

AMD Athlon™ Processor

x86 Code Optimization

Guide



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Contents

	Revision History	xv
1	Introduction	1
	About this Document	1
	AMD Athlon™ Processor Family	3
	AMD Athlon Processor Microarchitecture Summary	4
2	Top Optimizations	7
	Optimization Star	8
	Group I Optimizations — Essential Optimizations	8
	Memory Size and Alignment Issues	8
	Use the 3DNow!™ PREFETCH and PREFETCHW Instructions	8
	Select DirectPath Over VectorPath Instructions	9
	Group II Optimizations—Secondary Optimizations	9
	Load-Execute Instruction Usage	9
	Take Advantage of Write Combining	10
	Use 3DNow! Instructions	10
	Avoid Branches Dependent on Random Data	10
	Avoid Placing Code and Data in the Same 64-Byte Cache Line	11
3	C Source Level Optimizations	13
	Ensure Floating-Point Variables and Expressions are of Type Float	13
	Use 32-Bit Data Types for Integer Code	13
	Consider the Sign of Integer Operands	14
	Use Array Style Instead of Pointer Style Code	15
	Completely Unroll Small Loops	18
	Avoid Unnecessary Store-to-Load Dependencies	18
	Consider Expression Order in Compound Branch Conditions	20

Switch Statement Usage	21
Optimize Switch Statements	21
Use Prototypes for All Functions	21
Use Const Type Qualifier	22
Generic Loop Hoisting	22
Generalization for Multiple Constant Control Code	23
Declare Local Functions as Static	24
Dynamic Memory Allocation Consideration	25
Introduce Explicit Parallelism into Code	25
Explicitly Extract Common Subexpressions	26
C Language Structure Component Considerations	27
Sort Local Variables According to Base Type Size	28
Accelerating Floating-Point Divides and Square Roots	29
Avoid Unnecessary Integer Division	31
Copy Frequently De-referenced Pointer Arguments to Local Variables	31
4 Instruction Decoding Optimizations	33
Overview	33
Select DirectPath Over VectorPath Instructions	34
Load-Execute Instruction Usage	34
Use Load-Execute Integer Instructions	34
Use Load-Execute Floating-Point Instructions with Floating-Point Operands	35
Avoid Load-Execute Floating-Point Instructions with Integer Operands	35
Align Branch Targets in Program Hot Spots	36
Use Short Instruction Lengths	36
Avoid Partial Register Reads and Writes	37
Replace Certain SHLD Instructions with Alternative Code	38
Use 8-Bit Sign-Extended immediates	38

Use 8-Bit Sign-Extended Displacements	39
Code Padding Using Neutral Code Fillers	39
Recommendations for the AMD Athlon Processor	40
Recommendations for AMD-K6® Family and AMD Athlon Processor Blended Code	41
5 Cache and Memory Optimizations	45
Memory Size and Alignment Issues	45
Avoid Memory Size Mismatches	45
Align Data Where Possible	46
Use the 3DNow! PREFETCH and PREFETCHW Instructions	46
Take Advantage of Write Combining	50
Avoid Placing Code and Data in the Same 64-Byte Cache Line	50
Store-to-Load Forwarding Restrictions	51
Store-to-Load Forwarding Pitfalls—True Dependencies	51
Summary of Store-to-Load Forwarding Pitfalls to Avoid	54
Stack Alignment Considerations	54
Align TBYTE Variables on Quadword Aligned Addresses	55
C Language Structure Component Considerations	55
Sort Variables According to Base Type Size	56
6 Branch Optimizations	57
Avoid Branches Dependent on Random Data	57
AMD Athlon Processor Specific Code	58
Blended AMD-K6 and AMD Athlon Processor Code	58
Always Pair CALL and RETURN	59
Replace Branches with Computation in 3DNow! Code	60
Muxing Constructs	60
Sample Code Translated into 3DNow! Code	61
Avoid the Loop Instruction	65
Avoid Far Control Transfer Instructions	65
Avoid Recursive Functions	66

7	Scheduling Optimizations	67
	Schedule Instructions According to their Latency	67
	Unrolling Loops.	67
	Complete Loop Unrolling	67
	Partial Loop Unrolling.	68
	Use Function Inlining.	71
	Overview	71
	Always Inline Functions if Called from One Site	72
	Always Inline Functions with Fewer than 25 Machine Instructions.	72
	Avoid Address Generation Interlocks.	72
	Use MOVZX and MOVSX	73
	Minimize Pointer Arithmetic in Loops	73
	Push Memory Data Carefully.	75
8	Integer Optimizations	77
	Replace Divides with Multiplies	77
	Multiplication by Reciprocal (Division) Utility	77
	Unsigned Division by Multiplication of Constant.	78
	Signed Division by Multiplication of Constant.	79
	Use Alternative Code When Multiplying by a Constant.	81
	Use MMX™ Instructions for Integer-Only Work.	83
	Repeated String Instruction Usage.	84
	Latency of Repeated String Instructions.	84
	Guidelines for Repeated String Instructions	84
	Use XOR Instruction to Clear Integer Registers.	86
	Efficient 64-Bit Integer Arithmetic.	86
	Efficient Implementation of Population Count Function.	91
	Derivation of Multiplier Used for Integer Division by Constants	93
	Unsigned Derivation for Algorithm, Multiplier, and Shift Factor	93

	Signed Derivation for Algorithm, Multiplier, and Shift Factor	95
9	Floating-Point Optimizations	97
	Ensure All FPU Data is Aligned	97
	Use Multiplies Rather than Divides	97
	Use FFREEP Macro to Pop One Register from the FPU Stack	98
	Floating-Point Compare Instructions	98
	Use the FXCH Instruction Rather than FST/FLD Pairs	99
	Avoid Using Extended-Precision Data	99
	Minimize Floating-Point-to-Integer Conversions	100
	Floating-Point Subexpression Elimination	103
	Check Argument Range of Trigonometric Instructions Efficiently	103
	Take Advantage of the FSINCOS Instruction	105
10	3DNow!™ and MMX™ Optimizations	107
	Use 3DNow! Instructions	107
	Use FEMMS Instruction	107
	Use 3DNow! Instructions for Fast Division	108
	Optimized 14-Bit Precision Divide	108
	Optimized Full 24-Bit Precision Divide	108
	Pipelined Pair of 24-Bit Precision Divides	109
	Newton-Raphson Reciprocal	109
	Use 3DNow! Instructions for Fast Square Root and Reciprocal Square Root	110
	Optimized 15-Bit Precision Square Root	110
	Optimized 24-Bit Precision Square Root	110
	Newton-Raphson Reciprocal Square Root	111
	Use MMX PMADDWD Instruction to Perform Two 32-Bit Multiplies in Parallel	111
	3DNow! and MMX Intra-Operand Swapping	112

Fast Conversion of Signed Words to Floating-Point	113
Use MMX PXOR to Negate 3DNow! Data	113
Use MMX PCMP Instead of 3DNow! PFCMP.	114
Use MMX Instructions for Block Copies and Block Fills	115
Use MMX PXOR to Clear All Bits in an MMX Register	118
Use MMX PCMPEQD to Set All Bits in an MMX Register.	119
Use MMX PAND to Find Absolute Value in 3DNow! Code	119
Optimized Matrix Multiplication.	119
Efficient 3D-Clipping Code Computation Using 3DNow! Instructions	122
Use 3DNow! PAVGUSB for MPEG-2 Motion Compensation	123
Stream of Packed Unsigned Bytes	125
Complex Number Arithmetic.	126
11 General x86 Optimization Guidelines	127
Short Forms	127
Dependencies	128
Register Operands	128
Stack Allocation	128
Appendix A AMD Athlon™ Processor Microarchitecture	129
Introduction.	129
AMD Athlon Processor Microarchitecture.	130
Superscalar Processor	130
Instruction Cache	131
Predecode	132
Branch Prediction.	132
Early Decoding	133
Instruction Control Unit	134
Data Cache	134
Integer Scheduler.	135

	Integer Execution Unit	135
	Floating-Point Scheduler	136
	Floating-Point Execution Unit	137
	Load-Store Unit (LSU)	138
	L2 Cache Controller	139
	Write Combining	139
	AMD Athlon System Bus	139
Appendix B	Pipeline and Execution Unit Resources Overview	141
	Fetch and Decode Pipeline Stages	141
	Integer Pipeline Stages	144
	Floating-Point Pipeline Stages	146
	Execution Unit Resources	148
	Terminology	148
	Integer Pipeline Operations	149
	Floating-Point Pipeline Operations	150
	Load/Store Pipeline Operations	151
	Code Sample Analysis	152
Appendix C	Implementation of Write Combining	155
	Introduction	155
	Write-Combining Definitions and Abbreviations	156
	What is Write Combining?	156
	Programming Details	156
	Write-Combining Operations	157
	Sending Write-Buffer Data to the System	159
Appendix D	Performance-Monitoring Counters	161
	Overview	161
	Performance Counter Usage	161
	PerfEvtSel[3:0] MSRs (MSR Addresses C001_0000h–C001_0003h)	162

	PerfCtr[3:0] MSRs (MSR Addresses C001_0004h–C001_0007h)	167
	Starting and Stopping the Performance-Monitoring Counters	168
	Event and Time-Stamp Monitoring Software.	168
	Monitoring Counter Overflow	169
Appendix E	Programming the MTRR and PAT	171
	Introduction	171
	Memory Type Range Register (MTRR) Mechanism	171
	Page Attribute Table (PAT).	177
Appendix F	Instruction Dispatch and Execution Resources	187
Appendix G	DirectPath versus VectorPath Instructions	219
	Select DirectPath Over VectorPath Instructions.	219
	DirectPath Instructions	219
	VectorPath Instructions	231
	Index	237

List of Figures

Figure 1. AMD Athlon™ Processor Block Diagram	131
Figure 2. Integer Execution Pipeline	135
Figure 3. Floating-Point Unit Block Diagram	137
Figure 4. Load/Store Unit	138
Figure 5. Fetch/Scan/Align/Decode Pipeline Hardware	142
Figure 6. Fetch/Scan/Align/Decode Pipeline Stages	142
Figure 7. Integer Execution Pipeline	144
Figure 8. Integer Pipeline Stages	144
Figure 9. Floating-Point Unit Block Diagram	146
Figure 10. Floating-Point Pipeline Stages	146
Figure 11. PerfEvtSel[3:0] Registers	162
Figure 12. MTRR Mapping of Physical Memory	173
Figure 13. MTRR Capability Register Format	174
Figure 14. MTRR Default Type Register Format	175
Figure 15. Page Attribute Table (MSR 277h)	177
Figure 16. MTRRphysBasen Register Format	183
Figure 17. MTRRphysMaskn Register Format	184

List of Tables

Table 1.	Latency of Repeated String Instructions.	84
Table 2.	Integer Pipeline Operation Types	149
Table 3.	Integer Decode Types	149
Table 4.	Floating-Point Pipeline Operation Types	150
Table 5.	Floating-Point Decode Types	150
Table 6.	Load/Store Unit Stages	151
Table 7.	Sample 1 – Integer Register Operations	153
Table 8.	Sample 2 – Integer Register and Memory Load Operations.	154
Table 9.	Write Combining Completion Events	158
Table 10.	AMD Athlon™ System Bus Commands Generation Rules	159
Table 11.	Performance-Monitoring Counters.	164
Table 12.	Memory Type Encodings.	174
Table 13.	Standard MTRR Types and Properties.	176
Table 14.	PATi 3-Bit Encodings.	178
Table 15.	Effective Memory Type Based on PAT and MTRRs.	179
Table 16.	Final Output Memory Types.	180
Table 17.	MTRR Fixed Range Register Format	182
Table 18.	MTRR-Related Model-Specific Register (MSR) Map	185
Table 19.	Integer Instructions	188
Table 20.	MMX™ Instructions.	208
Table 21.	MMX Extensions	211
Table 22.	Floating-Point Instructions	212
Table 23.	3DNow!™ Instructions.	217
Table 24.	3DNow! Extensions	218
Table 25.	DirectPath Integer Instructions	220
Table 26.	DirectPath MMX Instructions.	227
Table 27.	DirectPath MMX Extensions.	228
Table 28.	DirectPath Floating-Point Instructions	229

Table 29. VectorPath Integer Instructions	231
Table 30. VectorPath MMX Instructions	234
Table 31. VectorPath MMX Extensions	234
Table 32. VectorPath Floating-Point Instructions	235

Revision History

Date	Rev	Description
Nov. 1999	E	<p>Added "About this Document" on page 1.</p> <p>Further clarification of "Consider the Sign of Integer Operands" on page 14.</p> <p>Added the optimization, "Use Array Style Instead of Pointer Style Code" on page 15.</p> <p>Added the optimization, "Accelerating Floating-Point Divides and Square Roots" on page 29.</p> <p>Clarified examples in "Copy Frequently De-referenced Pointer Arguments to Local Variables" on page 31.</p> <p>Further clarification of "Select DirectPath Over VectorPath Instructions" on page 34.</p> <p>Further clarification of "Align Branch Targets in Program Hot Spots" on page 36.</p> <p>Further clarification of REP instruction as a filler in "Code Padding Using Neutral Code Fillers" on page 39.</p> <p>Further clarification of "Use the 3DNow!™ PREFETCH and PREFETCHW Instructions" on page 46.</p> <p>Modified examples 1 and 2 of "Unsigned Division by Multiplication of Constant" on page 78.</p> <p>Added the optimization, "Efficient Implementation of Population Count Function" on page 91.</p> <p>Further clarification of "Use FFREEP Macro to Pop One Register from the FPU Stack" on page 98.</p> <p>Further clarification of "Minimize Floating-Point-to-Integer Conversions" on page 100.</p> <p>Added the optimization, "Check Argument Range of Trigonometric Instructions Efficiently" on page 103.</p> <p>Added the optimization, "Take Advantage of the FSINCOS Instruction" on page 105.</p> <p>Further clarification of "Use 3DNow!™ Instructions for Fast Division" on page 108.</p> <p>Further clarification "Use FEMMS Instruction" on page 107.</p> <p>Further clarification of "Use 3DNow!™ Instructions for Fast Square Root and Reciprocal Square Root" on page 110.</p> <p>Clarified "3DNow!™ and MMX™ Intra-Operand Swapping" on page 112.</p> <p>Corrected PCMPGT information in "Use MMX™ PCMP Instead of 3DNow!™ PFCMP" on page 114.</p> <p>Added the optimization, "Use MMX™ Instructions for Block Copies and Block Fills" on page 115.</p> <p>Modified the rule for "Use MMX™ PXOR to Clear All Bits in an MMX™ Register" on page 118.</p> <p>Modified the rule for "Use MMX™ PCMPEQD to Set All Bits in an MMX™ Register" on page 119.</p> <p>Added the optimization, "Optimized Matrix Multiplication" on page 119.</p> <p>Added the optimization, "Efficient 3D-Clipping Code Computation Using 3DNow!™ Instructions" on page 122.</p> <p>Added the optimization, "Complex Number Arithmetic" on page 126.</p> <p>Added Appendix E, "Programming the MTRR and PAT".</p> <p>Rearranged the appendices.</p> <p>Added Index.</p>

1

Introduction

The AMD Athlon™ processor is the newest microprocessor in the AMD K86™ family of microprocessors. The advances in the AMD Athlon processor take superscalar operation and out-of-order execution to a new level. The AMD Athlon processor has been designed to efficiently execute code written for previous-generation x86 processors. However, to enable the fastest code execution with the AMD Athlon processor, programmers should write software that includes specific code optimization techniques.

About this Document

This document contains information to assist programmers in creating optimized code for the AMD Athlon processor. In addition to compiler and assembler designers, this document has been targeted to C and assembly language programmers writing execution-sensitive code sequences.

This document assumes that the reader possesses in-depth knowledge of the x86 instruction set, the x86 architecture (registers, programming modes, etc.), and the IBM PC-AT platform.

This guide has been written specifically for the AMD Athlon processor, but it includes considerations for

previous-generation processors and describes how those optimizations are applicable to the AMD Athlon processor. This guide contains the following chapters:

Chapter 1: Introduction. Outlines the material covered in this document. Summarizes the AMD Athlon microarchitecture.

Chapter 2: Top Optimizations. Provides convenient descriptions of the most important optimizations a programmer should take into consideration.

Chapter 3: C Source Level Optimizations. Describes optimizations that C/C++ programmers can implement.

Chapter 4: Instruction Decoding Optimizations. Describes methods that will make the most efficient use of the three sophisticated instruction decoders in the AMD Athlon processor.

Chapter 5: Cache and Memory Optimizations. Describes optimizations that makes efficient use of the large L1 caches and high-bandwidth buses of the AMD Athlon processor.

Chapter 6: Branch Optimizations. Describes optimizations that improves branch prediction and minimizes branch penalties.

Chapter 7: Scheduling Optimizations. Describes optimizations that improves code scheduling for efficient execution resource utilization.

Chapter 8: Integer Optimizations. Describes optimizations that improves integer arithmetic and makes efficient use of the integer execution units in the AMD Athlon processor.

Chapter 9: Floating-Point Optimizations. Describes optimizations that makes maximum use of the superscalar and pipelined floating-point unit (FPU) of the AMD Athlon processor.

Chapter 10: 3DNow!™ and MMX™ Optimizations. Describes guidelines for Enhanced 3DNow! and MMX code optimization techniques.

Chapter 11: General x86 Optimizations Guidelines. Lists generic optimizations techniques applicable to x86 processors.

Appendix A: AMD Athlon Processor Microarchitecture. Describes in detail the microarchitecture of the AMD Athlon processor.

Appendix B: Pipeline and Execution Unit Resources Overview. Describes in detail the execution units and its relation to the instruction pipeline.

Appendix C: Implementation of Write Combining. Describes the algorithm used by the AMD Athlon processor to write combine.

Appendix D: Performance Monitoring Counters. Describes the usage of the performance counters available in the AMD Athlon processor.

Appendix E: Programming the MTRR and PAT. Describes the steps needed to program the Memory Type Range Registers and the Page Attribute Table.

Appendix F: Instruction Dispatch and Execution Resources. Lists the instruction's execution resource usage.

Appendix G: DirectPath versus VectorPath Instructions. Lists the x86 instructions that are DirectPath and VectorPath instructions.

AMD Athlon™ Processor Family

The AMD Athlon processor family uses state-of-the-art decoupled decode/execution design techniques to deliver next-generation performance with x86 binary software compatibility. This next-generation processor family advances x86 code execution by using flexible instruction predecoding, wide and balanced decoders, aggressive out-of-order execution, parallel integer execution pipelines, parallel floating-point execution pipelines, deep pipelined execution for higher delivered operating frequency, dedicated backside cache memory, and a new high-performance double-rate 64-bit local bus. As an x86 binary-compatible processor, the AMD Athlon processor implements the industry-standard x86 instruction set by decoding and executing the x86 instructions using a proprietary microarchitecture. This microarchitecture allows the delivery of maximum performance when running x86-based PC software.

AMD Athlon™ Processor Microarchitecture Summary

The AMD Athlon processor brings superscalar performance and high operating frequency to PC systems running industry-standard x86 software. A brief summary of the next-generation design features implemented in the AMD Athlon processor is as follows:

- High-speed double-rate local bus interface
- Large, split 128-Kbyte level-one (L1) cache
- Dedicated backside level-two (L2) cache
- Instruction predecode and branch detection during cache line fills
- Decoupled decode/execution core
- Three-way x86 instruction decoding
- Dynamic scheduling and speculative execution
- Three-way integer execution
- Three-way address generation
- Three-way floating-point execution
- 3DNow!™ technology and MMX™ single-instruction multiple-data (SIMD) instruction extensions
- Super data forwarding
- Deep out-of-order integer and floating-point execution
- Register renaming
- Dynamic branch prediction

The AMD Athlon processor communicates through a next-generation high-speed local bus that is beyond the current Socket 7 or Super7™ bus standard. The local bus can transfer data at twice the rate of the bus operating frequency by using both the rising and falling edges of the clock (see “AMD Athlon™ System Bus” on page 139 for more information).

To reduce on-chip cache miss penalties and to avoid subsequent data load or instruction fetch stalls, the AMD Athlon processor has a dedicated high-speed backside L2 cache. The large 128-Kbyte L1 on-chip cache and the backside L2 cache allow the

AMD Athlon execution core to achieve and sustain maximum performance.

As a decoupled decode/execution processor, the AMD Athlon processor makes use of a proprietary microarchitecture, which defines the heart of the AMD Athlon processor. With the inclusion of all these features, the AMD Athlon processor is capable of decoding, issuing, executing, and retiring multiple x86 instructions per cycle, resulting in superior scalable performance.

The AMD Athlon processor includes both the industry-standard MMX SIMD integer instructions and the 3DNow! SIMD floating-point instructions that were first introduced in the AMD-K6®-2 processor. The design of 3DNow! technology was based on suggestions from leading graphics and independent software vendors (ISVs). Using SIMD format, the AMD Athlon processor can generate up to four 32-bit, single-precision floating-point results per clock cycle.

The 3DNow! execution units allow for high-performance floating-point vector operations, which can replace x87 instructions and enhance the performance of 3D graphics and other floating-point-intensive applications. Because the 3DNow! architecture uses the same registers as the MMX instructions, switching between MMX and 3DNow! has no penalty.

The AMD Athlon processor designers took another innovative step by carefully integrating the traditional x87 floating-point, MMX, and 3DNow! execution units into one operational engine. With the introduction of the AMD Athlon processor, the switching overhead between x87, MMX, and 3DNow! technology is virtually eliminated. The AMD Athlon processor combined with 3DNow! technology brings a better multimedia experience to mainstream PC users while maintaining backwards compatibility with all existing x86 software.

Although the AMD Athlon processor can extract code parallelism on-the-fly from off-the-shelf, commercially available x86 software, specific code optimization for the AMD Athlon processor can result in even higher delivered performance. This document describes the proprietary microarchitecture in the AMD Athlon processor and makes recommendations for optimizing execution of x86 software on the processor.

The coding techniques for achieving peak performance on the AMD Athlon processor include, but are not limited to, those for the AMD-K6, AMD-K6-2, Pentium[®], Pentium Pro, and Pentium II processors. However, many of these optimizations are not necessary for the AMD Athlon processor to achieve maximum performance. Due to the more flexible pipeline control and aggressive out-of-order execution, the AMD Athlon processor is not as sensitive to instruction selection and code scheduling. This flexibility is one of the distinct advantages of the AMD Athlon processor.

The AMD Athlon processor uses the latest in processor microarchitecture design techniques to provide the highest x86 performance for today's PC. In short, the AMD Athlon processor offers true next-generation performance with x86 binary software compatibility.

2

Top Optimizations

This chapter contains concise descriptions of the best optimizations for improving the performance of the AMD Athlon™ processor. Subsequent chapters contain more detailed descriptions of these and other optimizations. The optimizations in this chapter are divided into two groups and listed in order of importance.

Group I – Essential Optimizations

Group I contains essential optimizations. Users should follow these critical guidelines closely. The optimizations in Group I are as follows:

- **Memory Size and Alignment Issues**—Avoid memory size mismatches—Align data where possible
- **Use the 3DNow!™ PREFETCH and PREFETCHW Instructions**
- **Select DirectPath Over VectorPath Instructions**

Group II – Secondary Optimizations

Group II contains secondary optimizations that can significantly improve the performance of the AMD Athlon processor. The optimizations in Group II are as follows:

- **Load-Execute Instruction Usage**—Use Load-Execute instructions—Avoid load-execute floating-point instructions with integer operands
- **Take Advantage of Write Combining**
- **Use 3DNow! Instructions**
- **Avoid Branches Dependent on Random Data**

- **Avoid Placing Code and Data in the Same 64-Byte Cache Line**

Optimization Star



The top optimizations described in this chapter are flagged with a star. In addition, the star appears beside the more detailed descriptions found in subsequent chapters.

Group I Optimizations – Essential Optimizations

Memory Size and Alignment Issues

See “Memory Size and Alignment Issues” on page 45 for more details.

Avoid Memory Size Mismatches



Avoid memory size mismatches when instructions operate on the same data. For instructions that store and reload the same data, keep operands aligned and keep the loads/stores of each operand the same size.

Align Data Where Possible



Avoid misaligned data references. A misaligned store or load operation suffers a minimum one-cycle penalty in the AMD Athlon processor load/store pipeline.

Use the 3DNow!™ PREFETCH and PREFETCHW Instructions



For code that can take advantage of prefetching, use the 3DNow! PREFETCH and PREFETCHW instructions to increase the effective bandwidth to the AMD Athlon processor, which significantly improves performance. All the prefetch instructions are essentially integer instructions and can be used

anywhere, in any type of code (integer, x87, 3DNow!, MMX, etc.). Use the following formula to determine prefetch distance:

$$\text{Prefetch Length} = 200 (DS/C)$$

- Round up to the nearest cache line.
- DS is the data stride per loop iteration.
- C is the number of cycles per loop iteration when hitting in the L1 cache.

See “Use the 3DNow!™ PREFETCH and PREFETCHW Instructions” on page 46 for more details.

Select DirectPath Over VectorPath Instructions



Use DirectPath instructions rather than VectorPath instructions. DirectPath instructions are optimized for decode and execute efficiently by minimizing the number of operations per x86 instruction. Three DirectPath instructions can be decoded in parallel. Using VectorPath instructions will block DirectPath instructions from decoding simultaneously.

See Appendix G, “DirectPath versus VectorPath Instructions” on page 219 for a list of DirectPath and VectorPath instructions.

Group II Optimizations—Secondary Optimizations

Load-Execute Instruction Usage

See “Load-Execute Instruction Usage” on page 34 for more details.

Use Load-Execute Instructions



Wherever possible, use load-execute instructions to increase code density with the one exception described below. The split-instruction form of load-execute instructions can be used to avoid scheduler stalls for longer executing instructions and to explicitly schedule the load and execute operations.

Avoid Load-Execute Floating-Point Instructions with Integer Operands



Do not use load-execute floating-point instructions with **integer operands**. The floating-point load-execute instructions with integer operands are VectorPath and generate two OPs in a cycle, while the discrete equivalent enables a third DirectPath instruction to be decoded in the same cycle.

Take Advantage of Write Combining



This guideline applies only to operating system, device driver, and BIOS programmers. In order to improve system performance, the AMD Athlon processor aggressively combines multiple memory-write cycles of any data size that address locations within a 64-byte cache line aligned write buffer.

See Appendix C, “Implementation of Write Combining” on page 155 for more details.

Use 3DNow!™ Instructions



Unless accuracy requirements dictate otherwise, perform floating-point computations using the 3DNow! instructions instead of x87 instructions. The SIMD nature of 3DNow! instructions achieves twice the number of FLOPs that are achieved through x87 instructions. 3DNow! instructions also provide for a flat register file instead of the stack-based approach of x87 instructions.

See Table 23 on page 217 for a list of 3DNow! instructions. For information about instruction usage, see the *3DNow!™ Technology Manual*, order# 21928.

Avoid Branches Dependent on Random Data



Avoid data-dependent branches around a single instruction. Data-dependent branches acting upon basically random data can cause the branch prediction logic to mispredict the branch about 50% of the time. Design branch-free alternative code sequences, which results in shorter average execution time.

See “Avoid Branches Dependent on Random Data” on page 57 for more details.

Avoid Placing Code and Data in the Same 64-Byte Cache Line



Consider that the AMD Athlon processor cache line is twice the size of previous processors. Code and data should not be shared in the same 64-byte cache line, especially if the data ever becomes modified. In order to maintain cache coherency, the AMD Athlon processor may thrash its caches, resulting in lower performance.

In general the following should be avoided:

- Self-modifying code
- Storing data in code segments

See “Avoid Placing Code and Data in the Same 64-Byte Cache Line” on page 50 for more details.

3

C Source Level Optimizations

This chapter details C programming practices for optimizing code for the AMD Athlon™ processor. Guidelines are listed in order of importance.

Ensure Floating-Point Variables and Expressions are of Type Float

For compilers that generate 3DNow!™ instructions, make sure that all floating-point variables and expressions are of type float. Pay special attention to floating-point constants. These require a suffix of “F” or “f” (for example, 3.14f) in order to be of type float, otherwise they default to type double. To avoid automatic promotion of float arguments to double, always use function prototypes for all functions that accept float arguments.

Use 32-Bit Data Types for Integer Code

Use 32-bit data types for integer code. Compiler implementations vary, but typically the following data types are included—*int*, *signed*, *signed int*, *unsigned*, *unsigned int*, *long*, *signed long*, *long int*, *signed long int*, *unsigned long*, and *unsigned long int*.

Consider the Sign of Integer Operands

In many cases, the data stored in integer variables determines whether a signed or an unsigned integer type is appropriate. For example, to record the weight of a person in pounds, no negative numbers are required so an unsigned type is appropriate. However, recording temperatures in degrees Celsius may require both positive and negative numbers so a signed type is needed.

Where there is a choice of using either a signed or an unsigned type, it should be considered that certain operations are faster with unsigned types while others are faster for signed types.

Integer-to-floating-point conversion using integers larger than 16-bit is faster with signed types, as the x86 FPU provides instructions for converting signed integers to floating-point, but has no instructions for converting unsigned integers. In a typical case, a 32-bit integer is converted as follows:

Example 1 (Avoid):

```
double x;          =====>  MOV  [temp+4], 0
unsigned int i;    MOV  EAX, i
                  MOV  [temp], eax
x = i;             FILD QWORD PTR [temp]
                  FSTP QWORD PTR [x]
```

This code is slow not only because of the number of instructions but also because a size mismatch prevents store-to-load-forwarding to the FILD instruction.

Example (Preferred):

```
double x;          =====>  FILD DWORD PTR [i]
int i;             FSTP QWORD PTR [x]
x = i;
```

Computing quotients and remainders in integer division by constants are faster when performed on unsigned types. In a typical case, a 32-bit integer is divided by four as follows:

Example (Avoid):

```
int i;          =====>   MOV   EAX, i
                                     CDQ
i = i / 4;      AND   EDX, 3
                                     ADD   EAX, EDX
                                     SAR   EAX, 2
                                     MOV   i, EAX
```

Example (Preferred):

```
unsigned int i; =====>   SHR   i, 2

i = i / 4;
```

In summary:

Use unsigned types for:

- Division and remainders
- Loop counters
- Array indexing

Use signed types for:

- Integer-to-float conversion

Use Array Style Instead of Pointer Style Code

The use of pointers in C makes work difficult for the optimizers in C compilers. Without detailed and aggressive pointer analysis, the compiler has to assume that writes through a pointer can write to any place in memory. This includes storage allocated to other variables, creating the issue of aliasing, i.e., the same block of memory is accessible in more than one way.

In order to help the optimizer of the C compiler in its analysis, avoid the use of pointers where possible. One example where this is trivially possible is in the access of data organized as arrays. C allows the use of either the array operator `[]` or pointers to access the array. Using array-style code makes the task of the optimizer easier by reducing possible aliasing.

For example, `x[0]` and `x[2]` can not possibly refer to the same memory location, while `*p` and `*q` could. It is highly recommended to use the array style, as significant performance advantages can be achieved with most compilers.

Note that source code transformations will interact with a compiler's code generator and that it is difficult to control the generated machine code from the source level. It is even possible that source code transformations for improving performance and compiler optimizations "fight" each other. Depending on the compiler and the specific source code it is therefore possible that pointer style code will be compiled into machine code that is faster than that generated from equivalent array style code. It is advisable to check the performance after any source code transformation to see whether performance indeed increased.

Example 1 (Avoid):

```
typedef struct {
    float x,y,z,w;
} VERTEX;

typedef struct {
    float m[4][4];
} MATRIX;

void XForm (float *res, const float *v, const float *m, int
numverts)
{
    float dp;
    int i;
    const VERTEX* vv = (VERTEX *)v;

    for (i = 0; i < numverts; i++) {
        dp = vv->x * *m++;
        dp += vv->y * *m++;
        dp += vv->z * *m++;
        dp += vv->w * *m++;

        *res++ = dp; /* write transformed x */

        dp = vv->x * *m++;
        dp += vv->y * *m++;
        dp += vv->z * *m++;
        dp += vv->w * *m++;

        *res++ = dp; /* write transformed y */

        dp = vv->x * *m++;
        dp += vv->y * *m++;
        dp += vv->z * *m++;
        dp += vv->w * *m++;
    }
}
```



```

        *res++ = dp; /* write transformed z */

        dp = vv->x * *m++;
        dp += vv->y * *m++;
        dp += vv->z * *m++;
        dp += vv->w * *m++;

        *res++ = dp; /* write transformed w */

        ++vv; /* next input vertex */
        m -= 16; /* reset to start of transform matrix */
    }
}

```

Example 2 (Preferred):

```

typedef struct {
    float x,y,z,w;
} VERTEX;

typedef struct {
    float m[4][4];
} MATRIX;

void XForm (float *res, const float *v, const float *m, int
numverts)
{
    int i;
    const VERTEX* vv = (VERTEX *)v;
    const MATRIX* mm = (MATRIX *)m;
    VERTEX* rr = (VERTEX *)res;

    for (i = 0; i < numverts; i++) {
        rr->x = vv->x*mm->m[0][0] + vv->y*mm->m[0][1] +
            vv->z*mm->m[0][2] + vv->w*mm->m[0][3];
        rr->y = vv->x*mm->m[1][0] + vv->y*mm->m[1][1] +
            vv->z*mm->m[1][2] + vv->w*mm->m[1][3];
        rr->z = vv->x*mm->m[2][0] + vv->y*mm->m[2][1] +
            vv->z*mm->m[2][2] + vv->w*mm->m[2][3];
        rr->w = vv->x*mm->m[3][0] + vv->y*mm->m[3][1] +
            vv->z*mm->m[3][2] + vv->w*mm->m[3][3];
    }
}

```

Completely Unroll Small Loops

Take advantage of the AMD Athlon processor's large, 64-Kbyte instruction cache and completely unroll small loops. Unrolling loops can be beneficial to performance, especially if the loop body is small which makes the loop overhead significant. Many compilers are not aggressive at unrolling loops. For loops that have a small fixed loop count and a small loop body, completely unrolling the loops at the source level is recommended.

