	No, but Snoop WBs must go to Normal Memory Space.
WT	WT	No
WB	WT	No, but Snoop and Replacement WBs must go to normal memory space.

Coherency requirements must be met when normal memory is cached in write-back mode. In this case, the snoop and replacement write-backs that occur during SMM must go to normal memory, even though SMIACT# is active. This requirement is compatible with SMM security requirements, because these write backs can not decode the SMRAM, and the memory system must be able to handle this situation properly.

If SMRAM is overlaid with normal memory space, additional system design features are needed to ensure that cache coherency is maintained. Table 8-8 lists the cache flushing requirements for entering and exiting the SMM when the SMRAM is overlaid with normal memory space.

Table 8-8. Cache Flushing (Overlaid SMRAM)

Normal Memory Cacheable	SMRAM Cacheable	FLUSH Entering SMM	FLUSH Exiting SMM
No	No	No	No
No	WT	No	Yes
WT or WB	No	Yes	No
WT or WB	WT	Yes	Yes

If SMI# and FLUSH# are asserted together, the Write-Back Enhanced Intel486 processor guarantees that FLUSH# is recognized first, followed by the SMI#. If the cache is configured in the write-back mode, the modified lines are written back to the normal user space, followed by the two special cycles. The SMI# is then recognized and the transition to SMM occurs, as shown in Figure 8-16.

Cache flushing during SMM exit is accomplished by asserting the FLUSH# pin after the SMIACT# pin is deasserted (within 1 CLK). To guarantee this behavior, follow the constraints on setup and hold timings for the interaction of FLUSH# and SMIACT# as specified for the Write-Back Enhanced IntelDX4 processor.

The WBINVD instruction should not be used to flush the cache when exiting SMM. Instead, the FLUSH# pin should be asserted after the SMIACT# pin is deasserted (within one CLK). The cache coherency requirements associated with SMM and write-through vs. write-back caches also apply to second-level cache control designs. The appropriate second-level cache flushing also is required upon entering and exiting the SMM.

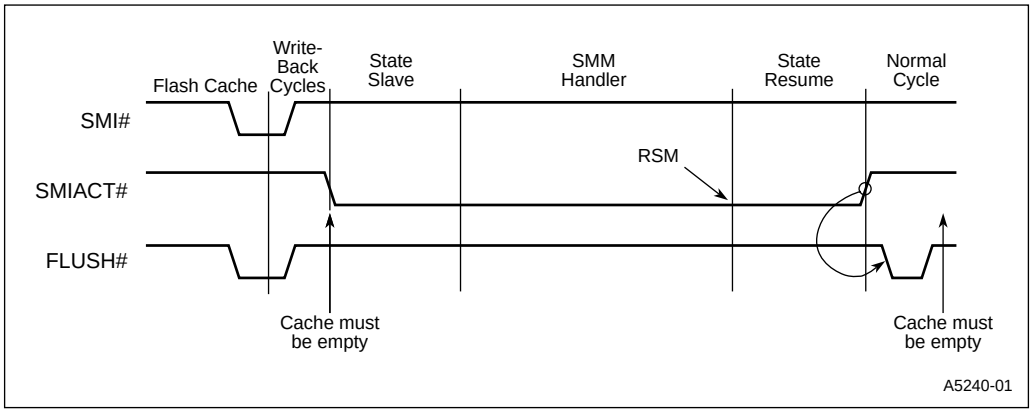


Figure 8-16. Write-Back Enhanced IntelDX4™ Processor Cache Flushing for Overlaid SMRAM upon Entry and Exit of Cached SMM

8.6.2.2 Snoop During SMM

Snoops cycles are allowed during SMM. However, because the SMRAM is always cached as a write-through, there can never be a snoop hit to a modified line in the SMRAM address space. Consequently, if there is a snoop hit to a modified line, it corresponds to the normal address space. In this case, even though SMIACT# is asserted, the memory controller must drive the snoop write-back cycle to the normal memory space and not to the SMRAM address space.

If the overlaid normal memory is cacheable, FLUSH# must be asserted when entering SMM, causing all modified lines of normal memory to be written back. As a result, there cannot be a snoop hit to a modified line in the cacheable normal memory space that is overlaid with the SMRAM space.

If the overlaid normal memory is not cacheable, no flushing is necessary when entering SMM. If normal memory is not overlaid with SMRAM, no flushing is required upon entering SMM and it is possible that a snoop can hit a modified line cached from anywhere in normal memory space while the processor is in SMM.

8.6.3 A20M# Pin and SMBASE Relocation

Systems based on a PC-compatible architecture contain a feature that enables the processor address bit A20 to be forced to 0. This limits physical memory to a maximum of 1 Mbyte, and is provided to ensure compatibility with those programs that relied on the physical address wrap around functionality of the 8088 processor. The A20M# pin on Intel486 processors provides this function. When A20M# is active, all external bus cycles drive A20M# low, and all internal cache accesses are performed with A20M# low.

The A20M# pin is recognized while the processor is in SMM. The functionality of the A20M# input must be recognized in the following two instances:

1. If the SMM handler needs to access system memory space above 1 Mbyte (for example, when saving memory to disk for a zero-volt suspend), the A20M# pin must be deasserted before the memory above 1 Mbyte is addressed.
2. If SMRAM has been relocated to address space above 1 Mbyte, and A20M# is active upon entering SMM, the processor attempts to access SMRAM at the relocated address, but with A20 low. This could cause the system to crash, because there would be no valid SMM interrupt handler at the accessed location.

In order to account for the above two situations, the system designer must ensure that A20M# is deasserted on entry to SMM. A20M# must be driven inactive before the first cycle of the SMM state save, and must be returned to its original level after the last cycle of the SMM state restore. This can be done by blocking the assertion of A20M# when SMIACT# is active.

8.6.4 Processor Reset During SMM

The system designer should take into account the following restrictions while implementing the processor RESET logic:

1. When running software written for the 80286 processor, an SRESET is used to switch the processor from Protected Mode to Real Mode. Note that SRESET has a higher interrupt priority than SMIACT#. When the processor is in SMM, the SRESET to the processor during SMM should be blocked until the processor exits SMM. SRESET must be blocked starting from the time SMI# is driven active and ending at least 20 CLK cycles after SMIACT# is de-asserted. Be careful not to block the global system RESET, which may be necessary to recover from a system crash.
2. During execution of the RSM instruction to exit SMM, there is a small time window between the de-assertion of SMIACT# and the completion of the RSM microcode. If SRESET is asserted during this window, it is possible that the SMRAM space will be violated. The system designer must guarantee that SRESET is blocked until at least 20 processor clock cycles after SMIACT# has been driven inactive.
3. Any request for a processor SRESET for the purpose of switching the processor from Protected Mode to Real Mode must be acknowledged after the processor has exited SMM. In order to maintain software transparency, the system logic must latch any SRESET signals that are blocked during SMM.

8.6.5 SMM and Second-Level Write Buffers

Before an Intel486 processor enters SMM, it empties its internal write buffers. This is necessary so that the data in the write buffers is written to normal memory space, not SMM space. Once the processor is ready to begin writing an SMM state save to SMRAM, it asserts SMIACT#. SMIACT# may be driven active by the processor before the system memory controller has had an opportunity to empty the second-level write buffers.

To prevent the data from these second level write buffers from being written to the wrong location, the system memory controller must direct the memory write cycles to either SMM space or normal memory space. This can be accomplished by saving the status of SMIACT# along with the address for each word in the write buffers.

8.6.6 Nested SMI#s and I/O Restart

Special care must be taken when executing an SMM handler for the purpose of restarting an I/O instruction. When the processor executes a RSM instruction with the I/O restart slot set, the restored EIP is modified to point to the instruction immediately preceding the SMI# request, so that the I/O instruction can be re-executed. If a new SMI# request is received while the processor is executing an SMM handler, the processor services this SMI# request before restarting the original I/O instruction. If the I/O restart slot is set when the processor executes the RSM instruction for the second SMM handler, the RSM microcode decrements the restored EIP again. EI, therefore, points to an address different than the originally interrupted instruction, and the processor begins execution of the interrupted application code at an incorrect entry point.

To prevent this problem, the SMM handler routine must not set the I/O restart slot during the second of two consecutive SMM handlers.

8.7 SMM SOFTWARE CONSIDERATIONS

8.7.1 SMM Code Considerations

The default operand size and the default address size are 16 bits; however, operand-size override and address-size override prefixes can be used as needed to directly access data anywhere within the 4-Gbyte logical address space.

With operand-size override prefixes, the SMM handler can use jumps, calls, and returns to transfer control to any location within the 4-Gbyte space. Note, however, the following restrictions:

- Any control transfer that does not have an operand-size override prefix truncates EIP to 16 low-order bits.
- Due to the Real Mode style of base-address formation, a far jump or call cannot transfer control to a segment with a base address of more than 20 bits (one Mbyte).

8.7.2 Exception Handling

Upon entry into SMM, external interrupts that require handlers are disabled (the IF bit in the EFLAGS is cleared). This is necessary because, while the processor is in SMM, it is running in a separate memory space. Consequently the vectors stored in the interrupt descriptor table (IDT) for the prior mode are not applicable. Before allowing exception handling (or software interrupts), the SMM program must initialize new interrupt and exception vectors. The interrupt vector table for SMM has the same format as for Real Mode. Until the interrupt vector table is correctly initialized, the SMM handler must not generate an exception (or software interrupt). Even though hardware interrupts are disabled, exceptions and software interrupts can occur. Only a correctly written SMM handler can prevent internal exceptions. When new exception vectors are initialized, internal exceptions can be serviced. The following restrictions apply:

1. Due to the Real 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.
2. An interrupt or exception cannot transfer control to a segment offset of more than 16 bits (64 Kbytes).
3. If exceptions or interrupts are allowed to occur, only the low order 16 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 work-around could be to perform software adjustment of the return address on the stack.)
4. The SMBASE relocation feature affects the way the processor returns from an interrupt or exception during an SMI# handler.

8.7.3 Halt During SMM

HALT should not be executed during SMM, unless interrupts have been enabled (see Section 8.7.2 “Exception Handling”). Interrupts are disabled in SMM. INTR, NMI, and SMI# are the only events that take the processor out of HALT.

8.7.4 Relocating SMRAM to an Address Above One Megabyte

Within SMM (or Real Mode), the segment base registers can be updated only by changing the segment register. 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 four bits to determine the segment base address). If SMRAM is relocated to an address above one megabyte, the segment registers can no longer be initialized to point to SMRAM.

These areas can be accessed by using address override prefixes to generate an offset to the correct address. For example, if the SMBASE has been relocated immediately below 16 Mbytes, the DS and ES registers are still initialized to 0000 0000H. We can still access data in SMRAM by using 32-bit displacement registers:

```
mov   esi,00FFxxxxH;       64K segment
                           ;immediately
                           ;below 16 M
mov   ax,ds:[esi]
```

9

Hardware Interface

Chapter Contents

CHAPTER 9
HARDWARE INTERFACE

9.1 INTRODUCTION

The Intel486™ processor has separate parallel buses for addresses and data. The bidirectional data bus is 32 bits wide. The address bus consists of two components: 30 address lines (A[31:2]) and 4-byte enable lines (BE[3:0]#). The address lines form the upper 30 bits of the address and the byte enables select individual bytes within a 4-byte location. The address lines are bidirectional for use in cache line invalidations (see Figure 9-1).

The Intel486 processor's burst bus mechanism enables high-speed cache fills from external memory. Burst cycles can strobe data into the processor at a rate of one item every clock. Non-burst cycles have a maximum rate of one item every two clocks. Burst cycles are not limited to cache fills: all read bus cycles requiring more than a single data cycle can be burst.

During bus hold, the Intel486 processor relinquishes control of the local bus by floating its address, data, and control lines. The Intel486 processor has an address hold (AHOLD) feature in addition to bus hold. During address hold, only the address bus is floated; the data and control buses can remain active. Address hold is used for cache line invalidations.

The Intel486 processor supports the IEEE 1149.1 boundary scan.

This section provides a brief description of the Intel486 processor input and output signals arranged by functional groups. The # symbol at the end of a signal name indicates that the active or asserted state occurs when the signal is at a low voltage. When # is not present after the signal name, the signal is active at a high voltage level. The term "ready" is used to indicate that the cycle is terminated with RDY# or BRDY#.

This chapter and Chapter 10, "Bus Operation," describe bus cycles and data cycles. A bus cycle is at least two-clocks long and begins with ADS# active in the first clock. and RDY# and/or BRDY# are active in the last clock. Data is transferred to or from the Intel486 processor during a data cycle. A bus cycle contains one or more data cycles.

NOTE

The ULP486 GX processor has a 16-bit data bus architecture.

9.2 SIGNAL DESCRIPTIONS

9.2.1 Clock (CLK)

CLK provides the fundamental timing and the internal operating frequency for the Intel486 processor. All external timing parameters are specified with respect to the rising edge of CLK.

The Intel486 processor can operate over a wide frequency range; however the CLK frequency cannot change rapidly while RESET is inactive. The CLK frequency must be stable for proper chip operation because a single edge of CLK is used internally to generate two phases. CLK only needs TTL levels for proper operation. Figure 9-2 illustrates the CLK waveform.

NOTE

The ULP486 SX and ULP486 GX utilize an advanced DDL circuit that allows dynamic clock frequency changes. See the individual processor datasheets for further information.

9.2.2 IntelDX4™ Processor Clock Multiplier Selectable Input (CLKMUL)

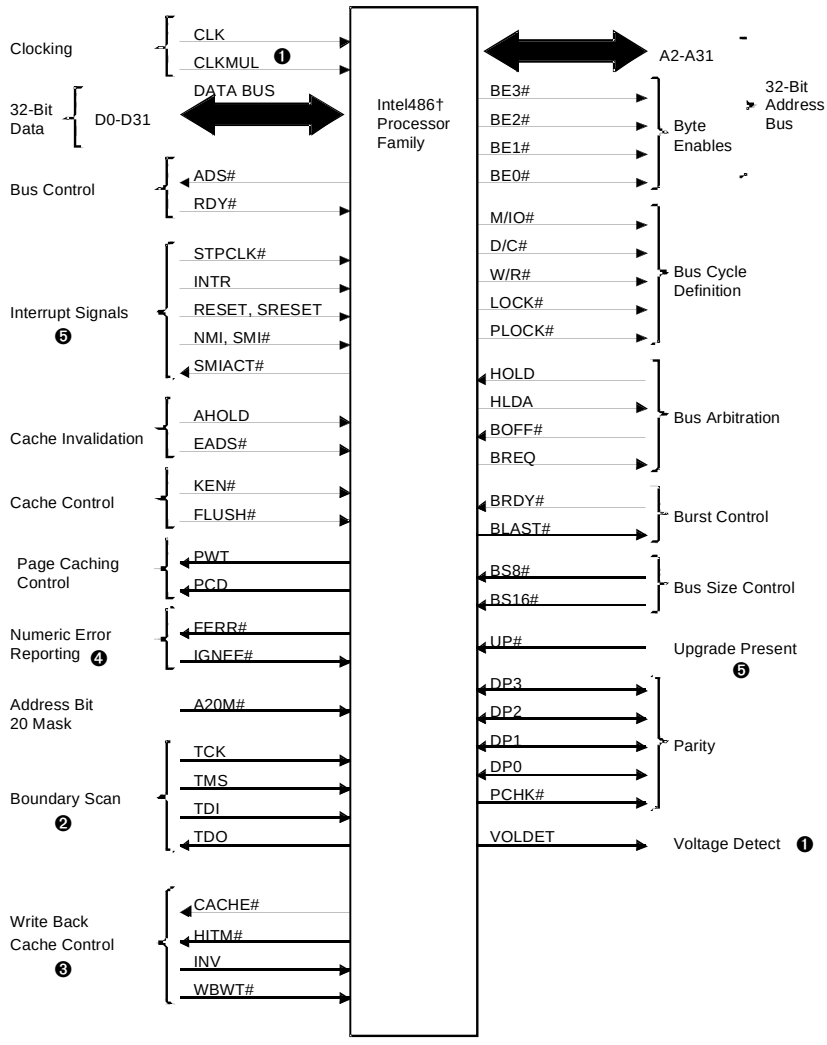
The IntelDX4 processor differs from the IntelDX2™ processor in that it provides for two internal clock multiplier ratios: speed-doubled mode and speed-tripled mode. Speed-doubled mode is identical to the IntelDX2 processor mode of operation, in which the internal core is operating at twice the external bus frequency. Selecting speed-tripled mode causes the internal core frequency to operate at three times the external bus frequency. The IntelDX4 processor determines the desired clock multiplier ratio by sampling the status of the CLKMUL input during cold (power on) processor resets.

NOTE

The clock multiplier ratio cannot be changed during warm resets. Also, SRESET cannot be used to select the clock multiplier ratio.

NOTE

The speed-doubled IntelDX4 processor option is neither tested nor guaranteed. Designers that wish to implement the speed-doubled mode of operation should use the IntelDX2 processor.



1. IntelDX4™ processor only
2. Not on Intel486™ SX processor in PGA package.
3. Pins on Write-Back Enhanced Intel486 processors when in Enhanced Bus Mode/Write-Back Cache Mode
4. Not on Intel486 SX processor.
5. SMI#, SMIACT#, STPCLK, SRESET, UP# not on 50-MHz Intel486 DX processor

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Figure 9-1. Functional Signal Groupings

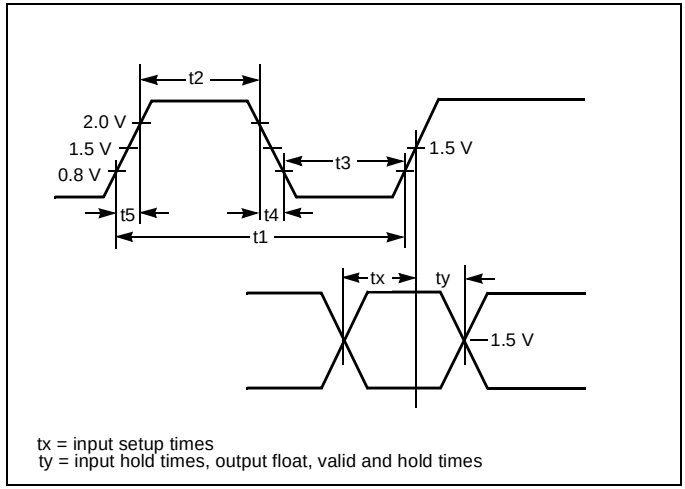


Figure 9-2. CLK Waveform

To determine which clock multiplier to use, the IntelDX4 processor samples the status of CLKMUL while RESET is active. If CLKMUL is driven low during RESET, the frequency of the core will be twice the external bus frequency (speed-doubled mode). If driven high or left floating, speed-tripled mode is selected (see Table 9-1). In order to allow maximum flexibility, CLKMUL can be jumper-configurable to either V_{CC} to indicate speed-tripled mode or V_{SS} to indicate speed-doubled mode (see Figure 9-3).

Table 9-1. Clock Multiplier Selection

CLKMUL at RESET	Clock Multiplier	External Clock Freq. (MHz)	Internal Clock Freq. (MHz)
V_{CC}† or	3	25	75
Not Driven		33	100
V_{SS}‡	2	50	100

†This mode is neither tested nor supported.

‡This mode is tested and supported.

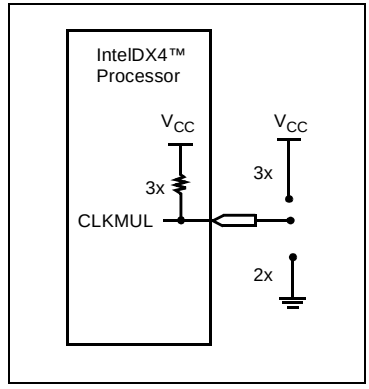


Figure 9-3. Voltage Detect (VOLDET) Sense Pin

The clock multiplier selection method is fully backward compatible with Intel486 processor-based system designs. The CLKMUL signal occupies a pin that is labeled as an "INC" on other Intel486 processors. Therefore, this pin is not driven in other Intel486 processor system designs. The IntelDX4 processor contains an internal pull-up resistor on the CLKMUL signal. As shown in Table 9-2, when CLKMUL is not driven, the internal core frequency defaults to speed-tripled mode.

The internal pull-up resistor on the CLKMUL pin is disabled while the IntelDX4 processor is in the Stop Grant or Stop Clock modes. On a system with CLKMUL connected to V_{SS}, this prevents a low level DC current path from drawing current while the processor is in the Stop Grant or Stop Clock states.

9.2.3 Address Bus (A[31:2], BE[3:0]#)

A[31:2] and BE[3:0]# form the address bus and provide physical memory and I/O port addresses. The Intel486 processor is capable of addressing 4 gigabytes of physical memory space (00000000H through FFFFFFFFH), and 64 Kbytes of I/O address space (00000000H through 0000FFFFH). A[31:2] identify addresses to a 4-byte location. BE[3:0]# identify which bytes within the 4-byte location are involved in the current transfer.

Addresses are driven back into the Intel486 processor over A[31:4] during cache line invalidations. The address lines are active high. When used as inputs into the processor, A[31:4] must meet the setup and hold times t_{22} and t_{23}. A[31:2] are not driven during bus or address hold.

The byte enable outputs, BE[3:0]#, determine which bytes must be driven valid for read and write cycles to external memory.

- BE3# applies to D[31:24]
- BE2# applies to D[23:16]
- BE1# applies to D[15:8]
- BE0# applies to D[7:0]

BE[3:0]# can be decoded to generate A0, A1 and BHE# signals used in 8- and 16-bit systems (see Table 10-5 in Chapter 10, "Bus Operation"). BE[3:0]# are active low and are not driven during bus hold.

9.2.4 Data Lines (D[31:0])

The bidirectional lines D[31:0] form the data bus for the Intel486 processor. D[7:0] define the least significant byte and D[31:24] the most significant byte. Data transfers to 8- or 16-bit devices are enabled using the data bus sizing feature, which is controlled by the BS8# or BS16# input signals. D[31:0] are active high. For reads, D[31:0] must meet the setup and hold times t_{22} and t_{23}. D[31:0] are not driven during read cycles and bus hold.

9.2.5 Parity

9.2.5.1 Data Parity Input/Outputs (DP[3:0])

DP[3:0] are the data parity pins for the processor. There is one pin for each byte of the data bus. Even parity is generated or checked by the parity generators/checkers. Even parity means that there are an even number of high inputs on the eight corresponding data bus pins and parity pin.

Data parity is generated on all write data cycles with the same timing as the data driven by the Intel486 processor. Even parity information must be driven back to the Intel486 processor on these pins with the same timing as read information to ensure that the correct parity check status is indicated by the Intel486 processor.

The values read on these pins do not affect program execution. It is the responsibility of the system to take appropriate actions if a parity error occurs.

Input signals on DP[3:0] must meet setup and hold times t_{22} and t_{23} for proper operation.

9.2.5.2 Parity Status Output (PCHK#)

Parity status is driven on the PCHK# pin, and a parity error is indicated by this pin being low. For read operations, PCHK# is driven the clock after ready to indicate the parity status for the data sampled at the end of the previous clock. Parity is checked during code reads, memory reads and I/O reads. Parity is not checked during interrupt acknowledge cycles. PCHK# only checks the parity status for enabled bytes as indicated by the byte enable and bus size signals. It is valid only in the clock immediately after read data is returned to the Intel486 processor. At all other times, it is inactive (high). PCHK# is never floated.

Driving PCHK# is the only effect that bad input parity has on the Intel486 processor. The Intel486 processor does not vector to a bus error interrupt when bad data parity is returned. In systems that do not employ parity, PCHK# can be ignored. In systems not using parity, DP[3:0] should be connected to V_{CC} through a pull-up resistor.

9.2.6 Bus Cycle Definition

9.2.6.1 M/IO#, D/C#, W/R# Outputs

M/IO#, D/C# and W/R# are the primary bus cycle definition signals. They are driven valid as the ADS# signal is asserted. M/IO# distinguishes between memory and I/O cycles, D/C# distinguishes between data and control cycles and W/R# distinguishes between write and read cycles.

Table 9-3 shows bus cycle definitions as a function of M/IO#, D/C# and W/R#. Note the difference between the Intel486 processor and Intel386™ processor bus cycle definitions. The halt bus cycle type has been moved to location 001 in the Intel486 processor from location 101 in the Intel386 processor. Location 101 is now reserved.

Special bus cycles are discussed in Section 10.3.11, “Special Bus Cycles.”

Table 9-2. ADS# Initiated Bus Cycle Definitions

M/IO#	D/C#	W/R#	Bus Cycle Initiated
0	0	0	Interrupt Acknowledge
0	0	1	Halt/Special Cycle
0	1	0	I/O Read
0	1	1	I/O Write
1	0	0	Code Read
1	0	1	Reserved
1	1	0	Memory Read
1	1	1	Memory Write

9.2.6.2 Bus Lock Output (LOCK#)

LOCK# indicates that the Intel486 processor is running a read-modify-write cycle in which the external bus must not be relinquished between the read and write cycles. Read-modify-write cycles are used to implement memory-based semaphores. Multiple reads or writes can be locked.

When LOCK# is asserted, the current bus cycle is locked and the Intel486 processor should be allowed exclusive access to the system bus. LOCK# goes active in the first clock of the first locked bus cycle and goes inactive after ready is returned indicating the last locked bus cycle.

The Intel486 processor does not acknowledge bus hold when LOCK# is asserted (although it does allow an address hold). LOCK# is active low and is floated during bus hold. Locked read cycles are not transformed into cache fill cycles if KEN# is returned active. Refer to Section 10.3.7, “Pseudo-Locked Cycles,” for a detailed discussion of locked bus cycles.

9.2.6.3 Pseudo-Lock Output (PLOCK#)

The pseudo-lock feature allows atomic reads and writes of memory operands greater than 32 bits. These operands require more than one cycle to transfer. The Intel486 processor asserts PLOCK# during segment table descriptor reads (64 bits) and cache line fills (128 bits).

When PLOCK# is asserted, no other master is given control of the bus between cycles. A bus hold request (HOLD) is not acknowledged during pseudo-locked reads and writes, with one exception. During non-cacheable non-burst code prefetches, HOLD is recognized on memory cycle boundaries even though PLOCK# is asserted. The Intel486 processor drives PLOCK# active until the addresses for the last bus cycle of the transaction have been driven, regardless of whether BRDY# or RDY# are returned.

A pseudo-locked transfer is meaningful only if the memory operand is aligned and if its completely contained within a single cache line.

Because PLOCK# is a function of the bus size and KEN# inputs, PLOCK# should be sampled only in the clock ready is returned. PLOCK# is active low and is not driven during bus hold (see Section 10.3.7, "Pseudo-Locked Cycles").

9.2.6.4 PLOCK# Floating-Point Considerations

For processors with an on-chip FPU, the following must be noted for PLOCK# operation. A 64-bit floating-point number must be aligned to an 8-byte boundary to guarantee an atomic access. Normally, PLOCK# and BLAST# are inverses of each other. However, during the first cycle of a 64-bit floating-point write, both PLOCK# and BLAST# are asserted. Intel486 processors with on-chip FPUs also assert PLOCK# during floating-point long reads and writes (64 bits), segmentable description reads (64 bits), and code line fills (128 bits).

9.2.7 Bus Control

The bus control signals allow the Intel486 processor to indicate when a bus cycle has begun, and allow other system hardware to control burst cycles, data bus width, and bus cycle termination.

9.2.7.1 Address Status Output (ADS#)

The ADS# output indicates that the address and bus cycle definition signals are valid. This signal goes active in the first clock of a bus cycle and goes inactive in the second and subsequent clocks of the cycle. ADS# is also inactive when the bus is idle.

ADS# is used by the external bus circuitry as the indication that the Intel486 processor has started a bus cycle. The external circuit must sample the bus cycle definition pins on the next rising edge of the clock after ADS# is driven active.

ADS# is active low and is not driven during bus hold.

9.2.7.2 Non-Burst Ready Input (RDY#)

RDY# indicates that the current bus cycle is complete. In response to a read, RDY# indicates that the external system has presented valid data on the data pins. In response to a write request, RDY# indicates that the external system has accepted the Intel486 processor data. RDY# is ignored when the bus is idle and at the end of the first clock of the bus cycle. Because RDY# is sampled during address hold, data can be returned to the processor when AHOLD is active.

RDY# is active low, and is not provided with an internal pull-up resistor. This input must satisfy setup and hold times t_{16} and t_{17} for proper chip operation.

9.2.8 Burst Control

9.2.8.1 Burst Ready Input (BRDY#)

BRDY# performs the same function during a burst cycle that RDY# performs during a non-burst cycle. BRDY# indicates that the external system has presented valid data on the data pins in response to a read or that the external system has accepted the Intel486 processor data in response to a write. BRDY# is ignored when the bus is idle and at the end of the first clock in a bus cycle.

During a burst cycle, BRDY# is sampled each clock. If it is active, the data presented on the data bus pins is strobed into the Intel486 processor. ADS# is negated during the second through last data cycles in the burst, but address lines A[3:2] and the byte enables change to reflect the next data item expected by the Intel486 processor.

If RDY# is returned simultaneously with BRDY#, BRDY# is ignored and the burst cycle is prematurely aborted. An additional complete bus cycle is initiated after an aborted burst cycle if the cache line fill was not complete. BRDY# is treated as a normal ready for the last data cycle in a burst transfer or for non-burstable cycles (see Section 10.3.2, “Multiple and Burst Cycle Bus Transfers” for burst cycle timing).

BRDY# is active low and is provided with a small internal pull-up resistor. BRDY# must satisfy the setup and hold times t_{16} and t_{17}.

9.2.8.2 Burst Last Output (BLAST#)

BLAST# indicates that the next time BRDY# is returned it will be treated as a normal RDY#, terminating the line fill or other multiple-data-cycle transfer. BLAST# is active for all bus cycles regardless of whether they are cacheable or not. This pin is active low and is not driven during bus hold.

9.2.9 Interrupt Signals

The interrupt signals can interrupt or suspend execution of the processor's instruction stream.

9.2.9.1 Reset Input (RESET)

The RESET input must be used at power-up to initialize the processor. RESET forces the processor to begin execution at a known state. The processor cannot begin execution of instructions until at least 1 ms after V_{CC} and CLK reach their proper DC and AC specifications. The RESET pin should remain active during this time to ensure proper processor operation. However, for warm boot-ups RESET should remain active for at least 15 CLK periods. RESET is active high. RESET is asynchronous but must meet setup and hold times t_{20} and t_{21} for recognition in any specific clock.

RESET returns SMBASE to the default value of 30000H. If SMBASE relocation is not used, RESET can be used as the only reset (see Chapter 8, "System Management Mode (SMM) Architectures").

The Intel486 processor is placed in the Power Down Mode if RESERVED# is sampled active at the falling edge of RESET.

9.2.9.2 Soft Reset Input (SRESET)

The SRESET (soft reset) input has the same functions as RESET, but does not change the SMBASE, and RESERVED# is not sampled on the falling edge of SRESET. If the system uses SMBASE relocation, the soft resets should be handled using the SRESET input. SRESET should not be used for the cold boot-up power-on reset.

The SRESET input pin is provided to save the status of SMBASE during an Intel 80286 processor-compatible mode change. SRESET leaves the location of SMBASE intact while resetting other units, including the on-chip cache. See Section 9.2.18.4, "Soft Reset (SRESET)" on page 9-20 for Write-Back Enhanced Intel486 processor differences. For compatibility, the system should use SRESET to flush the on-chip cache. The FLUSH# input pin should be used to flush the on-chip cache. SRESET should not be used to initiate test modes.

9.2.9.3 System Management Interrupt Request Input (SMI#)

SMI# is the system management mode interrupt request signal. The SMI# request is acknowledged by the SMIACT# signal. After the SMI# interrupt is recognized, the SMI# signal is masked internally until the RSM instruction is executed and the interrupt service routine is complete. SMI# is falling-edge sensitive after internal synchronization.

The SMI# input must be held inactive for at least four clocks after it is asserted to reset the edge triggered logic. SMI# is provided with a pull-up resistor to maintain compatibility with designs that do not use this feature. SMI# is an asynchronous signal, but setup and hold times t_{20} and t_{21} must be met in order to guarantee recognition on a specific clock.

9.2.9.4 System Management Mode Active Output (SMIACT#)

SMIACT# indicates that the processor is operating in System Management Mode. The processor asserts SMIACT# in response to an SMI interrupt request on the SMI# pin. SMIACT# is driven active after the processor has completed all pending write cycles (including emptying the write buffers), and before the first access to SMRAM, in which the processor saves (writes) its state (or context) to SMRAM. SMIACT# remains active until the last access to SMRAM when the processor restores (reads) its state from SMRAM. The SMIACT# signal does not float in response to HOLD. The SMIACT# signal is used by the system logic to decode SMRAM.

9.2.9.5 Maskable Interrupt Request Input (INTR)

INTR indicates that an external interrupt has been generated. Interrupt processing is initiated when the IF flag is active in the EFLAGS register.

The Intel486 processor generates two locked interrupt acknowledge bus cycles in response to asserting the INTR pin. An 8-bit interrupt number is latched from an external interrupt controller at the end of the second interrupt acknowledge cycle. INTR must remain active until the interrupt acknowledges have been performed to assure program interruption. Refer to Section 10.3.10, "Interrupt Acknowledge," for a detailed discussion of interrupt acknowledge cycles.

The INTR pin is active high and is not provided with an internal pull-down resistor. INTR is asynchronous, but the INTR setup and hold times t_{20} and t_{21} must be met to assure recognition on any specific clock.

9.2.9.6 Non-maskable Interrupt Request Input (NMI)

NMI is the non-maskable interrupt request signal. Asserting NMI causes an interrupt with an internally supplied vector value of 2. External interrupt acknowledge cycles are not generated because the NMI interrupt vector is internally generated. When NMI processing begins, the NMI signal is masked internally until the IRET instruction is executed.

NMI is rising edge sensitive after internal synchronization. NMI must be held low for at least four CLK periods before this rising edge for proper operation. NMI is not provided with an internal pull-down resistor. NMI is asynchronous but setup and hold times, t_{20} and t_{21} must be met to assure recognition on any specific clock.

9.2.9.7 Stop Clock Interrupt Request Input (STPCLK#)

The Intel486 processor provides an interrupt mechanism, STPCLK#, that allows system hardware to control the processor's power consumption. The STPCLK# signal can be asserted to stop the internal clock (output of the PLL) to the processor core in a controlled manner. This low-power state is called the Stop Grant state. In addition, the STPCLK# interrupt allows the system to change the input frequency within the specified range or completely stop the CLK input frequency (input to the PLL). If the CLK input is completely stopped, the processor enters into the Stop Clock state—the lowest power state. If the frequency is changed or stopped, the Intel486 processor does not return to the Stop Grant state until the CLK input has been running at a constant frequency for the time period necessary to stabilize the PLL (minimum of 1 ms).

The Intel486 processor generates a Stop Grant bus cycle in response to the STPCLK# interrupt request. STPCLK# is active low and is provided with an internal pull-up resistor. STPCLK# is an asynchronous signal, but must remain active until the processor issues the Stop Grant bus cycle (see Section 10.3.11.3, "Stop Grant Indication Cycle").

9.2.10 Bus Arbitration Signals

This section describes the mechanism by which the processor relinquishes control of its local bus when the local bus is requested by another bus master.

9.2.10.1 Bus Request Output (BREQ)

The Intel486 processor asserts BREQ when a bus cycle is pending internally. Thus, BREQ is always asserted in the first clock of a bus cycle, along with ADS#. If the Intel486 processor currently is not driving the bus (due to HOLD, AHOLD, or BOFF#), BREQ is asserted in the same clock that ADS# would have been asserted if the Intel486 processor were driving the bus. After the first clock of the bus cycle, BREQ may change state. It is asserted if additional cycles are necessary to complete a transfer (via BS8#, BS16#, KEN#), or if more cycles are pending internally. However, if no additional cycles are necessary to complete the current transfer, BREQ can be negated before ready comes back for the current cycle. External logic can use the BREQ signal to arbitrate among multiple processors. This pin is driven regardless of the state of bus hold or address hold. BREQ is active high and is never floated. During a hold state, internal events may cause BREQ to be de-asserted prior to any bus cycles.

9.2.10.2 Bus Hold Request Input (HOLD)

HOLD allows another bus master complete control of the Intel486 processor bus. The Intel486 processor responds to an active HOLD signal by asserting HLDA and placing most of its output and input/output pins in a high impedance state (floated) after completing its current bus cycle, burst cycle, or sequence of locked cycles. In addition, if the Intel486 processor receives a HOLD request while performing a code fetch, and that cycle is backed off (BOFF#), the Intel486 processor will recognize HOLD before restarting the cycle. The code fetch can be non-cacheable or cacheable and non-burst or burst. The BREQ, HLDA, PCHK# and FERR# pins are not floated during bus hold. The Intel486 processor maintains its bus in this state until the HOLD is de-asserted. Refer to Section 10.3.9, "Bus Hold," for timing diagrams for bus hold cycles and HOLD request acknowledge during BOFF#.

Unlike the Intel386 processor, the Intel486 processor recognizes HOLD during reset. Pull-up resistors are not provided for the outputs that are floated in response to HOLD. HOLD is active high and is not provided with an internal pull-down resistor. HOLD must satisfy setup and hold times t_{18} and t_{19} for proper chip operation.

9.2.10.3 Bus Hold Acknowledge Output (HLDA)

HLDA indicates that the Intel486 processor has given the bus to another local bus master. HLDA goes active in response to a hold request presented on the HOLD pin. HLDA is driven active in the same clock in which the Intel486 processor floats its bus.

HLDA is driven inactive when leaving bus hold, and the Intel486 processor resumes driving the bus. The Intel486 processor does not cease internal activity during bus hold because the internal cache satisfies the majority of bus requests. HLDA is active high and remains driven during bus hold.

9.2.10.4 Backoff Input (BOFF#)

Asserting the BOFF# input forces the Intel486 processor to release control of its bus in the next clock. The pins floated are exactly the same as those floated in response to HOLD. The response to BOFF# differs from the response to HOLD in two ways: First, the bus is floated immediately in response to BOFF#, whereas the Intel486 processor completes the current bus cycle before floating its bus in response to HOLD. Second the Intel486 processor does not assert HLDA in response to BOFF#.

The Intel486 processor remains in bus hold until BOFF# is negated. Upon negation, the Intel486 processor restarts the bus cycle that was aborted when BOFF# was asserted. To the internal execution engine the effect of BOFF# is the same as inserting a few wait states to the original cycle. Refer to Section 10.3.12, “Bus Cycle Restart,” for a description of bus cycle restart.

Any data returned to the Intel486 processor while BOFF# is asserted is ignored. BOFF# has higher priority than RDY# or BRDY#. If both BOFF# and ready are returned in the same clock, BOFF# takes effect. If BOFF# is asserted while the bus is idle, the Intel486 processor floats its bus in the next clock. BOFF# is active low and must meet setup and hold times t_{18} and t_{19} for proper chip operation.

9.2.11 Cache Invalidation

The AHOLD and EADS# inputs are used during cache invalidation cycles. AHOLD conditions the Intel486 processor address lines, A[31:4], to accept an address input. EADS# indicates that an external address is actually valid on the address inputs. Activating EADS# causes the Intel486 processor to read the external address bus and perform an internal cache invalidation cycle to the address indicated. Refer to Section 10.3.8, “Invalidate Cycles,” for cache invalidation cycle timing.

9.2.11.1 Address Hold Request Input (AHOLD)

AHOLD is the address hold request. It allows another bus master access to the Intel486 processor address bus for performing an internal cache invalidation cycle. Asserting AHOLD forces the Intel486 processor to stop driving its address bus in the next clock. While AHOLD is active only the address bus is floated, the remainder of the bus can remain active. For example, data can be returned for a previously specified bus cycle when AHOLD is active. The Intel486 processor does not initiate another bus cycle during address hold. Because the Intel486 processor floats its bus immediately in response to AHOLD, an address hold acknowledge is not required. If AHOLD is asserted while a bus cycle is in progress and no readies are returned during the time AHOLD is asserted, the Intel486 processor re-drives the same address (that it originally sent out) once AHOLD is negated.

AHOLD is recognized during reset. Because the entire cache is invalidated by reset, any invalidation cycles run during reset is unnecessary. AHOLD is active high and is provided with a small internal pull-down resistor. It must satisfy the setup and hold times t_{18} and t_{19} for proper chip operation. AHOLD also determines whether or not the built-in self-test features of the Intel486 processor are exercised on assertion of RESET. For more information on these features, see "Built-In Self Test (BIST)" in Appendix B.

9.2.11.2 External Address Valid Input (EADS#)

EADS# indicates that a valid external address has been driven onto the Intel486 processor address pins. This address is used to perform an internal cache invalidation cycle. The external address is checked with the current cache contents. If the specified address matches an area in the cache, that area is immediately invalidated.

An invalidation cycle can be run by asserting EADS# regardless of the state of AHOLD, HOLD and BOFF#. EADS# is active low and is provided with an internal pull-up resistor. EADS# must satisfy the setup and hold times t_{12} and t_{13} for proper chip operation.

9.2.12 Cache Control

9.2.12.1 Cache Enable Input (KEN#)

KEN# is the cache enable pin. KEN# is used to determine whether the data being returned by the current cycle is cacheable. When KEN# is active and the Intel486 processor generates a cycle that can be cached (most read cycles), the cycle is transformed into a cache line fill cycle.

A cache line is 16 bytes long. During the first cycle of a cache line fill, the byte-enable pins should be ignored and data should be returned as if all four byte enables were asserted. The Intel486 processor runs between 4 and 16 contiguous bus cycles to fill the line depending on the bus data width selected by BS8# and BS16#. Refer to Section 10.3.3, "Cacheable Cycles," for a description of cache line fill cycles.

The KEN# input is active low and is provided with a small internal pull-up resistor. It must satisfy the setup and hold times t_{14} and t_{15} for proper chip operation.

9.2.12.2 Cache Flush Input (FLUSH#)

The FLUSH# input forces the Intel486 processor to flush its entire internal cache. FLUSH# is active low and must be asserted for one clock only. FLUSH# is asynchronous but setup and hold times t_{20} and t_{21} must be met for recognition on any specific clock.

FLUSH# also determines whether or not the three-state test mode of the Intel486 processor is invoked on assertion of RESET (see "Three-State Output Test Mode" in Appendix B).

9.2.13 Page Cacheability (PWT, PCD)

The PWT and PCD output signals correspond to two user attribute bits in the page table entry. When paging is enabled, PWT and PCD correspond to bits 3 and 4 of the page table entry, respectively. For cycles that are not paged when paging is enabled (for example I/O cycles) PWT and PCD correspond to bits 3 and 4 in Control Register 3. When paging is disabled, the Intel486 processor ignores the PCD and PWT bits and assumes they are zero for the purpose of caching and driving PCD and PWT.

PCD is masked by the CD (cache disable) bit in Control Register 0 (CR0). When CD=1 (cache line fills disabled) the Intel486 processor forces PCD high. When CD=0, PCD is driven with the value of the page table entry/directory.

The purpose of PCD is to provide a cacheable/non-cacheable indication on a page by page basis. The Intel486 processor does not perform a cache fill to any page in which bit 4 of the page table entry is set. PWT corresponds to the write-back bit and can be used by an external cache to provide this functionality. PCD and PWT bits are assigned a value of zero during Real Mode and when paging is disabled. Refer to Section 7.6, "Page Cacheability," for a discussion of non-cacheable pages.

PCD and PWT have the same timing as the cycle definition pins (M/IO#, D/C#, W/R#). PCD and PWT are active high and are not driven during bus hold.

NOTE

The PWT and PCD bits function differently in the write-back mode of the Write-Back Enhanced Intel486 processors (see Section 7.6.1, "Write-Back Enhanced IntelDX4™ Processor and Processor Page Cacheability").

9.2.14 RESERVED#

The RESERVED# input detects the presence of an in-circuit emulator, then powers down the core, and three-states all outputs of the original processor, so that the original processor consumes very low current. This state is known as Reserved Power Down Mode. RESERVED# is active low and sampled at all times, including after power-up and during reset.

9.2.15 Numeric Error Reporting (FERR#, IGNNE#)

To allow PC-type floating-point error reporting, IntelDX2 and IntelDX4 processors provide two pins, FERR# and IGNNE#.

9.2.15.1 Floating-Point Error Output (FERR#)

The processor asserts FERR# when an unmasked floating-point error is encountered. FERR# is similar to the ERROR# pin on the Intel387 math coprocessor. FERR# can be used by external logic for PC-type floating-point error reporting in systems with an IntelDX2 or IntelDX4 processor. FERR# is active low and is not floated during bus hold.

In some cases, FERR# is asserted when the next floating-point instruction is encountered. In other cases, it is asserted before the next floating-point instruction is encountered, depending on the execution state of the instruction that caused the exception.

The following class of floating-point exceptions assert FERR# at the time the exception occurs (i.e., before encountering the next floating-point instruction):

1. The stack fault, invalid operation, and denormal exceptions on all transcendental instructions, integer arithmetic instructions, FSQRT, FSCALE, FPREM(1), FXTRACT, FBLD, and FBSTP.
2. Any exceptions on store instructions (including integer store instructions).

The following class of floating-point exceptions assert FERR# only after encountering the next floating-point instruction:

1. Exceptions other than on all transcendental instructions, integer arithmetic instructions, FSQRT, FSCALE, FPREM(1), FXTRACT, FBLD, and FBSTP.
2. Any exception on all basic arithmetic, load, compare, and control instructions (i.e., all other instructions).

In the event of a pending unmasked floating-point exception the FNINIT, FNCLEX, FNSTENV, FNSAVE, FNSTSW and FNSTCW instructions assert the FERR# pin. Shortly after the assertion of the pin, an interrupt window is opened during which the processor samples and services interrupts, if any. If no interrupts are sampled within this window, the processor then executes these instructions with the pending unmasked exception. However, for the FNCLEX, FNINIT, FNSTENV and FNSAVE instructions, the FERR# pin is de-asserted to enable the execution of these instructions. For details, please refer to the *Intel486™ Processor Family Programmer's Reference Manual*.

9.2.15.2 Ignore Numeric Error Input (IGNNE#)

When IGNNE# is asserted and FERR# is still activated, IntelDX2 and IntelDX4 processors ignore numeric errors and continue executing non-control floating-point instructions. When IGNNE# is not asserted and a pending unmasked numeric exception exists (SW.ES=1), the Intel486 processor behaves as follows:

When the Intel486 processor encounters the floating-point instructions FNINIT, FNCLEX, FNSTENV, FNSAVE, FNSTSW or FNSTCW, the processor asserts the FERR# pin. Subsequently, the processor opens an interrupt sampling window. The interrupts are checked and serviced during this window. If no interrupts are sampled within this window the processor then executes these instructions in spite of the pending unmasked exception. For further details, please refer to the *Intel486™ Processor Family Programmer's Reference Manual*.

When the Intel486 processor encounters any floating-point instruction other than FNINIT, FNCLEX, FNSTENV, FNSAVE, FNSTSW or FNSTCW, the processor stops execution, asserts the FERR# pin, and waits for an external interrupt.

IGNNE# has no effect when the NE bit in control register 0 is set.

The IGNNE# input is active low and provided with a small internal pull-up resistor. This input is asynchronous, but must meet setup and hold times t_{20} and t_{21} to ensure recognition on any specific clock.

NOTE

The IGNNE# and FERR# pins doe not exist on the Intel486 SX processors.

9.2.16 Bus Size Control (BS16#, BS8#)

The BS16# and BS8# inputs allow external 16- and 8-bit buses to be supported with a small number of external components. The Intel486 processor samples these pins every clock. The bus size is determined by the value sampled in the clock before ready. When asserting BS16# or BS8#, only 16 or 8 bits of the data bus must be valid. If both BS16# and BS8# are asserted, an 8-bit bus width is selected.

When BS16# or BS8# are asserted, the Intel486 processor converts a larger data request to the appropriate number of smaller transfers. The byte enables are also modified appropriately for the bus size selected.

BS16# and BS8# are active low and are provided with small internal pull-up resistors. BS16# and BS8# must satisfy the setup and hold times t_{14} and t_{15} for proper chip operation.

NOTE

The BS8# and BS16# are not available on the Ultra-Low Power Intel486 GX processor.

9.2.17 Address Bit 20 Mask (A20M#)

Asserting the A20M# input causes the Intel486 processor to mask physical address bit 20 before performing a lookup in the internal cache and before driving a memory cycle to the outside world. When A20M# is asserted, the Intel486 processor emulates the 1-Mbyte address wraparound that occurs on the 8086. A20M# is active low and must be asserted only when the processor is in Real Mode. A20M# is not defined in Protected Mode. A20M# is asynchronous but should meet setup and hold times t_{20} and t_{21} for recognition in any specific clock. For correct operation of the chip, A20M# should not be active at the falling edge of RESET.

A20M# exhibits a minimum 4 clock latency, from time of assertion to masking of the A20 bit. A20M# is ignored during cache invalidation cycles. I/O writes require A20M# to be asserted a minimum of 2 clocks prior to RDY being returned for the I/O write. This ensures recognition of the address mask before the Intel486 processor begins executing the instruction following OUT. If A20M# is asserted after the ADS# of a data cycle, the A20 address signal is not masked during this cycle but is masked in the next cycle. During a prefetch (cacheable or not), if A20M# is asserted after the first ADS#, A20 is not masked for the duration of the prefetch even if BS16# or BS8# is asserted.

9.2.18 Write-Back Enhanced IntelDX4™ Processor Signals and Other Enhanced Bus Features

This section describes the pins that interface with the system to support the Enhanced Bus mode/write-back cache features at system level.

9.2.18.1 Cacheability (CACHE#)

The CACHE# output indicates the internal cacheability on read cycles and a burst write-back on write cycles. CACHE# is asserted for cacheable reads, cacheable code fetches and write-backs. It is driven inactive for non-cacheable reads, special cycles, I/O cycles and write-through cycles. This is different from the PCD (page cache disable) pin. The operational differences between CACHE# and PCD are listed in Table 9-3. See Table 9-4 for operational differences between CACHE# and other Intel486 processor signals.

Table 9-3. Differences between CACHE# and PCD

Bus Operation	CACHE#	PCD
All reads (1)	same as PCD(3)	same as PCD(3)
Replacement write-back	low	low
Snoop-forced write-back	low	low
S-state write-through	high	same as PCD(3)
I-state write-through (2)	high	same as PCD(3)

NOTES:
1. Includes line fills and non-cacheable reads. During locked read cycles CACHE# is inactive. The non-cacheable reads may or may not be burst.
2. Due to the non-allocate on write policy, this includes both cacheable and non-cacheable writes. PCD distinguishes between the two, but CACHE# does not.
3. This behavior is the same as the existing specification of the Intel486™ processor in write-through mode.

Table 9-4. CACHE# vs. Other Intel486™ Processor Signals

Pin Symbol	Relation To This Signal
ADS#	CACHE# is driven to valid state with ADS#.
RDY#, BRDY#	CACHE# is de-asserted with the first RDY# or BRDY#.
HLDA, BOFF#	CACHE# floats under these signals.
KEN#	The combination of CACHE# and KEN# determines if a read miss is converted into a cache line fill.

9.2.18.2 Cache Flush (FLUSH#)

FLUSH# is an existing pin that operates differently if the processor is configured for Enhanced Bus mode (write-back) operation. In Enhanced Bus mode, FLUSH# is treated as an interrupt and acts similarly to the WBINVD instruction. It is sampled at each clock, but is recognized only on an instruction boundary. Pending writes are completed before FLUSH# is serviced, and all prefetching is stopped. Depending on the number of modified lines in the cache, the flush could take up to a minimum of 1280 bus clocks or 2560 processor clocks and a maximum of 5000+ bus clocks to scan the cache, perform the write backs, invalidate the cache and run two special cycles. After all modified lines are written back to memory, two special bus cycles, the first flush ACK cycle and the second flush ACK cycle, are issued, in that order. These cycles differ from the special cycles issued after WBINVD only in that address line 2 = 1. SRESET, STPCLK#, INTR, NMI and SMI# are not recognized during a flush write-back, whereas BOFF#, AHOLD and HOLD are recognized.

FLUSH# may be asserted just for a single clock or may be retained asserted, but should be de-asserted at or prior to the RDY# returned from the first flush ACK special bus cycle. If asserted during INVD or WBINVD, FLUSH# is recognized. If asserted simultaneously with SMI#, then SMI# is recognized after FLUSH# is serviced.

FLUSH# may be driven at any time. If driven during SRESET, it must be held for one clock after SRESET is de-asserted to be recognized.

9.2.18.3 Hit/Miss to a Modified Line (HITM#)

HITM# is a cache coherency protocol pin that is driven only in Enhanced Bus mode. When a snoop cycle is generated (with INV = 0 or INV = 1), HITM# indicates whether the processor contains the snooped line in the M-state. HITM# asserted indicates that the line will be written back in total, unless the processor is already generating a replacement write-back of the same line.

HITM# is valid on the bus two system clocks after EADS# is asserted on the bus. If asserted, HITM# remains asserted until the last RDY# or BRDY# of the snoop write-back cycle is returned. It is de-asserted before the next ADS# (see Table 9-5).

Table 9-5. HITM# vs. Other Intel486™ Processor Signals

Pin Symbol	Relation To This Signal
EADS#	HITM# is asserted due to an EADS#-driven snoop, provided the snooped line is in the M-state in the cache.
HLDA, BOFF#	HITM# does not float under these signals.
ADS#, CACHE#	The beginning of a snoop write-back cycle is identified by the assertion of ADS#, CACHE#, and HITM#.

9.2.18.4 Soft Reset (SRESET)

When in Enhanced Bus mode, SRESET has the following differences: SRESET, unlike RESET, does not cause the AHOLD, A20M#, FLUSH#, RESERVED#, and WB/WT# pins to be sampled (i.e., special test modes and on-chip cache configuration can not be accessed with SRESET.)

On SRESET, the internal SMRAM base register retains its previous value and the processor does not flush, write-back or disable the internal cache. CR0.CD and CR0.NW retain previous values, CR0.4 is set to 1, and the remaining bits are cleared. Because SRESET is treated as an interrupt, it is possible to have a bus cycle while SRESET is asserted. A bus cycle could be due to an on-going instruction, emptying the write buffers of the processor, or snoop write-back cycles if there is a snoop hit to an M-state line while SRESET is asserted.

NOTES

For both Standard Bus mode and Enhanced Bus mode:

SMI# must be blocked during SRESET. It must also be blocked for a minimum of two clocks after SRESET is de-asserted.

SRESET must be blocked during SMI#. It must also be blocked for a minimum of 20 clocks after SMIACT# is de-asserted.

9.2.18.5 Invalidation Request (INV)

INV is a cache coherency protocol pin that is used only in Enhanced Bus mode. It is sampled by the processor on EADS#-driven snoop cycles. It is necessary to assert this pin to simulate the Standard mode processor invalidate cycle on write-through-only lines. INV also invalidates the write-back lines. However, when the snooped line is in the M-state, the line is written back and then invalidated.

INV is sampled when EADS# is asserted. When INV is not asserted with EADS#, the snoop cycle has no effect on a write-through-only line or on a line allocated as write-back but not yet modified. If the line is write-back and modified, it is written back to memory but is not de-allocated (invalidated) from the internal cache. The address of the snooped cache line is provided on the address bus (see in Table 9-6).

Table 9-6. INV vs. Other Intel486™ Processor Signals

Pin Symbol	Relation To This Signal
EADS#	EADS# determines when INV is sampled.
A[31:4]	The address of the snooped cache line is provided on these pins.

9.2.18.6 Write-Back/Write-Through (WB/WT#)

WB/WT# enables Enhanced Bus mode (write-back cache). It also allows the system to define a cached line as write-through or write-back.

WB/WT# is sampled at the falling edge of RESET to determine if Enhanced Bus mode is enabled (WB/WT# must be driven for two clocks before and two clocks after RESET to be recognized by the processor). If sampled low or floated, the Write-Back Enhanced IntelDX4 processor operates in the Intel486 processor Standard mode. For write-through only operation, (i.e. Standard mode), WB/WT# does not need to be connected.

In Enhanced Bus mode, WB/WT# allows the system hardware to force any allocated line to be treated as write-through or write-back. As with cacheability, both the processor and the external system must agree that a line may be treated as write-back for the internal cache to be allocated as write-back. The default is always write-through. The processor's indication of write-back vs. write-through is from the PWT pin, in which function and timing are the same as in the Standard mode of the Intel486 processor.

To define write-back or write-through configuration of a line, WB/WT# is sampled in the same clock in which the first RDY# or BRDY# is returned during a line fill (allocation) cycle (see Table 9-7).

Table 9-7. WB/WT# vs. Other Intel486™ Processor Signals

Pin Symbol	Relation to This Signal
RDY#, BRDY#	WB/WT# is sampled with the first RDY# or BRDY#.
PWT	The combination of WB/WT# and PWT determine whether the Write-Back Enhanced IntelDX4™ processor treats the line as WB.
PCD, CACHE#, KEN#	The state of WB/WT# does not matter if PCD, CACHE# or KEN# define the line to be non-cacheable.
W/R#	WB/WT# is significant only on read fill cycles.
RESET	WB/WT# is sampled on the falling edge of RESET to define the cache configuration.

9.2.18.7 Pseudo-Lock Output (PLOCK#)

In the Enhanced Bus mode, PLOCK# is always driven inactive. In this mode, a 64-bit data read (caused by an FP operand access or a segment descriptor read) is treated as a multiple cycle read request, which may be a burst or a non-burst access based on whether BRDY# or RDY# is returned by the system. Because only write-back cycles (caused by snoop write-back or replacement write-back) are burstable, a 64-bit write is driven out as two non-burst bus cycles. BLAST# is asserted during both writes. Refer to Section 10.3, "Bus Functional Description," for details on pseudo-locked bus cycles.

9.2.19 IntelDX4™ Processor Voltage Detect Sense Output (VOLDET)

A voltage detect sense pin (VOLDET) has been added to the IntelDX4 processor PGA package. This pin allows external system logic to distinguish between a 5 V IntelDX2™ processor and the 3.3 V IntelDX4 processor. The pin passively indicates to external logic whether the installed PGA processor requires 5 V (in the case of the IntelDX2 processor) or 3.3 V (in the case of the IntelDX4 processor). Pin S4 has been defined as the VOLDET pin because this pin is defined as an INC pin on the IntelDX2 processor. This pin is provided in the PGA package only.

To use this feature, a weak external pull-up resistor should be connected to the VOLDET pin. This pin samples high (logic 1) if the installed processor is a 5 V IntelDX2 processor. This pin samples low (logic 0) if a IntelDX4 processor is installed. Upon sampling the logic level of this pin, external logic can enable the proper V_{CC} level to the processor. In power sensitive applications, an active element is preferred for the pull-up device because it can be disabled after sampling, eliminating the DC current path that results when the installed processor is the IntelDX4 processor.

Figure 9-4 shows a logical representation of the voltage detect sense mechanism.

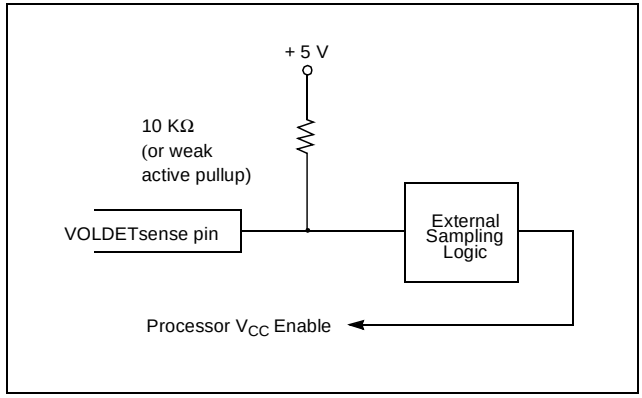


Figure 9-4. Voltage Detect (VOLDET) Sense Pin

This pin can remain a no connect for those system designs that do not wish to utilize this voltage detect feature.

9.2.20 Boundary Scan Test Signals†

The following boundary scan test signals are available on all Intel486 processors except the Intel486 SX processor in PGA packages.

9.2.20.1 Test Clock (TCK)

TCK is an input to the Intel486 processor and provides the clocking function required by the JTAG boundary scan feature. TCK is used to clock state information and data into and out of the component. State select information and data are clocked into the component on the rising edge of TCK on TMS and TDI, respectively. Data is clocked out of the part on the falling edge of TCK on TDO.

In addition to using TCK as a free running clock, it may be stopped in a low, O, state, indefinitely as described in IEEE 1149.1. While TCK is stopped in the low state, the boundary scan latches retain their state.

When boundary scan is not used, TCK should be tied high or left as a NC. (This is important during power up to avoid the possibility of glitches on the TCK which could prematurely initiate boundary scan operations.) TCK is supplied with an internal pull-up resistor.

TCK is a clock signal and is used as a reference for sampling other JTAG signals. On the rising edge of TCK, TMS and TDI are sampled. On the falling edge of TCK, TDO is driven.

9.2.20.2 Test Mode Select (TMS)

TMS is decoded by the JTAG TAP (Tap Access Port) to select the operation of the test logic, as described in Section B.5.4, “Test Access Port (TAP) Controller.”

To guarantee deterministic behavior of the TAP controller, TMS is provided with an internal pull-up resistor. If boundary scan is not used, TMS may be tied high or left unconnected. TMS is sampled on the rising edge of TCK. TMS is used to select the internal TAP states required to load boundary scan instructions to data on TDI. For proper initialization of the JTAG logic, TMS should be driven high, “1,” for at least four TCK cycles following the rising edge of RESET.

9.2.20.3 Test Data Input (TDI)

TDI is the serial input used to shift JTAG instructions and data into the component. The shifting of instructions and data occurs during the SHIFT-IR and SHIFT-DR TAP controller states, respectively. These states are selected using the TMS signal, as described in “Test Access Port (TAP) Controller” in Appendix B.

An internal pull-up resistor is provided on TDI to ensure a known logic state if an open circuit occurs on the TDI path. Note that when “1” is continuously shifted into the instruction register, the BYPASS instruction is selected. TDI is sampled on the rising edge of TCK, during the SHIFT-IR and the SHIFT-DR states. During all other TAP controller states, TDI is a “don't care.” TDI is sampled only when TMS and TCK have been used to select the SHIFT-IR or SHIFT-DR states in the TAP controller. For proper initialization of JTAG logic, TDI should be driven high for at least four TCK cycles following the rising edge of RESET.

† Some steppings do not support boundary scan. Check with your Intel representative for stepping data and errata.

9.2.20.4 Test Data Output (TDO)

TDO is the serial output used to shift JTAG instructions and data out of the component. The shifting of instructions and data occurs during the SHIFT-IR and SHIFT-DR TAP controller states, respectively. These states are selected using the TMS signal, as described in "Test Access Port (TAP) Controller" in Appendix B. When not in SHIFT-IR or SHIFT-DR states, TDO is driven to a high impedance state to allow connecting TDO to different devices in parallel. TDO is driven on the falling edge of TCK during the SHIFT-IR and SHIFT-DR TAP controller states. At all other times TDO is driven to the high impedance state. TDO is only driven when TMS and TCK have been used to select the SHIFT-IR or SHIFT-DR states in the TAP controller.

9.3 INTERRUPT AND NON-MASKABLE INTERRUPT INTERFACE

The Intel486 processor provides four asynchronous interrupt inputs: INTR (interrupt request), NMI (non-maskable interrupt), SMI# (system management interrupt) and STPCLK# (stop clock interrupt). This section describes the hardware interface between the instruction execution unit and the pins. For a description of the algorithmic response to interrupts, refer to Section 3.15, "Interrupts." For interrupt timings refer to Section 10.3.10, "Interrupt Acknowledge."

9.3.1 Interrupt Logic

The Intel486 processor contains a two-clock synchronizer on the interrupt line. An interrupt request reaches the internal instruction execution unit two clocks after the INTR pin is asserted if proper setup is provided to the first stage of the synchronizer.

There is no special logic in the interrupt path other than the synchronizer. The INTR signal is level sensitive and must remain active for the instruction execution unit to recognize it. The interrupt is not serviced by the Intel486 processor if the INTR signal does not remain active.

The instruction execution unit looks at the state of the synchronized interrupt signal at specific clocks during the execution of instructions (if interrupts are enabled). These specific clocks are at instruction boundaries, or iteration boundaries in the case of string move instructions. Interrupts are accepted at these boundaries only.

An interrupt must be presented to the Intel486 processor INTR pin three clocks before the end of an instruction for the interrupt to be acknowledged. Presenting the interrupt three clocks before the end of an instruction allows the interrupt to pass through the two-clock synchronizer, leaving one clock to prevent the initiation of the next sequential instruction and begin interrupt service. If the interrupt is not received in time to prevent the next instruction, it will be accepted at the end of the next instruction, assuming INTR is still held active.

The longest latency between when an interrupt request is presented on the INTR pin and when the interrupt service begins is determined as follows:

> longest instruction used + the two clocks for synchronization + one clock required to vector into the interrupt service microcode.

9.3.2 NMI Logic

The NMI pin has a synchronizer much like that used on the INTR line. The NMI logic is otherwise different from that of the maskable interrupt.

NMI is edge triggered, as opposed to the level triggered INTR signal. The rising edge of the NMI signal is used to generate the interrupt request. The NMI input need not remain active until the interrupt is actually serviced. The NMI pin must remain active only for a single clock if the required setup and hold times are met. NMI operates properly if it is held active for an arbitrary number of clocks.

The NMI input must be held inactive for at least four clocks after it is asserted to reset the edge triggered logic. A subsequent NMI may not be generated if the NMI is not held inactive for at least four clocks after being asserted.

The NMI input is internally masked when the NMI routine is entered. The NMI input remains masked until an IRET (return from interrupt) instruction is executed. Masking the NMI signal prevents recursive NMI calls. If another NMI occurs while the NMI is masked off, the pending NMI is executed after the current NMI is done. Only one NMI can be pending while NMI is masked.

9.3.3 SMI# Logic

SMI# is edge triggered like NMI, but the interrupt request is generated on the falling-edge. SMI# is an asynchronous signal, but must meet setup and hold times t_{20} and t_{21} in order to guarantee recognition on a specific clock. The SMI# input need not remain active until the interrupt is actually serviced. The SMI# input only needs to remain active for a single clock if the required setup and hold times are met. SMI# also works correctly if it is held active for an arbitrary number of clocks.

The SMI# input must be held inactive for at least four clocks after it is asserted to reset the edge triggered logic. A subsequent SMI# might not be recognized if the SMI# input is not held inactive for at least four clocks after being asserted.

SMI#, like NMI, is not affected by the IF bit in the EFLAGS register and is recognized on an instruction boundary. An SMI# does not break locked bus cycles. SMI# has a higher priority than NMI and is not masked during an NMI.

After the SMI# interrupt is recognized, the SMI# signal is masked internally until the RSM instruction is executed and the interrupt service routine is complete. Masking the SMI# prevents recursive SMI# calls. The SMI# input must be de- asserted for at least four clocks to reset the edge triggered logic. If another SMI# occurs while the SMI# is masked, the pending SMI# is recognized and executed on the next instruction boundary after the current SMI# completes. This instruction boundary occurs before execution of the next instruction in the interrupted application code, resulting in back-to-back SMM handlers. Only one SMI# can be pending while SMI# is masked.

The SMI# signal is synchronized internally and should be asserted at least three CLK periods prior to asserting the RDY# signal to guarantee recognition on a specific instruction boundary. This is important for servicing an I/O trap with an SMI# handler.

9.3.4 STPCLK# Logic

STPCLK# is level triggered and active low. STPCLK# is an asynchronous signal, but must remain active until the processor issues the Stop Grant bus cycle. STPCLK# may be de-asserted at any time after the processor generates the Stop Grant bus cycle. When the processor enters the Stop Grant state, the internal pull-up resistor of STPCLK#, CLKMUL (for IntelDX4 processor), and RESERVED# are disabled to reduce processor power consumption. The STPCLK# input must be driven high (not floated) in order to exit the Stop Grant state. After RDY# or BRDY# is returned active for the Stop Grant bus cycle, STPCLK# must be de-asserted for a minimum of five clocks before being asserted again.

When the processor recognizes a STPCLK# interrupt, the processor stops execution on the next instruction boundary (unless superseded by a higher priority interrupt) stops the prefetch unit, empties all internal pipelines and the write buffers, generates a Stop Grant bus cycle, and stops the internal clock. At this point, the processor is in the Stop Grant state.

The processor cannot respond to a STPCLK# request from an HLDA state because it cannot empty the write buffers and, therefore, cannot generate a Stop Grant cycle.

The rising edge of STPCLK# tells the processor that it can return to program execution at the instruction following the interrupted instruction.

Unlike the normal interrupts, INTR and NMI, the STPCLK# interrupt does not initiate acknowledge cycles or interrupt table reads. The STPCLK# order of priority among external interrupts is shown in Section 3.15.6, "Interrupt and Exception Priorities.".

9.4 WRITE BUFFERS

The Intel486 processor contains four write buffers to enhance the performance of consecutive writes to memory. The buffers can be filled at a rate of one write per clock until all buffers are filled.

When all four buffers are empty and the bus is idle, a write request propagates directly to the external bus, bypassing the write buffers. If the bus is not available at the time the write is generated internally, the write is placed in the write buffers and propagates to the bus as soon as the bus becomes available. The write is stored in the on-chip cache immediately if the write is a cache hit.

Writes are driven onto the external bus in the same order in which they are received by the write buffers. Under certain conditions, a memory read can go onto the external bus before the memory writes pending in the buffer, even though the writes occurred earlier in the program execution.

A memory read is reordered in front of all writes in the buffers only under the following conditions: If all writes pending in the buffers are cache hits and the read is a cache miss. Under these conditions, the Intel486 processor does not read from an external memory location that needs to be updated by one of the pending writes.

Reordering of a read with the writes pending in the buffers can only occur once before all the buffers are emptied. Reordering read once maintains cache consistency. Consider the following example: The processor writes to location X. Location X is in the internal cache, so it is updated there immediately. However, the bus is busy, so the write out to main memory is buffered (see Figure 9-5). Under these conditions, any reads to location X are cache hits and the most up-to-date data is read.

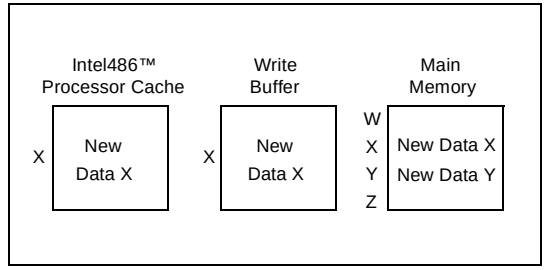


Figure 9-5. Reordering of a Reads with Write Buffers

The next instruction causes a read to location Y. Location Y is not in the cache (a cache miss). Because the write in the write buffer is a cache hit, the read is reordered. When location Y is read, it is put into the cache. The possibility exists that location Y will replace location X in the cache. If this is true, location X would no longer be cached (see Figure 9-6).

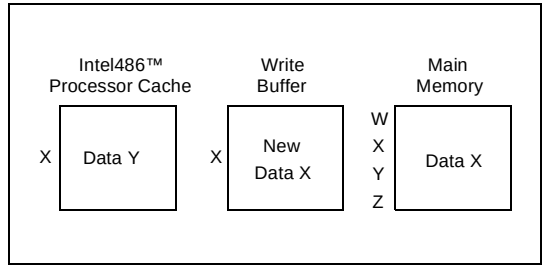


Figure 9-6. Reordering of a Reads with Write Buffers

Cache consistency has been maintained up to this point. If a subsequent read is to location X (now a cache miss) and it was reordered in front of the buffered write to location X, stale data would be read. This is why only one read is allowed to be reordered. Once a read is reordered, all writes in the write buffer are flagged as cache misses to ensure that no more reads are reordered. Because one of the conditions to reorder a read is that all writes in the write buffer must be cache hits, no further reordering is allowed until all flagged writes propagate to the bus. Similarly, if an invalidation cycle is run, all entries in the write buffer are flagged as cache misses.