Example 1 (Avoid):

```
// 3D-transform: multiply vector V by 4x4 transform matrix M
for (i=0; i<4; i++) {
    r[i] = 0;
    for (j=0; j<4; j++) {
        r[i] += M[j][i]*V[j];
    }
}
```

Example 2 (Preferred):

```
// 3D-transform: multiply vector V by 4x4 transform matrix M
r[0] = M[0][0]*V[0] + M[1][0]*V[1] + M[2][0]*V[2] +
        M[3][0]*V[3];
r[1] = M[0][1]*V[0] + M[1][1]*V[1] + M[2][1]*V[2] +
        M[3][1]*V[3];
r[2] = M[0][2]*V[0] + M[1][2]*V[1] + M[2][2]*V[2] +
        M[3][2]*V[3];
r[3] = M[0][3]*V[0] + M[1][3]*V[1] + M[2][3]*V[2] +
        M[3][3]*V[3];
```

Avoid Unnecessary Store-to-Load Dependencies

A store-to-load dependency exists when data is stored to memory, only to be read back shortly thereafter. See “Store-to-Load Forwarding Restrictions” on page 51 for more details. The AMD Athlon processor contains hardware to accelerate such store-to-load dependencies, allowing the load to obtain the store data before it has been written to memory. However, it is still faster to avoid such dependencies altogether and keep the data in an internal register.

Avoiding store-to-load dependencies is especially important if they are part of a long dependency chains, as might occur in a recurrence computation. If the dependency occurs while operating on arrays, many compilers are unable to optimize the

code in a way that avoids the store-to-load dependency. In some instances the language definition may prohibit the compiler from using code transformations that would remove the store-to-load dependency. It is therefore recommended that the programmer remove the dependency manually, e.g., by introducing a temporary variable that can be kept in a register. This can result in a significant performance increase. The following is an example of this.

Example 1 (Avoid):

```
double x[VECLEN], y[VECLEN], z[VECLEN];
unsigned int k;

for (k = 1; k < VECLLEN; k++) {
    x[k] = x[k-1] + y[k];
}

for (k = 1; k < VECLLEN; k++) {
    x[k] = z[k] * (y[k] - x[k-1]);
}
```

Example 2 (Preferred):

```
double x[VECLEN], y[VECLEN], z[VECLEN];
unsigned int k;
double t;

t = x[0];
for (k = 1; k < VECLLEN; k++) {
    t = t + y[k];
    x[k] = t;
}

t = x[0];
for (k = 1; k < VECLLEN; k++) {
    t = z[k] * (y[k] - t);
    x[k] = t;
}
```

Consider Expression Order in Compound Branch Conditions

Branch conditions in C programs are often compound conditions consisting of multiple boolean expressions joined by the boolean operators `&&` and `||`. C guarantees a short-circuit evaluation of these operators. This means that in the case of `||`, the first operand to evaluate to `TRUE` terminates the evaluation, i.e., following operands are not evaluated at all. Similarly for `&&`, the first operand to evaluate to `FALSE` terminates the evaluation. Because of this short-circuit evaluation, it is not always possible to swap the operands of `||` and `&&`. This is especially the case when the evaluation of one of the operands causes a side effect. However, in most cases the exchange of operands is possible.

When used to control conditional branches, expressions involving `||` and `&&` are translated into a series of conditional branches. The ordering of the conditional branches is a function of the ordering of the expressions in the compound condition, and can have a significant impact on performance. It is unfortunately not possible to give an easy, closed-form formula on how to order the conditions. Overall performance is a function of a variety of the following factors:

- probability of a branch mispredict for each of the branches generated
- additional latency incurred due to a branch mispredict
- cost of evaluating the conditions controlling each of the branches generated
- amount of parallelism that can be extracted in evaluating the branch conditions
- data stream consumed by an application (mostly due to the dependence of mispredict probabilities on the nature of the incoming data in data dependent branches)

It is therefore recommended to experiment with the ordering of expressions in compound branch conditions in the most active areas of a program (so called hot spots) where most of the execution time is spent. Such hot spots can be found through the use of profiling. A "typical" data stream should be fed to the program while doing the experiments.

Switch Statement Usage

Optimize Switch Statements

Switch statements are translated using a variety of algorithms. The most common of these are jump tables and comparison chains/trees. It is recommended to sort the cases of a switch statement according to the probability of occurrences, with the most probable first. This will improve performance when the switch is translated as a comparison chain. It is further recommended to make the case labels small, contiguous integers, as this will allow the switch to be translated as a jump table.

Example 1 (Avoid):

```
int days_in_month, short_months, normal_months, long_months;

switch (days_in_month) {
    case 28:
    case 29: short_months++; break;
    case 30: normal_months++; break;
    case 31: long_months++; break;
    default: printf ("month has fewer than 28 or more than 31
                    days\n");
}
```

Example 2 (Preferred):

```
int days_in_month, short_months, normal_months, long_months;

switch (days_in_month) {
    case 31: long_months++; break;
    case 30: normal_months++; break;
    case 28:
    case 29: short_months++; break;
    default: printf ("month has fewer than 28 or more than 31
                    days\n");
}
```

Use Prototypes for All Functions

In general, use prototypes for all functions. Prototypes can convey additional information to the compiler that might enable more aggressive optimizations.

Use Const Type Qualifier

Use the “const” type qualifier as much as possible. This optimization makes code more robust and may enable higher performance code to be generated due to the additional information available to the compiler. For example, the C standard allows compilers to not allocate storage for objects that are declared “const”, if their address is never taken.

Generic Loop Hoisting

To improve the performance of inner loops, it is beneficial to reduce redundant constant calculations (i.e., loop invariant calculations). However, this idea can be extended to invariant control structures.

The first case is that of a constant “if()” statement in a “for()” loop.

Example 1:

```
for( i ... ) {
    if( CONSTANT0 ) {
        DoWork0( i );    // does not affect CONSTANT0
    } else {
        DoWork1( i );    // does not affect CONSTANT0
    }
}
```

The above loop should be transformed into:

```
if( CONSTANT0 ) {
    for( i ... ) {
        DoWork0( i );
    }
} else {
    for( i ... ) {
        DoWork1( i );
    }
}
```

This will make your inner loops tighter by avoiding repetitious evaluation of a known “if()” control structure. Although the branch would be easily predicted, the extra instructions and decode limitations imposed by branching are saved, which are usually well worth it.

Generalization for Multiple Constant Control Code

To generalize this further for multiple constant control code some more work may have to be done to create the proper outer loop. Enumeration of the constant cases will reduce this to a simple switch statement.

Example 2:

```
for( i ... ) {
    if( CONSTANT0 ) {
        DoWork0( i );           //does not affect CONSTANT0
                                // or CONSTANT1
    } else {
        DoWork1( i );           //does not affect CONSTANT0
                                // or CONSTANT1
    }
    if( CONSTANT1 ) {
        DoWork2( i );           //does not affect CONSTANT0
                                // or CONSTANT1
    } else {
        DoWork3( i );           //does not affect CONSTANT0
                                // or CONSTANT1
    }
}
```

The above loop should be transformed into:

```
#define combine( c1, c2 ) (((c1) << 1) + (c2))
switch( combine( CONSTANT0!=0, CONSTANT1!=0 ) ) {
    case combine( 0, 0 ):
        for( i ... ) {
            DoWork0( i );
            DoWork2( i );
        }
        break;
    case combine( 1, 0 ):
        for( i ... ) {
            DoWork1( i );
            DoWork2( i );
        }
        break;
    case combine( 0, 1 ):
        for( i ... ) {
            DoWork0( i );
            DoWork3( i );
        }
        break;
```

```
case combine( 1, 1 ):
    for( i ... ) {
        DoWork1( i );
        DoWork3( i );
    }
    break;
default:
    break;
}
```

The trick here is that there is some up-front work involved in generating all the combinations for the switch constant and the total amount of code has doubled. However, it is also clear that the inner loops are "if()-free". In ideal cases where the "DoWork*()" functions are inlined, the successive functions will have greater overlap leading to greater parallelism than would be possible in the presence of intervening "if()" statements.

The same idea can be applied to constant "switch()" statements, or combinations of "switch()" statements and "if()" statements inside of "for()" loops. The method for combining the input constants gets more complicated but will be worth it for the performance benefit.

However, the number of inner loops can also substantially increase. If the number of inner loops is prohibitively high, then only the most common cases need to be dealt with directly, and the remaining cases can fall back to the old code in a "default:" clause for the "switch()" statement.

This typically comes up when the programmer is considering runtime generated code. While runtime generated code can lead to similar levels of performance improvement, it is much harder to maintain, and the developer must do their own optimizations for their code generation without the help of an available compiler.

Declare Local Functions as Static

Functions that are not used outside the file in which they are defined should always be declared static, which forces internal linkage. Otherwise, such functions default to external linkage,

which might inhibit certain optimizations with some compilers—for example, aggressive inlining.

Dynamic Memory Allocation Consideration

Dynamic memory allocation ('malloc' in C language) should always return a pointer that is suitably aligned for the largest base type (quadword alignment). Where this aligned pointer cannot be guaranteed, use the technique shown in the following code to make the pointer quadword aligned, if needed. This code assumes the pointer can be cast to a long.

Example:

```
double* p;  
double* np;
```

```
p = (double *)malloc(sizeof(double)*number_of_doubles+7L);  
np = (double *)((((long)(p))+7L) & (-8L));
```

Then use 'np' instead of 'p' to access the data. 'p' is still needed in order to deallocate the storage.

Introduce Explicit Parallelism into Code

Where possible, long dependency chains should be broken into several independent dependency chains which can then be executed in parallel exploiting the pipeline execution units. This is especially important for floating-point code, whether it is mapped to x87 or 3DNow! instructions because of the longer latency of floating-point operations. Since most languages, including ANSI C, guarantee that floating-point expressions are not re-ordered, compilers can not usually perform such optimizations unless they offer a switch to allow ANSI non-compliant reordering of floating-point expressions according to algebraic rules.

Note that re-ordered code that is algebraically identical to the original code does not necessarily deliver identical computational results due to the lack of associativity of floating point operations. There are well-known numerical considerations in applying these optimizations (consult a book on numerical analysis). In some cases, these optimizations may

lead to unexpected results. Fortunately, in the vast majority of cases, the final result will differ only in the least significant bits.

Example 1 (Avoid):

```
double a[100],sum;
int i;

sum = 0.0f;
for (i=0; i<100; i++) {
    sum += a[i];
}
```

Example 2 (Preferred):

```
double a[100],sum1,sum2,sum3,sum4,sum;
int i;

sum1 = 0.0;
sum2 = 0.0;
sum3 = 0.0;
sum4 = 0.0;
for (i=0; i<100; i+4) {
    sum1 += a[i];
    sum2 += a[i+1];
    sum3 += a[i+2];
    sum4 += a[i+3];
}
sum = (sum4+sum3)+(sum1+sum2);
```

Notice that the 4-way unrolling was chosen to exploit the 4-stage fully pipelined floating-point adder. Each stage of the floating-point adder is occupied on every clock cycle, ensuring maximal sustained utilization.

Explicitly Extract Common Subexpressions

In certain situations, C compilers are unable to extract common subexpressions from floating-point expressions due to the guarantee against reordering of such expressions in the ANSI standard. Specifically, the compiler can not re-arrange the computation according to algebraic equivalencies before extracting common subexpressions. In such cases, the programmer should manually extract the common subexpression. It should be noted that re-arranging the expression may result in different computational results due to the lack of associativity of floating-point operations, but the results usually differ in only the least significant bits.

Example 1**Avoid:**

```
double a,b,c,d,e,f;

e = b*c/d;
f = b/d*a;
```

Preferred:

```
double a,b,c,d,e,f,t;

t = b/d;
e = c*t;
f = a*t;
```

Example 2**Avoid:**

```
double a,b,c,e,f;

e = a/c;
f = b/c;
```

Preferred:

```
double a,b,c,e,f,t;

t = 1/c;
e = a*t;
f = b*t;
```

C Language Structure Component Considerations

Many compilers have options that allow padding of structures to make their size multiples of words, doublewords, or quadwords, in order to achieve better alignment for structures. In addition, to improve the alignment of structure members, some compilers might allocate structure elements in an order that differs from the order in which they are declared. However, some compilers might not offer any of these features, or their implementation might not work properly in all situations. Therefore, to achieve the best alignment of structures and structure members while minimizing the amount of padding regardless of compiler optimizations, the following methods are suggested.

Sort by Base Type Size

Sort structure members according to their base type size, declaring members with a larger base type size ahead of members with a smaller base type size.

Pad by Multiple of Largest Base Type Size

Pad the structure to a multiple of the largest base type size of any member. In this fashion, if the first member of a structure is naturally aligned, all other members are naturally aligned as well. The padding of the structure to a multiple of the largest based type size allows, for example, arrays of structures to be perfectly aligned.

The following example demonstrates the reordering of structure member declarations:

Original ordering (Avoid):

```
struct {
    char    a[5];
    long    k;
    double  x;
} baz;
```

New ordering, with padding (Preferred):

```
struct {
    double  x;
    long    k;
    char    a[5];
    char    pad[7];
} baz;
```

See “C Language Structure Component Considerations” on page 55 for a different perspective.

Sort Local Variables According to Base Type Size

When a compiler allocates local variables in the same order in which they are declared in the source code, it can be helpful to declare local variables in such a manner that variables with a larger base type size are declared ahead of the variables with smaller base type size. Then, if the first variable is allocated so that it is naturally aligned, all other variables are allocated contiguously in the order they are declared, and are naturally aligned without any padding.

Some compilers do not allocate variables in the order they are declared. In these cases, the compiler should automatically allocate variables in such a manner as to make them naturally aligned with the minimum amount of padding. In addition, some compilers do not guarantee that the stack is aligned suitably for the largest base type (that is, they do not guarantee

quadword alignment), so that quadword operands might be misaligned, even if this technique is used and the compiler does allocate variables in the order they are declared.

The following example demonstrates the reordering of local variable declarations:

Original ordering (Avoid):

```
short  ga, gu, gi;
long   foo, bar;
double x, y, z[3];
char   a, b;
float  baz;
```

Improved ordering (Preferred):

```
double z[3];
double x, y;
long   foo, bar;
float  baz;
short  ga, gu, gi;
```

See “Sort Variables According to Base Type Size” on page 56 for more information from a different perspective.

Accelerating Floating-Point Divides and Square Roots

Divides and square roots have a much longer latency than other floating-point operations, even though the AMD Athlon processor provides significant acceleration of these two operations. In some codes, these operations occur so often as to seriously impact performance. In these cases, it is recommended to port the code to 3DNow! inline assembly or to use a compiler that can generate 3DNow! code. If code has hot spots that use single-precision arithmetic only (i.e., all computation involves data of type float) and for some reason cannot be ported to 3DNow!, the following technique may be used to improve performance.

The x87 FPU has a precision-control field as part of the FPU control word. The precision-control setting determines what precision results get rounded to. It affects the basic arithmetic operations, including divides and square roots. AMD Athlon and AMD-K6® family processors implement divide and square root in such fashion as to only compute the number of bits

necessary for the currently selected precision. This means that setting precision control to single precision (versus Win32 default of double precision) lowers the latency of those operations.

The Microsoft® Visual C environment provides functions to manipulate the FPU control word and thus the precision control. Note that these functions are not very fast, so changes of precision control should be inserted where it creates little overhead, such as outside a computation-intensive loop. Otherwise the overhead created by the function calls outweighs the benefit from reducing the latencies of divide and square root operations.

The following example shows how to set the precision control to single precision and later restore the original settings in the Microsoft Visual C environment.

Example:

```
/* prototype for _controlfp() function */
#include <float.h>
unsigned int orig_cw;

/* Get current FPU control word and save it */

orig_cw = _controlfp (0,0);

/* Set precision control in FPU control word to single
precision. This reduces the latency of divide and square
root operations.
*/

_controlfp (_PC_24, MCW_PC);

/* restore original FPU control word */

_controlfp (orig_cw, 0xffffffff);
```

Avoid Unnecessary Integer Division

Integer division is the slowest of all integer arithmetic operations and should be avoided wherever possible. One possibility for reducing the number of integer divisions is multiple divisions, in which division can be replaced with multiplication as shown in the following examples. This replacement is possible only if no overflow occurs during the computation of the product. This can be determined by considering the possible ranges of the divisors.

Example 1 (Avoid):

```
int i,j,k,m;  
  
m = i / j / k;
```

Example 2 (Preferred):

```
int i,j,k,l;  
  
m = i / (j * k);
```

Copy Frequently De-referenced Pointer Arguments to Local Variables

Avoid frequently de-referencing pointer arguments inside a function. Since the compiler has no knowledge of whether aliasing exists between the pointers, such de-referencing can not be optimized away by the compiler. This prevents data from being kept in registers and significantly increases memory traffic.

Note that many compilers have an “assume no aliasing” optimization switch. This allows the compiler to assume that two different pointers always have disjoint contents and does not require copying of pointer arguments to local variables.

Otherwise, copy the data pointed to by the pointer arguments to local variables at the start of the function and if necessary copy them back at the end of the function.

Example 1 (Avoid):

```
//assumes pointers are different and q!=r
void isqrt ( unsigned long a,
            unsigned long *q,
            unsigned long *r)
{
    *q = a;
    if (a > 0)
    {
        while (*q > (*r = a / *q))
        {
            *q = (*q + *r) >> 1;
        }
    }
    *r = a - *q * *q;
}
```

Example 2 (Preferred):

```
//assumes pointers are different and q!=r
void isqrt ( unsigned long a,
            unsigned long *q,
            unsigned long *r)
{
    unsigned long qq, rr;
    qq = a;
    if (a > 0)
    {
        while (qq > (rr = a / qq))
        {
            qq = (qq + rr) >> 1;
        }
    }
    rr = a - qq * qq;
    *q = qq;
    *r = rr;
}
```


4

Instruction Decoding Optimizations

This chapter discusses ways to maximize the number of instructions decoded by the instruction decoders in the AMD Athlon™ processor. Guidelines are listed in order of importance.

Overview

The AMD Athlon processor instruction fetcher reads 16-byte aligned code windows from the instruction cache. The instruction bytes are then merged into a 24-byte instruction queue. On each cycle, the in-order front-end engine selects for decode up to three x86 instructions from the instruction-byte queue.

All instructions (x86, x87, 3DNow!™, and MMX™) are classified into two types of decodes—DirectPath and VectorPath (see “DirectPath Decoder” and “VectorPath Decoder” on page 133 for more information). DirectPath instructions are common instructions that are decoded directly in hardware. VectorPath instructions are more complex instructions that require the use of a sequence of multiple operations issued from an on-chip ROM.

Up to three DirectPath instructions can be selected for decode per cycle. Only one VectorPath instruction can be selected for decode per cycle. DirectPath instructions and VectorPath instructions cannot be simultaneously decoded.

Select DirectPath Over VectorPath Instructions



Use DirectPath instructions rather than VectorPath instructions. DirectPath instructions are optimized for decode and execute efficiently by minimizing the number of operations per x86 instruction, which includes ‘register←register op memory’ as well as ‘register←register op register’ forms of instructions. Up to three DirectPath instructions can be decoded per cycle. VectorPath instructions will block the decoding of DirectPath instructions.

The very high majority of instructions used by a compiler has been implemented as DirectPath instructions in the AMD Athlon processor. Assembly writers must still take into consideration the usage of DirectPath versus VectorPath instructions.

See Appendix F, “Instruction Dispatch and Execution Resources” on page 187 and Appendix G, “DirectPath versus VectorPath Instructions” on page 219 for tables of DirectPath and VectorPath instructions.

Load-Execute Instruction Usage

Use Load-Execute Integer Instructions



Most load-execute integer instructions are DirectPath decodable and can be decoded at the rate of three per cycle. Splitting a load-execute integer instruction into two separate instructions—a load instruction and a “reg, reg” instruction—reduces decoding bandwidth and increases register pressure, which results in lower performance. The split-instruction form can be used to avoid scheduler stalls for longer executing instructions and to explicitly schedule the load and execute operations.

Use Load-Execute Floating-Point Instructions with Floating-Point Operands



When operating on single-precision or double-precision floating-point data, wherever possible use floating-point load-execute instructions to increase code density.

Note: This optimization applies only to floating-point instructions with floating-point operands and not with integer operands, as described in the next optimization.

This coding style helps in two ways. First, denser code allows more work to be held in the instruction cache. Second, the denser code generates fewer internal OPs and, therefore, the FPU scheduler holds more work, which increases the chances of extracting parallelism from the code.

Example 1 (Avoid):

```
FLD     QWORD PTR [TEST1]
FLD     QWORD PTR [TEST2]
FMUL   ST, ST(1)
```

Example 2 (Preferred):

```
FLD     QWORD PTR [TEST1]
FMUL   QWORD PTR [TEST2]
```

Avoid Load-Execute Floating-Point Instructions with Integer Operands



Do not use load-execute floating-point instructions with *integer* operands: FIADD, FISUB, FISUBR, FIMUL, FIDIV, FIDIVR, FICOM, and FICOMP. Remember that floating-point instructions can have integer operands while integer instruction cannot have floating-point operands.

Floating-point computations involving integer-memory operands should use separate FILD and arithmetic instructions. This optimization has the potential to increase decode bandwidth and OP density in the FPU scheduler. The floating-point load-execute instructions with integer operands are VectorPath and generate two OPs in a cycle, while the discrete equivalent enables a third DirectPath instruction to be decoded in the same cycle. In some situations this optimizations can also reduce execution time if the FILD can be scheduled several instructions ahead of the arithmetic instruction in order to cover the FILD latency.

Example 1 (Avoid):

```
FLD      QWORD PTR [foo]
FIMUL   DWORD PTR [bar]
FIADD   DWORD PTR [baz]
```

Example 2 (Preferred):

```
FILD    DWORD PTR [bar]
FILD    DWORD PTR [baz]
FLD     QWORD PTR [foo]
FMULP   ST(2), ST
FADDP   ST(1), ST
```

Align Branch Targets in Program Hot Spots

In program hot spots (i.e., innermost loops in the absence of profiling data), place branch targets at or near the beginning of 16-byte aligned code windows. This technique helps to maximize the number of instructions that are filled into the instruction-byte queue while preventing I-cache space in branch intensive code.

Use Short Instruction Lengths

Assemblers and compilers should generate the tightest code possible to optimize use of the I-cache and increase average decode rate. Wherever possible, use instructions with shorter lengths. Using shorter instructions increases the number of instructions that can fit into the instruction-byte queue. For example, use 8-bit displacements as opposed to 32-bit displacements. In addition, use the single-byte format of simple integer instructions whenever possible, as opposed to the 2-byte opcode ModR/M format.

Example 1 (Avoid):

```
81 C0 78 56 34 12  add eax, 12345678h ;uses 2-byte opcode
                                     ; form (with ModR/M)
81 C3 FB FF FF FF  add ebx, -5      ;uses 32-bit
                                     ; immediate
0F 84 05 00 00 00  jz $label1     ;uses 2-byte opcode,
                                     ; 32-bit immediate
```

Example 2 (Preferred):

```

05 78 56 34 12  add eax, 12345678h  ;uses single byte
                                     ; opcode form
83 C3 FB          add ebx, -5        ;uses 8-bit sign
                                     ; extended immediate
74 05             jz  $label1        ;uses 1-byte opcode,
                                     ; 8-bit immediate

```

Avoid Partial Register Reads and Writes

In order to handle partial register writes, the AMD Athlon processor execution core implements a data-merging scheme.

In the execution unit, an instruction writing a partial register merges the modified portion with the current state of the remainder of the register. Therefore, the dependency hardware can potentially force a false dependency on the most recent instruction that writes to any part of the register.

Example 1 (Avoid):

```

MOV     AL, 10      ;inst 1
MOV     AH, 12      ;inst 2 has a false dependency on
                   ; inst 1
                   ;inst 2 merges new AH with current
                   ; EAX register value forwarded
                   ; by inst 1

```

In addition, an instruction that has a read dependency on any part of a given architectural register has a read dependency on the most recent instruction that modifies any part of the same architectural register.

Example 2 (Avoid):

```

MOV     BX, 12h     ;inst 1
MOV     BL, DL      ;inst 2, false dependency on
                   ; completion of inst 1
MOV     BH, CL      ;inst 3, false dependency on
                   ; completion of inst 2
MOV     AL, BL      ;inst 4, depends on completion of
                   ; inst 2

```

Replace Certain SHLD Instructions with Alternative Code

Certain instances of the SHLD instruction can be replaced by alternative code using SHR and LEA. The alternative code has lower latency and requires less execution resources. SHR and LEA (32-bit version) are DirectPath instructions, while SHLD is a VectorPath instruction. SHR and LEA preserves decode bandwidth as it potentially enables the decoding of a third DirectPath instruction.

Example 1

(Avoid):

```
SHLD REG1, REG2, 1
```

(Preferred):

```
SHR REG2, 31  
LEA REG1, [REG1*2 + REG2]
```

Example 2

(Avoid):

```
SHLD REG1, REG2, 2
```

(Preferred):

```
SHR REG2, 30  
LEA REG1, [REG1*4 + REG2]
```

Example 3

(Avoid):

```
SHLD REG1, REG2, 3
```

(Preferred):

```
SHR REG2, 29  
LEA REG1, [REG1*8 + REG2]
```

Use 8-Bit Sign-Extended Immediates

Using 8-bit sign-extended immediates improves code density with no negative effects on the AMD Athlon processor. For example, ADD BX, -5 should be encoded “83 C3 FB” and not “81 C3 FF FB”.

Use 8-Bit Sign-Extended Displacements

Use 8-bit sign-extended displacements for conditional branches. Using short, 8-bit sign-extended displacements for conditional branches improves code density with no negative effects on the AMD Athlon processor.

Code Padding Using Neutral Code Fillers

Occasionally a need arises to insert neutral code fillers into the code stream, e.g., for code alignment purposes or to space out branches. Since this filler code can be executed, it should take up as few execution resources as possible, not diminish decode density, and not modify any processor state other than advancing EIP. A one byte padding can easily be achieved using the NOP instructions (XCHG EAX, EAX; opcode 0x90). In the x86 architecture, there are several multi-byte "NOP" instructions available that do not change processor state other than EIP:

- MOV REG, REG
- XCHG REG, REG
- CMOVcc REG, REG
- SHR REG, 0
- SAR REG, 0
- SHL REG, 0
- SHRD REG, REG, 0
- SHLD REG, REG, 0
- LEA REG, [REG]
- LEA REG, [REG+00]
- LEA REG, [REG*1+00]
- LEA REG, [REG+00000000]
- LEA REG, [REG*1+00000000]

Not all of these instructions are equally suitable for purposes of code padding. For example, SHLD/SHRD are microcoded which reduces decode bandwidth and takes up execution resources.

Recommendations for the AMD Athlon™ Processor

For code that is optimized specifically for the AMD Athlon processor, the optimal code fillers are NOP instructions (opcode 0x90) with up to two REP prefixes (0xF3). In the AMD Athlon processor, a NOP with up to two REP prefixes can be handled by a single decoder with no overhead. As the REP prefixes are redundant and meaningless, they get discarded, and NOPs are handled without using any execution resources. The three decoders of AMD Athlon processor can handle up to three NOPs, each with up to two REP prefixes each, in a single cycle, for a neutral code filler of up to nine bytes.

***Note:** When used as a filler instruction, REP/REPNE prefixes can be used in conjunction only with NOPs. REP/REPNE has undefined behavior when used with instructions other than a NOP.*

If a larger amount of code padding is required, it is recommended to use a JMP instruction to jump across the padding region. The following assembly language macros show this:

```
NOP1_ATHLON TEXTEQU <DB 090h>
NOP2_ATHLON TEXTEQU <DB 0F3h, 090h>
NOP3_ATHLON TEXTEQU <DB 0F3h, 0F3h, 090h>
NOP4_ATHLON TEXTEQU <DB 0F3h, 0F3h, 090h, 090h>
NOP5_ATHLON TEXTEQU <DB 0F3h, 0F3h, 090h, 0F3h, 090h>
NOP6_ATHLON TEXTEQU <DB 0F3h, 0F3h, 090h, 0F3h, 0F3h, 090h>
NOP7_ATHLON TEXTEQU <DB 0F3h, 0F3h, 090h, 0F3h, 0F3h, 090h,
    090h>
NOP8_ATHLON TEXTEQU <DB 0F3h, 0F3h, 090h, 0F3h, 0F3h, 090h,
    0F3h, 090h>
NOP9_ATHLON TEXTEQU <DB 0F3h, 0F3h, 090h, 0F3h, 0F3h, 090h,
    0F3h, 0F3h, 090h>
NOP10_ATHLONTEXTEQU <DB 0EBh, 008h, 90h, 90h, 90h, 90h,
    90h, 90h, 90h, 90h>
```


Recommendations for AMD-K6® Family and AMD Athlon™ Processor Blended Code

On x86 processors other than the AMD Athlon processor (including the AMD-K6 family of processors), the REP prefix and especially multiple prefixes cause decoding overhead, so the above technique is not recommended for code that has to run well both on AMD Athlon processor and other x86 processors (blended code). In such cases the instructions and instruction sequences below are recommended. For neutral code fillers longer than eight bytes in length, the JMP instruction can be used to jump across the padding region.

Note that each of the instructions and instruction sequences below utilizes an x86 register. To avoid performance degradation, the register used in the padding should be selected so as to not lengthen existing dependency chains, i.e., one should select a register that is not used by instructions in the vicinity of the neutral code filler. Note that certain instructions use registers implicitly. For example, PUSH, POP, CALL, and RET all make implicit use of the ESP register. The 5-byte filler sequence below consists of two instructions. If flag changes across the code padding are acceptable, the following instructions may be used as single instruction, 5-byte code fillers:

- TEST EAX, 0FFFF0000h
- CMP EAX, 0FFFF0000h

The following assembly language macros show the recommended neutral code fillers for code optimized for the AMD Athlon processor that also has to run well on other x86 processors. Note for some padding lengths, versions using ESP or EBP are missing due to the lack of fully generalized addressing modes.

```
NOP2_EAX TEXTEQU <DB 08Bh,0C0h> ;mov eax, eax
NOP2_EBX TEXTEQU <DB 08Bh,0DBh> ;mov ebx, ebx
NOP2_ECX TEXTEQU <DB 08Bh,0C9h> ;mov ecx, ecx
NOP2_EDX TEXTEQU <DB 08Bh,0D2h> ;mov edx, edx
NOP2_ESI TEXTEQU <DB 08Bh,0F6h> ;mov esi, esi
NOP2_EDI TEXTEQU <DB 08Bh,0FFh> ;mov edi, edi
NOP2_ESP TEXTEQU <DB 08Bh,0E4h> ;mov esp, esp
NOP2_EBP TEXTEQU <DB 08Bh,0EDh> ;mov ebp, ebp
```

```
NOP3_EAX TEXTEQU <DB 08Dh,004h,020h> ;lea eax, [eax]
NOP3_EBX TEXTEQU <DB 08Dh,01Ch,023h> ;lea ebx, [ebx]
```

```
NOP3_ECX TEXTEQU <DB 08Dh,00Ch,021h> ;lea ecx, [ecx]
NOP3_EDX TEXTEQU <DB 08Dh,014h,022h> ;lea edx, [edx]
NOP3_ESI TEXTEQU <DB 08Dh,024h,024h> ;lea esi, [esi]
NOP3_EDI TEXTEQU <DB 08Dh,034h,026h> ;lea edi, [edi]
NOP3_ESP TEXTEQU <DB 08Dh,03Ch,027h> ;lea esp, [esp]
NOP3_EBP TEXTEQU <DB 08Dh,06Dh,000h> ;lea ebp, [ebp]

NOP4_EAX TEXTEQU <DB 08Dh,044h,020h,000h> ;lea eax, [eax+00]
NOP4_EBX TEXTEQU <DB 08Dh,05Ch,023h,000h> ;lea ebx, [ebx+00]
NOP4_ECX TEXTEQU <DB 08Dh,04Ch,021h,000h> ;lea ecx, [ecx+00]
NOP4_EDX TEXTEQU <DB 08Dh,054h,022h,000h> ;lea edx, [edx+00]
NOP4_ESI TEXTEQU <DB 08Dh,064h,024h,000h> ;lea esi, [esi+00]
NOP4_EDI TEXTEQU <DB 08Dh,074h,026h,000h> ;lea edi, [edi+00]
NOP4_ESP TEXTEQU <DB 08Dh,07Ch,027h,000h> ;lea esp, [esp+00]

;lea eax, [eax+00];nop
NOP5_EAX TEXTEQU <DB 08Dh,044h,020h,000h,090h>

;lea ebx, [ebx+00];nop
NOP5_EBX TEXTEQU <DB 08Dh,05Ch,023h,000h,090h>

;lea ecx, [ecx+00];nop
NOP5_ECX TEXTEQU <DB 08Dh,04Ch,021h,000h,090h>

;lea edx, [edx+00];nop
NOP5_EDX TEXTEQU <DB 08Dh,054h,022h,000h,090h>

;lea esi, [esi+00];nop
NOP5_ESI TEXTEQU <DB 08Dh,064h,024h,000h,090h>

;lea edi, [edi+00];nop
NOP5_EDI TEXTEQU <DB 08Dh,074h,026h,000h,090h>

;lea esp, [esp+00];nop
NOP5_ESP TEXTEQU <DB 08Dh,07Ch,027h,000h,090h>

;lea eax, [eax+00000000]
NOP6_EAX TEXTEQU <DB 08Dh,080h,0,0,0,0>

;lea ebx, [ebx+00000000]
NOP6_EBX TEXTEQU <DB 08Dh,09Bh,0,0,0,0>

;lea ecx, [ecx+00000000]
NOP6_ECX TEXTEQU <DB 08Dh,089h,0,0,0,0>

;lea edx, [edx+00000000]
NOP6_EDX TEXTEQU <DB 08Dh,092h,0,0,0,0>

;lea esi, [esi+00000000]
NOP6_ESI TEXTEQU <DB 08Dh,0B6h,0,0,0,0>
```

```

;lea edi,[edi+00000000]
NOP6_EDI TEXTEQU <DB 08Dh,0BFh,0,0,0,0>

;lea ebp,[ebp+00000000]
NOP6_EBP TEXTEQU <DB 08Dh,0ADh,0,0,0,0>

;lea eax,[eax*1+00000000]
NOP7_EAX TEXTEQU <DB 08Dh,004h,005h,0,0,0,0>

;lea ebx,[ebx*1+00000000]
NOP7_EBX TEXTEQU <DB 08Dh,01Ch,01Dh,0,0,0,0>

;lea ecx,[ecx*1+00000000]
NOP7_ECX TEXTEQU <DB 08Dh,00Ch,00Dh,0,0,0,0>

;lea edx,[edx*1+00000000]
NOP7_EDX TEXTEQU <DB 08Dh,014h,015h,0,0,0,0>

;lea esi,[esi*1+00000000]
NOP7_ESI TEXTEQU <DB 08Dh,034h,035h,0,0,0,0>

;lea edi,[edi*1+00000000]
NOP7_EDI TEXTEQU <DB 08Dh,03Ch,03Dh,0,0,0,0>

;lea ebp,[ebp*1+00000000]
NOP7_EBP TEXTEQU <DB 08Dh,02Ch,02Dh,0,0,0,0>

;lea eax,[eax*1+00000000] ;nop
NOP8_EAX TEXTEQU <DB 08Dh,004h,005h,0,0,0,0,90h>

;lea ebx,[ebx*1+00000000] ;nop
NOP8_EBX TEXTEQU <DB 08Dh,01Ch,01Dh,0,0,0,0,90h>

;lea ecx,[ecx*1+00000000] ;nop
NOP8_ECX TEXTEQU <DB 08Dh,00Ch,00Dh,0,0,0,0,90h>

;lea edx,[edx*1+00000000] ;nop
NOP8_EDX TEXTEQU <DB 08Dh,014h,015h,0,0,0,0,90h>

;lea esi,[esi*1+00000000] ;nop
NOP8_ESI TEXTEQU <DB 08Dh,034h,035h,0,0,0,0,90h>

;lea edi,[edi*1+00000000] ;nop
NOP8_EDI TEXTEQU <DB 08Dh,03Ch,03Dh,0,0,0,0,90h>

;lea ebp,[ebp*1+00000000] ;nop
NOP8_EBP TEXTEQU <DB 08Dh,02Ch,02Dh,0,0,0,0,90h>

;JMP
NOP9 TEXTEQU <DB 0EBh,007h,90h,90h,90h,90h,90h,90h>

```


5

Cache and Memory Optimizations

This chapter describes code optimization techniques that take advantage of the large L1 caches and high-bandwidth buses of the AMD Athlon™ processor. Guidelines are listed in order of importance.

Memory Size and Alignment Issues

Avoid Memory Size Mismatches



Avoid memory size mismatches when instructions operate on the same data. **For instructions that store and reload the same data, keep operands aligned and keep the loads/stores of each operand the same size.** The following code examples result in a store-to-load-forwarding (STLF) stall:

Example 1 (Avoid):

```
MOV    DWORD PTR [FOO], EAX
MOV    DWORD PTR [FOO+4], EDX
FLD    QWORD PTR [FOO]
```

Avoid large-to-small mismatches, as shown in the following code:

Example 2 (Avoid):

```
FST    QWORD PTR [FOO]
MOV    EAX, DWORD PTR [FOO]
MOV    EDX, DWORD PTR [FOO+4]
```

Align Data Where Possible



In general, avoid misaligned data references. All data whose size is a power of 2 is considered aligned if it is *naturally* aligned. For example:

- QWORD accesses are aligned if they access an address divisible by 8.
- DWORD accesses are aligned if they access an address divisible by 4.
- WORD accesses are aligned if they access an address divisible by 2.
- TBYTE accesses are aligned if they access an address divisible by 8.

A misaligned store or load operation suffers a minimum one-cycle penalty in the AMD Athlon processor load/store pipeline. In addition, using misaligned loads and stores increases the likelihood of encountering a store-to-load forwarding pitfall. For a more detailed discussion of store-to-load forwarding issues, see “Store-to-Load Forwarding Restrictions” on page 51.

Use the 3DNow!™ PREFETCH and PREFETCHW Instructions



For code that can take advantage of prefetching, use the 3DNow! **PREFETCH** and **PREFETCHW** instructions to increase the effective bandwidth to the AMD Athlon processor. The **PREFETCH** and **PREFETCHW** instructions take advantage of the AMD Athlon processor’s high bus bandwidth to hide long latencies when fetching data from system memory. The prefetch instructions are essentially integer instructions and can be used anywhere, in any type of code (integer, x87, 3DNow!, MMX, etc.).

Large data sets typically require unit-stride access to ensure that all data pulled in by **PREFETCH** or **PREFETCHW** is actually used. If necessary, algorithms or data structures should be reorganized to allow unit-stride access.

PREFETCH/W versus PREFETCHNTA/T0/T1/T2

The PREFETCHNTA/T0/T1/T2 instructions in the MMX extensions are processor implementation dependent. To maintain compatibility with the 25 million AMD-K6®-2 and AMD-K6-III processors already sold, use the 3DNow! PREFETCH/W instructions instead of the various prefetch flavors in the new MMX extensions.

PREFETCHW Usage

Code that intends to modify the cache line brought in through prefetching should use the PREFETCHW instruction. While PREFETCHW works the same as a PREFETCH on the AMD-K6-2 and AMD-K6-III processors, PREFETCHW gives a hint to the AMD Athlon processor of an intent to modify the cache line. The AMD Athlon processor will mark the cache line being brought in by PREFETCHW as Modified. Using PREFETCHW can save an additional 15-25 cycles compared to a PREFETCH and the subsequent cache state change caused by a write to the prefetched cache line.

Multiple Prefetches

Programmers can initiate multiple outstanding prefetches on the AMD Athlon processor. While the AMD-K6-2 and AMD-K6-III processors can have only one outstanding prefetch, the AMD Athlon processor can have up to six outstanding prefetches. When all six buffers are filled by various memory read requests, the processor will simply ignore any new prefetch requests until a buffer frees up. Multiple prefetch requests are essentially handled in-order. If data is needed first, then that data should be prefetched first.

The example below shows how to initiate multiple prefetches when traversing more than one array.

Example (Multiple Prefetches):

```
.CODE
.K3D

; original C code
;
; #define LARGE_NUM 65536
;
; double array_a[LARGE_NUM];
; double array_b[LARGE_NUM];
; double array_c[LARGE_NUM];
; int i;
;
; for (i = 0; i < LARGE_NUM; i++) {
;     a[i] = b[i] * c[i]
; }
```

```

MOV     ECX, (-LARGE_NUM)           ;used biased index
MOV     EAX, OFFSET array_a        ;get address of array_a
MOV     EDX, OFFSET array_b        ;get address of array_b
MOV     ECX, OFFSET array_c        ;get address of array_c

$loop:

PREFETCHW [EAX+196]                ;two cachelines ahead
PREFETCH  [EDX+196]                ;two cachelines ahead
PREFETCH  [ECX+196]                ;two cachelines ahead
FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE] ;b[i]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE] ;b[i]*c[i]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE] ;a[i] = b[i]*c[i]
FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE+8] ;b[i+1]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE+8] ;b[i+1]*c[i+1]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE+8] ;a[i+1] =
; b[i+1]*c[i+1]

FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE+16] ;b[i+2]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE+16] ;b[i+2]*c[i+2]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE+16] ;a[i+2] =
; [i+2]*c[i+2]

FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE+24] ;b[i+3]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE+24] ;b[i+3]*c[i+3]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE+24] ;a[i+3] =
; b[i+3]*c[i+3]

FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE+32] ;b[i+4]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE+32] ;b[i+4]*c[i+4]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE+32] ;a[i+4] =
; b[i+4]*c[i+4]

FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE+40] ;b[i+5]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE+40] ;b[i+5]*c[i+5]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE+40] ;a[i+5] =
; b[i+5]*c[i+5]

FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE+48] ;b[i+6]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE+48] ;b[i+6]*c[i+6]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE+48] ;a[i+6] =
; b[i+6]*c[i+6]

FLD      QWORD PTR [EDX+ECX*8+ARR_SIZE+56] ;b[i+7]
FMUL     QWORD PTR [ECX+ECX*8+ARR_SIZE+56] ;b[i+7]*c[i+7]
FSTP     QWORD PTR [EAX+ECX*8+ARR_SIZE+56] ;a[i+7] =
; b[i+7]*c[i+7]

ADD     ECX, 8                      ;next 8 products
JNZ     $loop                       ;until none left

END

```


The following optimization rules were applied to this example.

- Loops should be unrolled to make sure that the data stride per loop iteration is equal to the length of a cache line. This avoids overlapping PREFETCH instructions and thus optimal use of the available number of outstanding PREFETCHes.
- Since the array "array_a" is written rather than read, PREFETCHW is used instead of PREFETCH to avoid overhead for switching cache lines to the correct MESI state. The PREFETCH lookahead has been optimized such that each loop iteration is working on three cache lines while six active PREFETCHes bring in the next six cache lines.
- Index arithmetic has been reduced to a minimum by use of complex addressing modes and biasing of the array base addresses in order to cut down on loop overhead.

Determining Prefetch Distance

Given the latency of a typical AMD Athlon processor system and expected processor speeds, the following formula should be used to determine the prefetch distance in bytes for a single array:

$$\text{Prefetch Distance} = 200 \left(\frac{DS}{C} \right) \text{ bytes}$$

- Round up to the nearest 64-byte cache line.
- The number 200 is a constant based upon expected AMD Athlon processor clock frequencies and typical system memory latencies.
- DS is the data stride in bytes per loop iteration.
- C is the number of cycles for one loop to execute entirely from the L1 cache.

The prefetch distance for multiple arrays are typically even longer.

Prefetch at Least 64 Bytes Away from Surrounding Stores

The PREFETCH and PREFETCHW instructions can be affected by false dependencies on stores. If there is a store to an address that matches a request, that request (the PREFETCH or PREFETCHW instruction) may be blocked until the store is written to the cache. Therefore, code should prefetch data that is located at least 64 bytes away from any surrounding store's data address.

Take Advantage of Write Combining



Operating system and device driver programmers should take advantage of the write-combining capabilities of the AMD Athlon processor. The AMD Athlon processor has a very aggressive write-combining algorithm, which improves performance significantly.

See Appendix C, “Implementation of Write Combining” on page 155 for more details.

Avoid Placing Code and Data in the Same 64-Byte Cache Line



Sharing code and data in the same 64-byte cache line may cause the L1 caches to thrash (unnecessary castout of code/data) in order to maintain coherency between the separate instruction and data caches. The AMD Athlon processor has a cache-line size of 64-bytes, which is twice the size of previous processors. Programmers must be aware that code and data should not be shared within this larger cache line, especially if the data becomes modified.

For example, programmers should consider that a memory indirect JMP instruction may have the data for the jump table residing in the same 64-byte cache line as the JMP instruction, which would result in lower performance.

Although rare, do not place critical code at the border between 32-byte aligned code segments and a data segments. The code at the start or end of your data segment should be as rarely executed as possible or simply padded with garbage.

In general, the following should be avoided:

- self-modifying code
- storing data in code segments

Store-to-Load Forwarding Restrictions

Store-to-load forwarding refers to the process of a load reading (forwarding) data from the store buffer (LS2). There are instances in the AMD Athlon processor load/store architecture when either a load operation is not allowed to read needed data from a store in the store buffer, or a load OP detects a false data dependency on a store in the store buffer.

In either case, the load cannot complete (load the needed data into a register) until the store has retired out of the store buffer and written to the data cache. A store-buffer entry cannot retire and write to the data cache until *every* instruction before the store has completed and retired from the reorder buffer.

The implication of this restriction is that all instructions in the reorder buffer, up to and including the store, must complete and retire out of the reorder buffer before the load can complete. Effectively, the load has a false dependency on every instruction up to the store.

The following sections describe store-to-load forwarding examples that are acceptable and those that should be avoided.

Store-to-Load Forwarding Pitfalls – True Dependencies

A load is allowed to read data from the store-buffer entry only if all of the following conditions are satisfied:

- The start address of the load matches the start address of the store.
- The load operand size is equal to or smaller than the store operand size.
- Neither the load or store is misaligned.
- The store data is not from a high-byte register (AH, BH, CH, or DH).

The following sections describe common-case scenarios to avoid whereby a load has a true dependency on a LS2-buffered store but cannot read (forward) data from a store-buffer entry.

Narrow-to-Wide Store-Buffer Data Forwarding Restriction

If the following conditions are present, there is a narrow-to-wide store-buffer data forwarding restriction:

- The operand size of the store data is smaller than the operand size of the load data.
- The range of addresses spanned by the store data covers some sub-region of range of addresses spanned by the load data.

Avoid the type of code shown in the following two examples.

Example 1 (Avoid):

```
MOV EAX, 10h
MOV WORD PTR [EAX], BX      ;word store
...
MOV ECX, DWORD PTR [EAX]   ;doubleword load
                           ;cannot forward upper
                           ; byte from store buffer
```

Example 2 (Avoid):

```
MOV EAX, 10h
MOV BYTE PTR [EAX + 3], BL ;byte store
...
MOV ECX, DWORD PTR [EAX]   ;doubleword load
                           ;cannot forward upper byte
                           ; from store buffer
```

Wide-to-Narrow Store-Buffer Data Forwarding Restriction

If the following conditions are present, there is a wide-to-narrow store-buffer data forwarding restriction:

- The operand size of the store data is greater than the operand size of the load data.
- The start address of the store data does not match the start address of the load.

Example 3 (Avoid):

```
MOV EAX, 10h
ADD DWORD PTR [EAX], EBX   ;doubleword store
MOV CX, WORD PTR [EAX + 2] ;word load-cannot forward high
                           ; word from store buffer
```

Use example 5 instead of example 4.

Example 4 (Avoid):

```
MOVQ      [foo], MM1      ;store upper and lower half
...
ADD      EAX, [foo]       ;fine
ADD      EDX, [foo+4]     ;uh-oh!
```

Example 5 (Preferred):

```

MOVD    [foo], MM1    ;store lower half
PUNPCKHDQ MM1, MM1    ;get upper half into lower half
MOVD    [foo+4], MM1  ;store lower half
...
ADD     EAX, [foo]    ;fine
ADD     EDX, [foo+4]  ;fine

```

Misaligned Store-Buffer Data Forwarding Restriction

If the following condition is present, there is a misaligned store-buffer data forwarding restriction:

- The store or load address is misaligned. For example, a quadword store is not aligned to a quadword boundary, a doubleword store is not aligned to doubleword boundary, etc.

A common case of misaligned store-data forwarding involves the passing of misaligned quadword floating-point data on the doubleword-aligned integer stack. Avoid the type of code shown in the following example.

Example 6 (Avoid):

```

MOV     ESP, 24h
FSTP   QWORD PTR [ESP] ;esp=24
.      ;store occurs to quadword
.      ; misaligned address
.
FLD    QWORD PTR[ESP]  ;quadword load cannot forward
                        ; from quadword misaligned
                        ; 'fstp[esp]' store OP

```

High-Byte Store-Buffer Data Forwarding Restriction

If the following condition is present, there is a high-byte store-data buffer forwarding restriction:

- The store data is from a high-byte register (AH, BH, CH, DH).

Avoid the type of code shown in the following example.

Example 7 (Avoid):

```

MOV EAX, 10h
MOV [EAX], BH    ;high-byte store
.
MOV DL, [EAX]    ;load cannot forward from
                  ; high-byte store

```

One Supported Store-to-Load Forwarding Case

There is one case of a mismatched store-to-load forwarding that is supported by the by AMD Athlon processor. The lower 32 bits from an aligned QWORD write feeding into a DWORD read is allowed.

Example 8 (Allowed):

```
MOVQ    [AlignedQword], mm0
...
MOV     EAX, [AlignedQword]
```

Summary of Store-to-Load Forwarding Pitfalls to Avoid

To avoid store-to-load forwarding pitfalls, code should conform to the following guidelines:

- Maintain consistent use of operand size across all loads and stores. Preferably, use doubleword or quadword operand sizes.
- Avoid misaligned data references.
- Avoid narrow-to-wide and wide-to-narrow forwarding cases.
- When using word or byte stores, avoid loading data from anywhere in the same doubleword of memory other than the identical start addresses of the stores.

Stack Alignment Considerations

Make sure the stack is suitably aligned for the local variable with the largest base type. Then, using the technique described in “C Language Structure Component Considerations” on page 55, all variables can be properly aligned with no padding.

Extend to 32 Bits Before Pushing onto Stack

Function arguments smaller than 32 bits should be extended to 32 bits before being pushed onto the stack, which ensures that the stack is always doubleword aligned on entry to a function.

If a function has no local variables with a base type larger than doubleword, no further work is necessary. If the function does have local variables whose base type is larger than a doubleword, additional code should be inserted to ensure proper alignment of the stack. For example, the following code achieves quadword alignment:

Example (Preferred):

```
Prolog:
PUSH    EBP
MOV     EBP, ESP
SUB     ESP, SIZE_OF_LOCALS    ;size of local variables
AND     ESP, -8
                ;push registers that need to be preserved

Epilog:                ;pop register that needed to be preserved
MOV     ESP, EBP
POP     EBP
RET
```

With this technique, function arguments can be accessed via EBP, and local variables can be accessed via ESP. In order to free EBP for general use, it needs to be saved and restored between the prolog and the epilog.

Align TBYTE Variables on Quadword Aligned Addresses

Align variables of type TBYTE on quadword aligned addresses. In order to make an array of TBYTE variables that are aligned, array elements are 16-bytes apart. In general, TBYTE variables should be avoided. Use double-precision variables instead.

C Language Structure Component Considerations

Structures ('struct' in C language) should be made the size of a multiple of the largest base type of any of their components. To meet this requirement, padding should be used where necessary.

Language definitions permitting, to minimize padding, structure components should be sorted and allocated such that the components with a larger base type are allocated ahead of those with a smaller base type. For example, consider the following code:

Example:

```
struct {
    char a[5];
    long k;
    double x;
} baz;
```

The structure components should be allocated (lowest to highest address) as follows:

x, k, a[4], a[3], a[2], a[1], a[0], padbyte6, ..., padbyte0

See “C Language Structure Component Considerations” on page 27 for more information from a C source code perspective.

Sort Variables According to Base Type Size

Sort local variables according to their base type size and allocate variables with larger base type size ahead of those with smaller base type size. Assuming the first variable allocated is naturally aligned, all other variables are naturally aligned without any padding. The following example is a declaration of local variables in a C function:

Example:

```
short ga, gu, gi;
long foo, bar;
double x, y, z[3];
char a, b;
float baz;
```

Allocate in the following order from left to right (from higher to lower addresses):

x, y, z[2], z[1], z[0], foo, bar, baz, ga, gu, gi, a, b;

See “Sort Local Variables According to Base Type Size” on page 28 for more information from a C source code perspective.

6

Branch Optimizations

While the AMD Athlon™ processor contains a very sophisticated branch unit, certain optimizations increase the effectiveness of the branch prediction unit. This chapter discusses rules that improve branch prediction and minimize branch penalties. Guidelines are listed in order of importance.

Avoid Branches Dependent on Random Data



Avoid conditional branches depending on random data, as these are difficult to predict. For example, a piece of code receives a random stream of characters “A” through “Z” and branches if the character is before “M” in the collating sequence. Data-dependent branches acting upon basically random data causes the branch prediction logic to mispredict the branch about 50% of the time.

If possible, design branch-free alternative code sequences, which results in shorter average execution time. This technique is especially important if the branch body is small. Examples 1 and 2 illustrate this concept using the CMOV instruction. Note that the AMD-K6® processor does not support the CMOV instruction. Therefore, blended AMD-K6 and AMD Athlon processor code should use examples 3 and 4.

AMD Athlon™ Processor Specific Code

Example 1 – Signed integer ABS function (X = labs(X)):

```

MOV     ECX, [X]      ;load value
MOV     EBX, ECX     ;save value
NEG     ECX          ;-value
CMOVS   ECX, EBX     ;if -value is negative, select value
MOV     [X], ECX     ;save labs result

```

Example 2 – Unsigned integer min function (z = x < y ? x : y):

```

MOV     EAX, [X]     ;load X value
MOV     EBX, [Y]     ;load Y value
CMP     EAX, EBX     ;EBX<=EAX ? CF=0 : CF=1
CMOVNC  EAX, EBX     ;EAX=(EBX<=EAX) ? EBX:EAX
MOV     [Z], EAX     ;save min (X,Y)

```

Blended AMD-K6® and AMD Athlon™ Processor Code

Example 3 – Signed integer ABS function (X = labs(X)):

```

MOV     ECX, [X]     ;load value
MOV     EBX, ECX     ;save value
SAR     ECX, 31      ;x < 0 ? 0xffffffff : 0
XOR     EBX, ECX     ;x < 0 ? ~x : x
SUB     EBX, ECX     ;x < 0 ? (~x)+1 : x
MOV     [X], EBX     ;x < 0 ? -x : x

```

Example 4 – Unsigned integer min function (z = x < y ? x : y):

```

MOV     EAX, [x]     ;load x
MOV     EBX, [y]     ;load y
SUB     EAX, EBX     ;x < y ? CF : NC ; x - y
SBB     ECX, ECX     ;x < y ? 0xffffffff : 0
AND     ECX, EAX     ;x < y ? x - y : 0
ADD     ECX, EBX     ;x < y ? x - y + y : y
MOV     [z], ECX     ;x < y ? x : y

```

Example 5 – Hexadecimal to ASCII conversion

(y=x < 10 ? x + 0x30: x + 0x41):

```

MOV     AL, [X]      ;load X value
CMP     AL, 10       ;if x is less than 10, set carry flag
SBB     AL, 69h      ;0..9 -> 96h, Ah..Fh -> A1h...A6h
DAS     AL           ;0..9: subtract 66h, Ah..Fh: Sub. 60h
MOV     [Y],AL       ;save conversion in y

```

Example 6 – Increment Ring Buffer Offset:

```
//C Code
char buf[BUFSIZE];
int a;

if (a < (BUFSIZE-1)) {
    a++;
} else {
    a = 0;
}

;-----
;Assembly Code
MOV     EAX, [a]           ; old offset
CMP     EAX, (BUFSIZE-1)  ; a < (BUFSIZE-1) ? CF : NC
INC     EAX                ; a++
SBB     EDX, EDX          ; a < (BUFSIZE-1) ? 0xffffffff : 0
AND     EAX, EDX          ; a < (BUFSIZE-1) ? a++ : 0
MOV     [a], EAX          ; store new offset
```

Example 7 – Integer Signum Function:

```
//C Code
int a, s;

if (!a) {
    s = 0;
} else if (a < 0) {
    s = -1;
} else {
    s = 1;
}

;-----
;Assembly Code
MOV     EAX, [a]           ;load a
CDQ                                ;t = a < 0 ? 0xffffffff : 0
CMP     EDX, EAX           ;a > 0 ? CF : NC
ADC     EDX, 0             ;a > 0 ? t+1 : t
MOV     [s], EDX          ;signum(x)
```

Always Pair CALL and RETURN

When the 12 entry return address stack gets out of synchronization, the latency of returns increase. The return address stack becomes out of sync when:

- calls and returns do not match
- the depth of the return stack is exceeded because of too many levels of nested functions calls

Replace Branches with Computation in 3DNow!™ Code

Branches negatively impact the performance of 3DNow! code. Branches can operate only on one data item at a time, i.e., they are inherently scalar and inhibit the SIMD processing that makes 3DNow! code superior. Also, branches based on 3DNow! comparisons require data to be passed to the integer units, which requires either transport through memory, or the use of “MOVD reg, MMreg” instructions. If the body of the branch is small, one can achieve higher performance by replacing the branch with computation. The computation simulates predicated execution or conditional moves. The principal tools for this are the following instructions: PCMPGT, PFCMPGT, PFCMPGE, PFMIN, PFMAX, PAND, PANDN, POR, PXOR.

Muxing Constructs

The most important construct to avoiding branches in 3DNow!™ and MMX™ code is a 2-way muxing construct that is equivalent to the ternary operator “?:” in C and C++. It is implemented using the PCMP/PFCMP, PAND, PANDN, and POR instructions. To maximize performance, it is important to apply the PAND and PANDN instructions in the proper order.

Example 1 (Avoid):

```
; r = (x < y) ? a : b
;
; in:  mm0  a
;      mm1  b
;      mm2  x
;      mm3  y
; out: mm1  r

PCMPGTD  MM3, MM2 ; y > x ? 0xffffffff : 0
MOVQ     MM4, MM3 ; duplicate mask
PANDN    MM3, MM0 ; y > x ? 0 : a
PAND     MM1, MM4 ; y > x ? b : 0
POR      MM1, MM3 ; r = y > x ? b : a
```

Because the use of PANDN destroys the mask created by PCMP, the mask needs to be saved, which requires an additional register. This adds an instruction, lengthens the dependency chain, and increases register pressure. Therefore 2-way muxing constructs should be written as follows.

Example 2 (Preferred):

```

; r = (x < y) ? a : b
;
; in:  mm0  a
;      mm1  b
;      mm2  x
;      mm3  y
; out: mm1  r

PCMPGTD  MM3, MM2  ; y > x ? 0xffffffff : 0
PAND     MM1, MM3  ; y > x ? b : 0
PANDN    MM3, MM0  ; y > x > 0 : a
POR      MM1, MM3  ; r = y > x ? b : a "
```

Sample Code Translated into 3DNow!™ Code

The following examples use scalar code translated into 3DNow! code. Note that it is not recommended to use 3DNow! SIMD instructions for scalar code, because the advantage of 3DNow! instructions lies in their “SIMDness”. These examples are meant to demonstrate general techniques for translating source code with branches into branchless 3DNow! code. Scalar source code was chosen to keep the examples simple. These techniques work in an identical fashion for vector code.

Each example shows the C code and the resulting 3DNow! code.

Example 1:**C code:**

```

float x,y,z;
if (x < y) {
    z += 1.0;
}
else {
    z -= 1.0;
}
```

3DNow! code:

```

;in:  MM0 = x
;      MM1 = y
;      MM2 = z
;out: MM0 = z
MOVQ   MM3, MM0    ;save x
MOVQ   MM4, one    ;1.0
PFCMPGE MM0, MM1   ;x < y ? 0 : 0xffffffff
PSLLD  MM0, 31     ;x < y ? 0 : 0x80000000
PXOR   MM0, MM4    ;x < y ? 1.0 : -1.0
PFADD  MM0, MM2    ;x < y ? z+1.0 : z-1.0
```

Example 2:**C code:**

```
float x,z;
z = abs(x);
if (z >= 1) {
    z = 1/z;
}
```

3DNow! code:

```
;in:  MM0 = x
;out: MM0 = z
MOVQ   MM5, mabs ;0xffffffff
PAND   MM0, MM5 ;z=abs(x)
PFRCPL MM2, MM0 ;1/z approx
MOVQ   MM1, MM0 ;save z
PFRCPL MM0, MM2 ;1/z step
PFRCPL MM0, MM2 ;1/z final
PFMIN  MM0, MM1 ;z = z < 1 ? z : 1/z
```

Example 3:**C code:**

```
float x,z,r,res;
z = fabs(x)
if (z < 0.575) {
    res = r;
}
else {
    res = PI/2 - 2*r;
}
```

3DNow! code:

```
;in:  MM0 = x
;      MM1 = r
;out: MM0 = res
MOVQ   MM7, mabs ;mask for absolute value
PAND   MM0, MM7 ;z = abs(x)
MOVQ   MM2, bnd ;0.575
PCMPGTD MM2, MM0 ;z < 0.575 ? 0xffffffff : 0
MOVQ   MM3, pio2 ;pi/2
MOVQ   MM0, MM1 ;save r
PFADD  MM1, MM1 ;2*r
PFSUBR MM1, MM3 ;pi/2 - 2*r
PAND   MM0, MM2 ;z < 0.575 ? r : 0
PANDN  MM2, MM1 ;z < 0.575 ? 0 : pi/2 - 2*r
POR    MM0, MM2 ;z < 0.575 ? r : pi/2 - 2 * r
```

Example 4:**C code:**

```

#define PI 3.14159265358979323
float x,z,r,res;
/* 0 <= r <= PI/4 */
z = abs(x)
if (z < 1) {
    res = r;
}
else {
    res = PI/2-r;
}

```

3DNow! code:

```

;in:  MM0 = x
;     MM1 = r
;out: MM1 = res
MOVQ   MM5, mabs ; mask to clear sign bit
MOVQ   MM6, one  ; 1.0
PAND   MM0, MM5 ; z=abs(x)
PCMPGTD MM6, MM0 ; z < 1 ? 0xffffffff : 0
MOVQ   MM4, pio2 ; pi/2
PFSUB  MM4, MM1 ; pi/2-r
PANDN  MM6, MM4 ; z < 1 ? 0 : pi/2-r
PFMAX  MM1, MM6 ; res = z < 1 ? r : pi/2-r

```

Example 5:**C code:**

```

#define PI 3.14159265358979323
float x,y,xa,ya,r,res;
int   xs,df;
xs = x < 0 ? 1 : 0;
xa = fabs(x);
ya = fabs(y);
df = (xa < ya);
if (xs && df) {
    res = PI/2 + r;
}
else if (xs) {
    res = PI - r;
}
else if (df) {
    res = PI/2 - r;
}
else {
    res = r;
}

```

3DNow! code:

```

;in:  MM0 = r
;     MM1 = y
;     MM2 = x
;out: MM0 = res
MOVQ   MM7, sgn      ;mask to extract sign bit
MOVQ   MM6, sgn      ;mask to extract sign bit
MOVQ   MM5, mabs     ;mask to clear sign bit
PAND   MM7, MM2      ;xs = sign(x)
PAND   MM1, MM5      ;ya = abs(y)
PAND   MM2, MM5      ;xa = abs(x)
MOVQ   MM6, MM1      ;y
PCMPGTD MM6, MM2     ;df = (xa < ya) ? 0xffffffff : 0
PSLLD  MM6, 31      ;df = bit<31>
MOVQ   MM5, MM7      ;xs
PXOR   MM7, MM6      ;xs^df ? 0x80000000 : 0
MOVQ   MM3, npio2    ;-pi/2
PXOR   MM5, MM3      ;xs ? pi/2 : -pi/2
PSRAD  MM6, 31      ;df ? 0xffffffff : 0
PANDN  MM6, MM5      ;xs ? (df ? 0 : pi/2) : (df ? 0 : -pi/2)
PFSUB  MM6, MM3      ;pr = pi/2 + (xs ? (df ? 0 : pi/2) :
                    ; (df ? 0 : -pi/2))
POR    MM0, MM7      ;ar = xs^df ? -r : r
PFADD  MM0, MM6      ;res = ar + pr

```


Avoid the Loop Instruction

The LOOP instruction in the AMD Athlon processor requires eight cycles to execute. Use the preferred code shown below:

Example 1 (Avoid):

```
LOOP LABEL
```

Example 2 (Preferred):

```
DEC ECX  
JNZ LABEL
```

Avoid Far Control Transfer Instructions

Avoid using far control transfer instructions. Far control transfer branches can not be predicted by the branch target buffer (BTB).

Avoid Recursive Functions

Avoid recursive functions due to the danger of overflowing the return address stack. Convert end-recursive functions to iterative code. An end-recursive function is when the function call to itself is at the end of the code.

Example 1 (Avoid):

```
long fac(long a)
{
    if (a==0) {
        return (1);
    } else {
        return (a*fac(a-1));
    }
    return (t);
}
```

Example 2 (Preferred):

```
long fac(long a)
{
    long t=1;
    while (a > 0) {
        t *= a;
        a--;
    }
    return (t);
}
```

7

Scheduling Optimizations

This chapter describes how to code instructions for efficient scheduling. Guidelines are listed in order of importance.

Schedule Instructions According to their Latency

The AMD Athlon™ processor can execute up to three x86 instructions per cycle, with each x86 instruction possibly having a different latency. The AMD Athlon processor has flexible scheduling, but for absolute maximum performance, schedule instructions, especially FPU and 3DNow!™ instructions, according to their latency. Dependent instructions will then not have to wait on instructions with longer latencies.

See Appendix F, “Instruction Dispatch and Execution Resources” on page 187 for a list of latency numbers.

Unrolling Loops

Complete Loop Unrolling

Make use of the large AMD Athlon processor 64-Kbyte instruction cache and unroll loops to get more parallelism and reduce loop overhead, even with branch prediction. Complete

unrolling reduces register pressure by removing the loop counter. To completely unroll a loop, remove the loop control and replicate the loop body N times. In addition, completely unrolling a loop increases scheduling opportunities.

Only unrolling very large code loops can result in the inefficient use of the L1 instruction cache. Loops can be unrolled completely, if all of the following conditions are true:

- The loop is in a frequently executed piece of code.
- The loop count is known at compile time.
- The loop body, once unrolled, is less than 100 instructions, which is approximately 400 bytes of code.

Partial Loop Unrolling

Partial loop unrolling can increase register pressure, which can make it inefficient due to the small number of registers in the x86 architecture. However, in certain situations, partial unrolling can be efficient due to the performance gains possible. Partial loop unrolling should be considered if the following conditions are met:

- Spare registers are available
- Loop body is small, so that loop overhead is significant
- Number of loop iterations is likely > 10

Consider the following piece of C code:

```
double a[MAX_LENGTH], b[MAX_LENGTH];

for (i=0; i< MAX_LENGTH; i++) {
    a[i] = a[i] + b[i];
}
```

Without loop unrolling, the code looks like the following:

Without Loop Unrolling:

```

MOV ECX, MAX_LENGTH
MOV EAX, OFFSET A
MOV EBX, OFFSET B

$add_loop:
FLD    QWORD PTR [EAX]
FADD   QWORD PTR [EBX]
FSTP   QWORD PTR [EAX]
ADD    EAX, 8
ADD    EBX, 8
DEC    ECX
JNZ    $add_loop

```

The loop consists of seven instructions. The AMD Athlon processor can decode/retire three instructions per cycle, so it cannot execute faster than three iterations in seven cycles, or 3/7 floating-point adds per cycle. However, the pipelined floating-point adder allows one add every cycle. In the following code, the loop is partially unrolled by a factor of two, which creates potential endcases that must be handled outside the loop:

With Partial Loop Unrolling:

```

MOV    ECX, MAX_LENGTH
MOV    EAX, offset A
MOV    EBX, offset B
SHR    ECX, 1
JNC    $add_loop
FLD    QWORD PTR [EAX]
FADD   QWORD PTR [EBX]
FSTP   QWORD PTR [EAX]
ADD    EAX, 8
ADD    EBX, 8

$add_loop:
FLD    QWORD PTR[EAX]
FADD   QWORD PTR[EBX]
FSTP   QWORD PTR[EAX]
FLD    QWORD PTR[EAX+8]
FADD   QWORD PTR[EBX+8]
FSTP   QWORD PTR[EAX+8]
ADD    EAX, 16
ADD    EBX, 16
DEC    ECX
JNZ    $add_loop

```

Now the loop consists of 10 instructions. Based on the decode/retire bandwidth of three OPs per cycle, this loop goes

no faster than three iterations in 10 cycles, or 6/10 floating-point adds per cycle, or 1.4 times as fast as the original loop.