In multiple processor systems and/or systems using DMA techniques such as bus snooping, locked semaphores should be used to maintain cache consistency.

9.4.1 Write Buffers and I/O Cycles

Input/Output (I/O) cycles must be handled in a different manner by the write buffers.

I/O reads are never reordered in front of buffered memory writes. This ensures that the Intel486 processor updates all memory locations before reading status from an I/O device.

The Intel486 processor never buffers single I/O writes. When processing an OUT instruction, internal execution stops until the I/O write completes on the external bus. This allows time for the external system to drive an invalidate into the Intel486 processor or to mask interrupts before the processor progresses to the instruction following OUT. REP OUTS instructions are buffered.

A read cycle must be generated explicitly to a non-cacheable location in memory to guarantee that a read bus cycle is performed. This read is not allowed to proceed to the bus until after the I/O write has completed because I/O writes are not buffered. The I/O device has time to recover to accept another write during the read cycle.

9.4.2 Write Buffers on Locked Bus Cycles

Locked bus cycles are used for read-modify-write accesses to memory. During a read-modify-write access, a memory base variable is read, modified and then written back to the same memory location. It is important that no other bus cycles, generated by other bus masters or by the Intel486 processor itself, be allowed on the external bus between the read and write portion of the locked sequence.

During a locked read cycle, the Intel486 processor always accesses external memory; it does not look for the location in the on-chip cache. For write cycles, data is written to the internal cache (if cache hit) and the external memory. All data pending in the Intel486 processor's write buffers is written to memory before a locked cycle is allowed to proceed to the external bus.

The Intel486 processor asserts LOCK# after the write buffers are emptied during a locked bus cycle. With LOCK# asserted, the processor reads the data, operates on the data, and places the results in a write buffer. The contents of the write buffer are then written to external memory. LOCK# becomes inactive after the write part of the locked cycle.

9.5 Reset and Initialization

The Intel486 processor has a built in self test (BIST) that can be run during reset. BIST is invoked when the AHOLD pin is asserted for one clock before and de-asserted one clock after RESET is de-asserted. RESET must be active for 15 clocks with or without BIST being enabled. To ensure proper results, neither FLUSH# nor SRESET can be asserted while BIST is executing. Refer to Appendix B, "Testability," for information on Intel486 processor testability.

The Intel486 processor registers have the values shown in Table 9-8 after RESET is performed. The EAX register contains information on the success or failure of the BIST if the self test is executed. The DX register always contains a component identifier at the conclusion of RESET. The upper byte of DX (DH) contains 04 and the lower byte (DL) contains the revision identifier (see Table 9-9).

RESET forces the Intel486 processor to terminate all execution and local bus activity. No instruction or bus activity occurs as long as RESET is active.

All entries in the cache are invalidated by RESET.

9.5.1 Floating-Point Register Values

In addition to the register values listed above, IntelDX2 and IntelDX4 processors have the floating-point register values shown in Table 9-10.

If the BIST is performed, the floating-point registers are initialized as if the FINIT/FNINIT (initialize processor) instruction were executed. If the BIST is not executed, the floating-point registers are unchanged.

The Intel486 processor starts executing instructions at location FFFFFFF0H after RESET. When the first Inter Segment Jump or Call is executed, address lines A[31:20] drop low for CS-relative memory cycles, and the Intel486 processor executes instructions only in the lower 1 Mbyte of physical memory. This allows the system designer to use ROM at the top of physical memory to initialize the system and take care of RESETs.

Table 9-8. Register Values after Reset

Register	Initial Value (BIST)	Initial Value (No BIST)
EAX	Zero (Pass)	Undefined
ECX	Undefined	Undefined
EDX	0400 + Revision ID	0400 + Revision ID
EBX	Undefined	Undefined
ESP	Undefined	Undefined
EBP	Undefined	Undefined
ESI	Undefined	Undefined
EDI	Undefined	Undefined
EFLAGS	00000002h	00000002h
EIP	0FFF0h	0FFF0h
ES	0000h	0000h
CS	F000h	F000h
SS	0000h	0000h
DS	0000h	0000h
FS	0000h	0000h
GS	0000h	0000h
IDTR	Base = 0, Limit = 3FFh	Base = 0, Limit = 3FFh
CR0	60000010h	60000010h
DR7	00000000h	00000000h

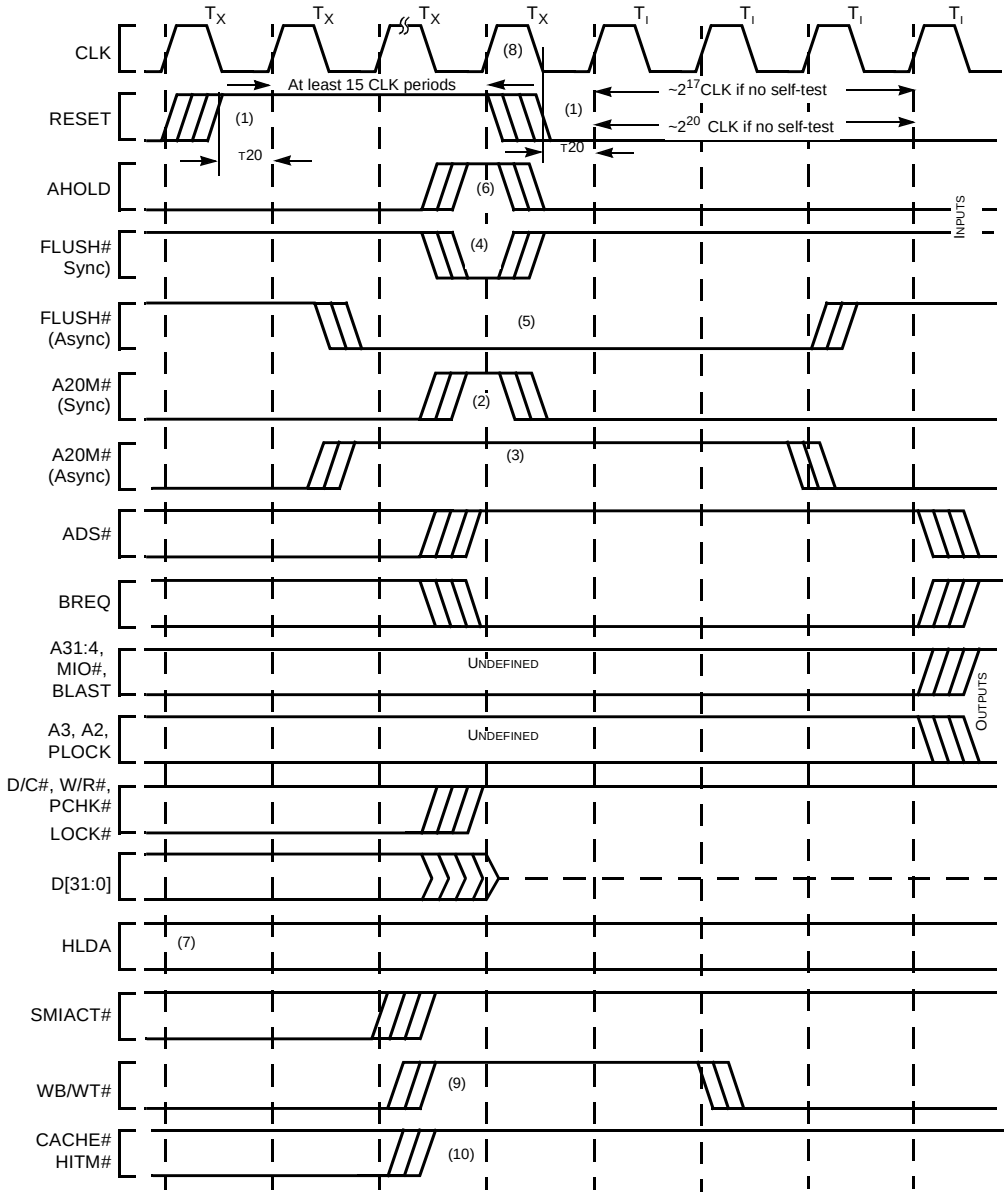
Table 9-9. Floating-Point Values after Reset

Register	Initial Value (BIST)	Initial Value (No BIST)
CW	037Fh	Unchanged
SW	0000h	Unchanged
TW	FFFFh	Unchanged
FIP	00000000h	Unchanged
FEA	00000000h	Unchanged
FCS	0000h	Unchanged
FDS	0000h	Unchanged
FOP	000h	Unchanged
FSTACK	Undefined	Unchanged

9.5.2 Pin State During Reset

The Intel486 processor recognizes and can respond to HOLD, AHOLD, and BOFF# requests regardless of the state of RESET. Thus, even though the processor is in reset, it can float its bus in response to any of these requests.

While in reset, the Intel486 processor bus is in the state shown in Figure 9-7 if the HOLD, AHOLD and BOFF# requests are inactive. Note that the address (A[31:2], BE[3:0]#) and cycle definition (M/IO#, D/C#, W/R#) pins are undefined from the time reset is asserted until the start of the first bus cycle. All undefined pins (except FERR#) assume known values at the beginning of the first bus cycle. The first bus cycle is always a code fetch to address FFFFFFF0H.



See notes on next page.

Figure 9-7. Pin States During RESET

Notes to Figure 9-7:
1. RESET is an asynchronous input. t_{20} must be met only to guarantee recognition on a specific clock edge.
2. When A20M# is driven synchronously, it must be driven high (inactive) for the CLK edge prior to the falling edge of RESET to ensure proper operation. A20M# setup and hold times must be met.
3. When A20M# is driven asynchronously, it should be driven low (active) for two CLKs prior to and two CLKs after the falling edge of RESET to ensure proper operation.
4. When FLUSH# is driven synchronously, it must be driven low (high) for the CLK edge prior to the falling edge of RESET to invoke the three-state Output Test Mode. All outputs are guaranteed three-stated within 10 CLKs of RESET being de-asserted. FLUSH# setup and hold times must be met.
5. When FLUSH# is driven asynchronously, it must be driven low (active) for two CLKs prior to and two CLKs after the falling edge of RESET to invoke the three-state Output Test Mode. All outputs are guaranteed three-stated within 10 CLKs of RESET being de-asserted.
6. AHOLD should be driven high (active) for the CLK edge prior to the falling edge of RESET to invoke the Built-in Self Test (BIST). AHOLD setup and hold times must be met.
7. Hold is recognized normally during RESET. On power-up, HLDA is indeterminate until RESET is recognized by the processor.
8. 15 CLKs RESET pulse width for warm resets. Power-up resets require RESET to be asserted for at least 1 ms after V_{CC} and CLK are stable.
9. WB/WT# should be driven high for at least one CLK before the falling edge of RESET and at least one CLK after the falling edge of RESET to enable the Enhanced Bus mode. Standard Bus mode is enabled if WB/WT# is sampled low or left floating at the falling edge of RESET.
10. The system may sample HITM# to detect the presence of the Enhanced Bus mode. If HITM# is high for one CLK after RESET is inactive, Enhanced Bus mode is present.

9.5.2.1 Controlling the CLK Signal in the Processor during Power On

Intel does not specify the power on requirements of the Intel486 processor allowable CLK input during the power on sequence. Clocking the processor before V_{CC} reaches its normal operating level can cause unpredictable results on Intel486 processors. The information in this section reflects what Intel considers a good clock design.

Intel strongly recommends that system designers ensure that a clock signal is not presented to the Intel486 processor until V_{CC} has stabilized at its normal operating level. This design recommendation can easily be met by gating the clock signal with a POWERGOOD signal. The POWERGOOD signal should reflect the status of V_{CC} at the Intel486 processor (which may be different from the power supply status in designs that provide power to the processor using a voltage regulator or converter).

Most clock synthesizers and some clock oscillators contain on-board gating logic. If external gating logic is implemented, it should be done on the original clock signal output from the clock oscillator/synthesizer. Gating the clock to the processor independently of the clock to the rest of the motherboard causes clock skew, which may violate processor or chipset timing requirements. If the clock signal to the motherboard is enabled with a POWERGOOD signal, verify that the motherboard logic does not require a clock input prior to this POWERGOOD signal. Some chip sets also gate the clock to the processor only after a POWERGOOD signal, which inherently meets the requirements of this design. Designs should implement the design as described in this section to maintain maximum flexibility with all Intel486 processor steppings.

9.5.2.2 FERR# Pin State During Reset for IntelDX2™ and IntelDX4™ Processors

FERR# reflects the state of the ES (error summary status) bit in the floating-point unit status word. The ES bit is initialized when the floating-point unit state is initialized. The floating-point unit's status word register can be initialized by BIST or by executing the FINIT/FNINIT instruction. Thus, after reset and before executing the first FINIT or FNINIT instruction, the values of the FERR# and the numeric status word register bits 7:0 depend on whether or not BIST is performed. Table 9-10 shows the state of FERR# signal after reset and before the execution of the FINIT/FNINIT instruction.

Table 9-10. FERR# Pin State after Reset and before FP Instructions

BIST Performed	FERR# Pin	FPU Status Word Register Bits 7:0
YES	Inactive (High)	Inactive (Low)
NO	Undefined (Low or High)	Undefined (Low or High)

After the first FINIT or FNINIT instruction, FERR# and the FPU status word register bits (7:0) are inactive, irrespective of the Built-In Self-Test (BIST).

9.5.2.3 Power Down Mode (In-circuit Emulator Support)

The Power Down mode on the Intel486 processor, when initiated by the Reserved# signal, reduces the power consumption of the Intel486 processor, as well as forces all of its output signals to be three-stated. The RERSERVED# pin on the Intel486 processor is used for enabling the Power Down mode.

When the RESERVED# pin is driven active upon power-up, the Intel486 processor's bus is floated immediately. The Intel486 processor enters Power Down mode when the RESERVED# pin is sampled asserted in the clock before the falling edge of RESET. The RESERVED# pin has no effect on the power down status, except during this edge. The Intel486 processor then remains in the Power Down mode until the next time the RESET signal is activated. For warm resets, with the upgrade processor in the system, the Intel486 processor remains three-stated and re-enters the Power Down mode once RESET is de-asserted. Similarly for power-up resets, if the upgrade processor is not taken out of the system, the Intel486 processor three-states its outputs upon sensing the RESERVED# pin active and enters the Power Down Mode after the falling edge of RESET.

9.6 CLOCK CONTROL

The Intel486 processor provides an interrupt mechanism (STPCLK#) that allows system hardware to control the power consumption of the processor by stopping the internal clock (output of the PLL) to the processor core in a controlled manner. This low-power state is called the Stop Grant state. In addition, the STPCLK# interrupt allows the system to change the input frequency within the specified range or completely stop the CLK input frequency (an input to the PLL). If the CLK input is stopped completely, the processor enters into the Stop Clock state—the lowest power state.

See Section 9.6.4.2 and Section 9.6.4.3, for a detailed description of the Stop Grant and Stop Clock states, respectively.

9.6.1 Stop Grant Bus Cycles

A special Stop Grant bus cycle is driven to the bus after the processor recognizes the STPCLK# interrupt. The definition of this bus cycle is the same as the HALT cycle definition for the standard Intel486 processor, with the exception that the Stop Grant bus cycle drives the value 0000 0010H on the address pins. The system hardware must acknowledge this cycle by returning RDY# or BRDY#. The processor does not enter the Stop Grant state until either RDY# or BRDY# has been returned.

The Stop Grant bus cycle is defined as follows:

M/IO# = 0, D/C# = 0, W/R# = 1, address bus = 0000 0010H (A_4 = 1), BE3:0# = 1011, data bus = undefined

The latency between a STPCLK# request and the Stop Grant bus cycle depends on the current instruction, the amount of data in the processor write buffers, and the system memory performance (see Figure 9-8).

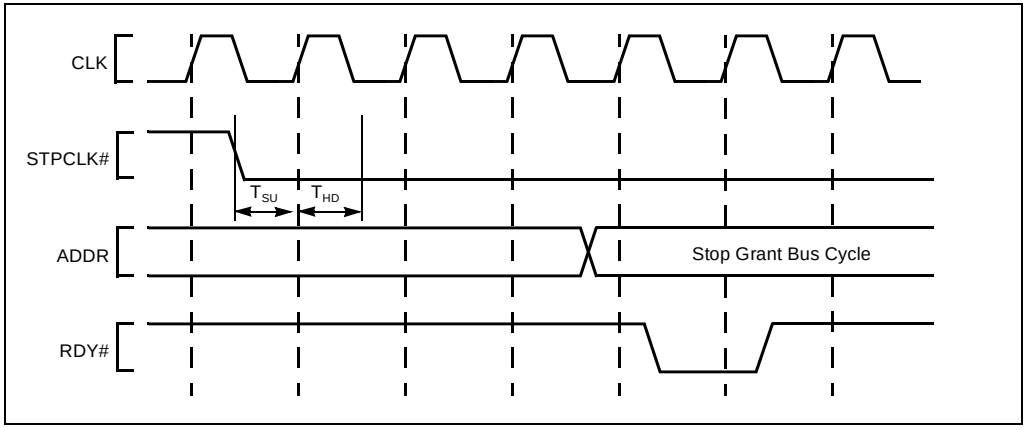


Figure 9-8. Stop Clock Protocol

9.6.2 Pin State During Stop Grant

During the Stop Grant state, most output and input/output signals of the processor maintain their previous condition (the level they held when entering the Stop Grant state). The data and data parity signals are three-stated. In response to HOLD being driven active during the Stop Grant state (when the CLK input is running), the processor generates HLDA and three-states all output and input/output signals that are three-stated during the HOLD/HLDA state. After HOLD is de-asserted, all signals return to their prior state before the HOLD/HLDA sequence.

In order to achieve the lowest possible power consumption during the Stop Grant state, the system designer must ensure that the input signals with pull-up resistors are not driven low and the input signals with pull-down resistors are not driven high. (Refer to the Quick Pin Reference in the datasheets for signals with internal pull-up and pull-down resistors.)

All inputs except the data bus pins must be driven to the power supply rails to ensure the lowest possible current consumption during Stop Grant or Stop Clock states. For compatibility with future processors, data pins should be driven low to achieve the lowest possible power consumption. Pull-down resistors/bus keepers are needed to minimize leakage current.

If HOLD is asserted during the Stop Grant state, all pins that are normally floated during HLDA are still floated by the processor. The floated pins should be driven to a low level (see Table 9-11).

Table 9-11. Pin State during Stop Grant Bus State

Signal	Type	State
A[3:2]	O	Previous state
A[31:4]	I/O	Previous state
D[31:0]	I/O	Floated
BE[3:0]#	O	Previous state
DP[3:0]	I/O	Floated
W/R#, D/C#, M/IO#	O	Previous state
ADS#	O	Inactive
LOCK#, PLOCK#	O	Inactive
BREQ	O	Previous state
HLDA	O	As per HOLD
BLAST#	O	Previous state
FERR#	O	Previous state
PCD, PWT	O	Previous state
PCHK#	O	Previous state
PWT, PCD	O	Previous state
SMIACT#	O	Previous state

9.6.3 Write-Back Enhanced IntelDX4™ Processor Pin States During Stop Grant State

During the Stop Grant state, most output signals of the processor maintain their previous condition, which is the level they held when entering the Stop Grant state. The data bus and data parity signals also maintain their previous state. In response to HOLD being driven active during the Stop Grant state when the CLK input is running, the Write-Back Enhanced IntelDX4 processor generates HLDA and three-states all output and input/output signals that are three-stated during the HOLD/HLDA state. After HOLD is de-asserted, all signals return to the state they were in prior to the HOLD/HLDA sequence.

All inputs should be driven to the power supply rails to ensure the lowest possible current consumption during the Stop Grant or Stop Clock states (see Table 9-12).

Table 9-12. Write-Back Enhanced IntelDX4™ Processor Pin States during Stop Grant Bus Cycle

Signal	Type	State
A[3:2]	O	Previous state
A[31:4]	I/O	Previous state
D[31:0]	I/O	Previous state
BE[3:0]#	O	Previous state
DP[3:0]	I/O	Previous state
W/R#, D/C#, M/IO#	O	Previous state
ADS#	O	Inactive (high)
LOCK#, PLOCK#	O	Inactive (high)
BREQ	O	Previous state
HLDA	O	As per HOLD
BLAST#	O	Previous state
FERR#	O	Previous state
PCHK#	O	Previous state
PWT, PCD	O	Previous state
CACHE#	O	Inactive(1) (high)
HITM#	O	Inactive(1) (high)
SMIACT#	O	Previous state

NOTES:
1. For the case of snoop cycles (via EADS#) during Stop Grant state, both HITM# and CACHE# may go active depending on the snoop hit in the internal cache.
2. During Stop Grant state, AHOLD, HOLD, BOFF# and EADS# are serviced normally.

The Write-Back Enhanced IntelDX4 processor has bus keepers features. The data bus and data parity pins have bus keepers that maintain the previous state while in the Stop Grant state. External resistors are no longer required, which prevents excess current during the Stop Grant state. (If external resistors are present, they should be strong enough to "flip" the bus hold circuitry and eliminate potential DC paths. Alternately, "weak" resistors may be added to prevent excessive current flow.)

In order to obtain the lowest possible power consumption during the Stop Grant state, system designers must ensure that the input signals with pull-up resistors are not driven low, and the input signals with pull-down resistors are not driven high.

9.6.4 Clock Control State Diagram

The following state descriptions and diagram show the state transitions during a Stop Clock cycle for the Intel486 processor. (Refer to Figure 9-9 for a Stop Clock state diagram.) Refer to Section 9.6.5 for Write-Back Enhanced Intel486 processors Clock Control State specifics.

9.6.4.1 Normal State

This is the normal operating state of the processor.

9.6.4.2 Stop Grant State

The Stop Grant state provides a fast wake-up state that can be entered by simply asserting the external STPCLK# interrupt pin. Once the Stop Grant bus cycle has been placed on the bus, and either RDY# or BRDY# is returned, the processor is in this state (depending on the CLK input frequency). The processor returns to the normal execution state approximately 10–20 clock periods after STPCLK# has been de-asserted.

While in the Stop Grant state, the pull-up resistors on STPCLK#, CLKMUL (for the IntelDX4 processor) and RESERVED# are disabled internally. The system must continue to drive these inputs to the state they were in immediately before the processor entered the Stop Grant state. For minimum processor power consumption, all other input pins should be driven to their inactive level while the processor is in the Stop Grant state.

A RESET or SRESET brings the processor from the Stop Grant state to the Normal state. The processor recognizes the inputs required for cache invalidations (HOLD, AHOLD, BOFF# and EADS#), as explained later in this section. The processor does not recognize any other inputs while in the Stop Grant state. Input signals to the processor are not recognized until one CLK after STPCLK# is de-asserted (see Figure 9-10).

While in the Stop Grant state, the processor does not recognize transitions on the interrupt signals (SMI#, NMI, and INTR). Driving an active edge on either SMI# or NMI does not guarantee recognition and service of the interrupt request following exit from the Stop Grant state. However, if one of the interrupt signals (SMI#, NMI, or INTR) is driven active while the processor is in the Stop Grant state, and held active for at least one CLK after STPCLK# is de-asserted, the corresponding interrupt is serviced. The Intel486 processor requires INTR to be held active until the processor issues an interrupt acknowledge cycle in order to guarantee recognition (see Figure 9-10).

When the processor is in the Stop Grant state, the system can stop or change the CLK input. When the CLK input to the processor is stopped or changed, the Intel486 processor requires the CLK input to be held at a constant frequency for a minimum of 1 ms before de-asserting STPCLK#. This 1-ms time period is necessary so that the PLL can stabilize, and it must be met before the processor returns to the Stop Grant state.

NOTE

On the Ultra-Low Power Intel486 family of processors, the 1 ms settling period is not necessary due to the digital delay line based clock circuit.

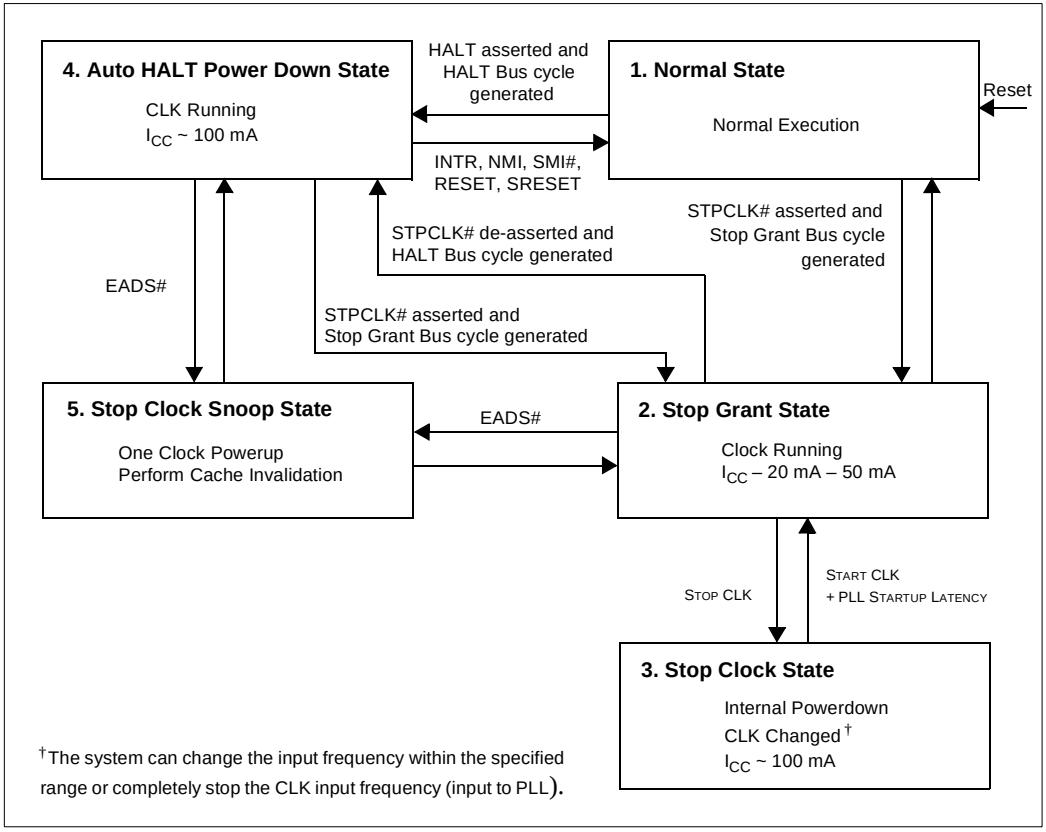


Figure 9-9. Intel486™ Processor Family Stop Clock State Machine

The processor generates a Stop Grant bus cycle only when entering that state from the Normal or the Auto HALT Power Down state. When the processor enters the Stop Grant state from the Stop Clock state or the Stop Clock Snoop state, the processor does not generate a Stop Grant bus cycle.

9.6.4.3 Stop Clock State

Stop Clock state is entered from the Stop Grant state by stopping the CLK input (either logic high or logic low). None of the processor input signals should change state while the CLK input is stopped. Any transition on an input signal (with the exception of INTR, NMI and SMI#) before the processor has returned to the Stop Grant state results in unpredictable behavior. If INTR is driven active while the CLK input is stopped, and held active until the processor issues an interrupt acknowledge bus cycle, it is serviced in the normal manner. The system design must ensure that the processor is in the correct state prior to asserting cache invalidation or interrupt signals to the processor.

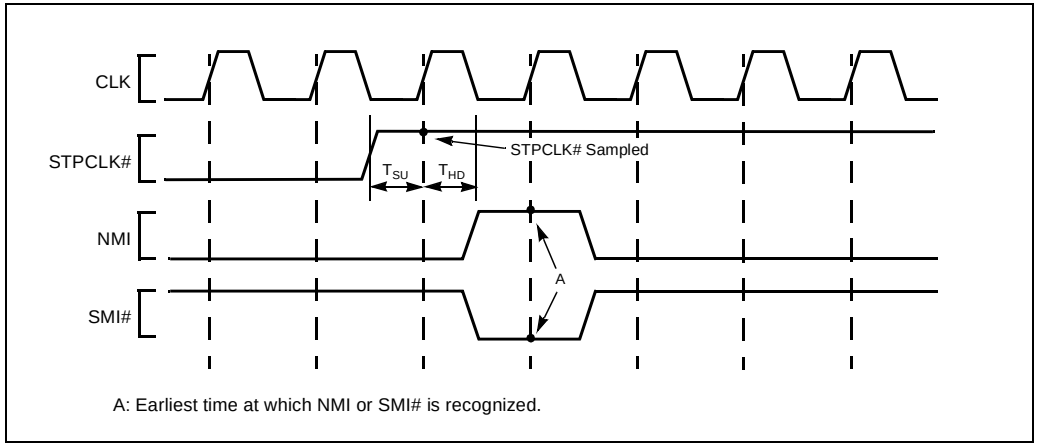


Figure 9-10. Recognition of Inputs when Exiting Stop Grant State

The processor returns to the Stop Grant state after the CLK input has been running at a constant frequency for a period of time equal to the PLL startup latency (see Section 9.6.4.2). The CLK input can be restarted to any frequency between the minimum and maximum frequency listed in the AC timing specifications.

9.6.4.4 Auto HALT Power Down State

The execution of a HALT instruction also causes the processor to automatically enter the Auto HALT Power Down state. The processor issues a normal HALT bus cycle before entering this state. The processor transitions to the Normal state on the occurrence of INTR, NMI, SMI#, RESET, or SRESET.

The system can generate a STPCLK# while the processor is in the Auto HALT Power Down state. The processor generates a Stop Grant bus cycle when it enters the Stop Grant state from the HALT state.

When the system de-asserts the STPCLK# interrupt, the processor returns execution to the HALT state. The processor generates a new HALT bus cycle when it re-enters the HALT state from the Stop Grant state.

9.6.4.5 Stop Clock Snoop State (Cache Invalidations)

When the processor is in the Stop Grant state or the Auto HALT Power Down state, the processor recognizes HOLD, AHOLD, BOFF# and EADS# for cache invalidation. When the system asserts HOLD, AHOLD, or BOFF#, the processor floats the bus accordingly. When the system then asserts EADS#, the processor transparently enters the Stop Clock Snoop state and powers up for one full core clock in order to perform the required cache snoop cycle. It then re-freezes the clock to the processor core and returns to the previous state. The processor does not generate a bus cycle when it returns to the previous state.

A FLUSH# event during the Stop Grant state or the Auto HALT Power Down state is latched and acted upon by asserting the internal FLUSH# signal for one clock upon re-entering the Normal state.

9.6.4.6 Auto Idle Power Down State

When the processor is known to be truly idle and waiting for RDY# or BRDY# from a memory or I/O bus cycle read, the Intel486 processor reduces its core clock rate to equal that of the external CLK frequency without affecting performance. When RDY# or BRDY# is asserted, the processor returns to clocking the core at the specified multiplier of the external CLK frequency. This functionality is transparent to software and external hardware.

9.6.5 Write-Back Enhanced IntelDX4™ Processor Clock Control State Diagram

Figure 9-11 shows the state transitions during Stop Clock for the Write-Back Enhanced IntelDX4 processor.

NOTE

The Stop Clock State Machine in the Standard bus configuration is identical to that of other Intel486 processors. (See Section 9.6.4, "Clock Control State Diagram" on page 9-37.)

9.6.5.1 Normal State

This is the normal operating state of the processor. When the processor is executing program/instruction and the STPCLK# pin is not asserted, the processor is said to be in its Normal state.

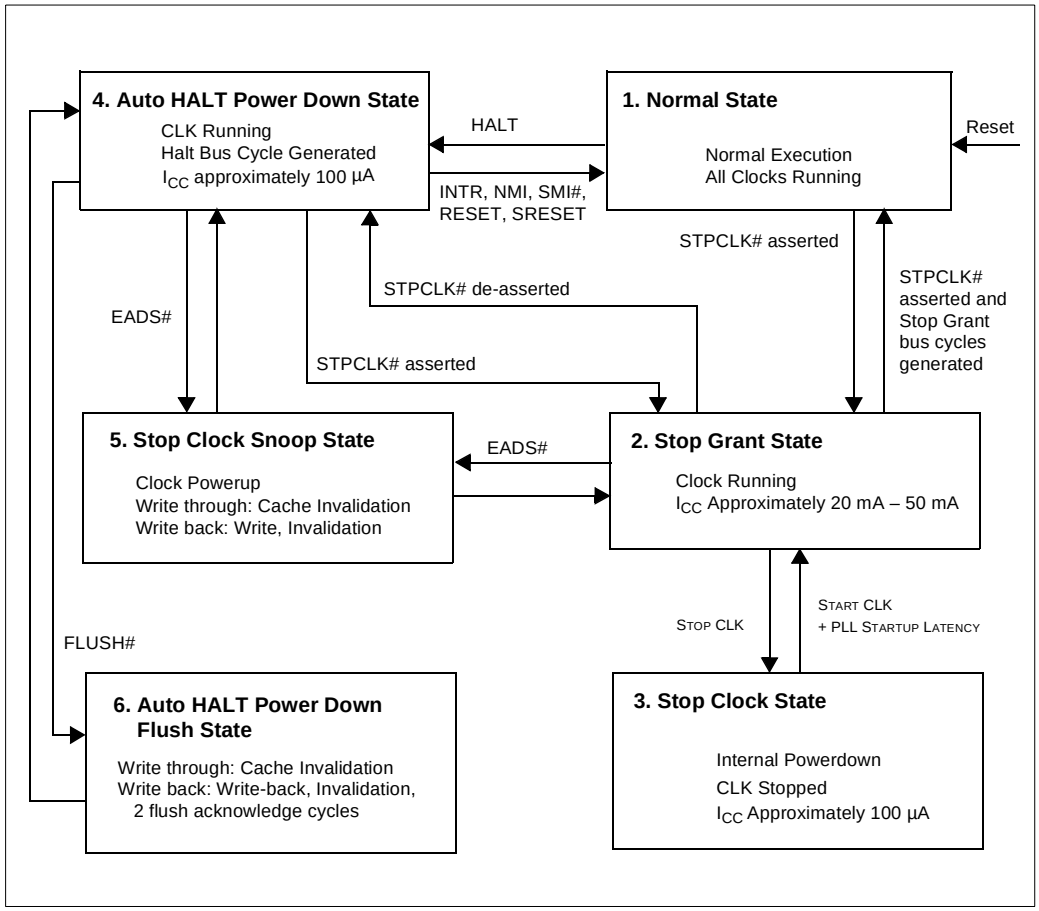


Figure 9-11. Write-Back Enhanced IntelDX4™ Processor Stop Clock State Machine (Enhanced Bus Configuration)

9.6.5.2 Stop Grant State

For minimum processor power consumption, all other input pins should be driven to their inactive level while the processor is in the Stop Grant state except for the data bus, data parity, WB/WT# and INV pins. WB/WT# should be driven low and INV should be driven high.

In both the Standard mode and Enhanced mode, the following conditions exist:

- A RESET, SRESET or de-assertion of STPCLK# brings the processor from the Stop Grant state to the Normal state.
- While in the Stop Grant state, the processor does not recognize transitions on the interrupt signals (SMI#, NMI, and INTR). This means SMI#, NMI, and INTR are not Stop Break events. The external logic should de-assert STPCLK# before issuing interrupts, or if an interrupt is asserted it should be kept asserted for at least one clock after STPCLK# is removed. (Note that the Write-Back Enhanced IntelDX4 processor requires that INTR be held active until the processor issues an interrupt acknowledge cycle in order to guarantee recognition).
- FLUSH# is not a Stop Break event. But if FLUSH# is asserted during the Stop Grant state, it is latched by the Write-Back Enhanced IntelDX4 processor and serviced later when STPCLK# is de-asserted.
- The processor latches and responds to the inputs BOFF#, EADS#, AHOLD, and HOLD. The processor does not recognize any other inputs while in the Stop Grant state except FLUSH#. Other input signals to the processor are not recognized until the CLK following the CLK in which STPCLK# is de-asserted (see Figure 9-11).
- The processor generates a Stop Grant bus cycle only when entering that state from the Normal or the Auto HALT Power Down state. The Stop Grant bus cycle is not generated when the processor enters the Stop Grant state from the Stop Clock state or the Stop Clock Snoop state.
- The processor does not enter the Stop Grant state until all the pending writes are completed, all pending interrupts are serviced, and the processor is idle.

9.6.5.3 Stop Clock State

The Stop Clock state is the lowest power consumption mode of the Intel486 processor, because it allows removal of the external clock. It also has the longest latency for returning to normal state. The Stop Clock state is entered from the Stop Grant state by stopping the CLK input. In the Stop Clock state, total processor power consumption drops to 100 A, which is approximately 200–250 times lower than the Stop Grant state. None of the processor input signals should change state while the CLK input is stopped. Any transition on an input signal before the processor has returned to the Stop Grant state results in unpredictable behavior. If INTR is driven active, it must remain active until the processor issues an interrupt acknowledge cycle.

In the Stop Clock state, the processor is dormant. It does not respond to transitions on any of the input pins, including snoops, flushes and interrupts. It is recommended that this mode only be entered if the processor cache is coherent with main memory and the processor is not processing interrupts. If this mode is entered with a dirty cache, no alternate master cycles can be allowed while the processor is in the Stop Clock state.

The processor returns to the Stop Grant state after the CLK input has been running at a constant frequency for a period of time equal to the PLL startup latency. The CLK input can be restarted to any frequency between the minimum and maximum frequency listed in the AC timing specifications.

In Enhanced Bus mode, if the processor is taken into the Stop Clock state with a dirty cache, alternate bus master cycles are not allowed while the processor remains in the Stop Clock state. In order to take the processor into the Stop Clock state with a clean cache, the cache must be flushed. During the time the cache is being flushed, the system must block interrupts to the processor. With all interrupts other than STPCLK# blocked, the processor does not write into the cache during the time from the completion of the flush and time it enters the Stop Grant state. This is necessary for the cache to be coherent. To ensure cache coherency, the system should drive KEN# inactive from the time the flush starts until the Stop Grant cycle is issued. The system can then put the processor in the Stop Clock state by stopping the clock.

If the processor is already in the Stop Grant state and entering the Stop Clock state is desired, the system must de-assert STPCLK# before flushing the cache in order to ensure cache coherency. The five-clock de-assertion specification for STPCLK# must also be met before the above sequence can occur.

9.6.5.4 Auto HALT Power Down State

Upon execution of a HALT instruction, the processor automatically enters a low power state called the Auto HALT Power Down state. The processor issues a normal HALT bus cycle when entering this state. Because interrupts are HALT break events, the processor transitions to the Normal state on the occurrence of INTR, NMI, SMI# or RESET (SRESET is also a HALT break event). If a FLUSH# occurs while the processor is in this state, the FLUSH# is serviced by transitioning to the Stop Clock Flush state. After the FLUSH# is completed, the processor returns to the Auto HALT Power Down state.

The system can generate a STPCLK# while the processor is in the Auto HALT Power Down state. The processor then generates a Stop Grant bus cycle and enters the Stop Grant state from the Auto HALT Power Down state. When the system de-asserts the STPCLK# interrupt, the processor returns to the Auto HALT Power Down state. The processor does not generate a new HALT bus cycle when it re-enters the Auto HALT Power Down state from the Stop Grant state.

9.6.6 Stop Clock Snoop State (Cache Invalidations)

When the processor is in the Stop Grant state or the Auto HALT Power Down state, the processor recognizes HOLD, AHOLD, BOFF#, and EADS# for cache invalidation. When the system asserts HOLD, AHOLD, or BOFF#, the processor floats the bus accordingly. When the system asserts EADS#, the processor transparently enters the Stop Clock Snoop state and powers up in order to perform the required cache snoop cycle and write-back cycles. It then refreezes the CLK to the processor core and returns to the previous state (i.e., either the Stop Grant state or the Auto HALT Power Down state). The processor does not generate a bus cycle when it returns to the previous state.

9.6.6.1 Auto HALT Power Down Flush State (Cache Flush) for the Write-Back Enhanced IntelDX4™ Processor

When the Write-Back Enhanced IntelDX4 processor is in either Standard or Enhanced Bus mode, and a FLUSH# event occurs during Auto HALT Power Down state, the processor transitions to the Auto HALT Power Down Flush state. If the on-chip cache is configured as a write-back cache, the CLK to the processor core is turned on until all the dirty lines are written back, the cache is invalidated, and the two flush acknowledge cycles are completed. If the on-chip cache is configured as a write-through cache, the CLK to the processor core is turned on until the cache is invalidated. The processor then refreezes the CLK and returns to the previous state (i.e., the Auto HALT Power Down state). Auto HALT Power Down Flush state is entered only from the Auto HALT Power Down state and not from the Stop Grant state.

9.6.7 Supply Current Model for Stop Clock Modes and Transitions

Figures 9-12 and 9-13 illustrate the effect of different Stop Clock state transitions on the supply current of the Intel486 processor.

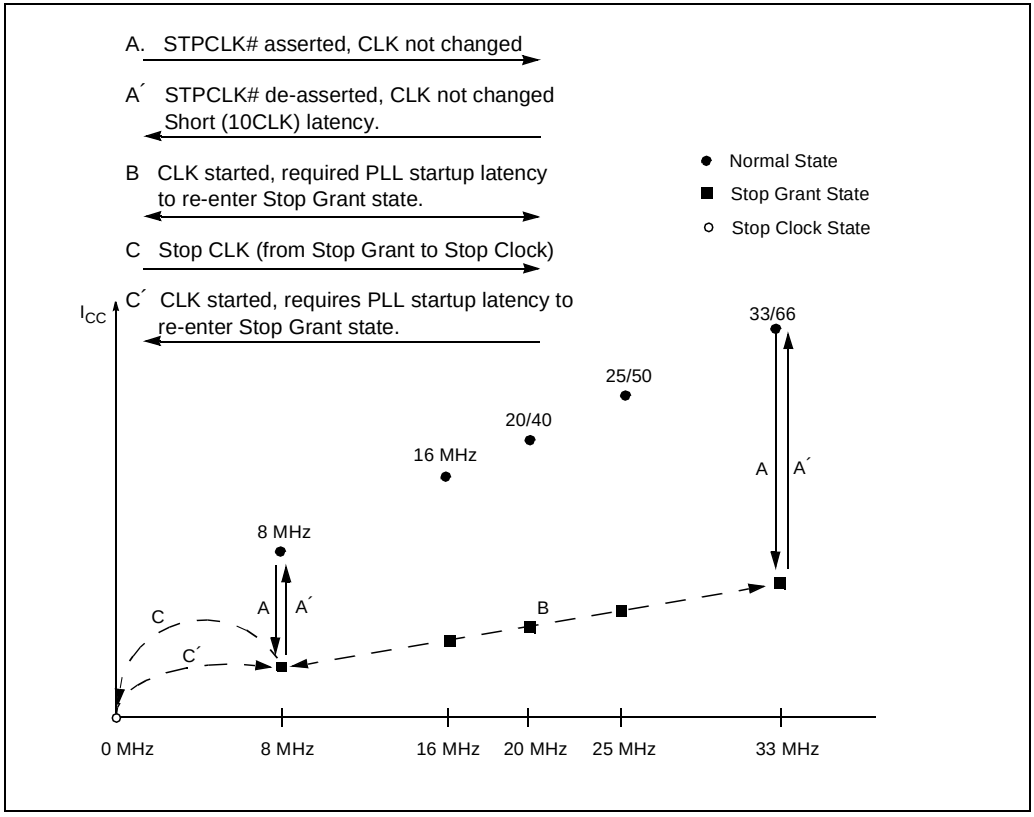


Figure 9-12. Supply Current Model for Stop Clock Modes and Transitions for the Intel486™ Processor

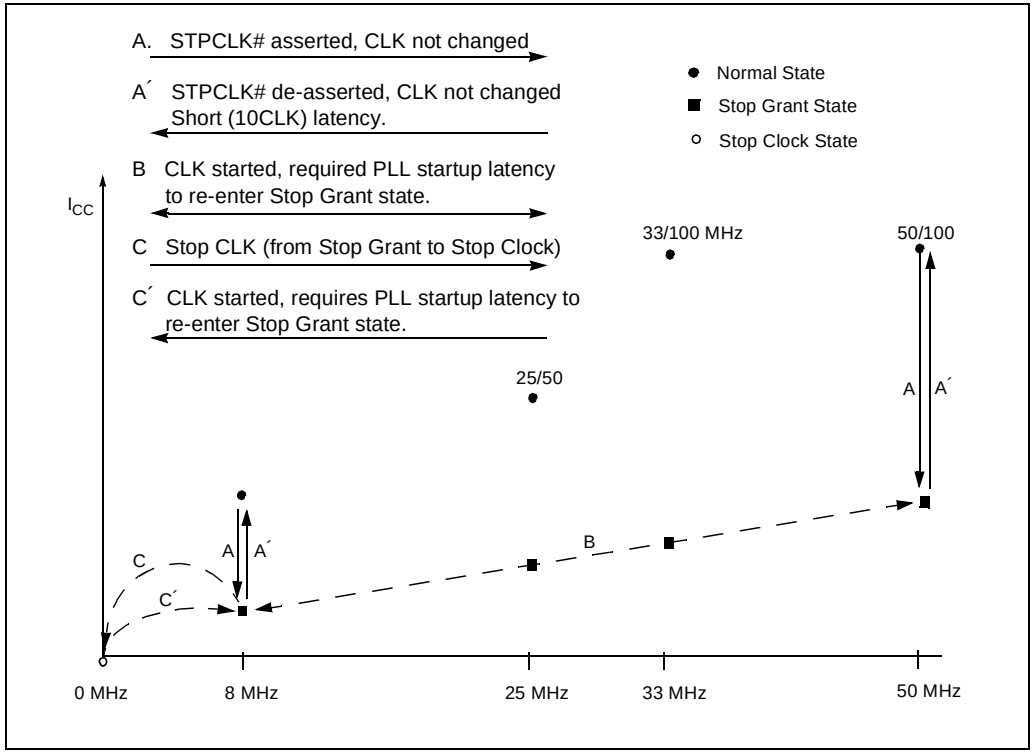


Figure 9-13. Supply Current Model for Stop Clock Modes and Transitions for the IntelDX4™ Processor

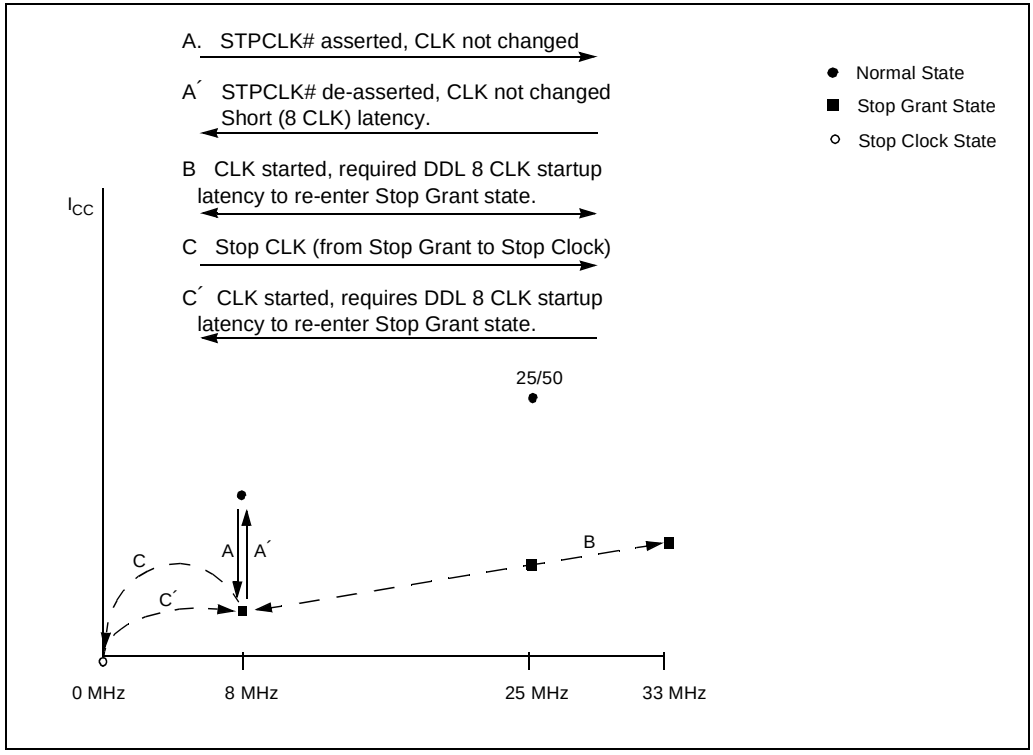


Figure 9-14. Supply Current Model for Stop Clock Modes and Transitions for the Ultra-Low Power Intel486™ SX and Ultra-Low Power Intel486 GX Processors

10

Bus Operation

Chapter Contents

CHAPTER 10
BUS OPERATION

All Intel486™ processors operate in Standard Bus (write-through) mode. However, when the internal cache of the Write-Back Enhanced IntelDX4™ processor can be configured in write-back mode, the processor bus then operates in the Enhanced Bus mode, which is described in Section 10.4. When the internal cache of the Write-Back Enhanced IntelDX4 processor is configured in write-through mode, the processor bus operates in Standard Bus mode, identical to the other embedded Intel486 processors.

10.1 DATA TRANSFER MECHANISM

All data transfers occur as a result of one or more bus cycles. Logical data operands of byte, word and doubleword lengths may be transferred without restrictions on physical address alignment. Data may be accessed at any byte boundary but two or three cycles may be required for unaligned data transfers. (See Section 10.1.2, “Dynamic Data Bus Sizing,” and Section 10.1.5, “Operand Alignment.”)

The Intel486 processor address signals are split into two components. High-order address bits are provided by the address lines, A[31:2]. The byte enables, BE[3:0]#, form the low-order address and provide linear selects for the four bytes of the 32-bit address bus.

The byte enable outputs are asserted when their associated data bus bytes are involved with the present bus cycle, as listed in Table 10-1. Byte enable patterns that have a deasserted byte enable separating two or three asserted byte enables never occur (see Table 10-5 on page 10-8). All other byte enable patterns are possible.

Table 10-1. Byte Enables and Associated Data and Operand Bytes

Byte Enable Signal	Associated Data Bus Signals	
BE0#	D[7:0]	(byte 0–least significant)
BE1#	D[15:8]	(byte 1)
BE2#	D[23:16]	(byte 2)
BE3#	D[31:24]	(byte 3–most significant)

Address bits A0 and A1 of the physical operand's base address can be created when necessary. Use of the byte enables to create A0 and A1 is shown in Table 10-2. The byte enables can also be decoded to generate BLE# (byte low enable) and BHE# (byte high enable). These signals are needed to address 16-bit memory systems. (See Section 10.1.3, “Interfacing with 8-, 16-, and 32-Bit Memories.”)

10.1.1 Memory and I/O Spaces

Bus cycles may access physical memory space or I/O space. Peripheral devices in the system can be either memory-mapped, I/O-mapped, or both. Physical memory addresses range from 00000000H to FFFFFFFFH (4 gigabytes). I/O addresses range from 00000000H to 0000FFFFH (64 Kbytes) for programmed I/O. (See Figure 10-1.)

Table 10-2. Generating A[31:0] from BE[3:0]# and A[31:A2]

Intel486™ Processor Address Signals								
A31	through	A2			BE3#	BE2#	BE1#	BE0#
Physical Address								
A31	...	A2	A1	A0				
A31	...	A2	0	0	X	X	X	0
A31	...	A2	0	1	X	X	0	1
A31	...	A2	1	0	X	0	1	1
A31	...	A2	1	1	0	1	1	1

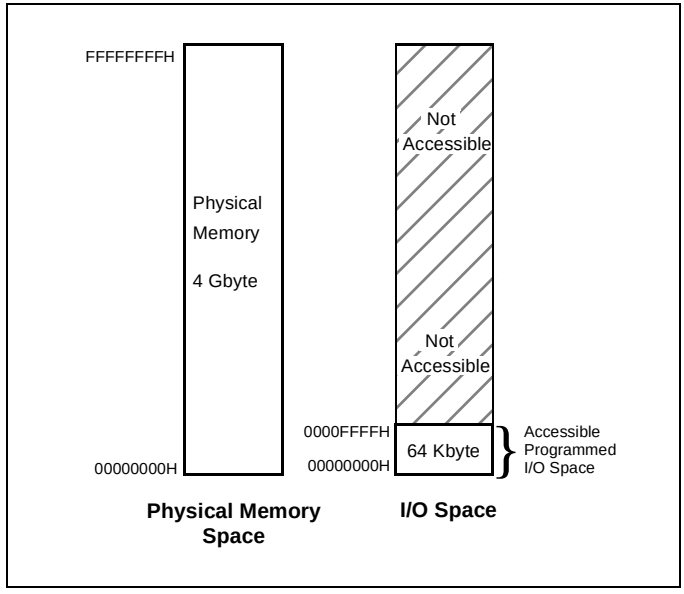


Figure 10-1. Physical Memory and I/O Spaces

10.1.1.1 Memory and I/O Space Organization

The Intel486 processor datapath to memory and input/output (I/O) spaces can be 8, 16, or 32 bits wide. The byte enable signals, BE[3:0]#, allow byte granularity when addressing any memory or I/O structure, whether 8, 16, or 32 bits wide.

The Intel486 processor includes bus control pins, BS16# and BS8#, which allow direct connection to 16- and 8-bit memories and I/O devices. Cycles of 32-, 16- and 8-bits may occur in any sequence, since the BS8# and BS16# signals are sampled during each bus cycle.

NOTE

The Ultra-Low Power Intel486 GX processor has a 16-bit external data bus. All data transfers are done on the low order data bits (D15-D0) and parity is generated and checked on pins DP0 and DP1. For this reason, dynamic data bus sizing (using pins BS16# and BS8#) is not supported.

Memory and I/O spaces that are 32-bit wide are organized as arrays of four bytes each. Each four bytes consists of four individually addressable bytes at consecutive byte addresses (see Figure 10-2). The lowest addressed byte is associated with data signals D[7:0]; the highest-addressed byte with D[31:24]. Each 4 bytes begin at an address that is divisible by four.

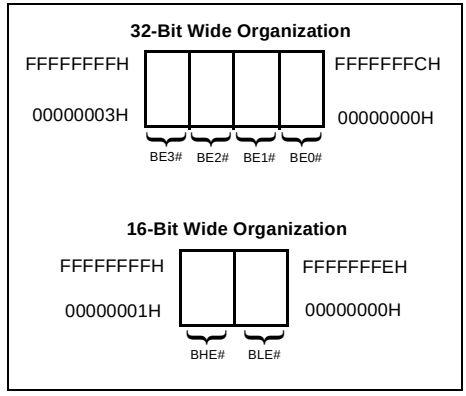


Figure 10-2. Physical Memory and I/O Space Organization

16-bit memories are organized as arrays of two bytes each. Each two bytes begins at addresses divisible by two. The byte enables BE[3:0]#, must be decoded to A1, BLE# and BHE# to address 16-bit memories.

To address 8-bit memories, the two low order address bits A0 and A1 must be decoded from BE[3:0]#. The same logic can be used for 8- and 16-bit memories, because the decoding logic for BLE# and A0 are the same. (See Section 10.1.3, “Interfacing with 8-, 16-, and 32-Bit Memories.”)

10.1.2 Dynamic Data Bus Sizing

Dynamic data bus sizing is a feature that allows processor connection to 32-, 16- or 8-bit buses for memory or I/O. The Intel486 processors can access all three bus sizes, except for the Ultra-Low Power Intel486 GX processor, which has a 16-bit data bus. Transfers to or from 32-, 16- or 8-bit devices are supported by dynamically determining the bus width during each bus cycle. Address decoding circuitry may assert BS16# for 16-bit devices or BS8# for 8-bit devices during each bus cycle. BS8# and BS16# must be deasserted when addressing 32-bit devices. An 8-bit bus width is selected if both BS16# and BS8# are asserted.

BS16# and BS8# force the Intel486 processor to run additional bus cycles to complete requests larger than 16 or 8 bits. A 32-bit transfer is converted into two 16-bit transfers (or 3 transfers if the data is misaligned) when BS16# is asserted. Asserting BS8# converts a 32-bit transfer into four 8-bit transfers.

Extra cycles forced by BS16# or BS8# should be viewed as independent bus cycles. BS16# or BS8# must be asserted during each of the extra cycles unless the addressed device has the ability to change the number of bytes it can return between cycles.

The Intel486 processor drives the byte enables appropriately during extra cycles forced by BS8# and BS16#. A[31:2] does not change if accesses are to a 32-bit aligned area. Table 10-3 shows the set of byte enables that is generated on the next cycle for each of the valid possibilities of the byte enables on the current cycle.

The dynamic bus sizing feature of the Intel486 processor is significantly different than that of the Intel386™ processor. Unlike the Intel386 processor, the Intel486 processor requires that data bytes be driven on the addressed data pins. The simplest example of this function is a 32-bit aligned, BS16# read. When the Intel486 processor reads the two high order bytes, they must be driven on the data bus pins D[31:16]. The Intel486 processor expects the two low order bytes on D[15:0]. The Intel386 processor expects both the high and low order bytes on D[15:0]. The Intel386 processor always reads or writes data on the lower 16 bits of the data bus when BS16# is asserted.

The external system must contain buffers to enable the Intel486 processor to read and write data on the appropriate data bus pins. Table 10-4 shows the data bus lines to which the Intel486 processor expects data to be returned for each valid combination of byte enables and bus sizing options.

Table 10-3. Next Byte Enable Values for BS*x*# Cycles

Current				Next with				Next with BS16#			
BE3#	BE2#	BE1#	BE0#	BE3#	BE2#	BE1#	BE0#	BE3#	BE2#	BE1#	BE0#
1	1	1	0	N	N	N	N	N	N	N	N
1	1	0	0	1	1	0	1	N	N	N	N
1	0	0	0	1	0	0	1	1	0	1	1
0	0	0	0	0	0	0	1	0	0	1	1
1	1	0	1	N	N	N	N	N	N	N	N
1	0	0	1	1	0	1	1	1	0	1	1
0	0	0	1	0	0	1	1	0	0	1	1
1	0	1	1	N	N	N	N	N	N	N	N
0	0	1	1	0	1	1	1	N	N	N	N
0	1	1	1	N	N	N	N	N	N	N	N

NOTE: "N" means that another bus cycle is not required to satisfy the request.

Table 10-4. Data Pins Read with Different Bus Sizes

BE3#	BE2#	BE1#	BE0#	w/o BS8#/BS16#	w BS8#	w BS16#
1	1	1	0	D[7:0]	D[7:0]	D[7:0]
1	1	0	0	D[15:0]	D[7:0]	D[15:0]
1	0	0	0	D[23:0]	D[7:0]	D[15:0]
0	0	0	0	D[31:0]	D[7:0]	D[15:0]
1	1	0	1	D[15:8]	D[15:8]	D[15:8]
1	0	0	1	D[23:8]	D[15:8]	D[15:8]
0	0	0	1	D[31:8]	D[15:8]	D[15:8]
1	0	1	1	D[23:16]	D[23:16]	D[23:16]
0	0	1	1	D[31:16]	D[23:16]	D[31:16]
0	1	1	1	D[31:24]	D[31:24]	D[31:24]

Valid data is only driven onto data bus pins corresponding to asserted byte enables during write cycles. Other pins in the data bus are driven but they contain no valid data. Unlike the Intel386 processor, the Intel486 processor does not duplicate write data onto parts of the data bus for which the corresponding byte enable is deasserted.

10.1.3 Interfacing with 8-, 16-, and 32-Bit Memories

In 32-bit physical memories, such as the one shown in Figure 10-3, each 4-byte word begins at a byte address that is a multiple of four. A[31:2] are used as a 4-byte word select. BE[3:0]# select individual bytes within the 4-byte word. BS8# and BS16# are deasserted for all bus cycles involving the 32-bit array.

For 16- and 8-bit memories, byte swapping logic is required for routing data to the appropriate data lines and logic is required for generating BHE#, BLE# and A1. In systems where mixed memory widths are used, extra address decoding logic is necessary to assert BS16# or BS8#.

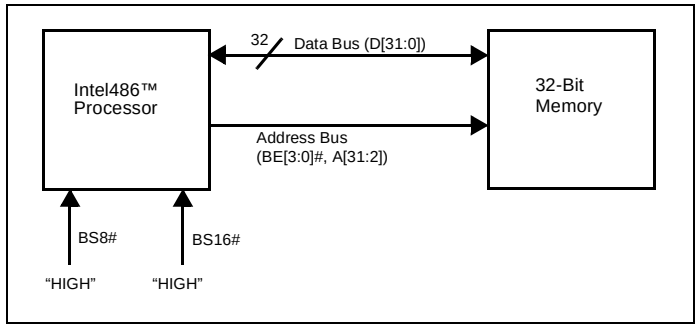


Figure 10-3. Intel486™ Processor with 32-Bit Memory

Figure 10-4 shows the Intel486 processor address bus interface to 32-, 16- and 8-bit memories. To address 16-bit memories the byte enables must be decoded to produce A1, BHE# and BLE# (A0). For 8-bit wide memories the byte enables must be decoded to produce A0 and A1. The same byte select logic can be used in 16- and 8-bit systems, because BLE# is exactly the same as A0 (see Table 10-5).

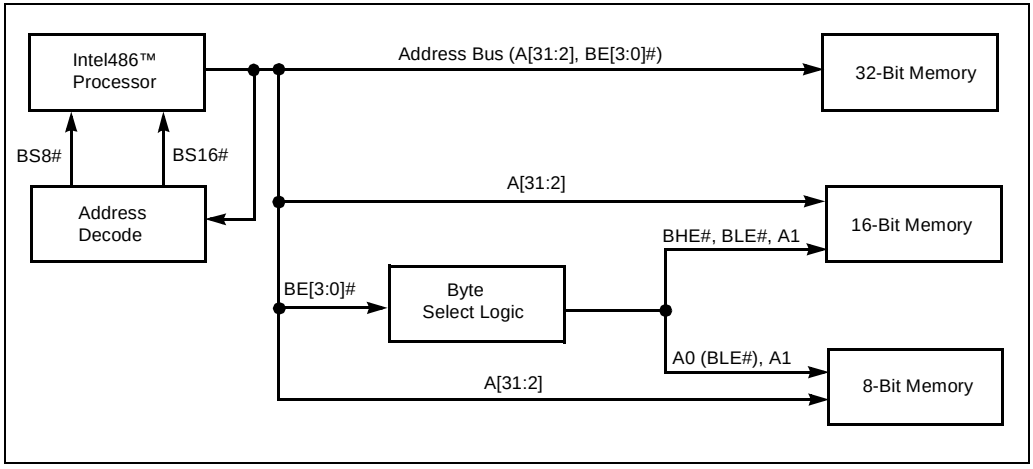


Figure 10-4. Addressing 16- and 8-Bit Memories

BE[3:0]# can be decoded as shown in Table 10-5. The byte select logic necessary to generate BHE# and BLE# is shown in Figure 10-5.

Table 10-5. Generating A1, BHE# and BLE# for Addressing 16-Bit Devices

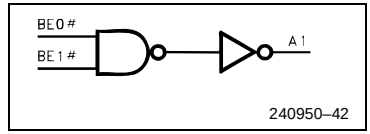
Intel486™ Processor				8-, 16-Bit Bus Signals			Comments
BE3#	BE2#	BE1#	BE0#	A1[3]	BHE#[2]	BLE# (A0)[1]	
1†	1†	1†	1†	x	x	x	x–no asserted bytes
1	1	1	0	0	1	0	
1	1	0	1	0	0	1	
1	1	0	0	0	0	0	
1	0	1	1	1	1	0	
1†	0†	1†	0†	x	x	x	x–not contiguous bytes
1	0	0	1	0	0	1	
1	0	0	0	0	0	0	
0	1	1	1	1	0	1	
0†	1†	1†	0†	x	x	x	x–not contiguous bytes
0†	1†	0†	1†	x	x	x	x–not contiguous bytes
0†	1†	0†	0†	x	x	x	x–not contiguous bytes
0		1	1	1	0	0	
0†	0†	1†	0†	x	x	x	x–not contiguous bytes
0	0	0	1	0	0	1	
0	0	0	0	0	0	0	

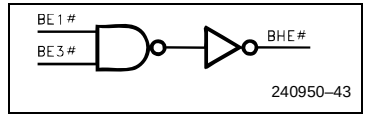
NOTES:
1. BLE# asserted when D[7:0] of 16-bit bus is asserted.
2. BHE# asserted when D[15:8] of 16-bit bus is asserted.
3. A1 low for all even words; A1 high for all odd words.

KEY:

x = don't care

† = a non-occurring pattern of byte enables; either none are asserted or the pattern has byte enables asserted for non-contiguous bytes





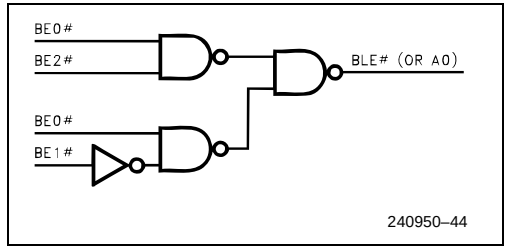


Figure 10-5. Logic to Generate A1, BHE# and BLE# for 16-Bit Buses

Combinations of BE[3:0]# that never occur are those in which two or three asserted byte enables are separated by one or more deasserted byte enables. These combinations are “don't care” conditions in the decoder. A decoder can use the non-occurring BE[3:0]# combinations to its best advantage.

Figure 10-6 shows an Intel486 processor data bus interface to 16- and 8-bit wide memories. External byte swapping logic is needed on the data lines so that data is supplied to and received from the Intel486 processor on the correct data pins (see Table 10-4).

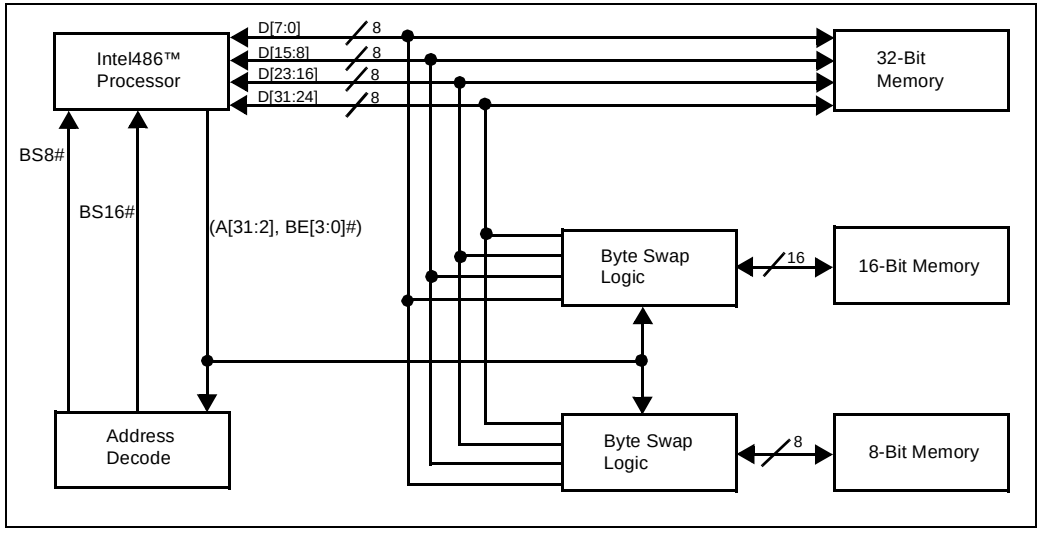


Figure 10-6. Data Bus Interface to 16- and 8-Bit Memories

10.1.4 Dynamic Bus Sizing during Cache Line Files

BS8# and BS16# can be driven during cache line fills. The Intel486 processor generates enough 8- or 16-bit cycles to fill the cache line. This can be up to sixteen 8-bit cycles.

The external system should assume that all byte enables are asserted for the first cycle of a cache line fill. The Intel486 processor generates proper byte enables for subsequent cycles in the line fill. Table 10-6 shows the appropriate A0 (BLE#), A1 and BHE# for the various combinations of the Intel486 processor byte enables on both the first and subsequent cycles of the cache line fill. The "†" marks all combinations of byte enables that are generated by the Intel486 processor during a cache line fill.

Table 10-6. Generating A0, A1 and BHE# from the Intel486™ Processor Byte Enables

BE3#	BE2#	BE1#	BE0#	First Cache Fill Cycle			Any Other Cycle		
				A0	A1	BHE#	A0	A1	BHE#
1	1	1	0	0	0	0	0	0	1
1	1	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0
†0	0	0	0	0	0	0	0	0	0
1	1	0	1	0	0	0	1	0	0
1	0	0	1	0	0	0	1	0	0
†0	0	0	1	0	0	0	1	0	0
1	0	1	1	0	0	0	0	1	1
†0	0	1	1	0	0	0	0	1	0
†0	1	1	1	0	0	0	1	1	0

KEY:

† = a non-occurring pattern of Byte Enables; either none are asserted or the pattern has byte enables asserted for non-contiguous bytes

10.1.5 Operand Alignment

Physical 4-byte words begin at addresses that are multiples of four. It is possible to transfer a logical operand that spans more than one physical 4-byte word of memory or I/O at the expense of extra cycles. Examples are 4-byte operands beginning at addresses that are not evenly divisible by 4, or 2-byte words split between two physical 4-byte words. These are referred to as unaligned transfers.

Operand alignment and data bus size dictate when multiple bus cycles are required. Table 10-7 describes the transfer cycles generated for all combinations of logical operand lengths, alignment, and data bus sizing. When multiple cycles are required to transfer a multibyte logical operand, the highest-order bytes are transferred first. For example, when the processor executes a 4-byte unaligned read beginning at byte location 11 in the 4-byte aligned space, the three high-order bytes are read in the first bus cycle. The low byte is read in a subsequent bus cycle.

Table 10-7. Transfer Bus Cycles for Bytes, Words and Dwords

	Byte-Length of Logical Operand								
	1	2				4			
Physical Byte Address in Memory (Low Order Bits)	xx	00	01	10	11	00	01	10	11
Transfer Cycles over 32-Bit Bus	b	w	w	w	hb lb	d	hb l3	hw lw	h3 lb
Transfer Cycles over 16-Bit Bus († = BS#16 asserted)	b	w	lb † hb †	w	hb lb	lw † hw †	hb lb † mw †	hw lw	mw † hb † lb
Transfer Cycles over 8-Bit Bus (‡ = BS8# Asserted)	b	lb ‡ hb ‡	lb ‡ hb‡	lb ‡ hb ‡	hb lb	lb ‡ mlb ‡ mhb ‡ hb ‡	hb lb ‡ mlb ‡ mhb ‡	mhb ‡ hb ‡ lb ‡ mlb ‡	mlb ‡ mhb ‡ hb ‡ lb

KEY:

b = byte transfer
w = 2-byte transfer
3 = 3-byte transfer
d = 4-byte transfer

h = high-order portion
l = low-order portion
m = mid-order portion

4-Byte Operand

lb	mlb	mhb	hb

↑ byte with lowest address

↑byte with highest address

The function of unaligned transfers with dynamic bus sizing is not obvious. When the external systems asserts BS16# or BS8#, forcing extra cycles, low-order bytes or words are transferred first (opposite to the example above). When the Intel486 processor requests a 4-byte read and the external system asserts BS16#, the lower two bytes are read first followed by the upper two bytes.

In the unaligned transfer described above, the processor requested three bytes on the first cycle. When the external system asserts BS16# during this 3-byte transfer, the lower word is transferred first followed by the upper byte. In the final cycle, the lower byte of the 4-byte operand is transferred, as shown in the 32-bit example above.

10.2 BUS ARBITRATION LOGIC

Bus arbitration logic is needed with multiple bus masters. Hardware implementations range from single-master designs to those with multiple masters and DMA devices.

Figure 10-7 shows a simple system in which only one master controls the bus and accesses the memory and I/O devices. Here, no arbitration is required.