Deriving Loop Control For Partially Unrolled Loops

A frequently used loop construct is a counting loop. In a typical case, the loop count starts at some lower bound `lo`, increases by some fixed, positive increment `inc` for each iteration of the loop, and may not exceed some upper bound `hi`. The following example shows how to partially unroll such a loop by an unrolling factor of `fac`, and how to derive the loop control for the partially unrolled version of the loop.

Example 1 (rolled loop):

```
for (k = lo; k <= hi; k += inc) {
    x[k] =
    ...
}
```

Example 2 (partially unrolled loop):

```
for (k = lo; k <= (hi - (fac-1)*inc); k += fac*inc) {
    x[k] =
    ...
    x[k+inc] =
    ...
    ...
    x[k+(fac-1)*inc] =
    ...
}

/* handle end cases */

for (k = k; k <= hi; k += inc) {
    x[k] =
    ...
}
```

Use Function Inlining

Overview

Make use of the AMD Athlon processor's large 64-Kbyte instruction cache by inlining small routines to avoid procedure-call overhead. Consider the cost of possible increased register usage, which can increase load/store instructions for register spilling.

Function inlining has the advantage of eliminating function call overhead and allowing better register allocation and instruction scheduling at the site of the function call. The disadvantage is decreasing code locality, which can increase execution time due to instruction cache misses. Therefore, function inlining is an optimization that has to be used judiciously.

In general, due to its very large instruction cache, the AMD Athlon processor is less susceptible than other processors to the negative side effect of function inlining. Function call overhead on the AMD Athlon processor can be low because calls and returns are executed at high speed due to the use of prediction mechanisms. However, there is still overhead due to passing function arguments through memory, which creates STLF (store-to-load-forwarding) dependencies. Some compilers allow for a reduction of this overhead by allowing arguments to be passed in registers in one of their calling conventions, which has the drawback of constraining register allocation in the function and at the site of the function call.

In general, function inlining works best if the compiler can utilize feedback from a profiler to identify the function call sites most frequently executed. If such data is not available, a reasonable heuristic is to concentrate on function calls inside loops. Functions that are directly recursive should not be considered candidates for inlining. However, if they are end-recursive, the compiler should convert them to an iterative equivalent to avoid potential overflow of the AMD Athlon processor return prediction mechanism (return stack) during deep recursion. For best results, a compiler should support function inlining across multiple source files. In addition, a compiler should provide inline templates for commonly used library functions, such as `sin()`, `strcmp()`, or `memcpy()`.

Always Inline Functions if Called from One Site

A function should always be inlined if it can be established that it is called from just one site in the code. For the C language, determination of this characteristic is made easier if functions are explicitly declared static unless they require external linkage. This case occurs quite frequently, as functionality that could be concentrated in a single large function is split across multiple small functions for improved maintainability and readability.

Always Inline Functions with Fewer than 25 Machine Instructions

In addition, functions that create fewer than 25 machine instructions once inlined should always be inlined because it is likely that the function call overhead is close to or more than the time spent executing the function body. For large functions, the benefits of reduced function call overhead gives diminishing returns. Therefore, a function that results in the insertion of more than 500 machine instructions at the call site should probably not be inlined. Some larger functions might consist of multiple, relatively short paths that are negatively affected by function overhead. In such a case, it can be advantageous to inline larger functions. Profiling information is the best guide in determining whether to inline such large functions.

Avoid Address Generation Interlocks

Loads and stores are scheduled by the AMD Athlon processor to access the data cache in program order. Newer loads and stores with their addresses calculated can be blocked by older loads and stores whose addresses are not yet calculated – this is known as an address generation interlock. Therefore, it is advantageous to schedule loads and stores that can calculate their addresses quickly, ahead of loads and stores that require the resolution of a long dependency chain in order to generate their addresses. Consider the following code examples.

Example 1 (Avoid):

```

ADD EBX, ECX                ;inst 1
MOV EAX, DWORD PTR [10h]   ;inst 2 (fast address calc.)
MOV ECX, DWORD PTR [EAX+EBX] ;inst 3 (slow address calc.)
MOV EDX, DWORD PTR [24h]   ;this load is stalled from
                           ; accessing data cache due
                           ; to long latency for
                           ; generating address for
                           ; inst 3

```

Example 2 (Preferred):

```

ADD EBX, ECX                ;inst 1
MOV EAX, DWORD PTR [10h]   ;inst 2
MOV EDX, DWORD PTR [24h]   ;place load above inst 3
                           ; to avoid address
                           ; generation interlock stall
MOV ECX, DWORD PTR [EAX+EBX] ;inst 3

```

Use MOVZX and MOVSX

Use the MOVZX and MOVSX instructions to zero-extend and sign-extend byte-size and word-size operands to doubleword length. For example, typical code for zero extension creates a superset dependency when the zero-extended value is used, as in the following code:

Example 1 (Avoid):

```

XOR     EAX, EAX
MOV     AL, [MEM]

```

Example 2 (Preferred):

```

MOVZX   EAX, BYTE PTR [MEM]

```

Minimize Pointer Arithmetic in Loops

Minimize pointer arithmetic in loops, especially if the loop body is small. In this case, the pointer arithmetic would cause significant overhead. Instead, take advantage of the complex addressing modes to utilize the loop counter to index into memory arrays. Using complex addressing modes does not have any negative impact on execution speed, but the reduced number of instructions preserves decode bandwidth.

Example 1 (Avoid):

```

int a[MAXSIZE], b[MAXSIZE], c[MAXSIZE], i;

for (i=0; i < MAXSIZE; i++) {
    c [i] = a[i] + b[i];
}

MOV     ECX, MAXSIZE    ;initialize loop counter
XOR     ESI, ESI        ;initialize offset into array a
XOR     EDI, EDI        ;initialize offset into array b
XOR     EBX, EBX        ;initialize offset into array c

$add_loop:
MOV     EAX, [ESI + a]  ;get element a
MOV     EDX, [EDI + b]  ;get element b
ADD     EAX, EDX        ;a[i] + b[i]
MOV     [EBX + c], EAX ;write result to c
ADD     ESI, 4          ;increment offset into a
ADD     EDI, 4          ;increment offset into b
ADD     EBX, 4          ;increment offset into c
DEC     ECX             ;decrement loop count
JNZ     $add_loop      ;until loop count 0

```

Example 2 (Preferred):

```

int a[MAXSIZE], b[MAXSIZE], c[MAXSIZE], i;

for (i=0; i < MAXSIZE; i++) {
    c [i] = a[i] + b[i];
}

MOV     ECX, MAXSIZE-1 ;initialize loop counter

$add_loop:
MOV     EAX, [ECX*4 + a] ;get element a
MOV     EDX, [ECX*4 + b] ;get element b
ADD     EAX, EDX        ;a[i] + b[i]
MOV     [ECX*4 + c], EAX ;write result to c
DEC     ECX             ;decrement index
JNS     $add_loop      ;until index negative

```

Note that the code in example 2 traverses the arrays in a downward direction (i.e., from higher addresses to lower addresses), whereas the original code in example 1 traverses the arrays in an upward direction. Such a change in the direction of the traversal is possible if each loop iteration is completely independent of all other loop iterations, as is the case here.

In code where the direction of the array traversal can't be switched, it is still possible to minimize pointer arithmetic by appropriately biasing base addresses and using an index

variable that starts with a negative value and reaches zero when the loop expires. Note that if the base addresses are held in registers (e.g., when the base addresses are passed as arguments of a function) biasing the base addresses requires additional instructions to perform the biasing at run time and a small amount of additional overhead is incurred. In the examples shown here the base addresses are used in the displacement portion of the address and biasing is accomplished at compile time by simply modifying the displacement.

Example 3 (Preferred):

```
int a[MAXSIZE], b[MAXSIZE], c[MAXSIZE], i;

for (i=0; i < MAXSIZE; i++) {
    c [i] = a[i] + b[i];
}

MOV    ECX, (-MAXSIZE)           ;initialize index

$add_loop:
MOV    EAX, [ECX*4 + a + MAXSIZE*4] ;get a element
MOV    EDX, [ECX*4 + b + MAXSIZE*4] ;get b element
ADD    EAX, EDX                   ;a[i] + b[i]
MOV    [ECX*4 + c + MAXSIZE*4], EAX ;write result to c
INC    ECX                         ;increment index
JNZ    $add_loop                  ;until index==0
```

Push Memory Data Carefully

Carefully choose the best method for pushing memory data. To reduce register pressure and code dependencies, follow example 2 below.

Example 1 (Avoid):

```
MOV    EAX, [MEM]
PUSH  EAX
```

Example 2 (Preferred):

```
PUSH  [MEM]
```


8

Integer Optimizations

This chapter describes ways to improve integer performance through optimized programming techniques. The guidelines are listed in order of importance.

Replace Divides with Multiplies

Replace integer division by constants with multiplication by the reciprocal. Because the AMD Athlon™ processor has a very fast integer multiply (5–9 cycles signed, 4–8 cycles unsigned) and the integer division delivers only one bit of quotient per cycle (22–47 cycles signed, 17–41 cycles unsigned), the equivalent code is much faster. The user can follow the examples in this chapter that illustrate the use of integer division by constants, or access the executables in the `opt_utilities` directory in the AMD documentation CD-ROM (order# 21860) to find alternative code for dividing by a constant.

Multiplication by Reciprocal (Division) Utility

The code for the utilities can be found at “Derivation of Multiplier Used for Integer Division by Constants” on page 93. All utilities were compiled for the Microsoft Windows® 95, Windows 98, and Windows NT® environments. All utilities are provided ‘as is’ and are not supported by AMD.

Signed Division Utility

In the `opt_utilities` directory of the AMD documentation CDROM, run `sdiv.exe` in a DOS window to find the fastest code for *signed* division by a constant. The utility displays the code after the user enters a signed constant divisor. Type “`sdiv > example.out`” to output the code to a file.

Unsigned Division Utility

In the `opt_utilities` directory of the AMD documentation CDROM, run `udiv.exe` in a DOS window to find the fastest code for *unsigned* division by a constant. The utility displays the code after the user enters an unsigned constant divisor. Type “`udiv > example.out`” to output the code to a file.

Unsigned Division by Multiplication of Constant**Algorithm: Divisors $1 \leq d < 2^{31}$, Odd d**

The following code shows an unsigned division using a constant value multiplier.

```
;In:  d = divisor, 1 <= d < 2^31, odd d
;Out: a = algorithm
;     m = multiplier
;     s = shift factor
```

```
;algorithm 0
MOV  EDX, dividend
MOV  EAX, m
MUL  EDX
SHR  EDX, s    ;EDX=quotient
```

```
;algorithm 1
MOV  EDX, dividend
MOV  EAX, m
MUL  EDX
ADD  EAX, m
ADC  EDX, 0
SHR  EDX, s    ;EDX=quotient
```

Derivation of a, m, s

The derivation for the algorithm (a), multiplier (m), and shift count (s), is found in the section “Unsigned Derivation for Algorithm, Multiplier, and Shift Factor” on page 93.

Algorithm: Divisors $2^{31} \leq d < 2^{32}$

For divisors $2^{31} \leq d < 2^{32}$, the possible quotient values are either 0 or 1. This makes it easy to establish the quotient by simple comparison of the dividend and divisor. In cases where the dividend needs to be preserved, example 1 below is recommended.

Example 1:

```

;In:    EDX = dividend
;Out:   EDX = quotient
XOR EDX, EDX;0
CMP EAX, d ;CF = (dividend < divisor) ? 1 : 0
SBB EDX, -1 ;quotient = 0+1-CF = (dividend < divisor) ? 0 : 1

```

In cases where the dividend does not need to be preserved, the division can be accomplished without the use of an additional register, thus reducing register pressure. This is shown in example 2 below:

Example 2:

```

;In:    EDX = dividend
;Out:   EAX = quotient
CMP EDX, d ;CF = (dividend < divisor) ? 1 : 0
MOV EAX, 0 ;0
SBB EAX, -1 ;quotient = 0+1-CF = (dividend < divisor) ? 0 : 1

```

Simpler Code for Restricted Dividend

Integer division by a constant can be made faster if the range of the dividend is limited, which removes a shift associated with most divisors. For example, for a divide by 10 operation, use the following code if the dividend is less than 40000005h:

```

MOV    EAX, dividend
MOV    EDX, 01999999Ah
MUL   EDX
MOV    quotient, EDX

```

Signed Division by Multiplication of Constant**Algorithm: Divisors**
 $2 \leq d < 2^{31}$

These algorithms work if the divisor is positive. If the divisor is negative, use $\text{abs}(d)$ instead of d , and append a 'NEG EDX' to the code. The code makes use of the fact that $n/-d = -(n/d)$.

```

;IN:    d = divisor, 2 <= d < 2^31
;OUT:   a = algorithm
;       m = multiplier
;       s = shift count

;algorithm 0
MOV    EAX, m
MOV    EDX, dividend
MOV    ECX, EDX
IMUL  EDX
SHR   ECX, 31
SAR   EDX, s
ADD   EDX, ECX ;quotient in EDX

```

```

;algorithm 1
MOV   EAX, m
MOV   EDX, dividend
MOV   ECX, EDX
IMUL  EDX
ADD   EDX, ECX
SHR   ECX, 31
SAR   EDX, s
ADD   EDX, ECX           ;quotient in EDX

```

Derivation for a, m, s

The derivation for the algorithm (a), multiplier (m), and shift count (s), is found in the section “Signed Derivation for Algorithm, Multiplier, and Shift Factor” on page 95.

Signed Division By 2

```

;IN: EAX = dividend
;OUT: EAX = quotient
CMP   EAX, 800000000h   ;CY = 1, if dividend >=0
SBB   EAX, -1           ;Increment dividend if it is < 0
SAR   EAX, 1           ;Perform a right shift

```

Signed Division By 2ⁿ

```

;IN: EAX = dividend
;OUT: EAX = quotient
CDQ                                       ;Sign extend into EDX
AND   EDX, (2^n-1)                       ;Mask correction (use divisor -1)
ADD   EAX, EDX                           ;Apply correction if necessary
SAR   EAX, (n)                           ;Perform right shift by
                                           ; log2 (divisor)

```

Signed Division By -2

```

;IN: EAX = dividend
;OUT: EAX = quotient
CMP   EAX, 800000000h   ;CY = 1, if dividend >= 0
SBB   EAX, -1           ;Increment dividend if it is < 0
SAR   EAX, 1           ;Perform right shift
NEG   EAX               ;Use (x/-2) == -(x/2)

```

Signed Division By -2ⁿ

```

;IN: EAX = dividend
;OUT: EAX = quotient
CDQ                                       ;Sign extend into EDX
AND   EDX, (2^n-1)                       ;Mask correction (-divisor -1)
ADD   EAX, EDX                           ;Apply correction if necessary
SAR   EAX, (n)                           ;Right shift by log2(-divisor)
NEG   EAX                                 ;Use (x/-(2^n)) == -(x/2^n)

```

Remainder of Signed Integer 2 or -2

```

;IN: EAX = dividend
;OUT: EAX = remainder
CDQ                                       ;Sign extend into EDX
AND   EDX, 1                             ;Compute remainder
XOR   EAX, EDX                           ;Negate remainder if
SUB   EAX, EDX                           ;Dividend was < 0
MOV   [remainder], EAX

```


Remainder of Signed Integer 2^n or $-(2^n)$

```

;IN:EAX = dividend
;OUT:EAX = remainder
CDQ                                ;Sign extend into EDX
AND  EDX, (2^n-1)                  ;Mask correction (abs(divison)-1)
ADD  EAX, EDX                      ;Apply pre-correction
AND  EAX, (2^n-1)                  ;Mask out remainder (abs(divison)-1)
SUB  EAX, EDX                      ;Apply pre-correction, if necessary
MOV  [remainder], EAX

```

Use Alternative Code When Multiplying by a Constant

A 32-bit integer multiply by a constant has a latency of five cycles. Therefore, use alternative code when multiplying by certain constants. In addition, because there is just one multiply unit, the replacement code may provide better throughput.

The following code samples are designed such that the original source also receives the final result. Other sequences are possible if the result is in a different register. Adds have been favored over shifts to keep code size small. Generally, there is a fast replacement if the constant has very few 1 bits in binary.

More constants are found in the file `multiply_by_constants.txt` located in the same directory where this document is located in the SDK.

```

by 2:   ADD  REG1, REG1                ;1 cycle
by 3:   LEA  REG1, [REG1*2+REG1]      ;2 cycles
by 4:   SHL  REG1, 2                  ;1 cycle
by 5:   LEA  REG1, [REG1*4+REG1]      ;2 cycles
by 6:   LEA  REG2, [REG1*4+REG1]      ;3 cycles
        ADD  REG1, REG2
by 7:   MOV  REG2, REG1                ;2 cycles
        SHL  REG1, 3
        SUB  REG1, REG2
by 8:   SHL  REG1, 3                  ;1 cycle
by 9:   LEA  REG1, [REG1*8+REG1]      ;2 cycles
by 10:  LEA  REG2, [REG1*8+REG1]      ;3 cycles
        ADD  REG1, REG2

```

by 11:	LEA	REG2, [REG1*8+REG1]	;3 cycles
	ADD	REG1, REG1	
	ADD	REG1, REG2	
by 12:	SHL	REG1, 2	
	LEA	REG1, [REG1*2+REG1]	;3 cycles
by 13:	LEA	REG2, [REG1*2+REG1]	;3 cycles
	SHL	REG1, 4	
	SUB	REG1, REG2	
by 14:	LEA	REG2, [REG1*4+REG1]	;3 cycles
	LEA	REG1, [REG1*8+REG1]	
	ADD	REG1, REG2	
by 15:	MOV	REG2, REG1	;2 cycles
	SHL	REG1, 4	
	SUB	REG1, REG2	
by 16:	SHL	REG1, 4	;1 cycle
by 17:	MOV	REG2, REG1	;2 cycles
	SHL	REG1, 4	
	ADD	REG1, REG2	
by 18:	ADD	REG1, REG1	;3 cycles
	LEA	REG1, [REG1*8+REG1]	
by 19:	LEA	REG2, [REG1*2+REG1]	;3 cycles
	SHL	REG1, 4	
	ADD	REG1, REG2	
by 20:	SHL	REG1, 2	;3 cycles
	LEA	REG1, [REG1*4+REG1]	
by 21:	LEA	REG2, [REG1*4+REG1]	;3 cycles
	SHL	REG1, 4	
	ADD	REG1, REG2	
by 22:	use	IMUL	
by 23:	LEA	REG2, [REG1*8+REG1]	;3 cycles
	SHL	REG1, 5	
	SUB	REG1, REG2	
by 24:	SHL	REG1, 3	;3 cycles
	LEA	REG1, [REG1*2+REG1]	
by 25:	LEA	REG2, [REG1*8+REG1]	;3 cycles
	SHL	REG1, 4	
	ADD	REG1, REG2	

```

by 26:   use IMUL

by 27:   LEA   REG2, [REG1*4+REG1]   ;3 cycles
        SHL   REG1, 5
        SUB   REG1, REG2

by 28:   MOV   REG2, REG1           ;3 cycles
        SHL   REG1, 3
        SUB   REG1, REG2
        SHL   REG1, 2

by 29:   LEA   REG2, [REG1*2+REG1]   ;3 cycles
        SHL   REG1, 5
        SUB   REG1, REG2

by 30:   MOV   REG2, REG1           ;3 cycles
        SHL   REG1, 4
        SUB   REG1, REG2
        ADD   REG1, REG1

by 31:   MOV   REG2, REG1           ;2 cycles
        SHL   REG1, 5
        SUB   REG1, REG2

by 32:   SHL   REG1, 5              ;1 cycle

```

Use MMX™ Instructions for Integer-Only Work

In many programs it can be advantageous to use MMX instructions to do integer-only work, especially if the function already uses 3DNow!™ or MMX code. Using MMX instructions relieves register pressure on the integer registers. As long as data is simply loaded/stored, added, shifted, etc., MMX instructions are good substitutes for integer instructions. Integer registers are freed up with the following results:

- May be able to reduce the number of integer registers to saved/restored on function entry/edit.
- Free up integer registers for pointers, loop counters, etc., so that they do not have to be spilled to memory, which reduces memory traffic and latency in dependency chains.

Be careful with regards to passing data between MMX and integer registers and of creating mismatched store-to-load forwarding cases. See “Unrolling Loops” on page 67.

In addition, using MMX instructions increases the available parallelism. The AMD Athlon processor can issue three integer OPs and two MMX OPs per cycle.

Repeated String Instruction Usage

Latency of Repeated String Instructions

Table 1 shows the latency for repeated string instructions on the AMD Athlon processor.

Table 1. Latency of Repeated String Instructions

Instruction	ECX=0 (cycles)	DF = 0 (cycles)	DF = 1 (cycles)
REP MOVS	11	$15 + (4/3*c)$	$25 + (4/3*c)$
REP STOS	11	$14 + (1*c)$	$24 + (1*c)$
REP LODS	11	$15 + (2*c)$	$15 + (2*c)$
REP SCAS	11	$15 + (5/2*c)$	$15 + (5/2*c)$
REP CMPS	11	$16 + (10/3*c)$	$16 + (10/3*c)$
Note: <i>c = value of ECX, (ECX > 0)</i>			

Table 1 lists the latencies with the direction flag (DF) = 0 (increment) and DF = 1. In addition, these latencies are assumed for aligned memory operands. Note that for MOVS/STOS, when DF = 1 (DOWN), the overhead portion of the latency increases significantly. However, these types are less commonly found. The user should use the formula and round up to the nearest integer value to determine the latency.

Guidelines for Repeated String Instructions

To help achieve good performance, this section contains guidelines for the careful scheduling of VectorPath repeated string instructions.

Use the Largest Possible Operand Size

Always move data using the largest operand size possible. For example, use REP MOVSD rather than REP MOVSW and REP MOVSW rather than REP MOVSB. Use REP STOSD rather than REP STOSW and REP STOSW rather than REP MOVSB.

Ensure DF=0 (UP)

Always make sure that DF = 0 (UP) (after execution of CLD) for REP MOVS and REP STOS. DF = 1 (DOWN) is only needed for certain cases of overlapping REP MOVS (for example, source and destination overlap).

While string instructions with DF = 1 (DOWN) are slower, only the overhead part of the cycle equation is larger and not the throughput part. See Table 1, “Latency of Repeated String Instructions,” on page 84 for additional latency numbers.

Align Source and Destination with Operand Size

For REP MOVS, make sure that both source and destination are aligned with regard to the operand size. Handle the end case separately, if necessary. If either source or destination cannot be aligned, make the destination aligned and the source misaligned. For REP STOS, make the destination aligned.

Inline REP String with Low Counts

Expand REP string instructions into equivalent sequences of simple x86 instructions, if the repeat count is constant and less than eight. Use an inline sequence of loads and stores to accomplish the move. Use a sequence of stores to emulate REP STOS. This technique eliminates the setup overhead of REP instructions and increases instruction throughput.

Use Loop for REP String with Low Variable Counts

If the repeated count is variable, but is likely less than eight, use a simple loop to move/store the data. This technique avoids the overhead of REP MOVS and REP STOS.

Using MOVQ and MOVNTQ for Block Copy/Fill

To fill or copy blocks of data that are larger than 512 bytes, or where the destination is in uncacheable memory, it is recommended to use the MMX instructions MOVQ/MOVNTQ instead of REP STOS and REP MOVS in order to achieve maximum performance. (See the guideline, “Use MMX™ Instructions for Block Copies and Block Fills” on page 115.)

Use XOR Instruction to Clear Integer Registers

To clear an integer register to all 0s, use “XOR reg, reg”. The AMD Athlon processor is able to avoid the false read dependency on the XOR instruction.

Example 1 (Acceptable):

```
MOV     REG, 0
```

Example 2 (Preferred):

```
XOR     REG, REG
```

Efficient 64-Bit Integer Arithmetic

This section contains a collection of code snippets and subroutines showing the efficient implementation of 64-bit arithmetic. Addition, subtraction, negation, and shifts are best handled by inline code. Multiplies, divides, and remainders are less common operations and should usually be implemented as subroutines. If these subroutines are used often, the programmer should consider inlining them. Except for division and remainder, the code presented works for both signed and unsigned integers. The division and remainder code shown works for unsigned integers, but can easily be extended to handle signed integers.

Example 1 (Addition):

```
;add operand in ECX:EBX to operand EDX:EAX, result in  
; EDX:EAX  
ADD     EAX, EBX  
ADC     EDX, ECX
```

Example 2 (Subtraction):

```
;subtract operand in ECX:EBX from operand EDX:EAX, result in  
; EDX:EAX  
SUB     EAX, EBX  
SBB     EDX, ECX
```

Example 3 (Negation):

```
;negate operand in EDX:EAX  
NOT     EDX  
NEG     EAX  
SBB     EDX, -1 ;fixup: increment hi-word if low-word was 0
```

Example 4 (Left shift):

```

;shift operand in EDX:EAX left, shift count in ECX (count
; applied modulo 64)
SHLD  EDX, EAX, CL      ;first apply shift count
SHL   EAX, CL          ; mod 32 to EDX:EAX
TEST  ECX, 32          ;need to shift by another 32?
JZ    $lshift_done     ;no, done
MOV   EDX, EAX        ;left shift EDX:EAX
XOR   EAX, EAX        ; by 32 bits

```

```
$lshift_done:
```

Example 5 (Right shift):

```

SHRD  EAX, EDX, CL      ;first apply shift count
SHR   EDX, CL          ; mod 32 to EDX:EAX
TEST  ECX, 32          ;need to shift by another 32?
JZ    $rshift_done     ;no, done
MOV   EAX, EDX        ;left shift EDX:EAX
XOR   EDX, EDX        ; by 32 bits

```

```
$rshift_done:
```

Example 6 (Multiplication):

```

;_llmul computes the low-order half of the product of its
; arguments, two 64-bit integers
;
;INPUT:  [ESP+8]:[ESP+4]  multiplicand
;        [ESP+16]:[ESP+12] multiplier
;
;OUTPUT: EDX:EAX        (multiplicand * multiplier) % 2^64
;
;DESTROYS:  EAX,ECX,EDX,EFlags

```

```

_llmul PROC
MOV   EDX, [ESP+8]      ;multiplicand_hi
MOV   ECX, [ESP+16]    ;multiplier_hi
OR    EDX, ECX         ;one operand >= 2^32?
MOV   EDX, [ESP+12]    ;multiplier_lo
MOV   EAX, [ESP+4]     ;multiplicand_lo
JNZ   $twomul         ;yes, need two multiplies
MUL   EDX              ;multiplicand_lo * multiplier_lo
RET                                ;done, return to caller

$twomul:
IMUL  EDX, [ESP+8]     ;p3_lo = multiplicand_hi*multiplier_lo
IMUL  ECX, EAX         ;p2_lo = multiplier_hi*multiplicand_lo
ADD   ECX, EDX        ; p2_lo + p3_lo
MUL   DWORD PTR [ESP+12] ;p1=multiplicand_lo*multiplier_lo
ADD   EDX, ECX        ;p1+p2_lo+p3_lo = result in EDX:EAX
RET                                ;done, return to caller

_llmul ENDP

```

Example 7 (Division):

```

;_ulldiv divides two unsigned 64-bit integers, and returns
; the quotient.
;
;INPUT:  [ESP+8]:[ESP+4]  dividend
;        [ESP+16]:[ESP+12] divisor
;
;OUTPUT: EDX:EAX        quotient of division
;
;DESTROYS: EAX,ECX,EDX,EFlags
_ulldiv PROC
PUSH    EBX                ;save EBX as per calling convention
MOV     ECX, [ESP+20]      ;divisor_hi
MOV     EBX, [ESP+16]      ;divisor_lo
MOV     EDX, [ESP+12]      ;dividend_hi
MOV     EAX, [ESP+8]       ;dividend_lo
TEST    ECX, ECX          ;divisor > 2^32-1?
JNZ     $big_divisor      ;yes, divisor > 32^32-1
CMP     EDX, EBX          ;only one division needed? (ECX = 0)
JAE     $two_divs         ;need two divisions
DIV     EBX                ;EAX = quotient_lo
MOV     EDX, ECX          ;EDX = quotient_hi = 0 (quotient in
; EDX:EAX)
POP     EBX                ;restore EBX as per calling convention
RET                                     ;done, return to caller

$two_divs:
MOV     ECX, EAX          ;save dividend_lo in ECX
MOV     EAX, EDX          ;get dividend_hi
XOR     EDX, EDX         ;zero extend it into EDX:EAX
DIV     EBX                ;quotient_hi in EAX
XCHG   EAX, ECX          ;ECX = quotient_hi, EAX = dividend_lo
DIV     EBX                ;EAX = quotient_lo
MOV     EDX, ECX          ;EDX = quotient_hi (quotient in EDX:EAX)
POP     EBX                ;restore EBX as per calling convention
RET                                     ;done, return to caller

$big_divisor:
PUSH    EDI                ;save EDI as per calling convention
MOV     EDI, ECX          ;save divisor_hi
SHR     EDX, 1            ;shift both divisor and dividend right
RCR     EAX, 1            ; by 1 bit
ROR     EDI, 1
RCR     EBX, 1
BSR     ECX, ECX          ;ECX = number of remaining shifts
SHRD   EBX, EDI, CL       ;scale down divisor and dividend
SHRD   EAX, EDX, CL       ; such that divisor is
SHR     EDX, CL           ; less than 2^32 (i.e. fits in EBX)
ROL     EDI, 1            ;restore original divisor_hi
DIV     EBX                ;compute quotient
MOV     EBX, [ESP+12]     ;dividend_lo

```



```

MOV     ECX, EAX           ;save quotient
IMUL   EDI, EAX           ;quotient * divisor hi-word
                               ; (low only)
MUL    DWORD PTR [ESP+20];quotient * divisor lo-word
ADD    EDX, EDI           ;EDX:EAX = quotient * divisor
SUB    EBX, EAX           ;dividend_lo - (quot.*divisor)_lo
MOV    EAX, ECX           ;get quotient
MOV    ECX, [ESP+16]      ;dividend_hi
SBB    ECX, EDX           ;subtract divisor * quot. from dividend
SBB    EAX, 0             ;adjust quotient if remainder negative
XOR    EDX, EDX          ;clear hi-word of quot(EAX<=FFFFFFFFh)
POP    EDI                ;restore EDI as per calling convention
POP    EBX                ;restore EBX as per calling convention
RET                                ;done, return to caller

_ulldiv ENDP

```

Example 8 (Remainder):

:_ullrem divides two unsigned 64-bit integers, and returns the remainder.

```

;
;INPUT:      [ESP+8]:[ESP+4]  dividend
;            [ESP+16]:[ESP+12] divisor
;
;OUTPUT:     EDX:EAX        remainder of division
;
;DESTROYS:   EAX,ECX,EDX,EFlags

_ullrem PROC
PUSH    EBX                ;save EBX as per calling convention
MOV     ECX, [ESP+20]      ;divisor_hi
MOV     EBX, [ESP+16]      ;divisor_lo
MOV     EDX, [ESP+12]      ;dividend_hi
MOV     EAX, [ESP+8]       ;dividend_lo
TEST    ECX, ECX           ;divisor > 2^32-1?
JNZ    $r_big_divisor     ;yes, divisor > 32^32-1
CMP     EDX, EBX           ;only one division needed? (ECX = 0)
JAE    $r_two_divs        ;need two divisions
DIV    EBX                 ;EAX = quotient_lo
MOV    EAX, EDX           ;EAX = remainder_lo
MOV    EDX, ECX           ;EDX = remainder_hi = 0
POP    EBX                ;restore EBX as per calling convention
RET                                ;done, return to caller

```

```

$r_two_divs:
MOV     ECX, EAX    ;save dividend_lo in ECX
MOV     EAX, EDX    ;get dividend_hi
XOR     EDX, EDX    ;zero extend it into EDX:EAX
DIV     EBX         ;EAX = quotient_hi, EDX = intermediate
                        ; remainder

MOV     EAX, ECX    ;EAX = dividend_lo
DIV     EBX         ;EAX = quotient_lo
MOV     EAX, EDX    ;EAX = remainder_lo
XOR     EDX, EDX    ;EDX = remainder_hi = 0
POP     EBX         ;restore EBX as per calling convention
RET

$r_big_divisor:
PUSH    EDI         ;save EDI as per calling convention
MOV     EDI, ECX    ;save divisor_hi
SHR     EDX, 1      ;shift both divisor and dividend right
RCR     EAX, 1      ; by 1 bit
ROR     EDI, 1
RCR     EBX, 1
BSR     ECX, ECX    ;ECX = number of remaining shifts
SHRD   EBX, EDI, CL ;scale down divisor and dividend such
SHRD   EAX, EDX, CL ; that divisor is less than 2^32
SHR     EDX, CL     ; (i.e. fits in EBX)
ROL     EDI, 1      ;restore original divisor (EDI:ESI)
DIV     EBX         ;compute quotient
MOV     EBX, [ESP+12] ;dividend lo-word
MOV     ECX, EAX    ;save quotient
IMUL   EDI, EAX     ;quotient * divisor hi-word (low only)
MUL    DWORD PTR [ESP+20] ;quotient * divisor lo-word
ADD     EDX, EDI    ;EDX:EAX = quotient * divisor
SUB     EBX, EAX    ;dividend_lo - (quot.*divisor)-lo
MOV     ECX, [ESP+16] ;dividend_hi
MOV     EAX, [ESP+20] ;divisor_lo
SBB    ECX, EDX    ;subtract divisor * quot. from
                        ; dividend

SBB    EDX, EDX    ;(remainder < 0)? 0xFFFFFFFF : 0
AND    EAX, EDX    ;(remainder < 0)? divisor_lo : 0
AND    EDX, [ESP+24] ;(remainder < 0)? divisor_hi : 0
ADD    EAX, EBX    ;remainder += (remainder < 0)?
ADC    EDX, ECX    ; divisor : 0
POP     EDI         ;restore EDI as per calling convention
POP     EBX         ;restore EBX as per calling convention
RET

_allrem ENDP

```

Efficient Implementation of Population Count Function

Population count is an operation that determines the number of set bits in a bit string. For example, this can be used to determine the cardinality of a set. The following example code shows how to efficiently implement a population count operation for 32-bit operands. The example is written for the inline assembler of Microsoft Visual C.