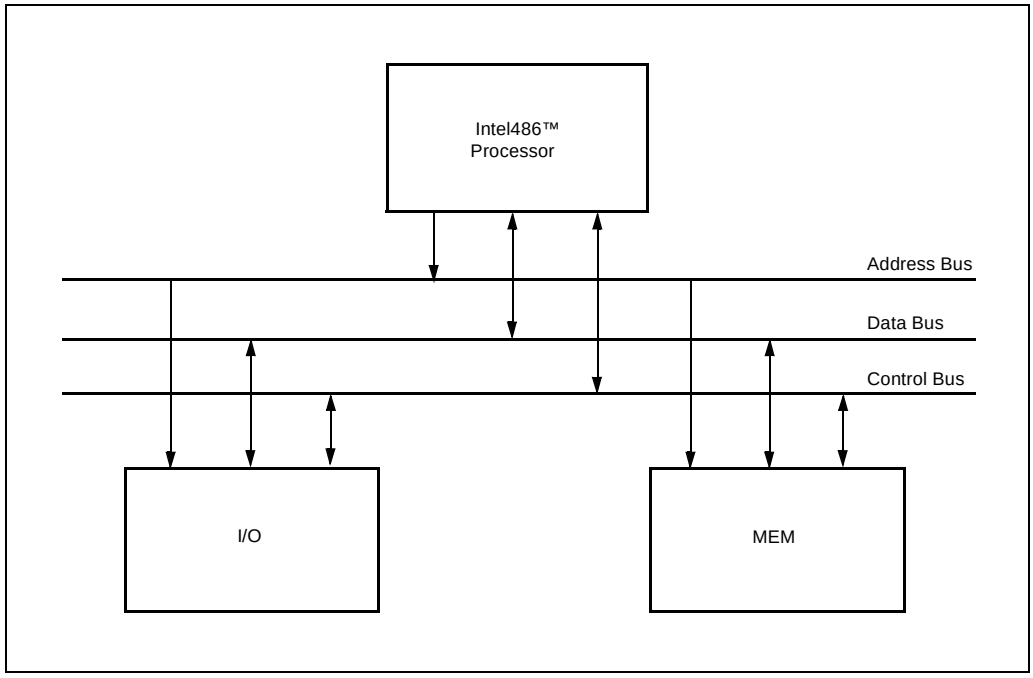


Figure 10-7. Single Master Intel486™ Processor System

Figure 10-8 shows a single processor and a DMA device. Here, arbitration is required to determine whether the processor, which acts as a master most of the time, or a DMA controller has control of the bus. When the DMA wants control of the bus, it asserts the HOLD request to the processor. The processor then responds with a HLDA output when it is ready to relinquish bus control to the DMA device. Once the DMA device completes its bus activity cycles, it negates the HOLD signal to relinquish the bus and return control to the processor.

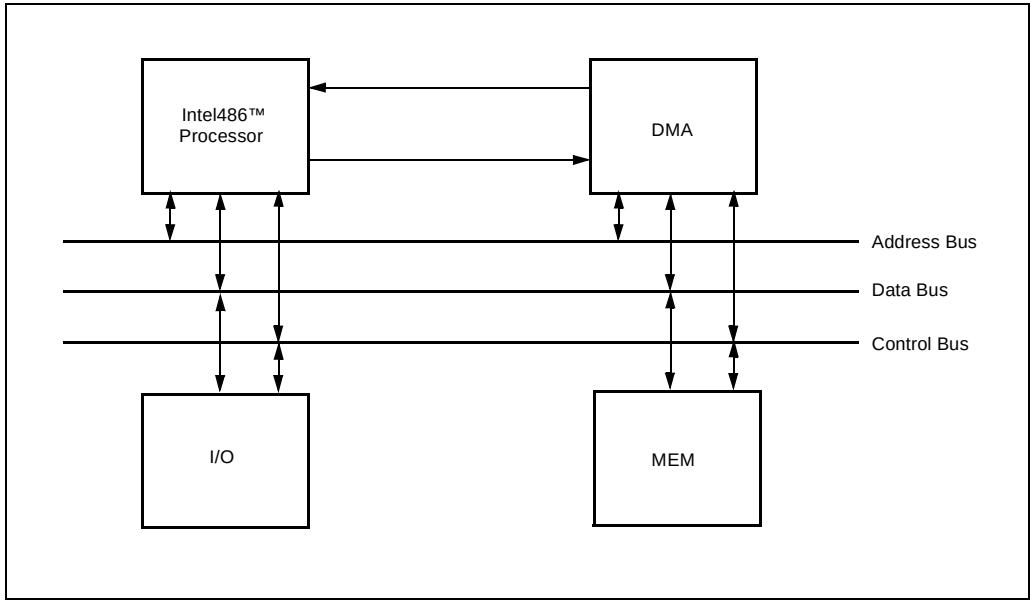


Figure 10-8. Single Intel486™ Processor with DMA

Figure 10-9 shows more than one primary bus master and two secondary masters, and the arbitration logic is more complex. The arbitration logic resolves bus contention by ensuring that all device requests are serviced one at a time using either a fixed or a rotating scheme. The arbitration logic then passes information to the Intel486 processor, which ultimately releases the bus. The arbitration logic receives bus control status information via the HOLD and HLDA signals and relays it to the requesting devices.

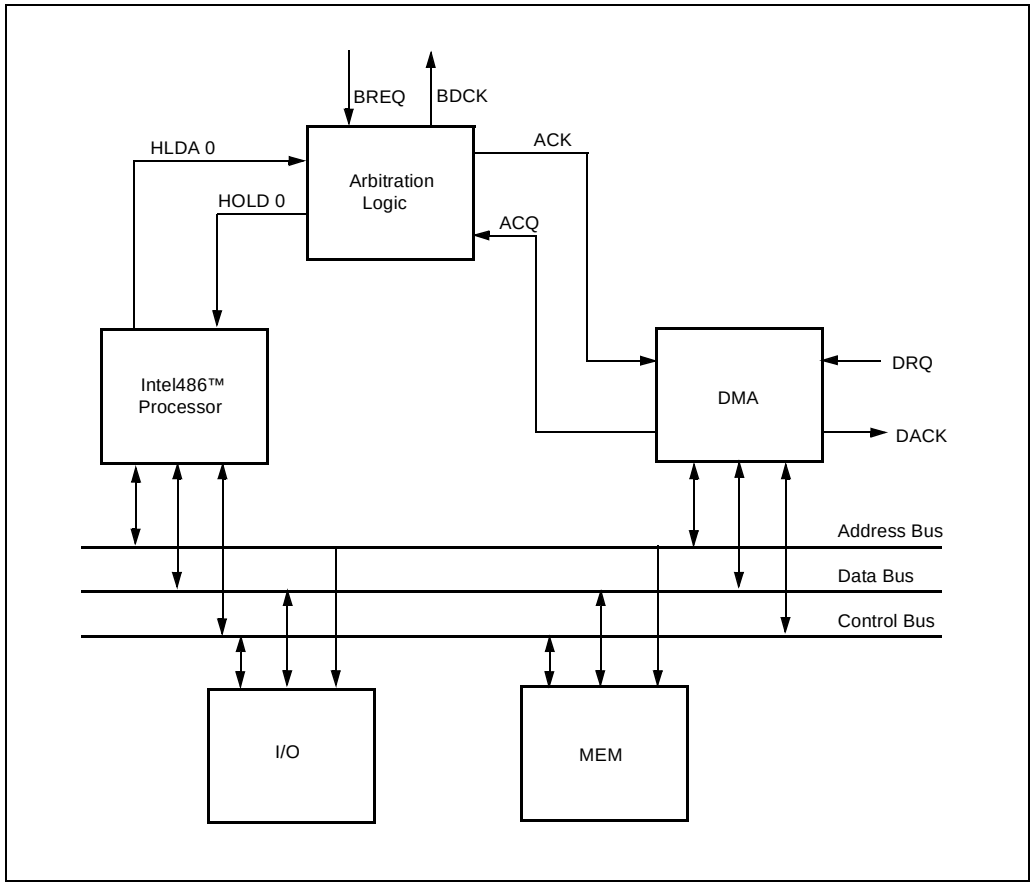


Figure 10-9. Single Intel486™ Processor with Multiple Secondary Masters

As systems become more complex and include multiple bus masters, hardware must be added to arbitrate and assign the management of bus time to each master. The second master may be a DMA controller that requires bus time to perform memory transfers or it may be a second processor that requires the bus to perform memory or I/O cycles. Any of these devices may act as a bus master. The arbitration logic must assign only one bus master at a time so that there is no contention between devices when accessing main memory.

The arbitration logic may be implemented in several different ways. The first technique is to "round-robin" or to "time slice" each master. Each master is given a block of time on the bus to match their priority and need for the bus.

Another method of arbitration is to assign the bus to a master when the bus is needed. Assigning the bus requires the arbitration logic to sample the BREQ or HOLD outputs from the potential masters and to assign the bus to the requestor. A priority scheme must be included to handle cases where more than one device is requesting the bus. The arbitration logic must assert HOLD to the device that must relinquish the bus. Once HLDA is asserted by all of these devices, the arbitration logic may assert HLDA or BACK# to the device requesting the bus. The requestor remains the bus master until another device needs the bus.

These two arbitration techniques can be combined to create a more elaborate arbitration scheme that is driven by a device that needs the bus but guarantees that every device gets time on the bus. It is important that an arbitration scheme be selected to best fit the needs of each system's implementation.

The Intel486 processor asserts BREQ when it requires control of the bus. BREQ notifies the arbitration logic that the processor has pending bus activity and requests the bus. When its HOLD input is inactive and its HLDA signal is deasserted, the Intel486 processor can acquire the bus. Otherwise if HOLD is asserted, then the Intel486 processor has to wait for HOLD to be deasserted before acquiring the bus. If the Intel486 processor does not have the bus, then its address, data, and status pins are 3-stated. However, the processor can execute instructions out of the internal cache or instruction queue, and does not need control of the bus to remain active.

The address buses shown in Figure 10-8 and Figure 10-9 are bidirectional to allow cache invalidations to the processors during memory writes on the bus.

10.3 BUS FUNCTIONAL DESCRIPTION

The Intel486 processor supports a wide variety of bus transfers to meet the needs of high performance systems. Bus transfers can be single cycle or multiple cycle, burst or non-burst, cacheable or non-cacheable, 8-, 16- or 32-bit, and pseudo-locked. Cache invalidation cycles and locked cycles provide support for multiprocessor systems.

This section explains basic non-cacheable, non-burst single cycle transfers. It also details multiple cycle transfers and introduces the burst mode. Cacheability is introduced in Section 10.3.3, "Cacheable Cycles." The remaining sections describe locked, pseudo-locked, invalidate, bus hold, and interrupt cycles.

Bus cycles and data cycles are discussed in this section. A bus cycle is at least two clocks long and begins with ADS# asserted in the first clock and RDY# or BRDY# asserted in the last clock. Data is transferred to or from the Intel486 processor during a data cycle. A bus cycle contains one or more data cycles.

Refer to Section 10.3.13, "Bus States," for a description of the bus states shown in the timing diagrams.

10.3.1 Non-Cacheable Non-Burst Single Cycles

10.3.1.1 No Wait States

The fastest non-burst bus cycle that the Intel486 processor supports is two clocks. These cycles are called 2-2 cycles because reads and writes take two cycles each. The first “2” refers to reads and the second “2” to writes. If a wait state needs to be added to the write, the cycle is called “2-3.”

Basic two-clock read and write cycles are shown in Figure 10-10. The Intel486 processor initiates a cycle by asserting the address status signal (ADS#) at the rising edge of the first clock. The ADS# output indicates that a valid bus cycle definition and address is available on the cycle definition lines and address bus.

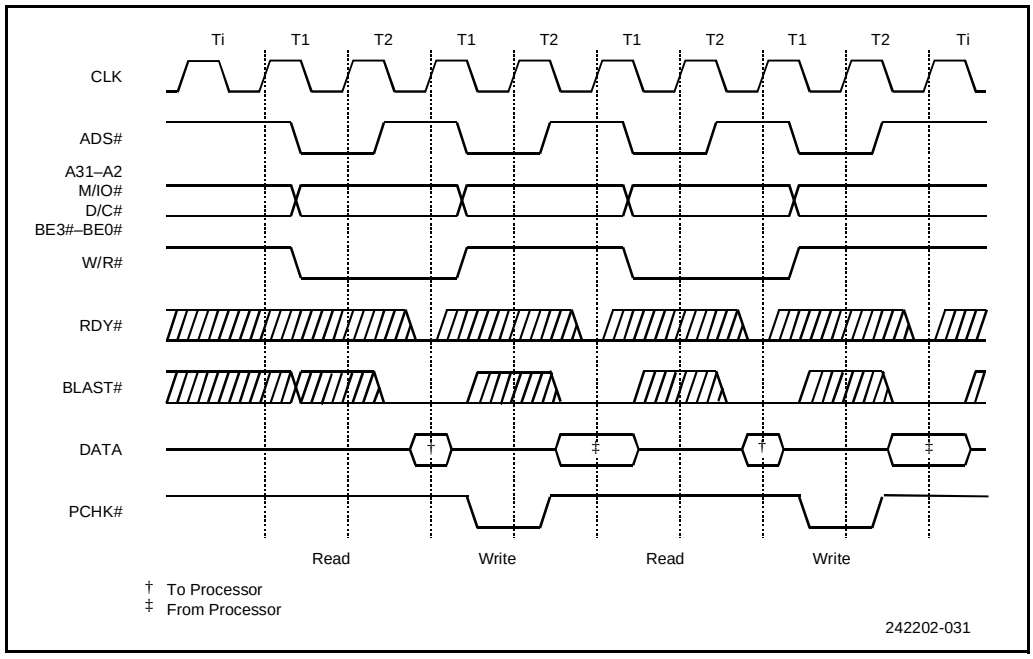


Figure 10-10. Basic 2-2 Bus Cycle

The non-burst ready input (RDY#) is asserted by the external system in the second clock. RDY# indicates that the external system has presented valid data on the data pins in response to a read or the external system has accepted data in response to a write.

The Intel486 processor samples RDY# at the end of the second clock. The cycle is complete if RDY# is asserted (LOW) when sampled. Note that RDY# is ignored at the end of the first clock of the bus cycle.

The burst last signal (BLAST#) is asserted (LOW) by the Intel486 processor during the second clock of the first cycle in all bus transfers illustrated in Figure 10-10. This indicates that each transfer is complete after a single cycle. The Intel486 processor asserts BLAST# in the last cycle, "T2", of a bus transfer.

The timing of the parity check output (PCHK#) is shown in Figure 10-10. The Intel486 processor drives the PCHK# output one clock after RDY# or BRDY# terminates a read cycle. PCHK# indicates the parity status for the data sampled at the end of the previous clock. The PCHK# signal can be used by the external system. The Intel486 processor does nothing in response to the PCHK# output.

10.3.1.2 Inserting Wait States

The external system can insert wait states into the basic 2-2 cycle by deasserting RDY# at the end of the second clock. RDY# must be deasserted to insert a wait state. Figure 10-11 illustrates a simple non-burst, non-cacheable signal with one wait state added. Any number of wait states can be added to an Intel486 processor bus cycle by maintaining RDY# deasserted.

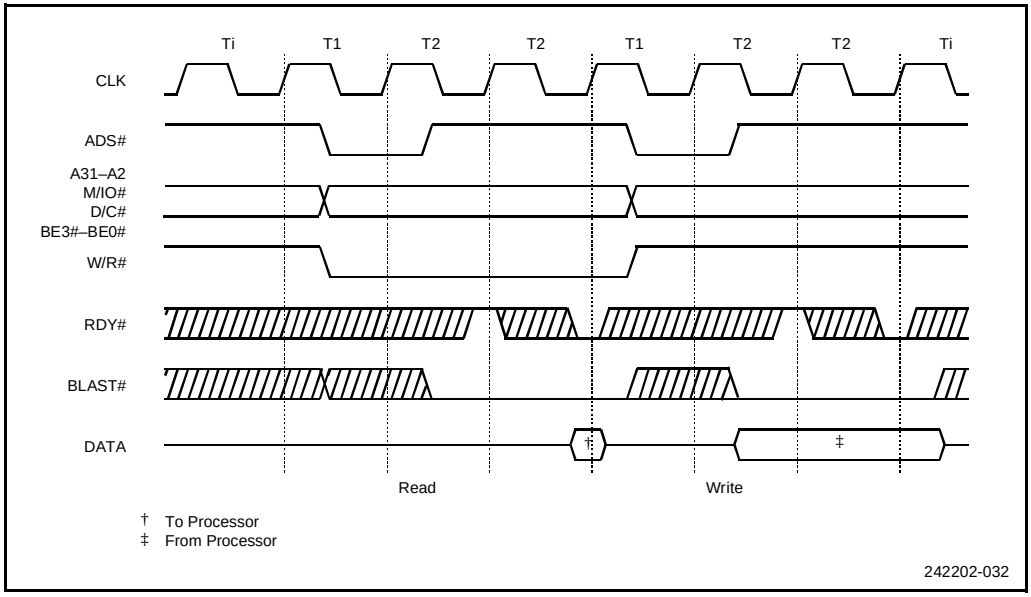


Figure 10-11. Basic 3-3 Bus Cycle

The burst ready input (BRDY#) must be deasserted on all clock edges where RDY# is deasserted for proper operation of these simple non-burst cycles.

10.3.2 Multiple and Burst Cycle Bus Transfers

Multiple cycle bus transfers can be caused by internal requests from the Intel486 processor or by the external memory system. An internal request for a 128-bit pre-fetch requires more than one cycle. Internal requests for unaligned data may also require multiple bus cycles. A cache line fill requires multiple cycles to complete.

The external system can cause a multiple cycle transfer when it can only supply 8- or 16-bits per cycle.

Only multiple cycle transfers caused by internal requests are considered in this section. Cacheable cycles and 8- and 16-bit transfers are covered in Section 10.3.3, “Cacheable Cycles,” and Section 10.3.5, “8- and 16-Bit Cycles.”

An internal request by an IntelDX2 or IntelDX4 processor for a 64-bit floating-point load must take more than one internal cycle.

10.3.2.1 Burst Cycles

The Intel486 processor can accept burst cycles for any bus requests that require more than a single data cycle. During burst cycles, a new data item is strobed into the Intel486 processor every clock rather than every other clock as in non-burst cycles. The fastest burst cycle requires two clocks for the first data item, with subsequent data items returned every clock.

The Intel486 processor is capable of bursting a maximum of 32 bits during a write. Burst writes can only occur if BS8# or BS16# is asserted. For example, the Intel486 processor can burst write four 8-bit operands or two 16-bit operands in a single burst cycle. But the Intel486 processor cannot burst multiple 32-bit writes in a single burst cycle.

Burst cycles begin with the Intel486 processor driving out an address and asserting ADS# in the same manner as non-burst cycles. The Intel486 processor indicates that it is willing to perform a burst cycle by holding the burst last signal (BLAST#) deasserted in the second clock of the cycle. The external system indicates its willingness to do a burst cycle by asserting the burst ready signal (BRDY#).

The addresses of the data items in a burst cycle all fall within the same 16-byte aligned area (corresponding to an internal Intel486 processor cache line). A 16-byte aligned area begins at location XXXXXXX0 and ends at location XXXXXXXF. During a burst cycle, only BE[3:0]#, A2, and A3 may change. A[31:4], M/IO#, D/C#, and W/R# remain stable throughout a burst. Given the first address in a burst, external hardware can easily calculate the address of subsequent transfers in advance. An external memory system can be designed to quickly fill the Intel486 processor internal cache lines.

Burst cycles are not limited to cache line fills. Any multiple cycle read request by the Intel486 processor can be converted into a burst cycle. The Intel486 processor only bursts the number of bytes needed to complete a transfer. For example, the IntelDX2 and Write-Back Enhanced IntelDX4 processors burst eight bytes for a 64-bit floating-point non-cacheable read.

The external system converts a multiple cycle request into a burst cycle by asserting BRDY# rather than RDY# (non-burst ready) in the first cycle of a transfer. For cycles that cannot be burst, such as interrupt acknowledge and halt, BRDY# has the same effect as RDY#. BRDY# is ignored if both BRDY# and RDY# are asserted in the same clock. Memory areas and peripheral devices that cannot perform bursting must terminate cycles with RDY#.

10.3.2.2 Terminating Multiple and Burst Cycle Transfers

The Intel486 processor deasserts BLAST# for all but the last cycle in a multiple cycle transfer. BLAST# is deasserted in the first cycle to inform the external system that the transfer could take additional cycles. BLAST# is asserted in the last cycle of the transfer to indicate that the next time BRDY# or RDY# is asserted the transfer is complete.

BLAST# is not valid in the first clock of a bus cycle. It should be sampled only in the second and subsequent clocks when RDY# or BRDY# is asserted.

The number of cycles in a transfer is a function of several factors including the number of bytes the Intel486 processor needs to complete an internal request (1, 2, 4, 8, or 16), the state of the bus size inputs (BS8# and BS16#), the state of the cache enable input (KEN#) and the alignment of the data to be transferred.

When the Intel486 processor initiates a request, it knows how many bytes are transferred and if the data is aligned. The external system must indicate whether the data is cacheable (if the transfer is a read) and the width of the bus by returning the state of the KEN#, BS8# and BS16# inputs one clock before RDY# or BRDY# is asserted. The Intel486 processor determines how many cycles a transfer will take based on its internal information and inputs from the external system.

BLAST# is not valid in the first clock of a bus cycle because the Intel486 processor cannot determine the number of cycles a transfer will take until the external system asserts KEN#, BS8# and BS16#. BLAST# should only be sampled in the second T2 state and subsequent T2 states of a cycle when the external system asserts RDY# or BRDY#.

The system may terminate a burst cycle by asserting RDY# instead of BRDY#. BLAST# remains deasserted until the last transfer. However, any transfers required to complete a cache line fill follow the burst order; for example, if burst order was 4, 0, C, 8 and RDY# was asserted after 0, the next transfers are from C and 8.

10.3.2.3 Non-Cacheable, Non-Burst, Multiple Cycle Transfers

Figure 10-12 illustrates a two-cycle, non-burst, non-cacheable read. This transfer is simply a sequence of two single cycle transfers. The Intel486 processor indicates to the external system that this is a multiple cycle transfer by deasserting BLAST# during the second clock of the first cycle. The external system asserts RDY# to indicate that it will not burst the data. The external system also indicates that the data is not cacheable by deasserting KEN# one clock before it asserts RDY#. When the Intel486 processor samples RDY# asserted, it ignores BRDY#.

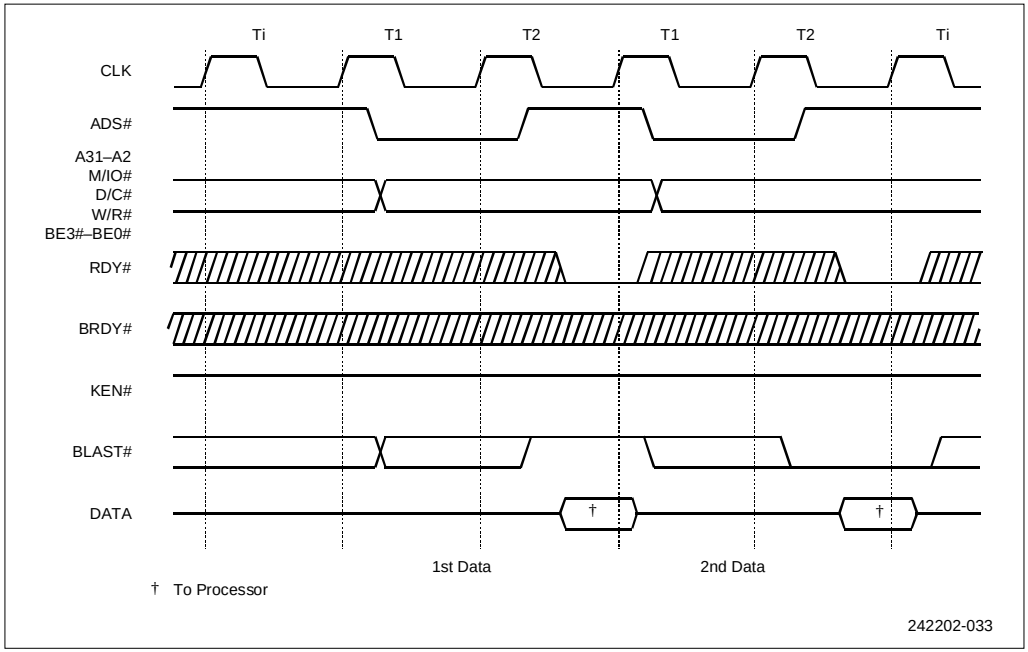


Figure 10-12. Non-Cacheable, Non-Burst, Multiple-Cycle Transfers

Each cycle in the transfer begins when ADS# is asserted and the cycle is complete when the external system asserts RDY#.

The Intel486 processor indicates the last cycle of the transfer by asserting BLAST#. The next RDY# asserted by the external system terminates the transfer.

10.3.2.4 Non-Cacheable Burst Cycles

The external system converts a multiple cycle request into a burst cycle by asserting BRDY# rather than RDY# in the first cycle of the transfer. This is illustrated in Figure 10-13.

There are several features to note in the burst read. ADS# is asserted only during the first cycle of the transfer. RDY# must be deasserted when BRDY# is asserted.

BLAST# behaves exactly as it does in the non-burst read. BLAST# is deasserted in the second clock of the first cycle of the transfer, indicating more cycles to follow. In the last cycle, BLAST# is asserted, prompting the external memory system to end the burst after asserting the next BRDY#.

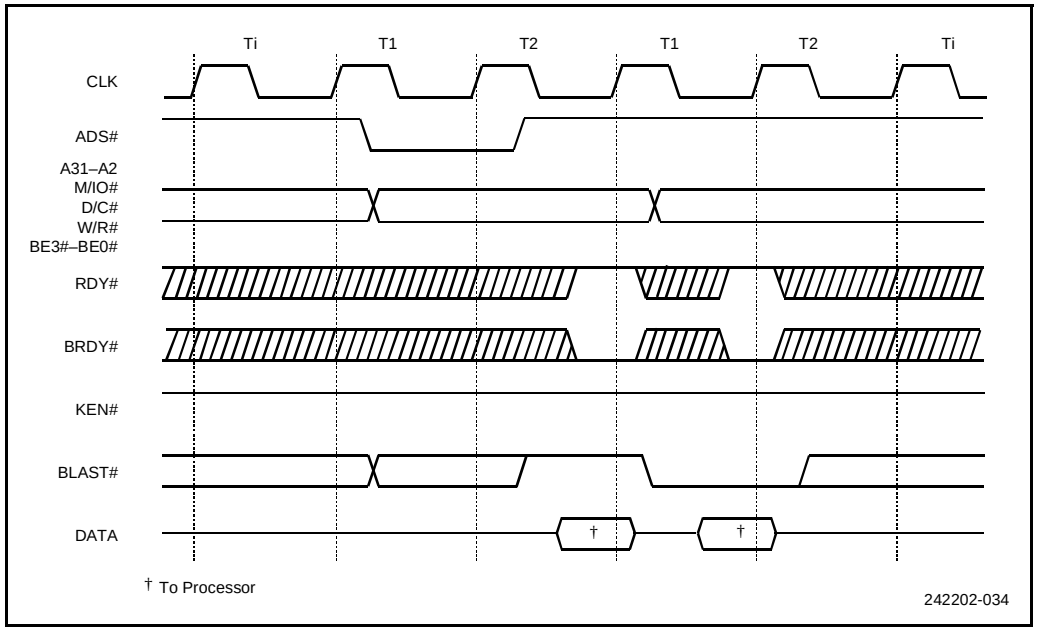


Figure 10-13. Non-Cacheable Burst Cycle

10.3.3 Cacheable Cycles

Any memory read can become a cache fill operation. The external memory system can allow a read request to fill a cache line by asserting KEN# one clock before RDY# or BRDY# during the first cycle of the transfer on the external bus. Once KEN# is asserted and the remaining three requirements described below are met, the Intel486 processor fetches an entire cache line regardless of the state of KEN#. KEN# must be asserted in the last cycle of the transfer for the data to be written into the internal cache. The Intel486 processor converts only memory reads or prefetches into a cache fill.

KEN# is ignored during write or I/O cycles. Memory writes are stored only in the on-chip cache if there is a cache hit. I/O space is never cached in the internal cache.

To transform a read or a prefetch into a cache line fill, the following conditions must be met:

1. The KEN# pin must be asserted one clock prior to RDY# or BRDY# being asserted for the first data cycle.
2. The cycle must be of a type that can be internally cached. (Locked reads, I/O reads, and interrupt acknowledge cycles are never cached.)
3. The page table entry must have the page cache disable bit (PCD) set to 0. To cache a page table entry, the page directory must have PCD=0. To cache reads or prefetches when paging is disabled, or to cache the page directory entry, control register 3 (CR3) must have PCD=0.
4. The cache disable (CD) bit in control register 0 (CR0) must be clear.

External hardware can determine when the Intel486 processor has transformed a read or prefetch into a cache fill by examining the KEN#, M/IO#, D/C#, W/R#, LOCK#, and PCD pins. These pins convey to the system the outcome of conditions 1–3 in the above list. In addition, the Intel486 processor drives PCD high whenever the CD bit in CR0 is set, so that external hardware can evaluate condition 4.

Cacheable cycles can be burst or non-burst.

10.3.3.1 Byte Enables during a Cache Line Fill

For the first cycle in the line fill, the state of the byte enables should be ignored. In a non-cacheable memory read, the byte enables indicate the bytes actually required by the memory or code fetch.

The Intel486 processor expects to receive valid data on its entire bus (32 bits) in the first cycle of a cache line fill. Data should be returned with the assumption that all the byte enable pins are asserted. However if BS8# is asserted, only one byte should be returned on data lines D[7:0]. Similarly if BS16# is asserted, two bytes should be returned on D[15:0].

The Intel486 processor generates the addresses and byte enables for all subsequent cycles in the line fill. The order in which data is read during a line fill depends on the address of the first item read. Byte ordering is discussed in Section 10.3.4, “Burst Mode Details.”

10.3.3.2 Non-Burst Cacheable Cycles

Figure 10-14 shows a non-burst cacheable cycle. The cycle becomes a cache fill when the Intel486 processor samples KEN# asserted at the end of the first clock. The Intel486 processor deasserts BLAST# in the second clock in response to KEN#. BLAST# is deasserted because a cache fill requires three additional cycles to complete. BLAST# remains deasserted until the last transfer in the cache line fill. KEN# must be asserted in the last cycle of the transfer for the data to be written into the internal cache.

Note that this cycle would be a single bus cycle if KEN# was not sampled asserted at the end of the first clock. The subsequent three reads would not have happened since a cache fill was not requested.

The BLAST# output is invalid in the first clock of a cycle. BLAST# may be asserted during the first clock due to earlier inputs. Ignore BLAST# until the second clock.

During the first cycle of the cache line fill the external system should treat the byte enables as if they are all asserted. In subsequent cycles in the burst, the Intel486 processor drives the address lines and byte enables. (See Section 10.3.4.2, "Burst and Cache Line Fill Order.")

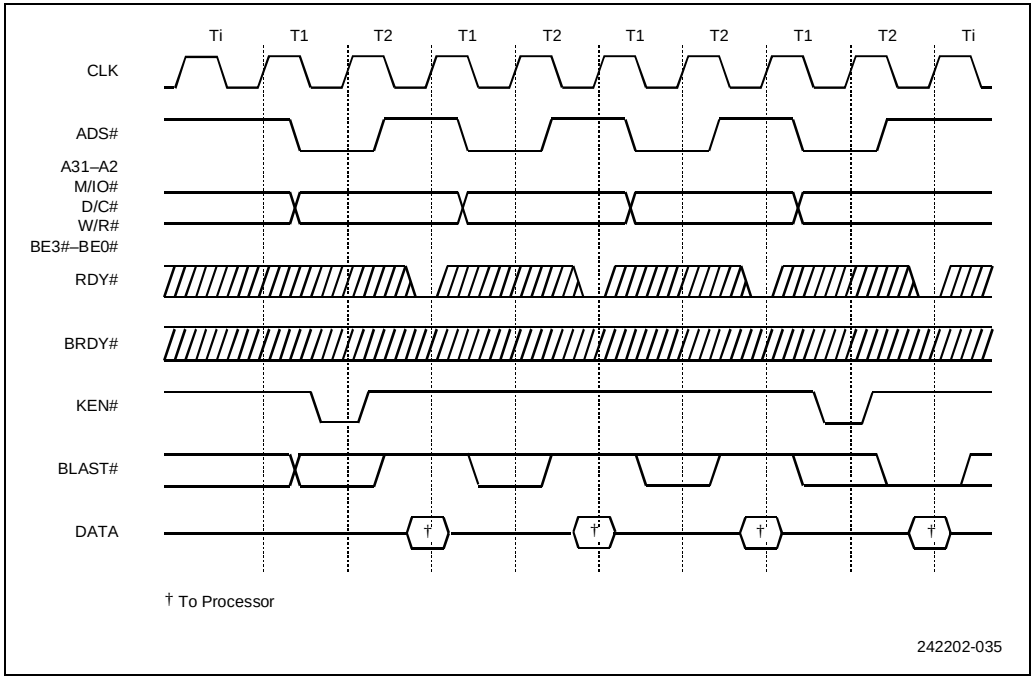


Figure 10-14. Non-Burst, Cacheable Cycles

10.3.3.3 Burst Cacheable Cycles

Figure 10-15 illustrates a burst mode cache fill. As in Figure 10-14, the transfer becomes a cache line fill when the external system asserts KEN# at the end of the first clock in the cycle.

The external system informs the Intel486 processor that it will burst the line in by asserting BRDY# at the end of the first cycle in the transfer.

Note that during a burst cycle, ADS# is only driven with the first address.

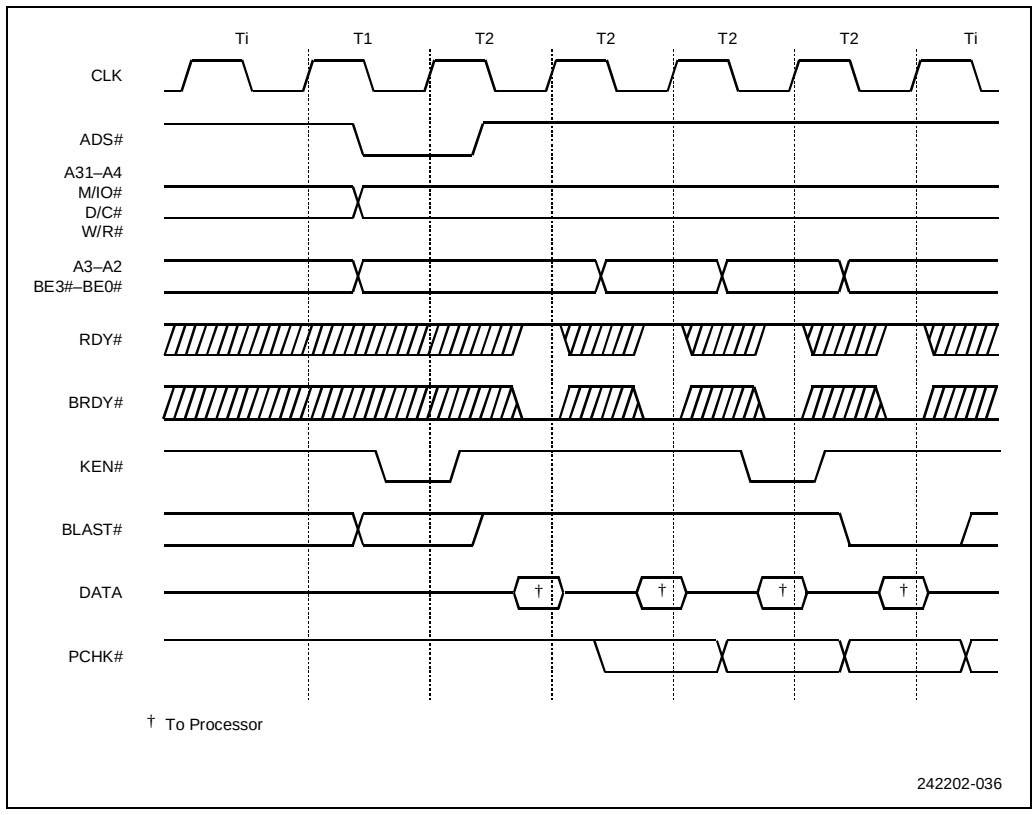


Figure 10-15. Burst Cacheable Cycle

10.3.3.4 Effect of Changing KEN# during a Cache Line Fill

KEN# can change multiple times as long as it arrives at its final value in the clock before RDY# or BRDY# is asserted. This is illustrated in Figure 10-16. Note that the timing of BLAST# follows that of KEN# by one clock. The Intel486 processor samples KEN# every clock and uses the value returned in the clock before BRDY# or RDY# to determine if a bus cycle would be a cache line fill. Similarly, it uses the value of KEN# in the last cycle before early RDY# to load the line just retrieved from memory into the cache. KEN# is sampled every clock and it must satisfy setup and hold times.

KEN# can also change multiple times before a burst cycle, as long as it arrives at its final value one clock before BRDY# or RDY# is asserted.

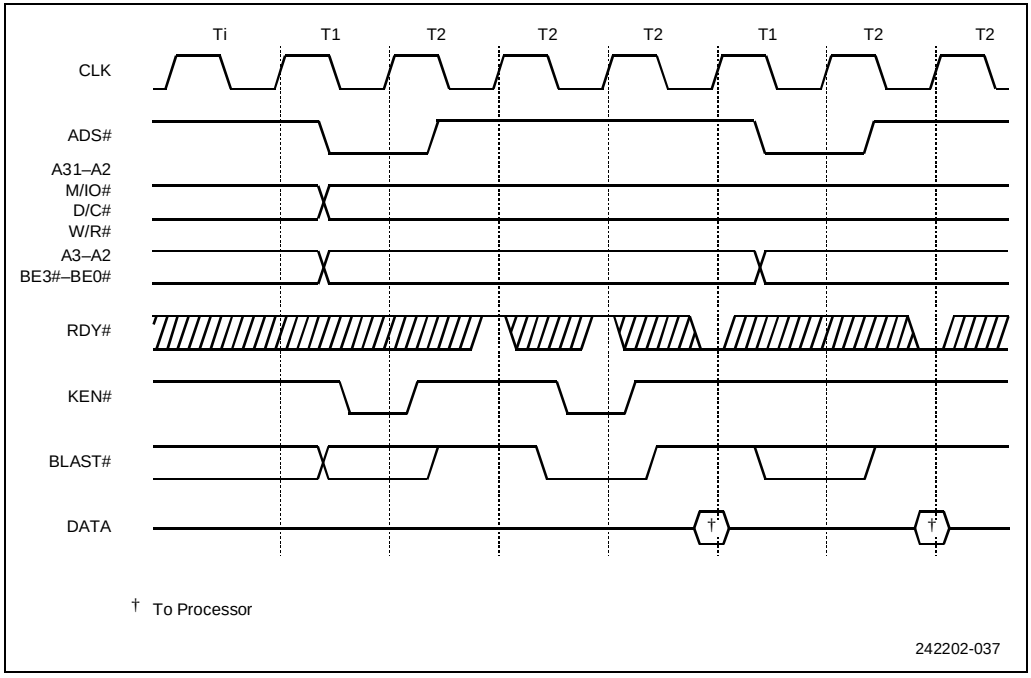


Figure 10-16. Effect of Changing KEN#

10.3.4 Burst Mode Details

10.3.4.1 Adding Wait States to Burst Cycles

Burst cycles need not return data on every clock. The Intel486 processor strobes data into the chip only when either RDY# or BRDY# is asserted. Deasserting BRDY# and RDY# adds a wait state to the transfer. A burst cycle where two clocks are required for every burst item is shown in Figure 10-17.

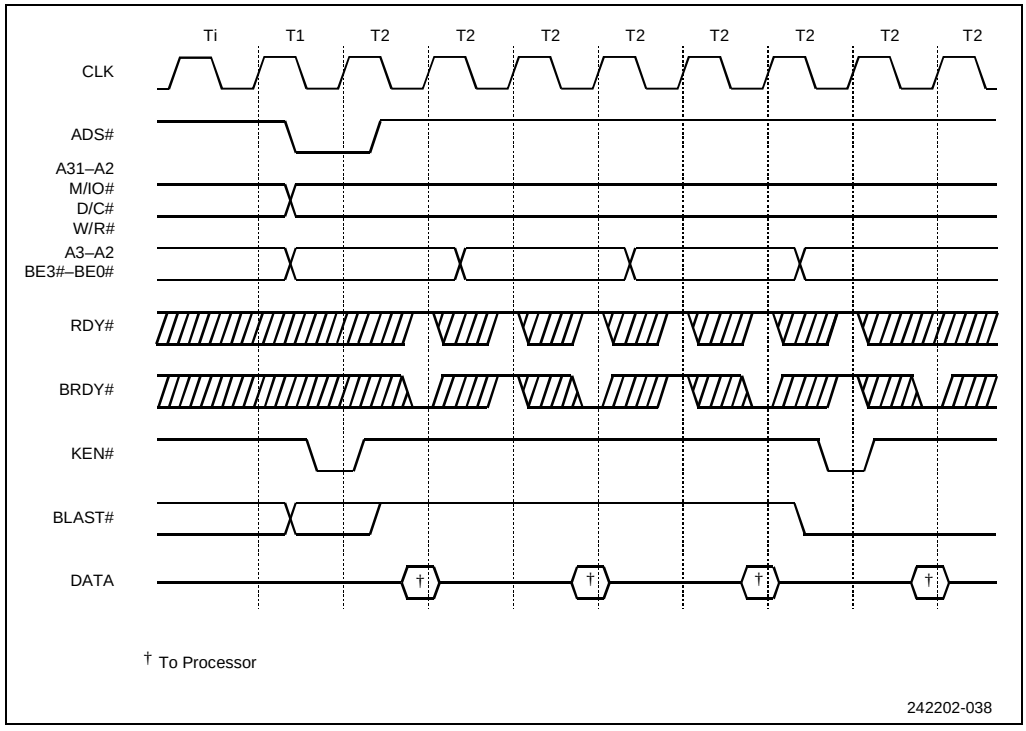


Figure 10-17. Slow Burst Cycle

10.3.4.2 Burst and Cache Line Fill Order

The burst order used by the Intel486 processor is shown in Table 10-8. This burst order is followed by any burst cycle (cache or not), cache line fill (burst or not) or code prefetch.

The Intel486 processor presents each request for data in an order determined by the first address in the transfer. For example, if the first address was 104 the next three addresses in the burst will be 100, 10C and 108. An example of burst address sequencing is shown in Figure 10-18.

Table 10-8. Burst Order (Both Read and Write Bursts)

First Address	Second Address	Third Address	Fourth Address
0	4	8	C
4	0	C	8
8	C	0	4
C	8	4	0

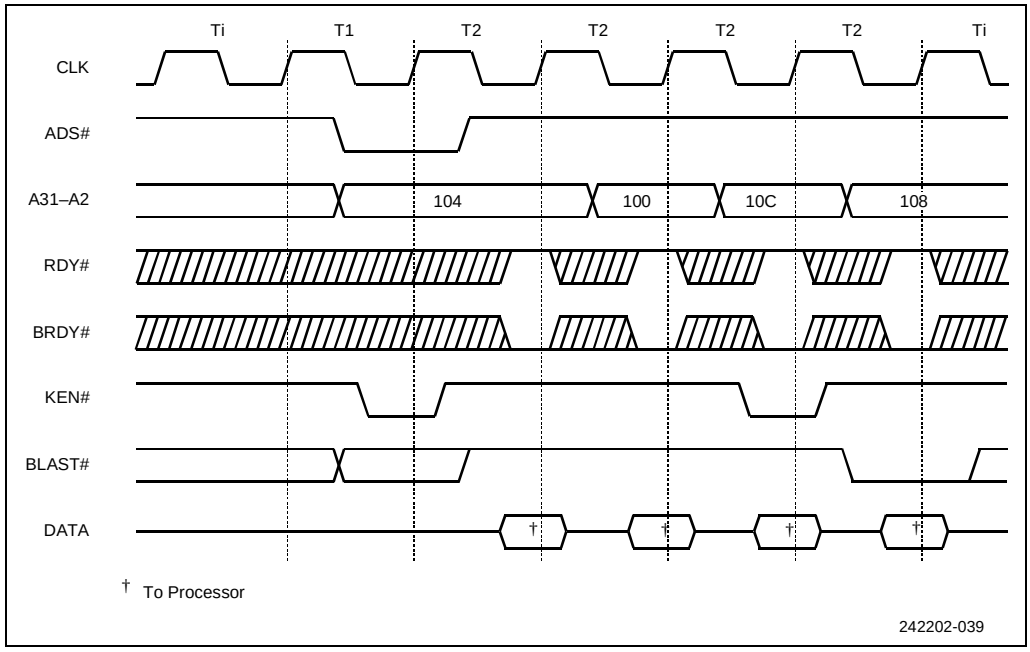


Figure 10-18. Burst Cycle Showing Order of Addresses

The sequences shown in Table 10-8 accommodate systems with 64-bit buses as well as systems with 32-bit data buses. The sequence applies to all bursts, regardless of whether the purpose of the burst is to fill a cache line, perform a 64-bit read, or perform a pre-fetch. If either BS8# or BS16# is asserted, the Intel486 processor completes the transfer of the current 32-bit word before progressing to the next 32-bit word. For example, a BS16# burst to address 4 has the following order: 4-6-0-2-C-E-8-A.

10.3.4.3 Interrupted Burst Cycles

Some memory systems may not be able to respond with burst cycles in the order defined in Table 10-8. To support these systems, the Intel486 processor allows a burst cycle to be interrupted at any time. The Intel486 processor automatically generates another normal bus cycle after being interrupted to complete the data transfer. This is called an interrupted burst cycle. The external system can respond to an interrupted burst cycle with another burst cycle.

The external system can interrupt a burst cycle by asserting RDY# instead of BRDY#. RDY# can be asserted after any number of data cycles terminated with BRDY#.

An example of an interrupted burst cycle is shown in Figure 10-19. The Intel486 processor immediately asserts ADS# to initiate a new bus cycle after RDY# is asserted. BLAST# is deasserted one clock after ADS# begins the second bus cycle, indicating that the transfer is not complete.

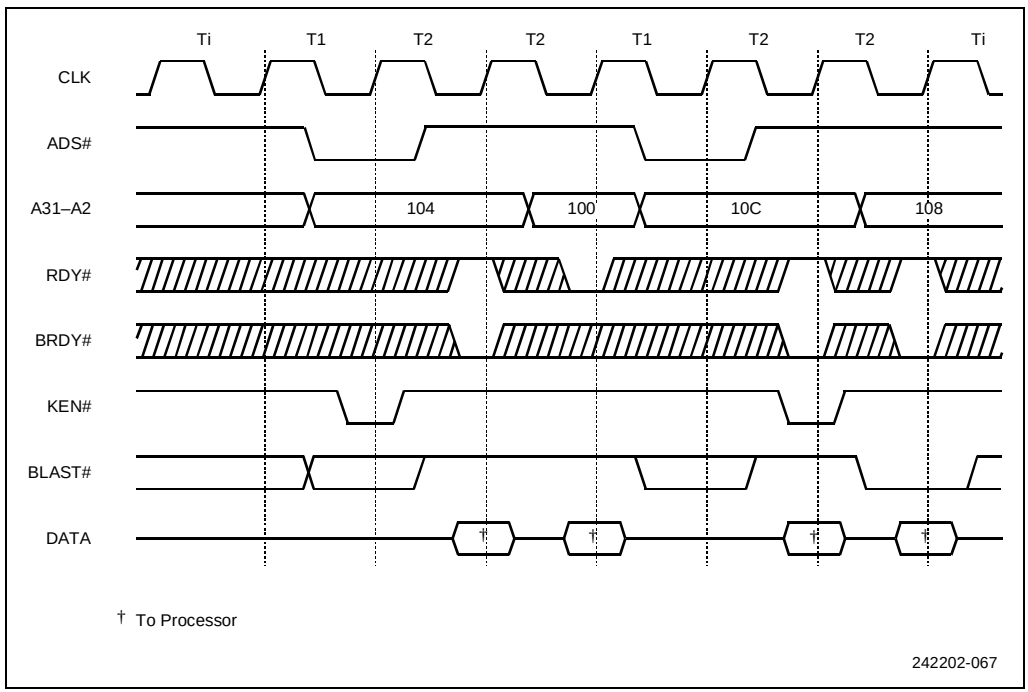


Figure 10-19. Interrupted Burst Cycle

KEN# need not be asserted in the first data cycle of the second part of the transfer shown in Figure 10-20. The cycle had been converted to a cache fill in the first part of the transfer and the Intel486 processor expects the cache fill to be completed. Note that the first half and second half of the transfer in Figure 10-19 are both two-cycle burst transfers.

The order in which the Intel486 processor requests operands during an interrupted burst transfer is shown by Table 10-7 on page 10-12. Mixing RDY# and BRDY# does not change the order in which operand addresses are requested by the Intel486 processor.

An example of the order in which the Intel486 processor requests operands during a cycle in which the external system mixes RDY# and BRDY# is shown in Figure 10-20. The Intel486 processor initially requests a transfer beginning at location 104. The transfer becomes a cache line fill when the external system asserts KEN#. The first cycle of the cache fill transfers the contents of location 104 and is terminated with RDY#. The Intel486 processor drives out a new request (by asserting ADS#) to address 100. If the external system terminates the second cycle with BRDY#, the Intel486 processor next requests/expects address 10C. The correct order is determined by the first cycle in the transfer, which may not be the first cycle in the burst if the system mixes RDY# with BRDY#.

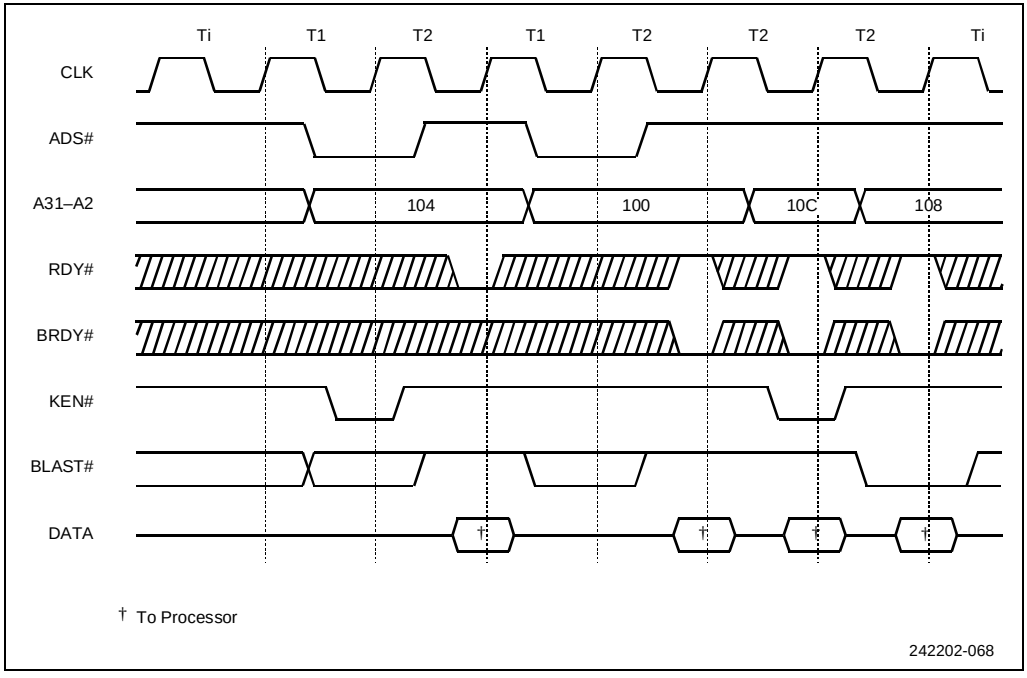


Figure 10-20. Interrupted Burst Cycle with Non-Obvious Order of Addresses

10.3.5 8- and 16-Bit Cycles

The Intel486 processor supports both 16- and 8-bit external buses through the BS16# and BS8# inputs. BS16# and BS8# allow the external system to specify, on a cycle-by-cycle basis, whether the addressed component can supply 8, 16 or 32 bits. BS16# and BS8# can be used in burst cycles as well as non-burst cycles. If both BS16# and BS8# are asserted for any bus cycle, the Intel486 processor responds as if only BS8# is asserted.

The timing of BS16# and BS8# is the same as that of KEN#. BS16# and BS8# must be asserted before the first RDY# or BRDY# is asserted. Asserting BS16# and BS8# can force the Intel486 processor to run additional cycles to complete what would have been only a single 32-bit cycle. BS8# and BS16# may change the state of BLAST# when they force subsequent cycles from the transfer.

Figure 10-21 shows an example in which BS8# forces the Intel486 processor to run two extra cycles to complete a transfer. The Intel486 processor issues a request for 24 bits of information. The external system asserts BS8#, indicating that only eight bits of data can be supplied per cycle. The Intel486 processor issues two extra cycles to complete the transfer.

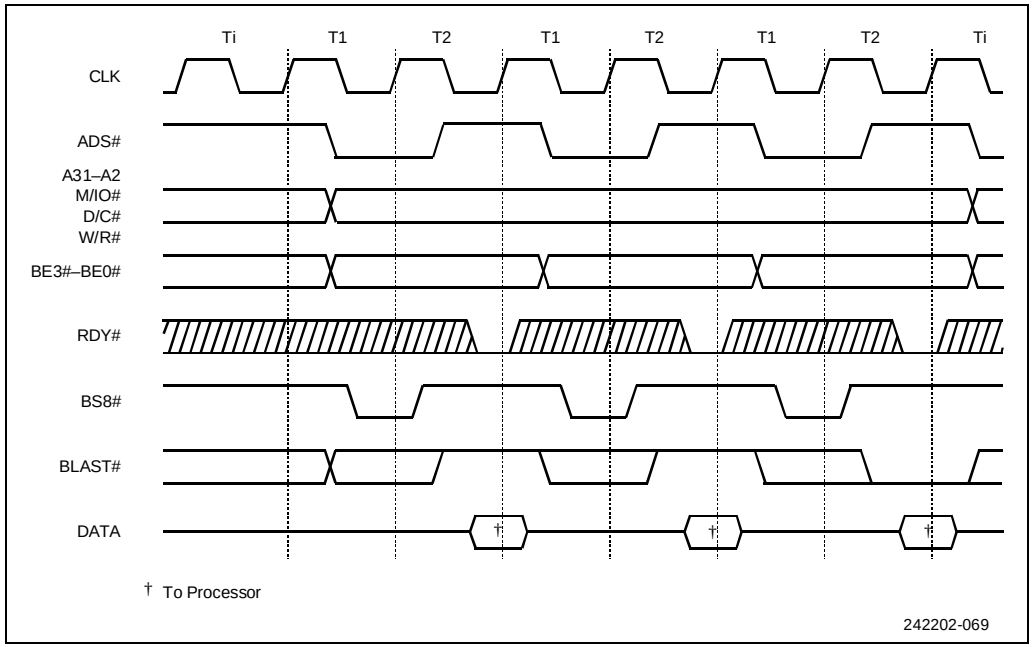


Figure 10-21. 8-Bit Bus Size Cycle

Extra cycles forced by BS16# and BS8# signals should be viewed as independent bus cycles. BS16# and BS8# should be asserted for each additional cycle unless the addressed device can change the number of bytes it can return between cycles. The Intel486 processor deasserts BLAST# until the last cycle before the transfer is complete.

Refer to Section 10.1.2, "Dynamic Data Bus Sizing," for the sequencing of addresses when BS8# or BS16# are asserted.

During burst cycles, BS8# and BS16# operate in the same manner as during non-burst cycles. For example, a single non-cacheable read could be transferred by the Intel486 processor as four 8-bit burst data cycles. Similarly, a single 32-bit write could be written as four 8-bit burst data cycles. An example of a burst write is shown in Figure 10-22. Burst writes can only occur if BS8# or BS16# is asserted.

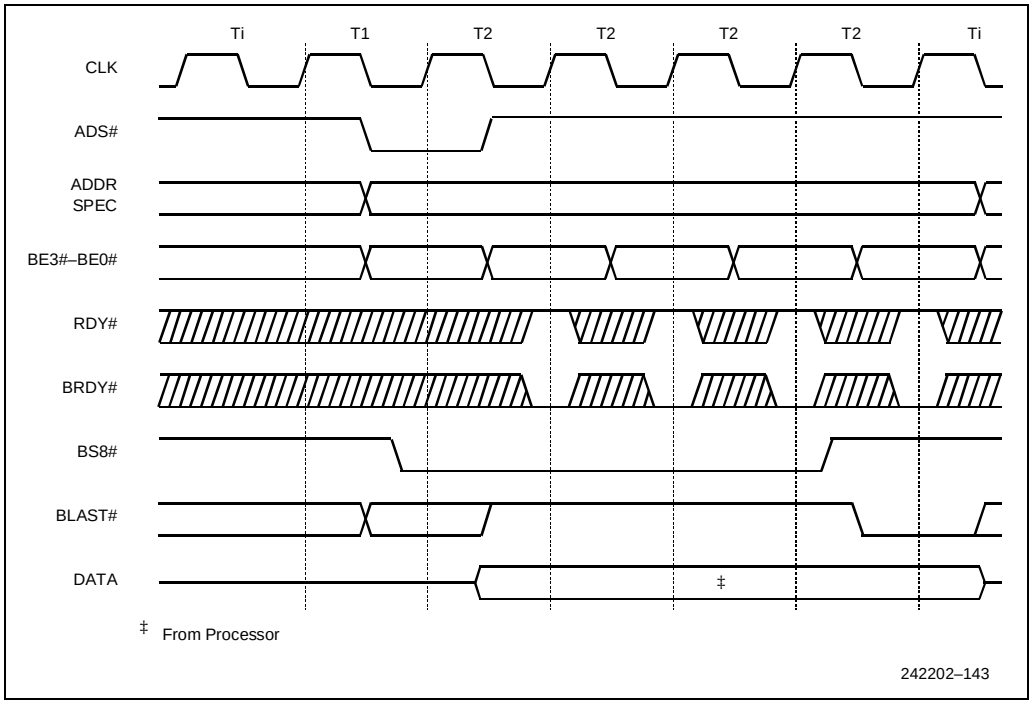


Figure 10-22. Burst Write as a Result of BS8# or BS16#

10.3.6 Locked Cycles

Locked cycles are generated in software for any instruction that performs a read-modify-write operation. During a read-modify-write operation, the Intel486 processor can read and modify a variable in external memory and ensure that the variable is not accessed between the read and write.

Locked cycles are automatically generated during certain bus transfers. The XCHG (exchange) instruction generates a locked cycle when one of its operands is memory-based. Locked cycles are generated when a segment or page table entry is updated and during interrupt acknowledge cycles. Locked cycles are also generated when the LOCK instruction prefix is used with selected instructions.

Locked cycles are implemented in hardware with the LOCK# pin. When LOCK# is asserted, the Intel486 processor is performing a read-modify-write operation and the external bus should not be relinquished until the cycle is complete. Multiple reads or writes can be locked. A locked cycle is shown in Figure 10-23. LOCK# is asserted with the address and bus definition pins at the beginning of the first read cycle and remains asserted until RDY# is asserted for the last write cycle. For unaligned 32-bit read-modify-write operations, the LOCK# remains asserted for the entire duration of the multiple cycle. It deasserts when RDY# is asserted for the last write cycle.

When LOCK# is asserted, the Intel486 processor recognizes address hold and backoff but does not recognize bus hold. It is left to the external system to properly arbitrate a central bus when the Intel486 processor generates LOCK#.

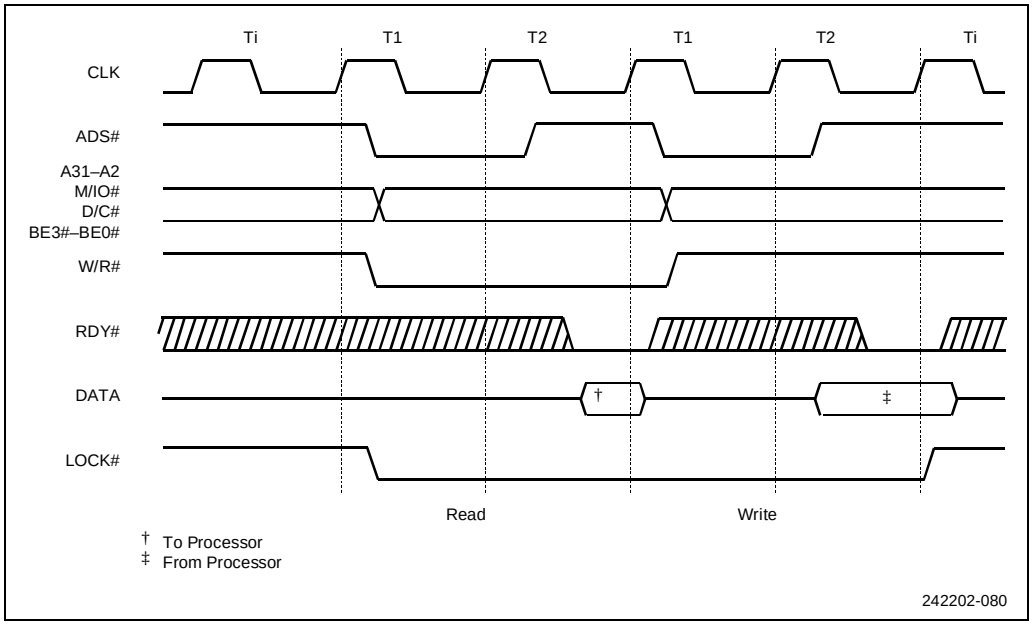


Figure 10-23. Locked Bus Cycle

10.3.7 Pseudo-Locked Cycles

Pseudo-locked cycles assure that no other master is given control of the bus during operand transfers that take more than one bus cycle.

For the Intel486 processor, examples include 64-bit description loads and cache line fills.

Pseudo-locked transfers are indicated by the PLOCK# pin. The memory operands must be aligned for correct operation of a pseudo-locked cycle.

PLOCK# need not be examined during burst reads. A 64-bit aligned operand can be retrieved in one burst (note that this is only valid in systems that do not interrupt bursts).

The system must examine PLOCK# during 64-bit writes since the Intel486 processor cannot burst write more than 32 bits. However, burst can be used within each 32-bit write cycle if BS8# or BS16# is asserted. BLAST is de-asserted in response to BS8# or BS16#. A 64-bit write is driven out as two non-burst bus cycles. BLAST# is asserted during both 32-bit writes, because a burst is not possible. PLOCK# is asserted during the first write to indicate that another write follows. This behavior is shown in Figure 10-24.

The first cycle of a 64-bit floating-point write is the only case in which both PLOCK# and BLAST# are asserted. Normally PLOCK# and BLAST# are the inverse of each other.

During all of the cycles in which PLOCK# is asserted, HOLD is not acknowledged until the cycle completes. This results in a large HOLD latency, especially when BS8# or BS16# is asserted. To reduce the HOLD latency during these cycles, windows are available between transfers to allow HOLD to be acknowledged during non-cacheable code prefetches. PLOCK# is asserted because BLAST# is deasserted, but PLOCK# is ignored and HOLD is recognized during the prefetch.

PLOCK# can change several times during a cycle, settling to its final value in the clock in which RDY# is asserted.

10.3.7.1 Floating-Point Read and Write Cycles

For IntelDX2 and Write-Back Enhanced IntelDX4 processors, 64-bit floating-point read and write cycles are also examples of operand transfers that take more than one bus cycle.

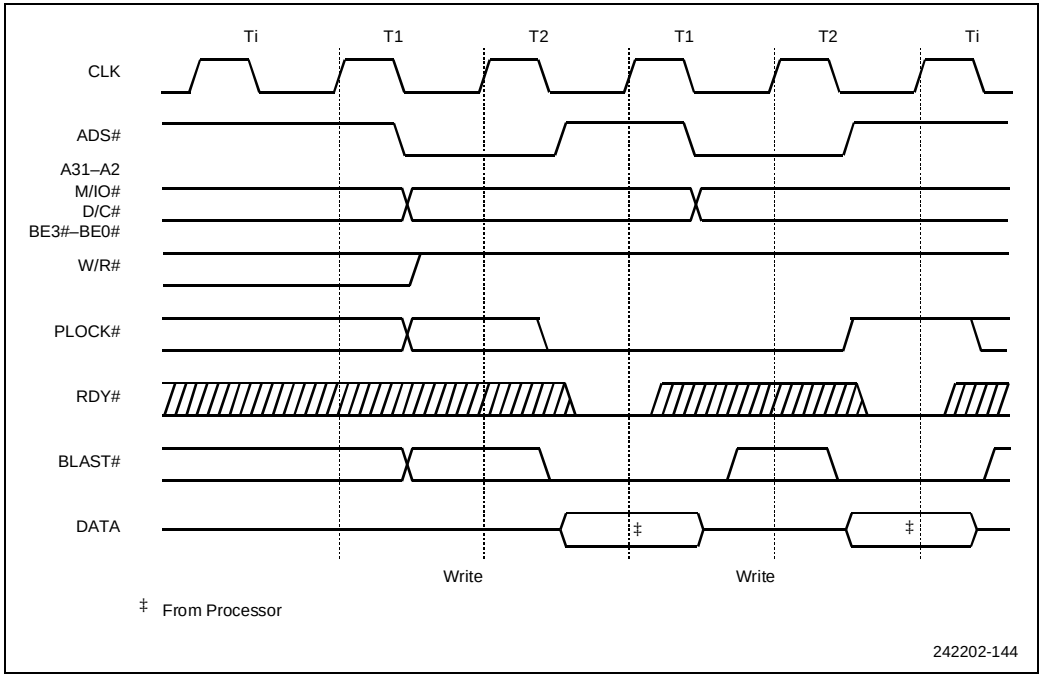


Figure 10-24. Pseudo Lock Timing

10.3.8 Invalidate Cycles

Invalidate cycles keep the Intel486 processor internal cache contents consistent with external memory. The Intel486 processor contains a mechanism for monitoring writes by other devices to external memory. When the Intel486 processor finds a write to a section of external memory contained in its internal cache, the Intel486 processor's internal copy is invalidated.

Invalidations use two pins, address hold request (AHOLD) and valid external address (EADS#). There are two steps in an invalidation cycle. First, the external system asserts the AHOLD input forcing the Intel486 processor to immediately relinquish its address bus. Next, the external system asserts EADS#, indicating that a valid address is on the Intel486 processor address bus. Figure 10-25 shows the fastest possible invalidation cycle. The Intel486 processor recognizes AHOLD on one CLK edge and floats the address bus in response. To allow the address bus to float and avoid contention, EADS# and the invalidation address should not be driven until the following CLK edge. The Intel486 processor reads the address over its address lines. If the Intel486 processor finds this address in its internal cache, the cache entry is invalidated. Note that the Intel486 processor address bus is input/output, unlike the Intel386 processor's bus, which is output only.

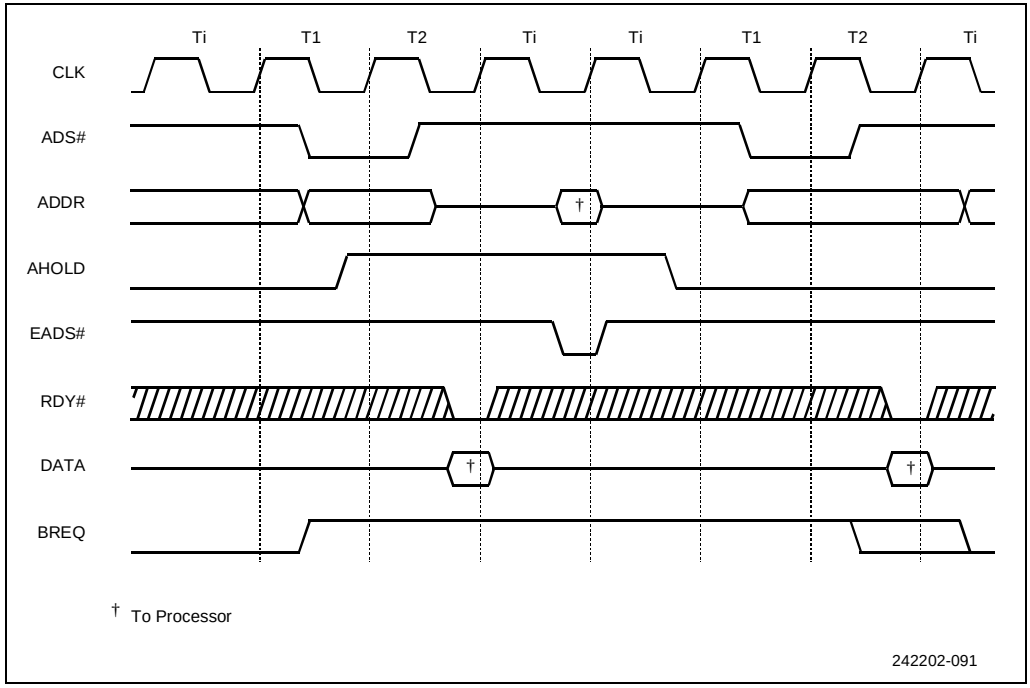


Figure 10-25. Fast Internal Cache Invalidation Cycle

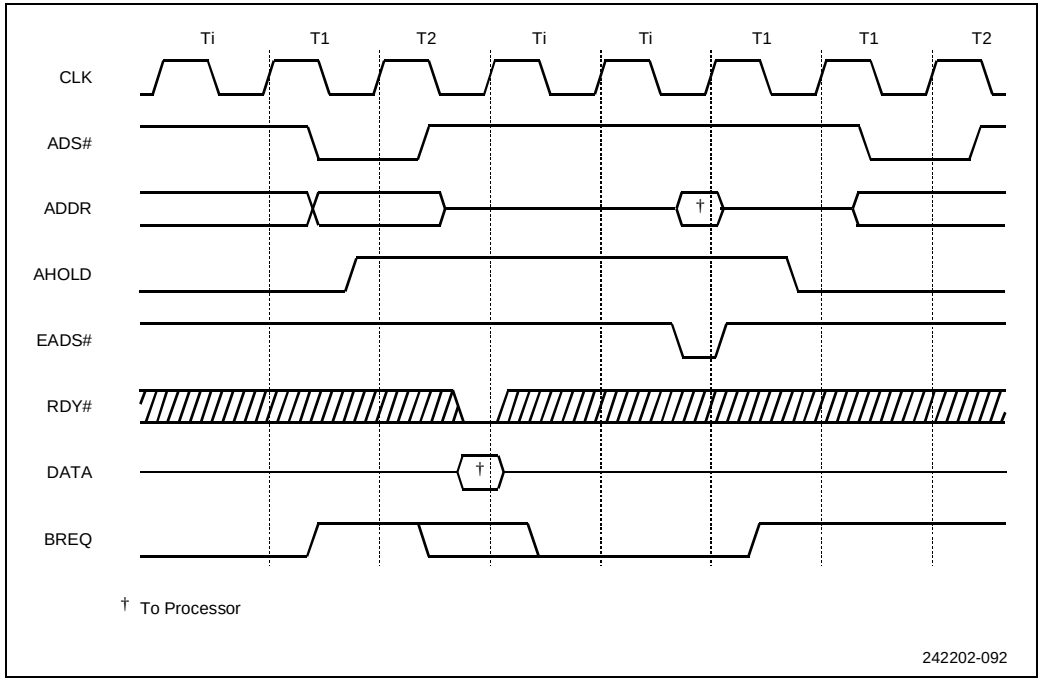


Figure 10-26. Typical Internal Cache Invalidation Cycle

10.3.8.1 Rate of Invalidate Cycles

The Intel486 processor can accept one invalidate per clock except in the last clock of a line fill. One invalidate per clock is possible as long as EADS# is deasserted in ONE or BOTH of the following cases:

1. In the clock in which RDY# or BRDY# is asserted for the last time.
2. In the clock following the clock in which RDY# or BRDY# is asserted for the last time.

This definition allows two system designs. Simple designs can restrict invalidates to one every other clock. The simple design need not track bus activity. Alternatively, systems can request one invalidate per clock provided that the bus is monitored.

10.3.8.2 Running Invalidate Cycles Concurrently with Line Fills

Precautions are necessary to avoid caching stale data in the Intel486 processor cache in a system with a second-level cache. An example of a system with a second-level cache is shown in Figure 10-27.

An external device can write to main memory over the system bus while the Intel486 processor is retrieving data from the second-level cache. The Intel486 processor must invalidate a line in its internal cache if the external device is writing to a main memory address that is also contained in the Intel486 processor cache.

A potential problem exists if the external device is writing to an address in external memory, and at the same time the Intel486 processor is reading data from the same address in the second-level cache. The system must force an invalidation cycle to invalidate the data that the Intel486 processor has requested during the line fill.

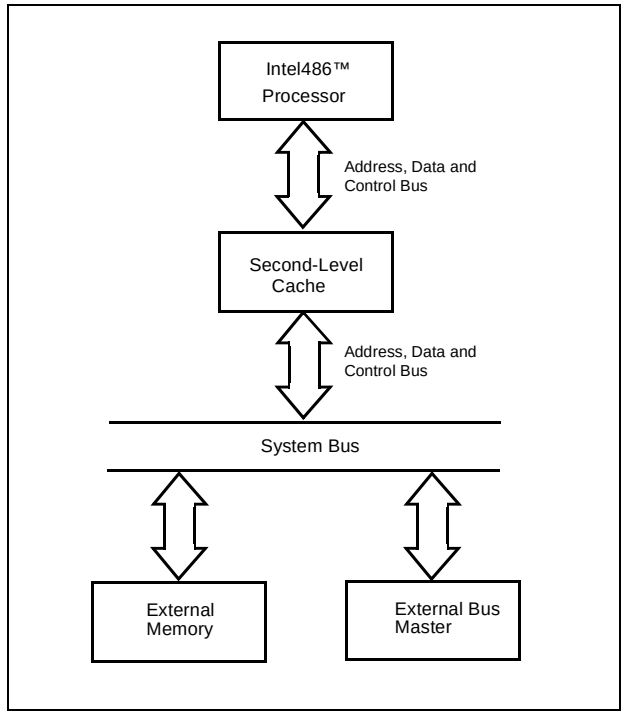


Figure 10-27. System with Second-Level Cache

If the system asserts EADS# before the first data in the line fill is returned to the Intel486 processor, the system must return data consistent with the new data in the external memory upon resumption of the line fill after the invalidation cycle. This is illustrated by the asserted EADS# signal labeled "1" in Figure 10-28.

If the system asserts EADS# at the same time or after the first data in the line fill is returned (in the same clock that the first RDY# or BRDY# is asserted or any subsequent clock in the line fill) the data is read into the Intel486 processor input buffers but it is not stored in the on-chip cache. This is illustrated by asserted EADS# signal labeled "2" in Figure 10-28. The stale data is used to satisfy the request that initiated the cache fill cycle.

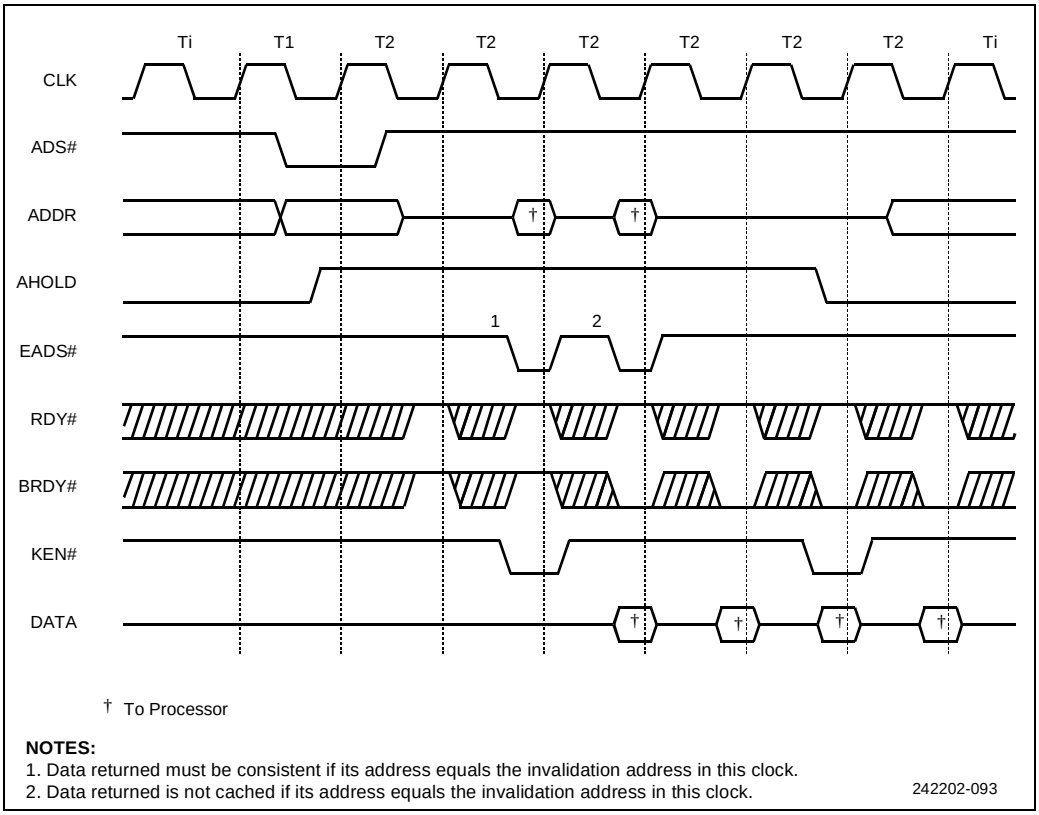


Figure 10-28. Cache Invalidation Cycle Concurrent with Line Fill

10.3.9 Bus Hold

The Intel486 processor provides a bus hold, hold acknowledge protocol using the bus hold request (HOLD) and bus hold acknowledge (HLDA) pins. Asserting the HOLD input indicates that another bus master has requested control of the Intel486 processor bus. The Intel486 processor responds by floating its bus and asserting HLDA when the current bus cycle, or sequence of locked cycles, is complete. An example of a HOLD/HLDA transaction is shown in Figure 10-29. Unlike the Intel386 processor, the Intel486 processor can respond to HOLD by floating its bus and asserting HLDA while RESET is asserted.

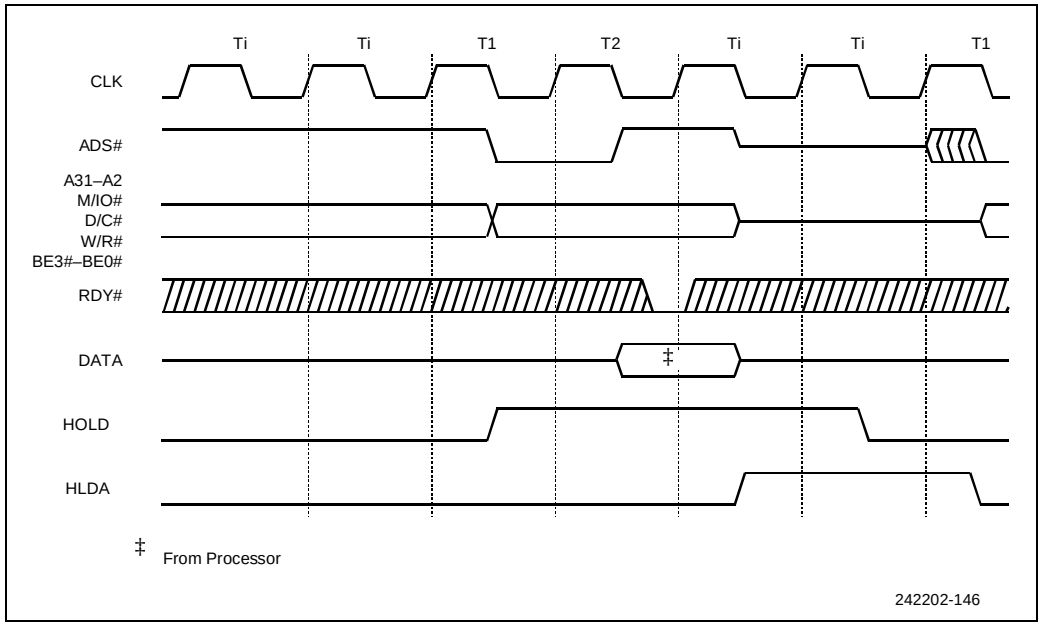


Figure 10-29. HOLD/HLDA Cycles

Note that HOLD is recognized during un-aligned writes (less than or equal to 32 bits) with BLAST# being asserted for each write. For a write greater than 32-bits or an un-aligned write, HOLD# recognition is prevented by PLOCK# getting asserted. However, HOLD is recognized during non-cacheable, non-burstable code prefetches even though PLOCK# is asserted.

For cacheable and non-burst or burst cycles, HOLD is acknowledged during backoff only if HOLD and BOFF# are asserted during an active bus cycle (after ADS# asserted) and before the first RDY# or BRDY# has been asserted (see Figure 10-30). The order in which HOLD and BOFF# are asserted is unimportant (as long as both are asserted prior to the first RDY#/BRDY# asserted by the system). Figure 10-30 shows the case where HOLD is asserted first; HOLD could be asserted simultaneously or after BOFF# and still be acknowledged.

The pins floated during bus hold are: BE[3:0]#, PCD, PWT, W/R#, D/C#, M/O#, LOCK#, PLOCK#, ADS#, BLAST#, D[31:0], A[31:2], and DP[3:0].

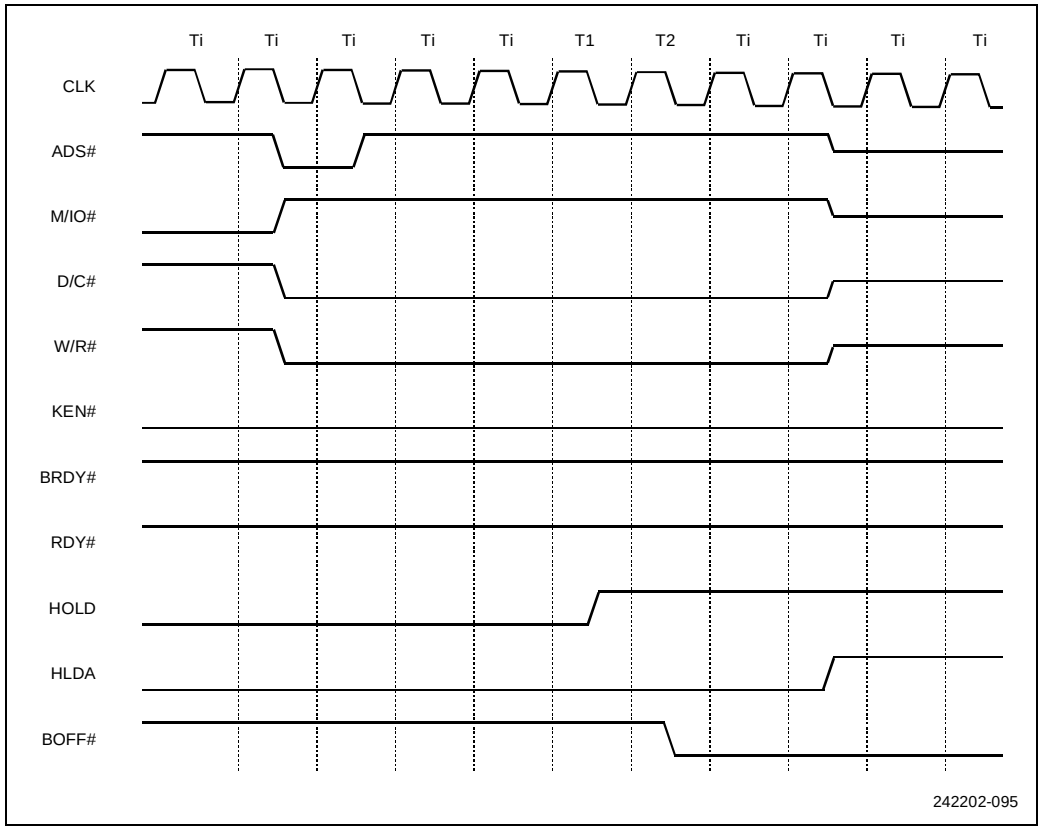


Figure 10-30. HOLD Request Acknowledged during BOFF#

10.3.10 Interrupt Acknowledge

The Intel486 processor generates interrupt acknowledge cycles in response to maskable interrupt requests that are generated on the interrupt request input (INTR) pin. Interrupt acknowledge cycles have a unique cycle type generated on the cycle type pins.

An example of an interrupt acknowledge transaction is shown in Figure 10-31. Interrupt acknowledge cycles are generated in locked pairs. Data returned during the first cycle is ignored. The interrupt vector is returned during the second cycle on the lower 8 bits of the data bus. The Intel486 processor has 256 possible interrupt vectors.

The state of A2 distinguishes the first and second interrupt acknowledge cycles. The byte address driven during the first interrupt acknowledge cycle is 4 (A[31:3] low, A2 high, BE[3:1]# high, and BE0# low). The address driven during the second interrupt acknowledge cycle is 0 (A[31:2] low, BE[3:1]# high, BE0# low).

Each of the interrupt acknowledge cycles is terminated when the external system asserts RDY# or BRDY#. Wait states can be added by holding RDY# or BRDY# deasserted. The Intel486 processor automatically generates four idle clocks between the first and second cycles to allow for 8259A recovery time.

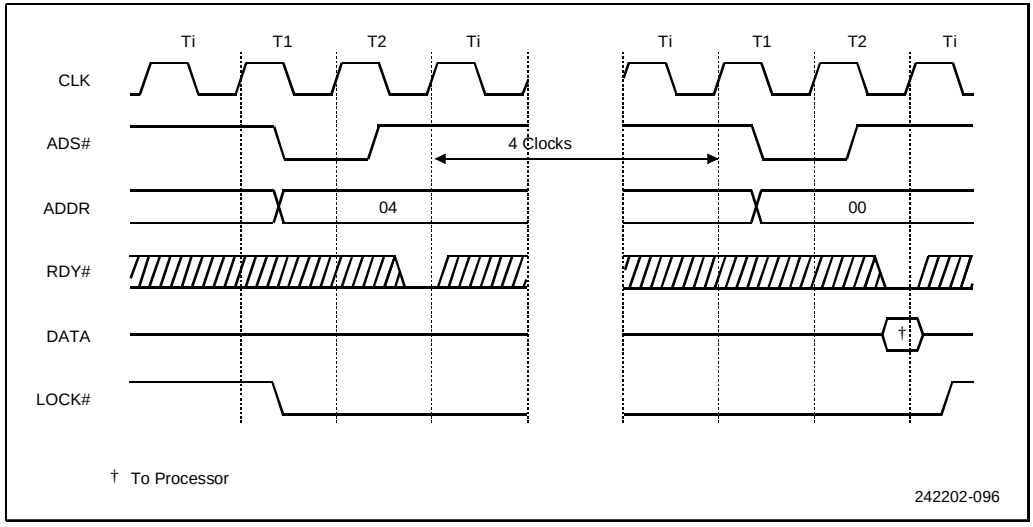


Figure 10-31. Interrupt Acknowledge Cycles

10.3.11 Special Bus Cycles

The Intel486 processor provides special bus cycles to indicate that certain instructions have been executed, or certain conditions have occurred internally. The special bus cycles are identified by the status of the pins shown in Table 10-9.

During these cycles the address bus is driven low while the data bus is undefined.

Two of the special cycles indicate halt or shutdown. Another special cycle is generated when the Intel486 processor executes an INVD (invalidate data cache) instruction and could be used to flush an external cache. The Write Back cycle is generated when the Intel486 processor executes the WBINVD (write-back invalidate data cache) instruction and could be used to synchronize an external write-back cache.

The external hardware must acknowledge these special bus cycles by asserting RDY# or BRDY#.

10.3.11.1 HALT Indication Cycle

The Intel486 processor halts as a result of executing a HALT instruction. A HALT indication cycle is performed to signal that the processor has entered into the HALT state. The HALT indication cycle is identified by the bus definition signals in special bus cycle state and by a byte address of 2. BE0# and BE2# are the only signals that distinguish HALT indication from shutdown indication, which drives an address of 0. During the HALT cycle, undefined data is driven on D[31:0]. The HALT indication cycle must be acknowledged by RDY# asserted.

A halted Intel486 processor resumes execution when INTR (if interrupts are enabled), NMI, or RESET is asserted.

10.3.11.2 Shutdown Indication Cycle

The Intel486 processor shuts down as a result of a protection fault while attempting to process a double fault. A shutdown indication cycle is performed to indicate that the processor has entered a shutdown state. The shutdown indication cycle is identified by the bus definition signals in special bus cycle state and a byte address of 0.

10.3.11.3 Stop Grant Indication Cycle

A special Stop Grant bus cycle is driven to the bus after the processor recognizes the STPCLK# interrupt. The definition of this bus cycle is the same as the HALT cycle definition for the Intel486 processor, with the exception that the Stop Grant bus cycle drives the value 0000 0010H on the address pins. The system hardware must acknowledge this cycle by asserting RDY# or BRDY#. The processor does not enter the Stop Grant state until either RDY# or BRDY# has been asserted. (See Figure 10-32.)

The Stop Grant Bus Cycle is defined as follows:

M/IO# = 0, D/C# = 0, W/R# = 1, Address Bus = 0000 0010H (A4 = 1), BE[3:0]# = 1011, Data bus = undefined.

The latency between a STPCLK# request and the Stop Grant bus cycle is dependent on the current instruction, the amount of data in the processor write buffers, and the system memory performance.

Table 10-9. Special Bus Cycle Encoding

Cycle Name	M/IO#	D/C#	W/R#	BE[3:0]#	A4-A2
Write-Back†	0	0	1	0111	000
First Flush Ack Cycle†	0	0	1	0111	001
Flush†	0	0	1	1101	000
Second Flush Ack Cycle†	0	0	1	1101	001
Shutdown	0	0	1	1110	000
HALT	0	0	1	1011	000
Stop Grant Ack Cycle	0	0	1	1011	100

† These cycles are specific to the Write-Back Enhanced IntelDX4™ processor. The FLUSH# cycle is applicable to all Intel486™ processors. See appropriate sections for details.

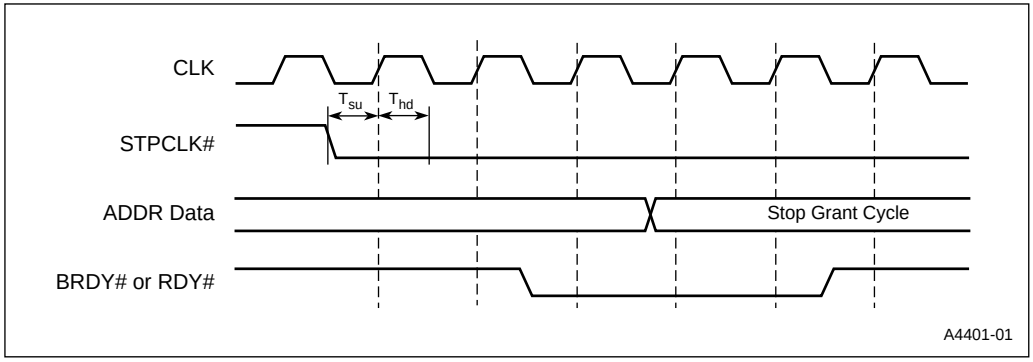


Figure 10-32. Stop Grant Bus Cycle

10.3.12 Bus Cycle Restart

In a multi-master system, another bus master may require the use of the bus to enable the Intel486 processor to complete its current bus request. In this situation, the Intel486 processor must restart its bus cycle after the other bus master has completed its bus transaction.

A bus cycle may be restarted if the external system asserts the backoff (BOFF#) input. The Intel486 processor samples the BOFF# pin every clock cycle. When BOFF# is asserted, the Intel486 processor floats its address, data, and status pins in the next clock (see Figures 10-33 and 10-34). Any bus cycle in progress when BOFF# is asserted is aborted and any data returned to the processor is ignored. The pins that are floated in response to BOFF# are the same as those that are floated in response to HOLD. HLDA is not generated in response to BOFF#. BOFF# has higher priority than RDY# or BRDY#. If either RDY# or BRDY# are asserted in the same clock as BOFF#, BOFF# takes effect.

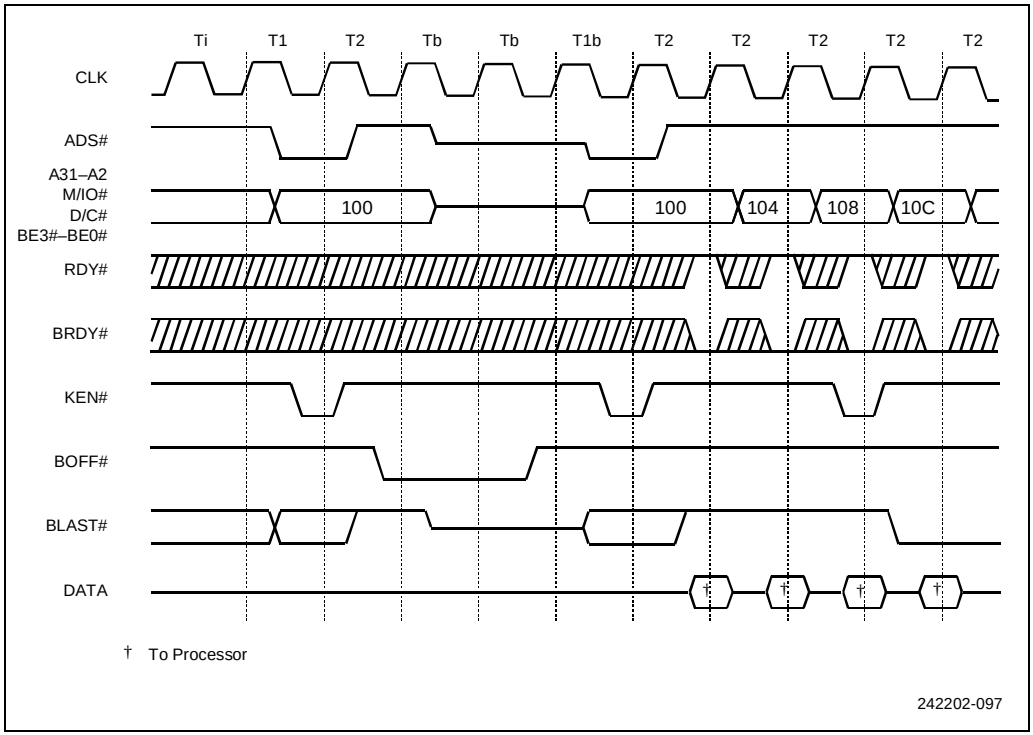


Figure 10-33. Restarted Read Cycle

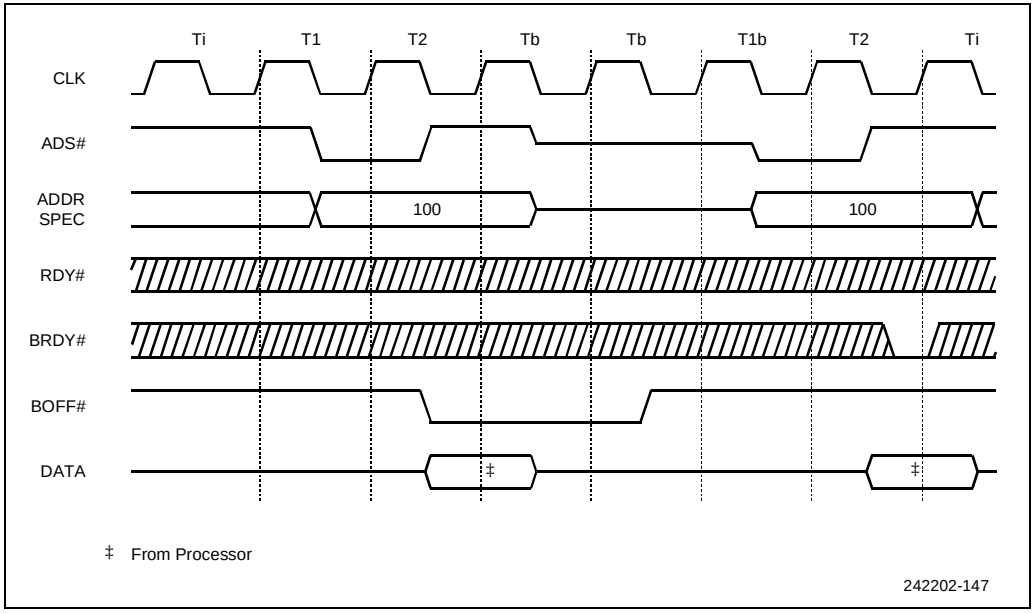


Figure 10-34. Restarted Write Cycle

The device asserting BOFF# is free to run cycles while the Intel486 processor bus is in its high impedance state. If backoff is requested after the Intel486 processor has started a cycle, the new master should wait for memory to assert RDY# or BRDY# before assuming control of the bus. Waiting for RDY# or BRDY# provides a handshake to ensure that the memory system is ready to accept a new cycle. If the bus is idle when BOFF# is asserted, the new master can start its cycle two clocks after issuing BOFF#.

The external memory can view BOFF# in the same manner as BLAST#. Asserting BOFF# tells the external memory system that the current cycle is the last cycle in a transfer.

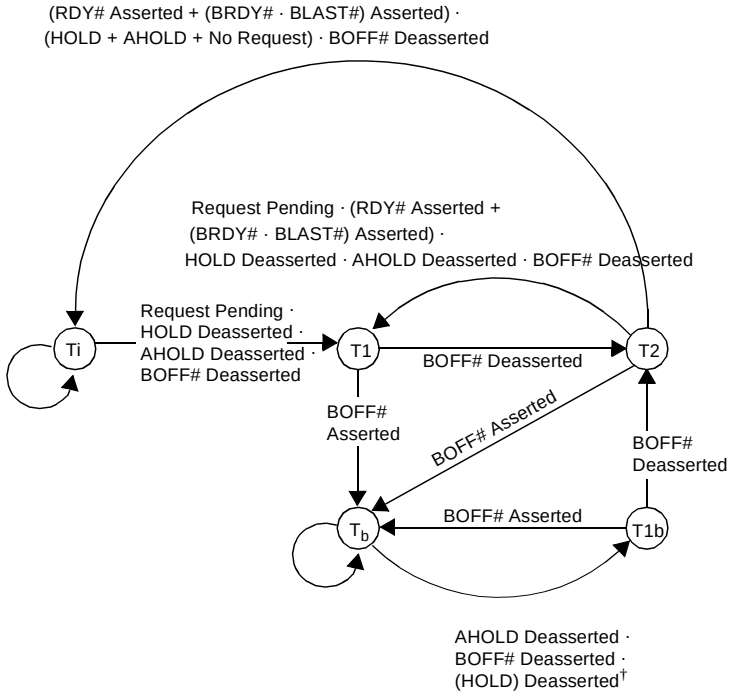
The bus remains in the high impedance state until BOFF# is deasserted. Upon negation, the Intel486 processor restarts its bus cycle by driving out the address and status and asserting ADS#. The bus cycle then continues as usual.

Asserting BOFF# during a burst, BS8#, or BS16# cycle forces the Intel486 processor to ignore data returned for that cycle only. Data from previous cycles is still valid. For example, if BOFF# is asserted on the third BRDY# of a burst, the Intel486 processor assumes the data returned with the first and second BRDY# is correct and restarts the burst beginning with the third item. The same rule applies to transfers broken into multiple cycles by BS8# or BS16#.

Asserting BOFF# in the same clock as ADS# causes the Intel486 processor to float its bus in the next clock and leave ADS# floating low. Because ADS# is floating low, a peripheral may think that a new bus cycle has begun even though the cycle was aborted. There are two possible solutions to this problem. The first is to have all devices recognize this condition and ignore ADS# until RDY# is asserted. The second approach is to use a "two clock" backoff: in the first clock AHOLD is asserted, and in the second clock BOFF# is asserted. This guarantees that ADS# is not floating low. This is necessary only in systems where BOFF# may be asserted in the same clock as ADS#.

10.3.13 Bus States

A bus state diagram is shown in Figure 10-35. A description of the signals used in the diagram is given in Table 10-10.



† HOLD is only factored into this state transition if T_b was entered while a non-cacheable. non-burst, code prefetch was in progress. Otherwise, ignore HOLD.

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Figure 10-35. Bus State Diagram

Table 10-10. Bus State Description

State	Means
Ti	Bus is idle. Address and status signals may be driven to undefined values, or the bus may be floated to a high impedance state.
T1	First clock cycle of a bus cycle. Valid address and status are driven and ADS# is asserted.
T2	Second and subsequent clock cycles of a bus cycle. Data is driven if the cycle is a write, or data is expected if the cycle is a read. RDY# and BRDY# are sampled.
$T1_b$	First clock cycle of a restarted bus cycle. Valid address and status are driven and ADS# is asserted.
T_b	Second and subsequent clock cycles of an aborted bus cycle.

10.3.14 Floating-Point Error Handling for the IntelDX2™ and IntelDX4™ Processors

The IntelDX2 and IntelDX4 processors provide two options for reporting floating-point errors. The simplest method is to raise interrupt 16 whenever an unmasked floating-point error occurs. This option may be enabled by setting the NE bit in control register 0 (CR0).

The IntelDX2 and IntelDX4 processors also provide the option of allowing external hardware to determine how floating-point errors are reported. This option is necessary for compatibility with the error reporting scheme used in DOS-based systems. The NE bit must be cleared in CR0 to enable user-defined error reporting. User-defined error reporting is the default condition because the NE bit is cleared on reset.

Two pins, floating-point error (FERR#, an output) and ignore numeric error (IGNNE#, an input) are provided to direct the actions of hardware if user-defined error reporting is used. The IntelDX2 and IntelDX4 processors assert the FERR# output to indicate that a floating-point error has occurred. FERR# corresponds to the ERROR# pin on the Intel387™ math coprocessor. However, there is a difference in the behavior of the two.

In some cases FERR# is asserted when the next floating-point instruction is encountered, and in other cases it is asserted before the next floating-point instruction is encountered, depending upon the execution state of the instruction causing the exception.

10.3.14.1 Floating-Point Exceptions

The following class of floating-point exceptions drive FERR# at the time the exception occurs (i.e., before encountering the next floating-point instruction).

1. The stack fault, invalid operation, and denormal exceptions on all transcendental instructions, integer arithmetic instructions, FSQRT, FSEALE, FPREM(1), FXTRACT, FBLD, and FBSTP.
2. Any exceptions on store instructions (including integer store instructions).

The following class of floating-point exceptions drive FERR# only after encountering the next floating-point instruction.

3. Exceptions other than on all transcendental instructions, integer arithmetic instructions, FSQRT, FSCALE, FPREM(1), FXTRACT, FBLD, and FBSTP.
4. Any exception on all basic arithmetic, load, compare, and control instructions (i.e., all other instructions).

For both sets of exceptions above, the Intel387 math coprocessor asserts ERROR# when the error occurs and does not wait for the next floating-point instruction to be encountered.

IGNNE# is an input to the IntelDX2 and IntelDX4 processors. When the NE bit in CR0 is cleared, and IGNNE# is asserted, the IntelDX2 and IntelDX4 processors ignore user floating-point errors and continue executing floating-point instructions. When IGNNE# is deasserted, the IGNNE# is an input to these processors that freeze on floating-point instructions that get errors (except for the control instructions FNCLEX, FNINIT, FNSAVE, FNSTENV, FNSTCW, FNSTSW, FNSTSW AX, FNENI, FNDISI and FNSETPM). IGNNE# may be asynchronous to the IntelDX2 and IntelDX4 processor clock.

In systems with user-defined error reporting, the FERR# pin is connected to the interrupt controller. When an unmasked floating-point error occurs, an interrupt is raised. If IGNNE# is high at the time of this interrupt, the IntelDX2 and IntelDX4 processors freeze (disallowing execution of a subsequent floating-point instruction) until the interrupt handler is invoked. By driving the IGNNE# pin low (when clearing the interrupt request), the interrupt handler can allow execution of a floating-point instruction, within the interrupt handler, before the error condition is cleared (by FNCLEX, FNINIT, FNSAVE or FNSTENV). If execution of a non-control floating-point instruction, within the floating-point interrupt handler, is not needed, the IGNNE# pin can be tied high.

10.3.15 IntelDX2™ and IntelDX4™ Processors Floating-Point Error Handling in AT-Compatible Systems

The IntelDX2 and IntelDX4 processors provide special features to allow the implementation of an AT-compatible numerics error reporting scheme. These features DO NOT replace the external circuit. Logic is still required that decodes the OUT F0 instruction and latches the FERR# signal. The use of these Intel Processor features is described below.

- The NE bit in the Machine Status Register
- The IGNNE# pin
- The FERR# pin

The NE bit determines the action taken by the IntelDX2 and IntelDX4 processors when a numerics error is detected. When set, this bit signals that non-DOS compatible error handling is implemented. In this mode the IntelDX2 and IntelDX4 processors take a software exception (16) if a numerics error is detected.

If the NE bit is reset, the IntelDX2 and IntelDX4 processors use the IGNNE# pin to allow an external circuit to control the time at which non-control numerics instructions are allowed to execute. Note that floating-point control instructions such as FNINIT and FNSAVE can be executed during a floating-point error condition regardless of the state of IGNNE#.

To process a floating-point error in the DOS environment, the following sequence must take place:

1. The error is detected by the IntelDX2 and IntelDX4 processor that activates the FERR# pin.
2. FERR# is latched so that it can be cleared by the OUT F0 instruction.
3. The latched FERR# signal activates an interrupt at the interrupt controller. This interrupt is usually handled on IRQ13.
4. The Interrupt Service Routine (ISR) handles the error and then clears the interrupt by executing an OUT instruction to port F0. The address F0 is decoded externally to clear the FERR# latch. The IGNNE# signal is also activated by the decoder output.
5. Usually the ISR then executes an FNINIT instruction or other control instruction before restarting the program. FNINIT clears the FERR# output.

Figure 10-36 illustrates a sample circuit that performs the function described above. Note that this circuit has not been tested and is included as an example of required error handling logic.

Note that the IGNNE# input allows non-control instructions to be executed prior to the time the FERR# signal is reset by the IntelDX2 and IntelDX4 processors. This function is implemented to allow exact compatibility with the AT implementation. Most programs re-initialize the Floating-Point Unit (FPU) before continuing after an error is detected. The FPU can be re-initialized using one of the following four instructions: FCLEX, FINIT, FSAVE and FSTENV.

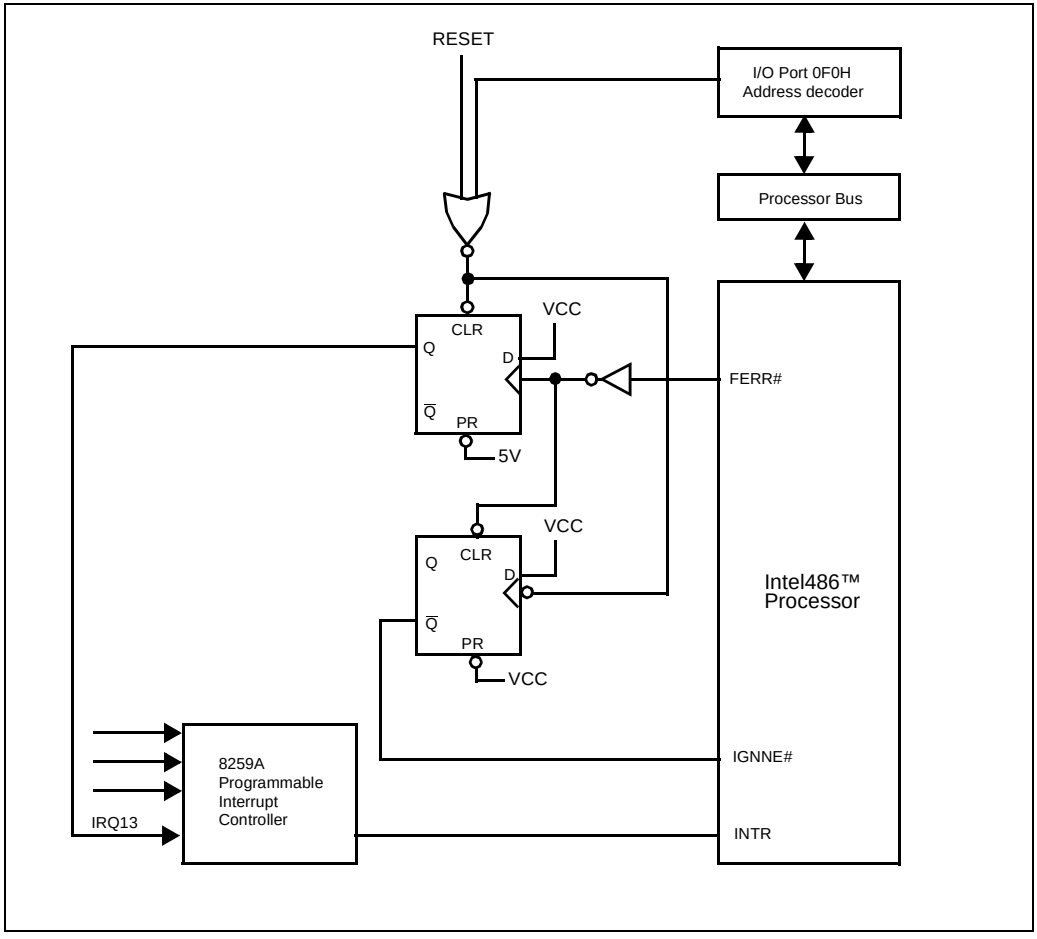

Figure 10-36. DOS-Compatible Numerics Error Circuit

10.4 ENHANCED BUS MODE OPERATION FOR THE WRITE-BACK ENHANCED IntelDX4™ PROCESSOR

All Intel486™ processors operate in Standard Bus (write-through) mode. However, when the internal cache of the Write-Back Enhanced IntelDX4 processor is configured in write-back mode, the processor bus operates in the Enhanced Bus mode. This section describes how the Write-Back Enhanced Intel486 processor bus operation changes for the Enhanced Bus mode when the internal cache is configured in write-back mode.

10.4.1 Summary of Bus Differences

The following is a list of the differences between the Enhanced Bus and Standard Bus modes. In Enhanced Bus mode:

1. Burst write capability is extended to four doubleword burst cycles (for write-back cycles only).
2. Four new signals: INV, WB/WT#, HITM#, and CACHE#, have been added to support the write-back operation of the internal cache. These signals function the same as the equivalent signals on the Pentium® OverDrive® processor pins.
3. The SRESET signal has been modified so that it does not write back, invalidate, or disable the cache. Special test modes are also not initiated through SRESET.
4. The FLUSH# signal behaves the same as the WBINVD instruction. Upon assertion, FLUSH# writes back all modified lines, invalidates the cache, and issues two special bus cycles.
5. The PLOCK# signal remains deasserted.

10.4.2 Burst Cycles

Figure 10-37 shows a basic burst read cycle of the Write-Back Enhanced IntelDX4 processor. In the Enhanced Bus mode, both PCD and CACHE# are asserted if the cycle is internally cacheable. The Write-Back Enhanced IntelDX4 processor samples KEN# in the clock before the first BRDY#. If KEN# is asserted by the system, this cycle is transformed into a multiple-transfer cycle. With each data item returned from external memory, the data is “cached” only if KEN# is asserted again in the clock before the last BRDY# signal. Data is sampled only in the clock in which BRDY# is asserted. If the data is not sent to the processor every clock, it causes a “slow burst” cycle.

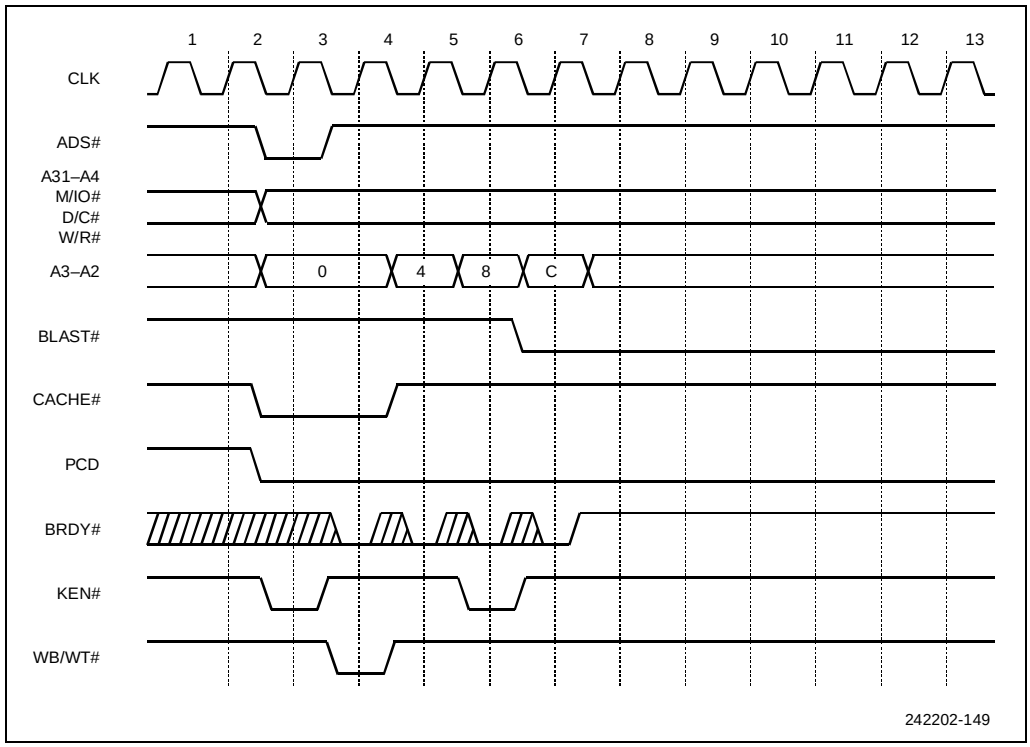

Figure 10-37. Basic Burst Read Cycle

10.4.2.1 Non-Cacheable Burst Operation

When CACHE# is asserted on a read cycle, the processor follows with BLAST# high when KEN# is asserted. However, the converse is not true. The Write-Back Enhanced IntelDX4 processor may elect to read burst data that are identified as non-cacheable by either CACHE# or KEN#. In this case, BLAST# is also high in the same cycle as the first BRDY# (in clock four). To improve performance, the memory controller should try to complete the cycle as a burst cycle.

The assertion of CACHE# on a write cycle signifies a replacement or snoop write-back cycle. These cycles consist of four doubleword transfers (either bursts or non-burst). The signals KEN# and WB/WT# are not sampled during write-back cycles because the processor does not attempt to redefine the cacheability of the line.

10.4.2.2 Burst Cycle Signal Protocol

The signals from ADS# through BLAST#, which are shown in Figure 10-37, have the same function and timing in both Standard Bus and Enhanced Bus modes. Burst cycles can be up to 16-bytes long (four aligned doublewords) and can start with any one of the four doublewords. The sequence of the addresses is determined by the first address and the sequence follows the order shown in Table 10-8 on page 10-28. The burst order for reads is the same as the burst order for writes. (See Section 10.3.4.2, “Burst and Cache Line Fill Order.”)

An attempted line fill caused by a read miss is indicated by the assertion of CACHE# and W/R#. For a line fill to occur, the system must assert KEN# twice: one clock prior to the first BRDY# and one clock prior to last BRDY#. It takes only one deassertion of KEN# to mark the line as non-cacheable. A write-back cycle of a cache line, due to replacement or snoop, is indicated by the assertion of CACHE# low and W/R# high. KEN# has no effect during write-back cycles. CACHE# is valid from the assertion of ADS# through the clock in which the first RDY# or BRDY# is asserted. CACHE# is deasserted at all other times. PCD behaves the same in Enhanced Bus mode as in Standard Bus mode, except that it is low during write-back cycles.

The Write-Back Enhanced IntelDX4 processor samples WB/WT# once, in the *same* clock as the first BRDY#. This sampled value of WB/WT# is combined with PWT to bring the line into the internal cache, either as a write-back line or write-through line.

10.4.3 Cache Consistency Cycles

The system performs snooping to maintain cache consistency. Snoop cycles can be performed under AHOLD, BOFF#, or HOLD, as described in Table 10-11.

Table 10-11. Snoop Cycles under AHOLD, BOFF#, or HOLD

AHOLD	Floats the address bus. ADS# is asserted under AHOLD only to initiate a snoop write-back cycle. An ongoing burst cycle is completed under AHOLD. For non-burst cycles, a specific non-burst transfer (ADS#-RDY# transfer) is completed under AHOLD and fractured before the next assertion of ADS#. A snoop write-back cycle is reordered ahead of a fractured non-burst cycle and the non-burst cycle is completed only after the snoop write-back cycle is completed, provided there are no other snoop write-back cycles scheduled.
BOFF#	Overrides AHOLD and takes effect in the next clock. On-going bus cycles will stop in the clock following the assertion of BOFF# and resume when BOFF# is de-asserted. The snoop write-back cycle begins after BOFF# is de-asserted followed by the backed-off cycle.
HOLD	HOLD is acknowledged only between bus cycles, except for a non-cacheable, non-burst code prefetch cycle. In a non-cacheable, non-burst code prefetch cycle, HOLD is acknowledged after the system asserts RDY#. Once HOLD is asserted, the processor blocks all bus activities until the system releases the bus (by de-asserting HOLD).

The snoop cycle begins by checking whether a particular cache line has been "cached" and invalidates the line based on the state of the INV pin. If the Write-Back Enhanced IntelDX4 processor is configured in Enhanced Bus mode, the system must drive INV high to invalidate a particular cache line. The Write-Back Enhanced IntelDX4 processor does not have an output pin to indicate a snoop hit to an S-state line or an E-state line. However, the Write-Back Enhanced IntelDX4 processor invalidates the line if the system snoop hits an S-state, E-state, or M-state line, provided INV was driven high during snooping. If INV is driven low during a snoop cycle, a modified line is written back to memory and remains in the cache as a write-back line; a write-through line also remains in the cache as a write-through line.

After asserting AHOLD or BOFF#, the external bus master driving the snoop cycle must wait for two clocks before driving the snoop address and asserting EADS#. If snooping is done under HOLD, the master performing the snoop must wait for at least one clock cycle before driving the snoop addresses and asserting EADS#. INV should be driven low during read operations to minimize invalidations, and INV should be driven high to invalidate a cache line during write operations. The Write-Back Enhanced IntelDX4 processor asserts HITM# if the cycle hits a modified line in the cache. This output signal becomes valid two clock periods after EADS# is valid on the bus. HITM# remains asserted until the modified line is written back and remains asserted until the RDY# or BRDY# of the snoop cycle is asserted. Snoop operations could interrupt an ongoing bus operation in both the Standard Bus and Enhanced Bus modes. The Write-Back Enhanced IntelDX4 processor can accept EADS# in every clock period while in Standard Bus mode. In Enhanced Bus mode, the Write-Back Enhanced IntelDX4 processor can accept EADS# every other clock period or until a snoop hits an M-state line. The Write-Back Enhanced IntelDX4 processor does not accept any further snoop cycles inputs until the previous snoop write-back operation is completed.

All write-back cycles adhere to the burst address sequence of 0-4-8-C. The CACHE#, PWT, and PCD output pins are asserted and the KEN# and WB/WT# input pins are ignored. Write-back cycles can be either burst or non-burst. All write-back operations write 16 bytes of data to memory corresponding to the modified line that hit during the snoop.

NOTE

Note that the Write-Back Enhanced IntelDX4 processor accepts BS8# and BS16# line-fill cycles, but not on replacement or snoop-forced write-back cycles.

10.4.3.1 Snoop Collision with a Current Cache Line Operation

The system can also perform snooping concurrent with a cache access and may collide with a current cache bus cycle. Table 10-12 lists some scenarios and the results of a snoop operation colliding with an on-going cache fill or replacement cycle.

Table 10-12. Various Scenarios of a Snoop Write-Back Cycle Colliding with an On-Going Cache Fill or Replacement Cycle

Arbitration Control	Snoop to the Line That Is Being Filled	Snoop to a Different Line than the Line Being Filled	Snoop to the Line That Is Being Replaced	Snoop to a Different Line than the Line Being Replaced
AHOLD	Read all line fill data into cache line buffer. Update cache only if snoop occurred with INV = 0 No write-back cycle because the line has not been modified yet.	Complete fill if the cycle is burst. Start snoop write-back. If the cycle is non-burst, the snoop write-back is reordered ahead of the line fill. After the snoop write-back cycle is completed, continue with line fill.	Complete replacement write-back if the cycle is burst. Processor does not initiate a snoop write-back, but asserts HITM# until the replacement write-back is completed. If the replacement cycle is non-burst, the snoop write-back is re-ordered ahead of the replacement write-back cycle. The processor does not continue with the replacement write-back cycle.	Complete replacement write-back if it is a burst cycle. Initiate snoop write-back. If the replacement write-back is a non-burst cycle, the snoop write-back cycle is re-ordered in front of the replacement cycle. After the snoop write-back, the replacement write-back is continued from the interrupt point.
BOFF#	Stop reading line fill data Wait for BOFF# to be deasserted. Continue read from backed off point Update cache only if snoop occurred with INV = '0'.	Stop fill Wait for BOFF# to be deasserted. Do snoop write-back Continue fill from interrupt point.	Stop replacement write-back Wait for BOFF# to be deasserted. Initiate snoop write-back Processor does not continue replacement write-back.	Stop replacement write-back Wait for BOFF# to be de-asserted Initiate snoop write-back Continue replacement write-back from point of interrupt.
HOLD	HOLD is not acknowledged until the current bus cycle (i.e., the line operation) is completed, except for a non-cacheable, non-burst code prefetch cycle. Consequently there can be no collision with the snoop cycles using HOLD, except as mentioned earlier. In this case the snoop write-back is re-ordered ahead of an on-going non-burst, non-cached code prefetch cycle. After the write-back cycle is completed, the code prefetch cycle continues from the point of interrupt.			

10.4.3.2 Snoop under AHOLD

Snooping under AHOLD begins by asserting AHOLD to force the Write-Back Enhanced IntelDX4 processor to float the address bus, as shown in Figure 10-38. The ADS# for the write-back cycle is guaranteed to occur no sooner than the second clock following the assertion of HITM# (i.e., there is a dead clock between the assertion of HITM# and the first ADS# of the snoop write-back cycle).

When a line is written back, KEN#, WB/WT#, BS8#, and BS16# are ignored, and PWT and PCD are always low during write-back cycles.

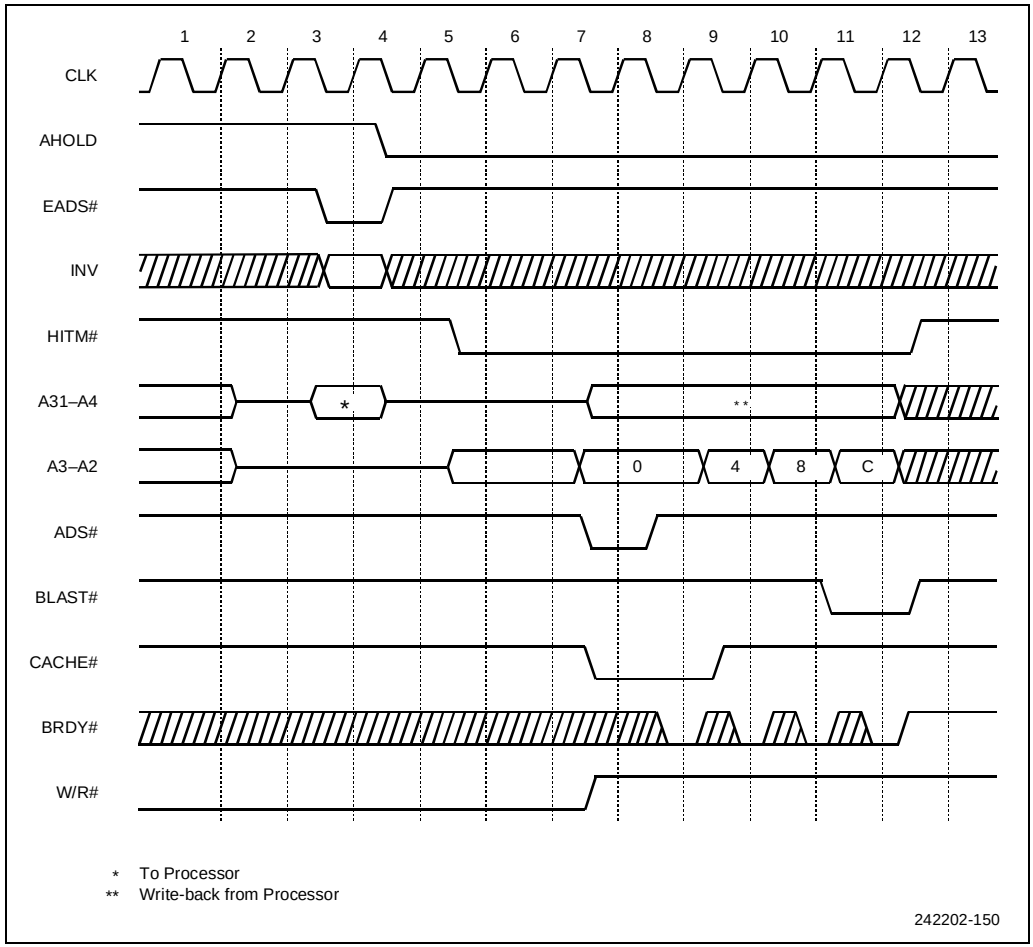

Figure 10-38. Snoop Cycle Invalidating a Modified Line

The next ADS# for a new cycle can occur immediately after the last RDY# or BRDY# of the write-back cycle. The Write-Back Enhanced IntelDX4 processor does not guarantee a dead clock between cycles unless the second cycle is a snoop-forced write-back cycle. This allows snoop-forced write-backs to be backed off (BOFF#) when snooping under AHOLD.

HITM# is guaranteed to remain asserted until the RDY# or BRDY# signals corresponding to the last doubleword of the write-back cycle is returned. HITM# is de-asserted from the clock edge in which the last BRDY# or RDY# for the snoop write-back cycle is asserted. The write-back cycle could be a burst or non-burst cycle. In either case, 16 bytes of data corresponding to the modified line that has a snoop hit is written back.

Snoop under AHOLD Overlaying a Line-Fill Cycle

The assertion of AHOLD during a line fill is allowed on the Write-Back Enhanced IntelDX4 processor. In this case, when a snoop cycle is overlaid by an on-going line-fill cycle, the chipset must generate the burst addresses internally for the line fill to complete, because the address bus has the valid snoop address. The write-back mode is more complex compared to the write-through mode because of the possibility of a line being written back. Figure 10-39 shows a snoop cycle overlaying a line-fill cycle, when the snooped line is not the same as the line being filled.

In Figure 10-39, the snoop to an M-state line causes a snoop write-back cycle. The Write-Back Enhanced IntelDX4 processor asserts HITM# two clocks after the EADS#, but delays the snoop write-back cycle until the line fill is completed, because the line fill shown in Figure 10-39 is a burst cycle. In this figure, AHOLD is asserted one clock after ADS#. In the clock after AHOLD is asserted, the Write-Back Enhanced IntelDX4 processor floats the address bus (not the Byte Enables). Hence, the memory controller must determine burst addresses in this period. The chipset must comprehend the special ordering required by all burst sequences of the Write-Back Enhanced IntelDX4 processor. HITM# is guaranteed to remain asserted until the write-back cycle completes.

If AHOLD continues to be asserted over the forced write-back cycle, the memory controller also must supply the write-back addresses to the memory. The Write-Back Enhanced IntelDX4 processor always runs the write-back with an address sequence of 0-4-8-C.

In general, if the snoop cycle overlays any burst cycle (not necessarily a line-fill cycle) the snoop write-back is delayed because of the on-going burst cycle. First, the burst cycle goes to completion and only then does the snoop write-back cycle start.

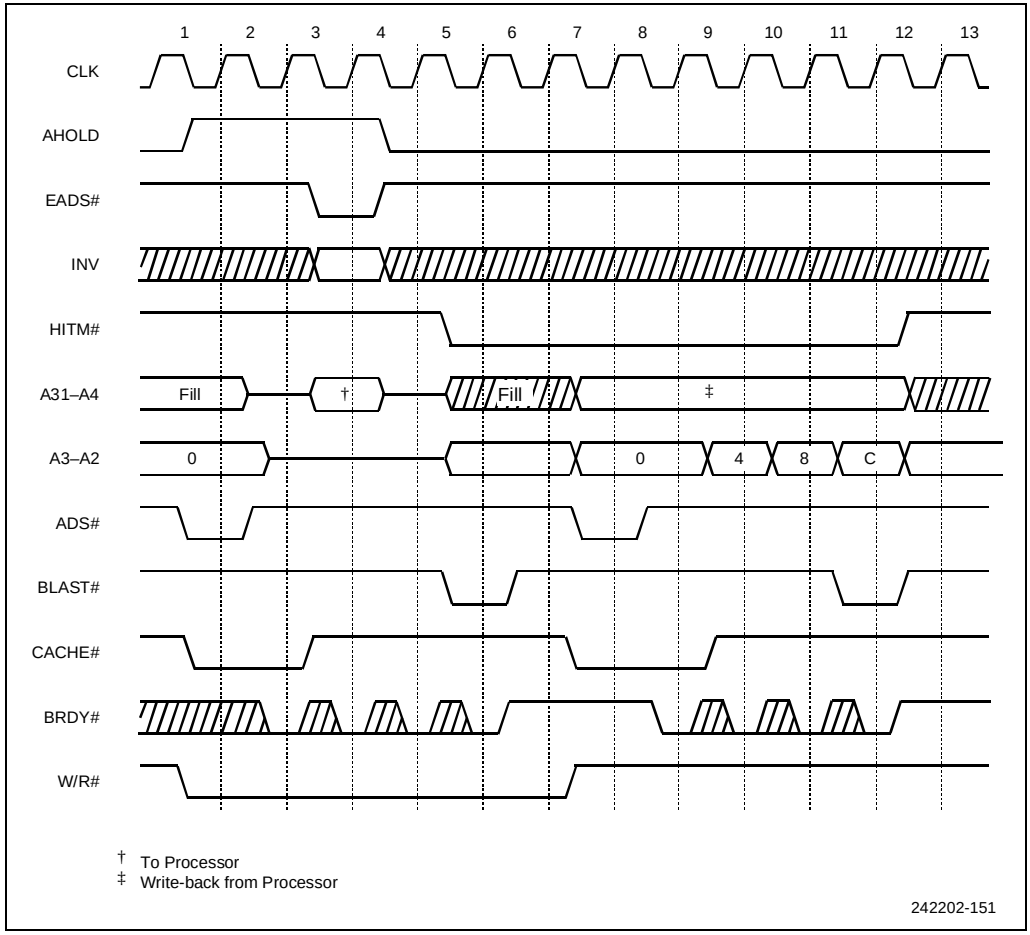

Figure 10-39. Snoop Cycle Overlaying a Line-Fill Cycle

AHOLD Snoop Overlaying a Non-Burst Cycle

When AHOLD overlays a non-burst cycle, snooping is based on the completion of the current non-burst transfer (ADS#-RDY# transfer). Figure 10-40 shows a snoop cycle under AHOLD overlaying a non-burst line-fill cycle. HITM# is asserted two clocks after EADS#, and the non-burst cycle is fractured after the RDY# for a specific single transfer is asserted. The snoop write-back cycle is re-ordered ahead of an ongoing non-burst cycle. After the write-back cycle is completed, the fractured non-burst cycle continues. The snoop write-back ALWAYS precedes the completion of a fractured cycle, regardless of the point at which AHOLD is de-asserted, and AHOLD must be de-asserted before the fractured non-burst cycle can complete.

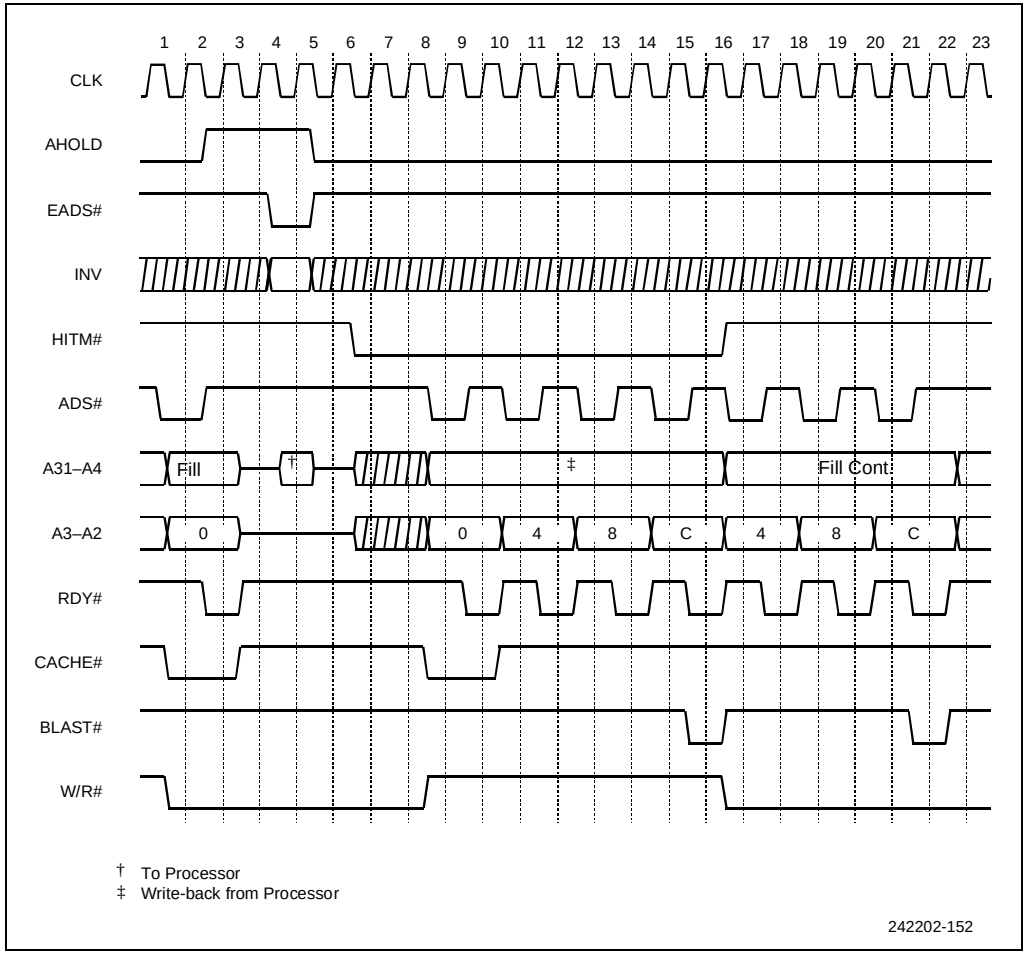

Figure 10-40. Snoop Cycle Overlaying a Non-Burst Cycle

AHOLD Snoop to the Same Line that is being Filled

A system snoop does not cause a write-back cycle to occur if the snoop hits a line while the line is being filled. The processor does not allow a line to be modified until the fill is completed (and a snoop only produces a write-back cycle for a modified line). Although a snoop to a line that is being filled does not produce a write-back cycle, the snoop still has an effect based on the following rules:

1. The processor always snoops the line being filled.
2. In all cases, the processor uses the operand that triggered the line fill.

3. If the snoop occurs when INV = "1", the processor never updates the cache with the fill data.
4. If the snoop occurs when INV = "0", the processor loads the line into the internal cache.

10.4.3.3 Snoop During Replacement Write-Back

If the cache contains valid data during a line fill, one of the cache lines may be replaced as determined by the Least Recently Used (LRU) algorithm. Refer to Chapter 7, "On-Chip Cache" for a detailed discussion of the LRU algorithm. If the line being replaced is modified, this line is written back to maintain cache coherency. When a replacement write-back cycle is in progress, it might be necessary to snoop the line that is being written back (see Figure 10-41).

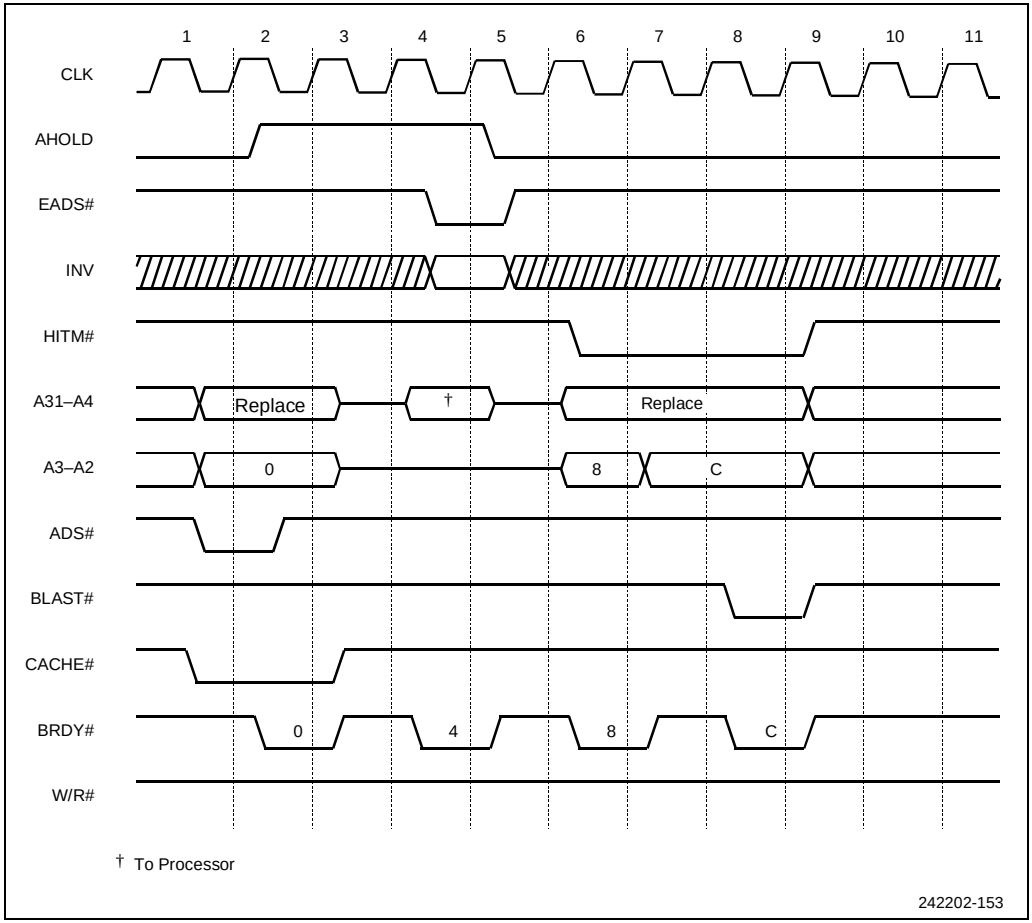

Figure 10-41. Snoop to the Line that is Being Replaced

If the replacement write-back cycle is burst and there is a snoop hit to the same line as the line that is being replaced, the on-going replacement cycle runs to completion. HITM# is asserted until the line is written back and the snoop write-back is not initiated. In this case, the replacement write-back is converted to the snoop write-back, and HITM# is asserted and de-asserted without a specific ADS# to initiate the write-back cycle.

If there is a snoop hit to a different line from the line being replaced, and if the replacement write-back cycle is burst, the replacement cycle goes to completion. Only then is the snoop write-back cycle initiated.

If the replacement write-back cycle is a non-burst cycle, and if there is a snoop hit to the same line as the line being replaced, it fractures the replacement write-back cycle after RDY# is asserted for the current non-burst transfer. The snoop write-back cycle is reordered in front of the fractured replacement write-back cycle and is completed under HITM#. However, after AHOLD is deasserted, the replacement write-back cycle is not completed.

If there is a snoop hit to a line that is different from the one being replaced, the non-burst replacement write-back cycle is fractured, and the snoop write-back cycle is reordered ahead of the replacement write-back cycle. After the snoop write-back is completed, the replacement write-back cycle continues.

10.4.3.4 Snoop under BOFF#

BOFF# is capable of fracturing any transfer, burst or non-burst. The output pins (see Table 10-8 and Table 10-12) of the Write-Back Enhanced IntelDX4 processor are floated in the clock period following the assertion of BOFF#. If the system snoop hits a modified line using BOFF#, the snoop write-back cycle is reordered ahead of the current cycle. BOFF# must be de-asserted for the processor to perform a snoop write-back cycle and resume the fractured cycle. The fractured cycle resumes with a new ADS# and begins with the first uncompleted transfer. Snoops are permitted under BOFF#, but write-back cycles are not started until BOFF# is de-asserted. Consequently, multiple snoop cycles can occur under a continuously asserted BOFF#, but only up to the first asserted HITM#.

Snoop under BOFF# during Cache Line Fill

As shown in Figure 10-42, BOFF# fractures the second transfer of a non-burst cache line-fill cycle. The system begins snooping by driving EADS# and INV in clock six. The assertion of HITM# in clock eight indicates that the snoop cycle hit a modified line and the cache line is written back to memory. The assertion of HITM# in clock eight and CACHE# and ADS# in clock ten identifies the beginning of the snoop write-back cycle. ADS# is guaranteed to be asserted no sooner than two clock periods after the assertion of HITM#. Write-back cycles always use the four-doubleword address sequence of 0-4-8-C (burst or non-burst). The snoop write-back cycle begins upon the de-assertion of BOFF# with HITM# asserted throughout the duration of the snoop write-back cycle.

If the snoop cycle hits a line that is different from the line being filled, the cache line fill resumes after the snoop write-back cycle completes, as shown in Figure 10-42.

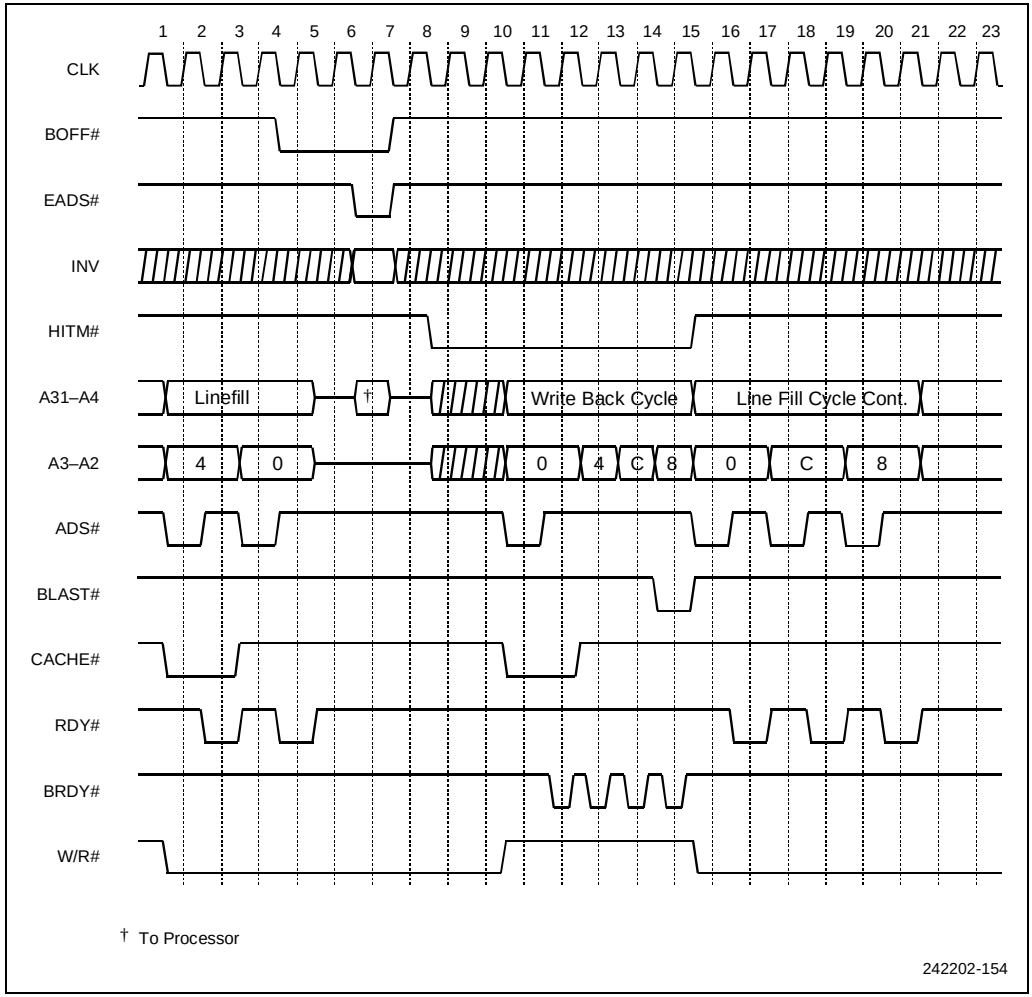

Figure 10-42. Snoop under BOFF# during a Cache Line-Fill Cycle

An ADS# is always issued when a cycle resumes after being fractured by BOFF#. The address of the fractured data transfer is reissued under this ADS#, and CACHE# is not issued unless the fractured operation resumes from the first transfer (e.g., first doubleword). If the system asserts BOFF# and RDY# simultaneously, as shown in clock four on Figure 10-42, BOFF# dominates and RDY# is ignored. Consequently, the Write-Back Enhanced IntelDX4 processor accepts only up to the x4h doubleword, and the line fill resumes with the x0h doubleword. ADS# initiates the resumption of the line-fill operation in clock period 15. HITM# is de-asserted in the clock period following the clock period in which the last RDY# or BRDY# of the write-back cycle is asserted. Hence, HITM# is guaranteed to be de-asserted before the ADS# of the next cycle.