Function `popcount()` implements a branchless computation of the population count. It is based on a $O(\log(n))$ algorithm that successively groups the bits into groups of 2, 4, 8, 16, and 32, while maintaining a count of the set bits in each group. The algorithms consist of the following steps:

Step 1

Partition the integer into groups of two bits. Compute the population count for each 2-bit group and store the result in the 2-bit group. This calls for the following transformation to be performed for each 2-bit group:

```
00b -> 00b
01b -> 01b
10b -> 01b
11b -> 10b
```

If the original value of a 2-bit group is v , then the new value will be $v - (v \gg 1)$. In order to handle all 2-bit groups simultaneously, it is necessary to mask appropriately to prevent spilling from one bit group to the next lower bit group. Thus:

```
w = v - ((v >> 1) & 0x55555555)
```

Step 2

Add the population count of adjacent 2-bit group and store the sum to the 4-bit group resulting from merging these adjacent 2-bit groups. To do this simultaneously to all groups, mask out the odd numbered groups, mask out the even numbered groups, and then add the odd numbered groups to the even numbered groups:

```
x = (w & 0x33333333) + ((w >> 2) & 0x33333333)
```

Each 4-bit field now has value 0000b, 0001b, 0010b, 0011b, or 0100b.

Step 3

For the first time, the value in each k-bit field is small enough that adding two k-bit fields results in a value that still fits in the k-bit field. Thus the following computation is performed:

$$y = (x + (x \gg 4)) \& 0x0F0F0F0F$$

The result is four 8-bit fields whose lower half has the desired sum and whose upper half contains "junk" that has to be masked out. In a symbolic form:

```
x          = 0aaa0bbb0ccc0ddd0eee0fff0ggg0hhh
x >> 4    = 00000aaa0bbb0ccc0ddd0eee0fff0ggg
sum       = 0aaaWWWi i i i XXXXj j j j YYYYYkkkkZZZZ
```

The WWWW, XXXX, YYYYY, and ZZZZ values are the interesting sums with each at most 1000b, or 8 decimal.

Step 4

The four 4-bit sums can now be rapidly accumulated by means of a multiply with a "magic" multiplier. This can be derived from looking at the following chart of partial products:

```
0p0q0r0s * 01010101 =
                :0p0q0r0s
                0p:0q0r0s
                0p0q:0r0s
                0p0q0r:0s
                000pxxww:vvuutt0s
```

Here p, q, r, and s are the 4-bit sums from the previous step, and vv is the final result in which we are interested. Thus, the final result:

$$z = (y * 0x01010101) \gg 24$$
Example:

```
unsigned int popcount(unsigned int v)
{
    unsigned int retVal;
    __asm {
        MOV    EAX, [v]           ;v
        MOV    EDX, EAX          ;v
        SHR    EAX, 1             ;v >> 1
        AND    EAX, 055555555h    ;(v >> 1) & 0x55555555
        SUB    EDX, EAX           ;w = v - ((v >> 1) & 0x55555555)
        MOV    EAX, EDX          ;w
        SHR    EDX, 2             ;w >> 2
        AND    EAX, 033333333h    ;w & 0x33333333
        AND    EDX, 033333333h    ;(w >> 2) & 0x33333333
```

```

ADD    EAX, EDX        ;x = (w & 0x33333333) + ((w >> 2) &
                        ; 0x33333333)
MOV    EDX, EDX        ;x
SHR    EAX, 4          ;x >> 4
ADD    EAX, EDX        ;x + (x >> 4)
AND    EAX, 00F0F0F0Fh ;y = (x + (x >> 4) & 0x0F0F0F0F)
IMUL  EAX, 001010101h ;y * 0x01010101
SHR    EAX, 24         ;population count = (y *
                        ; 0x01010101) >> 24
MOV    retVal, EAX     ;store result
}
return (retVal);
}

```

Derivation of Multiplier Used for Integer Division by Constants

Unsigned Derivation for Algorithm, Multiplier, and Shift Factor

The utility `udiv.exe` was compiled using the code shown in this section.

The following code derives the multiplier value used when performing integer division by constants. The code works for unsigned integer division and for odd divisors between 1 and $2^{31}-1$, inclusive. For divisors of the form $d = d' \cdot 2^n$, the multiplier is the same as for d' and the shift factor is $s + n$.

/ Code snippet to determine algorithm (a), multiplier (m), and shift factor (s) to perform division on unsigned 32-bit integers by constant divisor. Code is written for the Microsoft Visual C compiler. */*

```

/*
In:   d = divisor, 1 <= d < 2^31, d odd
Out:  a = algorithm
      m = multiplier
      s = shift factor

;algorithm 0
MOV    EDX, dividend
MOV    EAX, m
MUL   EDX
SHR    EDX, s      ;EDX=quotient

```

```

;algorithm 1
MOV   EDX, dividend
MOV   EAX, m
MUL   EDX
ADD   EAX, m
ADC   EDX, 0
SHR   EDX, s    ;EDX=quotient
*/

typedef unsigned __int64    U64;
typedef unsigned long      U32;

U32 d, l, s, m, a, r;
U64 m_low, m_high, j, k;
U32 log2 (U32 i)
{
    U32 t = 0;
    i = i >> 1;
    while (i) {
        i = i >> 1;
        t++;
    }
    return (t);
}

/* Generate m, s for algorithm 0. Based on: Granlund, T.;
Montgomery, P.L.: "Division by Invariant Integers using
Multiplication". SIGPLAN Notices, Vol. 29, June 1994, page
61. */

l      = log2(d) + 1;
j      = (((U64)(0xffffffff)) % ((U64)(d)));
k      = (((U64)(1)) << (32+l)) / ((U64)(0xffffffff-j));
m_low  = (((U64)(1)) << (32+l)) / d;
m_high = (((U64)(1)) << (32+l)) + k) / d;
while (((m_low >> 1) < (m_high >> 1)) && (l > 0)) {
    m_low  = m_low  >> 1;
    m_high = m_high >> 1;
    l      = l - 1;
}
if ((m_high >> 32) == 0) {
    m = ((U32)(m_high));
    s = 1;
    a = 0;
}

```

```

/* Generate m, s for algorithm 1. Based on: Magenheimer,
D.J.; et al: "Integer Multiplication and Division on the HP
Precision Architecture". IEEE Transactions on Computers, Vol
37, No. 8, August 1988, page 980. */

else {
    s = log2(d);
    m_low = (((U64)(1)) << (32+s)) / ((U64)(d));
    r      = ((U32)((((U64)(1)) << (32+s)) % ((U64)(d))));
    m = (r < ((d>>1)+1)) ? ((U32)(m_low)) : ((U32)(m_low))+1;
    a = 1;
}

/* Reduce multiplier/shift factor for either algorithm to
smallest possible */

while (!(m&1)) {
    m = m >> 1;
    s--;
}

```

Signed Derivation for Algorithm, Multiplier, and Shift Factor

The utility `sdiv.exe` was compiled using the following code.

```

/* Code snippet to determine algorithm (a), multiplier (m),
and shift count (s) for 32-bit signed integer division,
given divisor d. Written for Microsoft Visual C compiler. */

/*
IN:   d = divisor, 2 <= d < 2^31
OUT:  a = algorithm
      m = multiplier
      s = shift count

;algorithm 0
MOV   EAX, m
MOV   EDX, dividend
MOV   ECX, EDX
IMUL  EDX
SHR   ECX, 31
SAR   EDX, s
ADD   EDX, ECX           ; quotient in EDX

```

```

;algorithm 1
MOV   EAX, m
MOV   EDX, dividend
MOV   ECX, EDX
IMUL  EDX
ADD   EDX, ECX
SHR   ECX, 31
SAR   EDX, s
ADD   EDX, ECX           ; quotient in EDX
*/

typedef unsigned __int64   U64;
typedef unsigned long     U32;

U32 log2 (U32 i)
{
    U32 t = 0;
    i = i >> 1;
    while (i) {
        i = i >> 1;
        t++;
    }
    return (t);
}

U32 d, l, s, m, a;
U64 m_low, m_high, j, k;

/* Determine algorithm (a), multiplier (m), and shift count
(s) for 32-bit signed integer division. Based on: Granlund,
T.; Montgomery, P.L.: "Division by Invariant Integers using
Multiplication". SIGPLAN Notices, Vol. 29, June 1994, page
61. */

l      = log2(d);
j      = (((U64)(0x80000000)) % ((U64)(d)));
k      = (((U64)(1)) << (32+l)) / ((U64)(0x80000000-j));
m_low  = (((U64)(1)) << (32+l)) / d;
m_high = (((U64)(1)) << (32+l)) + k) / d;
while (((m_low >> 1) < (m_high >> 1)) && (l > 0)) {
    m_low  = m_low  >> 1;
    m_high = m_high >> 1;
    l      = l - 1;
}
m = ((U32)(m_high));
s = l;
a = (m_high >> 31) ? 1 : 0;

```


9

Floating-Point Optimizations

This chapter details the methods used to optimize floating-point code to the pipelined floating-point unit (FPU). Guidelines are listed in order of importance.

Ensure All FPU Data is Aligned

As discussed in “Memory Size and Alignment Issues” on page 45, floating-point data should be naturally aligned. That is, words should be aligned on word boundaries, doublewords on doubleword boundaries, and quadwords on quadword boundaries. Misaligned memory accesses reduce the available memory bandwidth.

Use Multiplies Rather than Divides

If accuracy requirements allow, floating-point division by a constant should be converted to a multiply by the reciprocal. Divisors that are powers of two and their reciprocal are exactly representable, except in the rare case that the reciprocal overflows or underflows, and therefore does not cause an accuracy issue. Unless such an overflow or underflow occurs, a division by a power of two should always be converted to a multiply. Although the AMD Athlon™ processor has high-performance division, multiplies are significantly faster than divides.

Use FFREEP Macro to Pop One Register from the FPU Stack

In FPU intensive code, frequently accessed data is often pre-loaded at the bottom of the FPU stack before processing floating-point data. After completion of processing, it is desirable to remove the pre-loaded data from the FPU stack as quickly as possible. The classical way to clean up the FPU stack is to use either of the following instructions:

```
FSTP    ST(0)    ;removes one register from stack
```

```
FCOMPP                ;removes two registers from stack
```

On the AMD Athlon processor, a faster alternative is to use the FFREEP instruction below. Note that the FFREEP instruction, although insufficiently documented in the past, is supported by all 32-bit x86 processors. The opcode bytes for FFREEP ST(i) are listed in Table 22 on page 212.

```
FFREEP  ST(0)    ;removes one register from stack
```

FFREEP ST(i) works like FFREE ST(i) except that it increments the FPU top-of-stack after doing the FFREE work. In other words, FFREEP ST(i) marks ST(i) as empty, then increments the x87 stack pointer. On the AMD Athlon processor, the FFREEP instruction converts to an internal NOP, which can go down any pipe with no dependencies.

Many assemblers do not support the FFREEP instruction. In these cases, a simple text macro can be created to facilitate use of the FFREEP ST(0).

```
FFREEP_ST0    TEXTEQU    <DB 0DFh, 0C0h>
```

Floating-Point Compare Instructions

For branches that are dependent on floating-point comparisons, use the following instructions:

- FCOMI
- FCOMIP
- FUCOMI
- FUCOMIP

These instructions are much faster than the classical approach using FSTSW, because FSTSW is essentially a serializing instruction on the AMD Athlon processor. When FSTSW cannot be avoided (for example, backward compatibility of code with older processors), no FPU instruction should occur between an FCOM[P], FICOM[P], FUCOM[P], or FTST and a dependent FSTSW. This optimization allows the use of a fast forwarding mechanism for the FPU condition codes internal to the AMD Athlon processor FPU and increases performance.

Use the FXCH Instruction Rather than FST/FLD Pairs

Increase parallelism by breaking up dependency chains or by evaluating multiple dependency chains simultaneously by explicitly switching execution between them. Although the AMD Athlon processor FPU has a deep scheduler, which in most cases can extract sufficient parallelism from existing code, long dependency chains can stall the scheduler while issue slots are still available. The maximum dependency chain length that the scheduler can absorb is about six 4-cycle instructions.

To switch execution between dependency chains, use of the FXCH instruction is recommended because it has an apparent latency of zero cycles and generates only one OP. The AMD Athlon processor FPU contains special hardware to handle up to three FXCH instructions per cycle. Using FXCH is preferred over the use of FST/FLD pairs, even if the FST/FLD pair works on a register. An FST/FLD pair adds two cycles of latency and consists of two OPs.

Avoid Using Extended-Precision Data

Store data as either single-precision or double-precision quantities. Loading and storing extended-precision data is comparatively slower.

Minimize Floating-Point-to-Integer Conversions

C++, C, and Fortran define floating-point-to-integer conversions as truncating. This creates a problem because the active rounding mode in an application is typically round-to-nearest-even. The classical way to do a double-to-int conversion therefore works as follows:

Example 1 (Fast):

```
SUB    [I], EDX                ;trunc(X)=rndint(X)-correction
FLD    QWORD PTR [X]          ;load double to be converted
FSTCW  [SAVE_CW]              ;save current FPU control word
MOVZX  EAX, WORD PTR[SAVE_CW];retrieve control word
OR     EAX, 0C00h             ;rounding control field = truncate
MOV    WORD PTR [NEW_CW], AX  ;new FPU control word
FLDCW  [NEW_CW]               ;load new FPU control word
FISTP  DWORD PTR [I]          ;do double->int conversion
FLDCW  [SAVE_CW]              ;restore original control word
```

The AMD Athlon processor contains special acceleration hardware to execute such code as quickly as possible. In most situations, the above code is therefore the fastest way to perform floating-point-to-integer conversion and the conversion is compliant both with programming language standards and the IEEE-754 standard.

According to the recommendations for inlining (see “Always Inline Functions with Fewer than 25 Machine Instructions” on page 72), the above code should not be put into a separate subroutine (e.g., `ftol`). It should rather be inlined into the main code.

In some codes, floating-point numbers are converted to an integer and the result is immediately converted back to floating-point. In such cases, the `FRNDINT` instruction should be used for maximum performance instead of `FISTP` in the code above. `FRNDINT` delivers the integral result directly to an FPU register in floating-point form, which is faster than first using `FISTP` to store the integer result and then converting it back to floating-point with `FILD`.

If there are multiple, consecutive floating-point-to-integer conversions, the cost of `FLDCW` operations should be minimized by saving the current FPU control word, forcing the

FPU into truncating mode, and performing all of the conversions before restoring the original control word.

The speed of the above code is somewhat dependent on the nature of the code surrounding it. For applications in which the speed of floating-point-to-integer conversions is extremely critical for application performance, experiment with either of the following substitutions, which may or may not be faster than the code above.

The first substitution simulates a truncating floating-point to integer conversion provided that there are no NaNs, infinities, and overflows. This conversion is therefore not IEEE-754 compliant. This code works properly only if the current FPU rounding mode is round-to-nearest-even, which is usually the case.

Example 2 (Potentially faster).

```

FLD    QWORD PTR [X]      ;load double to be converted
FST    DWORD PTR [TX]    ;store X because sign(X) is needed
FIST   DWORD PTR [I]     ;store rndint(x) as default result
FISUB  DWORD PTR [I]     ;compute DIFF = X - rndint(X)
FSTP   DWORD PTR [DIFF]  ;store DIFF as we need sign(DIFF)
MOV    EAX, [TX]         ;X
MOV    EDX, [DIFF]       ;DIFF
TEST   EDX, EDX          ;DIFF == 0 ?
JZ     $DONE             ;default result is OK, done
XOR    EDX, EAX          ; need correction if sign(X) != sign(DIFF)
SAR    EAX, 31           ;(X<0) ? 0xFFFFFFFF : 0
SAR    EDX, 31           ; sign(X)!=sign(DIFF)?0xFFFFFFFF:0
LEA    EAX, [EAX+EAX+1]  ;(X<0) ? 0xFFFFFFFF : 1
AND    EDX, EAX          ;correction: -1, 0, 1
SUB    [I], EDX          ;trunc(X)=rndint(X)-correction
$DONE:

```

The second substitution simulates a truncating floating-point to integer conversion using only integer instructions and therefore works correctly independent of the FPU's current rounding mode. It does not handle NaNs, infinities, and overflows according to the IEEE-754 standard. Note that the first instruction of this code may cause an STLF size mismatch resulting in performance degradation if the variable to be converted has been stored recently.

Example 3 (Potentially faster):

```

MOV    ECX, DWORD PTR[X+4]    ;get upper 32 bits of double
XOR    EDX, EDX                ;i = 0
MOV    EAX, ECX                ;save sign bit
AND    ECX, 07FF00000h        ;isolate exponent field
CMP    ECX, 03FF00000h        ;if abs(x) < 1.0
JB     $DONE2                  ; then i = 0
MOV    EDX, DWORD PTR[X]      ;get lower 32 bits of double
SHR    ECX, 20                 ;extract exponent
SHRD   EDX, EAX, 21            ;extract mantissa
NEG    ECX                     ;compute shift factor for extracting
ADD    ECX, 1054               ;non-fractional mantissa bits
OR     EDX, 080000000h         ;set integer bit of mantissa
SAR    EAX, 31                 ;x < 0 ? 0xffffffff : 0
SHR    EDX, CL                 ;i = trunc(abs(x))
XOR    EDX, EAX                ;i = x < 0 ? ~i : i
SUB    EDX, EAX                ;i = x < 0 ? -i : i
$DONE2:
MOV    [I], EDX                ;store result

```

For applications which can tolerate a floating-point-to-integer conversion that is not compliant with existing programming language standards (but is IEEE-754 compliant), perform the conversion using the rounding mode that is currently in effect (usually round-to-nearest-even).

Example 4 (Fastest):

```

FLD    QWORD PTR [X]          ; get double to be converted
FISTP  DWORD PTR [I]          ; store integer result

```

Some compilers offer an option to use the code from example 4 for floating-point-to-integer conversion, using the default rounding mode.

Lastly, consider setting the rounding mode throughout an application to truncate and using the code from example 4 to perform extremely fast conversions that are compliant with language standards and IEEE-754. This mode is also provided as an option by some compilers. Note that use of this technique also changes the rounding mode for all other FPU operations inside the application, which can lead to significant changes in numerical results and even program failure (for example, due to lack of convergence in iterative algorithms).

Floating-Point Subexpression Elimination

There are cases which do not require an FXCH instruction after every instruction to allow access to two new stack entries. In the cases where two instructions share a source operand, an FXCH is not required between the two instructions. When there is an opportunity for subexpression elimination, reduce the number of superfluous FXCH instructions by putting the shared source operand at the top of the stack. For example, using the function:

```
func( (x*y), (x+z) )
```

Example 1 (Avoid):

```
FLD    Z
FLD    Y
FLD    X
FADD   ST, ST(2)
FXCH   ST(1)
FMUL   ST, ST(2)
CALL   FUNC
FSTP   ST(0)
```

Example 2 (Preferred):

```
FLD    Z
FLD    Y
FLD    X
FMUL   ST(1), ST
FADDP  ST(2), ST
CALL   FUNC
```

Check Argument Range of Trigonometric Instructions Efficiently

The transcendental instructions FSIN, FCOS, FPTAN, and FSINCOS are architecturally restricted in their argument range. Only arguments with a magnitude of $\leq 2^{63}$ can be evaluated. If the argument is out of range, the C2 bit in the FPU status word is set, and the argument is returned as the result. Software needs to guard against such (extremely infrequent) cases.

If an “argument out of range” is detected, a range reduction subroutine is invoked which reduces the argument to less than 2^{63} before the instruction is attempted again. While an argument $> 2^{63}$ is unusual, it often indicates a problem elsewhere in the code and the code may completely fail in the absence of a properly guarded trigonometric instruction. For example, in the case of FSIN or FCOS generated from a sin() or cos() function invocation in the HLL, the downstream code might reasonably expect that the returned result is in the range [-1,1].

A naive solution for guarding a trigonometric instruction may check the C2 bit in the FPU status word after each FSIN, FCOS, FPTAN, and FSINCOS instruction, and take appropriate action if it is set (indicating an argument out of range).

Example 1 (Avoid):

```
FLD    QWORD PTR [x] ;argument
FSIN   ;compute sine
FSTSW  AX             ;store FPU status word to AX
TEST   AX, 0400h     ;is the C2 bit set?
JZ     $in_range     ;nope, argument was in range, all OK
CALL   $reduce_range ;reduce argument in ST(0) to < 2^63
FSIN   ;compute sine (in-range argument
        ; guaranteed)

$in_range:
```

Such a solution is inefficient since the FSTSW instruction is serializing with respect to all x87/3DNow!/MMX instructions and should thus be avoided (see the section “Floating-Point Compare Instructions” on page 98). Use of FSTSW in the above fashion slows down the common path through the code.

Instead, it is advisable to check the argument before one of the trigonometric instructions is invoked.

Example 2 (Preferred):

```
FLD    QWORD PTR [x] ;argument
FLD    DWORD PTR [two_to_the_63] ;2^63
FCOMIP ST,ST(1)     ;argument <= 2^63 ?
JBE    $in_range     ;Yes, It is in range.
CALL   $reduce_range ;reduce argument in ST(0) to < 2^63
$in_range:
FSIN   ;compute sine (in-range argument
        ; guaranteed)
```


Since out-of-range arguments are extremely uncommon, the conditional branch will be perfectly predicted, and the other instructions used to guard the trigonometric instruction can execute in parallel to it.

Take Advantage of the FSINCOS Instruction

Frequently, a piece of code that needs to compute the sine of an argument also needs to compute the cosine of that same argument. In such cases, the FSINCOS instruction should be used to compute both trigonometric functions concurrently, which is faster than using separate FSIN and FCOS instructions to accomplish the same task.

Example 1 (Avoid):

```
FLD    QWORD PTR [x]
FLD    DWORD PTR [two_to_the_63]
FCOMIP ST,ST(1)
JBE    $in_range
CALL   $reduce_range
$in_range:
FLD    ST(0)
FCOS
FSTP   QWORD PTR [cosine_x]
FSIN
FSTP   QWORD PTR [sine_x]
```

Example 2 (Preferred):

```
FLD    QWORD PTR [x]
FLD    DWORD PTR [two_to_the_63]
FCOMIP ST,ST(1)
JBE    $in_range
CALL   $reduce_range
$in_range:
FSINCOS
FSTP   QWORD PTR [cosine_x]
FSTP   QWORD PTR [sine_x]
```


10

3DNow!™ and MMX™ Optimizations

This chapter describes 3DNow! and MMX code optimization techniques for the AMD Athlon™ processor. Guidelines are listed in order of importance. 3DNow! porting guidelines can be found in the *3DNow!™ Instruction Porting Guide*, order# 22621.

Use 3DNow!™ Instructions



Unless accuracy requirements dictate otherwise, perform floating-point computations using the 3DNow! instructions instead of x87 instructions. The SIMD nature of 3DNow! achieves twice the number of FLOPs that are achieved through x87 instructions. 3DNow! instructions provide for a flat register file instead of the stack-based approach of x87 instructions.

See the *3DNow!™ Technology Manual*, order# 21928 for information on instruction usage.

Use FEMMS Instruction

Though there is no penalty for switching between x87 FPU and 3DNow!/MMX instructions in the AMD Athlon processor, the FEMMS instruction should be used to ensure the same code also runs optimally on AMD-K6® family processors. The

FEMMS instruction is supported for backward compatibility with AMD-K6 family processors, and is aliased to the EMMS instruction.

3DNow! and MMX instructions are designed to be used concurrently with no switching issues. Likewise, enhanced 3DNow! instructions can be used simultaneously with MMX instructions. However, x87 and 3DNow! instructions share the same architectural registers so there is no easy way to use them concurrently without cleaning up the register file in between using FEMMS/EMMS.

Use 3DNow!™ Instructions for Fast Division

3DNow! instructions can be used to compute a very fast, highly accurate reciprocal or quotient.

Optimized 14-Bit Precision Divide

This divide operation executes with a total latency of seven cycles, assuming that the program hides the latency of the first MOVD/MOVQ instructions within preceding code.

Example:

MOVD	MM0, [MEM]	;	0		W	
PFRCP	MM0, MM0	;	1/W		1/W	(approximate)
MOVQ	MM2, [MEM]	;	Y		X	
PFMUL	MM2, MM0	;	Y/W		X/W	

Optimized Full 24-Bit Precision Divide

This divide operation executes with a total latency of 15 cycles, assuming that the program hides the latency of the first MOVD/MOVQ instructions within preceding code.

Example:

MOVD	MM0, [W]	;	0		W	
PFRCP	MM1, MM0	;	1/W		1/W	(approximate)
PUNPCKLDQ	MM0, MM0	;	W		W	(MMX instr.)
PFRCPIT1	MM0, MM1	;	1/W		1/W	(refine)
MOVQ	MM2, [X_Y]	;	Y		X	
PFRCPIT2	MM0, MM1	;	1/W		1/W	(final)
PFMUL	MM2, MM0	;	Y/W		X/W	

Pipelined Pair of 24-Bit Precision Divides

This divide operation executes with a total latency of 21 cycles, assuming that the program hides the latency of the first MOVD/MOVQ instructions within preceding code.

Example:

MOVQ	MM0, [DIVISORS]	; y	x	
PFRCP	MM1, MM0	; 1/x	1/x	(approximate)
MOVQ	MM2, MM0	; y	x	
PUNPCKHDQ	MM0, MM0	; y	y	
PFRCP	MM0, MM0	; 1/y	1/y	(approximate)
PUNPCKLDQ	MM1, MM0	; 1/y	1/x	(approximate)
MOVQ	MM0, [DIVIDENDS]	; z	w	
PFRCPIT1	MM2, MM1	; 1/y	1/x	(intermediate)
PFRCPIT2	MM2, MM1	; 1/y	1/x	(final)
PFMUL	MM0, MM2	; z/y	w/x	

Newton-Raphson Reciprocal

Consider the quotient $q = a/b$. An (on-chip) ROM-based table lookup can be used to quickly produce a 14-to-15-bit precision approximation of $1/b$ using just one PFRCP instruction. A full 24-bit precision reciprocal can then be quickly computed from this approximation using a Newton Raphson algorithm.

The general Newton-Raphson recurrence for the reciprocal is as follows:

$$Z_{i+1} = Z_i \cdot (2 - b \cdot Z_i)$$

Given that the initial approximation is accurate to at least 14 bits, and that a full IEEE single-precision mantissa contains 24 bits, just one Newton-Raphson iteration is required. The following sequence shows the 3DNow! instructions that produce the initial reciprocal approximation, compute the full precision reciprocal from the approximation, and finally, complete the desired divide of a/b .

```

X0 = PFRCP(b)
X1 = PFRCPIT1(b, X0)
X2 = PFRCPIT2(X1, X0)
q = PFMUL(a, X2)

```

The 24-bit final reciprocal value is X₂. In the AMD Athlon processor 3DNow! technology implementation the operand X₂ contains the correct round-to-nearest single precision reciprocal for approximately 99% of all arguments.

Use 3DNow!™ Instructions for Fast Square Root and Reciprocal Square Root

3DNow! instructions can be used to compute a very fast, highly accurate square root and reciprocal square root.

Optimized 15-Bit Precision Square Root

This square root operation can be executed in only 7 cycles, assuming a program hides the latency of the first MOVD instruction within previous code. The reciprocal square root operation requires four less cycles than the square root operation.

Example:

```
MOVD      MM0, [MEM]      ;      0 | a
PFRSQRT   MM1, MM0       ; 1/sqrt(a) | 1/sqrt(a) (approximate)
PUNPCKLDQ MM0, MM0       ;      a | a      (MMX instr.)
PFMUL     MM0, MM1       ; sqrt(a) | sqrt(a)
```

Optimized 24-Bit Precision Square Root

This square root operation can be executed in only 19 cycles, assuming a program hides the latency of the first MOVD instruction within previous code. The reciprocal square root operation requires four less cycles than the square root operation.

Example:

```
MOVD      MM0, [MEM]      ;      0 | a
PFRSQRT   MM1, MM0       ; 1/sqrt(a) | 1/sqrt(a) (approx.)
MOVQ      MM2, MM1       ; X_0 = 1/(sqrt a) (approx.)
PFMUL     MM1, MM1       ; X_0 * X_0 | X_0 * X_0 (step 1)
PUNPCKLDQ MM0, MM0       ;      a | a      (MMX instr)
PFRSQIT1  MM1, MM0       ; (intermediate) (step 2)
PFRCPIT2  MM1, MM2       ; 1/sqrt(a) | 1/sqrt(a) (step 3)
PFMUL     MM0, MM1       ; sqrt(a) | sqrt(a)
```

Newton-Raphson Reciprocal Square Root

The general Newton-Raphson reciprocal square root recurrence is:

$$Z_{i+1} = 1/2 \cdot Z_i \cdot (3 - b \cdot Z_i^2)$$

To reduce the number of iterations, the initial approximation read from a table. The 3DNow! reciprocal square root approximation is accurate to at least 15 bits. Accordingly, to obtain a single-precision 24-bit reciprocal square root of an input operand *b*, one Newton-Raphson iteration is required, using the following sequence of 3DNow! instructions:

```
X0 = PFRSQRT(b)
X1 = PFMUL(X0,X0)
X2 = PFRSQIT1(b,X1)
X3 = PFRCPIT2(X2,X0)
X4 = PFMUL(b,X3)
```

The 24-bit final reciprocal square root value is *X₃*. In the AMD Athlon processor 3DNow! implementation, the estimate contains the correct round-to-nearest value for approximately 87% of all arguments. The remaining arguments differ from the correct round-to-nearest value by one unit-in-the-last-place. The square root (*X₄*) is formed in the last step by multiplying by the input operand *b*.

Use MMX™ PMADDWD Instruction to Perform Two 32-Bit Multiplies in Parallel

The MMX PMADDWD instruction can be used to perform two signed 16x16→32 bit multiplies in parallel, with much higher performance than can be achieved using the IMUL instruction. The PMADDWD instruction is designed to perform four 16x16→32 bit signed multiplies and accumulate the results pairwise. By making one of the results in a pair a zero, there are now just two multiplies. The following example shows how to multiply 16-bit signed numbers *a*,*b*,*c*,*d* into signed 32-bit products *a*×*c* and *b*×*d*:

Example:

```

PXOR      MM2, MM2      ; 0 | 0
MOVD      MM0, [ab]     ; 0 0 | b a
MOVD      MM1, [cd]     ; 0 0 | d c
PUNPCKLWD MM0, MM2      ; 0 b | 0 a
PUNCPKLDW MM1, MM2      ; 0 d | 0 c
PMADDWD   MM0, MM1      ; b*d | a*c

```

3DNow!™ and MMX™ Intra-Operand Swapping

AMD Athlon™ Specific Code

If the swapping of MMX register halves is necessary, use the PSWAPD instruction, which is a new AMD Athlon 3DNow! DSP extension. Use of this instruction should only be for AMD Athlon specific code. “PSWAPD MMreg1, MMreg2” performs the following operation:

```

mmreg1[63:32] = mmreg2[31:0])
mmreg1[31:0] = mmreg2[63:32])

```

See the *AMD Extensions to the 3DNow! and MMX Instruction Set Manual*, order #22466 for more usage information.

Blended Code

Otherwise, for blended code, which needs to run well on AMD-K6 and AMD Athlon family processors, the following code is recommended:

Example 1 (Preferred, faster):

```

;MM1 = SWAP (MM0), MM0 destroyed
MOVQ      MM1, MM0      ;make a copy
PUNPCKLDQ MM0, MM0      ;duplicate lower half
PUNPCKHDQ MM1, MM0      ;combine lower halves

```

Example 2 (Preferred, fast):

```

;MM1 = SWAP (MM0), MM0 preserved
MOVQ      MM1, MM0      ;make a copy
PUNPCKHDQ MM1, MM1      ;duplicate upper half
PUNPCKLDQ MM1, MM0      ;combine upper halves

```

Both examples accomplish the swapping, but the first example should be used if the original contents of the register do not need to be preserved. The first example is faster due to the fact that the MOVQ and PUNPCKLDQ instructions can execute in parallel. The instructions in the second example are dependent on one another and take longer to execute.

Fast Conversion of Signed Words to Floating-Point

In many applications there is a need to quickly convert data consisting of packed 16-bit signed integers into floating-point numbers. The following two examples show how this can be accomplished efficiently on AMD processors.

The first example shows how to do the conversion on a processor that supports AMD's 3DNow! extensions, such as the AMD Athlon processor. It demonstrates the increased efficiency from using the PI2FW instruction. Use of this instruction should only be for AMD Athlon processor specific code. See the *AMD Extensions to the 3DNow!™ and MMX™ Instruction Set Manual*, order #22466 for more information on this instruction.

The second example demonstrates how to accomplish the same task in blended code that achieves good performance on the AMD Athlon processor as well as on the AMD-K6 family processors that support 3DNow! technology.

Example 1 (AMD Athlon specific code using 3DNow! DSP extension):

```

MOVD      MM0, [packed_sword]      ;0 0 | b a
PUNPCKLWD MM0, MM0                ;b b | a a
PI2FW     MM0, MM0                ;xb=float(b) | xa=float(a)
MOVQ     [packed_float], MM0      ;store xb | xa

```

Example 2 (AMD-K6 Family and AMD Athlon processor blended code):

```

MOVD      MM1, [packed_sword]      ;0 0 | b a
PXOR      MM0, MM0                ;0 0 | 0 0
PUNPCKLWD MM0, MM1                ;b 0 | a 0
PSRAD     MM0, 16                 ;sign extend: b | a
PI2FD     MM0, MM0                ;xb=float(b) | xa=float(a)
MOVQ     [packed_float], MM0      ;store xb | xa

```

Use MMX™ PXOR to Negate 3DNow!™ Data

For both the AMD Athlon and AMD-K6 processors, it is recommended that code use the MMX PXOR instruction to change the sign bit of 3DNow! operations instead of the 3DNow! PFMUL instruction. On the AMD Athlon processor, using PXOR allows for more parallelism, as it can execute in either the FADD or FMUL pipes. PXOR has an execution latency of two, but because it is a MMX instruction, there is an initial one

cycle bypassing penalty, and another one cycle penalty if the result goes to a 3DNow! operation. The PFMUL execution latency is four, therefore, in the worst case, the PXOR and PMUL instructions are the same in terms of latency. On the AMD-K6 processor, there is only a one cycle latency for PXOR, versus a two cycle latency for the 3DNow! PFMUL instruction.

Use the following code to negate 3DNow! data:

```
mshn      DQ 8000000080000000h
PXOR      MM0, [mshn]           ;toggle sign bit
```

Use MMX™ PCMP Instead of 3DNow!™ PFCMP

Use the MMX PCMP instruction instead of the 3DNow! PFCMP instruction. On the AMD Athlon processor, the PCMP has a latency of two cycles while the PFCMP has a latency of four cycles. In addition to the shorter latency, PCMP can be issued to either the FADD or the FMUL pipe, while PFCMP is restricted to the FADD pipe.

Note: The PFCMP instruction has a ‘GE’ (greater or equal) version (PFCMPGE) that is missing from PCMP.

Both Numbers Positive

If both arguments are positive, PCMP always works.

One Negative, One Positive

If one number is negative and the other is positive, PCMP still works, except when one number is a positive zero and the other is a negative zero.

Both Numbers Negative

Be careful when performing integer comparison using PCMPGT on two negative 3DNow! numbers. The result is the inverse of the PFCMPGT floating-point comparison. For example:

```
-2 = 84000000
-4 = 84800000
```

PCMPGT gives 84800000 > 84000000, but -4 < -2. To address this issue, simply reverse the comparison by swapping the source operands.

Use MMX™ Instructions for Block Copies and Block Fills

For moving or filling small blocks of data (e.g., less than 512 bytes) between cacheable memory areas, the REP MOVS and REP STOS families of instructions deliver good performance and are straightforward to use. For moving and filling larger blocks of data, or to move/fill blocks of data where the destination is in non-cacheable space, it is recommended to make use of MMX instructions and MMX extensions. The following examples all use quadword-aligned blocks of data. In cases where memory blocks are not quadword aligned, additional code is required to handle end cases as needed.

AMD-K6® and AMD Athlon™ Processor Blended Code

The following example code, written for the inline assembler of Microsoft Visual C, is suitable for moving/filling a large quadword aligned block of data in the following situations:

- Blended code, i.e., code that needs to perform well on both AMD Athlon and AMD-K6 family processors
- AMD Athlon processor specific code where the destination is in cacheable memory and immediate data re-use of the data at the destination is expected
- AMD-K6 family specific code where the destination is in non-cacheable memory

Example 1:

```
/* block copy (source and destination QWORD aligned) */
```

```
__asm {
    mov     eax, [src_ptr]
    mov     edx, [dst_ptr]
    mov     ecx, [blk_size]
    shr    ecx, 6

    align 16
```

```
$xfer:
    movq    mm0, [eax]
    add    edx, 64
    movq    mm1, [eax+8]
    add    eax, 64
    movq    mm2, [eax-48]
    movq    [edx-64], mm0
    movq    mm0, [eax-40]
    movq    [edx-56], mm1
    movq    mm1, [eax-32]
    movq    [edx-48], mm2
    movq    mm2, [eax-24]
    movq    [edx-40], mm0
    movq    mm0, [eax-16]
    movq    [edx-32], mm1
    movq    mm1, [eax-8]
    movq    [edx-24], mm2
    movq    [edx-16], mm0
    dec    ecx
    movq    [edx-8], mm1
    jnz    $xfer
    femms
}

/* block fill (destination QWORD aligned) */

__asm {
    mov    edx, [dst_ptr]
    mov    ecx, [blk_size]
    shr   ecx, 6
    movq   mm0, [fill_data]

    align 16

    $fill:
    movq   [edx], mm0
    movq   [edx+8], mm0
    movq   [edx+16], mm0
    movq   [edx+24], mm0
    movq   [edx+32], mm0
    movq   [edx+40], mm0
    add    edx, 64
    movq   [edx-16], mm0
    decq   ecx
    mov    [edx-8], mm0
    jnz    $fill
    femms
}
```

AMD Athlon™ Processor Specific Code

The following example code, written for the inline assembler of Microsoft Visual C, is suitable for moving/filling a quadword aligned block of data in the following situations:

- AMD Athlon processor specific code where the destination of the block copy is in non-cacheable memory space
- AMD Athlon processor specific code where the destination of the block copy is in cacheable space, but no immediate data re-use of the data at the destination is expected.

Example 2:

```

/* block copy (source and destination QWORD aligned) */
__asm {
    mov     eax, [src_ptr]
    mov     edx, [dst_ptr]
    mov     ecx, [blk_size]
    shr     ecx, 6

    align 16

$xfcr_nc:
    prefetchnta [eax+256]
    movq    mm0, [eax]
    add     edx, 64
    movq    mm1, [eax+8]
    add     eax, 64
    movq    mm2, [eax-48]
    movntq  [edx-64], mm0
    movq    mm0, [eax-40]
    movntq  [edx-56], mm1
    movq    mm1, [eax-32]
    movntq  [edx-48], mm2
    movq    mm2, [eax-24]
    movntq  [edx-40], mm0
    movq    mm0, [eax-16]
    movntq  [edx-32], mm1
    movq    mm1, [eax-8]
    movntq  [edx-24], mm2
    movntq  [edx-16], mm0
    dec     ecx
    movntq  [edx-8], mm1
    jnz     $xfcr_nc
    femms
    sfence
}

```

```
/* block fill (destination QWORD aligned) */  
  
__asm {  
  
    mov     edx, [dst_ptr]  
    mov     ecx, [blk_size]  
    shr     ecx, 6  
    movq    mm0, [fill_data]  
  
    align 16  
  
$fill_nc:  
    movntq  [edx], mm0  
    movntq  [edx+8], mm0  
    movntq  [edx+16], mm0  
    movntq  [edx+24], mm0  
    movntq  [edx+32], mm0  
    movntq  [edx+40], mm0  
    movntq  [edx+48], mm0  
    movntq  [edx+56], mm0  
    add     edx, 64  
    dec     ecx  
    jnz     $fill_nc  
    femms  
    sfence  
}
```

Use MMX™ PXOR to Clear All Bits in an MMX™ Register

To clear all the bits in an MMX register to zero, use:

```
PXOR MMreg, MMreg
```

Note that PXOR MMreg, MMreg is dependent on previous writes to MMreg. Therefore, using PXOR in the manner described can lengthen dependency chains, which in return may lead to reduced performance. An alternative in such cases is to use:

```
zero DD 0
```

```
MOVD MMreg, DWORD PTR [zero]
```

i.e., to load a zero from a statically initialized and properly aligned memory location. However, loading the data from memory runs the risk of cache misses. Cases where MOVD is superior to PXOR are therefore rare and PXOR should be used in general.

Use MMX™ PCMPEQD to Set All Bits in an MMX™ Register

To set all the bits in an MMX register to one, use:

```
PCMPEQD MMreg, MMreg
```

Note that PCMPEQD MMreg, MMreg is dependent on previous writes to MMreg. Therefore, using PCMPEQD in the manner described can lengthen dependency chains, which in return may lead to reduced performance. An alternative in such cases is to use:

```
ones DQ 0FFFFFFFFFFFFFFFFh
```

```
MOVQ MMreg, QWORD PTR [ones]
```

i.e., to load a quadword of 0xFFFFFFFFFFFFFFFF from a statically initialized and properly aligned memory location. However, loading the data from memory runs the risk of cache misses. Cases where MOVQ is superior to PCMPEQD are therefore rare and PCMPEQD should be used in general.

Use MMX™ PAND to Find Absolute Value in 3DNow!™ Code

Use the following to compute the absolute value of 3DNow! floating-point operands:

```
mabs DQ 7FFFFFFFF7FFFFFFFFh
PAND MM0, [mabs] ;mask out sign bit
```

Optimized Matrix Multiplication

The multiplication of a 4x4 matrix with a 4x1 vector is commonly used in 3D graphics for geometry transformation. This routine serves to translate, scale, rotate, and apply perspective to 3D coordinates represented in homogeneous coordinates. The following code sample is a 3DNow! optimized, general 3D vertex transformation routine that completes in 16 cycles on the AMD Athlon processor:

/* Function XForm performs a fully generalized 3D transform on an array of vertices pointed to by "v" and stores the transformed vertices in the location pointed to by "res". Each vertex consists of four floats. The 4x4 transform matrix is pointed to by "m". The matrix elements are also floats. The argument "numverts" indicates how many vertices have to be transformed. The computation performed for each vertex is:

```
res->x = v->x*m[0][0] + v->y*m[1][0] + v->z*m[2][0] + v->w*m[3][0]
res->y = v->x*m[0][1] + v->y*m[1][1] + v->z*m[2][1] + v->w*m[3][1]
res->z = v->x*m[0][2] + v->y*m[1][2] + v->z*m[2][2] + v->w*m[3][2]
res->w = v->x*m[0][3] + v->y*m[1][3] + v->z*m[2][3] + v->w*m[3][3]
```

*/

```
#define M00 0
#define M01 4
#define M02 8
#define M03 12
#define M10 16
#define M11 20
#define M12 24
#define M13 28
#define M20 32
#define M21 36
#define M22 40
#define M23 44
#define M30 48
#define M31 52
#define M32 56
#define M33 60
```

```
void XForm (float *res, const float *v, const float *m, int numverts)
{
    _asm {
        MOV     EDX, [V]           ;EDX = source vector ptr
        MOV     EAX, [M]           ;EAX = matrix ptr
        MOV     EBX, [RES]         ;EBX = destination vector ptr
        MOV     ECX, [NUMVERTS]    ;ECX = number of vertices to transform

        ;3DNow! version of fully general 3D vertex tranformation.
        ;Optimal for AMD Athlon (completes in 16 cycles)

        FEMMS           ;clear MMX state

        ALIGN     16         ;for optimal branch alignment
```


\$\$xform:

```

ADD      EBX, 16                ;res++
MOVQ     MM0, QWORD PTR [EDX]   ;v->y | v->x
MOVQ     MM1, QWORD PTR [EDX+8] ;v->w | v->z
ADD      EDX, 16                ;v++
MOVQ     MM2, MM0                ;v->y | v->x
MOVQ     MM3, QWORD PTR [EAX+M00] ;m[0][1] | m[0][0]
PUNPCKLDQ MM0, MM0              ;v->x | v->x
MOVQ     MM4, QWORD PTR [EAX+M10] ;m[1][1] | m[1][0]
PFMUL    MM3, MM0                ;v->x*m[0][1] | v->x*m[0][0]
PUNPCKHDQ MM2, MM2              ;v->y | v->y
PFMUL    MM4, MM2                ;v->y*m[1][1] | v->y*m[1][0]
MOVQ     MM5, QWORD PTR [EAX+M02] ;m[0][3] | m[0][2]
MOVQ     MM7, QWORD PTR [EAX+M12] ;m[1][3] | m[1][2]
MOVQ     MM6, MM1                ;v->w | v->z
PFMUL    MM5, MM0                ;v->x*m[0][3] | v0>x*m[0][2]
MOVQ     MM0, QWORD PTR [EAX+M20] ;m[2][1] | m[2][0]
PUNPCKLDQ MM1, MM1              ;v->z | v->z
PFMUL    MM7, MM2                ;v->y*m[1][3] | v->y*m[1][2]
MOVQ     MM2, QWORD PTR [EAX+M22] ;m[2][3] | m[2][2]
PFMUL    MM0, MM1                ;v->z*m[2][1] | v->z*m[2][0]
PFADD    MM3, MM4                ;v->x*m[0][1]+v->y*m[1][1] |
; v->x*m[0][0]+v->y*m[1][0]
MOVQ     MM4, QWORD PTR [EAX+M30] ;m[3][1] | m[3][0]
PFMUL    MM2, MM1                ;v->z*m[2][3] | v->z*m[2][2]
PFADD    MM5, MM7                ;v->x*m[0][3]+v->y*m[1][3] |
; v->x*m[0][2]+v->y*m[1][2]
MOVQ     MM1, QWORD PTR [EAX+M32] ;m[3][3] | m[3][2]
PUNPCKHDQ MM6, MM6              ;v->w | v->w
PFADD    MM3, MM0                ;v->x*m[0][1]+v->y*m[1][1]+v->z*m[2][1] |
; v->x*m[0][0]+v->y*m[1][0]+v->z*m[2][0]
PFMUL    MM4, MM6                ;v->w*m[3][1] | v->w*m[3][0]
PFMUL    MM1, MM6                ;v->w*m[3][3] | v->w*m[3][2]
PFADD    MM5, MM2                ;v->x*m[0][3]+v->y*m[1][3]+v->z*m[2][3] |
; v->x*m[0][2]+v->y*m[1][2]+v->z*m[2][2]
PFADD    MM3, MM4                ;v->x*m[0][1]+v->y*m[1][1]+v->z*m[2][1]+
; v->w*m[3][1] | v->x*m[0][0]+v->y*m[1][0]+
; v->z*m[2][0]+v->w*m[3][0]
MOVQ     [EBX-16], MM3           ;store res->y | res->x
PFADD    MM5, MM1                ;v->x*m[0][3]+v->y*m[1][3]+v->z*m[2][3]+
; v->w*m[3][3] | v->x*m[0][2]+v->y*m[1][2]+
; v->z*m[2][2]+v->w*m[3][2]
MOVQ     [EBX-8], MM5           ;store res->w | res->z
DEC      ECX                    ;numverts--
JNZ      $$XFORM                ;until numverts == 0

FEMMS                            ;clear MMX state
}
}

```

Efficient 3D-Clipping Code Computation Using 3DNow!™ Instructions

Clipping is one of the major activities occurring in a 3D graphics pipeline. In many instances, this activity is split into two parts which do not necessarily have to occur consecutively:

- Computation of the clip code for each vertex, where each bit of the clip code indicates whether the vertex is outside the frustum with regard to a specific clip plane.
- Examination of the clip code for a vertex and clipping if the clip code is non-zero.

The following example shows how to use 3DNow! instructions to efficiently implement a clip code computation for a frustum that is defined by:

- $-w \leq x \leq w$
- $-w \leq y \leq w$
- $-w \leq z \leq w$

```
.DATA

RIGHT    EQU 01h
LEFT     EQU 02h
ABOVE    EQU 04h
BELOW    EQU 08h
BEHIND   EQU 10h
BEFORE   EQU 20h

                ALIGN 8

ABOVE_RIGHT   DD    RIGHT
               DD    ABOVE
BELOW_LEFT    DD    LEFT
               DD    BELOW
BEHIND_BEFORE DD    BEFORE
               DD    BEHIND

.CODE

;; Generalized computation of 3D clip code (out code)
;;
;; Register usage: IN      MM5   y | x
;;                  MM6   w | z
;;
;;
;;                  OUT     MM2   clip code (out code)
```

```

;;
;;          DESTROYS   MM0,MM1,MM2,MM3,MM4

PXOR      MM0, MM0          ; 0 | 0
MOVQ     MM1, MM6          ; w | z
MOVQ     MM4, MM5          ; y | x
PUNPCKHDQ MM1, MM1        ; w | w
MOVQ     MM3, MM6          ; w | z
MOVQ     MM2, MM5          ; y | x
PFSUBR   MM3, MM0          ; -w | -z
PFSUBR   MM2, MM0          ; -y | -x
PUNPCKLDQ MM3, MM6        ; z | -z
PFCMPGT  MM4, MM1          ; y>w?FFFFFFFF:0 | x>w?FFFFFFFF:0
MOVQ     MM0, QWORD PTR [ABOVE_RIGHT] ; ABOVE | RIGHT
PFCMPGT  MM3, MM1          ; z>w?FFFFFFFF:0 | -z>w?FFFFFFFF:0
PFCMPGT  MM2, MM1          ; -y>w?FFFFFFFF:0 | -x>w?FFFFFFFF:0
MOVQ     MM1, QWORD PTR [BEHIND_BEFORE] ; BEHIND | BEFORE
PAND     MM4, MM0          ; y > w ? ABOVE:0 | x > w ? RIGHT:0
MOVQ     MM0, QWORD PTR [BELOW_LEFT]   ; BELOW | LEFT
PAND     MM3, MM1          ; z > w ? BEHIND:0 | -z > w ? BEFORE:0
PAND     MM2, MM0          ; -y > w ? BELOW:0 | -x > w ? LEFT:0
POR      MM2, MM4          ; BELOW,ABOVE | LEFT,RIGHT
POR      MM2, MM3          ; BELOW,ABOVE,BEHIND | LEFT,RIGHT,BEFORE
MOVQ     MM1, MM2          ; BELOW,ABOVE,BEHIND | LEFT,RIGHT,BEFORE
PUNPCKHDQ MM2, MM2        ; BELOW,ABOVE,BEHIND | BELOW,ABOVE,BEHIND
POR      MM2, MM1          ; zclip, yclip, xclip = clip code

```

Use 3DNow!™ PAVGUSB for MPEG-2 Motion Compensation

Use the 3DNow! PAVGUSB instruction for MPEG-2 motion compensation. The PAVGUSB instruction produces the rounded averages of the eight unsigned 8-bit integer values in the source operand (a MMX register or a 64-bit memory location) and the eight corresponding unsigned 8-bit integer values in the destination operand (a MMX register). The PAVGUSB instruction is extremely useful in DVD (MPEG-2) decoding where motion compensation performs a lot of byte averaging between and within macroblocks. The PAVGUSB instruction helps speed up these operations. In addition, PAVGUSB can free up some registers and make unrolling the averaging loops possible.

The following code fragment uses original MMX code to perform averaging between the source macroblock and destination macroblock:

Example 1 (Avoid):

```

MOV     ESI, DWORD PTR Src_MB
MOV     EDI, DWORD PTR Dst_MB
MOV     EDX, DWORD PTR SrcStride
MOV     EBX, DWORD PTR DstStride
MOVQ   MM7, QWORD PTR [ConstFEFE]
MOVQ   MM6, QWORD PTR [Const0101]
MOV     ECX, 16

L1:
MOVQ   MM0, [ESI]           ;MM0=QWORD1
MOVQ   MM1, [EDI]           ;MM1=QWORD3
MOVQ   MM2, MM0
MOVQ   MM3, MM1
PAND   MM2, MM6
PAND   MM3, MM6
PAND   MM0, MM7             ;MM0 = QWORD1 & 0xfefefefe
PAND   MM1, MM7             ;MM1 = QWORD3 & 0xfefefefe
POR    MM2, MM3             ;calculate adjustment
PSRLQ  MM0, 1               ;MM0 = (QWORD1 & 0xfefefefe)/2
PSRLQ  MM1, 1               ;MM1 = (QWORD3 & 0xfefefefe)/2
PAND   MM2, MM6
PADDB  MM0, MM1             ;MM0 = QWORD1/2 + QWORD3/2 w/o
                             ; adjustment
PADDB  MM0, MM2             ;add 1sb adjustment
MOVQ   [EDI], MM0
MOVQ   MM4, [ESI+8]         ;MM4=QWORD2
MOVQ   MM5, [EDI+8]         ;MM5=QWORD4
MOVQ   MM2, MM4
MOVQ   MM3, MM5
PAND   MM2, MM6
PAND   MM3, MM6
PAND   MM4, MM7             ;MM0 = QWORD2 & 0xfefefefe
PAND   MM5, MM7             ;MM1 = QWORD4 & 0xfefefefe
POR    MM2, MM3             ;calculate adjustment
PSRLQ  MM4, 1               ;MM0 = (QWORD2 & 0xfefefefe)/2
PSRLQ  MM5, 1               ;MM1 = (QWORD4 & 0xfefefefe)/2
PAND   MM2, MM6
PADDB  MM4, MM5             ;MM0 = QWORD2/2 + QWORD4/2 w/o
                             ; adjustment
PADDB  MM4, MM2             ;add 1sb adjustment
MOVQ   [EDI+8], MM4

ADD    ESI, EDX
ADD    EDI, EBX
LOOP  L1

```

The following code fragment uses the 3DNow! PAVGUSB instruction to perform averaging between the source macroblock and destination macroblock:

Example 2 (Preferred):

```

MOV     EAX, DWORD PTR Src_MB
MOV     EDI, DWORD PTR Dst_MB
MOV     EDX, DWORD PTR SrcStride
MOV     EBX, DWORD PTR DstStride
MOV     ECX, 16

L1:
MOVQ   MM0, [EAX]           ;MM0=QWORD1
MOVQ   MM1, [EAX+8]        ;MM1=QWORD2
PAVGUSB MM0, [EDI]         ;(QWORD1 + QWORD3)/2 with
                           ; adjustment
PAVGUSB MM1, [EDI+8]       ;(QWORD2 + QWORD4)/2 with
                           ; adjustment

ADD     EAX, EDX
MOVQ   [EDI], MM0
MOVQ   [EDI+8], MM1
ADD     EDI, EBX
LOOP   L1

```

Stream of Packed Unsigned Bytes

The following code is an example of how to process a stream of packed unsigned bytes (like RGBA information) with faster 3DNow! instructions.

Example:

```

outside loop:
PXOR   MM0, MM0

inside loop:
MOVD   MM1, [VAR] ;      0 | v[3],v[2],v[1],v[0]
PUNPCKLBW MM1, MM0 ;0,v[3],0,v[2] | 0,v[1],0,v[0]
MOVQ   MM2, MM1 ;0,v[3],0,v[2] | 0,v[1],0,v[0]
PUNPCKLWD MM1, MM0 ; 0,0,0,v[1] | 0,0,0,v[0]
PUNPCKHWD MM2, MM0 ; 0,0,0,v[3] | 0,0,0,v[2]
PI2FD   MM1, MM1 ; float(v[1]) | float(v[0])
PI2FD   MM2, MM2 ; float(v[3]) | float(v[2])

```

Complex Number Arithmetic

Complex numbers have a “real” part and an “imaginary” part. Multiplying complex numbers (ex. $3 + 4i$) is an integral part of many algorithms such as Discrete Fourier Transform (DFT) and complex FIR filters. Complex number multiplication is shown below:

```
(src0.real + src0.imag) * (src1.real + src1.imag) = result
result = (result.real + result.imag)
result.real <= src0.real*src1.real - src0.imag*src1.imag
result.imag <= src0.real*src1.imag + src0.imag*src1.real
```

Example:

```
(1+2i) * (3+4i) => result.real + result.imag
result.real <= 1*3 - 2*4 = -5
result.imag <= 1*4i + 2i*3 = 10i
result = -5 +10i
```

Assuming that complex numbers are represented as two element vectors [v.real, v.imag], one can see the need for swapping the elements of src1 to perform the multiplies for result.imag, and the need for a mixed positive/negative accumulation to complete the parallel computation of result.real and result.imag.

PSWAPD performs the swapping of elements for src1 and PFPNACC performs the mixed positive/negative accumulation to complete the computation. The code example below summarizes the computation of a complex number multiply.

Example:

```
;MM0 = s0.imag | s0.real ;reg_hi | reg_lo
;MM1 = s1.imag | s1.real

PSWAPD MM2, MM0 ;M2 = s0.real | s0.imag
PFMUL MM0, MM1 ;M0 = s0.imag*s1.imag | s0.real*s1.real
PFMUL MM1, MM2 ;M1 = s0.real*s1.imag | s0.imag*s1.real
PFPNACC MM0, MM1 ;M0 = res.imag | res.real
```

PSWAPD supports independent source and result operands and enables PSWAPD to also perform a copy function. In the above example, this eliminates the need for a separate “MOVQ MM2, MM0” instruction.

11

General x86 Optimization Guidelines

This chapter describes general code optimization techniques specific to superscalar processors (that is, techniques common to the AMD-K6® processor, AMD Athlon™ processor, and Pentium® family processors). In general, all optimization techniques used for the AMD-K6 processor, Pentium, and Pentium Pro processors either improve the performance of the AMD Athlon processor or are not required and have a neutral effect (usually due to fewer coding restrictions with the AMD Athlon processor).

Short Forms

Use shorter forms of instructions to increase the effective number of instructions that can be examined for decoding at any one time. Use 8-bit displacements and jump offsets where possible.

Example 1 (Avoid):

```
CMP     REG, 0
```

Example 2 (Preferred):

```
TEST   REG, REG
```

Although both of these instructions have an execute latency of one, fewer opcode bytes need to be examined by the decoders for the TEST instruction.

Dependencies

Spread out true dependencies to increase the opportunities for parallel execution. Anti-dependencies and output dependencies do not impact performance.

Register Operands

Maintain frequently used values in registers rather than in memory. This technique avoids the comparatively long latencies for accessing memory.

Stack Allocation

When allocating space for local variables and/or outgoing parameters within a procedure, adjust the stack pointer and use moves rather than pushes. This method of allocation allows random access to the outgoing parameters so that they can be set up when they are calculated instead of being held somewhere else until the procedure call. In addition, this method reduces ESP dependencies and uses fewer execution resources.

Appendix A

AMD Athlon™ Processor Microarchitecture

Introduction

When discussing processor design, it is important to understand the following terms—*architecture*, *microarchitecture*, and *design implementation*. The term *architecture* refers to the instruction set and features of a processor that are visible to software programs running on the processor. The architecture determines what software the processor can run. The architecture of the AMD Athlon processor is the industry-standard x86 instruction set.

The term *microarchitecture* refers to the design techniques used in the processor to reach the target cost, performance, and functionality goals. The AMD Athlon processor microarchitecture is a decoupled decode/execution design approach. In other words, the decoders essentially operate independent of the execution units, and the execution core uses a small number of instructions and simplified circuit design for fast single-cycle execution and fast operating frequencies.

The term *design implementation* refers to the actual logic and circuit designs from which the processor is created according to the microarchitecture specifications.

AMD Athlon™ Processor Microarchitecture

The innovative AMD Athlon processor microarchitecture approach implements the x86 instruction set by processing simpler operations (OPs) instead of complex x86 instructions. These OPs are specially designed to include direct support for the x86 instructions while observing the high-performance principles of fixed-length encoding, regularized instruction fields, and a large register set. Instead of executing complex x86 instructions, which have lengths from 1 to 15 bytes, the AMD Athlon processor executes the simpler fixed-length OPs, while maintaining the instruction coding efficiencies found in x86 programs. The enhanced microarchitecture used in the AMD Athlon processor enables higher processor core performance and promotes straightforward extendibility for future designs.

Superscalar Processor

The AMD Athlon processor is an aggressive, out-of-order, three-way superscalar x86 processor. It can fetch, decode, and issue up to three x86 instructions per cycle with a centralized instruction control unit (ICU) and two independent instruction schedulers—an integer scheduler and a floating-point scheduler. These two schedulers can simultaneously issue up to nine OPs to the three general-purpose integer execution units (IEUs), three address-generation units (AGUs), and three floating-point/3DNow!™/MMX™ execution units. The AMD Athlon moves integer instructions down the integer execution pipeline, which consists of the integer scheduler and the IEUs, as shown in Figure 1 on page 131. Floating-point instructions are handled by the floating-point execution pipeline, which consists of the floating-point scheduler and the x87/3DNow!/MMX execution units.

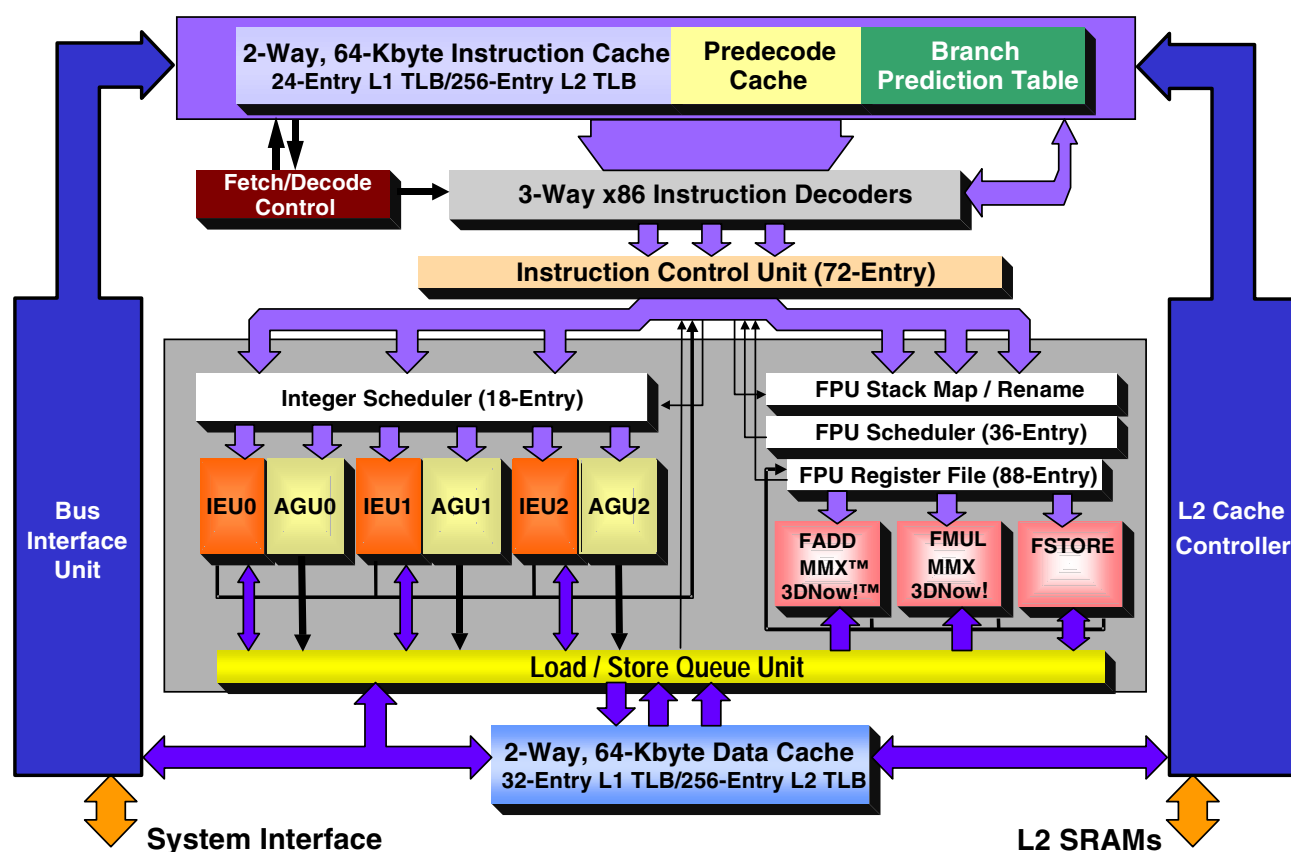


Figure 1. AMD Athlon™ Processor Block Diagram

Instruction Cache

The out-of-order execute engine of the AMD Athlon processor contains a very large 64-Kbyte L1 instruction cache. The L1 instruction cache is organized as a 64-Kbyte, two-way, set-associative array. Each line in the instruction array is 64 bytes long. Functions associated with the L1 instruction cache are instruction loads, instruction prefetching, instruction predecoding, and branch prediction. Requests that miss in the L1 instruction cache are fetched from the backside L2 cache or, subsequently, from the local memory using the bus interface unit (BIU).

The instruction cache generates fetches on the naturally aligned 64 bytes containing the instructions and the next sequential line of 64 bytes (a prefetch). The principal of *program spatial locality* makes data prefetching very effective and avoids or reduces execution stalls due to the amount of time wasted reading the necessary data. Cache line

replacement is based on a least-recently used (LRU) replacement algorithm.

The L1 instruction cache has an associated two-level translation look-aside buffer (TLB) structure. The first-level TLB is fully associative and contains 24 entries (16 that map 4-Kbyte pages and eight that map 2-Mbyte or 4-Mbyte pages). The second-level TLB is four-way set associative and contains 256 entries, which can map 4-Kbyte pages.

Predecode

Predecoding begins as the L1 instruction cache is filled. Predecode information is generated and stored alongside the instruction cache. This information is used to help efficiently identify the boundaries between variable length x86 instructions, to distinguish DirectPath from VectorPath early-decode instructions, and to locate the opcode byte in each instruction. In addition, the predecode logic detects code branches such as CALLs, RETURNs and short unconditional JMPs. When a branch is detected, predecoding begins at the target of the branch.

Branch Prediction

The fetch logic accesses the branch prediction table in parallel with the instruction cache and uses the information stored in the branch prediction table to predict the direction of branch instructions.

The AMD Athlon processor employs combinations of a branch target address buffer (BTB), a global history bimodal counter (GHBC) table, and a return address stack (RAS) hardware in order to predict and accelerate branches. Predicted-taken branches incur only a single-cycle delay to redirect the instruction fetcher to the target instruction. In the event of a mispredict, the minimum penalty is ten cycles.

The BTB is a 2048-entry table that caches in each entry the predicted target address of a branch.

In addition, the AMD Athlon processor implements a 12-entry return address stack to predict return addresses from a near or far call. As CALLs are fetched, the next EIP is pushed onto the

return stack. Subsequent RETs pop a predicted return address off the top of the stack.

Early Decoding

The DirectPath and VectorPath decoders perform early-decoding of instructions into MacroOPs. A MacroOP is a fixed length instruction which contains one or more OPs. The outputs of the early decoders keep all (DirectPath or VectorPath) instructions in program order. Early decoding produces three MacroOPs per cycle from either path. The outputs of both decoders are multiplexed together and passed to the next stage in the pipeline, the instruction control unit.