Figure 10-42 also shows the system asserting RDY# to indicate a non-burst line-fill cycle. Burst cache line-fill cycles behave similarly to non-burst cache line-fill cycles when snooping using BOFF#. If the system snoop hits the same line as the line being filled (burst or non-burst), the Write-Back Enhanced IntelDX4 processor does not assert HITM# and does not issue a snoop write-back cycle, because the line was not modified, and the line fill resumes upon the de-assertion of BOFF#. However, the line fill is cached only if INV is driven low during the snoop cycle.

Snoop under BOFF# during Replacement Write-Back

If the system snoop under BOFF# hits the line that is currently being replaced (burst or non-burst), the entire line is written back as a snoop write-back line, and the replacement write-back cycle is not continued. However, if the system snoop hits a different line than the one currently being replaced, the replacement write-back cycle continues after the snoop write-back cycle has been completed. Figure 10-43 shows a system snoop hit to the same line as the one being replaced (non-burst).

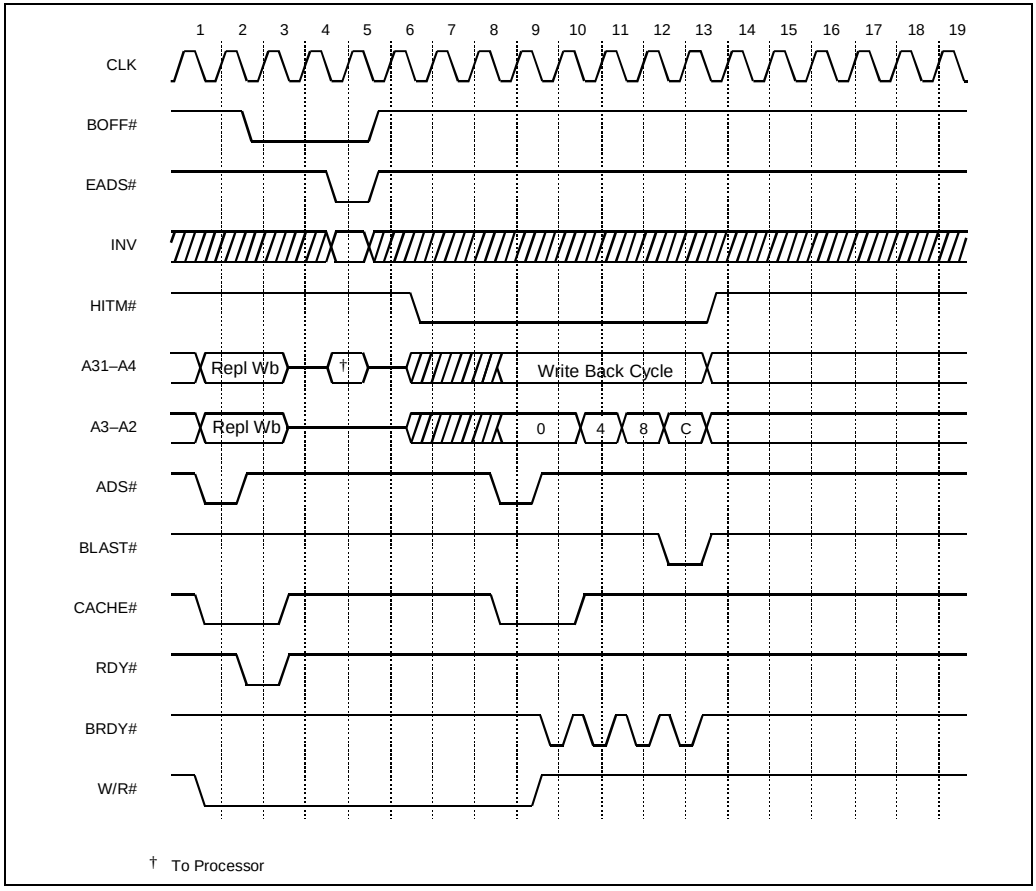

Figure 10-43. Snoop under BOFF# to the Line that is Being Replaced

10.4.3.5 Snoop under HOLD

HOLD can only fracture a non-cacheable, non-burst code prefetch cycle. For all other cycles, the Write-Back Enhanced IntelDX4 processor does not assert HLDA until the entire current cycle is completed. If the system snoop hits a modified line under HLDA during a non-cacheable, non-burstable code prefetch, the snoop write-back cycle is reordered ahead of the fractured cycle. The fractured non-cacheable, non-burst code prefetch resumes with an ADS# and begins with the first uncompleted transfer. Snoops are permitted under HLDA, but write-back cycles do not occur until HOLD is de-asserted. Consequently, multiple snoop cycles are permitted under a continuously asserted HLDA only up to the first asserted HITM#.

Snoop under HOLD during Cache Line Fill

As shown in Figure 10-44, HOLD (asserted in clock two) does not fracture the burst cache line-fill cycle until the line fill is completed (in clock five). Upon completing the line fill in clock five, the Write-Back Enhanced IntelDX4 processor asserts HLDA and the system begins snooping by driving EADS# and INV in the following clock period. The assertion of HITM# in clock nine indicates that the snoop cycle has hit a modified line and the cache line is written back to memory. The assertion of HITM# in clock nine and CACHE# and ADS# in clock 11 identifies the beginning of the snoop write-back cycle. The snoop write-back cycle begins upon the de-assertion of HOLD, and HITM# is asserted throughout the duration of the snoop write-back cycle.

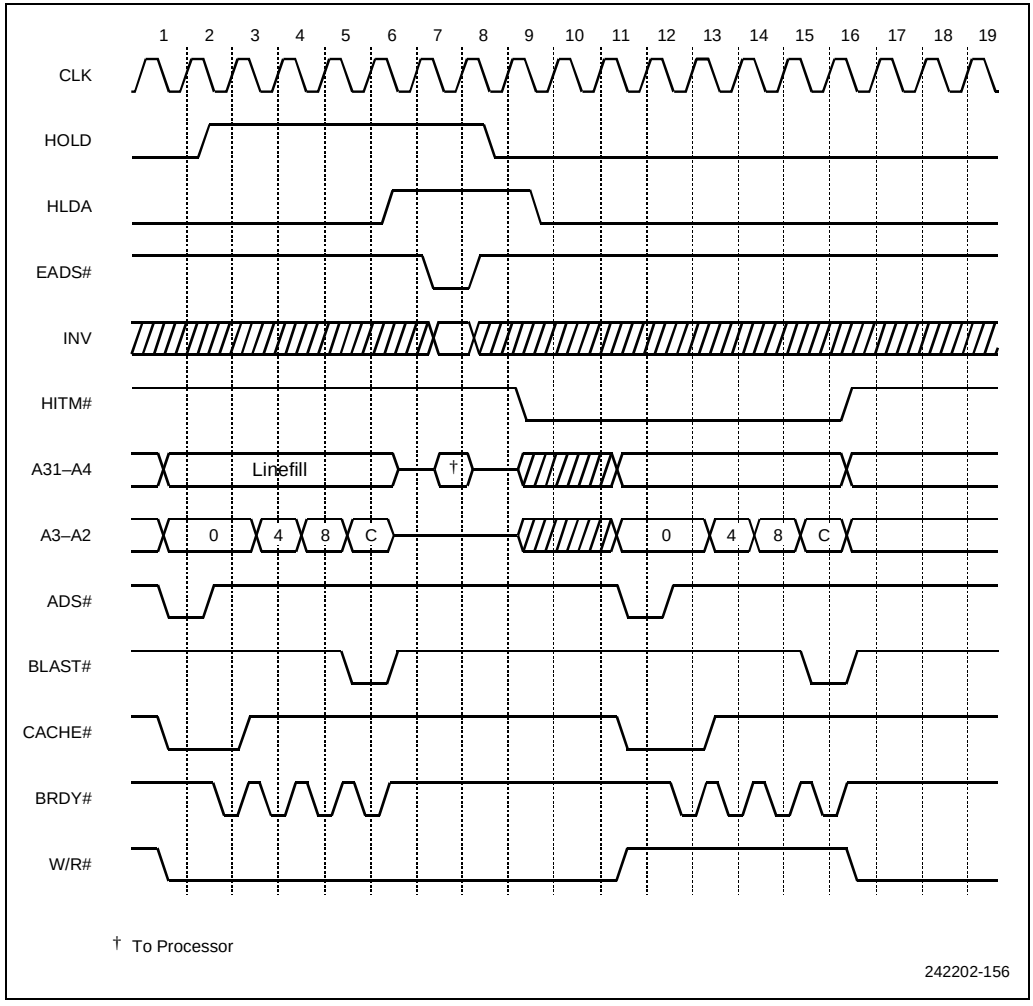

Figure 10-44. Snoop under HOLD during Line Fill

If HOLD is asserted during a non-cacheable, non-burst code prefetch cycle, as shown in Figure 10-45, the Write-Back Enhanced IntelDX4 processor issues HLDA in clock seven (which is the clock period in which the next RDY# is asserted). If the system snoop hits a modified line, the snoop write-back cycle begins after HOLD is released. After the snoop write-back cycle is completed, an ADS# is issued and the code prefetch cycle resumes.

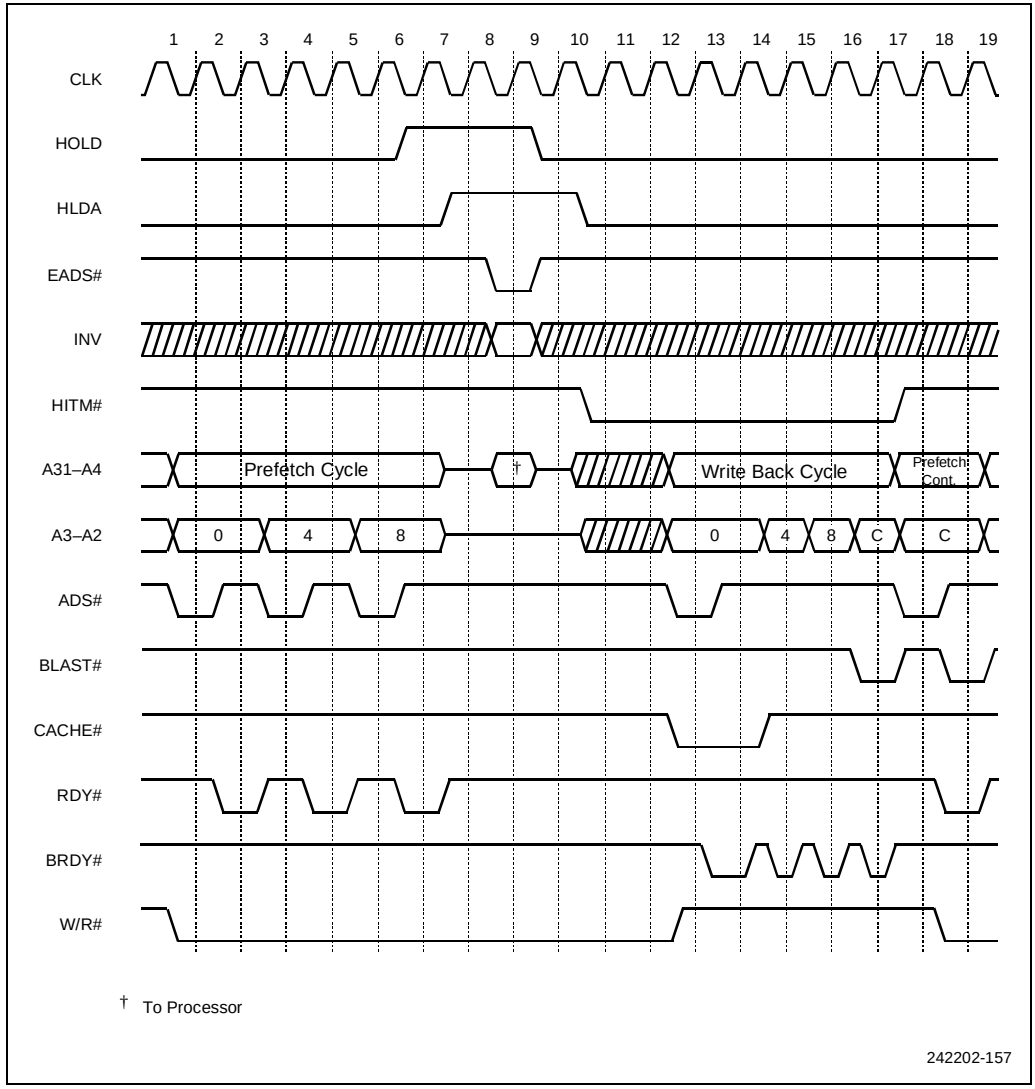

Figure 10-45. Snoop using HOLD during a Non-Cacheable, Non-Burstable Code Prefetch

10.4.3.6 Snoop under HOLD during Replacement Write-Back

Collision of snoop cycles under a HOLD during the replacement write-back cycle can never occur, because HLDA is asserted only after the replacement write-back cycle (burst or non-burst) is completed.

10.4.4 Locked Cycles

In both Standard and Enhanced Bus modes, the Write-Back Enhanced IntelDX4 processor architecture supports atomic memory access. A programmer can modify the contents of a memory variable and be assured that the variable is not accessed by another bus master between the read of the variable and the update of that variable. This function is provided for instructions that contain a LOCK prefix, and also for instructions that implicitly perform locked read modify write cycles. In hardware, the LOCK function is implemented through the LOCK# pin, which indicates to the system that the processor is performing this sequence of cycles, and that the processor should be allowed atomic access for the location accessed during the first locked cycle.

A locked operation is a combination of one or more read cycles followed by one or more write cycles with the LOCK# pin asserted. Before a locked read cycle is run, the processor first determines if the corresponding line is in the cache. If the line is present in the cache, and is in an E or S state, it is invalidated. If the line is in the M state, the processor does a write-back and then invalidates the line. A locked cycle to an M, S, or E state line is always forced out to the bus. If the operand is misaligned across cache lines, the processor could potentially run two write back cycles before starting the first locked read. In this case the sequence of bus cycles is: write back, write back, locked read, locked read, locked write and the final locked write. Note that although a total of six cycles are generated, the LOCK# pin is asserted only during the last four cycles, as shown in Figure 10-46.

LOCK# is not deasserted if AHOLD is asserted in the middle of a locked cycle. LOCK# remains asserted even if there is a snoop write-back during a locked cycle. LOCK# is floated if BOFF# is asserted in the middle of a locked cycle. However, it is driven LOW again when the cycle restarts after BOFF#. Locked read cycles are never transformed into line fills, even if KEN# is asserted. If there are back-to-back locked cycles, the Write-Back Enhanced IntelDX4 processor does not insert a dead clock between these two cycles. HOLD is recognized if there are two back-to-back locked cycles, and LOCK# floats when HLDA is asserted.

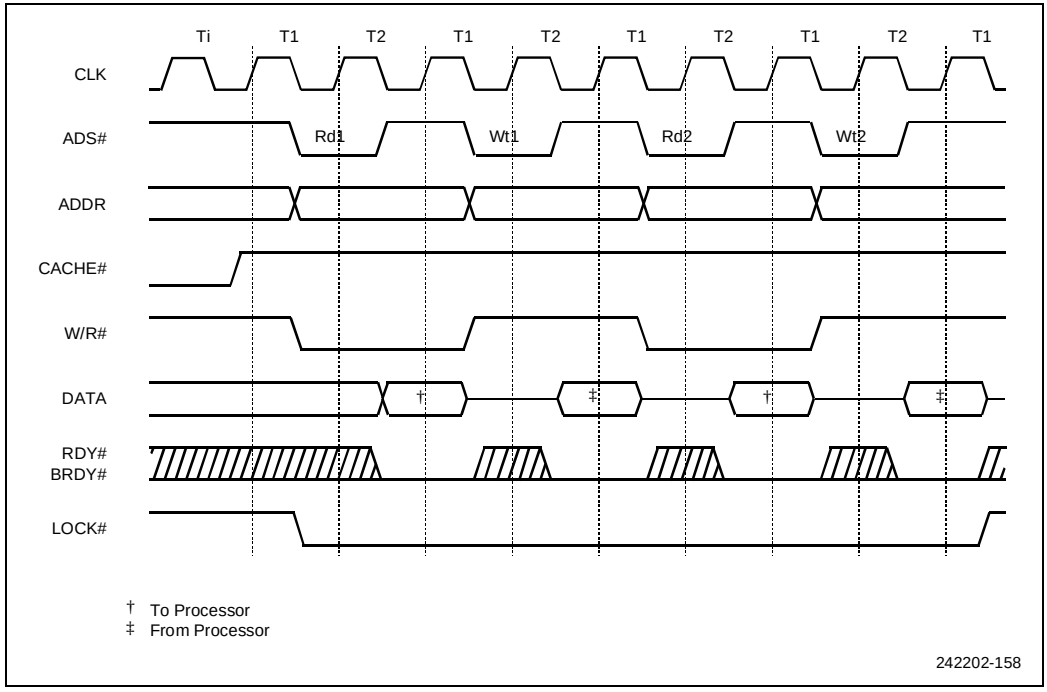

Figure 10-46. Locked Cycles (Back-to-Back)

10.4.4.1 Snoop/Lock Collision

If there is a snoop cycle overlaying a locked cycle, the snoop write-back cycle fractures the locked cycle. As shown in Figure 10-47, after the read portion of the locked cycle is completed, the snoop write-back starts under HITM#. After the write-back is completed, the locked cycle continues. But during all this time (including the write-back cycle), the LOCK# signal remains asserted.

Because HOLD is not acknowledged if LOCK# is asserted, snoop-lock collisions are restricted to AHOLD and BOFF# snooping.

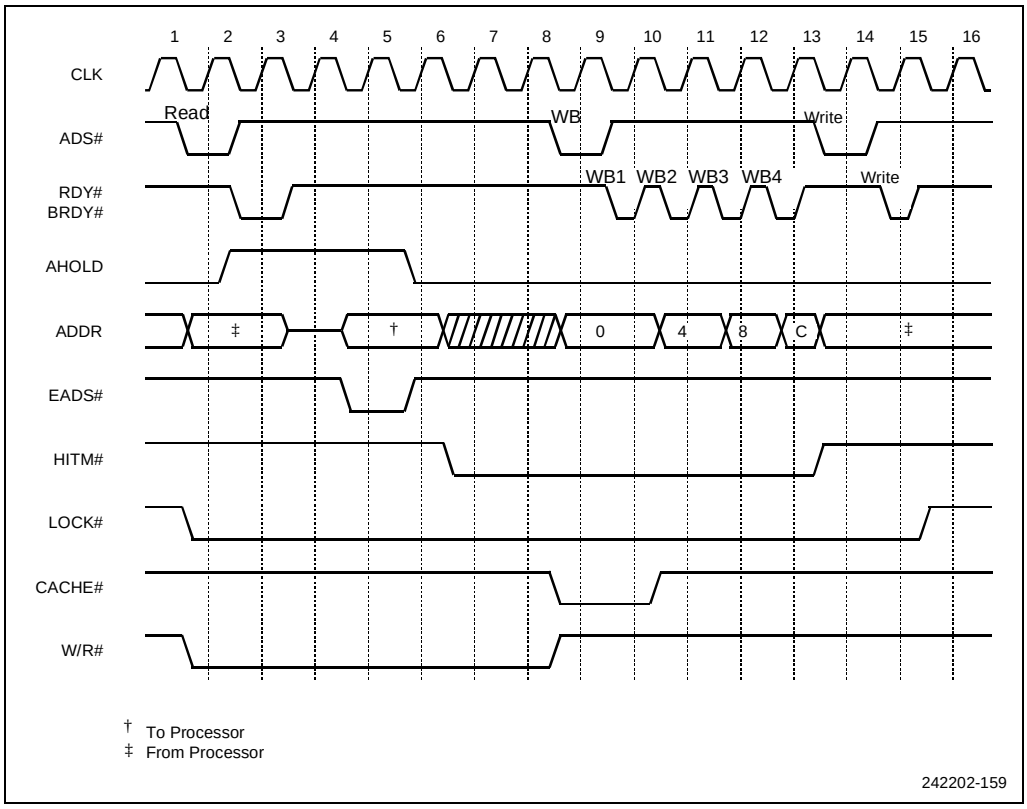

Figure 10-47. Snoop Cycle Overlaying a Locked Cycle

10.4.5 Flush Operation

The Write-Back Enhanced IntelDX4 processor executes a flush operation when the FLUSH# pin is asserted, and no outstanding bus cycles, such as a line fill or write back, are being processed. In the Enhanced Bus mode, the processor first writes back all the modified lines to external memory. After the write-back is completed, two special cycles are generated, indicating to the external system that the write-back is done. All lines in the internal cache are invalidated after all the write-back cycles are done. Depending on the number of modified lines in the cache, the flush could take a minimum of 1280 bus clocks (2560 processor clocks) and up to a maximum of 5000+ bus clocks to scan the cache, perform the write backs, invalidate the cache, and run the flush acknowledge cycles. FLUSH# is implemented as an interrupt in the Enhanced Bus mode, and is recognized only on an instruction boundary. Write-back system designs should look for the flush acknowledge cycles to recognize the end of the flush operation. Figure 10-48 shows the flush operation of the Write-Back Enhanced IntelDX4 processor when configured in the Enhanced Bus mode.

If the processor is in Standard Bus mode, the processor does not issue special acknowledge cycles in response to the FLUSH# input, although the internal cache is invalidated. The invalidation of the cache in this case, takes only two bus clocks.

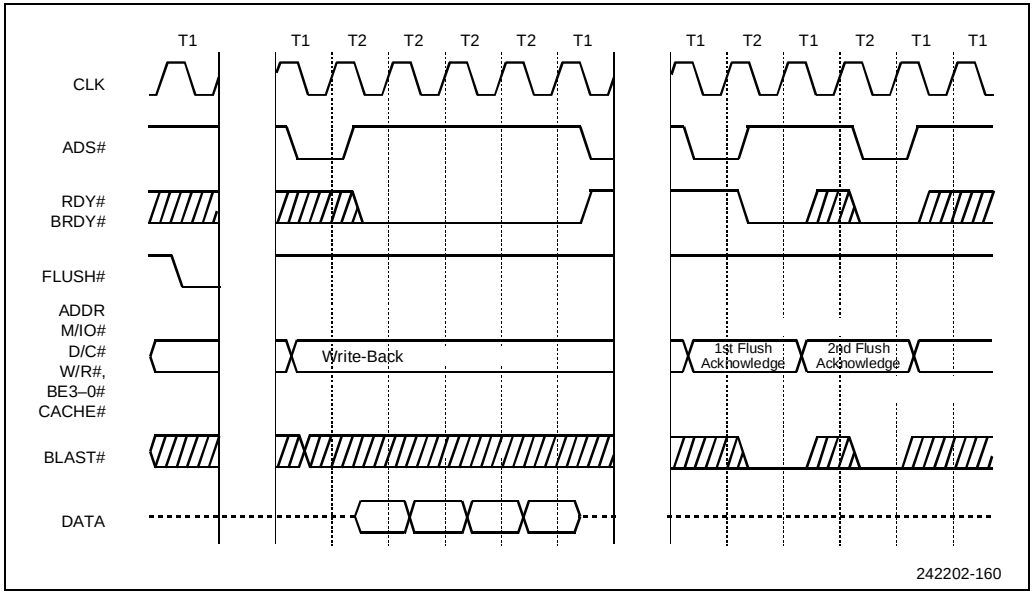

Figure 10-48. Flush Cycle

10.4.6 Pseudo Locked Cycles

In Enhanced Bus mode, PLOCK# is always deasserted for both burst and non-burst cycles. Hence, it is possible for other bus masters to gain control of the bus during operand transfers that take more than one bus cycle. A 64-bit aligned operand can be read in one burst cycle or two non-burst cycles if BS8# and BS16# are not asserted. Figure 10-49 shows a 64-bit floating-point operand or Segment Descriptor read cycle, which is burst by the system asserting BRDY#.

10.4.6.1 Snoop under AHOLD during Pseudo-Locked Cycles

AHOLD can fracture a 64-bit transfer if it is a non-burst cycle. If the 64-bit cycle is burst, as shown in Figure 10-49, the entire transfer goes to completion and only then does the snoop write-back cycle start.

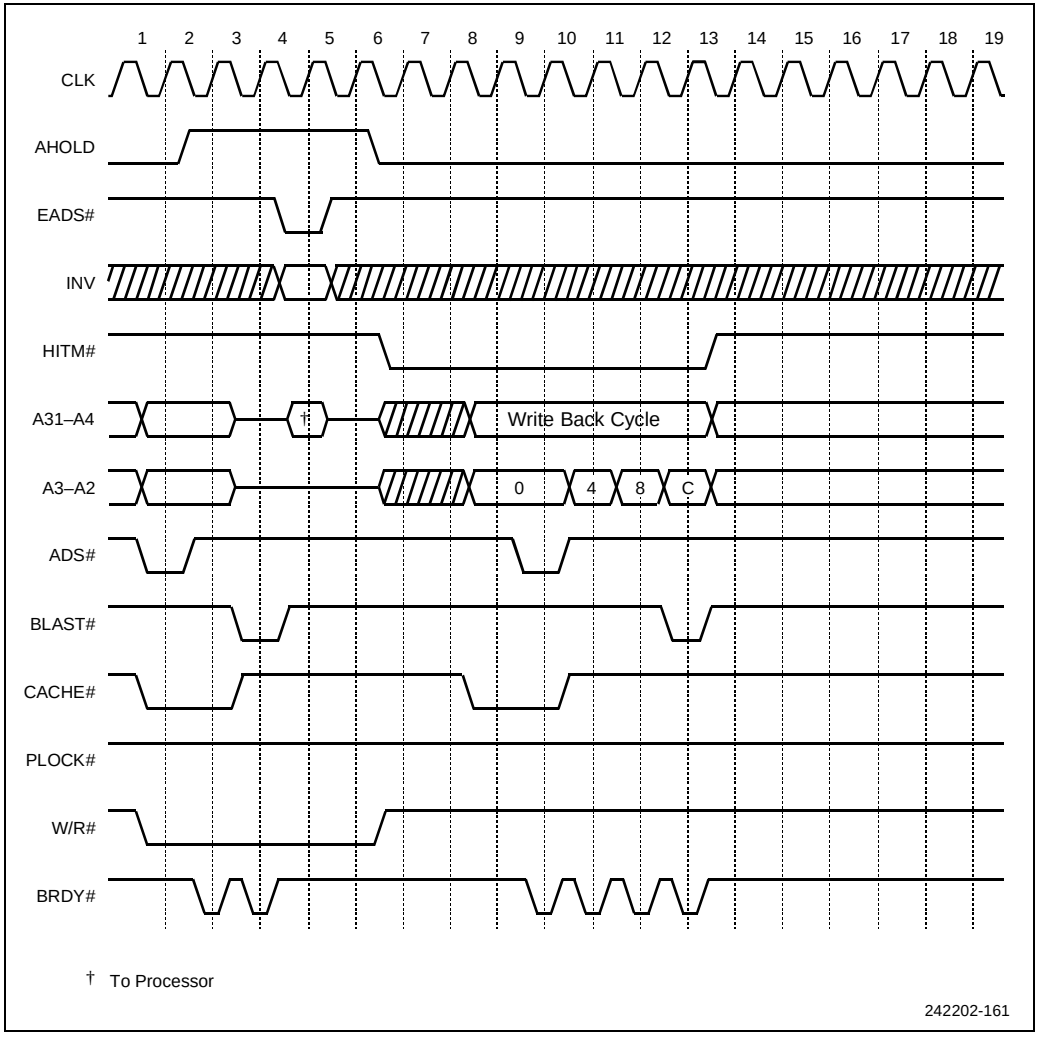

Figure 10-49. Snoop under AHOLD Overlaying Pseudo-Locked Cycle

10.4.6.2 Snoop under Hold during Pseudo-Locked Cycles

As shown in Figure 10-50, HOLD does not fracture the 64-bit burst transfer. The Write-Back Enhanced IntelDX4 processor does not issue HLDA until clock four. After the 64-bit transfer is completed, the Write-Back Enhanced IntelDX4 processor writes back the modified line to memory (if snoop hits a modified line). If the 64-bit transfer is non-burst, the Write-Back Enhanced IntelDX4 processor can issue HLDA in between bus cycles for a 64-bit transfer.

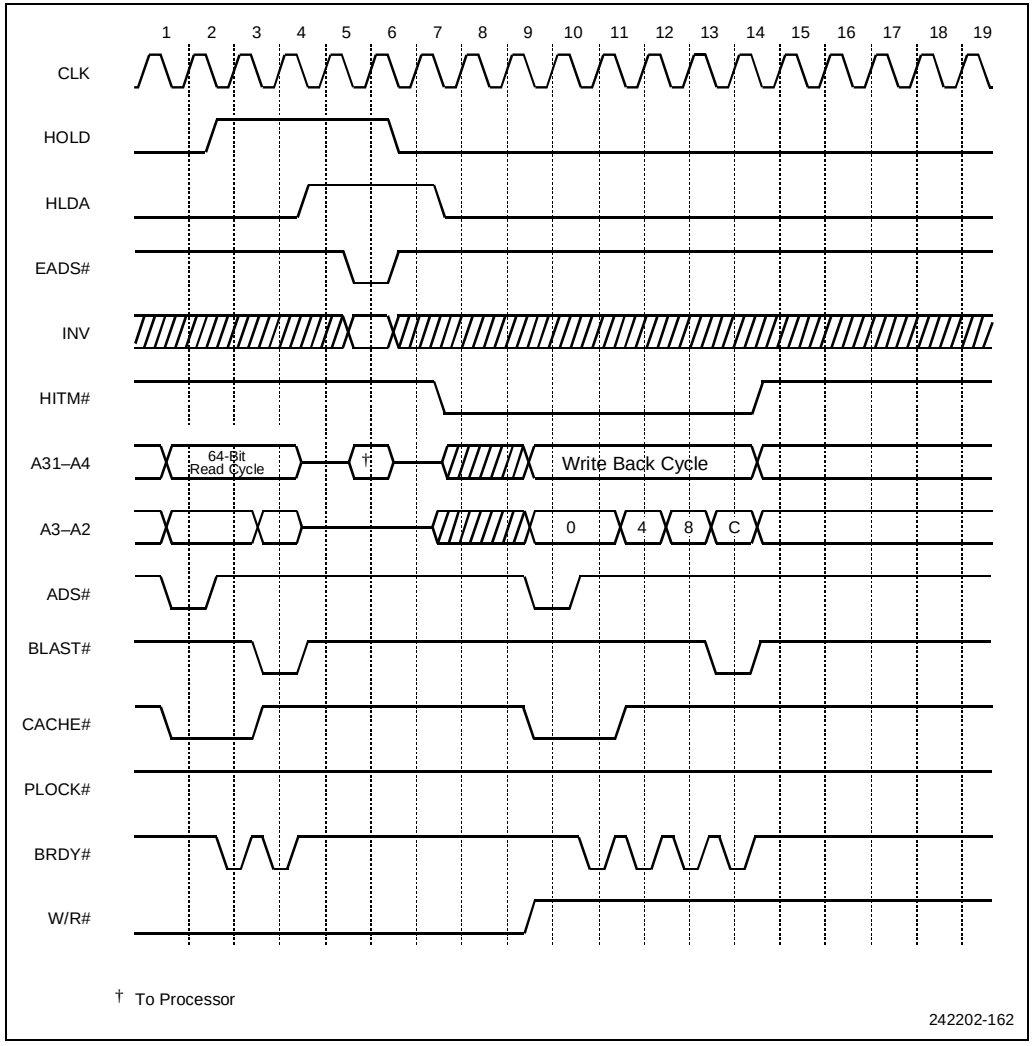

Figure 10-50. Snoop under HOLD Overlaying Pseudo-Locked Cycle

10.4.6.3 Snoop under BOFF# Overlaying a Pseudo-Locked Cycle

BOFF# is capable of fracturing any bus operation. In Figure 10-51, BOFF# fractured a current 64-bit read cycle in clock four. If there is a snoop hit under BOFF#, the snoop write-back operation begins after BOFF# is deasserted. The 64-bit write cycle resumes after the snoop write-back operation completes.

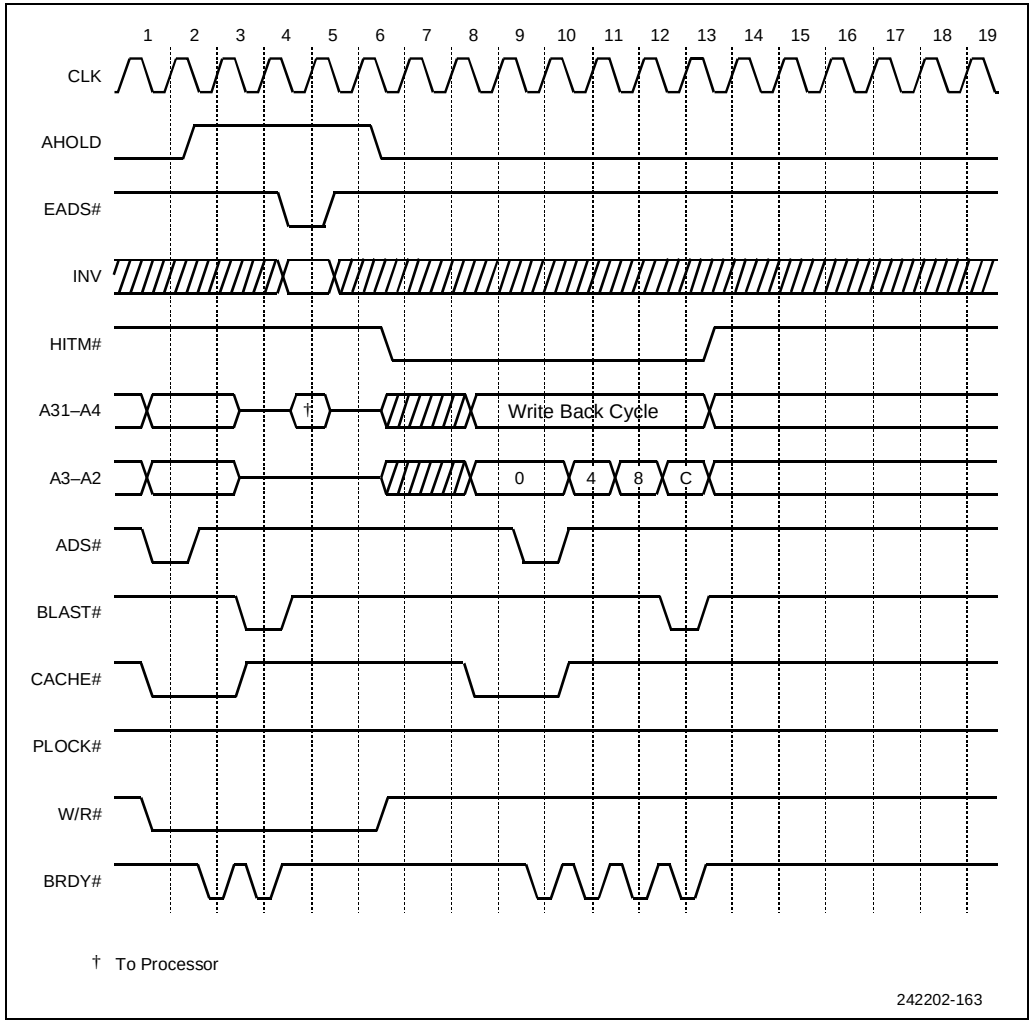

Figure 10-51. Snoop under BOFF# Overlaying a Pseudo-Locked Cycle

11

Debugging Support

Chapter Contents

CHAPTER 11
DEBUGGING SUPPORT

The Intel486™ processor provides several features that simplify the debugging process. The three categories of on-chip debugging aids are:

1. Code execution breakpoint opcode (0CCH)
2. Single-step capability provided by the TF bit in the Flag register
3. Code and data breakpoint capability provided by the Debug Registers DR[3:0], DR6, and DR7

11.1 BREAKPOINT INSTRUCTION

A single-byte opcode breakpoint instruction is available for use by software debuggers. The breakpoint opcode, 0CCH, generates an exception 3 trap when executed. In typical use, a debugger program “plants” the breakpoint instruction at all desired code execution breakpoints. The single-byte breakpoint opcode is an alias for the two-byte general software interrupt instruction INT *n*, where *n*=3. The only difference between INT 3 (0CCh) and INT *n* is that INT 3 is never IOPL-sensitive, whereas INT *n* is IOPL-sensitive in Protected Mode and Virtual 8086 Mode.

11.2 SINGLE-STEP TRAP

When the single-step flag (TF, bit 8) in the EFLAG register is set at the end of an instruction, a single-step exception occurs. The single-step exception is auto vectored to exception number 1. Precisely, exception 1 occurs as a trap after the instruction following the instruction that set TF. In typical practice, a debugger sets the TF bit of a flag register image on the debugger's stack. Typically, it then transfers control to the user program and loads the flag image with a signal instruction, the IRET instruction. The single-step trap occurs after executing one instruction of the user program.

Because exception 1 occurs as a trap (that is, it occurs after the instruction has executed), the CS:EIP pushed onto the debugger's stack points to the next unexecuted instruction of the program being debugged. Therefore, by ending with an IRET instruction, an exception 1 handler can efficiently support single-stepping through a user program.

11.3 DEBUG REGISTERS

The Debug Registers are an advanced debugging feature of the Intel486 processor. They allow data access breakpoints and code execution breakpoints. Because the breakpoints are indicated by on-chip registers, an instruction execution breakpoint can be placed in ROM code or in code shared by several tasks, neither of which can be supported by the INT3 breakpoint opcode.

The Intel486 processor contains six Debug Registers, providing the ability to specify up to four distinct breakpoint addresses, breakpoint control options, and read breakpoint status. Initially after reset, breakpoints are in the disabled state. Therefore, no breakpoints occur unless the debug registers are programmed. Breakpoints set up in the Debug Registers are auto-vectored to exception number 1.

11.3.1 Linear Address Breakpoint Registers (DR[3:0])

Up to four breakpoint addresses can be specified by writing to Debug Registers DR[3:0], shown in Figure 11-1. The breakpoint addresses specified are 32-bit linear addresses. Intel486 processor hardware continuously compares the linear breakpoint addresses in DR[3:0] with the linear addresses generated by executing software (a linear address is the result of computing the effective address and adding the 32-bit segment base address). Note that when paging is not enabled, the linear address equals the physical address. If paging is enabled, the linear address is translated to a physical 32-bit address by the on-chip paging unit. Regardless of whether paging is enabled or not, however, the breakpoint registers hold linear addresses.

11.3.2 Debug Control Register (DR7)

A Debug Control Register, DR7 shown in Figure 11-1, allows several debug control functions, such as enabling the breakpoints and setting up other control options for the breakpoints. The fields within the Debug Control Register, DR7, are as follows:

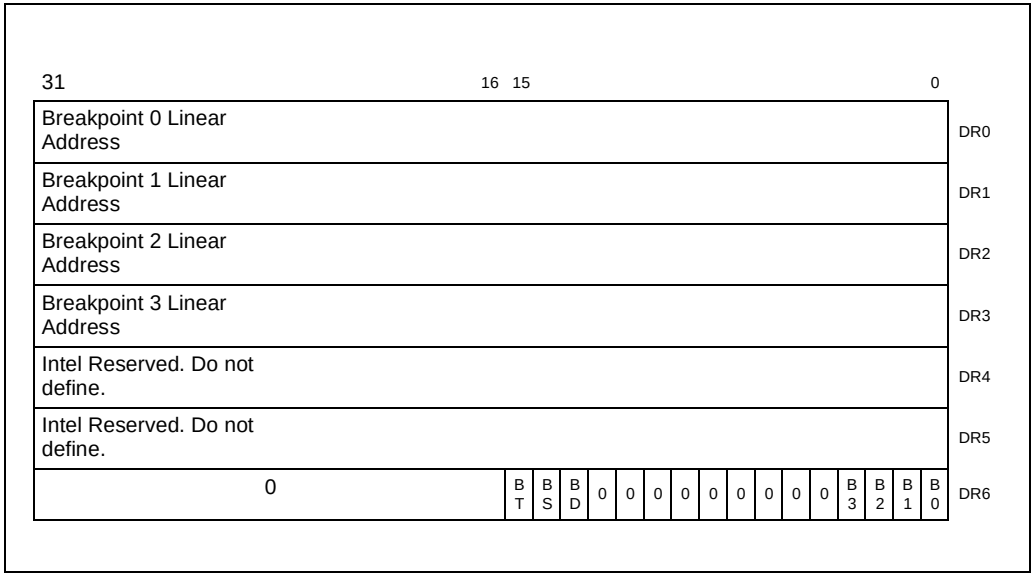

Figure 11-1. Debug Registers

LEN*i* (breakpoint length specification bits)

A 2-bit LEN field exists for each of the four breakpoints. LEN specifies the length of the associated breakpoint field. The choices for data breakpoints are: 1 byte, 2 bytes, and 4 bytes. Instruction execution breakpoints must have a length of 1 (LENi = 00). Encoding of the LENi field is as described in Table 11-1.

The LEN*i* field controls the size of breakpoint field *i* by controlling whether all low-order linear address bits in the breakpoint address register are used to detect the breakpoint event. Therefore, all breakpoint fields are aligned: 2-byte breakpoint fields begin on word boundaries, and 4-byte breakpoint fields begin on dword boundaries.

Figure 11-2 is an example of various size breakpoint fields. Assume the breakpoint linear address in DR2 is 00000005H. In that situation, the Figure 11-2 indicates the region of the breakpoint field for lengths of 1, 2, or 4 bytes.

RWi (memory access qualifier bits)

A 2-bit RW field exists for each of the four breakpoints. The 2-bit RW field specifies the type of usage that must occur to activate the associated breakpoint.

Table 11-1. LENi Encoding

LENi Encoding	Breakpoint Field Width	Usage of Least Significant Bits in Breakpoint Address Register i, (i=0-3)
00	1 byte	All 32-bits used to specify a single-byte breakpoint field.
01	2 bytes	A[31:1] used to specify a two-byte, word-aligned breakpoint field. A0 in Breakpoint Address Register is not used.
10	Undefined—do not use this encoding	
11	4 bytes	A[31:1] used to specify a four-byte, dword-aligned breakpoint field. A0 and A1 in Breakpoint Address Register are not used.

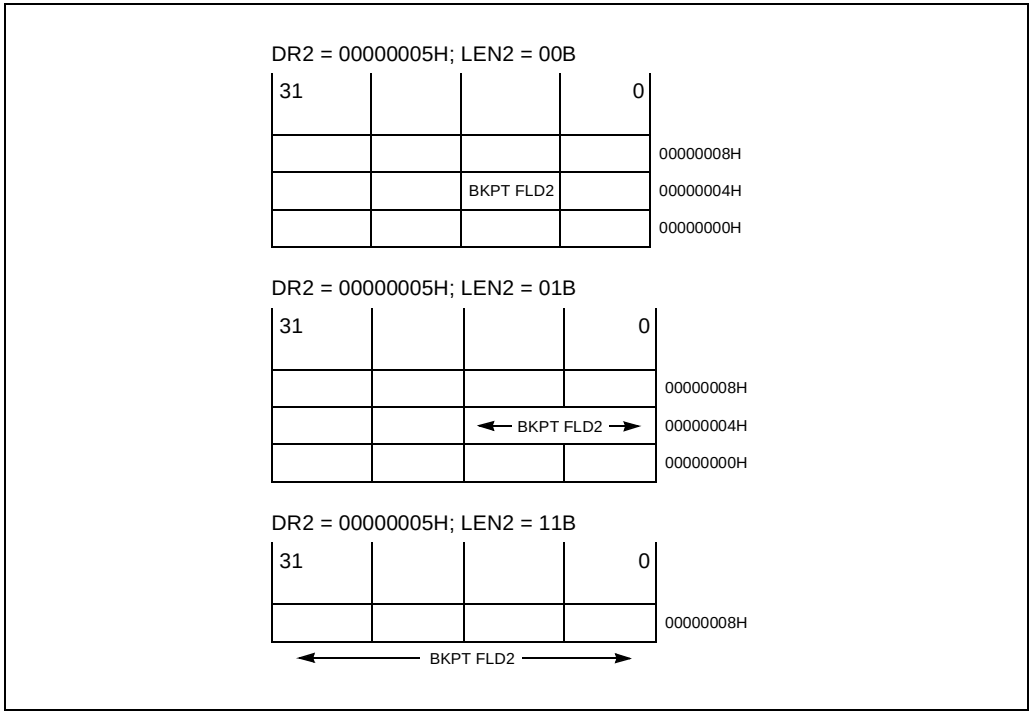

Figure 11-2. Size Breakpoint Fields

RW encoding 00 is used to set up an instruction execution breakpoint. RW encodings 01 or 11 are used to set up write-only or read/write data breakpoints.

Table 11-2. RW Encoding

RW Encoding	Usage Causing Breakpoint
00	Instruction execution only
01	Data writes only
10	Undefined–do not use this encoding
11	Data reads and writes only

Note that instruction execution breakpoints are taken as faults (i.e., before the instruction executes), but data breakpoints are taken as traps (i.e., after the data transfer takes place).

Using LEN*i* and RW*i* to Set Data Breakpoint *i*

A data breakpoint can be set up by writing the linear address into DR*i* (*i* = 0–3). For data breakpoints, RW*i* can equal 01 (write-only) or 11 (write/read). LEN can equal 00, 01, or 11.

When a data access entirely or partly falls within the data breakpoint field, the data breakpoint condition has occurred, and if the breakpoint is enabled, an exception 1 trap occurs.

Using LEN*i* and RW*i* to Set Instruction Execution Breakpoint *i*

An instruction execution breakpoint can be set up by writing the address of the beginning of the instruction (including prefixes if any) into DR*i* (*i* = 0–3). RW*i* must equal 00 and LEN must equal 00 for instruction execution breakpoints.

When the instruction beginning at the breakpoint address is about to be executed, the instruction execution breakpoint condition has occurred, and if the breakpoint is enabled, an exception 1 fault occurs before the instruction is executed.

Note that an instruction execution breakpoint address must be equal to the beginning byte address of an instruction (including prefixes) for the instruction execution breakpoint to occur.

GD (Global Debug Register access detect)

The Debug Registers can be accessed only in Real Mode or at privilege level 0 in Protected Mode. The GD bit, when set, provides extra protection against any Debug Register access even in Real Mode or at privilege level 0 in Protected Mode. This additional protection feature is provided to guarantee that a software debugger can have full control over the Debug Register resources when required. The GD bit, when set, causes an exception 1 fault when an instruction attempts to read or write any Debug Register. The GD bit is automatically cleared when the exception 1 handler is invoked, allowing the exception 1 handler free access to the debug registers.

GE and LE (Exact data breakpoint match, global and local)

The breakpoint mechanism of the Intel486 processor differs from that of the Intel386 processor. The Intel486 processor always does exact data breakpoint matching, regardless of GE/LE bit settings. Any data breakpoint trap is reported exactly after completion of the instruction that caused the operand transfer. Exact reporting is provided by forcing the Intel486 processor execution unit to wait for completion of data operand transfers before beginning execution of the next instruction.

When the Intel486 processor performs a task switch, the LE bit is cleared. Thus, the LE bit supports fast task switching out of tasks that have enabled the exact data breakpoint match for their task-local breakpoints. The LE bit is cleared by the Intel486 processor during a task switch to avoid having exact data breakpoint match enabled in the new task. Note that exact data breakpoint match must be re-enabled under software control.

The Intel486 processor GE bit is unaffected during a task switch. The GE bit supports exact data breakpoint match that remains enabled during all tasks executing in the system.

Note that instruction execution breakpoints are always reported exactly.

Gi and Li (breakpoint enable, global and local)

When either G*i* or L*i* is set, then the associated breakpoint (as defined by the linear address in DR*i*, the length in LEN*i* and the usage criteria in RW*i*) is enabled. When either G*i* or L*i* is set, and the Intel486 processor detects the i^{th} breakpoint condition, the exception 1 handler is invoked.

When the Intel486 processor performs a task switch to a new Task State Segment (TSS), all L*i* bits are cleared. Thus, the L*i* bits support fast task switching out of tasks that use some task-local breakpoint registers. The L*i* bits are cleared by the Intel486 processor during a task switch to avoid spurious exceptions in the new task. Note that the breakpoints must be re-enabled under software control.

All Intel486 processor G*i* bits are unaffected during a task switch. The G*i* bits support breakpoints that are active in all tasks executing in the system.

11.3.3 Debug Status Register (DR6)

A Debug Status Register (DR6 shown in Figure 11-1) allows the exception 1 handler to easily determine why it was invoked. Note that the exception 1 handler can be invoked as a result of one of several events:

- DR0 Breakpoint fault/trap
- DR1 Breakpoint fault/trap
- XDR2 Breakpoint fault/trap
- XDR3 Breakpoint fault/trap
- XSingle-step (TF) trap
- XTask switch trap
- XFault due to attempted debug register access when GD=1

The Debug Status Register contains single-bit flags for each of the possible events that invoke exception 1. Note below that some of these events are faults (exception taken before the instruction is executed), whereas other events are traps (exception taken after the debug events occurred).

The flags in DR6 are set by hardware but never cleared by hardware. Exception 1 handler software should clear DR6 before returning to the user program to avoid future confusion in identifying the source of exception 1.

The fields within the Debug Status Register, DR6, are as follows:

B*i* (debug fault/trap due to breakpoint 0–3)

Four breakpoint indicator flags, B[3:0], correspond one-to-one with the breakpoint registers in DR[3:0]. A flag Bi is set when the condition described by DRi, LENi, and RWi occurs.

If G*i* or L*i* is set, and if the i^{th} breakpoint is detected, the Intel486 processor invokes the exception 1 handler. The exception is handled as a fault when an instruction execution breakpoint occurs, or as a trap if a data breakpoint occurs.

NOTE

A flag B*i* is set whenever the hardware detects a match condition on enabled breakpoint *i*. When a match is detected on at least one enabled breakpoint *i*, the hardware immediately sets all B*i* bits that correspond to breakpoint conditions matching at that instant, whether enabled or not. Although the exception 1 handler may see that multiple B*i* bits are set, only those set B*i* bits that correspond to enabled breakpoints (L*i* or G*i* set) are true indications of why the exception 1 handler was invoked.

BD (debug fault due to attempted register access when GD bit set)

This bit is set when the exception 1 handler is invoked due to an instruction that attempts to read or write to the debug registers when the GD bit was set. If such an event occurs, then the GD bit is automatically cleared when the exception 1 handler is invoked, allowing the handler access to the debug registers.

BS (debug trap due to single-step)

This bit is set when the exception 1 handler is invoked due to the TF bit in the flag register being set (for single-stepping).

BT (debug trap due to task switch)

This bit is set when the exception 1 handler was invoked due to a task switch that occurs on a task having an Intel486 processor TSS with the T bit set. Note the task switch into the new task occurs normally, but before the first instruction of the task is executed, the exception 1 handler is invoked. With respect to the task switch operation, the operation is considered to be a trap.

11.3.4 Use of Resume Flag(RF) in Flag Register

The Resume Flag (RF) in the flag word can suppress an instruction execution breakpoint when the exception 1 handler returns to a user program at a user address that is also an instruction execution breakpoint.

12

Instruction Set Summary

Chapter Contents

CHAPTER 12
INSTRUCTION SET SUMMARY

This chapter describes the entire encoding structure and provides definitions of all fields occurring within the Intel486™ processor instructions. Detailed information on the CPUID instruction can be found in Appendix D, “Feature Determination.”

12.1 INSTRUCTION SET

The Intel486 processor instruction set can be divided into the following categories of operations:

- Data Transfer
- Arithmetic
- Shift/Rotate
- String Manipulation
- Bit Manipulation
- Control Transfer
- High Level Language Support
- Operating System Support
- Processor Control

All Intel486 processor instructions operate on either 0, 1, 2 or 3 operands; where an operand resides in a register, in the instruction itself, or in memory. Most zero-operand instructions (e.g., CLI, STI) take only one byte. One-operand instructions generally are two bytes long. The average instruction is 3.2-bytes long. Because the Intel486 processor has a 32-byte instruction queue, an average of 10 instructions are prefetched. The use of two operands permits the following types of common instructions:

- Register to register
- Memory to register
- Memory to memory
- Immediate to register
- Register to memory
- Immediate to memory

The operands can be 8-, 16-, or 32-bits long. As a general rule, when executing 32-bit code, operands are 8 or 32 bits; when executing existing 80286 or 8086 processor code (16-bit code), operands are 8 or 16 bits. Prefixes can be added to all instructions to override the default length of the operands (i.e., to use 32-bit operands for 16-bit code, or 16-bit operands for 32-bit code).

12.1.1 Floating-Point Instructions

In addition to the instructions listed above, the IntelDX2 and IntelDX4 processors have floating-point instructions and Floating-Point Control instructions. Note that all Floating-Point Unit instruction mnemonics begin with an F.

12.2 INSTRUCTION ENCODING

12.2.1 Overview

All instruction encodings are subsets of the general instruction format shown in Figure 12-1. Instructions consist of one or two primary opcode bytes, possibly an address specifier consisting of the "mod r/m" byte and "scaled index" byte, a displacement if required, and an immediate data field if required.

Within the primary opcode or opcodes, smaller encoding fields may be defined. These fields vary according to the class of operation. The fields define such information as direction of the operation, size of the displacements, register encoding, or sign extension.

Almost all instructions referring to an operand in memory have an addressing mode byte following the primary opcode byte(s). This byte, the mod r/m byte, specifies the address mode to be used. Certain encodings of the mod r/m byte indicate a second addressing byte, the scale-index-base byte, that follows the mod r/m byte to fully specify the addressing mode.

Addressing modes can include a displacement immediately following the mod r/m byte or scaled index byte. When a displacement exists, the possible sizes are 8, 16, or 32 bits.

When the instruction specifies an immediate operand, the it follows any displacement bytes. The immediate operand, when specified, is always the last field of the instruction.

Figure 12-1 illustrates several of the fields that can appear in an instruction, such as the mod field and the r/m field, but the figure does not show all fields. Several smaller fields also appear in certain instructions, sometimes within the opcode bytes themselves. Table 12-1 is a complete list of all fields appearing in the Intel486 processor instruction set. Following Table 12-1 are detailed tables for each field.

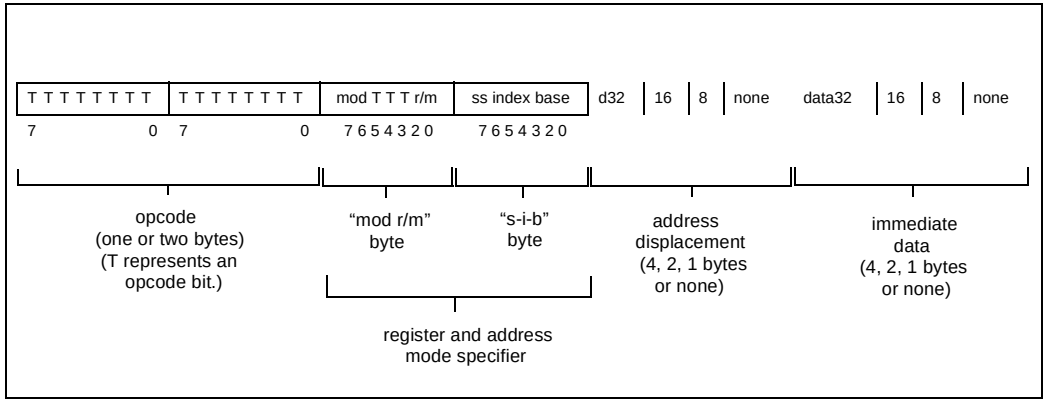

Figure 12-1. General Instruction Format

Table 12-1. Fields within Intel486™ Processor Instructions

Field Name	Description	Number of Bits
w	Specifies whether data is byte or full size (full size is either 16 or 32 bits)	1
d	Specifies direction of data operation	1
s	Specifies whether an immediate data field must be sign-extended	1
reg	General register specifier	3
mod r/m	Address mode specifier (effective address can be a general register)	2 for mod; 3 for r/m
ss	Scale factor for scaled index address mode	2
index	General register to be used as index register	3
base	General register to be used as base register	3
sreg2	Segment register specifier for CS, SS, DS, ES	2
sreg3	Segment register specifier for CS, SS, DS, ES, FS, GS	3
tttn	For conditional instructions, specifies a condition asserted or a condition negated	4

NOTE: Tables 12-15 through 12-19 show encoding of individual instructions.

12.2.2 32-Bit Extensions of the Instruction Set

With the Intel486 processor, the 8086/80186/80286 instruction set is extended in two orthogonal directions: 32-bit forms of all 16-bit instructions are added to support the 32-bit data types, and 32-bit addressing modes are made available for all instructions referencing memory. This orthogonal instruction set extension is accomplished having a Default (D) bit in the code segment descriptor, and by having two prefixes to the instruction set.

Whether the instruction defaults to operations of 16 bits or 32 bits depends on the setting of the D bit in the code segment descriptor, which gives the default length (either 32 bits or 16 bits) for both operands and effective addresses when executing that code segment. In Real Address Mode or Virtual 8086 Mode, no code segment descriptors are used, but the Intel486 processor assumes a D value of 0 when operating in those modes (for 16-bit default sizes compatible with the 8086/80186/80286).

Two prefixes, the Operand Size Prefix and the Effective Address Size Prefix, allow overriding individually the Default selection of operand size and effective address size. These prefixes may precede any opcode bytes and affect only the instruction they precede. If necessary, one or both of the prefixes may be placed before the opcode bytes. The Operand Size Prefix and the Effective Address Prefix toggle the operand size or the effective address size, respectively, to the value "opposite" the Default setting. For example, when the default operand size is for 32-bit data operations, the presence of the Operand Size Prefix toggles the instruction to 16-bit data operation. When the default effective address size is 16 bits, the presence of the Effective Address Size prefix toggles the instruction to use 32-bit effective address computations.

These 32-bit extensions are available in all Intel486 processor modes, including Real Address Mode or Virtual 8086 Mode. In these modes the default is always 16 bits, so prefixes are needed to specify 32-bit operands or addresses. For instructions with more than one prefix, the order of prefixes is unimportant.

Unless specified otherwise, instructions with 8-bit and 16-bit operands do not affect the contents of the high-order bits of the extended registers.

12.2.3 Encoding of Integer Instruction Fields

Within the instruction are several fields that indicate register selection, addressing mode and so on. The exact encodings of these fields are defined in this section.

12.2.3.1 Encoding of Operand Length (w) Field

For any given instruction that performs a data operation, the instruction executes as a 32-bit operation or a 16-bit operation. Within the constraints of the operation size, the w field encodes the operand size as either one byte or the full operation size, as shown in Table 12-2.

Table 12-2. Encoding of Operand Length (w) Field

w Field	Operand Size during 16-Bit Data Operations	Operand Size during 32-Bit Data Operations
0	8 Bits	8 Bits
1	16 Bits	32 Bits

12.2.3.2 Encoding of the General Register (reg) Field

The general register is specified by the reg field, which may appear in the primary opcode bytes, as the reg field of the “mod r/m” byte, or as the r/m field of the “mod r/m” byte.

Table 12-3. Encoding of reg Field when the (w) Field is Not Present in Instruction

reg Field	Register Selected during 16-Bit Data Operations	Register Selected during 32-Bit Data Operations
000	AX	EAX
001	CX	ECX
010	DX	EDX
011	BX	EBX
100	SP	ESP
101	BP	EBP
110	SI	ESI
111	DI	EDI

Table 12-4. Encoding of reg Field when the (w) Field is Present in Instruction

Register Specified by reg Field during 16-Bit Data Operations:		
reg	Function of w Field	
	(when w = 0)	(when w = 1)
000	AL	AX
001	CL	CX
010	DL	DX
011	BL	BX
100	AH	SP
101	CH	BP
110	DH	SI
111	BH	DI

Table 12-4. Encoding of reg Field when the (w) Field is Present in Instruction

Register Specified by reg Field during 32-Bit Data Operations		
reg	Function of w Field	
	(when w = 0)	(when w = 1)
000	AL	EAX
001	CL	ECX
010	DL	EDX
011	BL	EBX
100	AH	ESP
101	CH	EBP
110	DH	ESI
111	BH	EDI

12.2.3.3 Encoding of the Segment Register (sreg) Field

The sreg field in certain instructions is a 2-bit field allowing one of the four 80286 segment registers to be specified. The sreg field in other instructions is a 3-bit field, allowing the Intel486 processor FS and GS segment registers to be specified.

Table 12-5. 2-Bit sreg2 Field

2-bit sreg2 Field	Segment Register Selected
00	ES
01	CS
10	SS
11	DS

Table 12-6. 3-Bit sreg3 Field

3-bit sreg3 Field	Segment Register Selected
000	ES
001	CS
010	SS
011	DS
100	FS
101	GS
110	do not use
111	do not use

12.2.3.4 Encoding of Address Mode

Except for special instructions, such as PUSH or POP, where the addressing mode is pre-determined, the addressing mode for the current instruction is specified by addressing bytes following the primary opcode. The primary addressing byte is the “mod r/m” byte, and a second byte of addressing information, the “s-i-b” (scale-index-base) byte, can be specified.

The s-i-b (scale-index-base byte) byte is specified when using 32-bit addressing mode and the “mod r/m” byte has r/m = 100 and mod = 00, 01 or 10. When the sib byte is present, the 32-bit addressing mode is a function of the mod, ss, index, and base fields.

The primary addressing byte, the “mod r/m” byte, also contains three bits (shown as TTT in Figure 12-1) sometimes used as an extension of the primary opcode. The three bits, however, may also be used as a register field (reg).

When calculating an effective address, either 16-bit addressing or 32-bit addressing is used. 16-bit addressing uses 16-bit address components to calculate the effective address, and 32-bit addressing uses 32-bit address components to calculate the effective address. When 16-bit addressing is used, the “mod r/m” byte is interpreted as a 16-bit addressing mode specifier. When 32-bit addressing is used, the “mod r/m” byte is interpreted as a 32-bit addressing mode specifier.

Tables 12-7, 12-8, and 12-9 define encodings of all 16-bit and 32-bit addressing modes.

Table 12-7. Encoding of 16-Bit Address Mode with "mod r/m" Byte

mod r/m	Effective Address
00 000	DS:[BX+SI]
00 001	DS:[BX+DI]
00 010	SS:[BP+SI]
00 011	SS:[BP+DI]
00 100	DS:[SI]
00 101	DS:[DI]
00 110	DS:d16
00 111	DS:[BX]
01 000	DS:[BX+SI+d8]
01 001	DS:[BX+DI+d8]
01 010	SS:[BP+SI+d8]
01 011	SS:[BP+DI+d8]
01 100	DS:[SI+d8]
01 101	DS:[DI+d8]
01 110	SS:[BP+d8]
01 111	DS:[BX+d8]

mod r/m	Effective Address
10 000	DS:[BX+SI+d16]
10 001	DS:[BX+DI+d16]
10 010	SS:[BP+SI+d16]
10 011	SS:[BP+DI+d16]
10 100	DS:[SI+d16]
10 101	DS:[DI+d16]
10 110	SS:[BP+d16]
10 111	DS:[BX+d16]
11 000	register–see below
11 001	register–see below
11 010	register–see below
11 011	register–see below
11 100	register–see below
11 101	register–see below
11 110	register–see below
11 111	register–see below

Register Specified by r/m during 16-Bit Data Operations		
mod r/m	Function of w Field	
	(when w=0)	(when w =1)
11 000	AL	AX
11 001	CL	CX
11 010	DL	DX
11 011	BL	BX
11 100	AH	SP
11 101	CH	BP
11 110	DH	SI
11 111	BH	DI

Register Specified by r/m during 32-Bit Data Operations		
mod r/m	Function of w Field	
	(when w=0)	(when w =1)
11 000	AL	EAX
11 001	CL	ECX
11 010	DL	EDX
11 011	BL	EBX
11 100	AH	ESP
11 101	CH	EBP
11 110	DH	ESI
11 111	BH	EDI

Table 12-8. Encoding of 32-Bit Address Mode with "mod r/m" Byte (No "s-i-b" Byte Present)

mod r/m	Effective Address
00 000	DS:[EAX]
00 001	DS:[ECX]
00 010	DS:[EDX]
00 011	DS:[EBX]
00 100	s-i-b is present
00 101	DS:d32
00 110	DS:[ESI]
00 111	DS:[EDI]
01 000	DS:[EAX+d8]
01 001	DS:[ECX+d8]
01 010	DS:[EDX+d8]
01 011	DS:[EBX+d8]
01 100	s-i-b is present
01 101	SS:[EBP+d8]
01 110	DS:[ESI+d8]
01 111	DS:[EDI+d8]

mod r/m	Effective Address
10 000	DS:[EAX+d32]
10 001	DS:[ECX+d32]
10 010	DS:[EDX+d32]
10 011	DS:[EBX+d32]
10 100	s-i-b is present
10 101	SS:[EBP+d32]
10 110	DS:[ESI+d32]
10 111	DS:[EDI+d32]
11 000	register–see below
11 001	register–see below
11 010	register–see below
11 011	register–see below
11 100	register–see below
11 101	register–see below
11 110	register–see below
11 111	register–see below

Register Specified by reg or r/m during 16-Bit Data Operations:		
mod r/m	Function of w field	
	(when w=0)	(when w=1)
11 000	AL	AX
11 001	CL	CX
11 010	DL	DX
11 011	BL	BX
11 100	AH	SP
11 101	CH	BP
11 110	DH	SI
11 111	BH	DI

Register Specified by reg or r/m during 32-Bit Data Operations:		
mod r/m	Function of w field	
	(when w=0)	(when w=1)
11 000	AL	EAX
11 001	CL	ECX
11 010	DL	EDX
11 011	BL	EBX
11 100	AH	ESP
11 101	CH	EBP
11 110	DH	ESI
11 111	BH	EDI

Table 12-9. Encoding of 32-Bit Address Mode ("mod r/m" Byte and "s-i-b" Byte Present)

mod base	Effective Address
00 000	DS:[EAX+(scaled index)]
00 001	DS:[ECX+(scaled index)]
00 010	DS:[EDX+(scaled index)]
00 011	DS:[EBX+(scaled index)]
00 100	SS:[ESP+(scaled index)]
00 101	DS:[d32+(scaled index)]
00 110	DS:[ESI+(scaled index)]
00 111	DS:[EDI+(scaled index)]
01 000	DS:[EAX+(scaled index)+d8]
01 001	DS:[ECX+(scaled index)+d8]
01 010	DS:[EDX+(scaled index)+d8]
01 011	DS:[EBX+(scaled index)+d8]
01 100	SS:[ESP+(scaled index)+d8]
01 101	SS:[EBP+(scaled index)+d8]
01 110	DS:[ESI+(scaled index)+d8]
01 111	DS:[EDI+(scaled index)+d8]
10 000	DS:[EAX+(scaled index)+d32]
10 001	DS:[ECX+(scaled index)+d32]
10 010	DS:[EDX+(scaled index)+d32]
10 011	DS:[EBX+(scaled index)+d32]
10 100	SS:[ESP+(scaled index)+d32]
10 101	SS:[EBP+(scaled index)+d32]
10 110	DS:[ESI+(scaled index)+d32]
10 111	DS:[EDI+(scaled index)+d32]

NOTE: Mod field in "mod r/m" byte; ss, index, base fields in "s-i-b" byte.

ss	Scale Factor
00	x1
01	x2
10	x4
11	x8
Index	**Index Register**
000	EAX
001	ECX
010	EDX
011	EBX
100	no index reg†
101	EBP
110	ESI
111	EDI

NOTE: When index field is 100, indicating "no index register," then ss field MUST equal 00. When index is 100 and ss does not equal 00, the effective address is undefined.

12.2.3.5 Encoding of Operation Direction (d) Field

In many two-operand instructions the d field is present to indicate which operand is considered the source and which is the destination.

Table 12-10. Encoding of Operation Direction (d) Field

d	Direction of Operation
0	Register/Memory ← Register “reg” Field Indicates Source Operand; “mod r/m” or “mod ss index base” Indicates Destination Operand
1	Register ← Register/Memory “reg” Field Indicates Destination Operand; “mod r/m” or “mod ss index base” Indicates Source Operand

12.2.3.6 Encoding of Sign-Extend (s) Field

The s field occurs primarily to instructions with immediate data fields. The s field has an effect only when the size of the immediate data is 8 bits and is being placed in a 16-bit or 32-bit destination.

Table 12-11. Encoding of Sign-Extend (s) Field

s	Effect on Immediate Data 8	Effect on Immediate Data 16 | 32
0	None	None
1	Sign-Extend Data 8 to Fill 16-bit or 32-bit Destination	None

12.2.3.7 Encoding of Conditional Test (tttn) Field

For the conditional instructions (conditional jumps and set on condition), tttn is encoded with n, indicating to use the condition (n=0) or its negation (n=1), and ttt, indicating the condition to test.

Table 12-12. Encoding of Conditional Test (tttn) Field

Mnemonic	Condition	tttn
O	Overflow	0000
NO	No Overflow	0001
B/NAE	Below/Not Above or Equal	0010
NB/AE	Not Below/Above or Equal	0011
E/Z	Equal/Zero	0100
NE/NZ	Not Equal/Not Zero	0101
BE/NA	Below or Equal/Not Above	0110
NBE/A	Not Below or Equal/Above	0111
S	Sign	1000
NS	Not Sign	1001
P/PE	Parity/Parity Even	1010
NP/PO	Not Parity/Parity Odd	1011
L/NGE	Less Than/Not Greater or Equal	1100
NL/GE	Not Less Than/Greater or Equal	1101
LE/NG	Less Than or Equal/Greater Than	1110
NLE/G	Not Less or Equal/Greater Than	1111

12.2.3.8 Encoding of Control or Debug or Test Register (eee) Field

This field is used for loading and storing the Control, Debug and Test registers.

Table 12-13. Encoding of Control or Debug or Test Register (eee) Field

eee Code	TTReg Name
When Interpreted as Control Register Field:	
000	CR0
010	CR2
011	CR3
When Interpreted as Debug Register Field:	
000	DR0
001	DR1
010	DR2
011	DR3
110	DR6
111	DR7
When Interpreted as Test Register Field:	
011	TR3
100	TR4
101	TR5
110	TR6
111	TR7

NOTE: Do not use any other encoding

12.2.4 Encoding of Floating-Point Instruction Fields

Instructions for the FPU assume one of the five forms shown in Table 12-14. In all cases, instructions are at least two bytes long and begin with the bit pattern 11011B.