When the target 16-byte instruction window is obtained from the instruction cache, the predecode data is examined to determine which type of basic decode should occur—DirectPath or VectorPath.

DirectPath Decoder

DirectPath instructions can be decoded directly into a MacroOP, and subsequently into one or two OPs in the final issue stage. A DirectPath instruction is limited to those x86 instructions that can be further decoded into one or two OPs. The length of the x86 instruction does *not* determine DirectPath instructions. A maximum of three DirectPath x86 instructions can occupy a given aligned 8-byte block. 16-bytes are fetched at a time. Therefore, up to six DirectPath x86 instructions can be passed into the DirectPath decode pipeline.

VectorPath Decoder

Uncommon x86 instructions requiring two or more MacroOPs proceed down the VectorPath pipeline. The sequence of MacroOPs is produced by an on-chip ROM known as the MROM. The VectorPath decoder can produce up to three MacroOPs per cycle. Decoding a VectorPath instruction may prevent the simultaneous decode of a DirectPath instruction.

Instruction Control Unit

The instruction control unit (ICU) is the control center for the AMD Athlon processor. The ICU controls the following resources—the centralized in-flight reorder buffer, the integer scheduler, and the floating-point scheduler. In turn, the ICU is responsible for the following functions—MacroOP dispatch, MacroOP retirement, register and flag dependency resolution and renaming, execution resource management, interrupts, exceptions, and branch mispredictions.

The ICU takes the three MacroOPs per cycle from the early decoders and places them in a centralized, fixed-issue reorder buffer. This buffer is organized into 24 lines of three MacroOPs each. The reorder buffer allows the ICU to track and monitor up to 72 in-flight MacroOPs (whether integer or floating-point) for maximum instruction throughput. The ICU can simultaneously dispatch multiple MacroOPs from the reorder buffer to both the integer and floating-point schedulers for final decode, issue, and execution as OPs. In addition, the ICU handles exceptions and manages the retirement of MacroOPs.

Data Cache

The L1 data cache contains two 64-bit ports. It is a write-allocate and writeback cache that uses an LRU replacement policy. The data cache and instruction cache are both two-way set-associative and 64-Kbytes in size. It is divided into 8 banks where each bank is 8 bytes wide. In addition, this cache supports the MOESI (Modified, Owner, Exclusive, Shared, and Invalid) cache coherency protocol and data parity.

The L1 data cache has an associated two-level TLB structure. The first-level TLB is fully associative and contains 32 entries (24 that map 4-Kbyte pages and eight that map 2-Mbyte or 4-Mbyte pages). The second-level TLB is four-way set associative and contains 256 entries, which can map 4-Kbyte pages.

Integer Scheduler

The integer scheduler is based on a three-wide queuing system (also known as a reservation station) that feeds three integer execution positions or pipes. The reservation stations are six entries deep, for a total queuing system of 18 integer MacroOPs. Each reservation station divides the MacroOPs into integer and address generation OPs, as required.

Integer Execution Unit

The integer execution pipeline consists of three identical pipes—0, 1, and 2. Each integer pipe consists of an integer execution unit (IEU) and an address generation unit (AGU). The integer execution pipeline is organized to match the three MacroOP dispatch pipes in the ICU as shown in Figure 2 on page 135. MacroOPs are broken down into OPs in the schedulers. OPs issue when their operands are available either from the register file or result buses.

OPs are executed when their operands are available. OPs from a single MacroOP can execute out-of-order. In addition, a particular integer pipe can be executing two OPs from different MacroOPs (one in the IEU and one in the AGU) at the same time.

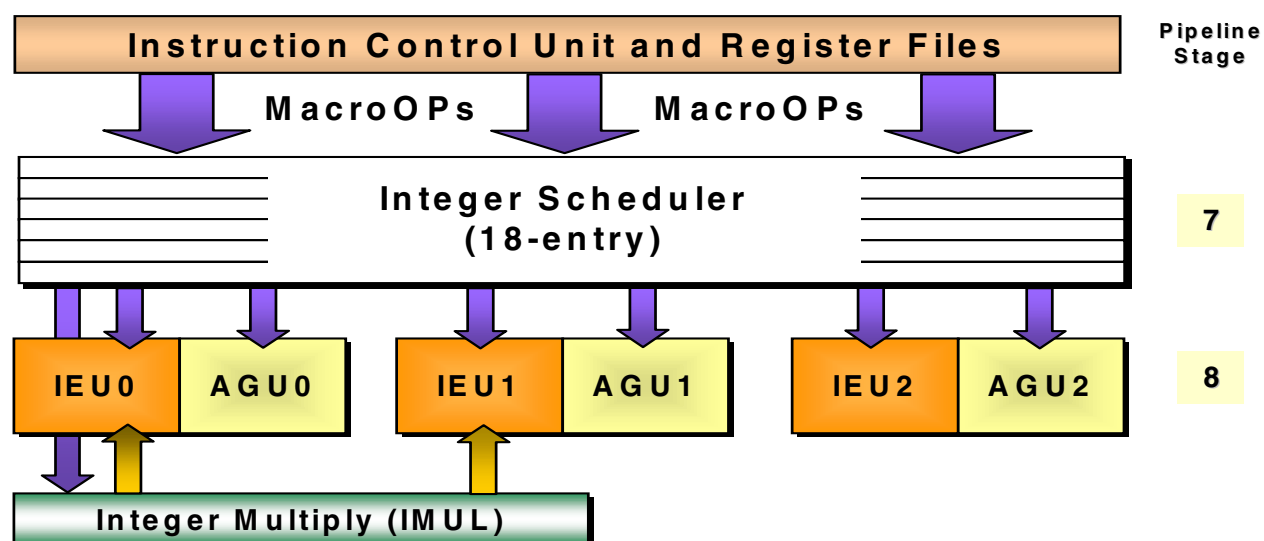


Figure 2. Integer Execution Pipeline

Each of the three IEUs are general purpose in that each performs logic functions, arithmetic functions, conditional functions, divide step functions, status flag multiplexing, and branch resolutions. The AGUs calculate the logical addresses for loads, stores, and LEAs. A load and store unit reads and writes data to and from the L1 data cache. The integer scheduler sends a completion status to the ICU when the outstanding OPs for a given MacroOP are executed.

All integer operations can be handled within any of the three IEUs with the exception of multiplies. Multiplies are handled by a pipelined multiplier that is attached to the pipeline at pipe 0. See Figure 2 on page 135. Multiplies always issue to integer pipe 0, and the issue logic creates results bus bubbles for the multiplier in integer pipes 0 and 1 by preventing non-multiply OPs from issuing at the appropriate time.

Floating-Point Scheduler

The AMD Athlon processor floating-point logic is a high-performance, fully-pipelined, superscalar, out-of-order execution unit. It is capable of accepting three MacroOPs of any mixture of x87 floating-point, 3DNow! or MMX operations per cycle.

The floating-point scheduler handles register renaming and has a dedicated 36-entry scheduler buffer organized as 12 lines of three MacroOPs each. It also performs OP issue, and out-of-order execution. The floating-point scheduler communicates with the ICU to retire a MacroOP, to manage comparison results from the FCOMI instruction, and to back out results from a branch misprediction.

Floating-Point Execution Unit

The floating-point execution unit (FPU) is implemented as a coprocessor that has its own out-of-order control in addition to the data path. The FPU handles all register operations for x87 instructions, all 3DNow! operations, and all MMX operations. The FPU consists of a stack renaming unit, a register renaming unit, a scheduler, a register file, and three parallel execution units. Figure 3 shows a block diagram of the dataflow through the FPU.

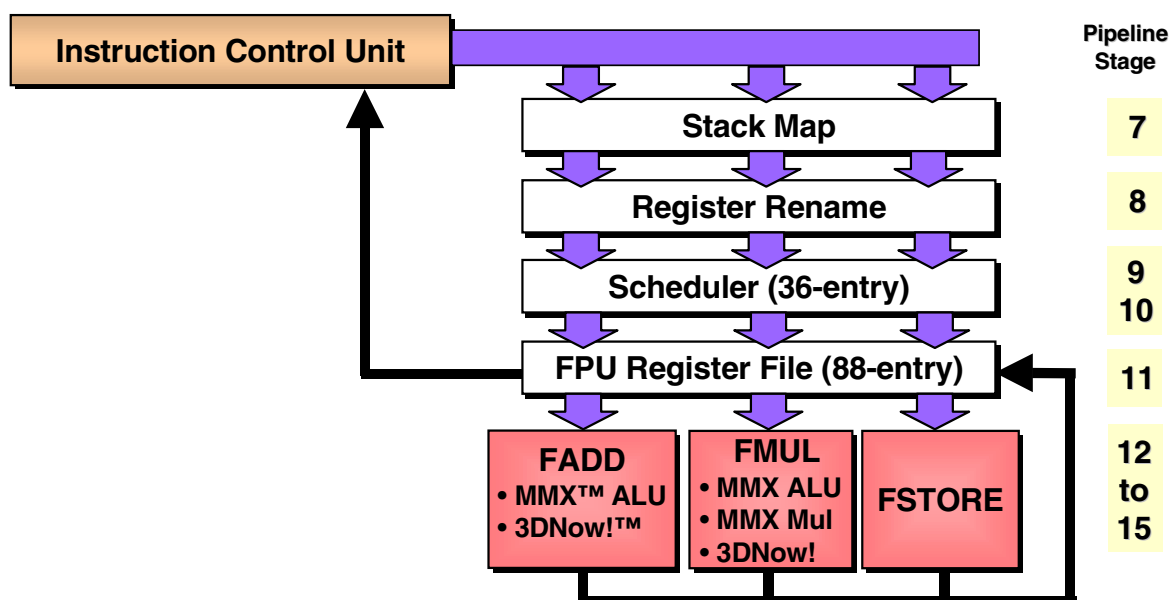


Figure 3. Floating-Point Unit Block Diagram

As shown in Figure 3 on page 137, the floating-point logic uses three separate execution positions or pipes for superscalar x87, 3DNow! and MMX operations. The first of the three pipes is generally known as the adder pipe (FADD), and it contains 3DNow! add, MMX ALU/shifter, and floating-point add execution units. The second pipe is known as the multiplier (FMUL). It contains a 3DNow!/MMX multiplier/reciprocal unit, an MMX ALU and a floating-point multiplier/divider/square root unit. The third pipe is known as the floating-point load/store (FSTORE), which handles floating-point constant loads (FLDZ, FLDPI, etc.), stores, FILDs, as well as many OP primitives used in VectorPath sequences.

Load-Store Unit (LSU)

The load-store unit (LSU) manages data load and store accesses to the L1 data cache and, if required, to the backside L2 cache or system memory. The 44-entry LSU provides a data interface for both the integer scheduler and the floating-point scheduler. It consists of two queues—a 12-entry queue for L1 cache load and store accesses and a 32-entry queue for L2 cache or system memory load and store accesses. The 12-entry queue can request a maximum of two L1 cache loads and two L1 cache (32-bits) stores per cycle. The 32-entry queue effectively holds requests that missed in the L1 cache probe by the 12-entry queue. Finally, the LSU ensures that the architectural load and store ordering rules are preserved (a requirement for x86 architecture compatibility).

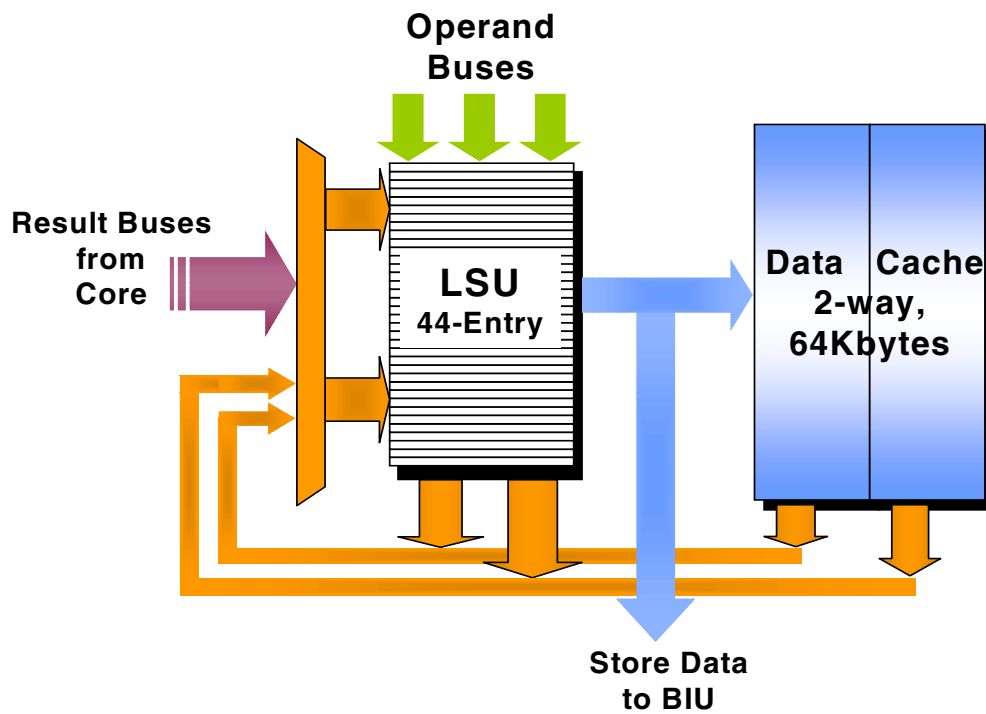


Figure 4. Load/Store Unit

L2 Cache Controller

The AMD Athlon processor contains a very flexible onboard L2 controller. It uses an independent backside bus to access up to 8-Mbytes of industry-standard SRAMs. There are full on-chip tags for a 512-Kbyte cache, while larger sizes use a partial tag system. In addition, there is a two-level data TLB structure. The first-level TLB is fully associative and contains 32 entries (24 that map 4-Kbyte pages and eight that map 2-Mbyte or 4-Mbyte pages). The second-level TLB is four-way set associative and contains 256 entries, which can map 4-Kbyte pages.

Write Combining

See Appendix C, “Implementation of Write Combining” on page 155 for detailed information about write combining.

AMD Athlon™ System Bus

The AMD Athlon system bus is a high-speed bus that consists of a pair of unidirectional 13-bit address and control channels and a bidirectional 64-bit data bus. The AMD Athlon system bus supports low-voltage swing, multiprocessing, clock forwarding, and fast data transfers. The clock forwarding technique is used to deliver data on both edges of the reference clock, therefore doubling the transfer speed. A four-entry 64-byte write buffer is integrated into the BIU. The write buffer improves bus utilization by combining multiple writes into a single large write cycle. By using the AMD Athlon system bus, the AMD Athlon processor can transfer data on the 64-bit data bus at 200 MHz, which yields an effective throughput of 1.6-Gbyte per second.

Appendix B

Pipeline and Execution Unit Resources Overview

The AMD Athlon™ processor contains two independent execution pipelines—one for integer operations and one for floating-point operations. The integer pipeline manages x86 integer operations and the floating-point pipeline manages all x87, 3DNow!™ and MMX™ instructions. This appendix describes the operation and functionality of these pipelines.

Fetch and Decode Pipeline Stages

Figure 5 on page 142 and Figure 6 on page 142 show the AMD Athlon processor instruction fetch and decoding pipeline stages. The pipeline consists of one cycle for instruction fetches and four cycles of instruction alignment and decoding. The three ports in stage 5 provide a maximum bandwidth of three MacroOPs per cycle for dispatching to the instruction control unit (ICU).

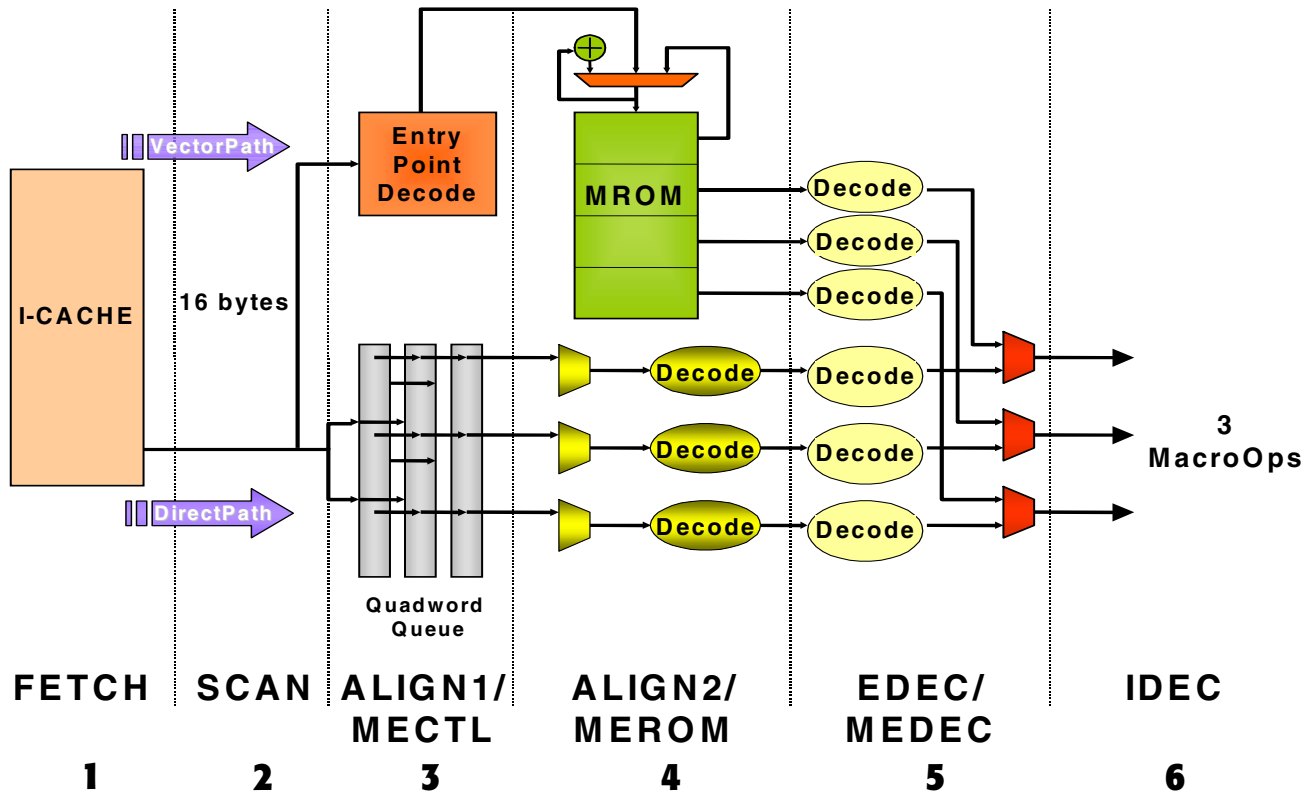


Figure 5. Fetch/Scan/Align/Decode Pipeline Hardware

The most common x86 instructions flow through the DirectPath pipeline stages and are decoded by hardware. The less common instructions, which require microcode assistance, flow through the VectorPath. Although the DirectPath decodes the common x86 instructions, it also contains VectorPath instruction data, which allows it to maintain dispatch order at the end of cycle 5.

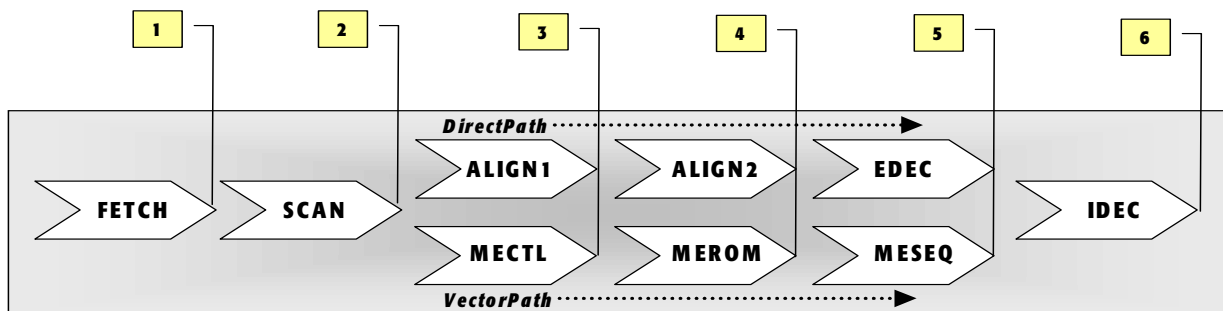


Figure 6. Fetch/Scan/Align/Decode Pipeline Stages

Cycle 1 – FETCH	The FETCH pipeline stage calculates the address of the next x86 instruction window to fetch from the processor caches or system memory.
Cycle 2 – SCAN	SCAN determines the start and end pointers of instructions. SCAN can send up to six <i>aligned</i> instructions (DirectPath and VectorPath) to ALIGN1 and only one VectorPath instruction to the microcode engine (MENG) per cycle.
Cycle 3 (DirectPath) – ALIGN1	Because each 8-byte buffer (quadword queue) can contain up to three instructions, ALIGN1 can buffer up to a maximum of nine instructions, or 24 instruction bytes. ALIGN1 tries to send three instructions from an 8-byte buffer to ALIGN2 per cycle.
Cycle 3 (VectorPath) – MECTL	For VectorPath instructions, the microcode engine control (MECTL) stage of the pipeline generates the microcode entry points.
Cycle 4 (DirectPath) – ALIGN2	ALIGN2 prioritizes prefix bytes, determines the opcode, ModR/M, and SIB bytes for each instruction and sends the accumulated prefix information to EDEC.
Cycle 4 (VectorPath) – MEROM	In the microcode engine ROM (MEROM) pipeline stage, the entry-point generated in the previous cycle, MECTL, is used to index into the MROM to obtain the microcode lines necessary to decode the instruction sent by SCAN.
Cycle 5 (DirectPath) – EDEC	The early decode (EDEC) stage decodes information from the DirectPath stage (ALIGN2) and VectorPath stage (MEROM) into MacroOPs. In addition, EDEC determines register pointers, flag updates, immediate values, displacements, and other information. EDEC then selects either MacroOPs from the DirectPath or MacroOPs from the VectorPath to send to the instruction decoder (IDEC) stage.
Cycle 5 (VectorPath) – MEDEC/MESEQ	The microcode engine decode (MEDEC) stage converts x86 instructions into MacroOPs. The microcode engine sequencer (MESEQ) performs the sequence controls (redirects and exceptions) for the MENG.
Cycle 6 – IDEC/Rename	At the instruction decoder (IDEC)/rename stage, integer and floating-point MacroOPs diverge in the pipeline. Integer MacroOPs are scheduled for execution in the next cycle. Floating-point MacroOPs have their floating-point stack

operands mapped to registers. Both integer and floating-point MacroOPs are placed into the ICU.

Integer Pipeline Stages

The integer execution pipeline consists of four or more stages for scheduling and execution and, if necessary, accessing data in the processor caches or system memory. There are three integer pipes associated with the three IEUs.

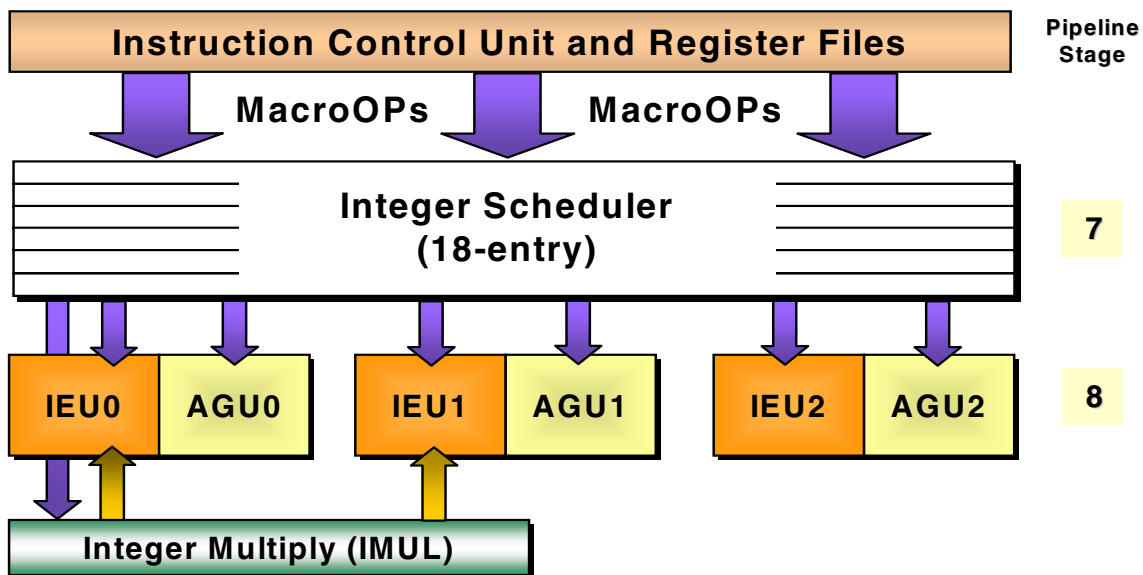


Figure 7. Integer Execution Pipeline

Figure 7 and Figure 8 show the integer execution resources and the pipeline stages, which are described in the following sections.

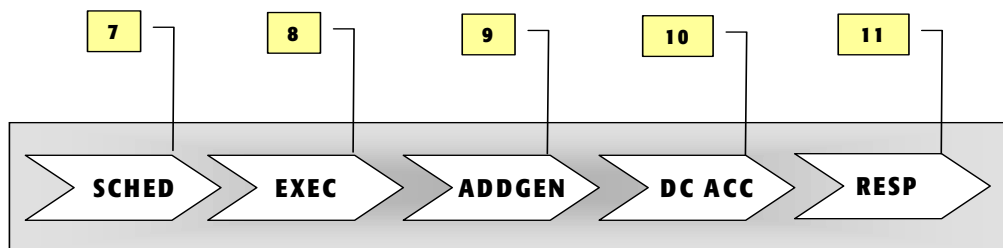


Figure 8. Integer Pipeline Stages

Cycle 7–SCHED

In the scheduler (SCHED) pipeline stage, the scheduler buffers can contain MacroOPs that are waiting for integer operands from the ICU or the IEU result bus. When all operands are received, SCHED schedules the MacroOP for execution and issues the OPs to the next stage, EXEC.

Cycle 8–EXEC

In the execution (EXEC) pipeline stage, the OP and its associated operands are processed by an integer pipe (either the IEU or the AGU). If addresses must be calculated to access data necessary to complete the operation, the OP proceeds to the next stages, ADDGEN and DCACC.

Cycle 9–ADDGEN

In the address generation (ADDGEN) pipeline stage, the load or store OP calculates a linear address, which is sent to the data cache TLBs and caches.

Cycle 10–DCACC

In the data cache access (DCACC) pipeline stage, the address generated in the previous pipeline stage is used to access the data cache arrays and TLBs. Any OP waiting in the scheduler for this data snarfs this data and proceeds to the EXEC stage (assuming all other operands were available).

Cycle 11–RESP

In the response (RESP) pipeline stage, the data cache returns hit/miss status and data for the request from DCACC.

Floating-Point Pipeline Stages

The floating-point unit (FPU) is implemented as a coprocessor that has its own out-of-order control in addition to the data path. The FPU handles all register operations for x87 instructions, all 3DNow! operations, and all MMX operations. The FPU consists of a stack renaming unit, a register renaming unit, a scheduler, a register file, and three parallel execution units. Figure 9 shows a block diagram of the dataflow through the FPU.

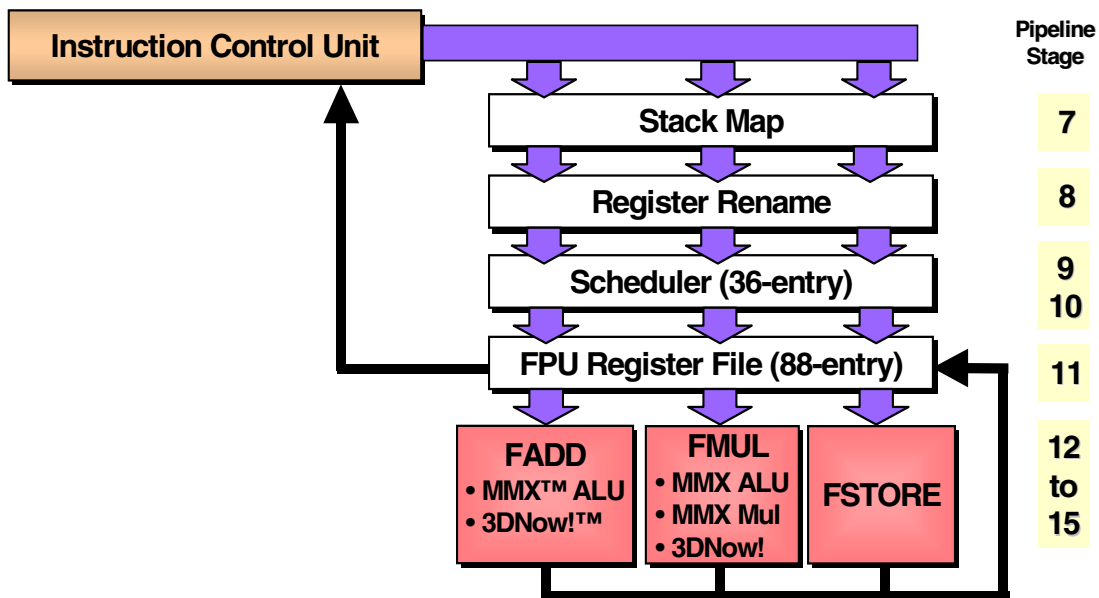


Figure 9. Floating-Point Unit Block Diagram

The floating-point pipeline stages 7–15 are shown in Figure 10 and described in the following sections. Note that the floating-point pipe and integer pipe separates at cycle 7.

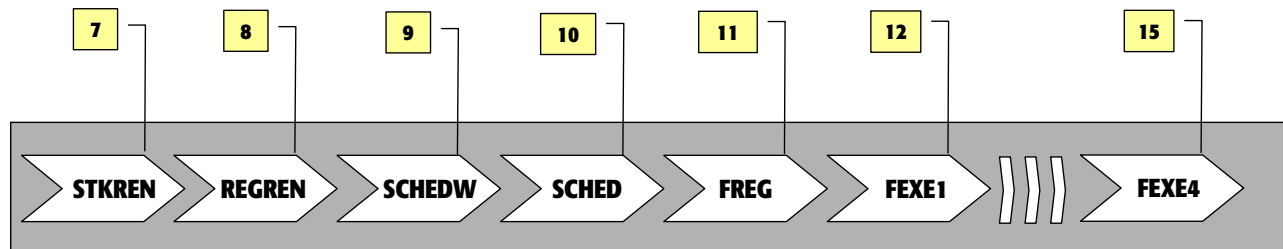


Figure 10. Floating-Point Pipeline Stages

- Cycle 7—STKREN** The stack rename (STKREN) pipeline stage in cycle 7 receives up to three MacroOPs from IDEC and maps stack-relative register tags to virtual register tags.
- Cycle 8—REGREN** The register renaming (REGREN) pipeline stage in cycle 8 is responsible for register renaming. In this stage, virtual register tags are mapped into physical register tags. Likewise, each destination is assigned a new physical register. The MacroOPs are then sent to the 36-entry FPU scheduler.
- Cycle 9—SCHEDW** The scheduler write (SCHEDW) pipeline stage in cycle 9 can receive up to three MacroOPs per cycle.
- Cycle 10—SCHED** The schedule (SCHED) pipeline stage in cycle 10 schedules up to three MacroOPs per cycle from the 36-entry FPU scheduler to the FREG pipeline stage to read register operands. MacroOPs are sent when their operands and/or tags are obtained.
- Cycle 11—FREG** The register file read (FREG) pipeline stage reads the floating-point register file for any register source operands of MacroOPs. The register file read is done before the MacroOPs are sent to the floating-point execution pipelines.
- Cycle 12–15—
Floating-Point
Execution (FEXEC1–4)** The FPU has three logical pipes—FADD, FMUL, and FSTORE. Each pipe may have several associated execution units. MMX execution is in both the FADD and FMUL pipes, with the exception of MMX instructions involving multiplies, which are limited to the FMUL pipe. The FMUL pipe has special support for long latency operations.
- DirectPath/VectorPath operations are dispatched to the FPU during cycle 6, but are not acted upon until they receive validation from the ICU in cycle 7.

Execution Unit Resources

Terminology

The execution units operate with two types of register values—*operands* and *results*. There are three operand types and two result types, which are described in this section.

Operands

The three types of operands are as follows:

- *Address register operands*—Used for address calculations of load and store instructions
- *Data register operands*—Used for register instructions
- *Store data register operands*—Used for memory stores

Results

The two types of results are as follows:

- *Data register results*—Produced by load or register instructions
- *Address register results*—Produced by LEA or PUSH instructions

Examples

The following examples illustrate the operand and result definitions:

```
ADD    EAX, EBX
```

The ADD instruction has two data register operands (EAX and EBX) and one data register result (EAX).

```
MOV    EBX, [ESP+4*ECX+8]    ;Load
```

The Load instruction has two address register operands (ESP and ECX as base and index registers, respectively) and a data register result (EBX).

```
MOV    [ESP+4*ECX+8], EAX    ;Store
```

The Store instruction has a data register operand (EAX) and two address register operands (ESP and ECX as base and index registers, respectively).

```
LEA    ESI, [ESP+4*ECX+8]
```

The LEA instruction has address register operands (ESP and ECX as base and index registers, respectively), and an address register result (ESI).

Integer Pipeline Operations

Table 2 shows the category or type of operations handled by the integer pipeline. Table 3 shows examples of the decode type.