Table 12-14. Encoding of Floating-Point Instruction Fields

	Instruction									Optional Fields	
	First Byte				Second Byte						
1	11011	OPA		1	mod		1	OPB	r/m	s-i-b	disp
2	11011	MF		OPA	mod		OPB		r/m	s-i-b	disp
3	11011	d	P	OPA	1	1	OPB		ST(i)		
4	11011	0	0	1	1	1	1	OP			
5	11011	0	1	1	1	1	1	OP			
	15–11	10	9	8	7	6	5	4 3 2 1 0			

OP = Instruction opcode, possible split into two fields OPA and OPB

MF = Memory Format
00–32-bit real
01–32-bit integer
10–64-bit real
11–16-bit integer

P = Pop
0–Do not pop stack
1–Pop stack after operation

d = Destination
0–Destination is ST(0)
1–Destination is ST(i)

R XOR d = 0–Destination (op) Source

R XOR d = 1–Source (op) Destination

ST(i) = Register stack element i
000 = Stack top
001 = Second stack element
111 = Eighth stack element

The mod (Mode field) and r/m (Register/Memory specifier) have the same interpretation as the corresponding fields of the integer instructions.

The s-i-b (Scale Index Base) byte and disp (displacement) are optionally present in instructions that have mod and r/m fields. Their presence depends on the values of mod and r/m, as for integer instructions.

12.3 CLOCK COUNT SUMMARY

To calculate elapsed time for an instruction, multiply the instruction clock count, as listed in Tables 12-15 through 12-19, by the processor core clock period (e.g., 10 ns for a 100-MHz IntelDX4 processor).

12.3.1 Instruction Clock Count Assumptions

The Intel486 processor instruction core clock count tables give clock counts assuming data and instruction accesses hit in the cache. The combined instruction and data cache hit rate is greater than 90%.

A cache miss forces the Intel486 processor to run an external bus cycle. The 32-bit burst bus is defined as r-b-w, where:

r = The number of bus clocks in the first cycle of a burst read or the number of clocks per data cycle in a non-burst read.

b = The number of bus clocks for the second and subsequent cycles in a burst read.

w = The number of bus clocks for a write.

The clock counts in the cache miss penalty column assume a 2-1-2 bus. For slower buses add r-2 clocks to the cache miss penalty for the first dword accessed. Other factors also affect instruction clock counts.

Instruction Clock Count Assumptions

1. The external bus is available for reads or writes at all times; otherwise, add bus clocks to reads until the bus is available.
2. Accesses are aligned. Add three core clocks to each misaligned access.
3. Cache fills complete before subsequent accesses to the same line. When a read misses the cache during a cache fill due to a previous read or pre-fetch, the read must wait for the cache fill to complete. When a read or write accesses a cache line still being filled, it must wait for the fill to complete.
4. When an effective address is calculated, the base register is not the destination register of the preceding instruction. When the base register is the destination register of the preceding instruction, add 1 to the core clock counts shown. Back-to-back PUSH and POP instructions are not affected by this rule.
5. An effective address calculation uses one base register and does not use an index register. However, when the effective address calculation uses an index register, one core clock may be added to the clock count shown.

6. The target of a jump is in the cache. If not, add r clocks for accessing the destination instruction of a jump. When the destination instruction is not completely contained in the first dword read, add a maximum of 3b bus clocks. When the destination instruction is not completely contained in the first 16 byte burst, add a maximum of r+3b bus clocks.
7. If no write buffer delay occurs, w bus clocks are added only when all write buffers are full.
8. Displacement and immediate must not be used together. If displacement and immediate are used together, one core clock may be added to the core clock count shown.
9. No invalidate cycles. Add a delay of one bus clock for each invalidate cycle if the invalidate cycle contends for the internal cache/external bus when the Intel486 processor needs to use it.
10. Page translation hits in TLB. A TLB miss adds 13, 21 or 28 bus clocks + 1 possible core clock to the instruction depending on whether the Accessed and/or Dirty bit in neither, one, or both of the page entries must be set in memory. This assumes that neither page entry is in the data cache and a page fault does not occur on the address translation.
11. No exceptions are detected during instruction execution. Refer to Table 12-17 for extra clocks when an interrupt is detected.
12. Instructions that read multiple consecutive data items (i.e., task switch, POPA, etc.) and miss the cache are assumed to start the first access on a 16-byte boundary. If not, an extra cache line fill may be necessary, which may add up to (r+3b) bus clocks to the cache miss penalty.

Table 12-15. Clock Count Summary (Sheet 1 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
INTEGER OPERATIONS				
MOV = Move:				
reg1 to reg2	1000 100w : 11 reg1 reg2	1		
reg2 to reg1	1000 101w : 11 reg1 reg2	1		
memory to reg	1000 100w : mod reg r/m	1	2	
Immediate to reg	1100 011w : 11000 reg : immediate data	1		
or	1011W reg : immediate data	1		
Immediate to Memory	1100 01w : mod 000 r/m : displacement immediate	1		
Memory to Accumulator	1010 000w : full displacement	1	2	
Accumulator to Memory	1010 001w : full displacement	1		
MOVSX/MOVZX = Move with Sign/Zero Extension				
reg2 to reg1	0000 1111 : 1011 z11w : 11 reg1 reg2	3		
memory to reg	0000 1111 : 1011 z11w : mod reg r/m	3	2	
z instruction 0 MOVZX 1 MOVSX				
PUSH = Push				
reg	1111 1111 : 11 110 reg	4		
or	01010 reg	1		
memory	1111 1111 : mod 110 r/m	4	1	1
immediate	0110 10s0 : immediate data	1		
PUSHA = Push All	0110 0000	11		
POP = Pop				
reg	1000 1111 : 11 000 reg	4	1	
or	01011 reg	1	2	
memory	1000 1111 : mod 000 r/m	5	2	1
POPA = Pop All	0110 0001	9	7/15	16/32
XCHG = Exchange				
reg1 with reg2	1000 011w : 11 reg1 reg2	3		2
Accumulator with reg	10010 reg	3		2
Memory with reg	1000 011w : mod reg r/m	5		2
NOP = No Operation	1001 0000	1		

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 2 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
LEA = Load EA to Register	1000 1101 : mod reg r/m			
no index register		1		
with index register		2		
Instruction ADD = Add ADC = Add with Carry AND = Logical AND OR = Logical OR SUB = Subtract SBB = Subtract with Borrow XOR = Logical Exclusive OR	TTT 000 010 100 001 101 011 110			
reg1 to reg2	00TT T00w : 11 reg1 reg2	1		
reg2 to reg1	00TT T01w : 11 reg1 reg2	1		
memory to register	00TT T01w : mod reg r/m	2	2	
register to memory	00TT T00w : mod reg r/m	3	6/2	U/L
immediate to register	1000 00sw : 11 TTT reg : immediate register	1		
immediate to Accumulator	00TT T10w : immediate data	1		
immediate to memory	1000 00sw : mod TTT r/m : immediate data	3	6/2	U/L
Instruction INC = Increment DEC = Decrement	TTT 000 001			
reg	1111 111w : 11 TTT reg	1		
or	01TTT reg	1		
memory	1111 111w : mod TTT r/m	3	6/2	U/L
Instruction NOT = Logical Complement NEG = Negate	TTT 010 011			
reg	1111 011w : 11 TTT reg	1		
memory	1111 011w : mod TTT r/m	3	6/2	U/L

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 3 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
CMP = Compare				
reg1 with reg2	0011 100w : 11 reg1 reg2	1		
reg2 with reg1	0011 101w : 11 reg1 reg2	1		
memory with register	0011 100w : mod reg r/m	2	2	
register with memory	0011 101w : mod reg r/m	2	2	
immediate with register	1000 00sw : 11 111 reg : immediate data	1		
immediate with acc.	0011 110w : immediate data	1		
immediate with memory	1000 00sw : mod 111 r/m : immediate data	2	2	
TEST = Logical Compare				
reg1 and reg2	1000 010w : 11 reg1 reg2	1		
memory and register	1000 010w : mod reg r/m	2	2	
immediate and register	1111 011w : 11 000 reg : immediate data	1		
immediate and acc.	1010100w : immediate data	1		
immediate and memory	1111 011w : mod 000 r/m : immediate data	2	2	
MUL = Multiply (unsigned)				
acc. with register	1111 011w : 11 100 reg			
Multiplier-Byte		13/18		MN/MX,3
Word		13/26		MN/MX,3
Dword		13/42		MN/MX,3
acc. with memory	1111 011w : mod 100 r/m			
Multiplier-Byte		13/18	1	MN/MX,3
Word		13/26	1	MN/MX,3
Dword		13/42	1	MN/MX,3

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 4 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
IMUL = Integer Multiply (unsigned)				
acc. with register	1111 011w : 11 101 reg			
Multiplier-Byte		13/18		MN/MX,3
Word		13/26		MN/MX,3
Dword		13/42		MN/MX,3
acc. with memory	1111 011w : mod 101 r/m			
Multiplier-Byte		13/18		MN/MX,3
Word		13/26		MN/MX,3
Dword		13/42		MN/MX,3
reg1 with reg2	0000 1111 : 10101111 : 11 reg1 reg2			
Multiplier-Byte		13/18		MN/MX,3
Word		13/26		MN/MX,3
Dword		13/42		MN/MX,3
register with memory	0000 1111 : 10101111 : mod reg r/m			
Multiplier-Byte		13/18	1	MN/MX,3
Word		13/26	1	MN/MX,3
Dword		13/42	1	MN/MX,3
reg1 with imm. to reg2	0110 10s1 : 11 reg1 reg2 : immediate data			
Multiplier-Byte		13/18		MN/MX,3
Word		13/26		MN/MX,3
Dword		13/42		MN/MX,3
mem. with imm. to reg.	0110 10s1 : mod reg r/m : immediate data			
Multiplier-Byte		13/18		MN/MX,3
Word		13/26		MN/MX,3
Dword		13/42		MN/MX,3

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 5 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
For the IntelDX4™ Processor Only:				
IMUL = Integer Multiply (signed)				
acc. with register	1111 011w : 11 101 reg			
Multiplier-Byte		5/5		MN/MX,3
Word		5/6		MN/MX,3
Dword		6/12		MN/MX,3
acc. with memory	1111 011w : mod 1 01 r/m			
Multiplier-Byte		5/5		MN/MX,3
Word		5/6		MN/MX,3
Dword		6/12		MN/MX,3
reg1 with reg2	0000 1111 : 1010 1111 : 11 reg1 reg2			
Multiplier-Byte		5/5		MN/MX,3
Word		5/6		MN/MX,3
Dword		6/12		MN/MX,3
register with memory	0000 1111 : 1010 1111 : mod reg r/m			
Multiplier-Byte		5/5		MN/MX,3
Word		5/6		MN/MX,3
Dword		6/12		MN/MX,3
reg1 with imm. to reg2	0110 10s1 : 11 reg1 reg2 : immediate data			
Multiplier-Byte		5/5		MN/MX,3
Word		5/6		MN/MX,3
Dword		6/12		MN/MX,3
mem. with imm. to reg.	0110 10s1 : mod reg r/m : immediate data			
Multiplier-Byte		5/5		MN/MX,3
Word		5/6		MN/MX,3
Dword		6/12		MN/MX,3
DIV = Divide (unsigned)				
acc. by register	1111 011w : 1111 0 reg			
Divisor-Byte		16		
Word		24		
Dword		40		
acc. by memory	1111 011w : mod 11 0 r/m			
Divisor-Byte		16		
Word		24		
Dword		40		

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 6 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
IDIV = Integer Divide (signed)				
acc. by register	1111 011w : 1111 1 reg			
Divisor-Byte		19		
Word		27		
Dword		43		
acc. by memory	1111 011w : mod 11 1 r/m			
Divisor-Byte		20		
Word		28		
Dword		44		
CBW = Convert Byte to Word	1001 1000	3		
CWD = Convert Word to Dword				
	1001 1001	3		

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 7 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
Instruction ROL = Rotate Left ROR = Rotate Right RCL = Rotate Through Carry Left RDR = Rotate Through Carry Right SHL/SAL = Shift Logical/ Arithmetic Left SHR = Shift Logical Right SAR = Shift Arithmetic Right	TTT 000 001 010 011 100 101 111			
Not Through Carry (ROL, ROR, SAR, SHL, and SHR)				
reg by 1	1101 000w : 11 TTT reg	3		
memory by 1	1101 000w : mod TTT r/m	4	6	
reg by CL	1101 001w : 11 TTT reg	3		
memory by CL	1101 001w : mod TTT r/m	4	6	
reg by immediate count	1100 000w : 11 TTT reg : imm. 8-bit data	2		
mem by immediate count	1100 000w : mod TTT r/m : imm. 8-bit data	4	6	
Through Carry (RCL and RCR)				
reg by 1	1101 000w : 11 TTT reg	3		
memory by 1	1101 000w : mod TTT r/m	4	6	
reg by CL	1101 001w : 11 TTT reg	8/30		MN/MX,4
memory by CL	1101 001w : mod TTT r/m	9/31		MN/MX,5
reg by immediate count	1100 000w : 11 TTT reg : imm. 8-bit data	8/30		MN/MX,4
mem by immediate count	1100 000w : mod TTT r/m : imm. 8-bit data	9/31		MN/MX,5
Instruction SHLD = Shift Left Double SHRD = Shift Right Double	**TTT** 100 101			
register with immediate	0000 1111 : 10TT T100 : 11 reg2 reg1 : imm. 8-bit data	2		
memory with immediate	0000 1111 : 10TT T100 : mod reg r/m : imm. 8-bit data	3	6	
register by CL	0000 1111 : 10TT T101 : 11 reg2 reg1	3		
memory by CL	0000 1111 : 10TT T101 : mod reg r/m	4	5	

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 8 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
BSWAP = Byte Swap	0000 1111 : 11001 reg	1		
XADD = Exchange and Add				
reg1, reg2	0000 1111 : 1100 000w : 11 reg2 reg1	3		
memory, reg	0000 1111 : 1100 000w : mod reg r/m	4	6/2	U/L
CMPXCHG = Compare and Exchange				
reg1, reg2	0000 1111 : 1011 000w : 11 reg2 reg1	6		
memory, reg	0000 1111 : 1011 000w : mod reg r/m	7/10	2	6
CONTROL TRANSFER (within segment)				
Note: Times are jump taken/not taken				
Jcccc = Jump on cccc				
8-bit displacementt	0111 tttn : 8-bit disp.	3/1		T/NT,23
full displacement	0000 1111 : 1000 tttn : full displacement	3/1		T/NT,23
Note: Times are jump taken/not taken				
SETcccc = Set Byte on cccc (Times are cccc true/false)				
reg	0000 1111 : 1001 tttn : 11 000 reg	4/3		
memory	0000 1111 : 1001 tttn : mod 0000 r/m	3/4		
Mnemonic cccc / Condition / tttn				
O — Overflow — 0000				
NO — No Overflow — 0001				
B/NAE — Below/Not Above or Equal — 0010				
NB/AE — Not Below/Above or Equal — 0011				
E/Z — Equal Zero — 0100				
NE/NZ — Not Equal/Not Zero — 0101				
BE/NA — Below or Equal/Not Above — 0110				
NBE/A — Not Below or Equal/Above — 0111				
S — Sign — 1000				
NS — Not Sign — 1001				
P/PE — Parity/Parity Even — 1010				
NP/PO — Not Parity/Parity Odd — 1011				
L/NGE — Less Than/Not Greater or Equal — 1100				
NL/GE — Not Less Than/Greater or Equal — 1101				
LE/NG — Less Than or Equal/Greater Than — 1110				
NLE/G — Not Less Than or Equal/Greater Than — 1111				
LOOP = LOOP CX Times	1110 0010 : 8-bit disp.	7/6		L/NL,23
LOOPZ/LOOPE = Loop with Zero/Equal				
	1110 0001 : 8-bit disp.	9/6		L/NL,23
LOOPNZ/LOOPNE = Loop While Not Zero				
	1110 0000 : 8-bit disp.	9/6		L/NL,23

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 9 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
JCXZ = Jump on CX Zero	1110 0011 : 8-bit disp.	8/5		T/NT,23
JECXZ = Jump on ECX Zero	1110 0011 : 8-bit disp.	8/5		T/NT,23
(Address Size Prefix Differentiates JCXZ for JECXZ)				
JMP = Unconditional Jump (within segment)				
Short	1110 1011 : 8-bit disp.	3		7,23
Direct	1110 1001 : full displacement	3		7,23
Register Indirect	1111 1111 : 11 100 reg	5		7,23
Memory Indirect	1111 1111 : mod 100 r/m	5	5	7
CALL = Call (within segment)				
Direct	1110 1000 : full displacement	3		7,23
Register Indirect	1111 1111 : 11 010 reg	5		7,23
Memory Indirect	1111 1111 : mod 010 reg	5	5	7
RET = Return from CALL (within segment)				
	1100 0011	5	5	
Adding Immediate to SP	1100 0010 : 16-bit disp.	5	5	
ENTER = Enter Procedure	1100 1000 : 16-bit disp., 8-bit level			
Level = 0		14		
Level = 1		17		
Level (L) > 1		17+3L		8
LEAVE = Leave Procedure	1100 1001	5	1	
MULTIPLE-SEGMENT INSTRUCTIONS				
MOV = Move				
reg. to segment reg.	1000 1110 : 11 sreg3 reg	3/9	0/3	RV/P,9
memory to segment reg.	1000 1110 : mod sreg3 r/m	3/9	2/5	RV/P,9
segment reg. to reg.	1000 1100 : 11 sreg3 reg	3		
segment reg. to memory	1000 1100 : mod sreg3 r/m	3		
PUSH = Push				
segment reg. (ES, CS, SS, or DS)	000sreg 2110	3		
segment reg. (FS or GS)	0000 1111 : 10 sreg3001	3		

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 10 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
POP = Pop				
segment reg. (ES, CS, SS, or DS)	000sreg 2111	3/0	2/5	RV/P,9
segment reg. (FS or GS)	0000 1111 : 10 sreg3001	3/9	2/5	RV/P,9
LDS = Load Pointer to DS	1100 0101 : mod reg r/m	6/12	7/10	RV/P,9
LES = Load Pointer to ES	1100 0100 : mod reg r/m	6/12	7/10	RV/P,9
LFS = Load Pointer to FS	0000 1111 : 1011 0100 : mod reg r/m	6/12	7/10	RV/P,9
LGS = Load Pointer to GS	0000 1111 : 1011 0101 : mod reg r/m	6/12	7/10	RV/P,9
LSS = Load Pointer to SS	0000 1111 : 1011 0010 : mod reg r/m	6/12	7/10	RV/P,9
CALL = Call				
Direct intersegment	1001 1010 : unsigned full offset, selector	18	2	R,7,22
to same level		20	3	P,9
thru Gate to same level		35	6	P,9
to inner level, no parameters		69	17	P,9
to inner level, x parameters (d) words		77+4X	17+n	P,11,9
to TSS		37+TS	3	P,10,9
thru Task Gate		38+TS	3	P,10,9,
Indirect intersegment	1111 1111 : mod 011 r/m	17	8	R,7
to same level		20	10	P,9
thru Gate to same level		35	13	P,9
to inner level, no parameters		69	24	P,9
to inner level, x parameters (d) words		77+4X	24+n	P,11,9
to TSS		37+TS	10	P,10,9
thru Task Gate		38+TS	10	P,10,9,
RET = Return from CALL				
intersegment	1100 1010	13	8	R,7
to same level		17	9	P,9
to outet lever		35	12	P,9
intersegment adding imm. to SP	1100 1010 : 16-bit disp.	14	8	R,7
to same level		18	9	P,9
to outer level		36	12	P,9

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 11 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
JMP = Unconditional Jump				
Direct intersegment	1110 1010 : unsigned full offset, selector	17	2	R,7,22
to same level		19	3	P,9
thru Call Gate to same level		32	6	P,9
thru TSS		42+TS	3	P,10,9
thru Task Gate		43+TS	3	P,10,9,
Indirect intersegment	1111 1111 : mod 011 r/m	13	9	R,7,9
to same level		18	10	P,9
thru Call Gate to same level		31	13	P,9
thru TSS		41+TS	10	P,10,9
thru Task Gate		42+TS	10	P,10,9,
BIT MANIPULATION				
BT = Test Bit				
register, immediate	0000 1111 : 1011 1010 : 11 100 reg : imm. 8-bit data	3		
memory, immediate	0000 1111 : 1011 1010 : mod 100 r/m : imm. 8-bit data	3	1	
reg1, reg2	0000 1111 : 1010 0011 : 11 reg2 reg1	3		
memory, reg	0000 1111 : 1010 0011 : mod reg r/m	8	2	
Instruction BTS = Test Bit and Set BTR = Test Bit and Reset BTC = Test Bit and Compliment	TTT 101 110 111			
register, immediate	0000 1111 : 1011 1010 : 11 TTT reg imm. 8-bit data	6		
memory, immediate	0000 1111 : 1011 1010 : mod TTT r/m imm. 8-bit data	8		U/L
reg1, reg2	0000 1111 : 10TT T011 : 1 1 reg2 reg1	6		
memory, reg	0000 1111 : 10TT T011 : mod reg r/m	13		U/L
BSF = Scan Bit Forward				
reg1, reg2	0000 1111 : 1011 1100 : 11 reg2 reg1	6/42		MN/MX, 12
memory, reg	0000 1111 : 1011 1100 : mod reg r/m	7/43	2	MN/MX, 15
BSR = Scan Bit Reverse				
reg1, reg2	0000 1111 : 1011 1101 : 11 reg2 reg1	6/103		MN/MX, 14
memory, reg	0000 1111 : 1011 1101 : mod reg r/m	7/104	1	MN/MX, 15

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 12 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
STRING INSTRUCTIONS				
CMPS = Compare Byte Word	1010 011w	8	6	16
LODS = Load Byte/Word to AL/AX/EAX				
	1010 111w	5	2	
MOVS = Move Byte/Word	1010 010w	7	2	16
SCAS = Scan Byte/Word	1010 111w	6	2	
STOS = Store Byte/Word from AL/AX/EX				
	1010 101w	5		
XLAT = Translate String	1101 0111	4	2	
REPEATED STRING INSTRUCTIONS Repeated by Count in CX or ECX (C=Count in CX or ECX)				
REPE CMPS = Compare String (Find Non-match)	1111 0011 : 1010 011w			
C = 0		5		16, 17
C > 0		7+7c		
REPNE CMPS = Compare String (Find Match)	1111 0010 : 1010 011w			
C = 0		5		16, 17
C > 0		7+7c		
REP LODS = Load String	1111 0010 : 1010 110w			
C = 0		5		16, 18
C > 0		7+4c		
REP MOVS = Move String	1111 0010 : 1010 010w			
C = 0		5	1	16
C = 1		13		16,19
C > 1		12+3c		
REPE SCAS = Scan String (Find Non-AL/AX/EAX)	1111 0011 : 1010 111w			
C = 0		5		
C > 0		7+5c		20
REPNE SCAS = Scan String (Find AL/AX/EAX)	1111 0010 : 1010 111w			
C = 0		5		
C > 0		7+5c		20

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 13 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
REP STOS = Store String	1111 0010 : 1010 101w			
C = 0		5		
C > 0		7+4c		
FLAG CONTROL				
CLC = Clear Carry Flag	1111 1000	2		
STC = Set Carry Flag	1111 1001	2		
CMC = Complement Carry Flag	1111 0101	2		
CLD = Clear Direction Flag	1111 1100	2		
STD = Set Direction Flag	1111 1101	2		
CLI = Clear Interrupt Enable Flag	1111 1010	5		
STI = Set Interrupt Enable Flag	1111 1011	5		
LAHF = Load AH into Flag	1001 1111	3		
FLAG CONTROL				
SAHF = Store AH into Flag	1001 1110	2		
PUSHF = Push Flags	1001 1100	4/3		RV/P
POFF = Pop Flags	1001 1101	9/6		RV/P
DECIMAL ARITHMETIC				
AAA = ASCII Adjust to Add	0011 0111	3		
AAS = ASCII Adjust for Subtract	0011 1111	3		
AAM = ASCII Adjust for Multiply	1101 0100 : 0000 1010	15		
AAD = ASCII Adjust for Divide	1101 0101 : 0000 1010	14		
DAA = Decimal Adjust for Add	0010 0111	2		
DAS = Decimal Adjust for Subtract	0010 1111	2		
PROCESSOR CONTROL INSTRUCTIONS				
HLT = Halt	1111 0100	4		

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 14 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
MOV = Move To and From Control/Debug/Test Registers				
CR0 from register	0000 1111 : 0010 0010 : 11 000 reg	17	2	
CR2/CR3 from register	0000 1111 : 0010 0010 : 11 eee reg	4		
Reg from CR0-3	0000 1111 : 0010 0000 : 11 eee reg	4		
DR0-3 from register	0000 1111 : 0010 0011 : 11 eee reg	10		
DR6-7 from register	0000 1111 : 0010 0011 : 11 eee reg	10		
Register from DR6-7	0000 1111 : 0010 0001 : 11 eee reg	9		
Register from DR0-3	0000 1111 : 0010 0001 : 11 eee reg	9		
TR3 from register	0000 1111 : 0010 0110 : 11 011 reg	4		
TR4-7 from register	0000 1111 : 0010 0110 : 11 eee reg	4		
Register from TR3	0000 1111 : 0010 0100 : 11 011 reg	3		
Register from TR4-7	0000 1111 : 0010 0100 : 11 eee reg	4		
CPUID = CPU Identification	0000 1111 : 1010 0010			
EAX = 1 EAX = 0, >1		14 9		
CLTS = Clear Task Switched Flag	0000 1111 : 0000 0110	7	2	
INVD = Invalidate Data Cache	0000 1111 : 0000 1000	4		
WBINVD = Write-Back and Invalidate Data Cache	0000 1111 : 0000 1001	5		
INVLPG = Invalidate TLB Entry				
INVLPG memory	0000 1111 : 0000 0001 : mod 111 r/m	12/11		H/NH
PREFIX BYTES				
Address Size Prefix	0110 0111	1		
LOCK = Bus Lock Prefix	1111 0000	1		
Operand Size Prefix	0110 0110	1		
Segment Override Prefix				
CS:	0010 1110	1		
DS:	0011 1110	1		
ES:	0010 0110	1		
FS:	0110 0100	1		
GS:	0110 0101	1		
SS:	0011 0110	1		

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 15 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
PROTECTION CONTROL				
ARPL = Adjust Requested Privilege Level				
From register	0110 0011 : 11 reg1 reg2	9		
From memory	0110 0011 : mod reg r/m	9		
LAR = Load Access Rights				
From register	0000 1111 : 0000 0010 : 11 reg1 reg2	11	3	
From memory	0000 1111 : 0000 0010 : mod reg r/m	11	5	
LGDT = Load Global Descriptor				
Table register	0000 1111 : 0000 0001 : mod 010 r/m	12	5	
LIDT = Load Interrupt Descriptor				
Table register	0000 1111 : 0000 0001 : mod 011 r/m	12	5	
LLDT = Load Local Descriptor				
Table register from reg.	0000 1111 : 0000 0000 : 11 010 reg	11	3	
Table register from mem.	0000 1111 : 0000 0000 : mod 010 r/m	11	6	
LMSW = Load Machine Status Word				
From register	0000 1111 : 0000 0001 : 11 110 reg	13		
From memory	0000 1111 : 0000 0001 : mod 110 r/m	13	1	
LSL = Load Segment Limit				
From register	0000 1111 : 0000 0011 : 11 reg1 reg2	10	3	
From memory	0000 1111 : 0000 0011 : mod reg r/m	10	6	
LTR = Load Task Register				
From register	0000 1111 : 0000 0000 : 11 011 reg	20		
From memory	0000 1111 : 0000 0000 : mod 011 r/m	20		
SGDT = Store Global Descriptor Table				
	0000 1111 : 0000 0001 : mod 000 r/m	10		
SIDT = Store Interrupt Descriptor Table				
	0000 1111 : 0000 0001 : mod 001 r/m	2		
SLDT = Store Local Descriptor Table				
To register	0000 1111 : 0000 0000 : 11 000 reg	2		
To memory	0000 1111 : 0000 0001 : mod 000 r/m	3		
SMSW = Store Machine Status Word				
To register	0000 1111 : 0000 0001 : 11 000 reg	2		
To memory	0000 1111 : 0000 0001 : mod 100 r/m	3		

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 16 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
STR = Store Task Register				
To register	0000 1111 : 0000 0000 : 11 001 r/m	2		
To memory	0000 1111 : 0000 0000 : mod 001 r/m	3		
VERR = Verify Read Access				
Register	0000 1111 : 0000 0000 : 11 100 r/m	11	3	
Memory	0000 1111 : 0000 0000 : mod 100 r/m	11	7	
VERW = Verify Write Access				
To register	0000 1111 : 0000 0000 : 11 101 r/m	11	3	
To memory	0000 1111 : 0000 0000 : mod 101 r/m	11	7	
INTERRUPT INSTRUCTIONS				
INTn = Interrupt Type n	1100 1101 : type	INT+ 4/0		RV/P, 21
INT3 = Interrupt Type 3	1100 1100	INT+0		21
INTO = Interrupt 4 if Overflow Flag Set				
	1100 1110			
Taken		INT+2		21
Not Taken		3		21

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-15. Clock Count Summary (Sheet 17 of 17)

Instruction	Format	Cache Hit	Penalty if Cache Miss	Notes
BOUND = Interrupt 5 if Detect Value Out Range				
	0110 0010 : mod reg r/m			
If in range		7	7	21
If out of range		INT+ 24	7	21
IRET = Interrupt Return	1100 1111			
Real Mode/Virtual Mode		15	8	
Protected Mode				
To same level		20	11	9
To outer level		36	19	9
To nested task		TS+32	4	9,10
(EFLAGS.NT=1)				
RSM = Exit System Management Mode				
	0000 1111 : 1010 1010			
SMBASE Relocation		452		
Auto HALT Restart		456		
I/O Trap Restart		465		
External Interrupt		INT+ 11		21
NMI = Non-Maskable Interrupt		INT+3		21
Page Fault		INT+ 24		21
VM86 Exceptions				
CLK		INT+8		21
STI		INT+8		21
INTn		INT+9		
PUSHF		INT+9		21
POPF		INT+8		21
IRET		INT+9		
IN				
Fixed Port		INT+50		21
Variable Port		INT+51		21
OUT				
Fixed Port		INT+50		21
Variable Port		INT+51		21
INS		INT+50		21
OUTS		INT+50		21
REP INS		INT+51		21
REPOUTS		INT+51		21

NOTE: See Table 12-18 for notes and abbreviations for items in this table.

Table 12-16. Task Switch Clock Counts

Method	Value for TS	
	Cache Hit	Miss Penalty
VM/Intel486™ processor/286 TSS to Intel486 processor TSS	162	55
VM/Intel486 processor/286 TSS to 286 TSS	144	31

NOTE: See Table 12-18 for definitions and notes for items in this table.

Table 12-17. Interrupt Clock Counts

Method	Value for INT		
	Cache Hit	Miss Penalty	Notes
Real Mode	26	2	
Protected Mode			
Interrupt/Trap gate, same level	44	6	9
Interrupt/Trap gate, different level	71	17	9
Task Gate	37 + TS	3	9, 10
Virtual Mode			
Interrupt/Trap gate, different level	82	17	
Task Gate	37 + TS	3	10

NOTE: See Table 12-18 for definitions and notes for items in this table.

Table 12-18. Notes and Abbreviations (for Tables 12-15 through 12-17) (Sheet 1 of 2)

The following abbreviations are used in Tables 12-15 through 12-17:	
Abbreviation	**Definition**
16/32	16/32 bit modes
U/L	unlocked/locked
MN/MX	minimum/maximum
L/NL	loop/no loop
RV/P	real and virtual mode/protected mode
R	real mode
P	protected mode
T/NT	taken/not taken
H/NH	hit/no hit

Table 12-18. Notes and Abbreviations (for Tables 12-15 through 12-17) (Sheet 2 of 2)

The following notes refer to Tables 12-15 through 12-17
1. Assuming that the operand address and stack address fall in different cache sets.
2. Always locked, no cache hit case.
3. Clocks= 10 + max($\log_2$(|m|),n)
4. Clocks = {quotient(count/operand length)}*7+9 = 8 if count ≤ operand length (8/16/32)
5. Clocks = {quotient(count/operand length)}*7+9 = 9 if count ≤ operand length (8/16/32)
6. Equal/not equal cases (penalty is the same regardless of lock)
7. Assuming that addresses for memory read (for indirection), stack puch/pop and branch fall in different cache sets.
8. Penalty for cache miss: add 6 clocks for every 16 bytes copied to new stack frame.
9. Add 11 clocks for each unaccessed descriptor load.
10. Refer to task switch clock counts table for value of TS.
11. Add 4 extra clocks to the cache miss penalty for each 16 bytes.
For notes 12-13:b=0-3, non-zero byte number); (i=0-1, non-zero nibble number); (n=0-3, non-bit number in nibble);
12. Clocks = 8 + 4 (b+1) + 3(i+1) + 3(n+1) = 6 if second operand = 0
13. Clocks = 9 + 4 (b+1) + 3(i+1) + 3(n+1) = 7 if second operand = 0
For notes 14-15:(n=bit position 0-31)
14. Clocks = 7 + 3(32-n) = 6 if second operand = 0
15. Clocks = 8 + 3(32-n) = 7 if second operand = 0
16. Assuming that the two string addresses fall in different cache sets.
17. Cache miss penalty: add 6 clocks for every 16 bytes compared. Entire penalty on first compare.
18. Cache miss penalty: add 2 clocks for every 16 bytes of data. Entire penalty on first load.
19. Cache miss penalty: add 4 clocks for every 16 bytes moved (1 clock for the first operation and 3 for the second).
20. Cache miss penalty: add 4 clocks for every 16 bytes scanned (2 clocks each for first and second operations).
21. Refer to interrupt clock counts table for value of INT.
22. Clock count includes one clock for using both displacement and immediate.
23. Refer to assumption 6 in the case of a cache miss.
24. Virtual Mode Extensions are disabled.
25. Protected Virtual Interrupts are disabled.

Table 12-19. I/O Instructions Clock Count Summary

Instruction	Format	Real Mode	Protected Mode (CPL≤IOPL)	Protected Mode (CPL>IOPL)	Virtual 86 Mode	Notes
IN = Input from:						
Fixed Port	1110 010w : port number	14	9	29	27	
Variable Port	1110 110w	14	8	28	27	
OUT = Output to:						
Fixed Port	1110 011w : port number	16	11	31	29	
Variable Port	1110 110w	16	10	30	29	
INS = Input Byte/Word from DX Port						
	0110 110w	17	10	32	30	
OUTS = Output Byte/Word to DX Port						
	0110 111w	17	10	32	30	1
REP INS = Input String						
	1111 0010 : 0110 110w	16+8c	10+8c	30+8c	29+8c	2
REP OUTS = Output String						
	1111 0010 : 0110 111w	17+5c	11+5c	31+5c	30+5c	3

NOTES:
1. Two clock cache miss penalty in all cases.
2. c = count in CX or ECX.
3. Cache miss penalty in all modes: Add two clocks for every 16 bytes. Entire penalty on second operation.

Table 12-20. Floating-Point Clock Count Summary (Sheet 1 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
DATA TRANSFER					
FLD = Real Load to ST(0)					
32-bit memory	11011 001 : mod 000 r/m : s-i-b/disp.	3	2		
64-bit memory	11011 101 : mod 000 r/m : s-i-b/disp.	3	3		
80-bit memory	11011 011 : mod 101 r/m : s-i-b/disp.	6	4		
ST(i)	11011 001 : 11000 ST(i)	4			
FILD = Integer Load to ST(0)					
16-bit memory	11011 111 : mod 000 r/m : s-i-b/disp.	14.5(13-16)	2	4	
32-bit memory	11011 011 : mod 000 r/m : s-i-b/disp.	11.5(9-12)	2	4(2-4)	
64-bit memory	11011 111 : mod 101 r/m : s-i-b/disp.	16.8(10-18)	3	7.8(2-8)	
FBLD = BCD Load to ST(0)					
	11011 111 : mod 100 r/m : s-i-b/disp.	75(70-103)	4	7.7(2-8)	
FST = Store Real from ST(0)					
32-bit memory	11011 011 : mod 010 r/m : s-i-b/disp.	7			1
64-bit memory	11011 101 : mod 010 r/m : s-i-b/disp.	8			2
ST(i)	11011 101 : 11001 ST(i)	3			
FSTP = Store Real from ST(0) and Pop					
32-bit memory	11011 011 : mod 011 r/m : s-i-b/disp.	7			1
64-bit memory	11011 101 : mod 011 r/m : s-i-b/disp.	8			2
80-bit memory	11011 011 : mod 111 r/m : s-i-b/disp.	6			
ST(i)	11011 101 : 11001 ST(i)	3			
FIST = Store Integer from ST(0)					
16-bit memory	11011 111 : mod 010 r/m : s-i-b/disp.	33.4(29-34)			

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 2 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
32-bit memory	11011 011 : mod 010 r/m : s-i-b/disp.	32.4(28-34)			
FISTP = Store Integer from ST(0) and Pop					
16-bit memory	11011 111 : mod 011 r/m : s-i-b/disp.	33.4(29-34)			
32-bit memory	11011 011 : mod 011 r/m : s-i-b/disp.	33.4(29-34)			
64-bit memory	11011 111 : mod 111 r/m : s-i-b/disp.	33.4(29-34)			
FBSTP = Store BCD from ST(0) and Pop					
	11011 111 : mod 110 r/m : s-i-b/disp.	175(172-176)			
FXCH = Exchange ST(0) and ST(i)					
	11011 001 : 11001 ST(i)	4			
COMPARISON INSTRUCTIONS					
FCOM = Compare ST(0) with Real					
32-bit memory	11011 000 : mod 010 r/m : s-i-b/disp.	4	2	1	
64-bit memory	11011 100 : mod 010 r/m : s-i-b/disp.	4	3	1	
ST(i)	11011 000 : 11010 ST(i)	4			
FCOMP = Compare ST(0) with Real and Pop					
32-bit memory	11011 000 : mod 011 r/m : s-i-b/disp.	4	2	1	
64-bit memory	11011 100 : mod 011 r/m : s-i-b/disp.	4	3	1	
ST(i)	11011 000 : 11011 ST(i)	4		1	
FCOMPP = Compare ST(0) with ST(1) and Pop Twice					
	11011 110 : 1101 1001	5		1	
FICOM = Compare ST(0) with Integer					
16-bit memory	11011 110 : mod 010 r/m : s-i-b/disp.	18(16-20)	2	1	
32-bit memory	11011 010 : mod 010 r/m : s-i-b/disp.	16.5(15-17)	2	1	
FICOMP = Compare ST(0) with Integer					
16-bit memory	11011 110 : mod 011 r/m : s-i-b/disp.	18(16-20)	2	1	

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 3 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
32-bit memory	11011 010 : mod 011 r/m : s-i-b/disp.	16.5(15-17)	2	1	
FTST = Compare ST(0) with 0.0					
	11011 011 : 1110 0100	4		1	
FUCOM = Unordered compare ST(0) with ST(i)					
	11011 101 : 11100 ST(i)	4		1	
FUCOMP = Unordered compare ST(0) with ST(i) and Pop					
	11011 101 : 11101 ST(i)	4		1	
FUCOMPP = Unordered compare ST(0) with ST(1) and Pop Twice					
	11011 101 : 11101 1001	5		1	
FXAM = Examine ST(0)					
	11011 001 : 1110 0101	8			
CONSTANTS					
FLDZ = Load +0.0 Into ST(0)					
	11011 001 : 1110 1110 :	4			
FLD1 = Load +1.0 Into ST(0)					
	11011 001 : 1110 1000 :	4			
FLDP1 = Load π Into ST(0)					
	11011 001 : 1110 1011 :	8		2	
FLDL2T = Load log2(10) Into ST(0)					
	11011 001 : 1110 1001 :	8		2	
FLDL2E = Load log2(e) Into ST(0)					
	11011 001 : 1110 1010 :	8		2	
FLDLG2 = Load log10(2) Into ST(0)					
	11011 001 : 1110 1100 :	8		2	

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 4 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range-Upper Range)	Notes
FLDLN2 = Load loge(2) Into ST(0)					
	11011 001 : 1110 1101 :	8		2	
ARITHMETIC					
FADD = Add Real with ST(0)					
ST(0)←ST(0) + 32-bit memory					
	11011 000 : mod 000 r/m : s-i-b/disp.	10(8-20)	2	7(5-17)	
ST(0)←ST(0) + 64-bit memory					
	11011 100 : mod 000 r/m : s-i-b/disp.	10(8-20)	3	7(5-17)	
ST(d)←ST(0) + ST(i)					
	11011 d00 : 11000 ST(i)	10(8-20)		7(5-17)	
FADDP = Add real with ST(0) and Pop (ST(i)← ST(0) +ST(i))					
	11011 110 : 11000 ST(i) :	10(8-20)		7(5-17)	

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 5 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
ARITHMETIC (Cont'd.)					
FSUB = Subtract Real from ST(0)					
ST(0)←ST(0) – 32-bit memory					
	11011 000 : mod 100 r/m : s-i-b/disp.	10(8-20)	2	7(5-17)	
ST(0)←ST(0) – 64-bit memory					
	11011 100 : mod 100 r/m : s-i-b/disp.	10(8-20)	3	7(5-17)	
ST(d)←ST(0) – ST(i)					
	11011 d00 : 11001 ST(i)	10(8-20)		7(5-17)	
FSUBP = Subtract real from ST(0) and Pop (ST(i)← ST(0) -ST(i))					
	11011 110 : 11001 ST(i)	10(8-20)		7(5-17)	
FSUBR = Subtract Real reversed (Subtract ST(0) from Real)					
ST(0)←32-bit memory – ST(0)					
	11011 000 : mod 101 r/m : s-i-b/disp.	10(8-20)	2	7(5-17)	
ST(0)←64-bit memory – ST(0)					
	11011 100 : mod 101 r/m : s-i-b/disp.	10(8-20)	3	7(5-17)	
ST(d)←ST(i) – ST(0)					
	11011 d00 : 11001 ST(i)	10(8-20)		7(5-17)	
FSUBRP = Subtract Real reversed and Pop (ST(i)← ST(i) -ST(0))					
	11011 110 : 11100 ST(i)	10(8-20)		7(5-17)	
FMUL = Multiply Real with ST(0)					
ST(0)←ST(0) X 32-bit memory					
	11011 000 : mod 001 r/m : s-i-b/disp.	11	2	8	
ST(0)←ST(0) X 64-bit memory					

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 6 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
	11011 100 : mod 001 r/m : s-i-b/disp.	14	3	11	
ST(d)←ST(0) X ST(i)					
	11011 d00 : 11001 ST(i)	16		13	
FMULP = Multiply ST(0) with ST(i) and Pop (ST(i)← ST(0) XST(i))					
	11011 110 : 11001 ST(i)	16		13	
FDIV = Divide ST(0) by Real					
ST(0)←ST(0)/ 32-bit memory					
	11011 000 : mod 110 r/m : s-i-b/disp.	73	2	70	3
ST(0)←ST(0)/ 64-bit memory					
	11011 100 : mod 110 r/m : s-i-b/disp.	73	3	70	3
ST(d)←ST(0)/ ST(i)					
	11011 d00 : 11111 ST(i)	73		70	3
FDIVP = Divide ST(0) by ST(i) and Pop (ST(i)← ST(0)/ ST(i))					
	11011 110 : 11111 ST(i)	73		70	3
FDIVR = Divide real reversed (Real/ST(0))					
ST(0)← 32-bit memory/ ST(0)					
	11011 000 : mod 111 r/m : s-i-b/disp.	73	2	70	3
ST(0)← 64-bit memory/ ST(0)					
	11011 100 : mod 111 r/m : s-i-b/disp.	73	3	70	3
ST(d)← ST(i)/ ST(0)					
	11011 d00 : 11110 ST(i)	73		70	3
FDIVRP = Divide real reversed and Pop (ST(i)← ST(i)/ ST(0))					
	11011 110 : 11110 ST(i)	73		70	3

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 7 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
FIADD = Add Integer to ST(0)					
ST(0)←ST(0) + 16-bit memory					
	11011 110 : mod 000 r/m : s-i-b/disp.	24(20-35)	2	7(5-17)	
ST(0)←ST(0) + 32-bit memory					
	11011 010 : mod 000 r/m : s-i-b/disp.	22.5(19-32)	2	7(5-17)	
FISUB = Subtract Integer from ST(0)					
ST(0)←ST(0) – 16-bit memory					
	11011 110 : mod 100 r/m : s-i-b/disp.	24(20-35)	2	7(5-17)	
ST(0)←ST(0) – 32-bit memory					
	11011 010 : mod 100 r/m : s-i-b/disp.	22.5(19-32)	2	7(5-17)	
FISUBR = Integer Subtract Reversed					
ST(0)←16-bit memory-ST(0)					
	11011 110 : mod 101 r/m : s-i-b/disp.	24(20-35)	2	7(5-17)	
ST(0)←32-bit memory-ST(0)					
	11011 010 : mod 101 r/m : s-i-b/disp.	22.5(19-32)	2	7(5-17)	
FIMUL = Multiply Integer with ST(0)					
ST(0)←ST(0) X 16-bit memory					
	11011 110 : mod 101 r/m : s-i-b/disp.	25(23-27)	2	8	
ST(0)←ST(0) X 32-bit memory					
	11011 010 : mod 001 r/m : s-i-b/disp.	23.5(19-32)	2	8	
FIDIV = Integer Divide					
ST(0)←ST(0)/ 16-bit memory					
	11011 110 : mod 110 r/m : s-i-b/disp.	87(85-89)	2	70	3
ST(0)←ST(0)/ 32-bit memory					
	11011 010 : mod 110 r/m : s-i-b/disp.	85.5(84-86)	2	70	3

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 8 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range-Upper Range)	Notes
FIDVR = Integer Divide Reversed					
ST(0)←16-bit memory/ST(0)					
	11011 110 : mod 111 r/m : s-i-b/disp.	87(85-89)	2	70	3
ST(0)←32-bit memory/ST(0)					
	11011 010 : mod 111 r/m : s-i-b/disp.	85.5(84-86)	2	70	3
FSQRT = Square Root					
	11011 001 : 1111 1010	85.5(83-87)		70	
FSCALE = Scale ST(0) by ST(1)					
	11011 001 : 1111 1101	31(30-32)		2	
FXTRACT = Extract Components of ST(0)					
	11011 001 : 1111 0100	19(16-20)		4(2-4)	
FPREM = Partial Reminder					
	11011 001 : 1111 1000	84(70-138)		2(2-8)	
FPREM1 = Partial Reminder (IEEE)					
	11011 001 : 1111 0101	94.5(72-167)		5.5(2-18)	

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 9 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
FRNDINT = Round ST(0) to Integer	11011 001 : 1111 1100	29.1(21-30)		7.4(2-8)	
FABS = Absolute value of ST(0)	11011 001 : 1110 0001	3			
FCHS = Change Sign of ST(0)	11011 001 : 1110 0000	6			
TRANSCENDENTAL					
FCOS = Cosine of ST(0)	11011 001 : 1111 1111	241(193-279)		2	6,7
FPTAN = Partial Tangent of ST(0)	11011 001 : 1111 0010	244(200-273)		70	6,7
FPATAN = Partial Arctangent	11011 001 : 1111 0011	289(218-303)		5(2-17)	6
FSIN = Sine of ST(0)	11011 001 : 1111 1110	241(193-279)		2	6,7
FSINCOS = Sine and Cosine of ST(0)	11011 001 : 1111 1011	291(243-329)		2	6,7
F2XM1 = 2ST(0)-1	11011 001 : 1111 0000	242(140-279)		2	6
FYL2X = ST(1) x log2(ST(0))	11011 001 : 1111 0001	311(196-329)		13	6
FYL2XP1 = ST(1) x log2(ST(0) + 1.0)	11011 001 : 1111 1001	313(171-326)		13	6
PROCESSOR CONTROL					
FINIT = Initialize FPU					

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 10 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range-Upper Range)	Notes
	11011 001 : 1110 0011	17			4
FSTSW AX = Store status word into AX					
	11011 111 : 1110 0000	3			5
FSTSW = Store status word into memory					
	11011 101 : mod 111 r/m : s-i-b/disp.	3			5

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 11 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
FLDCW = Load control word					
	11011 001 : mod 101 r/m : s-i-b/disp.	4	2		
FSTCW = Store control word					
	11011 001 : mod 111 r/m : s-i-b/disp.	3			5
FCLEX = Clear exceptions					
	11011 011 : 1110 0010	7			4
FSTENV = Store environment					
	11011 011 : mod 110 r/m : s-i-b/disp.				
Real and Virtual Modes 16-bit address		67			4
Real and Virtual Modes 32-bit address		67			4
Protected Mode 16-bit address		56			4
Protected Mode 32-bit address		56			4
FLDENV = Load Environment					
	11011 011 : mod 100 r/m : s-i-b/disp.				
Real and Virtual Modes 16-bit address		44	2		
Real and Virtual Modes 32-bit address		44	2		
Protected Mode 16-bit address		34	2		
Protected Mode 32-bit address		34	2		
FSAVE = Save State					
	11011 101 : mod 110 r/m : s-i-b/disp.				
Real and Virtual Modes 16-bit address		154			4
Real and Virtual Modes 32-bit address		154			4
Protected Mode 16-bit address		143			4
Protected Mode 32-bit address		143			4
FRSTOR = Restore State					
	11011 101 : mod 100 r/m : s-i-b/disp.				

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Table 12-20. Floating-Point Clock Count Summary (Sheet 12 of 12)

Instruction	Format	Cache Hit Avg (Lower Range... Upper Range)	Penalty if Cache Miss	Concurrent Execution Avg (Lower Range- Upper Range)	Notes
Real and Virtual Modes 16-bit address Real and Virtual Modes 32-bit address Protected Mode 16-bit address Protected Mode 32-bit address		131 131 120 120	23 27 23 27		
FINCSTP = Increment Stack Pointer	11011 001 : 1111 0111	3			
FDECSTP = Decrement Stack Pointer	11011 001 : 1111 0110	3			
FFREE = Free ST(i)	11011 101 : 11000 ST(i)	3			
FNOP = No Operations	11011 101 : 1101 0000	3			
WAIT = Wait until FPU ready (min/max)					

NOTES:
1. If operand is 0 clock counts = 27.
2. If operand is 0 clock counts = 28.
3. If CW.PC indicates 24 bit precision then subtract 38 clocks.
   If CW.PC indicates 53 bit precision then subtract 11 clocks.
4. If there is a numeric error pending from a previous instruction, add 17 clocks.
5. If there is a numeric error pending from a previous instruction, add 18 clocks.
6. The INT pin is polled several times while this function is executing to ensure short interrupt latency.
7. If ABS(operand) is greater than $\pi/4$ then add n clocks, where n=(operand/(π/4)).

Appendixes

Contents

APPENDIX A
SIGNAL DESCRIPTIONS

For pin diagrams and pin locations, refer to the individual processor datasheets.

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 1 of 8)

Symbol	Type	Name and Function
CLK	I	**Clock** provides the fundamental timing and the internal operating frequency for the Intel486 processor. All external timing parameters are specified with respect to the rising edge of CLK.
		ADDRESS BUS
A[31:4], A[3:2]	I/O O	The **Address Lines** A[31:2], together with the byte enables signals BE[3:0]#, define the physical area of memory or input/output space accessed. Address lines A[31:4] are used to drive addresses to the processor to perform cache line invalidations. Input signals must meet setup and hold times t_{22} and t_{23}. A[31:2] are not driven during bus or address hold.
BE[3:0]#	O	The **Byte Enable** signals indicate active bytes during read and write cycles. During the first cycle of a cache fill, the external system should assume that all byte enables are active. BE3# applies to D[31:24], BE2# applies to D[23:16], BE1# applies to D[15:8] and BE0# applies to D[7:0]. BE[3:0]# are active low and are not driven during bus hold.
		DATA BUS
D[31:0]	I/O	The **Data Lines** D[7:0] define the least significant byte of the data bus and lines D[31:24] define the most significant byte of the data bus. These signals must meet setup and hold times t_{22} and t_{23} for proper operation on reads. These pins are driven during the second and subsequent clocks of write cycles.
		DATA PARITY
DP[3:0]	I/O	One **Data Parity** pin exists for each byte of the data bus. Data parity is generated on all write data cycles with the same timing as the data driven by the Intel486 processor. Even parity information must be driven back into the processor on the data parity pins with the same timing as read information to ensure that the correct parity check status is indicated by the Intel486 processor. The signals read on these pins do not affect program execution. Input signals must meet setup and hold times t_{22} and t_{23}. DP[3:0] should be connected to V_{CC} through a pull-up resistor in systems that do not use parity. DP[3:0] are active high and are driven during the second and subsequent clocks of write cycles.

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 2 of 8)

<table>
<tr><th>Symbol</th><th>Type</th><th colspan="4">Name and Function</th></tr>
<tr><td rowspan="11">M/IO#
D/C#
W/R#</td><td rowspan="11">O
O
O</td><td colspan="4">The Memory/Input-Output, Data/Control and Write/Read lines are the primary bus definition signals. These signals are driven valid as the ADS# signal is asserted.</td></tr>
<tr><td>M/IO#</td><td>D/C#</td><td>W/R#</td><td>Bus Cycle Initiated</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>Interrupt Acknowledge</td></tr>
<tr><td>0</td><td>0</td><td>1</td><td>Halt/Special Cycle</td></tr>
<tr><td>0</td><td>1</td><td>0</td><td>I/O Read</td></tr>
<tr><td>0</td><td>1</td><td>1</td><td>I/O Write</td></tr>
<tr><td>1</td><td>0</td><td>0</td><td>Code Read</td></tr>
<tr><td>1</td><td>0</td><td>1</td><td>Reserved</td></tr>
<tr><td>1</td><td>1</td><td>0</td><td>Memory Read</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>Memory Write</td></tr>
<tr><td colspan="4">The bus definition signals are not driven during bus hold and follow the timing of the address bus. Refer to section 10.2.11, “Special Bus Cycles,” for a description of the special bus cycles.</td></tr>
<tr><td>LOCK#</td><td>O</td><td colspan="4">The Bus Lock pin indicates that the current bus cycle is locked. The Intel486 processor does not allow a bus hold when LOCK# is asserted (but address holds are allowed). LOCK# goes active in the first clock of the first locked bus cycle and goes inactive after the last clock of the last locked bus cycle. The last locked cycle ends when ready is asserted. LOCK# is active low and is not driven during bus hold. Locked read cycles are not transformed into cache fill cycles when KEN# is asserted.</td></tr>
<tr><td>PLOCK#</td><td>O</td><td colspan="4">The Pseudo-Lock pin indicates that the current bus transaction requires more than one bus cycle to complete. For the Intel486 processor, examples of such operations are segment table descriptor reads (64 bits) and cache line fills (128 bits). For Intel486 processors with an on-chip Floating-Point Unit, floating-point long reads and writes (64 bits) also require more than one bus cycle to complete.

The Intel486 processor asserts PLOCK# until the addresses for the last bus cycle of the transaction have been driven, regardless of whether RDY# or BRDY# have been asserted.

Normally PLOCK# and BLAST# are the inverse of each other. However, during the first bus cycle of a 64-bit floating-point write (for Intel486 processors with on-chip Floating-Point Unit) both PLOCK# and BLAST# are asserted.

PLOCK# is a function of the BS8#, BS16# and KEN# inputs. PLOCK# should be sampled only in the clock in which ready is asserted. PLOCK# is active low and is not driven during bus hold.</td></tr>
</table>

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 3 of 8)

Symbol	Type	Name and Function
		BUS CONTROL
ADS#	O	The **Address Status** output indicates that a valid bus cycle definition and address are available on the cycle definition lines and address bus. ADS# is driven active in the same clock in which the addresses are driven. ADS# is active low and is not driven during bus hold.
RDY#	I	The **Non-burst Ready** input indicates that the current bus cycle is complete. RDY# indicates that the external system has presented valid data on the data pins in response to a read or that the external system has accepted data from the Intel486 processor in response to a write. RDY# is ignored when the bus is idle and at the end of the first clock of the bus cycle. RDY# is active during address hold. Data can be returned to the processor while AHOLD is active. RDY# is active low, and is not provided with an internal pull-up resistor. RDY# must satisfy setup and hold times t_{16} and t_{17} for proper chip operation.
		BURST CONTROL
BRDY#	I	The **Burst Ready** input performs the same function during a burst cycle that RDY# performs during a non-burst cycle. BRDY# indicates that the external system has presented valid data in response to a read or that the external system has accepted data in response to a write. BRDY# is ignored when the bus is idle and at the end of the first clock in a bus cycle. BRDY# is sampled in the second and subsequent clocks of a burst cycle. The data presented on the data bus is strobed into the processor when BRDY# is sampled asserted. When RDY# is asserted simultaneously with BRDY#, BRDY# is ignored and the burst cycle is prematurely aborted. BRDY# is active low and is provided with a small pull-up resistor. BRDY# must satisfy the setup and hold times t_{16} and t_{17}.
BLAST#	O	The **Burst Last** signal indicates that the next time BRDY# is asserted, the burst bus cycle is complete. BLAST# is active for both burst and non-burst bus cycles. BLAST# is active low and is not driven during bus hold.
		INTERRUPTS
RESET	I	The **Reset** input forces the Intel486 processor to begin execution at a known state. The processor cannot begin execution of instructions until at least 1 ms after V_{CC} and CLK have reached their proper DC and AC specifications. The RESET pin should remain active during this time to ensure proper processor operation. RESET is active high. RESET is asynchronous but must meet setup and hold times t_{20} and t_{21} for recognition in any specific clock.
INTR	I	The **Maskable Interrupt** indicates that an external interrupt has been generated. When the internal interrupt flag is set in EFLAGS, active interrupt processing is initiated. The Intel486 processor generates two locked interrupt acknowledge bus cycles in response to the INTR pin being asserted. INTR must remain active until the interrupt acknowledges have been performed to ensure that the interrupt is recognized. INTR is active high and is not provided with an internal pull-down resistor. INTR is asynchronous, but must meet setup and hold times t_{20} and t_{21} for recognition in any specific clock.

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 4 of 8)

Symbol	Type	Name and Function
NMI	I	The **Non-Maskable Interrupt** request signal indicates that an external non-maskable interrupt has been generated. NMI is rising edge sensitive. NMI must be held low for at least four CLK periods before this rising edge. NMI is not provided with an internal pull-down resistor. NMI is asynchronous, but must meet setup and hold times t_{20} and t_{21} for recognition in any specific clock.
SRESET	I	The **Soft Reset** pin duplicates all the functionality of the RESET pin with the following two exceptions: 1. The SMBASE register retains its previous value. 2. When UP# (I) is asserted, SRESET does not have an effect on the host processor. For soft resets, SRESET should remain active for at least 15 CLK periods. SRESET is active high. SRESET is asynchronous but must meet setup and hold times t_{20} and t_{21} for recognition in any specific clock.
SMI#	I	The **System Management Interrupt** input is used to invoke System Management Mode (SMM). SMI# is a falling edge triggered signal that forces the processor into SMM at the completion of the current instruction. SMI# is recognized on an instruction boundary and at each iteration for repeat string instructions. SMI# does not break LOCKed bus cycles and cannot interrupt a currently executing SMM. The processor latches the falling edge of one pending SMI# signal while the processor is executing an existing SMI#. The nested SMI# is not recognized until after the execution of a Resume (RSM) instruction.
SMIACT#	O	The **System Management Interrupt Active** is an active low output, indicating that the processor is operating in SMM. It is asserted when the processor begins to execute the SMI# state save sequence and remains asserted (low) until the processor executes the last state restore cycle out of SMRAM.
STPCLK#	I	The **Stop Clock Request** input signal indicates that a request has been made to turn off the CLK input. When the processor recognizes a STPCLK#, the processor stops execution on the next instruction boundary, unless superseded by a higher priority interrupt, empties all internal pipelines and the write buffers, and generates a Stop Grant acknowledge bus cycle. STPCLK# is active low and is provided with an internal pull-up resistor. STPCLK# is an asynchronous signal, but must remain active until the processor issues the Stop Grant bus cycle. STPCLK# may be deasserted at any time after the processor has issued the Stop Grant bus cycle.
		BUS ARBITRATION
BREQ	O	The **Bus Request** signal indicates that the Intel486 processor has internally generated a bus request. BREQ is generated whether or not the Intel486 processor is driving the bus. BREQ is active high and is never floated.
HOLD	I	The **Bus Hold** request allows another bus master complete control of the processor bus. In response to HOLD going active, the Intel486 processor floats most of its output and input/output pins. HLDA is asserted after completing the current bus cycle, burst cycle or sequence of locked cycles. The Intel486 processor remains in this state until HOLD is deasserted. HOLD is active high and is not provided with an internal pull-down resistor. HOLD must satisfy setup and hold times t_{18} and t_{19} for proper operation.
HLDA	O	**Hold Acknowledge** goes active in response to a hold request presented on the HOLD pin. HLDA indicates that the Intel486 processor has given the bus to another local bus master. HLDA is driven active in the same clock in which the Intel486 processor floats its bus. HLDA is driven inactive when leaving bus hold. HLDA is active high and remains driven during bus hold.

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 5 of 8)

Symbol	Type	Name and Function
BOFF#	I	The **Backoff** input forces the Intel486 processor to float its bus in the next clock. The processor floats all pins normally floated during bus hold but HLDA is not asserted in response to BOFF#. BOFF# has higher priority than RDY# or BRDY#; when both are asserted in the same clock, BOFF# takes effect. The processor remains in bus hold until BOFF# is negated. If a bus cycle was in progress when BOFF# was asserted, the cycle is restarted. BOFF# is active low and must meet setup and hold times t_{18} and t_{19} for proper operation.
		CACHE INVALIDATION
AHOLD	I	The **Address Hold** request allows another bus master access to the processor's address bus for a cache invalidation cycle. The Intel486 processor stops driving its address bus in the clock following AHOLD going active. Only the address bus is floated during address hold, the remainder of the bus remains active. AHOLD is active high and is provided with a small internal pull-down resistor. For proper operation AHOLD must meet setup and hold times t_{18} and t_{19}.
EADS#	I	This signal indicates that a valid **External Address** has been driven onto the Intel486 processor address pins. This address is used to perform an internal cache invalidation cycle. EADS# is active low and is provided with an internal pull-up resistor. EADS# must satisfy setup and hold times t_{12} and t_{13} for proper operation.
		CACHE CONTROL
KEN#	I	The **Cache Enable** pin is used to determine whether the current cycle is cacheable. When the Intel486 processor generates a cycle that can be cached and KEN# is active one clock before RDY# or BRDY# during the first transfer of the cycle, the cycle becomes a cache line fill cycle. Asserting KEN# one clock before RDY# during the last read in the cache line fill causes the line to be placed in the on-chip cache. KEN# is active low and is provided with a small internal pull-up resistor. KEN# must satisfy setup and hold times t_{14} and t_{15} for proper operation.
FLUSH#	I	The **Cache Flush** input forces the Intel486 processor to flush its entire internal cache. FLUSH# is active low and need only be asserted for one clock. FLUSH# is asynchronous but setup and hold times t_{20} and t_{21} must be met for recognition in any specific clock.
		PAGE CACHEABILITY
PWT **PCD**	O O	The **Page Write-Through** and **Page Cache Disable** pins reflect the state of the page attribute bits, PWT and PCD, in the page table entry, page directory entry or control register 3 (CR3) when paging is enabled. When paging is disabled, the processor ignores the PCD and PWT bits and assumes they are zero for the purpose of caching and driving PCD and PWT pins. PWT and PCD have the same timing as the cycle definition pins (M/IO#, D/C#, and W/R#). PWT and PCD are active high and are not driven during bus hold. PCD is masked by the cache disable bit (CD) in Control Register 0.
		BUS SIZE CONTROL
BS16# **BS8#**	I I	The **Bus Size 16** and **Bus Size 8** pins (bus sizing pins) cause the Intel486 processor to run multiple bus cycles to complete a request from devices that cannot provide or accept 32 bits of data in a single cycle. The bus sizing pins are sampled every clock. The state of these pins in the clock before ready is used by the Intel486 processor to determine the bus size. These signals are active low and are provided with internal pull-up resistors. These inputs must satisfy setup and hold times t_{14} and t_{15} for proper operation. These pins are not present on the Ultra-Low Power Intel486 SX and GX processors.

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 6 of 8)

Symbol	Type	Name and Function
		ADDRESS MASK
A20M#	I	When the **Address Bit 20 Mask** pin is asserted, the Intel486 processor masks physical address bit 20 (A20) before performing a lookup to the internal cache or driving a memory cycle on the bus. A20M# emulates the address wraparound at one Mbyte, which occurs on the 8086 processor. A20M# is active low and should be asserted only when the processor is in Real Mode. This pin is asynchronous but should meet setup and hold times t_{20} and t_{21} for recognition in any specific clock. For proper operation, A20M# should be sampled high at the falling edge of RESET.
		TEST ACCESS PORT
TCK	I	**Test Clock** is an input to the Intel486 processor and provides the clocking function required by the JTAG Boundary scan feature. TCK is used to clock state information and data into component on the rising edge of TCK on TMS and TDI, respectively. Data is clocked out of the part on the falling edge of TCK and TDO. TCK is provided with an internal pull-up resistor.
TDI	I	**Test Data Input** is the serial input used to shift JTAG instructions and data into component. TDI is sampled on the rising edge of TCK, during the SHIFT-IR and SHIFT-DR TAP controller states. During all other tap controller states, TDI is a "don't care." TDI is provided with an internal pull-up resistor.
TDO	O	**Test Data Output** is the serial output used to shift JTAG instructions and data out of the component. TDO is driven on the falling edge of TCK during the SHIFT-IR and SHIFT-DR TAP controller states. At all other times TDO is driven to the high impedance state.
TMS	I	**Test Mode Select** is decoded by the JTAG TAP (Tap Access Port) to select the operation of the test logic. TMS is sampled on the rising edge of TCK. To guarantee deterministic behavior of the TAP controller TMS is provided with an internal pull-up resistor.
		PERFORMANCE UPGRADE SUPPORT
Reserved#	I	The **Reserved** input detects the presence of the in-circuit emulator, then powers down the core, and three-states all outputs of the original processor, so that the original processor consumes very low current. Reserved# is active low and sampled at all times, including after power-up and during reset.
		NUMERIC ERROR REPORTING FOR IntelDX2™ AND IntelDX4™ PROCESSORS
FERR#	O	The **Floating-Point Error** pin is driven active when a floating-point error occurs. FERR# is similar to the ERROR# pin on the Intel387 Math CoProcessor. FERR# is included for compatibility with systems using DOS type floating-point error reporting. FERR# does not go active when FP errors are masked in FPU register. FERR# is active low, and is not floated during bus hold. This pin is not present on the Ultra-Low Power Intel486 SX and GX processors.
IGNNE#	I	When the **Ignore Numeric Error** pin is asserted the processor ignores a numeric error and continue executing non-control floating-point instructions, but FERR# is still activated by the processor. When IGNNE# is deasserted, the processor freezes on a non-control floating-point instruction, when a previous floating-point instruction caused an error. IGNNE# has no effect when the NE bit in control register 0 is set. IGNNE# is active low and is provided with a small internal pull-up resistor. IGNNE# is asynchronous but setup and hold times t_{20} and t_{21} must be met to insure recognition on any specific clock. This pin is not present on the Ultra-Low Power Intel486 SX and GX processors.

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 7 of 8)

Symbol	Type	Name and Function
WRITE-BACK ENHANCED IntelDX4™ PROCESSOR SIGNAL PINS		
CACHE#	O	The **CACHE#** output indicates internal cacheability on read cycles and burst write-back on write cycles. CACHE# is asserted for cacheable reads, cacheable code fetches and write-backs. It is driven inactive for non-cacheable reads, I/O cycles, special cycles, and write-through cycles.
FLUSH#	I	**Cache Flush#** is an existing pin that operates differently when the processor is configured as Enhanced Bus mode (write-back). FLUSH# causes the processor to write back all modified lines and flush (invalidate) the cache. FLUSH# is asynchronous, but must meet setup and hold times t_{20} and t_{21} for recognition in any specific clock.
HITM#	O	The **Hit/Miss to a Modified Line** pin is a cache coherency protocol pin that is driven only in Enhanced Bus mode. When a snoop cycle is run, HITM# indicates that the processor contains the snooped line and that the line has been modified. Assertion of HITM# implies that the line is written back in its entirety, unless the processor is already in the process of doing a replacement write-back of the same line.
INV	I	The **Invalidation Request** pin is a cache coherency protocol pin that is used only in Enhanced Bus mode. It is sampled by the processor on EADS#-driven snoop cycles. It is necessary to assert this pin to get the effect of the processor invalidate cycle on write-through-only lines**.** INV also invalidates the write-back lines. However, when the snooped line is modified, the line is written back and then invalidated. INV must satisfy setup and hold times t_{12} and t_{13} for proper operation.
PLOCK#	O	In the Enhanced bus mode, **Pseudo-Lock Output** is always driven inactive. In this mode, a 64-bit data read (caused by an FP operand access or a segment descriptor read) is treated as a multiple cycle read request, which may be a burst or a non-burst access based on whether BRDY# or RDY# is asserted by the system. Because only write-back cycles (caused by Snoop write-back or replacement write-back) are write burstable, a 64-bit write is driven out as two non-burst bus cycles. BLAST# is asserted during both writes. Refer to the Bus Functional Description section 10.3 for details on Pseudo-Locked bus cycles.
SRESET	I	For the Write-Back Enhanced Intel486 processors, **Soft Reset** operates similar to other Intel486 processors. On SRESET, the internal SMRAM base register retains its previous value, does not flush, write-back or disable the internal cache. Because SRESET is treated as an interrupt, it is possible to have a bus cycle while SRESET is asserted. SRESET is serviced only on an instruction boundary. SRESET is asynchronous but must meet setup and hold times t_{20} and t_{21} for recognition in any specific clock.
WB/WT#	I	The **Write-Back/Write-Through** pin enables Enhanced Bus mode (write-back cache). It also defines a cached line as write-through or write-back. For cache configuration, WB/WT# must be valid during RESET and be active for at least two clocks before and two clocks after RESET is deasserted. To define write-back or write-through configuration of a line, WB/WT# is sampled in the same clock as the first RDY# or BRDY# is asserted during a line fill (allocation) cycle.

Table A-1. Embedded Intel486™ Processor Pin Descriptions (Sheet 8 of 8)

Symbol	Type	Name and Function
IntelDX4™ PROCESSOR CLKMUL, V_{CC}5, AND VOLDET		
CLKMUL	I	The **Clock Multiplier** input, defined during device RESET, defines the ratio of internal core frequency to external bus frequency. When sampled low, the core frequency operates at twice the external bus frequency (speed doubled mode). When driven high or left floating, speed triple mode is selected. CLKMUL has an internal pull-up speed to V_{CC} and may be left floating in designs that select speed tripled clock mode. This pin is present only on the IntelDX4 processor.
V_{CC}5	I	The **5 V Reference Voltage** input is the reference voltage for the 5 V-tolerant I/O buffers. This signal should be connected to +5 V ±5% for use with 5 V logic. When all inputs are from 3 V logic, this pin should be connected to 3.3 V. This pin is present only on the IntelDX4 processor.
VOLDET	O	A **Voltage Detect** signal allows external system logic to distinguish between a 5 V Intel486 processor and the 3.3 V IntelDX4 processor. This signal is active low for a 3.3 V IntelDX4 processor. This pin is available only on the PGA version of the IntelDX4 processor. This pin is present only on the IntelDX4 processor.

APPENDIX B
TESTABILITY

Testing for the Intel486™ processor can be divided into two categories: Built-in Self Test (BIST) and external testing. The BIST tests the non-random logic, control ROM (CROM), translation lookaside buffer (TLB) and on-chip cache memory. External tests can be run on the TLB and the on-chip cache. The Intel486 processor also has a test mode in which all outputs are three-stated.

B.1 BUILT-IN SELF TEST (BIST)

The BIST is initiated by holding the AHOLD (address hold) high for one CLK after RESET goes from high to low, as shown in Figure 9.6. The Intel486 processor does not run bus cycles until the BIST is concluded. Note that for the Intel486 processor, the RESET must be active for 15 clocks with or without BIST enabled for warm resets. SRESET should not be driven active (i.e., high) when entering or during BIST. See Table B-1 for approximate clocks and maximum completion times for different Intel486 processors.

The results of BIST is stored in the EAX register. The Intel486 processor has successfully passed the BIST if the contents of the EAX register are zero. When the results in EAX are not zero, then the BIST has detected a flaw in the Intel486 processor. The Intel486 processor performs reset and begins normal operation at the completion of the BIST.

The non-random logic, control ROM, on-chip cache and translation lookaside buffer (TLB) are tested during the BIST.

The cache portion of the BIST verifies that the cache is functional and that it is possible to read and write to the cache. The BIST manipulates test registers TR3, TR4 and TR5 while testing the cache. These test registers are described in Section B.2, “On-Chip Cache Testing.”

The cache testing algorithm writes a value to each cache entry, reads the value back, and checks that the correct value was read back. The algorithm may be repeated more than once for each of the 512 cache entries using different constants. The IntelDX4 processor has 1024 cache entries. All other Intel486 processors have 512 cache entries.

The TLB portion of the BIST verifies that the TLB is functional and that it is possible to read and write to the TLB. The BIST manipulates test registers TR6 and TR7 while testing the TLB. TR6 and TR7 are described in Section B.3.2, “TLB Test Registers TR6 and TR7.”

B.2 ON-CHIP CACHE TESTING

The on-chip cache testability hooks are designed to be accessible during the BIST and for assembly language testing of the cache.

The Intel486 processor contains a cache fill buffer and a cache read buffer. For testability writes, data must be written to the cache fill buffer before it can be written to a location in the cache. Data must be read from a cache location into the cache read buffer before the processor can access the data. The cache fill and cache read buffer are both 128 bits wide.

B.2.1 Cache Testing Registers TR3, TR4 andTR5

Figure B-1 shows the three cache testing registers: the Cache Data Test Register (TR3), the Cache Status Test Register (TR4) and the Cache Control Test Register (TR5). External access to these registers is provided through MOV reg, TREG and MOV TREG, reg instructions.

Table B-1. Maximum BIST Completion Time

Processor Type	Core Clock Freq.	Approximate Clocks	Approximate Time for Completions
Intel486™ SX	25 MHz	1.05 million	42 milliseconds
IntelDX2™	50 MHz	0.6 million	24 milliseconds
IntelDX4™	75 MHz	1.6 million	22 milliseconds

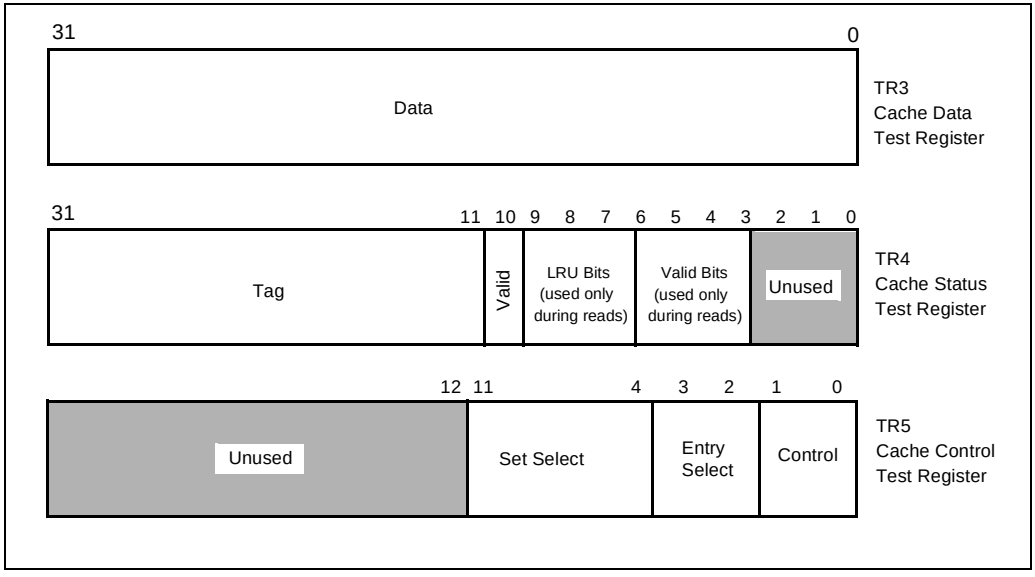

Figure B-1. Cache Test Registers (All Intel486™ Processors Except the IntelDX4™ Processor)

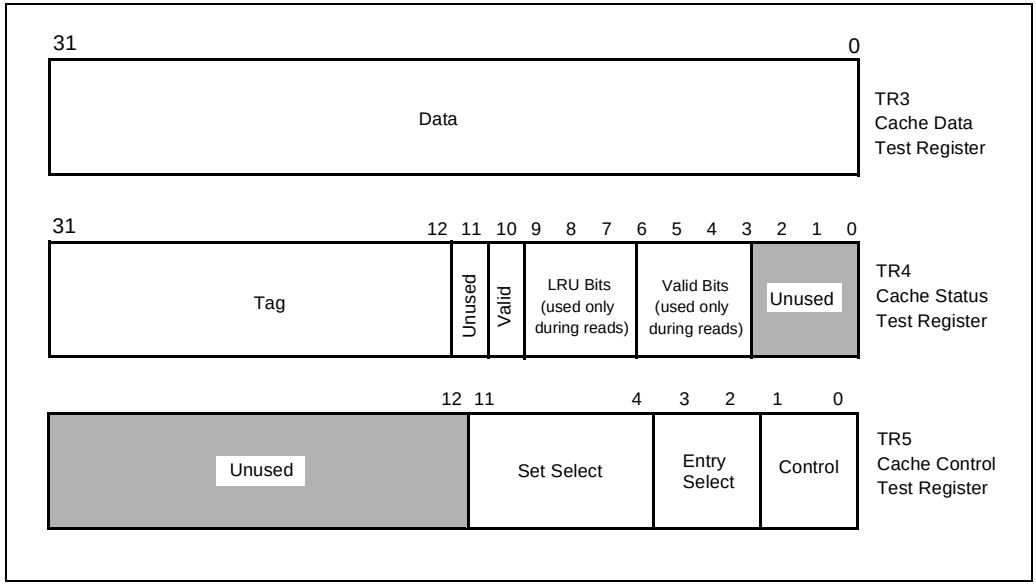

Figure B-2. IntelDX4™ Processor Cache Test Registers

Cache Data Test Register: TR3

The cache fill buffer and the cache read buffer can only be accessed through TR3. Data to be written to the cache fill buffer must first be written to TR3. Data read from the cache read buffer must be loaded into TR3.

TR3 is 32 bits wide while the cache fill and read buffers are 128 bits wide. 32 bits of data must be written to TR3 four times to fill the cache fill buffer. 32 bits of data must be read from TR3 four times to empty the cache read buffer. The entry select bits in TR5 determine which 32 bits of data TR3 will access in the buffers.

Cache Status Test Register: TR4

TR4 handles tag, LRU and valid bit information during cache tests. TR4 must be loaded with a tag and a valid bit before a write to the cache. After a read from a cache entry, TR4 contains the tag and valid bit from that entry, and the LRU bits and four valid bits from the accessed set. Note that the IntelDX4 processor has one less bit in the TR4 TAG field (see Figure B-1).

Cache Control Test Register: TR5

TR5 specifies the testability operation to be performed and the set and entry to be accessed. The set select field determines the set to be accessed. Note that the IntelDX4 processor has an 8-bit set select field and 256 sets. All other Intel486 processors have a 7-bit set select field and 128 sets (see Figure B-1).

The function of the two entry select bits depends on the state of the control bits. When the fill or read buffers are being accessed, the entry select bits point to the 32-bit location in the buffer being accessed. When a cache location is specified, the entry select bits point to one of the four entries in a set (refer to Table B-2).

Five testability functions can be performed on the cache. The two control bits in TR5 specify the operation to be executed. The five operations are:

1. Write cache fill buffer
2. Perform a cache testability write
3. Perform a cache testability read
4. Read the cache read buffer
5. Perform a cache flush

Table B-2 shows the encoding of the two control bits in TR5 for the cache testability functions. Table B-2 also shows the functionality of the entry and set select bits for each control operation.

The cache tests attempt to use as much of the normal operating circuitry as possible. Therefore, when cache tests are being performed, the cache must be disabled (i.e.,the CD and NW bits in control register 0 (CR0) must be set to 1 to disable the cache). See Chapter 7, "On-Chip Cache." for more information.

B.2.2 Cache Testing Registers for the IntelDX4™ Processor

The cache testing registers for the IntelDX4 processor differ slightly from the other Intel486 processors. TR3 in the IntelDX4 processor is identical to other Intel486 processors. TR4 in the IntelDX4 processor uses bits 31 to 12 for the Tag field, and bit 11 is unused. TR5 uses bits 11 to 4 for the Set Select field. The Test Registers for the IntelDX4 processor are shown in Figure B-2.

NOTE

Software written for the Intel486 processor for testing the cache using the Test Register produces failures due to the changes in the TAG bits and Set Select bits for the IntelDX4 processor.

Rewrite the code to take into account the 20 TAG bits and 8 Set Select bits to address the larger cache.

B.2.3 Cache Testability Write

A testability write to the cache is a two step process. First the cache fill buffer must be loaded with 128 bits of data and TR4 loaded with the tag and valid bit. Next the contents of the fill buffer are written to a cache location.

Loading the fill buffer is accomplished by first writing to the entry select bits in TR5 and setting the control bits in TR5 to 00. The entry select bits identify one of four 32-bit locations in the cache fill buffer to put 32 bits of data. Following the write to TR5, TR3 is written with 32 bits of data which are immediately placed in the cache fill buffer. Writing to TR3 initiates the write to the cache fill buffer. The cache fill buffer is loaded with 128 bits of data by writing to TR5 and TR3 four times using a different entry select location each time.

Table B-2. Cache Control Bit Encoding and Effect of Control Bits on Entry Select and Set Select Functionality

Control Bits				
Bit 1	**Bit 0**	**Operation**	**Entry Select Bits Function**	**Set Select Bits**
0	0	Enable: Fill Buffer Write Read Buffer Read	Select 32-bit location in fill/read buffer	—
0	1	Perform Cache Write	Select an entry in set	Select a set to write to
1	0	Perform Cache Read	Select an entry in set	Select a set to read from
1	1	Perform Cache Flush	—	—

TR4 must be loaded with the tag and valid bit (bit 10 in TR4) before the contents of the fill buffer are written to a cache location. The IntelDX4 processor has a 20-bit tag in TR4. All other Intel486 processors use a 21-bit tag in TR4.

The contents of the cache fill buffer are written to a cache location by writing TR5 with a control field of 01 along with the set select and entry select fields. The set select and entry select field indicate the location in the cache to be written. The normal cache LRU update circuitry updates the internal LRU bits for the selected set.

Note that a cache testability write can only be done when the cache is disabled for replaces (the CD bit is control register 0 is reset to 1). Care must be taken when directly writing to entries in the cache. When the entry is set to overlap an area of memory that is being used in external memory, that cache entry could inadvertently be used instead of the external memory. This is exactly the type of operation that one would desire if the cache were to be used as a high speed RAM. Also, a memory reference (or any external bus cycle) should not occur in between the move to TR4 and the move to TR5, in order to avoid having the value in TR4 change due to the memory reference.

B.2.4 Cache Testability Read

A cache testability read is a two step process. First the contents of the cache location are read into the cache read buffer. Next the data is examined by reading it out of the read buffer.

Reading the contents of a cache location into the cache read buffer is initiated by writing TR5 with the control bits set to 10 and the desired set select and two-bit entry select. The IntelDX4 processor has an eight-bit select field. All other Intel486 processors have a seven-bit select field. In response to the write to TR5, TR4 is loaded with the 21-bit tag field and the single valid bit from the cache entry read. TR4 is also loaded with the three LRU bits and four valid bits corresponding to the cache set that was accessed. The cache read buffer is filled with the 128-bit value which was found in the data array at the specified location.

The contents of the read buffer are examined by performing four reads of TR3. Before reading TR3 the entry select bits in TR5 must loaded to indicate which of the four 32-bit words in the read buffer to transfer into TR3 and the control bits in TR5 must be loaded with 00. The register read of TR3 initiates the transfer of the 32-bit value from the read buffer to the specified general purpose register.

Note that it is very important that the entire 128-bit quantity from the read buffer and also the information from TR4 be read before any memory references are allowed to occur. When memory operations are allowed to happen, the contents of the read buffer will be corrupted. This is because the testability operations use hardware that is used in normal memory accesses for the Intel486 processor whether the cache is enabled or not.

B.2.5 Flush Cache

The control bits in TR5 must be written with 11 to flush the cache. None of the other bits in TR5 have any meaning when 11 is written to the control bits. Flushing the cache resets the LRU bits and the valid bits to 0, but does not change the cache tag or data arrays.

When the cache is flushed by writing to TR5 the special bus cycle indicating a cache flush to the external system is not run (see Section 10.3.11, "Special Bus Cycles"). For normal operation, the cache should be flushed with the instruction INVD (Invalidate Data Cache) instruction or the WBINVD (Write-back and Invalidate Data Cache) instruction.

B.2.6 Additional Cache Testing Features for Write-Back Enhanced IntelDX4™ Processor

When in Enhanced Bus (Write-Back) mode, the Write-Back Enhanced IntelDX4™ cache testing is a superset of the Standard Bus (Write-Through) mode. The additional cache testing features for the Write-Back Enhanced IntelDX4 processor are summarized below.

There are two state bits per cache line (VH and VL) instead of one (V). The assignment of VH and VL state bits is shown in Table B-3.

Table B-3. State Bit Assignments for the Write-Back Enhanced IntelDX4™ Processor

State	VH, VL
M	1, 1
E	0, 1
S	1, 0
I	0, 0

The state assignments have been chosen so that VH is identical to the V-state of the IntelDX4 processor, when the Write-Back Enhanced IntelDX4 is in Standard Bus mode and where only S and I states are possible.

There are no changes to TR3 between the Standard Bus mode and the Enhanced Bus mode. The TR4 definition remains the same in Standard Bus mode as in Intel486 processors. The changes to TR4 in Enhanced Bus mode are shown in Figure B-3.

In Enhanced Bus mode, the cache line state bits of all four lines of the set are no longer available, which eliminates the possibility of a conflicting definition of state bits for the selected entry. The entry's state bits are moved to positions 0 and 1.

TR5 is also the same in Standard Bus mode as in standard Intel486 processors. A minor change to TR5 in Enhanced Bus mode is illustrated in Figure B-4.

In Enhanced Bus mode, control bit TR5.SLF (bit 13) is added to allow 1,1 of TR5.CTL (bits 1:0) to perform two different kinds of cache flushes. When SLF=0, CTL=1,1 performs a single clock invalidate of all lines in the cache, which does not write-back M-state lines. When SLF=1, the specific line addressed is written back (IF in M-State) and invalidated. The state of SLF is significant only when CTL=1,1.

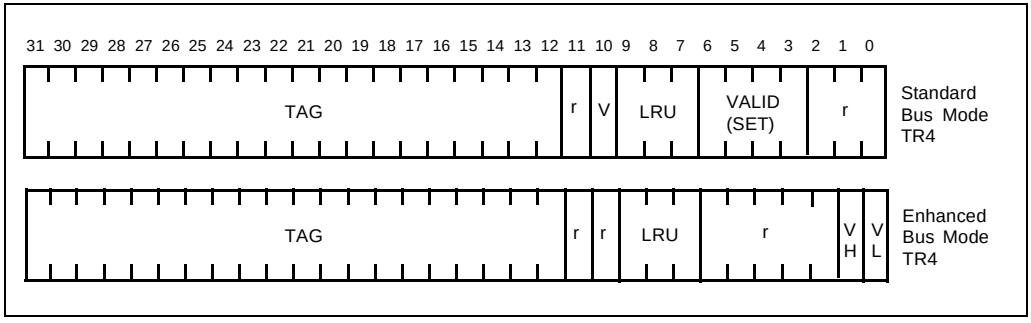

Figure B-3. TR4 Definition for Standard and Enhanced Bus Modes for the Write-Back Enhanced IntelDX4™ Processor

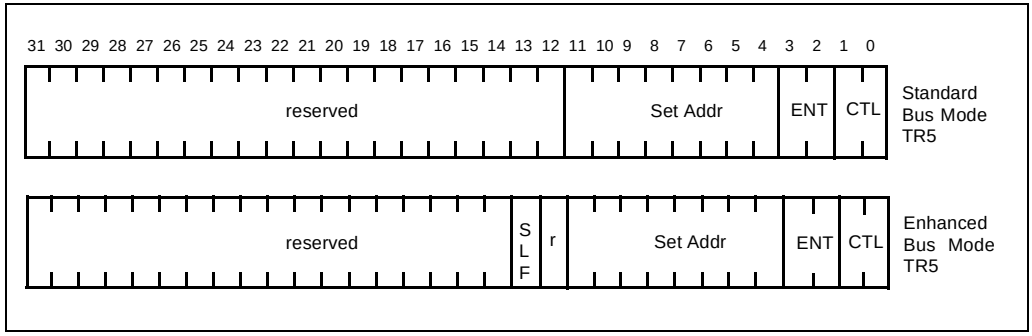

Figure B-4. TR5 Definition for Standard and Enhanced Bus Modes for the Write-Back Enhanced IntelDX4™ Processor

B.3 TRANSLATION LOOKASIDE BUFFER (TLB) TESTING

The Intel486 processor TLB testability hooks are similar to those in the Intel386 processor. The testability hooks have been enhanced to provide added test features and to include new features in the Intel486 processor. The TLB testability hooks are designed to be accessible during the BIST and for assembly language testing of the TLB.

B.3.1 Translation Lookaside Buffer Organization

The Intel486 processor TLB is 4-way set associative and has space for 32 entries. The TLB is logically split into three blocks shown in Figure B-5.

The data block is physically split into four arrays, each with space for eight entries. An entry in the data block is 22 bits wide containing a 20-bit physical address and two bits for the page attributes. The page attributes are the PCD (page cache disable) bit and the PWT (page write-through) bit. Refer to Section 7.6, "Page Cacheability," for a discussion of the PCD and PWT bits.

The tag block is also split into four arrays, one for each of the data arrays. A tag entry is 21 bits wide containing a 17-bit linear address and four protection bits. The protection bits are valid (V), user/supervisor (U/S), read/write (R/W) and dirty (D).

The third block contains eight three bit quantities used in the pseudo least recently used (LRU) replacement algorithm. These bits are called the LRU bits. Unlike the on-chip cache, the TLB replaces a valid line even when there is an invalid line in a set.

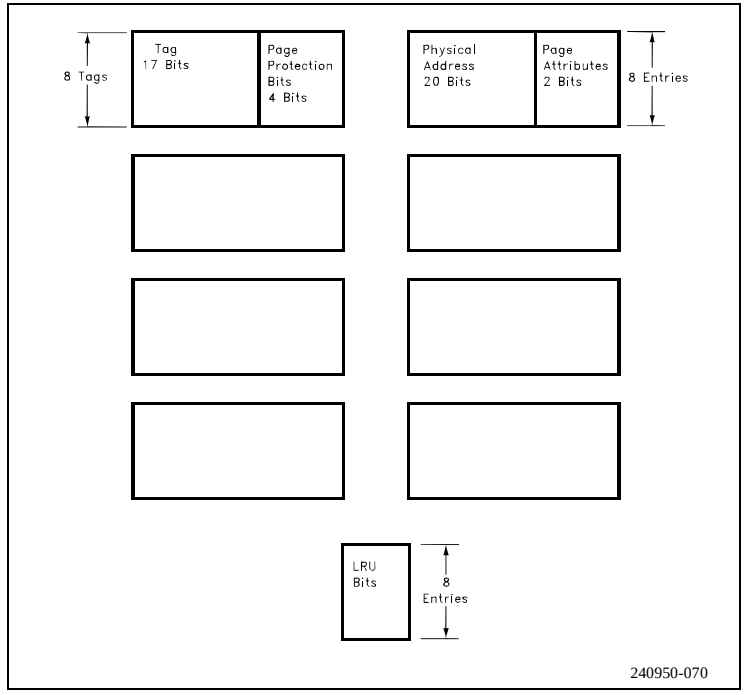

Figure B-5. TLB Organization

B.3.2 TLB Test Registers TR6 and TR7

The two TLB test registers are shown in Figure B-6. TR6 is the command test register and TR7 is the data test register. External access to these registers is provided through MOV reg,TREG and MOV TREG,reg instructions.

12.3.1.1 Command Test Register: TR6

TR6 contains the tag information and control information used in a TLB test. Loading TR6 with tag and control information initiates a TLB write or lookup test.

TR6 contains three bit fields, a 20-bit linear address (bits 31:12), seven bits for the TLB tag protection bits (bits 11:5) and one bit (bit 0) to define the type of operation to be performed on the TLB.

The 20-bit linear address forms the tag information used in the TLB access. The lower three bits of the linear address select which of the eight sets are accessed. The upper 17 bits of the linear address form the tag stored in the tag array.

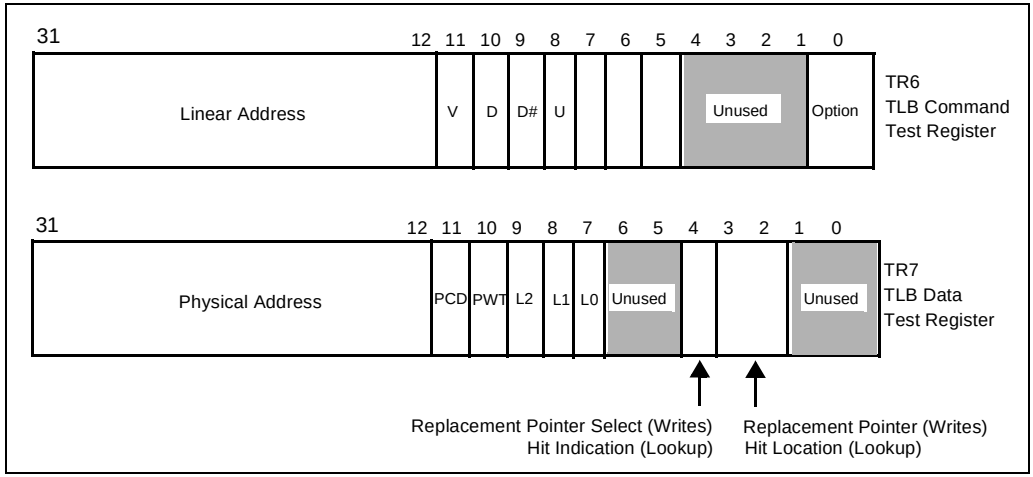

Figure B-6. TLB Test Registers

The seven TLB tag protection bits are described below.

V:The valid bit for this TLB entry

D,D#:The dirty bit for/from the TLB entry

U,U#:The user/supervisor bit for/from the TLB entry

W,W#:The read/write bit for/from the TLB entry

Two bits are used to represent the D, U/S and R/W bits in the TLB tag to permit the option of a forced miss or hit during a TLB lookup operation. The forced miss or hit occurs regardless of the state of the actual bit in the TLB. The meaning of these pairs of bits is given in Table B-4.

The operation bit in TR6 determines whether the TLB test operation is a write or a lookup. The function of the operation bit is given in Table B-5.

Table B-4. Meaning of a Pair of TR6 Protection Bits

TR6 Protection Bit (B)	TR6 Protection Bit# (B#)	Meaning on TLB Write Operation	Meaning on TLB Lookup Operation
0	0	Undefined	Miss any TLB TAG Bit B
0	1	Write 0 to TLB TAG Bit B	Match TLB TAG Bit B if 0
1	0	Write 1 to TLB TAG Bit B	Match TLB TAG Bit B if 1
1	1	Undefined	Match any TLB TAG Bit B

Table B-5. TR6 Operation Bit Encoding

TR6 Bit 0	TLB Operation to Be Performed
0	TLB Write
1	TLB Lookup

12.3.1.2 Data Test Register: TR7

TR7 contains the information stored or read from the data block during a TLB test operation. Before a TLB test write, TR7 contains the physical address and the page attribute bits to be stored in the entry. After a TLB test lookup hit, TR7 contains the physical address, page attributes, LRU bits and entry location from the access.

TR7 contains a 20-bit physical address (bits 31:12), PLD bit (bit 11), PWT bit (bit 10), and three bits for the LRU bits (bits 9:7). The LRU bits in TR7 are only used during a TLB lookup test. The functionality of TR7 bit 4 differs for TLB writes and lookups. The encoding of bit 4 is defined in Table B-6 and Table B-7. Finally, TR7 contains two bits (bits 3:2) to specify a TLB replacement pointer or the location of a TLB hit.

Table B-6. Encoding of Bit 4 of TR7 on Writes

TR7 Bit 4	Replacement Pointer Used on TLB Write
0	Pseudo-LRU Replacement Pointer
1	Data Test Register Bits 3:2

A replacement pointer is used during a TLB write. The pointer indicates which of the four entries in an accessed set is to be written. The replacement pointer can be specified to be the internal LRU bits or bits 3:2 in TR7. The source of the replacement pointer is specified by TR7 bit 4. The encoding of bit 4 during a write is given by Table B-6.

Note that both testability writes and lookups affect the state of the internal LRU bits regardless of the replacement pointer used. All TLB write operations (testability or normal operation) cause the written entry to become the most recently used. For example, during a testability write with the replacement pointer specified by TR7 bits 3:2, the indicated entry is written and that entry becomes the most recently used as specified by the internal LRU bits.

There are two TLB testing operations: write entries into the TLB, and perform TLB lookups. One major enhancement over TLB testing in the Intel386™ processor is that paging need not be disabled while executing testability writes or lookups.

Note that any time one TLB set contains the same linear address in more than one of its entries, looking up that linear address gives unpredictable results. Therefore a single linear address should not be written to one TLB set more than once.

Table B-7. Encoding of Bit 4 of TR7 on Lookups

TR7 Bit 4	Meaning after TLB Lookup Operation
0	TLB Lookup Resulted in a Miss
1	TLB Lookup Resulted in a Hit

B.3.3 TLB Write Test

To perform a TLB write TR7 must be loaded followed by a TR6 load. The register operations must be performed in this order because the TLB operation is triggered by the write to TR6.

TR7 is loaded with a 20-bit physical address and values for PCD and PWT to be written to the data portion of the TLB. In addition, bit 4 of TR7 must be loaded to indicate whether to use TR7 bits 3-2 or the internal LRU bits as the replacement pointer on the TLB write operation. Note that the LRU bits in TR7 are not used in a write test.

TR6 must be written to initiate the TLB write operation. Bit 0 in TR6 must be reset to zero to indicate a TLB write. The 20-bit linear address and the seven page protection bits must also be written in TR6 to specify the tag portion of the TLB entry. Note that the three least significant bits of the linear address specify which of the eight sets in the data block is loaded with the physical address data. Thus only 17 of the linear address bits are stored in the tag array.

B.3.4 TLB Lookup Test

To perform a TLB lookup it is only necessary to write the proper tags and control information into TR6. Bit 0 in TR6 must be set to 1 to indicate a TLB lookup. TR6 must be loaded with a 20-bit linear address and the seven protection bits. To force misses and matches of the individual protection bits on TLB lookups, set the seven protection bits as specified in Table B-4.

A TLB lookup operation is initiated by the write to TR6. TR7 indicates the result of the lookup operation following the write to TR6. The hit/miss indication can be found in TR7 bit 4 (see Table B-7).

TR7 contains the following information if bit 4 indicates that the lookup test resulted in a hit. Bits 3:2 specify the set in which the match occurred. The 22 most significant bits in TR7 contain the physical address and page attributes contained in the entry. Bits 9:7 contain the LRU bits associated with the accessed set. The state of the LRU bits is does not reflect their being updated for the current lookup.

When bit 4 in TR7 indicates that the lookup test resulted in a miss, the remaining bits in TR7 are undefined.

Again it should be noted that a TLB testability lookup operation affects the state of the LRU bits. The LRU bits are updated if a hit occurs. The entry which was hit becomes the most recently used.

B.4 THREE-STATE OUTPUT TEST MODE

The Intel486 processor provides the ability to float all its outputs and bidirectional pins, except for the VOLDET pin in the IntelDX4 processor. This includes all pins floated during bus hold as well as pins which are never floated in normal operation of the chip (HLDA, BREQ, FERR# and PCHK#). When the Intel486 processor is in the three-state output test mode external testing can be used to test board connections.

The three-state test mode is invoked if FLUSH# is sampled active at the falling edge of RESET. FLUSH# is an asynchronous signal. When driven, FLUSH# should be asserted for two clocks before and 2 clocks after RESET is de-asserted. When FLUSH# is driven synchronously, the three-state output test mode is initiated by driving FLUSH# so that it is sampled active in the clock prior to RESET going low and ensuring that specified setup and hold times are met. The outputs are guaranteed to three-state no later than 10 clocks after RESET goes low (see Figure B-4). The Intel486 processor remains in the three-state test mode until the next RESET.

B.5 Intel486™ PROCESSOR BOUNDARY SCAN (JTAG)

The Intel486 processor provides additional testability features compatible with the IEEE Standard Test Access Port and Boundary Scan Architecture (IEEE Std. 1149.1). (Note that the Intel486 SX processor in PGA package does not have JTAG capability.) The test logic provided allows for testing to insure that components function correctly, that interconnections between various components are correct, and that various components interact correctly on the printed circuit board.

The boundary scan test logic consists of a boundary scan register and support logic that are accessed through a test access port (TAP). The TAP provides a simple serial interface that makes it possible to test all signal traces with only a few probes.

The TAP can be controlled via a bus master. The bus master can be either automatic test equipment or a component (PLD) that interfaces to the four-pin test bus.

B.5.1 Boundary Scan Architecture

The boundary scan test logic contains the following elements:

- Test access port (TAP), consisting of input pins TMS, TCK, and TDI; and output pin TDO.
- TAP controller, which interprets the inputs on the test mode select (TMS) line and performs the corresponding operation. The operations performed by the TAP include controlling the instruction and data registers within the component.
- Instruction register (IR), which accepts instruction codes shifted into the test logic on the test data input (TDI) pin. The instruction codes are used to select the specific test operation to be performed or the test data register to be accessed.
- Test data registers: The Intel486 processor contains three test data registers: Bypass register (BPR), Device Identification register (DID), and Boundary Scan register (BSR).

The instruction and test data registers are separate shift-register paths connected in parallel and have a common serial data input and a common serial data output connected to the TAP signals, TDI and TDO, respectively.

B.5.2 Data Registers

The Intel486 processor contains the two required test data registers; bypass register and boundary scan register. In addition, they also have a device identification register.

Each test data register is serially connected to TDI and TDO, with TDI connected to the most significant bit and TDO connected to the least significant bit of the test data register.

Data is shifted one stage (bit position within the register) on each rising edge of the test clock (TCK). In addition the Intel486 processor contains a runbist register to support the RUNBIST boundary scan instruction.

B.5.2.1 Bypass Register

The Bypass Register is a one-bit shift register that provides the minimal length path between TDI and TDO. This path can be selected when no test operation is being performed by the component to allow rapid movement of test data to and from other components on the board. While the bypass register is selected data is transferred from TDI to TDO without inversion.

B.5.2.2 Boundary Scan Register

The Boundary Scan Register is a single shift register path containing the boundary scan cells that are connected to all input and output pins of the Intel486 processor. Figure B-7 shows the logical structure of the boundary scan register. While output cells determine the value of the signal driven on the corresponding pin, input cells only capture data; they do not affect the normal operation of the device. Data is transferred without inversion from TDI to TDO through the boundary scan register during scanning. The boundary scan register can be operated by the EXTEST and SAMPLE instructions. The boundary scan register order is described in Section B.5.5, "Boundary Scan Register Bits and Bit Orders."

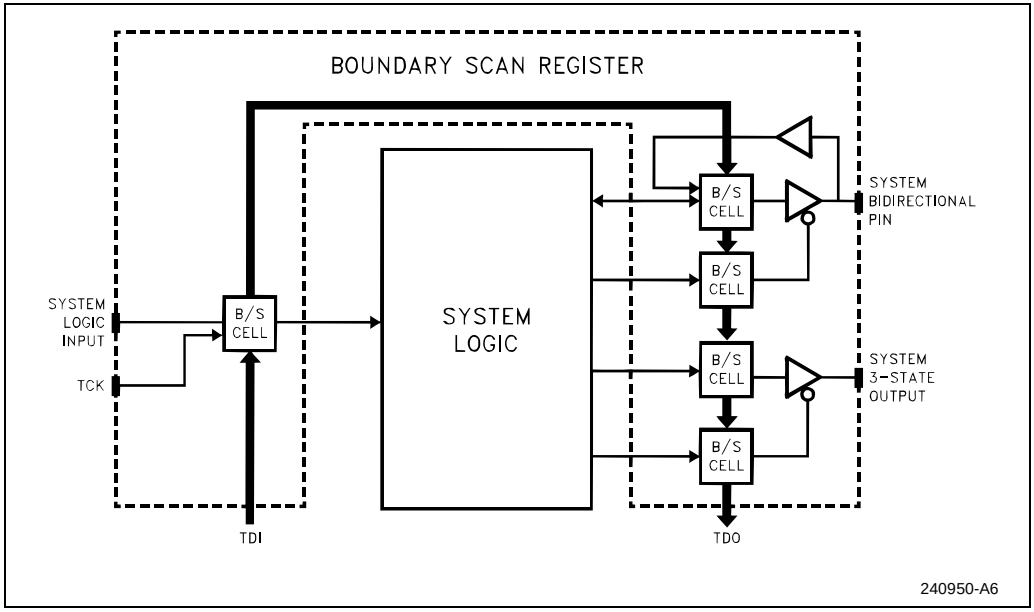

Figure B-7. Logical Structure of Boundary Scan Register

B.5.2.3 Device Identification Register

The Device Identification Register contains the manufacturer's identification code, part number code, and version code. Table B-8 lists the codes corresponding to the Intel486 processor.

B.5.2.4 Runbist Register

The Runbist Register is a one bit register used to report the results of the Intel486 processor BIST when it is initiated by the RUNBIST instruction. This register is loaded with a "1" prior to invoking the BIST and is then loaded with "0" upon successful completion.

B.5.3 Instruction Register

The Instruction Register (IR) allows instructions to be serially shifted into the device. The instruction selects the particular test to be performed, the test data register to be accessed, or both. The instruction register is four (4) bits wide. The most significant bit is connected to TDI and the least significant bit is connected to TDO. There are no parity bits associated with the Instruction register. Upon entering the Capture-IR TAP controller state, the Instruction register is loaded with the default instruction "0001," SAMPLE/PRELOAD. Instructions are shifted into the instruction register on the rising edge of TCK while the TAP controller is in the SHIFT-IR state.

B.5.3.1 Boundary Scan Instruction Set

The Intel486 processor supports all three mandatory boundary scan instructions (BYPASS, SAMPLE/PRELOAD, and EXTEST) along with two optional instructions (IDCODE and RUNBIST). Table B-9 lists the Intel486 processor boundary scan instruction codes. The instructions listed as PRIVATE cause TDO to become enabled in the Shift-DR state and cause "0" to be shifted out of TDO on the rising edge of TCK. Execution of the PRIVATE instructions does not cause hazardous operation of the Intel486 processor.

- EXTEST: The instruction code is "0000." The EXTEST instruction allows testing of circuitry external to the component package, typically board interconnects. It does so by driving the values loaded into the Intel486 processor's boundary scan register out on the output pins corresponding to each boundary scan cell and capturing the values on Intel486 processor input pins to be loaded into their corresponding boundary scan register locations. I/O pins are selected as input or output, depending on the value loaded into their control setting locations in the boundary scan register. Values shifted into input latches in the boundary scan register are never used by the internal logic of the Intel486 processor.

Table B-8. Boundary Scan Component Identification Codes

Processor Type	V_{CC} 1=3.3V 0=5V	Intel Architecture Type	Family	Model	MFG ID Intel=009H	1st Bit	Boundary Scan ID (Hex)
Intel486‰ SX processor (3.3V)	1	000001	0100	00010	00000001001	1	x8282013H
Intel486™ SX processor (3.3V, 2X CLK)	1	000001	0100	00010	00000001001	1	x8282013H
Intel486™ SX processor (5V)	0	000001	0100	00010	00000001001	1	x0282013H
Intel486™ SX processor (5V, 2X CLK)	0	000001	0100	00010	00000001001	1	x0282013H
Intel486™ DX processor (3.3V)	1	000001	0100	00001	00000001001	1	x8281013H
Intel486™ DX processor (3.3V, 2X CLK)	1	000001	0100	00001	00000001001	1	x8281013H
Intel486™ DX processor (5V)	0	000001	0100	00001	00000001001	1	x0281013H
Intel486™ DX processor (5V, 2X CLK)	0	000001	0100	00001	00000001001	1	x0281013H

†Contact Intel for details

Table B-8. Boundary Scan Component Identification Codes (Continued)

Processor Type	V_{CC} 1=3.3V 0=5V	Intel Architecture Type	Family	Model	MFG ID Intel=009H	1st Bit	Boundary Scan ID (Hex)
IntelDX2™ processor (3.3V)	1	000001	0100	00101	00000001001	1	x8285013H
IntelDX2™ processor (5V)	0	000001	0100	00101	00000001001	1	x0285013H
IntelDX4™ processor (3.3V)	1	000001	0100	01000	00000001001	1	x8288013H
Write-Back Enhanced IntelDX4™ processor (3.3V)	1	000001	0100	01001	00000001001	1	X8289013H

†Contact Intel for details

Table B-9. Boundary Scan Instruction Codes

Instruction Code	Instruction Name
0000	EXTEST
0001	SAMPLE
0010	IDCODE
0011	PRIVATE
0100	PRIVATE
0101	PRIVATE
0110	PRIVATE
0111	PRIVATE
1000	RUNBIST
1001	PRIVATE
1010	PRIVATE
1011	PRIVATE
1100	PRIVATE
1101	PRIVATE
1110	PRIVATE
1111	BYPASS

NOTE: After using the EXTEST instruction, the Intel486 processor must be reset before normal (non-boundary scan) use.

- SAMPLE/PRELOAD: The instruction code is "0001." The SAMPLE/PRELOAD has two functions that it performs. When the TAP controller is in the Capture-DR state, the SAMPLE/PRELOAD instruction allows a "snap-shot" of the normal operation of the component without interfering with that normal operation. The instruction causes boundary scan register cells associated with outputs to sample the value being driven by the Intel486 processor. It causes the cells associated with inputs to sample the value being driven into the Intel486 processor. On both outputs and inputs the sampling occurs on the rising edge of TCK. When the TAP controller is in the Update-DR state, the SAMPLE/PRELOAD instruction preloads data to the device pins to be driven to the board by executing the EXTEST instruction. Data is preloaded to the pins from the boundary scan register on the falling edge of TCK.
- IDODE: The instruction code is "0010." The IDCODE instruction selects the device identification register to be connected to TDI and TDO, allowing the device identification code to be shifted out of the device on TDO. Note that the device identification register is not altered by data being shifted in on TDI.
- BYPASS: The instruction code is "1111." The BYPASS instruction selects the bypass register to be connected to TDI and TDO, effectively bypassing the test logic on the Intel486 processor by reducing the shift length of the device to one bit. Note that an open circuit fault in the board level test data path causes the bypass register to be selected following an instruction scan cycle due to the pull-up resistor on the TDI input. This has been done to prevent any unwanted interference with the proper operation of the system logic.
- RUNBIST: The instruction code is "1000." The RUNBIST instruction selects the one (1) bit runbist register, loads a value of "1" into the runbist register, and connects it to TDO. It also initiates the built-in self test (BIST) feature of the Intel486 processor, which is able to detect approximately 60% of the stuck-at faults on the Intel486 processor. The Intel486 processor ac/dc specifications for V_{CC} and CLK must be met and RESET must have been asserted at least once prior to executing the RUNBIST boundary scan instruction. After loading the RUNBIST instruction code in the instruction register, the TAP controller must be placed in the Run-Test/Idle state. BIST begins on the first rising edge of TCK after entering the Run-Test/Idle state. The TAP controller must remain in the Run-Test/Idle state until BIST is completed. It requires 1.2 million clock (CLK) cycles to complete BIST and report the result to the runbist register. After completing the 1.2 million clock (CLK) cycles, the value in the runbist register should be shifted out on TDO during the Shift-DR state. A value of "0" being shifted out on TDO indicates BIST successfully completed. A value of "1" indicates a failure occurred. After executing the RUNBIST instruction, the Intel486 processor must be reset prior to normal operation.

B.5.4 Test Access Port (TAP) Controller

The TAP controller is a synchronous, finite state machine. It controls the sequence of operations of the test logic. The TAP controller changes state only in response to the following events:

1. A rising edge of TCK
2. Power-up.

The value of the test mode state (TMS) input signal at a rising edge of TCK controls the sequence of the state changes. The state diagram for the TAP controller is shown in Figure B-6. Test designers must consider the operation of the state machine in order to design the correct sequence of values to drive on TMS.

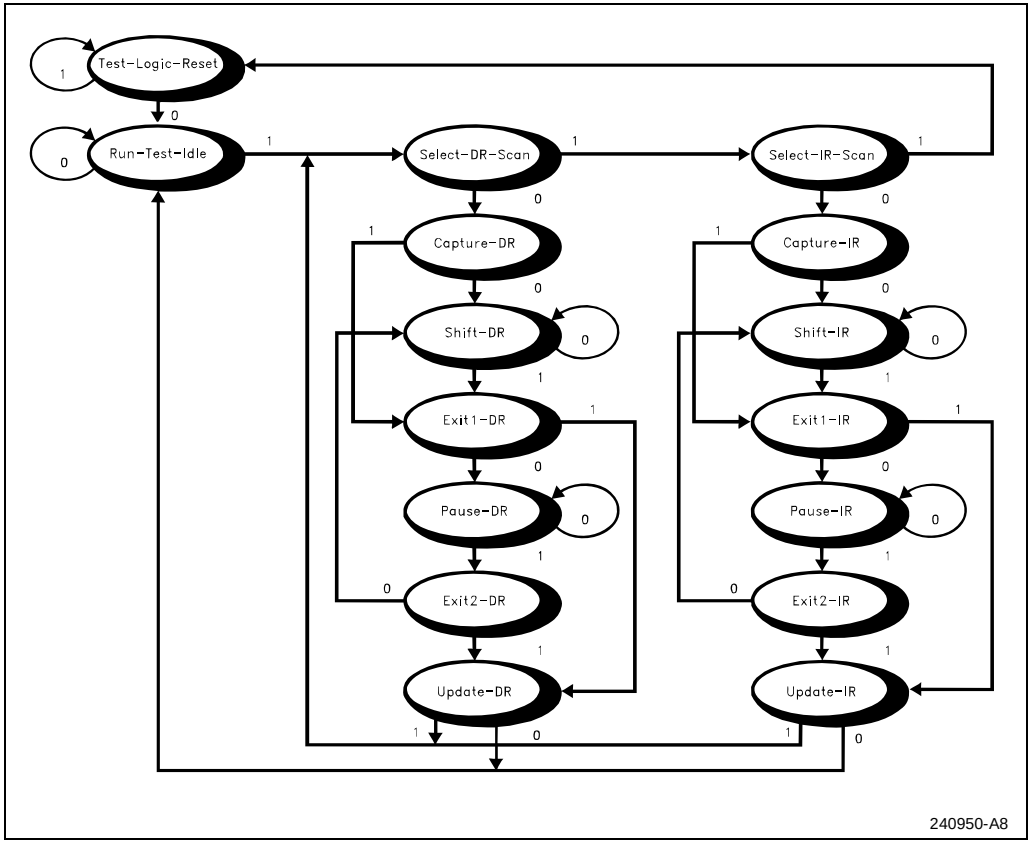

Figure B-8. TAP Controller State Diagram

B.5.4.1 Test-Logic-Reset State

In this state, the test logic is disabled so that normal operation of the device can continue unhindered. This is achieved by initializing the instruction register such that the IDCODE instruction is loaded. No matter what the original state of the controller, the controller enters Test-Logic-Reset state when the TMS input is held high (1) for at least five rising edges of TCK. The controller remains in this state while TMS is high. The TAP controller is also forced to enter this state at power-up.

B.5.4.2 Run-Test/Idle State

A controller state between scan operations. Once in this state, the controller remains in this state as long as TMS is held low. In devices supporting the RUNBIST instruction, the BIST is performed during this state and the result is reported in the runbist register. For instruction not causing functions to execute during this state, no activity occurs in the test logic. The instruction register and all test data registers retain their previous state. When TMS is high and a rising edge is applied to TCK, the controller moves to the Select-DR state.

B.5.4.3 Select-DR-Scan State

This is a temporary controller state. The test data register selected by the current instruction retains its previous state. If TMS is held low and a rising edge is applied to TCK when in this state, the controller moves into the Capture-DR state, and a scan sequence for the selected test data register is initiated. If TMS is held high and a rising edge is applied to TCK, the controller moves to the Select-IR-Scan state.

The instruction does not change in this state.

B.5.4.4 Capture-DR State

In this state, the boundary scan register captures input pin data if the current instruction is EXTEST or SAMPLE/PRELOAD. The other test data registers, which do not have parallel input, are not changed.

The instruction does not change in this state.

When the TAP controller is in this state and a rising edge is applied to TCK, the controller enters the Exit1-DR state if TMS is high or the Shift-DR state if TMS is low.

B.5.4.5 Shift-DR State

In this controller state, the test data register connected between TDI and TDO as a result of the current instruction shifts data one stage toward its serial output on each rising edge of TCK.

The instruction does not change in this state.

When the TAP controller is in this state and a rising edge is applied to TCK, the controller enters the Exit1-DR state if TMS is high or remains in the Shift-DR state if TMS is low.

B.5.4.6 Exit1-DR State

This is a temporary state. While in this state, if TMS is held high, a rising edge applied to TCK causes the controller to enter the Update-DR state, which terminates the scanning process. If TMS is held low and a rising edge is applied to TCK, the controller enters the Pause-DR state.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

B.5.4.7 Pause-DR State

The pause state allows the test controller to temporarily halt the shifting of data through the test data register in the serial path between TDI and TDO. An example of using this state could be to allow a tester to reload its pin memory from disk during application of a long test sequence.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

The controller remains in this state as long as TMS is low. When TMS goes high and a rising edge is applied to TCK, the controller moves to the Exit2-DR state.

B.5.4.8 Exit2-DR State

This is a temporary state. While in this state, if TMS is held high, a rising edge applied to TCK causes the controller to enter the Update-DR state, which terminates the scanning process. If TMS is held low and a rising edge is applied to TCK, the controller enters the Shift-DR state.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

B.5.4.9 Update-DR State

The boundary scan register is provided with a latched parallel output to prevent changes at the parallel output while data is shifted in response to the EXTEST and SAMPLE/PRELOAD instructions. When the TAP controller is in this state and the boundary scan register is selected, data is latched onto the parallel output of this register from the shift-register path on the falling edge of TCK. The data held at the latched parallel output does not change other than in this state.

All test data registers selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

B.5.4.10 Select-IR-Scan State

This is a temporary controller state. The test data register selected by the current instruction retains its previous value. If TMS is held low and a rising edge is applied to TCK when in this state, the controller moves into the Capture-IR state, and a scan sequence for the instruction register is initiated. If TMS is held high and a rising edge is applied to TCK, the controller moves to the Test-Logic-Reset state.

The instruction does not change in this state.

B.5.4.11 Capture-IR State

In this controller state the shift register contained in the instruction register loads the fixed value "0001" on the rising edge of TCK.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state. When the controller is in this state and a rising edge is applied to TCK, the controller enters the Exit1-IR state if TMS is held high, or the Shift-IR state if TMS is held low.

B.5.4.12 Shift-IR State

In this state the shift register contained in the instruction register is connected between TDI and TDO and shifts data one stage towards its serial output on each rising edge of TCK.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

When the controller is in this state and a rising edge is applied to TCK, the controller enters the Exit1-IR state if TMS is held high, or remains in the Shift-IR state if TMS is held low.

B.5.4.13 Exit1-IR State

This is a temporary state. While in this state, if TMS is held high, a rising edge applied to TCK causes the controller to enter the Update-IR state, which terminates the scanning process. If TMS is held low and a rising edge is applied to TCK, the controller enters the Pause-IR state.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

B.5.4.14 Pause-IR State

The pause state allows the test controller to temporarily halt the shifting of data through the instruction register.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

The controller remains in this state as long as TMS is low. When TMS goes high and a rising edge is applied to TCK, the controller moves to the Exit2-IR state.

B.5.4.15 Exit2-IR State

This is a temporary state. While in this state, if TMS is held high, a rising edge applied to TCK causes the controller to enter the Update-IR state, which terminates the scanning process. If TMS is held low and a rising edge is applied to TCK, the controller enters the Shift-IR state.

The test data register selected by the current instruction retains its previous value during this state. The instruction does not change in this state.

B.5.4.16 Update-IR State

The instruction shifted into the instruction register is latched onto the parallel output from the shift-register path on the falling edge of TCK. Once the new instruction has been latched, it becomes the current instruction.

Test data registers selected by the new current instruction retain the previous value.

B.5.5 Boundary Scan Register Bits and Bit Orders

The boundary scan register contains a cell for each pin, as well as cells for control of I/O and three-state pins.

B.5.5.1 Intel486™ SX Processor Boundary Scan Register Bits

The following is the bit order of the Intel486 SX processor boundary scan register (from left to right and top to bottom. See notes below):

TDO← A2, A3, A4, A5, RESERVED#, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17, A18, A19, A20, A21, A22, A23, A24, A25, A26, A27, A28, A29, A30, A31, DP0, D0, D1, D2, D3, D4, D5, D6, D7, DP1, D8, D9, D10, D11, D12, D13, D14, D15, DP2, D16, D17, D18, D19, D20, D21, D22, D23, DP3, D24, D25, D26, D27, D28, D29, D30, D31, STPCLK#, Reserved SMI#, SMIACT#, SRESET, NMI, INTR, FLUSH#, RESET, A20M#, EADS#, PCD, PWT, D/C#, M/IO#, BE3#, BE2#, BE1#, BE0#, BREQ, W/R#, HLDA, CLK, Reserved, AHOLD, HOLD, KEN#, RDY#, BS8#, BS16#, BOFF#, BRDY#, PCHK#, LOCK#, PLOCK#, BLAST#, ADS#, MISCCTL, BUSCTL, ABUSCTL, WRTL TDI

B.5.5.2 IntelDX2™ Processor Boundary Scan Register Bits

The following is the bit order of the IntelDX2 processor boundary scan register (from left to right and top to bottom. See notes below):

TDO← A2, A3, A4, A5, RESERVED#, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17, A18, A19, A20, A21, A22, A23, A24, A25, A26, A27, A28, A29, A30, A31, DP0, D0, D1, D2, D3, D4, D5, D6, D7, DP1, D8, D9, D10, D11, D12, D13, D14, D15, DP2, D16, D17, D18, D19, D20, D21, D22, D23, DP3, D24, D25, D26, D27, D28, D29, D30, D31, STPCLK#, IGNNE#, FERR#, SMI#, SMIACT#, SRESET, NMI, INTR, FLUSH#, RESET, A20M#, EADS#, PCD, PWT, D/C#, M/IO#, BE3#, BE2#, BE1#, BE0#, BREQ, W/R#, HLDA, CLK, Reserved, AHOLD, HOLD, KEN#, RDY#, BS8#, BS16#, BOFF#, BRDY#, PCHK#, LOCK#, PLOCK#, BLAST#, ADS#, MISCCTL, BUSCTL, ABUSCTL, WRTL ← TDI

B.5.5.3 IntelDX4™ Processor Boundary Scan Register Bits

The following is the bit order of the IntelDX4 processor boundary scan register (from left to right and top to bottom. See notes below):

TDO← A2, A3, A4, A5, RESERVED#, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17, A18, A19, A20, A21, A22, A23, A24, A25, A26, A27, A28, A29, A30, A31, DP0, D0, D1, D2, D3, D4, D5, D6, D7, DP1, D8, D9, D10, D11, D12, D13, D14, D15, DP2, D16, D17, D18, D19, D20, D21, D22, D23, DP3, D24, D25, D26, D27, D28, D29, D30, D31, STPCLK#, IGNNE#, FERR#, SMI#, SMIACT#, SRESET, NMI, INTR, FLUSH#, RESET, A20M#, EADS#, PCD, PWT, D/C#, M/IO#, BE3#, BE2#, BE1#, BE0#, BREQ, W/R#, HLDA, CLK, AHOLD, HOLD, KEN#, RDY#, CLKMUL, BS8#, BS16#, BOFF#, BRDY#, PCHK#, LOCK#, PLOCK#, BLAST#, ADS#, MISCCTL, BUSCTL, ABUSCTL, WRTL ← TDI

B.5.5.4 Write-Back Enhanced IntelDX4™ Processors Boundary Scan Register Bits

The following is the bit order of the Write-Back Enhanced IntelDX4 processor boundary scan register (from left to right and top to bottom. See notes below):

TDO← A2, A3, A4, A5, RESERVED#, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17, A18, A19, A20, A21, A22, A23, A24, A25, A26, A27, A28, A29, A30, A31, DP0, D0, D1, D2, D3, D4, D5, D6, D7, DP1, D8, D9, D10, D11, D12, D13, D14, D15, DP2, D16, D17, D18, D19, D20, D21, D22, D23, DP3, D24, D25, D26, D27, D28, D29, D30, D31, STPCLK#, IGNNE#, INV, CACHE#, FERR#, SMI#, WB/WT#, HITM#, SMIACT#, SRESET, NMI, INTR, FLUSH#, RESET, A20M#, EADS#, PCD, PWT, D/C#, M/IO#, BE3, BE2, BE1, BE0, BREQ, W/R#, HLDA, CLK, AHOLD, HOLD, KEN#, RDY#, CLKMUL, BS8#, BS16#, BOFF#, BRDY#, PCHK#, LOCK#, PLOCK#, BLAST#, ADS#, MISCCTL, BUSCTL, ABUSCTL, WRcTL ← TDI

NOTES

"Reserved" corresponds to no connect "NC" or "INC" signals on the Intel486 processor.

All the *CTL cells are control cells that are used to select the direction of bidirectional pins or three-state output pins. When "1" is loaded into the control cell (*CTL), the associated pin(s) are three-stated or selected as input. The following lists the control cells and their corresponding pins.

1. WRCTL controls the D[31:0] and DP[3:0] pins.
2. ABUSCTL controls the A[31:2] pins.
3. BUSCTL controls the ADS#, BLAST#, PLOCK#, LOCK#, WR#, BE0#, BE1#, BE2#, BE3#, MIO#, DC#, PWT, and PCD pins.
4. MISCCTL controls the PCHK#, HLDA, and BREQ pins.

B.5.6 TAP Controller Initialization

The TAP controller is automatically initialized when a device is powered up. In addition, the TAP controller can be initialized by applying a high signal level on the TMS input for five TCK periods.

B.5.7 Boundary Scan Description Language (BSDL) Files

See Appendix D for an example of a BSDL file for Intel486 processors.

APPENDIX C
ADVANCED FEATURES

Some non-essential information regarding the Intel486™ processor is considered Intel confidential and proprietary and is not documented in this publication. This information is provided in the Supplement to the *Pentium® Processor Family Developer's Manual* (order #241428) and is available with the appropriate non-disclosure agreements in place. Please contact Intel Corporation for details.

The Supplement to the *Pentium® Processor Family Developer's Manual* contains architecture extensions for the Intel486 and Pentium processors that are confidential and non-essential for standard applications. These extensions include low-level registers that provide access to features such as page extensions, Virtual Mode extensions, testing, and performance monitoring.

This information is specifically targeted at software developers who develop the following types of low-level software:

- Operating system kernels
- Virtual memory managers
- BIOS and processor test software
- Performance monitoring tools

For software developers designing other categories of software, this information does not apply. All of the required program development details are provided in the *Intel486™ Microprocessor Family Programmer's Reference Manual*. To obtain this document, contact the Intel Corporation Literature Center at:

Intel Corporation
P.O. Box 5937
Denver, CO 80217-9808

1-800-548-4725
(Reference Order Number 240486)

APPENDIX D
FEATURE DETERMINATION

D.1 CPUID INSTRUCTION

The Intel486™ processor implements the CPUID instruction to make information available to the system software about the family, model, and stepping of the processor. Support of this instruction is indicated by the ability of system software to write and read the bit in position EFLAGS.21, referred to as the EFLAGS.ID bit. The actual state of the EFLAGS.ID bit is irrelevant to the hardware. This bit is reset to zero upon device reset (RESET and SRESET) for compatibility with older Intel486 processor designs.

D.2 OPERATION

The CPUID instruction requires the software developer to pass an input parameter to the processor in the EAX register. The processor response is returned in registers EAX, EBX, ECX, and EDX.

1. When the parameter passed to EAX is zero, the register values returned upon instruction execution are:

   EAX[31:0] ← 1

   EBX[31:0] ←756E6547—”Genu”, with “G” in the low nibble of BL

   EDX[31:0] ← 49656E69—”ineI”, with “i” in the low nibble of DL

   ECX[31:0] ←6C65746E—”ntel”, with “n” in the low nibble of CL

   The values in EBX, ECX, and EDX indicate an Intel processor. When taken in the proper order, they decode to the string “GenuineIntel.”

2. When the parameter passed to EAX is 1, the register values returned upon instruction execution are:

   EAX[3:0] ←xxxx—Stepping ID

   EAX[7:4] ←xxxx—Model (See Table D-2.)

   EAX[11:8] ← 0100—Family

   EAX[15:12] ← 0000

   EAX[31:16] ←Intel Reserved

   EBX[31:0] ← 00000000

   ECX[31:0] ← 00000000

   EDX[0:0] ← 1—FPU on-chip

   EDX[3:1] ← 1—For more information on these bits, see Appendix A

   EDX[31:4] ← Intel Reserved

   The value returned in EAX after CPUID instruction execution is identical to the value loaded into EDX upon device reset. Software must avoid any dependency upon the state of reserved processor bits.

3. When the parameter in EAX is greater than one, the register values returned upon instruction execution are:

   EAX[31:0] ← 00000000

   EBX[31:0] ← 00000000

   EDX[31:0] ← 00000000

   ECX[31:0] ←00000000

D.3 FLAGS AFFECTED

No flags are affected.

D.4 EXCEPTIONS

None.

D.5 FOR MORE INFORMATION

Refer to the Intel application note AP-485, *Intel Processor Identification with the CPUID Instruction*, for more details.

Table D-1. CPUID Instruction Description

OPCODE	Instruction	Processor Core Clocks	EAX Input Value	Description
0F A2	CPUID	14 9	1 0 or greater than 1	Processor Identification Intel String/Null Registers

Table D-2. Intel486™ Processor Signatures

Family	Model	Stepping[1]	Description
0100	0000 and 0001	xxxx	Intel486™ DX Processors
0100	0010	xxxx	Intel486 SX Processors
0100	0011	xxxx	Intel487™ Processors[2]
0100	0011	xxxx	IntelDX2™ and IntelDX2 OverDrive® Processors
0100	0100	xxxx	Intel486 SL Processor[2]
0100	0101	xxxx	IntelSX2™ Processors
0100	1000	xxxx	IntelDX4™ and IntelDX4 OverDrive Processors
0100	1001	xxxx	Write-Back Enhanced IntelDX4 Processor
0101	0101	xxxx	Reserved for Pentium® OverDrive Processor for IntelDX4 Processor

NOTES:
1. Intel releases information about stepping numbers as needed.
2. This processor does not implement the CPUID instruction.

APPENDIX E
I/O BUFFER MODELS

For processor bus speeds above 33 MHz (e.g., 50 MHz), the capacitive derating curves are not guaranteed. For bus speeds of 50 MHz, I/O buffer modeling techniques should be used to accurately simulate (and predict) the behavior of processor signals in a particular environment.

This appendix presents sample I/O buffer model parameters for the Write-Back Enhanced IntelDX4™ processor. A text listing of the data is presented in the IBIS format.

I/O buffer model information is available for all Intel486™ processors described in this datasheet. Contact your Intel representative for the latest I/O buffer models for the Write-Back Enhanced IntelDX4 processor and other members of the Intel486 processor family.

E.1 SAMPLE IBIS FILES FOR THE WRITE-BACK ENHANCED IntelDX4™ PROCESSOR

The following pages present sample IBIS file outputs for the Write-Back Enhanced IntelDX4 processor.

E.2 SAMPLE TEXT LISTING OF IBIS FILES FOR THE WRITE-BACK ENHANCED IntelDX4™ PROCESSOR

```
|*****************************************************************************
[IBIS Ver]        1.1
[File name]       WBDX4PGA.ibs
[File Rev]        1.0
[Date]            5/13/95
[Source]          File originated at Intel Corporation, mainly as an example
                  of a proper IBIS ASCII 1.0 file.  However, data is believed
                  to be accurate.
[Note]            Pull-up, Pull-down VI curves, ramp times, and ESD
                  taken from a lab measurement on silicon.
                  Packaging values taken from a package characteristic table
                  from Intel (Chandler). Power supply is 3.3V with 5V tolerance
[Disclaimer]      This information is for modeling purposes only, and
                  is not guaranteed.
|*****************************************************************************
[Component]       CPU
[Manufacturer]    Intel
[Package]
                  typ         min         max
R_pkg             2329m       728m        3930m     | not in databook
L_pkg             17.79nH     8.56nH      27.01nH
C_pkg             6.03pF      1.89pF      10.16pF
```

```
********************************************************************************
[Pin]     signal_name     model_name      R_pin           L_pin         C_pin
C03       CLK             CLK             1248m           21.10n        9.79p
D15       A20M#           IN3             1202m           10.47n        4.14p
S13       ABUS10          IO2             1268m           12.22n        2.89p
R12       ABUS11          IO2             1100m           9.94n         3.86p
S07       ABUS12          IO2             1330m           11.14n        4.49p
Q10       ABUS13          IO2             860m            8.99n         1.81p
S05       ABUS14          IO2             816m            12.55n        5.25p
R07       ABUS15          IO2             832m            9.80n         2.08p
Q09       ABUS16          IO2             698m            7.86n         2.75p
Q03       ABUS17          IO2             2194m           17.37n        4.59p
R05       ABUS18          IO2             1376m           11.38n        4.62p
Q04       ABUS19          IO2             1118m           11.39n        2.61p
Q14       ABUS2           OUT1            1050m           9.68n         3.72p
Q08       ABUS20          IO2             756m            7.90n         2.77p
Q05       ABUS21          IO1             960m            10.51n        2.32p
Q07       ABUS22          IO1             980m            9.32n         3.53p
S03       ABUS23          IO1             494m            13.48n        3.30p
Q06       ABUS24          IO1             1030m           9.58n         3.67p
R02       ABUS25          IO1             1476m           13.38n        3.27p
S02       ABUS26          IO1             1690m           13.01n        5.49p
S01       ABUS27          IO1             1782m           15.08n        3.83p
R01       ABUS28          IO1             1694m           13.03n        5.50p
P02       ABUS29          IO1             1250m           12.12n        2.85p
R15       ABUS3           OUT1            1314m           12.48n        2.97p
P03       ABUS30          IO1             1162m           10.26n        4.03p
Q01       ABUS31          IO1             1572m           13.91n        3.45p
S16       ABUS4           IO2             1628m           12.68n        5.32p
Q12       ABUS5           IO2             724m            9.20n         1.88p
S15       ABUS6           IO2             1482m           13.41n        3.28p
Q13       ABUS7           IO2             954m            9.18n         3.46p
R13       ABUS8           IO2             1064m           11.09n        2.51p
Q11       ABUS9           IO2             730m            8.02n         2.84p
S17       ADS#            OUT1            1716m           14.71n        3.71p
A17       AHOLD           IN2             2404m           18.53n        4.98p
K15       BE0#            OUT2            1022m           9.54n         3.64p
J16       BE1#            OUT2            1062m           11.08n        2.51p
J15       BE2#            OUT2            914m            8.98n         3.35p
F17       BE3#            OUT2            1296m           12.38n        2.94p
R16       BLAST#          OUT1            1482m           11.93n        4.91p
D17       BOFF#           IN1             2158m           15.44n        6.78p
S04       BRDYC#          IN3             3230m           23.12n        6.50p
H15       BRDY#           IN1             1234m           12.04n        2.82p
Q15       BREQ            OUT2            2544m           19.31n        5.24p
C17       BS16#           IN2             2574m           19.48n        5.29p
D16       BS8#            IN2             2514m           17.29n        7.76p
B12       CACHE#          OUT2            1154m           10.22n        4.01p
P01       DBUS0           IO1             1496m           12.00n        4.95p
N02       DBUS1           IO1             1168m           11.67n        2.70p
E03       DBUS10          IO1             1358m           11.28n        4.57p
C01       DBUS11          IO1             1758m           14.95n        3.79p
```

G03	DBUS12	IO1	886m	8.83n	3.27p
D02	DBUS13	IO1	1420m	13.07n	3.17p
K03	DBUS14	IO1	1152m	10.21n	4.00p
F03	DBUS15	IO1	860m	9.96n	2.13p
J03	DBUS16	IO1	996m	10.71n	2.38p
D03	DBUS17	IO1	1092m	9.90n	3.84p
C02	DBUS18	IO1	1346m	11.22n	4.54p
B01	DBUS19	IO1	1570m	13.90n	3.44p
N01	DBUS2	IO1	1412m	11.56n	4.72p
A01	DBUS20	IO1	1746m	13.30n	5.64p
B02	DBUS21	IO1	1480m	13.40n	3.28p
A02	DBUS22	IO1	1628m	12.68n	5.32p
A04	DBUS23	IO1	1294m	12.37n	2.93p
A06	DBUS24	IO1	1092m	11.25n	2.56p
B06	DBUS25	IO1	1064m	9.76n	3.76p
C07	DBUS26	IO1	648m	8.78n	1.74p
CO6	DBUS27	IO1	862m	8.71n	3.20p
CO8	DBUS28	IO1	596m	8.49n	1.65p
AO8	DBUS29	IO1	1074m	9.81n	3.79p
H02	DBUS3	IO1	1744m	14.87n	3.76p
C09	DBUS30	IO1	578m	8.39n	1.61p
B08	DBUS31	IO1	866m	8.73n	3.21p
M03	DBUS4	IO1	972m	9.28n	3.51p
J02	DBUS5	IO1	988m	10.67n	2.37p
L02	DBUS6	IO1	1226m	10.60n	4.21p
L03	DBUS7	IO1	1600m	14.07n	3.50p
F02	DBUS8	IO1	1240m	12.07n	2.83p
D01	DBUS9	IO1	1840m	13.79n	5.90p
M15	D/C	OUT2	1474m	11.88n	4.89p
N03	DP0	IO1	1008m	10.78n	2.41p
F01	DP1	IO1	1528m	12.16n	5.04p
H03	DP2	IO1	1812m	13.64n	5.83p
A05	DP3	IO1	272m	10.84n	4.33p
B17	EADS#	IN2	1708m	14.67n	3.70p
C14	FERR#	OUT2	1612m	12.60n	5.27p
C15	FLUSH	IN2	1332m	11.15n	4.50p
A12	HITM#	OUT2	1182m	11.75n	2.73p
P15	HLDA	OUT2	1918m	15.83n	4.08p
E15	HOLD	IN2	1576m	12.41n	5.17p
A15	IGNNE#	IN3	1852m	13.85n	5.94p
A16	INTR	IN3	1782m	15.08n	3.83p
A10	INV	IN2	1002m	10.75n	2.40p
F15	KEN#	IN2	1436m	13.16n	3.19p
N15	LOCK#	OUT1	1008m	9.46n	3.61p
N16	M/IO	OUT2	464m	7.76n	1.40p
B15	NMI	IN3	1450m	11.76n	4.83p
L15	PWT	OUT2	1498m	13.50n	3.31p
J17	PCD	OUT2	1360m	11.29n	4.58p
Q17	PCHK#	OUT1	1612m	12.60n	5.27p
Q16	PLOCK#	OUT1	1320m	12.51n	2.98p
F16	RDY#	IN1	1810m	13.63n	5.82p
C16	RESET	IN3	1398m	12.95n	3.12p

```
C12      SMIACT#        OUT2           834m           8.56n        3.13p
B10      SMI#           IN3            790m           9.57n        2.00p
C10      SRESET         IN3            596m           8.49n        1.65p
G15      STPCLK#        IN3            1792m          15.13n       3.85p
B13      WBWT           IN2            1208m          10.50n       4.16p
N17      W/R            OUT1           1672m          12.91n       5.44p
********************************************************************************
The following model descriptions describe the different types of buffers.
********************************************************************************
                                    OUT1 MODEL
********************************************************************************
[Model]            OUT1
Model_type         Output
Polarity           Non-Inverting
Enable             Active-High
Signals            BE0#, BE1#, BE2#, BE3#, BREQ#, D/C#, FERR#, HLDA, M/IO#,
                   PCD, PWT
********************************************************************************
                   typ         min         max
C_comp             3.3pF       3.3pF       3.3pF
[Voltage range]    3.3V        2.7V        3.7V
********************************************************************************
[Pulldown]
         Voltage        I(typ)         I(min)         I(max)
         -5V            -2.27a         -1.68a         -2.6a
         -4.5V          -1.99a         -1.48a         -2.28a
         -4V            -1.71a         -1.27a         -1.95a
         -3.5V          -1.43a         -1.07a         -1.63a
         -3V            -1.15a         -0.87a         -1.31a
         -2.5V          -0.87a         -0.66a         -0.98a
         -2V            -0.59a         -0.46a         -0.66a
         -1.5V          -0.32a         -0.27a         -0.35a
         -1V            -68.4ma        -80.2ma        -75.6ma
         -0.5V          -23.2ma        -14.6ma        -32.2ma
         0              -7.2na         -16.5na        -12.7na
         0.5V           22.2ma         13.3ma         31.4ma
         1V             40.5ma         23.5ma         58.5ma
         1.5V           52.7ma         29.5ma         78.7ma
         2V             58.34ma        30.97ma        90.41ma
         2.5V           59.39ma        31.39ma        94.46ma
         3V             59.88ma        31.69ma        95.32ma
         3.5V           60.2ma         31.8ma         95.76ma
         4V             60.39ma        31.91ma        96.66ma
         4.5V           60.55ma        32ma           96.47ma
         5V             60.67ma        32.08ma        96.66ma
         5.5V           60.79ma        32.16ma        96.82ma
         6V             60.89ma        32.23ma        96.96ma
         6.5V           60.99ma        32.3ma         97.1ma
         7V             61.09ma        32.37ma        97.23ma
         7.5V           61.19ma        32.44ma        97.36ma
         8V             61.29ma        32.51ma        97.48ma
```

[GND_clamp]

Voltage	I(typ)	I(min)	I(max)
-1.0V	-64.0mA	-77.00mA	-55.00mA
-0.9V	-47.0mA	-57.54mA	-37.23mA
-0.8V	-27.0mA	-36.38mA	-17.76mA
-0.7V	-15.0mA	-22.00mA	-7.60mA
-0.6V	-7.5mA	-11.00mA	-4.23mA
-0.5V	-4.0mA	-5.92mA	-2.54mA
-0.4V	-2.5mA	-4.23mA	-0.85mA
-0.1V	0.0mA	0.00mA	0.00mA
0.0V	0.0mA	0.00mA	0.00mA

[Pullup]

Voltage	I(typ)	I(min)	I(max)
8V	-2.	-1.84	-2.25
7.5V	-1.6	-1.43	-1.6
6.5V	-1.32	-1.23	-1.27
6V	-1.04	-1.02	-0.95
5.5V	-0.76	-0.82	-0.63
5V	-0.49	-0.62	-0.32
4.5V	-0.22	-0.42	-97.48mA
4V	-60.91mA	-0.22	-95.62mA
3.5V	-60.04mA	-51.84mA	-94.11mA
3V	-58.94mA	-34.51mA	-92.13mA
2.5V	-57.47mA	-33.78mA	-89.56mA
2V	-55.51mA	-32.8mA	-83.82mA
1.5V	-49.48mA	-31.14mA	-71.1mA
1V	-37.6mA	-25.16mA	-52.1mA
0.5V	-19.84mA	-14.48mA	-26.99mA
0V	0.11uA	7.33nA	83.41nA
-0.5V	21.5mA	16.98mA	28.28mA
-1V	45.6mA	35.05mA	58.88mA
-1.5V	67.45mA	52.92mA	86.36mA
-2V	87.57mA	69.82mA	0.11
-2.5V	0.11	85.34mA	0.13
-3V	0.12	99.27mA	0.15
-3.5V	0.13	0.11	0.17
-4V	0.14	0.12	0.17
-4.5V	0.15	0.13	0.18
-5V	0.15	0.13	0.18
-5.5V	0.15	0.14	0.21
-6V	0.16	0.11	0.22
-6.5V	0.16	76.45mA	0.22

```
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         -1.7V          0.0mA          0.00mA         0.0mA
*******************************************************************************
[Ramp]
                   typ                 min                  max
dV/dt_r            1.27/0.549n         0.87/1.044n          1.60/0.328n
dV/dt_f            1.31/0.496n         0.83/0.855n          1.66/0.288n
*******************************************************************************
                                    OUT2 MODEL
*******************************************************************************
[Model]            OUT2
Model_type         Output
Polarity           Non-Inverting
Enable             Active-High
Signals            A[2-3]
*******************************************************************************
                   typ                 min                  max
C_comp             6.1pF               6.1pF                6.1pF
[Voltage range]    3.3V                2.7V                 3.7V
*******************************************************************************
[Pulldown]
         Voltage        I(typ)         I(min)         I(max)
         -5V            -2.27a         -1.68a         -2.6a
         -4.5V          -1.99a         -1.48a         -2.28a
         -4V            -1.71a         -1.27a         -1.95a
         -3.5V          -1.43a         -1.07a         -1.63a
         -3V            -1.15a         -0.87a         -1.31a
         -2.5V          -0.87a         -0.66a         -0.98a
         -2V            -0.59a         -0.46a         -0.66a
         -1.5V          -0.32a         -0.27a         -0.35a
         -1V            -68.4ma        -80.2ma        -75.6ma
         -0.5V          -23.2ma        -14.6ma        -32.2ma
         0              -7.2na         -16.5na        -12.7na
         0.5V           22.2ma         13.3ma         31.4ma
         1V             40.5ma         23.5ma         58.5ma
         1.5V           52.7ma         29.5ma         78.7ma
         2V             58.34ma        30.97ma        90.41ma
         2.5V           59.39ma        31.39ma        94.46ma
         3V             59.88ma        31.69ma        95.32ma
         3.5V           60.2ma         31.8ma         95.76ma
         4V             60.39ma        31.91ma        96.66ma
         4.5V           60.55ma        32ma           96.47ma
         5V             60.67ma        32.08ma        96.66ma
         5.5V           60.79ma        32.16ma        96.82ma
```

```
        6V              60.89ma         32.23ma         96.96ma
        6.5V            60.99ma         32.3ma          97.1ma
        7V              61.09ma         32.37ma         97.23ma
        7.5V            61.19ma         32.44ma         97.36ma
        8V              61.29ma         32.51ma         97.48ma
[GND_clamp]
        Voltage         I(typ)          I(min)          I(max)
        -1.0V           -64.0mA         -77.00mA        -55.00mA
        -0.9V           -47.0mA         -57.54mA        -37.23mA
        -0.8V           -27.0mA         -36.38mA        -17.76mA
        -0.7V           -15.0mA         -22.00mA        -7.60mA
        -0.6V           -7.5mA          -11.00mA        -4.23mA
        -0.5V           -4.0mA          -5.92mA         -2.54mA
        -0.4V           -2.5mA          -4.23mA         -0.85mA
        -0.1V           0.0mA           0.00mA          0.00mA
        0.0V            0.0mA           0.00mA          0.00mA
[Pullup]
        Voltage         I(typ)          I(min)          I(max)
        8V              -2.             -1.84           -2.25
        7.5V            -1.6            -1.43           -1.6
        6.5V            -1.32           -1.23           -1.27
        6V              -1.04           -1.02           -0.95
        5.5V            -0.76           -0.82           -0.63
        5V              -0.49           -0.62           -0.32
        4.5V            -0.22           -0.42           -97.48mA
        4V              -60.91mA        -0.22           -95.62mA
        3.5V            -60.04mA        -51.84mA        -94.11mA
        3V              -58.94mA        -34.51mA        -92.13mA
        2.5V            -57.47mA        -33.78mA        -89.56mA
        2V              -55.51mA        -32.8mA         -83.82mA
        1.5V            -49.48mA        -31.14mA        -71.1mA
        1V              -37.6mA         -25.16mA        -52.1mA
        0.5V            -19.84mA        -14.48mA        -26.99mA
        0V              0.11uA          7.33nA          83.41nA
        -0.5V           21.5mA          16.98mA         28.28mA
        -1V             45.6mA          35.05mA         58.88mA
        -1.5V           67.45mA         52.92mA         86.36mA
        -2V             87.57mA         69.82mA         0.11
        -2.5V           0.11            85.34mA         0.13
        -3V             0.12            99.27mA         0.15
        -3.5V           0.13            0.11            0.17
        -4V             0.14            0.12            0.17
        -4.5V           0.15            0.13            0.18
        -5V             0.15            0.13            0.18
        -5.5V           0.15            0.14            0.21
        -6V             0.16            0.11            0.22
        -6.5V           0.16            76.45mA         0.22
```

```
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         -1.7V          0.0mA          0.00mA         0.0mA
|*************************************************************************
Ramp]
                  typ                 min                  max
dV/dt_r           1.27/0.549n         0.87/1.044n          1.60/0.328n
dV/dt_f           1.31/0.496n         0.83/0.855n          1.66/0.288n
|*************************************************************************
                                   OUT3 MODEL
|*************************************************************************
[Model]           OUT3
Model_type        Output
Polarity          Non-Inverting
Enable            Active-High
| Signals         ADS#, BLAST#, LOCK#, PCHK#, PLOCK#, W/R, TD0
|*************************************************************************
                  typ                 min                  max
C_comp            6.1pF               6.1pF                6.1pF
[Voltage range]   3.3V                2.7V                 3.7V
|*************************************************************************
[Pulldown]
         Voltage        I(typ)         I(min)         I(max)
         -5V            -2.27a         -1.68a         -2.6a
         -4.5V          -1.99a         -1.48a         -2.28a
         -4V            -1.71a         -1.27a         -1.95a
         -3.5V          -1.43a         -1.07a         -1.63a
         -3V            -1.15a         -0.87a         -1.31a
         -2.5V          -0.87a         -0.66a         -0.98a
         -2V            -0.59a         -0.46a         -0.66a
         -1.5V          -0.32a         -0.27a         -0.35a
         -1V            -68.4ma        -80.2ma        -75.6ma
         -0.5V          -23.2ma        -14.6ma        -32.2ma
         0              -7.2na         -16.5na        -12.7na
         0.5V           22.2ma         13.3ma         31.4ma
         1V             40.5ma         23.5ma         58.5ma
         1.5V           52.7ma         29.5ma         78.7ma
         2V             58.34ma        30.97ma        90.41ma
         2.5V           59.39ma        31.39ma        94.46ma
         3V             59.88ma        31.69ma        95.32ma
         3.5V           60.2ma         31.8ma         95.76ma
         4V             60.39ma        31.91ma        96.66ma
         4.5V           60.55ma        32ma           96.47ma
         5V             60.67ma        32.08ma        96.66ma
         5.5V           60.79ma        32.16ma        96.82ma
```

```
        6V              60.89ma         32.23ma         96.96ma
        6.5V            60.99ma         32.3ma          97.1ma
        7V              61.09ma         32.37ma         97.23ma
        7.5V            61.19ma         32.44ma         97.36ma
        8V              61.29ma         32.51ma         97.48ma
[GND_clamp]
        Voltage         I(typ)          I(min)          I(max)
        -1.0V           -64.0mA         -77.00mA        -55.00mA
        -0.9V           -47.0mA         -57.54mA        -37.23mA
        -0.8V           -27.0mA         -36.38mA        -17.76mA
        -0.7V           -15.0mA         -22.00mA        -7.60mA
        -0.6V           -7.5mA          -11.00mA        -4.23mA
        -0.5V           -4.0mA          -5.92mA         -2.54mA
        -0.4V           -2.5mA          -4.23mA         -0.85mA
        -0.1V           0.0mA           0.00mA          0.00mA
        0.0V            0.0mA           0.00mA          0.00mA
[Pullup]
        Voltage         I(typ)          I(min)          I(max)
        8V              -2.             -1.84           -2.25
        7.5V            -1.6            -1.43           -1.6
        6.5V            -1.32           -1.23           -1.27
        6V              -1.04           -1.02           -0.95
        5.5V            -0.76           -0.82           -0.63
        5V              -0.49           -0.62           -0.32
        4.5V            -0.22           -0.42           -97.48mA
        4V              -60.91mA        -0.22           -95.62mA
        3.5V            -60.04mA        -51.84mA        -94.11mA
        3V              -58.94mA        -34.51mA        -92.13mA
        2.5V            -57.47mA        -33.78mA        -89.56mA
        2V              -55.51mA        -32.8mA         -83.82mA
        1.5V            -49.48mA        -31.14mA        -71.1mA
        1V              -37.6mA         -25.16mA        -52.1mA
        0.5V            -19.84mA        -14.48mA        -26.99mA
        0V              0.11uA          7.33nA          83.41nA
        -0.5V           21.5mA          16.98mA         28.28mA
        -1V             45.6mA          35.05mA         58.88mA
        -1.5V           67.45mA         52.92mA         86.36mA
        -2V             87.57mA         69.82mA         0.11
        -2.5V           0.11            85.34mA         0.13
        -3V             0.12            99.27mA         0.15
        -3.5V           0.13            0.11            0.17
        -4V             0.14            0.12            0.17
        -4.5V           0.15            0.13            0.18
        -5V             0.15            0.13            0.18
        -5.5V           0.15            0.14            0.21
        -6V             0.16            0.11            0.22
        -6.5V           0.16            76.45mA         0.22
```

```
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         -1.7V          0.0mA          0.00mA         0.0mA
*******************************************************************************
[Ramp]
                   typ                 min                  max
dV/dt_r            1.27/0.549n         0.87/1.044n          1.60/0.328n
dV/dt_f            1.31/0.496n         0.83/0.855n          1.66/0.288n
*******************************************************************************
                                    IO1 MODEL
*******************************************************************************
[Model]            IO1
Model_type         I/O
Polarity           Non-Inverting
Enable             Active-High
| Signals          A[21-31]
Vinl = 0.8V
Vinh = 2.0V
*******************************************************************************
                   typ                 min                  max
C_comp             3.9pF               3.9pF                3.9pF
[Voltage range]    3.3V                2.7V                 3.7V
*******************************************************************************
[Pulldown]
         Voltage        I(typ)          I(min)         I(max)
         -5V            -2.27a          -1.68a         -2.6a
         -4.5V          -1.99a          -1.48a         -2.28a
         -4V            -1.71a          -1.27a         -1.95a
         -3.5V          -1.43a          -1.07a         -1.63a
         -3V            -1.15a          -0.87a         -1.31a
         -2.5V          -0.87a          -0.66a         -0.98a
         -2V            -0.59a          -0.46a         -0.66a
         -1.5V          -0.32a          -0.27a         -0.35a
         -1V            -68.4ma         -80.2ma        -75.6ma
         -0.5V          -23.2ma         -14.6ma        -32.2ma
         0              -7.2na          -16.5na        -12.7na
         0.5V           22.2ma          13.3ma         31.4ma
         1V             40.5ma          23.5ma         58.5ma
         1.5V           52.7ma          29.5ma         78.7ma
         2V             58.34ma         30.97ma        90.41ma
         2.5V           59.39ma         31.39ma        94.46ma
         3V             59.88ma         31.69ma        95.32ma
         3.5V           60.2ma          31.8ma         95.76ma
         4V             60.39ma         31.91ma        96.66ma
         4.5V           60.55ma         32ma           96.47ma
```

```
        5V              60.67ma         32.08ma         96.66ma
        5.5V            60.79ma         32.16ma         96.82ma
        6V              60.89ma         32.23ma         96.96ma
        6.5V            60.99ma         32.3ma          97.1ma
        7V              61.09ma         32.37ma         97.23ma
        7.5V            61.19ma         32.44ma         97.36ma
        8V              61.29ma         32.51ma         97.48ma
[GND_clamp]
        Voltage         I(typ)          I(min)          I(max)
        -1.0V           -64.0mA         -77.00mA        -55.00mA
        -0.9V           -47.0mA         -57.54mA        -37.23mA
        -0.8V           -27.0mA         -36.38mA        -17.76mA
        -0.7V           -15.0mA         -22.00mA        -7.60mA
        -0.6V           -7.5mA          -11.00mA        -4.23mA
        -0.5V           -4.0mA          -5.92mA         -2.54mA
        -0.4V           -2.5mA          -4.23mA         -0.85mA
        -0.1V           0.0mA           0.00mA          0.00mA
        0.0V            0.0mA           0.00mA          0.00mA
[Pullup]
        Voltage         I(typ)          I(min)          I(max)
        8V              -2.             -1.84           -2.25
        7.5V            -1.6            -1.43           -1.6
        6.5V            -1.32           -1.23           -1.27
        6V              -1.04           -1.02           -0.95
        5.5V            -0.76           -0.82           -0.63
        5V              -0.49           -0.62           -0.32
        4.5V            -0.22           -0.42           -97.48mA
        4V              -60.91mA        -0.22           -95.62mA
        3.5V            -60.04mA        -51.84mA        -94.11mA
        3V              -58.94mA        -34.51mA        -92.13mA
        2.5V            -57.47mA        -33.78mA        -89.56mA
        2V              -55.51mA        -32.8mA         -83.82mA
        1.5V            -49.48mA        -31.14mA        -71.1mA
        1V              -37.6mA         -25.16mA        -52.1mA
        0.5V            -19.84mA        -14.48mA        -26.99mA
        0V              0.11uA          7.33nA          83.41nA
        -0.5V           21.5mA          16.98mA         28.28mA
        -1V             45.6mA          35.05mA         58.88mA
        -1.5V           67.45mA         52.92mA         86.36mA
        -2V             87.57mA         69.82mA         0.11
        -2.5V           0.11            85.34mA         0.13
        -3V             0.12            99.27mA         0.15
        -3.5V           0.13            0.11            0.17
        -4V             0.14            0.12            0.17
        -4.5V           0.15            0.13            0.18
        -5V             0.15            0.13            0.18
        -5.5V           0.15            0.14            0.21
        -6V             0.16            0.11            0.22
        -6.5V           0.16            76.45mA         0.22
```

```
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         -1.7V          0.0mA          0.00mA         0.0mA
*******************************************************************************
[Ramp]
                   typ                 min                  max
dV/dt_r            1.27/0.549n         0.87/1.044n          1.60/0.328n
dV/dt_f            1.31/0.496n         0.83/0.855n          1.66/0.288n
*******************************************************************************
                                    IO2 MODEL
*******************************************************************************
[Model]            IO2
Model_type         I/O
Polarity           Non-Inverting
Enable             Active-High
Signals            A[4-20]
Vinl = 0.8V
Vinh = 2.0V
*******************************************************************************
                   typ                 min                  max
C_comp             6.1pF               6.1pF                6.1pF
[Voltage range]    3.3V                2.7V                 3.7V
*******************************************************************************
[Pulldown]
         Voltage        I(typ)          I(min)         I(max)
         -5V            -2.27a          -1.68a         -2.6a
         -4.5V          -1.99a          -1.48a         -2.28a
         -4V            -1.71a          -1.27a         -1.95a
         -3.5V          -1.43a          -1.07a         -1.63a
         -3V            -1.15a          -0.87a         -1.31a
         -2.5V          -0.87a          -0.66a         -0.98a
         -2V            -0.59a          -0.46a         -0.66a
         -1.5V          -0.32a          -0.27a         -0.35a
         -1V            -68.4ma         -80.2ma        -75.6ma
         -0.5V          -23.2ma         -14.6ma        -32.2ma
         0              -7.2na          -16.5na        -12.7na
         0.5V           22.2ma          13.3ma         31.4ma
         1V             40.5ma          23.5ma         58.5ma
         1.5V           52.7ma          29.5ma         78.7ma
         2V             58.34ma         30.97ma        90.41ma
         2.5V           59.39ma         31.39ma        94.46ma
         3V             59.88ma         31.69ma        95.32ma
         3.5V           60.2ma          31.8ma         95.76ma
         4V             60.39ma         31.91ma        96.66ma
         4.5V           60.55ma         32ma           96.47ma
```

```
        5V              60.67ma         32.08ma         96.66ma
        5.5V            60.79ma         32.16ma         96.82ma
        6V              60.89ma         32.23ma         96.96ma
        6.5V            60.99ma         32.3ma          97.1ma
        7V              61.09ma         32.37ma         97.23ma
        7.5V            61.19ma         32.44ma         97.36ma
        8V              61.29ma         32.51ma         97.48ma
[GND_clamp]
        Voltage         I(typ)          I(min)          I(max)
        -1.0V           -64.0mA         -77.00mA        -55.00mA
        -0.9V           -47.0mA         -57.54mA        -37.23mA
        -0.8V           -27.0mA         -36.38mA        -17.76mA
        -0.7V           -15.0mA         -22.00mA        -7.60mA
        -0.6V           -7.5mA          -11.00mA        -4.23mA
        -0.5V           -4.0mA          -5.92mA         -2.54mA
        -0.4V           -2.5mA          -4.23mA         -0.85mA
        -0.1V           0.0mA           0.00mA          0.00mA
        0.0V            0.0mA           0.00mA          0.00mA
[Pullup]
        Voltage         I(typ)          I(min)          I(max)
        8V              -2.             -1.84           -2.25
        7.5V            -1.6            -1.43           -1.6
        6.5V            -1.32           -1.23           -1.27
        6V              -1.04           -1.02           -0.95
        5.5V            -0.76           -0.82           -0.63
        5V              -0.49           -0.62           -0.32
        4.5V            -0.22           -0.42           -97.48mA
        4V              -60.91mA        -0.22           -95.62mA
        3.5V            -60.04mA        -51.84mA        -94.11mA
        3V              -58.94mA        -34.51mA        -92.13mA
        2.5V            -57.47mA        -33.78mA        -89.56mA
        2V              -55.51mA        -32.8mA         -83.82mA
        1.5V            -49.48mA        -31.14mA        -71.1mA
        1V              -37.6mA         -25.16mA        -52.1mA
        0.5V            -19.84mA        -14.48mA        -26.99mA
        0V              0.11uA          7.33nA          83.41nA
        -0.5V           21.5mA          16.98mA         28.28mA
        -1V             45.6mA          35.05mA         58.88mA
        -1.5V           67.45mA         52.92mA         86.36mA
        -2V             87.57mA         69.82mA         0.11
        -2.5V           0.11            85.34mA         0.13
        -3V             0.12            99.27mA         0.15
        -3.5V           0.13            0.11            0.17
        -4V             0.14            0.12            0.17
        -4.5V           0.15            0.13            0.18
        -5V             0.15            0.13            0.18
        -5.5V           0.15            0.14            0.21
        -6V             0.16            0.11            0.22
        -6.5V           0.16            76.45mA         0.22
```

```
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         -1.7V          0.0mA          0.00mA         0.0mA
*******************************************************************************
[Ramp]
                   typ                 min                  max
dV/dt_r            1.27/0.549n         0.87/1.044n          1.60/0.328n
dV/dt_f            1.31/0.496n         0.83/0.855n          1.66/0.288n
*******************************************************************************
                                    IO3 MODEL
*******************************************************************************
[Model]            IO3
Model_type         I/O
Polarity           Non-Inverting
Enable             Active-High
Signals            D[0-31], DP[0-3]
Vinl = 0.8V
Vinh = 2.0V
*******************************************************************************
                   typ                 min                  max
C_comp             3.9pF               3.9pF                3.9pF
[Voltage range]    3.3V                2.7V                 3.7V
*******************************************************************************
[Pulldown]
         Voltage        I(typ)          I(min)         I(max)
         -5V            -2.27a          -1.68a         -2.6a
         -4.5V          -1.99a          -1.48a         -2.28a
         -4V            -1.71a          -1.27a         -1.95a
         -3.5V          -1.43a          -1.07a         -1.63a
         -3V            -1.15a          -0.87a         -1.31a
         -2.5V          -0.87a          -0.66a         -0.98a
         -2V            -0.59a          -0.46a         -0.66a
         -1.5V          -0.32a          -0.27a         -0.35a
         -1V            -68.4ma         -80.2ma        -75.6ma
         -0.5V          -23.2ma         -14.6ma        -32.2ma
         0              -7.2na          -16.5na        -12.7na
         0.5V           22.2ma          13.3ma         31.4ma
         1V             40.5ma          23.5ma         58.5ma
         1.5V           52.7ma          29.5ma         78.7ma
         2V             58.34ma         30.97ma        90.41ma
         2.5V           59.39ma         31.39ma        94.46ma
         3V             59.88ma         31.69ma        95.32ma
         3.5V           60.2ma          31.8ma         95.76ma
         4V             60.39ma         31.91ma        96.66ma
         4.5V           60.55ma         32ma           96.47ma
```

```
        5V              60.67ma         32.08ma         96.66ma
        5.5V            60.79ma         32.16ma         96.82ma
        6V              60.89ma         32.23ma         96.96ma
        6.5V            60.99ma         32.3ma          97.1ma
        7V              61.09ma         32.37ma         97.23ma
        7.5V            61.19ma         32.44ma         97.36ma
        8V              61.29ma         32.51ma         97.48ma
[GND_clamp]
        Voltage         I(typ)          I(min)          I(max)
        -1.0V           -64.0mA         -77.00mA        -55.00mA
        -0.9V           -47.0mA         -57.54mA        -37.23mA
        -0.8V           -27.0mA         -36.38mA        -17.76mA
        -0.7V           -15.0mA         -22.00mA        -7.60mA
        -0.6V           -7.5mA          -11.00mA        -4.23mA
        -0.5V           -4.0mA          -5.92mA         -2.54mA
        -0.4V           -2.5mA          -4.23mA         -0.85mA
        -0.1V           0.0mA           0.00mA          0.00mA
        0.0V            0.0mA           0.00mA          0.00mA
[Pullup]
        Voltage         I(typ)          I(min)          I(max)
        8V              -2.             -1.84           -2.25
        7.5V            -1.6            -1.43           -1.6
        6.5V            -1.32           -1.23           -1.27
        6V              -1.04           -1.02           -0.95
        5.5V            -0.76           -0.82           -0.63
        5V              -0.49           -0.62           -0.32
        4.5V            -0.22           -0.42           -97.48mA
        4V              -60.91mA        -0.22           -95.62mA
        3.5V            -60.04mA        -51.84mA        -94.11mA
        3V              -58.94mA        -34.51mA        -92.13mA
        2.5V            -57.47mA        -33.78mA        -89.56mA
        2V              -55.51mA        -32.8mA         -83.82mA
        1.5V            -49.48mA        -31.14mA        -71.1mA
        1V              -37.6mA         -25.16mA        -52.1mA
        0.5V            -19.84mA        -14.48mA        -26.99mA
        0V              0.11uA          7.33nA          83.41nA
        -0.5V           21.5mA          16.98mA         28.28mA
        -1V             45.6mA          35.05mA         58.88mA
        -1.5V           67.45mA         52.92mA         86.36mA
        -2V             87.57mA         69.82mA         0.11
        -2.5V           0.11            85.34mA         0.13
        -3V             0.12            99.27mA         0.15
        -3.5V           0.13            0.11            0.17
        -4V             0.14            0.12            0.17
        -4.5V           0.15            0.13            0.18
        -5V             0.15            0.13            0.18
        -5.5V           0.15            0.14            0.21
        -6V             0.16            0.11            0.22
        -6.5V           0.16            76.45mA         0.22
```

```
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         -1.7V          0.0mA          0.00mA         0.0mA
********************************************************************************
[Ramp]
                  typ                 min                  max
dV/dt_r           1.27/0.549n         0.87/1.044n          1.60/0.328n
dV/dt_f           1.31/0.496n         0.83/0.855n          1.66/0.288n
********************************************************************************
                                  INPUT1 MODEL
********************************************************************************
[Model]           INPUT1
Model_type        Input
Polarity          Non-Inverting
Enable            Active-High
Signals           A20M#, AHOLD, BOFF#, BRDY#, BS8#, BS16#, FLUSH#, HOLD, IGNNE#
                  INTR, KEN#, NMI, RDY#, RESET, EADS, TCK, TDI, TMS
Vinl = 0.8V
Vinh = 2.0V
********************************************************************************
                  typ                 min                  max
C_comp            1.7pF               1.7pF                1.7pF
[Voltage range]   3.3V                2.8V                 3.6V
********************************************************************************
[GND_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -1.0V          -64.0mA        -77.00mA       -55.00mA
         -0.9V          -47.0mA        -57.54mA       -37.23mA
         -0.8V          -27.0mA        -36.38mA       -17.76mA
         -0.7V          -15.0mA        -22.00mA       -7.60mA
         -0.6V          -7.5mA         -11.00mA       -4.23mA
         -0.5V          -4.0mA         -5.92mA        -2.54mA
         -0.4V          -2.5mA         -4.23mA        -0.85mA
         -0.1V          0.0mA          0.00mA         0.00mA
         0.0V           0.0mA          0.00mA         0.00mA
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         -1.7V          0.0mA          0.00mA         0.0mA
```

```
********************************************************************************
                                  INPUT2 MODEL
********************************************************************************
[Model]            INPUT2
Model_type         Input
Polarity           Non-Inverting
Enable             Active-High
Signals            CLK
Vinl = 0.8V
Vinh = 2.0V
********************************************************************************
                   typ                min                max
C_comp             2.8pF              2.8pF              2.8pF
[Voltage range]    3.3V               2.7V               3.7V
********************************************************************************
[GND_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -1.0V          -64.0mA        -77.00mA       -55.00mA
         -0.9V          -47.0mA        -57.54mA       -37.23mA
         -0.8V          -27.0mA        -36.38mA       -17.76mA
         -0.7V          -15.0mA        -22.00mA       -7.60mA
         -0.6V          -7.5mA         -11.00mA       -4.23mA
         -0.5V          -4.0mA         -5.92mA        -2.54mA
         -0.4V          -2.5mA         -4.23mA        -0.85mA
         -0.1V          0.0mA          0.00mA         0.00mA
         0.0V           0.0mA          0.00mA         0.00mA
[POWER_clamp]
         Voltage        I(typ)         I(min)         I(max)
         -2.7V          14.0mA         18.65mA        9.9mA
         -2.6V          11.2mA         14.90mA        7.5mA
         -2.5V          8.0mA          10.90mA        5.0mA
         -2.4V          4.3mA          6.80mA         2.9mA
         -2.3V          1.6mA          2.80mA         1.0mA
         -2.2V          0.0mA          0.00mA         0.0mA
         -2.1V          0.0mA          0.00mA         0.0mA
         [End]
```

APPENDIX F
BSDL LISTINGS

Below is a listing of a boundary scan description language (BSDL) file for the Write-Back Enhanced IntelDX4™ processor.

This file is provided as an example. Contact Intel for design information for this and other Intel486™ processors. See Section B.5, “Intel486™ Processor Boundary Scan (JTAG),” in Appendix B for a complete description of BSDL instructions and usage.

F.1 WRITE-BACK ENHANCED IntelDX4™ PROCESSOR LISTING

```
-- Copyright Intel Corporation 1993
--*************************************************************************
-- Intel Corporation makes no warranty for the use of its products
-- and assumes no responsibility for any errors which may appear in
-- this document nor does it make a commitment to update the information
-- contained herein.
--*************************************************************************
-- Boundary-Scan Description Language (BSDL Version 0.0) is a de-facto
-- standard means of describing essential features of ANSI/IEEE 1149.1-1990
-- compliant devices.  This language is under consideration by the IEEE for
-- formal inclusion within a supplement to the 1149.1-1990 standard.  The
-- generation of the supplement entails an extensive IEEE review and a formal
-- acceptance balloting procedure which may change the resultant form of the
-- language.  Be aware that this process may extend well into 1993, and at
-- this time the IEEE does not endorse or hold an opinion on the language.
--*************************************************************************
--
-- Write-Back Enhanced IntelDX4(TM) processor BSDL description
-- This file has been electrically verified.
-- ----------------------------------------------------------
-- Rev: 1.3 4/26/95


entity WBE_INTELDX4 is
   generic(PHYSICAL_PIN_MAP : string := "PGA_17x17");

   port (A20M     : in    bit;
         ABUS2    : out   bit;
         ABUS3    : out   bit;
         ABUS     : inout bit_vector (4 to 31); -- Address bus (words)
         ADS      : out   bit;
         AHOLD    : in    bit;
         BE       : out   bit_vector(0 to 3);
         BLAST    : out   bit;
         BOFF     : in    bit;
         BRDY     : in    bit;
         BREQ     : out   bit;
```

```
        BS8      : in    bit;
        BS16     : in    bit;
        CLK      : in    bit;
        CLKMUL   : in    bit;
        DBUS     : inout bit_vector(0 to 31);  -- Data bus
        DC       : out   bit;
        DP       : inout bit_vector(0 to 3);
        EADS     : in    bit;
        FERR     : out   bit;
        FLUSH    : in    bit;
        HLDA     : out   bit;
        HOLD     : in    bit;
        IGNNE    : in    bit;
        INC_PGA  : linkage bit; --Internal NC PGA
        INTR     : in    bit;
        KEN      : in    bit;
        LOCK     : out   bit;
        MIO      : out   bit;
        NC_PGA   : linkage bit; -- No Connect for PGA
        NMI      : in    bit;
        PCD      : out   bit;
        PCHK     : out   bit;
        PLOCK    : out   bit;
        PWT      : out   bit;
        RDY      : in    bit;
        RESET    : in    bit;
        SMI      : in    bit;  -- new
        SMIACT   : out   bit;  -- new
        SRESET   : in    bit;  -- new
        STPCLK   : in    bit;  -- new
        TCK, TMS, TDI : in bit;         -- Scan Port inputs
        TDO      : out   bit;           -- Scan Port output
        UP       : in    bit;
        VCC_PGA  : linkage bit_vector(1 to 23);   -- VCC
        VCC5     : linkage bit; --Reference Voltage
        VOLDET   : linkage bit; --Voltage Detect Pin
        VSS_PGA  : linkage bit_vector(1 to 28);   -- VSS
        WR       : out   bit;
        CACHE    : out   bit;  --New pin
        HITM     : out   bit;  --New pin
        INV      : in    bit;  --New pin
        WB_WT     : in    bit);  --New pin

    use STD_1149_1_1990.all;

    attribute PIN_MAP of WBE_INTELDX4 : entity is PHYSICAL_PIN_MAP;

    constant PGA_17x17 : PIN_MAP_STRING :=        -- Define Pin Out of PGA
         "A20M     : D15, "  &
         "ABUS2    : Q14, "  &
         "ABUS3    : R15, "  &
         "ABUS     : (S16, Q12, S15, Q13, R13, Q11, S13, R12,"  &
```

```
        "            S7,  Q10, S5,  R7,  Q9,  Q3,  R5,  Q4,  Q8,  Q5," &
        "            Q7,  S3,  Q6,  R2,  S2,  S1,  R1,  P2,  P3,  Q1)," &
        "ADS      : S17, "  &
        "AHOLD    : A17, "  &
        "BE       : (K15, J16, J15, F17), "  &
        "BLAST    : R16, "  &
        "BOFF     : D17, "  &
        "BRDY     : H15, "  &
        "BREQ     : Q15, "  &
        "BS8      : D16, "  &
        "BS16     : C17, "  &
        "CACHE    : B12, "  &
        "CLK      : C3,  "  &
        "CLKMUL   : R17, "  &
        "DBUS     : (P1, N2, N1, H2, M3, J2, L2, L3, F2, D1, E3, "  &
        "            C1, G3, D2, K3, F3, J3, D3, C2, B1, A1, B2, "  &
        "            A2, A4, A6, B6, C7, C6, C8, A8, C9, B8),"  &
        "DC       : M15, "  &
        "DP       : (N3,  F1,  H3,  A5), "  &
        "EADS     : B17, "  &
        "FERR     : C14, "  &
        "FLUSH    : C15, "  &
        "HLDA     : P15, "  &
        "HOLD     : E15, "  &
        "IGNNE    : A15, "  &
        "INC_PGA  : A13, "  &
        "INTR     : A16, "  &
        "KEN      : F15, "  &
        "LOCK     : N15, "  &
        "MIO      : N16, "  &
        "NC_PGA   : C13, "  &
        "NMI      : B15, "  &
        "PCD      : J17, "  &
        "PCHK     : Q17, "  &
        "PLOCK    : Q16, "  &
        "PWT      : L15, "  &
        "RDY      : F16, "  &
        "RESET    : C16, "  &
        "SMI      : B10, "  &
        "SMIACT   : C12, "  &
        "SRESET   : C10, "  &
        "STPCLK   : G15, "  &
        "TCK      : A3,  "  &
        "TDI      : A14, "  &
        "TDO      : B16, "  &
        "TMS      : B14, "  &
        "UP       : C11, "  &
        "VCC_PGA  : (R8,  R9,  R10, R11, R14, P16, M2,  M16, L16, K2,  K16, "
&
        "            H16, G2,  G16, E2,  E16, C4,  C5,  B7,  B9,  B11, "
&
        "            R3,  R6),"  &
```

```
        "VCC5     : J1,  "  &
        "VOLDET   : S04, "  &
        "VSS_PGA      : (S6,  S8,  S9,  S10, S11, S12, S14, R4,  Q2,  P17, M1,  "
&
        "            M17, L1,  L17, K1,  K17, H1,  H17, G1,  G17, E1,  E17, "
&
        "            B3,  B4,  B5,  A7,  A9,  A11), "  &
        "WB_WT    : B13, "  &
        "HITM     : A12, "  &
        "INV      : A10, "  &
        "WR       : N17  ";

   attribute Tap_Scan_In of    TDI      : signal is true;
   attribute Tap_Scan_Mode of  TMS      : signal is true;
   attribute Tap_Scan_Out of   TDO      : signal is true;
   attribute Tap_Scan_Clock of TCK      : signal is (25.0e6, BOTH);

   attribute Instruction_Length of WBE_INTELDX4: entity is 4;

   attribute Instruction_Opcode of WBE_INTELDX4: entity is
      "BYPASS  (1111),"    &
      "EXTEST  (0000),"    &
      "SAMPLE  (0001),"    &
      "IDCODE  (0010),"    &
      "RUNBIST (1000),"    &
      "PRIVATE (0011,0100,0101,0110,0111,1001,1010,1011,1100,1101,1110)";

   attribute Instruction_Capture of WBE_INTELDX4: entity is "0001";
   -- there is no Instruction_Disable attribute for WBE_INTELDX4

   attribute Instruction_Private of WBE_INTELDX4: entity is "private";

   attribute Instruction_Usage of WBE_INTELDX4: entity is
      "RUNBIST (registers BIST; "     &
      "IR SCAN MUST BE DONE WITH DEVICE IN HARD RESET;" &
      "Assert RESET and do IR Scan, then release RESET and do DR Scan;" &
      "result 0=pass, 1=fail;"        &
      "clock CLK in Run_Test_Idle;"   &
      "IR End State = Pause-IR;"      &
      "DR End State = Run-Test/Idle;" &
      "RINBIST length in hex = 125000H x ratio of TCK/CPUCLK)";


   attribute Idcode_Register of WBE_INTELDX4: entity is
      "0001"                  &  --version
      "1000001010001000"      &  -- WBE_INTELDX4 part ID
      "00000001001"           &  --manufacturers identity
      "1";                       --required by the standard
--
--
   attribute Register_Access of WBE_INTELDX4: entity is
      "BIST[1] (RUNBIST)" ;
```

```
--{*********************************************************************}
--{  The first cell is closest to TDO                                   }
--{*********************************************************************}


   attribute Boundary_Cells of WBE_INTELDX4: entity is "BC_2, BC_1, BC_6";
   attribute Boundary_Length of WBE_INTELDX4: entity is 113;
   attribute Boundary_Register of WBE_INTELDX4: entity is
      "0   (BC_2,  ABUS2,      output3, X,  111,  1,  Z)," &
      "1   (BC_2,  ABUS3,      output3, X,  111,  1,  Z)," &
      "2   (BC_6,  ABUS(4),    bidir,  X,  111,  1,  Z)," &
      "3   (BC_6,  ABUS(5),    bidir,  X,  111,  1,  Z)," &
      "4   (BC_1,  UP ,        input,  X)," &
      "5   (BC_6,  ABUS(6),    bidir,  X,  111,  1,  Z)," &
      "6   (BC_6,  ABUS(7),    bidir,  X,  111,  1,  Z)," &
      "7   (BC_6,  ABUS(8),    bidir,  X,  111,  1,  Z)," &
      "8   (BC_6,  ABUS(9),    bidir,  X,  111,  1,  Z)," &
      "9   (BC_6,  ABUS(10),   bidir,  X,  111,  1,  Z)," &
      "10  (BC_6,  ABUS(11),   bidir,  X,  111,  1,  Z)," &
      "11  (BC_6,  ABUS(12),   bidir,  X,  111,  1,  Z)," &
      "12  (BC_6,  ABUS(13),   bidir,  X,  111,  1,  Z)," &
      "13  (BC_6,  ABUS(14),   bidir,  X,  111,  1,  Z)," &
      "14  (BC_6,  ABUS(15),   bidir,  X,  111,  1,  Z)," &
      "15  (BC_6,  ABUS(16),   bidir,  X,  111,  1,  Z)," &
      "16  (BC_6,  ABUS(17),   bidir,  X,  111,  1,  Z)," &
      "17  (BC_6,  ABUS(18),   bidir,  X,  111,  1,  Z)," &
      "18  (BC_6,  ABUS(19),   bidir,  X,  111,  1,  Z)," &
      "19  (BC_6,  ABUS(20),   bidir,  X,  111,  1,  Z)," &
      "20  (BC_6,  ABUS(21),   bidir,  X,  111,  1,  Z)," &
      "21  (BC_6,  ABUS(22),   bidir,  X,  111,  1,  Z)," &
      "22  (BC_6,  ABUS(23),   bidir,  X,  111,  1,  Z)," &
      "23  (BC_6,  ABUS(24),   bidir,  X,  111,  1,  Z)," &
      "24  (BC_6,  ABUS(25),   bidir,  X,  111,  1,  Z)," &
      "25  (BC_6,  ABUS(26),   bidir,  X,  111,  1,  Z)," &
      "26  (BC_6,  ABUS(27),   bidir,  X,  111,  1,  Z)," &
      "27  (BC_6,  ABUS(28),   bidir,  X,  111,  1,  Z)," &
      "28  (BC_6,  ABUS(29),   bidir,  X,  111,  1,  Z)," &
      "29  (BC_6,  ABUS(30),   bidir,  X,  111,  1,  Z)," &
      "30  (BC_6,  ABUS(31),   bidir,  X,  111,  1,  Z)," &
      "31  (BC_6,  DP(0),      bidir,  X,  112,  1,  Z)," &
      "32  (BC_6,  DBUS(0),    bidir,  X,  112,  1,  Z)," &
      "33  (BC_6,  DBUS(1),    bidir,  X,  112,  1,  Z)," &
      "34  (BC_6,  DBUS(2),    bidir,  X,  112,  1,  Z)," &
      "35  (BC_6,  DBUS(3),    bidir,  X,  112,  1,  Z)," &
      "36  (BC_6,  DBUS(4),    bidir,  X,  112,  1,  Z)," &
      "37  (BC_6,  DBUS(5),    bidir,  X,  112,  1,  Z)," &
      "38  (BC_6,  DBUS(6),    bidir,  X,  112,  1,  Z)," &
      "39  (BC_6,  DBUS(7),    bidir,  X,  112,  1,  Z)," &
      "40  (BC_6,  DP(1),      bidir,  X,  112,  1,  Z)," &
      "41  (BC_6,  DBUS(8),    bidir,  X,  112,  1,  Z)," &
      "42  (BC_6,  DBUS(9),    bidir,  X,  112,  1,  Z)," &
```

```
"43  (BC_6,  DBUS(10),   bidir,  X,  112,  1,  Z),"   &
"44  (BC_6,  DBUS(11),   bidir,  X,  112,  1,  Z),"   &
"45  (BC_6,  DBUS(12),   bidir,  X,  112,  1,  Z),"   &
"46  (BC_6,  DBUS(13),   bidir,  X,  112,  1,  Z),"   &
"47  (BC_6,  DBUS(14),   bidir,  X,  112,  1,  Z),"   &
"48  (BC_6,  DBUS(15),   bidir,  X,  112,  1,  Z),"   &
"49  (BC_6,  DP(2),      bidir,  X,  112,  1,  Z),"   &
"50  (BC_6,  DBUS(16),   bidir,  X,  112,  1,  Z),"   &
"51  (BC_6,  DBUS(17),   bidir,  X,  112,  1,  Z),"   &
"52  (BC_6,  DBUS(18),   bidir,  X,  112,  1,  Z),"   &
"53  (BC_6,  DBUS(19),   bidir,  X,  112,  1,  Z),"   &
"54  (BC_6,  DBUS(20),   bidir,  X,  112,  1,  Z),"   &
"55  (BC_6,  DBUS(21),   bidir,  X,  112,  1,  Z),"   &
"56  (BC_6,  DBUS(22),   bidir,  X,  112,  1,  Z),"   &
"57  (BC_6,  DBUS(23),   bidir,  X,  112,  1,  Z),"   &
"58  (BC_6,  DP(3),      bidir,  X,  112,  1,  Z),"   &
"59  (BC_6,  DBUS(24),   bidir,  X,  112,  1,  Z),"   &
"60  (BC_6,  DBUS(25),   bidir,  X,  112,  1,  Z),"   &
"61  (BC_6,  DBUS(26),   bidir,  X,  112,  1,  Z),"   &
"62  (BC_6,  DBUS(27),   bidir,  X,  112,  1,  Z),"   &
"63  (BC_6,  DBUS(28),   bidir,  X,  112,  1,  Z),"   &
"64  (BC_6,  DBUS(29),   bidir,  X,  112,  1,  Z),"   &
"65  (BC_6,  DBUS(30),   bidir,  X,  112,  1,  Z),"   &
"66  (BC_6,  DBUS(31),   bidir,  X,  112,  1,  Z),"   &
"67  (BC_1,  STPCLK,     input, X),"   &
"68  (BC_1,  IGNNE,      input, X),"   &
"69  (BC_1,  INV,        input, X),"   &
"70  (BC_2,  CACHE,      output3, X,  110,  1,  Z),"   &
"71  (BC_2,  FERR,       output3, X,  109,  1,  Z),"   &
"72  (BC_1,  SMI ,       input, X),"   &
"73  (BC_1,  WB_WT ,      input, X),"   &
"74  (BC_2,  HITM ,      output3, X,  109,  1,  Z),"   &
"75  (BC_2,  SMIACT ,    output3, X,  109,  1,  Z),"   &
"76  (BC_1,  SRESET ,    input, X),"   &
"77  (BC_1,  NMI,        input, X),"   &
"78  (BC_1,  INTR,       input, X),"   &
"79  (BC_1,  FLUSH,      input, X),"   &
"80  (BC_1,  RESET,      input, X),"   &
"81  (BC_1,  A20M,       input, X),"   &
"82  (BC_1,  EADS,       input, X),"   &
"83  (BC_2,  PCD,        output3, X,  110,  1,  Z),"   &
"84  (BC_2,  PWT,        output3, X,  110,  1,  Z),"   &
"85  (BC_2,  DC,         output3, X,  110,  1,  Z),"   &
"86  (BC_2,  MIO,        output3, X,  110,  1,  Z),"   &
"87  (BC_2,  BE(3),      output3, X,  110,  1,  Z),"   &
"88  (BC_2,  BE(2),      output3, X,  110,  1,  Z),"   &
"89  (BC_2,  BE(1),      output3, X,  110,  1,  Z),"   &
"90  (BC_2,  BE(0),      output3, X,  110,  1,  Z),"   &
"91  (BC_2,  BREQ,       output3, X,  109,  1,  Z),"   &
"92  (BC_2,  WR,         output3, X,  110,  1,  Z),"   &
"93  (BC_2,  HLDA,       output3, X,  109,  1,  Z),"   &
"94  (BC_1,  CLK,         input, X),"   &
```

```
      "95  (BC_1,  AHOLD,       input, X),"   &
      "96  (BC_1,  HOLD,        input, X),"   &
      "97  (BC_1,  KEN,         input, X),"   &
      "98  (BC_1,  RDY,         input, X),"   &
      "99  (BC_1,  CLKMUL,      input, X),"   &
      "100 (BC_1,  BS8,         input, X),"   &
      "101 (BC_1,  BS16,        input, X),"   &
      "102 (BC_1,  BOFF,        input, X),"   &
      "103 (BC_1,  BRDY,        input, X),"   &
      "104 (BC_2,  PCHK,       output3, X,  109,  1,  Z),"   &
      "105 (BC_2,  LOCK,       output3, X,  110,  1,  Z),"   &
      "106 (BC_2,  PLOCK,      output3, X,  110,  1,  Z),"   &
      "107 (BC_2,  BLAST,      output3, X,  110,  1,  Z),"   &
      "108 (BC_2,  ADS,        output3, X,  110,  1,  Z),"   &
      "109 (BC_2,  *,          control, 1),"   &            -- DISMISC
      "110 (BC_2,  *,          control, 1),"   &            -- DISBUS
      "111 (BC_2,  *,          control, 1),"   &            -- DISABUS
      "112 (BC_2,  *,          control, 1)";                -- DISWR

end WBE_INTELDX4;
```

APPENDIX G
SYSTEM DESIGN NOTES

G.1 SMM ENVIRONMENT INITIALIZATION

When the Intel486™ processors are operating in Real Mode, the physical address at which instructions and data are fetched is determined by the segment register and an offset (i.e., CS and IP for instructions). When a new value is loaded into a segment register, the new value is shifted to the left by four bits and stored in a segment base register that corresponds to that particular segment (CSBASE, DSBASE, ESBASE, etc.). It is the value stored in the segment base register that is used to generate a physical address. For example, the linear address to be used for fetching instructions is determined by adding the value contained in the CS segment base register with the value in the IP register.

When the processor is in Protected Mode, the segment registers are used as selectors to a descriptor table. Each descriptor in a descriptor table contains information about the segment in use, including the segment's BASE address (i.e., CSBASE) and limit (the size of the segment), as well as the protection level, privileges, operand sizes, and the segment type. In Protected Mode, the linear address is determined by adding the base portion of the descriptor to the appropriate offset.

When in System Management Mode, the processor operates in a pseudo-Real Mode, with address calculation performed in the Real Mode manner. However, the processor adds the value in the segment base register with the value in the EIP register, rather than the IP register, so there are no limits as to the segment size. The physical address of an instruction is obtained by adding the value in CSBASE to the value in EIP.

When entering SMM, it may be necessary to initialize the segment registers to point to SMRAM (see Section 8.4.2, "Processor Environment" for their value on SMM entry). If SMBASE has not been relocated, then the necessary segment registers can be initialized to point to SMRAM by using the value in the CS register, 3000H, which points to the SMRAM address space.

When an SMI# occurs after SMBASE has been modified, CSBASE is loaded with the new value of SMBASE. However, the CS selector register still contains the value 3000H, not the value corresponding to the new SMBASE.

To initialize segment registers to point to the new SMRAM area, read the SMBASE value from the SMM state that was saved in memory. Because the data segment registers are initialized to 0, do not use them to access the SMM state save area. Instead, perform a read relative to the CS register by using a CS override prefix to a normal memory read. Although CS still contains 3000H, CSBASE contains the value of SMBASE, and CSBASE is used for the address generation.

Once the value of SMBASE is obtained, it must be shifted to the right by four bits to get the appropriate value to be placed in the segment registers. The CS register itself can be initialized by executing a far jump instruction to an address within SMBASE, which causes CS to be reloaded with a value corresponding to SMBASE.

Example E-1 describes one method of initializing the segment registers when SMBASE has been relocated. This method works if SMBASE is less than 1 Mbyte.

Example G-1. Initialization of Segment Registers within SMM

```
;read the value of SMBASE from the state save area
   movsi,FEF8H;SMBASE slot in SMM state save area
   moveax,cs:[si];copy SMBASE from SMBASE:FEF8H to eax

;scale the SMBASE value to a 16-bit quantity
   movcl,4
   roreax,cl           ;scaled value of SMBASE now in ax

;to load cs, execute a far jump to an address that has been stored
;at memory location PTR_ADDR

;store the SMBASE value and an offset to a memory location that can be used as
;an indirect jump address

   movdi,PTR_ADDR;PTR_ADDR is the location used to
        ;store the jump address
   movbx,OFFSET;OFFSET is the address where
        ;execution continues after the
        ;far jump

   movcs:[di],bx;store the offset for the far jump
   incdi
   incdi
   movcs:[di],ax;store the segment address for the
        ;far jump, which is SMBASE
   movbx,PTR_ADDR;bx now contains the address of the
        ;location holding the jump address

;initialize DS and ES with the correct address of SMBASE
   movds,ax
   moves,ax

;execute a far jump instruction to load the CS register
   jmpfar [bx];jump to address stored at memory
        ;location pointed to by bx

;CS now contains the correct value of SMBASE, and execution continues from the
;address SMBASE:OFFSET
```

G.2 ACCESSING SMRAM

G.2.1 Loading SMRAM with an Initial SMI Handler

Under normal conditions, the SMRAM address space should be accessible by the processor only while it is in SMM mode. However, some provision must be made for invoking the initial SMM interrupt handler routine.

Because System Management Mode must be transparent to all operating systems, the initial SMM handler must be loaded by the system BIOS. At some time during the power on sequence, the system BIOS must move the SMM handler routine from the BIOS ROM to the SMRAM. The system designer must provide a hardware mechanism that allows access to SMRAM while SMIACT# from the processor is inactive. One method is to provide an I/O port in the memory controller that forces memory cycles at a given address to be relocated to the SMRAM. Once the initial SMM handler has been loaded to SMRAM, the I/O port is disabled to protect against accidental accesses to SMRAM.

The system BIOS must provide an SMM handler at the address 38000H. If the system design takes advantage of the SMRAM relocation feature of the processor, this handler must change the SMBASE register in the SMM state save. Next, the BIOS must move the full featured SMM handler to the new address. An SMI# must be generated to change the SMBASE register before the BIOS passes control to the operating system.

G.2.2 SMRAM Hidden from DMA and Bus Masters

In a system that allows DMA or other devices to take control of the system bus, care must be taken to ensure that only the master processor can access SMRAM. When an external bus master requests use of the system bus (by asserting HOLD or BOFF#) while the processor is executing an SMM handler routine, the processor responds by passing control of the bus to the requesting device. The system memory controller must redirect any memory accesses that are not generated by the processor to normal system memory as if SMIACT# were inactive.

DMA accesses to the SMRAM area must be redirected to the correct address space when the initialization routine is loading SMRAM, as well as when the processor is in SMM.

It is not recommended to block bus control requests when in SMM, because the increased bus access latency could cause compatibility issues with some software or expansion hardware.

G.2.3 Accessing System Memory from within SMM

In order to enter a suspend state in which power is removed from some or all of system memory, it is necessary for the processor to have access to the entire system address space from within SMM. Access to system memory from within SMM requires that the memory controller decode both SMIACT# and the processor address to determine accesses to SMRAM. Only those memory addresses that are defined as being SMRAM space are directed to SMRAM. If SMRAM is located at an address that overlays normal system memory address space (see Section 8.6.1, “SMRAM Interface”), the processor must have a method of accessing both SMRAM (for code reads) and system memory simultaneously.

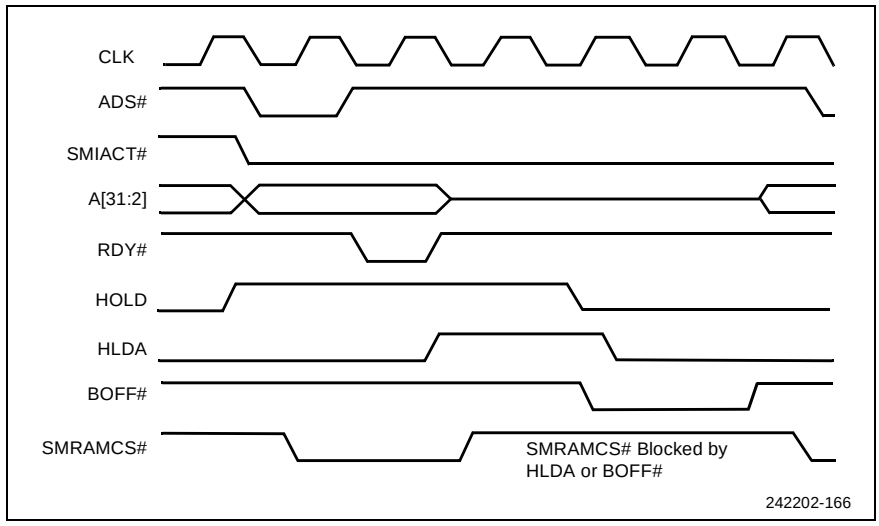

Figure G-1. Blocking Other Bus Masters from Accessing SMRAM

G.2.3.1 Hardware Method

Ideally, a method of accessing system memory that is mapped underneath SMRAM is provided by the system memory controller. The memory controller would provide a register that allows system memory at a given address to be remapped to a different address, which is not overlaid by SMRAM. When the SMM handler implements a suspend, it would first move all of system memory that is not underneath SMRAM to a non-volatile medium (such as a hard disk drive). Next, the SMRAM image would be transferred to the non-volatile medium. Finally, the memory underneath SMRAM would be accessed and copied to the non-volatile medium with a processor read to the remap address space, which is redirected to the overlaid system memory (see Figure G-2).

If the memory controller does not provide a method of accessing overlaid system memory, it is possible to implement a software procedure to accomplish the same goal. However, the software method is complex; a hardware method is preferred. A description of the software method follows.

G.2.3.2 Software Method

The ability to access the system memory that is located in the address space under SMRAM requires a method of resuming from SMM to a predetermined address space. This can be accomplished with the following procedure.

When resuming from SMM, the processor continues execution at the address contained in the CS and EIP slots within the SMM state save. However, the resume address cannot be changed by simply modifying the CS and EIP slots, because the processor uses the CS descriptor to determine the actual resume address. The descriptor registers are stored in reserved slots in the SMM state save, and they cannot be directly modified.

By replacing the suspend state save with a previously obtained image of a state save that returns to a known location, the SMM suspend handler can force a return to a given address, as explained in the following sequence:

1. During initial system power up, execute an SMI# from a predetermined address (the address immediately preceding the address to which you later wish to resume). This can be accomplished by generating an SMI# in response to an I/O instruction or executing a halt instruction and using an SMI# to exit the halt state.
2. Save the state save from this SMM to a safe location (SMRAM).
3. When the system must resume to a given address from another SMI#, the stored state save can be substituted for the state save generated from that particular SMM.

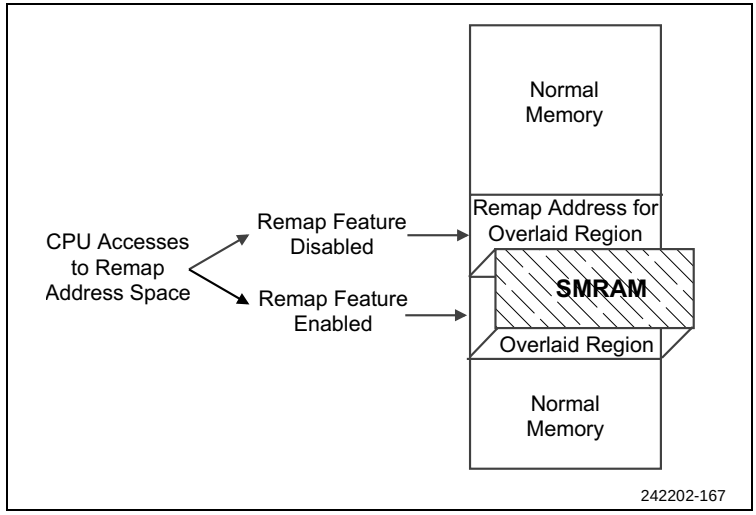

Figure G-2. Remapping Memory that is Overlaid by SMRAM

Now that SMM can be resumed at a predetermined address, access the entire system memory space from within SMM before executing a suspend:

1. During a suspend SMM, save all system memory except that which is located underneath SMRAM to a specified (and reserved) section of the hard disk. The ability to access system memory requires the memory controller to decode both SMIACT# and the processor address, and direct a limited section (64 or 128 Kbytes) of the processor address space to SMRAM. All other processor memory accesses should go to normal system memory.
2. Save the contents of the SMM state save to the hard disk.

3. Modify the SMM state save so the RSM instruction returns to a predefined address, that is not in the application that was interrupted. The code at this address must contain the remainder of the suspend SMM handler. The predefined address can be anywhere in the processor address space, because the contents of system memory have already been saved to disk.
4. Execute an RSM instruction, which exits SMM and returns control to a predetermined address (that must contain the rest of the SMM suspend handler).
5. Save the rest of system memory (that which is located underneath SMRAM) to the hard disk. This address space can now be accessed with normal move instructions, because we are no longer in SMM.
6. Save a flag (in CMOS memory) to indicate that the next reset should cause a resume from suspend.
7. Power-down the memory (and possibly the processor).
8. When power is restored, the processor is reset and begins execution of the power on self-test (POST) in BIOS. Early in the POST, the system should check the status of the suspend flag.
9. Load a preliminary SMM handler to location 38000H and generate an SMI#. The SMM handler should read the SMBASE slot from the SMM state save that was stored to hard disk. SMBASE is then modified to point to the final SMRAM location and the system resumes from SMM to the system BIOS.
10. Restore the contents of system memory located underneath SMRAM from the hard disk.
11. Generate a second SMI#, which executes an SMM handler at the original value of SMBASE (before the suspend SMM). The SMM handler restores the contents of the rest of system memory from the hard disk, and then restores the original SMM state save to the SMM state save area in SMRAM, discarding the most recent SMM state save.
12. Execute an RSM instruction, which returns execution to the application that was interrupted by the suspend request.

G.3 INTERRUPTS AND EXCEPTIONS DURING SMM HANDLER ROUTINES

To ensure transparency to existing system software, the SMM handler should not depend on interrupt or exception handlers provided by the operating system. However, in some cases it may be necessary to service interrupts or exceptions while in System Management Mode. In these cases, SMM-compliant interrupt and exception handlers, as well as an SMM-compliant interrupt vector table, should be provided.

G.3.1 SMM-Compliant Vector Tables

An SMI# interrupt request can be generated while code is running under any of the other three processor operating modes (Real, Virtual-86, or Protected). When entering the SMM handler, the processor enters a pseudo-real mode, and the beginning of the interrupt vector table must be located at the address 00000000H. Before allowing any interrupts or exceptions to occur, the SMM handler routine must provide a valid interrupt vector table. Any code that is executed before setting up an SMM-compliant interrupt vector table must be written carefully to ensure that no exceptions are generated.

The system memory controller could relocate accesses to the SMM interrupt vector table to a location within SMRAM. In this case, when SMIACT# is active, all accesses to the lowest 1 Kbyte of the processor address space would be redirected to SMRAM, which would contain an SMM-compliant vector table that has already been initialized.

If the system memory controller does not redirect interrupt vector table reads to an address within SMRAM, there are three steps required to provide an SMM-compliant interrupt vector table:

1. Save the contents of memory to SMRAM at address 00000000H.
2. Provide vectors for any possible interrupts or exceptions at the appropriate location in the vector table.
3. Restore the original memory contents from SMRAM before exiting the SMM handler routine.

G.3.2 Interrupts and Subroutines with SMRAM Relocation

There is an additional issue that must be considered if interrupts or exceptions are to be executed within SMM and SMRAM has been relocated. Interrupt or subroutine calls from within SMM operate in a manner similar to Real Mode. When a subroutine is called or an interrupt is recognized, the 16-bit CS and IP registers are pushed onto the stack to provide a return address.

When SMRAM is relocated to an address space above 1 Mbyte and an interrupt or subroutine call occurs, only 16 bits of the EIP register are pushed onto the stack. When returning from the subroutine or interrupt, the processor vectors to a location where the upper 16 bits of EIP are zero. This can be avoided for subroutines by using an address size override before calling the subroutine. However, the issue remains for interrupts.

G.4 IntelDX2™ AND IntelDX4™ PROCESSOR FLOATING-POINT OPERATION AND SMM

G.4.1 The Need to Save the FPU Environment

When the processor enters System Management Mode, the context information for the interrupted application is automatically saved to a specific state save address. When the SMM handler returns control to the interrupted application by executing the RSM instruction, the context information from the interrupted application is restored to the processor by reading from the state save location. This mechanism allows the SMM handler routine to modify most of the processor registers without the need to explicitly save them to memory. However, the registers in the processor's Floating-Point Unit (FPU) are not automatically saved when the processor enters SMM. If the SMM handler must modify any of the registers in the FPU, or if the register data will be lost due to entering a power down state, the SMM handler must first explicitly save the FPU state as it existed in the interrupted application.

There are two instances in which an SMM handler routine must be aware of the Floating-Point Unit (FPU):

1. When removing power from the processor / FPU for the purpose of executing a suspend sequence.
2. When the SMM handler uses FPU instructions.

In both of these cases, the SMM handler must save the state of the FPU as it was left by the interrupted application.

The information stored by the FPU state save instructions (FSAVE, FNSAVE, FSTENV, and FNSTENV) is dependent on the operating mode of the processor. The FPU state save instructions store the FPU state information in one of four formats: 16-bit Real Mode, 32-bit Real Mode, 16-bit Protected Mode, or 32-bit Protected Mode, depending on the processor operating mode. The content of the information saved also varies slightly, depending on the processor operating mode in which the save instruction was executed. For example, the 32-bit Protected Mode FNSAVE instruction saves the address of the last executed FPU instruction and its operands in the form of a segment selector and a 32-bit offset. In contrast, the 16-bit Real Mode FNSAVE instruction saves the address information in the form of a 20-bit physical address. Because the format in which the FPU state restore instructions (FRSTOR and FLDENV) recall the information also depends on the operating mode of the processor, the save and restore instructions must be executed from the same processor operating mode.

G.4.2 Saving the State of the Floating-Point Unit

When an SMM handler routine must save the state of the Floating-Point Unit, it must save all FPU state information necessary for the interrupted application to continue processing. This state information includes the contents of the Floating-Point Unit stack, which requires use of the FNSAVE or FSAVE instruction (FSTENV does not save the contents of the FPU stack). If the last executed non-control floating-point instruction caused an error (such as a divide by 0), the saved information must also include the address of the failing instruction and the addresses of any operands for that instruction. Without these addresses, it would be impossible for the FPU exception handler of the interrupted application to correct the error and restart the instruction.

The FNSAVE and FSAVE instructions differ in that FNSAVE does not wait for the FPU to check for an existing error condition before storing the FPU environment information. If an unmasked FPU exception condition is pending, execution of the FSAVE instruction forces the processor to wait until the error condition is cleared by the software exception handler. Because the processor is in System Management Mode, the appropriate exception handler is not available, and the FPU error is not corrected in the manner expected by the interrupted application program. For this reason, the FNSAVE instruction should be used when saving the environment of the FPU within SMM.

Because the SMM handler does not know the processor mode in which the interrupted application was executing (16- or 32-bit, Real or Protected), the SMM handler must execute the FNSAVE instruction in a mode in which all FPU state information is stored. The 32-bit Protected Mode format of the FNSAVE instruction is a superset of all other formats of the FNSAVE instruction. Therefore, executing the 32-bit Protected Mode FNSAVE instruction ensures that all FPU state information is saved.

Executing the FNSAVE instruction in 32-bit Protected Mode requires that the processor be temporarily placed in Protected Mode. Rather than perform all of the setup details and overhead necessary to place the processor into Protected Mode, including the initialization of all descriptors and descriptor tables, it is possible to temporarily place the processor into Protected Mode for the purpose of executing only a few carefully written instructions. This can be accomplished by setting the PE bit in the CR0 register, and then executing a short jump to clear the instruction pipelines.

It is important to note that any instruction that modifies a segment register will cause the processor to attempt to load a new descriptor from the descriptor table. (The occurrence of an interrupt or an exception would cause the processor to load a new descriptor, so interrupts must be disabled during this sequence.) Because neither the descriptors nor the descriptor table have been initialized, this would cause the system to crash. Therefore, all segment registers that are to be used in the FPU state save instructions must be initialized before entering Protected Mode.

Example G-2 is an example of code that can be used to place the processor in Protected Mode and save the FPU state.

Note that the no wait form (FNSAVE) of the save instruction must be used. In the event that the previous FPU instruction caused a Floating-Point error, we do not want to wait for this error to be serviced before executing the save instruction. Additionally, if the FSAVE instruction were used, the operand size override prefix would be incorrectly applied to the implicit WAIT instruction that precedes FSAVE, rather than to the save instruction itself.

Before exiting the SMM handler and returning to the interrupted application, the register contents of the Floating-Point Unit must be returned to their previous values. This can be accomplished by executing the 32-bit Protected Mode format of the FRSTOR instruction. Example G-3 gives an example code segment that can be used to restore the FPU to the state in which it was interrupted by the SMI request.

Note that the no wait form (FNRSTOR) of the restore instruction must be used. If the FRSTOR instruction were used, the operand size override prefix would be incorrectly applied to the implicit WAIT instruction that precedes FRSTOR, rather than to the save instruction itself.

G.5 SUPPORT FOR POWER-MANAGED PERIPHERALS

G.5.1 Shadow Registers

Before power is removed from any device, the state of that device must be saved in a protected memory space so that the device can be reinitialized to its previous state. If a peripheral contains a write-only register, the value in that register can be recovered by providing shadow registers that are both readable and writeable.

These shadow registers should be updated every time the peripheral registers are written, but they have no function other than tracking the data written to a particular register.

Example G-2. Saving the FPU State in 32-Bit Protected Mode

```
;first initialize the registers used to store the state save information
   movdx,SEGMENT       ;SEGMENT is the segment to be used by
                       ;the save instruction,
   movds,dx            ; normally it should point to SMRAM
   movsi,OFFSET        ;OFFSET is the offset used in the save
                       ;instruction

;set the PE bit in CR0
   moveax,cr0          ;read the old value of CR0
   or eax,00000001H    ;set the PE bit
   movcr0, eax

;enter protected mode by executing a short jump to clear the prefetch queue
   jmpprotect
protect:

;we can now save the state of the FPU in the protected mode format

   db 66H              ;use an operand size override prefix
                       ;to set 32-bit format
   fnsave[si]              ;FPU state saved to SEGMENT:OFFSET

;now return to real mode to continue with the SMM handler (no jump is
;required)

   moveax,cr0          ;clear the PE bit in CR0
   andeax,0FFFFFFFEH
   movcr0,eax
```

In addition to the write only registers in a system, there are several other registers that must be shadowed. Any device that requires registers to be programmed in a particular sequence must also have its registers shadowed. Examples in a typical personal computer include the programmable interrupt controller, the DMA controller, and the programmable timer/counter.

It is also possible to perform shadowing of some write only registers using SMM. Any time a write cycle is generated to a write only register, the system can generate an SMI#. The SMM handler can use the processor state information saved in the SMM state save to save the data from the interrupted I/O cycle to a predetermined location in the SMRAM space.

Example G-3. Restoring the FPU State from a 32-Bit Protected Mode Save

```
;first initialize the registers used to recall the state save information

   movdx,SEGMENT       ;SEGMENT is the segment to be used by
                           ;the restore instruction,
   movds,dx                ;normally it should point to SMRAM
   movsi,OFFSET        ;OFFSET is the offset used in the
                           ;restore instruction

;set the PE bit in CR0

   moveax,cr0          ;read the old value of CR0
   or eax,00000001H;set the PE bit
   movcr0, eax

;enter protected mode by executing a short jump to clear the prefetch queue

   jmpprotect
protect:

;we can now recall the state of the FPU from the previous FNSAVE instruction
;(in the protected mode format)

   db 66H                  ;use an operand size override prefix
                           ;to set 32-bit format
   fnrstor[si]         ;FPU state restored from
                           ;SEGMENT:OFFSET

;now return to real mode to continue with the SMM handler (no jump is
;required)

   moveax,cr0;clear the PE bit in CR0
   andeax,FFFFFFFEH
   movcr0,eax
```

The information contained in the SMM state save can be used (with the knowledge that the SMI# was in response to an I/O write instruction) to determine both the address and the data of the interrupted write instruction. The SMM handler can examine the OPCODEs of previous instructions by decrementing the IP (or EIP) register. Once the correct OPCODE is determined, it can be used with the values in the EAX and DX slots of the SMM state save to update the information in the memory used to shadow the I/O register. I/O write instructions occur in one of three forms: 1) a write to an address that is specified in the OPCODE; 2) a write to an address contained in the DX register; or 3) a string write to an address contained in the DX register.

The I/O write instructions have the following OPCODEs:

Table G-1. TI/O Write Instruction OPCODEs

Instruction	OPCODE	Notes
OUT x,al	E6x	x is the address of the I/O port
OUT x,ax	E7x	x is the address of the I/O port
OUT x,eax	E7x	x is the address of the I/O port
OUT dx,al	EE	
OUT dx,ax	EF	
OUT dx,eax	EF	
OUTSB	6E	
OUTSW	6F	
OUTSD	6F	

The SMM handler must know whether a particular I/O port is 16 or 32 bits in order to distinguish between 16 and 32 bit I/O write cycles.

The SMM handler can decrement the value of IP contained in the state save, and then examine the memory contents at that address. If the SMM handler knows that the last instruction was an I/O write instruction, and writes to I/O addresses 6EH, 6FH, 0EEH, and 0EFH will not cause an SMI#, it can use the SMM state save data for EAX and EDX to reconstruct the last instruction.

G.5.2 Handling Interrupted I/O Write Sequences

In a typical personal computer, there are several hardware devices that require the control registers for that device to be programmed in a particular order. For example, the interrupt controller, the DMA controller, the programmable timer/counter, the keyboard controller, and the real time clock all require a series of accesses to properly initialize the registers in that particular device. Some of these devices may require successive accesses to registers located at different addresses, while others may require several control registers to be programmed through write cycles to the same address.

If an SMI request interrupts an application that is in the process of initializing the registers in one of these devices, special care must be taken to ensure that the peripheral is returned to its original state when control is returned to the interrupted program. For some SMM handler events, it may be necessary to power down the device or change the state of a register within the device. In these cases, the SMM handler must return control to the interrupted application in such a way that the application can continue with the correct sequential access in the interrupted sequence.

To accomplish this, the SMM handler must restore the original values of all registers in the device, and restart the interrupted sequence so that the application may continue where it left off. This requires system hardware to shadow all registers that need to be accessed in the sequence, keep an index indicating which position in the sequence the register occupies, and keep a pointer so that SMM software knows to which register the last access was directed. This pointer would indicate the last register of each sequence that was programmed in the particular peripheral.

For example, programming the master interrupt controller requires a write to I/O port 20H (ICW1) followed by four write cycles to I/O port 21H (ICW2, ICW3, ICW4, and OCW1). If this sequence is interrupted by an SMI request, and the resulting SMM handler either modifies or powers down the interrupt controller, the SMM handler must return control to the interrupted application such that the following access to the interrupt controller would access the correct register in the sequence. System hardware must save the contents of each of the registers, as well as a pointer indicating which register was last written.

Before returning control to the interrupted application, the SMM handler must initialize ICW1–ICW4 and OCW1 to their previous values. It would then re-write the appropriate registers so that the first access by the application program would be to the location in the sequence following the last location it programmed before it was interrupted by the SMI request.

A similar procedure must be followed for each of the peripherals that require control registers to be initialized in a particular order.

A

B

C

D

E

F

G

H

I

R

S

T

U

V

W