Table 2. Integer Pipeline Operation Types

Category	Execution Unit
Integer Memory Load or Store Operations	L/S
Address Generation Operations	AGU
Integer Execution Unit Operations	IEU
Integer Multiply Operations	IMUL

Table 3. Integer Decode Types

x86 Instruction	Decode Type	OPs
MOV CX, [SP+4]	DirectPath	AGU, L/S
ADD AX, BX	DirectPath	IEU
CMP CX, [AX]	VectorPath	AGU, L/S, IEU
JZ Addr	DirectPath	IEU

As shown in Table 2, the MOV instruction early decodes in the DirectPath decoder and requires two OPs—an address generation operation for the indirect address and a data load from memory into a register. The ADD instruction early decodes in the DirectPath decoder and requires a single OP that can be executed in one of the three IEUs. The CMP instruction early decodes in the VectorPath and requires three OPs—an address generation operation for the indirect address, a data load from memory, and a compare to CX using an IEU. The final JZ instruction is a simple operation that early decodes in the DirectPath decoder and requires a single OP. Not shown is a load-op-store instruction, which translates into only one MacroOP (one AGU OP, one IEU OP, and one L/S OP).

Floating-Point Pipeline Operations

Table 4 shows the category or type of operations handled by the floating-point execution units. Table 5 shows examples of the decode types.

Table 4. Floating-Point Pipeline Operation Types

Category	Execution Unit
FPU/3DNow!/MMX Load/store or Miscellaneous Operations	FSTORE
FPU/3DNow!/MMX Multiply Operation	FMUL
FPU/3DNow!/MMX Arithmetic Operation	FADD

Table 5. Floating-Point Decode Types

x86 Instruction	Decode Type	OPs
FADD ST, ST(i)	DirectPath	FADD
FSIN	VectorPath	various
PFACC	DirectPath	FADD
PFRSQRT	DirectPath	FMUL

As shown in Table 4, the FADD register-to-register instruction generates a single MacroOP targeted for the floating-point scheduler. FSIN is considered a VectorPath instruction because it is a complex instruction with long execution times, as compared to the more common floating-point instructions. The MMX PFACC instruction is DirectPath decodeable and generates a single MacroOP targeted for the arithmetic operation execution pipeline in the floating-point logic. Just like PFACC, a single MacroOP is early decoded for the 3DNow! PFRSQRT instruction, but it is targeted for the multiply operation execution pipeline.

Load/Store Pipeline Operations

The AMD Athlon processor decodes any instruction that references memory into primitive load/store operations. For example, consider the following code sample:

```
MOV     AX, [EBX]           ;1 load MacroOP
PUSH   EAX                 ;1 store MacroOP
POP    EAX                 ;1 load MacroOP
ADD    [EAX], EBX         ;1 load/store and 1 IEU MacroOPs
FSTP  [EAX]               ;1 store MacroOP
MOVQ  [EAX], MM0          ;1 store MacroOP
```

As shown in Table 6, the load/store unit (LSU) consists of a three-stage data cache lookup.

Table 6. Load/Store Unit Stages

Stage 1 (Cycle 8)	Stage 2 (Cycle 9)	Stage 3 (Cycle 10)
Address Calculation / LS1 Scan	Transport Address to Data Cache	Data Cache Access / LS2 Data Forward

Loads and stores are first dispatched in order into a 12-entry deep reservation queue called LS1. LS1 holds loads and stores that are waiting to enter the cache subsystem. Loads and stores are allocated into LS1 entries at dispatch time in program order, and are required by LS1 to probe the data cache in program order. The AGUs can calculate addresses out of program order, therefore, LS1 acts as an address reorder buffer.

When a load or store is scanned out of the LS1 queue (Stage 1), it is deallocated from the LS1 queue and inserted into the data cache probe pipeline (Stage 2 and Stage 3). Up to two memory operations can be scheduled (scanned out of LS1) to access the data cache per cycle. The LSU can handle the following:

- Two 64-bit loads per cycle or
- One 64-bit load and one 64-bit store per cycle or
- Two 32-bit stores per cycle

Code Sample Analysis

The samples in Table 7 on page 153 and Table 8 on page 154 show the execution behavior of several series of instructions as a function of decode constraints, dependencies, and execution resource constraints.

The sample tables show the x86 instructions, the decode pipe in the integer execution pipeline, the decode type, the clock counts, and a description of the events occurring within the processor. The decode pipe gives the specific IEU used (see Figure 7 on page 144). The decode type specifies either VectorPath (VP) or DirectPath (DP).

The following nomenclature is used to describe the current location of a particular operation:

- D—Dispatch stage (Allocate in ICU, reservation stations, load-store (LS1) queue)
- I—Issue stage (Schedule operation for AGU or FU execution)
- E—Integer Execution Unit (IEU number corresponds to decode pipe)
- &—Address Generation Unit (AGU number corresponds to decode pipe)
- M—Multiplier Execution
- S—Load/Store pipe stage 1 (Schedule operation for load/store pipe)
- A—Load/Store pipe stage 2 (1st stage of data cache/LS2 buffer access)
- \$—Load/Store pipe stage 3 (2nd stage of data cache/LS2 buffer access)

Note: Instructions execute more efficiently (that is, without delays) when scheduled apart by suitable distances based on dependencies. In general, the samples in this section show poorly scheduled code in order to illustrate the resultant effects.

Table 7. Sample 1 – Integer Register Operations

Instruction Number	Instruction	Decode Pipe	Decode Type	Clocks							
				1	2	3	4	5	6	7	8
1	IMUL EAX, ECX	0	VP	D	I	M	M	M	M		
2	INC ESI	0	DP		D	I	E				
3	MOV EDI, 0x07F4	1	DP		D	I	E				
4	ADD EDI, EBX	2	DP		D		I	E			
5	SHL EAX, 8	0	DP			D			I	E	
6	OR EAX, 0x0F	1	DP			D				I	E
7	INC EBX	2	DP			D		I	E		
8	ADD ESI, EDX	0	DP				D	I	E		

Comments for Each Instruction Number

1. The IMUL is a VectorPath instruction. It cannot be decode or paired with other operations and, therefore, dispatches alone in pipe 0. The multiply latency is four cycles.
2. The simple INC operation is paired with instructions 3 and 4. The INC executes in IEU0 in cycle 4.
3. The MOV executes in IEU1 in cycle 4.
4. The ADD operation depends on instruction 3. It executes in IEU2 in cycle 5.
5. The SHL operation depends on the multiply result (instruction 1). The MacroOP waits in a reservation station and is eventually scheduled to execute in cycle 7 after the multiply result is available.
6. This operation executes in cycle 8 in IEU1.
7. This simple operation has a resource contention for execution in IEU2 in cycle 5. Therefore, the operation does not execute until cycle 6.
8. The ADD operation executes immediately in IEU0 after dispatching.

Table 8. Sample 2 – Integer Register and Memory Load Operations

Instruc Num	Instruction	Decode Pipe	Decode Type	Clocks											
				1	2	3	4	5	6	7	8	9	10	11	12
1	DEC EDX	0	DP	D	I	E									
2	MOV EDI, [ECX]	1	DP	D	I	&/S	A	\$							
3	SUB EAX, [EDX+20]	2	DP	D	I	&/S	A	\$/I	E						
4	SAR EAX, 5	0	DP		D				I	E					
5	ADD ECX, [EDI+4]	1	DP		D			I	&/S	A	\$				
6	AND EBX, 0x1F	2	DP		D	I	E								
7	MOV ESI, [0x0F100]	0	DP			D	I	&	S	A	\$				
8	OR ECX, [ESI+EAX*4+8]	1	DP			D					I	&/S	A	\$	E

Comments for Each Instruction Number

1. The ALU operation executes in IEU0.
2. The load operation generates the address in AGU1 and is simultaneously scheduled for the load/store pipe in cycle 3. In cycles 4 and 5, the load completes the data cache access.
3. The load-execute instruction accesses the data cache in tandem with instruction 2. After the load portion completes, the subtraction is executed in cycle 6 in IEU2.
4. The shift operation executes in IEU0 (cycle 7) after instruction 3 completes.
5. This operation is stalled on its address calculation waiting for instruction 2 to update EDI. The address is calculated in cycle 6. In cycle 7/8, the cache access completes.
6. This simple operation executes quickly in IEU2
7. The address for the load is calculated in cycle 5 in AGU0. However, the load is not scheduled to access the data cache until cycle 6. The load is blocked for scheduling to access the data cache for one cycle by instruction 5. In cycles 7 and 8, instruction 7 accesses the data cache concurrently with instruction 5.
8. The load execute instruction accesses the data cache in cycles 10/11 and executes the 'OR' operation in IEU1 in cycle 12.

Appendix C

Implementation of Write Combining

Introduction

This appendix describes the memory write-combining feature as implemented in the AMD Athlon™ processor family. The AMD Athlon processor supports the memory type and range register (MTRR) and the page attribute table (PAT) extensions, which allow software to define ranges of memory as either writeback (WB), write-protected (WP), writethrough (WT), uncacheable (UC), or write-combining (WC).

Defining the memory type for a range of memory as WC or WT allows the processor to conditionally combine data from multiple write cycles that are addressed within this range into a merge buffer. Merging multiple write cycles into a single write cycle reduces processor bus utilization and processor stalls, thereby increasing the overall system performance.

To understand the information presented in this appendix, the reader should possess a knowledge of K86™ processors, the x86 architecture, and programming requirements.

Write-Combining Definitions and Abbreviations

This appendix uses the following definitions and abbreviations:

- UC—Uncacheable memory type
- WC—Write-combining memory type
- WT—Writethrough memory type
- WP—Write-protected memory type
- WB—Writeback memory type
- One Byte—8 bits
- One Word—16 bits
- Longword—32 bits (same as a x86 doubleword)
- Quadword—64 bits or 2 longwords
- Octaword—128 bits or 2 quadwords
- Cache Block—64 bytes or 4 octawords or 8 quadwords

What is Write Combining?

Write combining is the merging of multiple memory write cycles that target locations within the address range of a write buffer. The AMD Athlon processor combines multiple memory-write cycles to a 64-byte buffer whenever the memory address is within a WC or WT memory type region. The processor continues to combine writes to this buffer without writing the data to the system, as long as certain rules apply (see Table 9 on page 158 for more information).

Programming Details

The steps required for programming write combining on the AMD Athlon processor are as follows:

1. Verify the presence of an AMD Athlon processor by using the CPUID instruction to check for the instruction family code and vendor identification of the processor. Standard function 0 on AMD processors returns a vendor identification string of “AuthenticAMD” in registers EBX, EDX, and ECX. Standard function 1 returns the processor

signature in register EAX, where EAX[11–8] contains the instruction family code. For the AMD Athlon processor, the instruction family code is six.

2. In addition, the presence of the MTRRs is indicated by bit 12 and the presence of the PAT extension is indicated by bit 16 of the extended features bits returned in the EDX register by CUID function 8000_0001h. See the *AMD Processor Recognition Application Note*, order# 20734 for more details on the CUID instruction.
3. Write combining is controlled by the MTRRs and PAT. Write combining should be enabled for the appropriate memory ranges. The AMD Athlon processor MTRRs and PAT are compatible with the Pentium® II.

Write-Combining Operations

In order to improve system performance, the AMD Athlon processor aggressively combines multiple memory-write cycles of any data size that address locations within a 64-byte write buffer that is aligned to a cache-line boundary. The data sizes can be bytes, words, longwords, or quadwords.

WC memory type writes can be combined in any order up to a full 64-byte sized write buffer.

WT memory type writes can only be combined up to a fully aligned quadword in the 64-byte buffer, and must be combined contiguously in ascending order. Combining may be opened at any byte boundary in a quadword, but is closed by a write that is either not “contiguous and ascending” or fills byte 7.

All other memory types for stores that go through the write buffer (UC and WP) cannot be combined.

Combining is able to continue until interrupted by one of the conditions listed in Table 9 on page 158. When combining is interrupted, one or more bus commands are issued to the system for that write buffer, as described by Table 10 on page 159.

Table 9. Write Combining Completion Events

Event	Comment
Non-WB write outside of current buffer	The first non-WB write to a different cache block address closes combining for previous writes. WB writes do not affect write combining. Only one line-sized buffer can be open for write combining at a time. Once a buffer is closed for write combining, it cannot be reopened for write combining.
I/O Read or Write	Any IN/INS or OUT/OUTS instruction closes combining. The implied memory type for all IN/OUT instructions is UC, which cannot be combined.
Serializing instructions	Any serializing instruction closes combining. These instructions include: MOVCRx, MOVDRx, WRMSR, INVD, INVLPG, WBINVD, LGDT, LLDT, LIDT, LTR, CPUID, IRET, RSM, INIT, HALT.
Flushing instructions	Any flush instruction causes the WC to complete.
Locks	Any instruction or processor operation that requires a cache or bus lock closes write combining before starting the lock. Writes within a lock can be combined.
Uncacheable Read	A UC read closes write combining. A WC read closes combining only if a cache block address match occurs between the WC read and a write in the write buffer.
Different memory type	Any WT write while write-combining for WC memory or any WC write while write combining for WT memory closes write combining.
Buffer full	Write combining is closed if all 64 bytes of the write buffer are valid.
WT time-out	If 16 processor clocks have passed since the most recent write for WT write combining, write combining is closed. There is no time-out for WC write combining.
WT write fills byte 7	Write combining is closed if a write fills the most significant byte of a quadword, which includes writes that are misaligned across a quadword boundary. In the misaligned case, combining is closed by the LS part of the misaligned write and combining is opened by the MS part of the misaligned store.
WT Nonsequential	If a subsequent WT write is not in ascending sequential order, the write combining completes. WC writes have no addressing constraints within the 64-byte line being combined.
TLB AD bit set	Write combining is closed whenever a TLB reload sets the accessed (A) or dirty (D) bits of a Pde or Pte.

Sending Write-Buffer Data to the System

Once write combining is closed for a 64-byte write buffer, the contents of the write buffer are eligible to be sent to the system as one or more AMD Athlon system bus commands. Table 10 lists the rules for determining what system commands are issued for a write buffer, as a function of the alignment of the valid buffer data.

Table 10. AMD Athlon™ System Bus Commands Generation Rules

1.	If all eight quadwords are either full (8 bytes valid) or empty (0 bytes valid), a Write-Quadword system command is issued, with an 8-byte mask representing which of the eight quadwords are valid. If this case is true, do not proceed to the next rule.
2.	If all longwords are either full (4 bytes valid) or empty (0 bytes valid), a Write-Longword system command is issued for each 32-byte buffer half that contains at least one valid longword. The mask for each Write-Longword system command indicates which longwords are valid in that 32-byte write buffer half. If this case is true, do not proceed to the next rule.
3.	Sequence through all eight quadwords of the write buffer, from quadword 0 to quadword 7. Skip over a quadword if no bytes are valid. Issue a Write-Quad system command if all bytes are valid, asserting one mask bit. Issue a Write-Longword system command if the quadword contains one aligned longword, asserting one mask bit. Otherwise, issue a Write-Byte system command if there is at least one valid byte, asserting a mask bit for each valid byte.

Appendix D

Performance-Monitoring Counters

This chapter describes how to use the AMD Athlon™ processor performance monitoring counters.

Overview

The AMD Athlon processor provides four 48-bit performance counters, which allows four types of events to be monitored simultaneously. These counters can either count events or measure duration. When counting events, a counter is incremented each time a specified event takes place or a specified number of events takes place. When measuring duration, a counter counts the number of processor clocks that occur while a specified condition is true. The counters can count events or measure durations that occur at any privilege level. Table 11 on page 164 lists the events that can be counted with the performance monitoring counters.

Performance Counter Usage

The performance monitoring counters are supported by eight MSR—PerfEvtSel[3:0] are the performance event select MSRs, and PerfCtr[3:0] are the performance counter MSRs.

These registers can be read from and written to using the RDMSR and WRMSR instructions, respectively.

The PerfEvtSel[3:0] registers are located at MSR locations C001_0000h to C001_0003h. The PerfCtr[3:0] registers are located at MSR locations C001_0004h to C001_0007h and are 64-byte registers.

The PerfEvtSel[3:0] registers can be accessed using the RDMSR/WRMSR instructions only when operating at privilege level 0. The PerfCtr[3:0] MSRs can be read from any privilege level using the RDPMC (read performance-monitoring counters) instruction, if the PCE flag in CR4 is set.

PerfEvtSel[3:0] MSRs (MSR Addresses C001_0000h–C001_0003h)

The PerfEvtSel[3:0] MSRs, shown in Figure 11, control the operation of the performance-monitoring counters, with one register used to set up each counter. These MSRs specify the events to be counted, how they should be counted, and the privilege levels at which counting should take place. The functions of the flags and fields within these MSRs are as are described in the following sections.

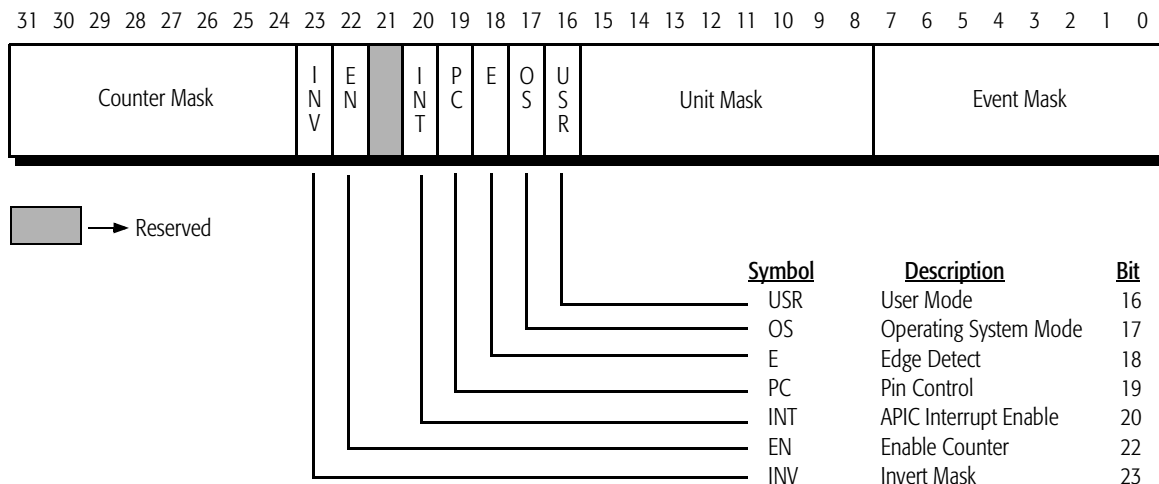


Figure 11. PerfEvtSel[3:0] Registers

Event Select Field (Bits 0–7)

These bits are used to select the event to be monitored. See Table 11 on page 164 for a list of event masks and their 8-bit codes.

Unit Mask Field (Bits 8–15)	These bits are used to further qualify the event selected in the event select field. For example, for some cache events, the mask is used as a MESI-protocol qualifier of cache states. See Table 11 on page 164 for a list of unit masks and their 8-bit codes.
USR (User Mode) Flag (Bit 16)	Events are counted only when the processor is operating at privilege levels 1, 2 or 3. This flag can be used in conjunction with the OS flag.
OS (Operating System Mode) Flag (Bit 17)	Events are counted only when the processor is operating at privilege level 0. This flag can be used in conjunction with the USR flag.
E (Edge Detect) Flag (Bit 18)	When this flag is set, edge detection of events is enabled. The processor counts the number of negated-to-asserted transitions of any condition that can be expressed by the other fields. The mechanism is limited in that it does not permit back-to-back assertions to be distinguished. This mechanism allows software to measure not only the fraction of time spent in a particular state, but also the average length of time spent in such a state (for example, the time spent waiting for an interrupt to be serviced).
PC (Pin Control) Flag (Bit 19)	When this flag is set, the processor toggles the PMi pins when the counter overflows. When this flag is clear, the processor toggles the PMi pins and increments the counter when performance monitoring events occur. The toggling of a pin is defined as assertion of the pin for one bus clock followed by negation.
INT (APIC Interrupt Enable) Flag (Bit 20)	When this flag is set, the processor generates an interrupt through its local APIC on counter overflow.
EN (Enable Counter) Flag (Bit 22)	This flag enables/disables the PerfEvtSelN MSR. When set, performance counting is enabled for this counter. When clear, this counter is disabled.
INV (Invert) Flag (Bit 23)	By inverting the Counter Mask Field, this flag inverts the result of the counter comparison, allowing both greater than and less than comparisons.
Counter Mask Field (Bits 31–24)	For events which can have multiple occurrences within one clock, this field is used to set a threshold. If the field is non-zero, the counter increments each time the number of events is

greater than or equal to the counter mask. Otherwise if this field is zero, then the counter increments by the total number of events.

Table 11. Performance-Monitoring Counters

Event Number	Source Unit	Notes / Unit Mask (bits 15–8)	Event Description
20h	LS	1xxx_xxxx b = reserved x1xx_xxxx b = HS xx1x_xxxx b = GS xxx1_xxxx b = FS xxxx_1xxx b = DS xxxx_x1xx b = SS xxxx_xx1x b = CS xxxx_xxx1 b = ES	Segment register loads
21h	LS		Stores to active instruction stream
40h	DC		Data cache accesses
41h	DC		Data cache misses
42h	DC	xxx1_xxxx b = Modified (M) xxxx_1xxx b = Owner (O) xxxx_x1xx b = Exclusive (E) xxxx_xx1x b = Shared (S) xxxx_xxx1 b = Invalid (I)	Data cache refills
43h	DC	xxx1_xxxx b = Modified (M) xxxx_1xxx b = Owner (O) xxxx_x1xx b = Exclusive (E) xxxx_xx1x b = Shared (S) xxxx_xxx1 b = Invalid (I)	Data cache refills from system
44h	DC	xxx1_xxxx b = Modified (M) xxxx_1xxx b = Owner (O) xxxx_x1xx b = Exclusive (E) xxxx_xx1x b = Shared (S) xxxx_xxx1 b = Invalid (I)	Data cache writebacks
45h	DC		L1 DTLB misses and L2 DTLB hits
46h	DC		L1 and L2 DTLB misses
47h	DC		Misaligned data references
64h	BU		DRAM system requests

Table 11. Performance-Monitoring Counters (Continued)

Event Number	Source Unit	Notes / Unit Mask (bits 15–8)	Event Description
65h	BU	1xxx_xxxx _b = reserved x1xx_xxxx _b = WB xx1x_xxxx _b = WP xxx1_xxxx _b = WT bits 11-10 = reserved xxxx_xx1x _b = WC xxxx_xxx1 _b = UC	System requests with the selected type
73h	BU	bits 15-11 = reserved xxxx_x1xx _b = L2 (L2 hit and no DC hit) xxxx_xx1x _b = Data cache xxxx_xxx1 _b = Instruction cache	Snoop hits
74h	BU	bits 15-10 = reserved xxxx_xx1x _b = L2 single bit error xxxx_xxx1 _b = System single bit error	Single-bit ECC errors detected/corrected
75h	BU	bits 15-12 = reserved xxxx_1xxx _b = I invalidates D xxxx_x1xx _b = I invalidates I xxxx_xx1x _b = D invalidates D xxxx_xxx1 _b = D invalidates I	Internal cache line invalidates
76h	BU		Cycles processor is running (not in HLT or STPCLK)
79h	BU	1xxx_xxxx _b = Data block write from the L2 (TLB RMW) x1xx_xxxx _b = Data block write from the DC xx1x_xxxx _b = Data block write from the system xxx1_xxxx _b = Data block read data store xxxx_1xxx _b = Data block read data load xxxx_x1xx _b = Data block read instruction xxxx_xx1x _b = Tag write xxxx_xxx1 _b = Tag read	L2 requests

Table 11. Performance-Monitoring Counters (Continued)

Event Number	Source Unit	Notes / Unit Mask (bits 15–8)	Event Description
7Ah	BU		Cycles that at least one fill request waited to use the L2
80h	PC		Instruction cache fetches
81h	PC		Instruction cache misses
82h	PC		Instruction cache refills from L2
83h	PC		Instruction cache refills from system
84h	PC		L1 ITLB misses (and L2 ITLB hits)
85h	PC		(L1 and) L2 ITLB misses
86h	PC		Snoop resyncs
87h	PC		Instruction fetch stall cycles
88h	PC		Return stack hits
89h	PC		Return stack overflow
C0h	FR		Retired instructions (includes exceptions, interrupts, resyncs)
C1h	FR		Retired Ops
C2h	FR		Retired branches (conditional, unconditional, exceptions, interrupts)
C3h	FR		Retired branches mispredicted
C4h	FR		Retired taken branches
C5h	FR		Retired taken branches mispredicted
C6h	FR		Retired far control transfers
C8h	FR		Retired near returns
C9h	FR		Retired near returns mispredicted
CAh	FR		Retired indirect branches with target mispredicted
CDh	FR		Interrupts masked cycles (IF=0)
CEh	FR		Interrupts masked while pending cycles (INTR while IF=0)
CFh	FR		Number of taken hardware interrupts
D0h	FR		Instruction decoder empty
D1h	FR		Dispatch stalls (event masks D2h through DAh below combined)
D2h	FR		Branch abort to retire
D3h	FR		Serialize
D4h	FR		Segment load stall

Table 11. Performance-Monitoring Counters (Continued)

Event Number	Source Unit	Notes / Unit Mask (bits 15–8)	Event Description
D5h	FR		ICU full
D6h	FR		Reservation stations full
D7h	FR		FPU full
D8h	FR		LS full
D9h	FR		All quiet stall
DAh	FR		Far transfer or resync branch pending
DCh	FR		Breakpoint matches for DR0
DDh	FR		Breakpoint matches for DR1
DEh	FR		Breakpoint matches for DR2
DFh	FR		Breakpoint matches for DR3

PerfCtr[3:0] MSRs (MSR Addresses C001_0004h–C001_0007h)

The performance-counter MSRs contain the event or duration counts for the selected events being counted. The RDPMC instruction can be used by programs or procedures running at any privilege level and in virtual-8086 mode to read these counters. The PCE flag in control register CR4 (bit 8) allows the use of this instruction to be restricted to only programs and procedures running at privilege level 0.

The RDPMC instruction is not serializing or ordered with other instructions. Therefore, it does not necessarily wait until all previous instructions have been executed before reading the counter. Similarly, subsequent instructions can begin execution before the RDPMC instruction operation is performed.

Only the operating system, executing at privilege level 0, can directly manipulate the performance counters, using the RDMSR and WRMSR instructions. A secure operating system would clear the PCE flag during system initialization, which disables direct user access to the performance-monitoring counters but provides a user-accessible programming interface that emulates the RDPMC instruction.

The WRMSR instruction cannot arbitrarily write to the performance-monitoring counter MSRs (PerfCtr[3:0]). Instead, the value should be treated as 64-bit sign extended, which

allows writing both positive and negative values to the performance counters. The performance counters may be initialized using a 64-bit signed integer in the range -2^{47} and $+2^{47}$. Negative values are useful for generating an interrupt after a specific number of events.

Starting and Stopping the Performance-Monitoring Counters

The performance-monitoring counters are started by writing valid setup information in one or more of the PerfEvtSel[3:0] MSR and setting the enable counters flag in the PerfEvtSel0 MSR. If the setup is valid, the counters begin counting following the execution of a WRMSR instruction, which sets the enable counter flag. The counters can be stopped by clearing the enable counters flag or by clearing all the bits in the PerfEvtSel[3:0] MSRs.

Event and Time-Stamp Monitoring Software

For applications to use the performance-monitoring counters and time-stamp counter, the operating system needs to provide an event-monitoring device driver. This driver should include procedures for handling the following operations:

- Feature checking
- Initialize and start counters
- Stop counters
- Read the event counters
- Reading of the time stamp counter

The event monitor feature determination procedure must determine whether the current processor supports the performance-monitoring counters and time-stamp counter. This procedure compares the family and model of the processor returned by the CPUID instruction with those of processors known to support performance monitoring. In addition, the procedure checks the MSR and TSC flags returned to register EDI by the CPUID instruction to determine if the MSRs and the RDTSC instruction are supported.

The initialization and start counters procedure sets the PerfEvtSel0 and/or PerfEvtSel1 MSR for the events to be counted and the method used to count them and initializes the counter MSRs (PerfCtr[3:0]) to starting counts. The stop counters procedure stops the performance counters. (See “Starting and Stopping the Performance-Monitoring Counters” on page 168 for more information about starting and stopping the counters.)

The read counters procedure reads the values in the PerfCtr[3:0] MSRs, and a read time-stamp counter procedure reads the time-stamp counter. These procedures can be used instead of enabling the RDTSC and RDPMC instructions, which allow application code to read the counters directly.

Monitoring Counter Overflow

The AMD Athlon processor provides the option of generating a debug interrupt when a performance-monitoring counter overflows. This mechanism is enabled by setting the interrupt enable flag in one of the PerfEvtSel[3:0] MSRs. The primary use of this option is for statistical performance sampling.

To use this option, the operating system should do the following:

- Provide an interrupt routine for handling the counter overflow as an APIC interrupt
- Provide an entry in the IDT that points to a stub exception handler that returns without executing any instructions
- Provide an event monitor driver that provides the actual interrupt handler and modifies the reserved IDT entry to point to its interrupt routine

When interrupted by a counter overflow, the interrupt handler needs to perform the following actions:

- Save the instruction pointer (EIP register), code segment selector, TSS segment selector, counter values and other relevant information at the time of the interrupt
- Reset the counter to its initial setting and return from the interrupt

An event monitor application utility or another application program can read the collected performance information of the profiled application.

Appendix E

Programming the MTRR and PAT

Introduction

The AMD Athlon™ processor includes a set of memory type and range registers (MTRRs) to control cacheability and access to specified memory regions. The processor also includes the Page Address Table for defining attributes of pages. This chapter documents the use and capabilities of this feature.

The purpose of the MTRRs is to provide system software with the ability to manage the memory mapping of the hardware. Both the BIOS software and operating systems utilize this capability. The AMD Athlon processor's implementation is compatible to the Pentium® II. Prior to the MTRR mechanism, chipsets usually provided this capability.

Memory Type Range Register (MTRR) Mechanism

The memory type and range registers allow the processor to determine cacheability of various memory locations prior to bus access and to optimize access to the memory system. The AMD Athlon processor implements the MTRR programming model in a manner compatible with Pentium II.

There are two types of address ranges: fixed and variable. (See Figure 12.) For each address range, there is a memory type. For each 4K, 16K or 64K segment within the first 1 Mbyte of memory, there is one fixed address MTRR. The fixed address ranges all exist in the first 1 Mbyte. There are eight variable address ranges above 1 Mbytes. Each is programmed to a specific memory starting address, size and alignment. If a variable range overlaps the lower 1 MByte and the fixed MTRRs are enabled, then the fixed-memory type dominates.

The address regions have the following priority with respect to each other:

1. Fixed address ranges
2. Variable address ranges
3. Default memory type (UC at reset)

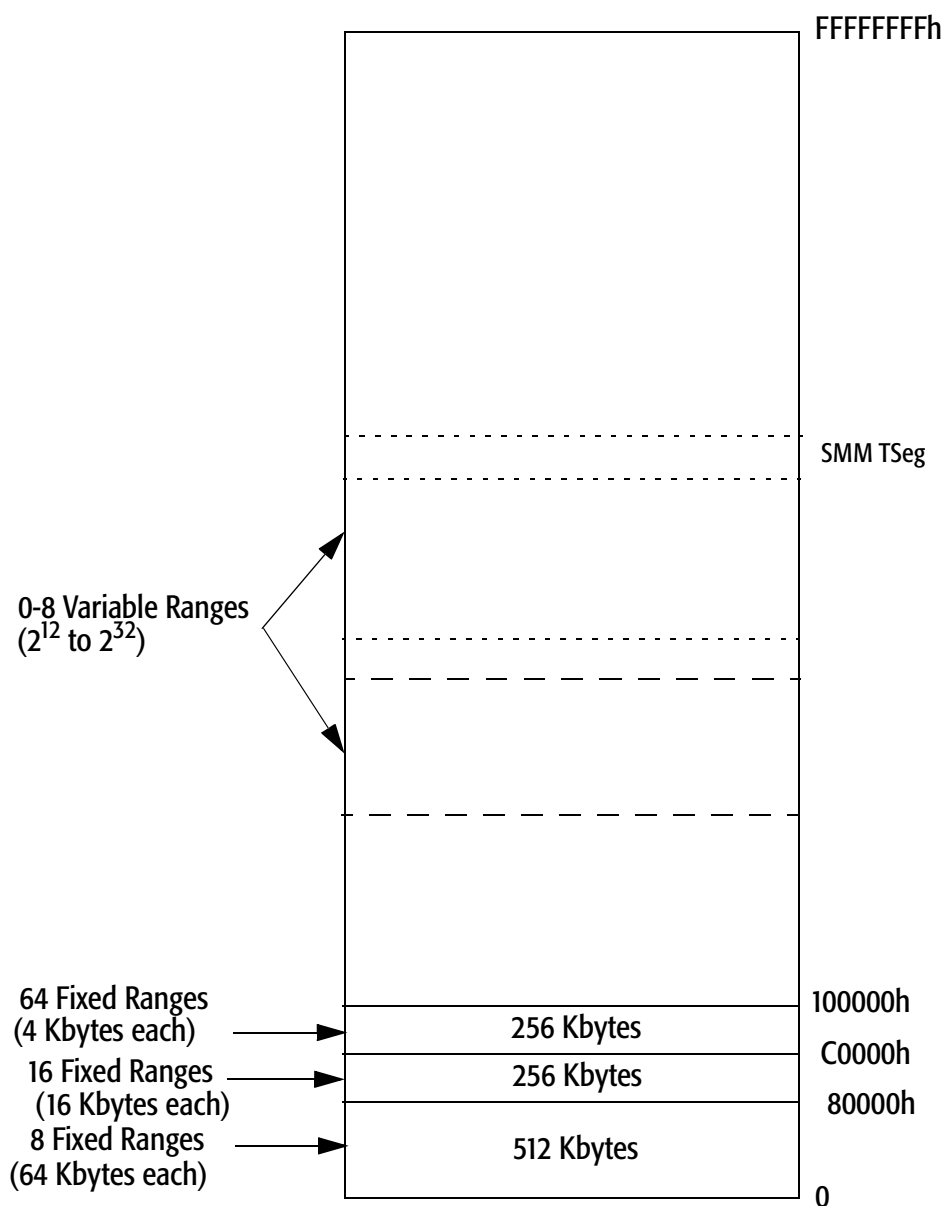


Figure 12. MTRR Mapping of Physical Memory

Memory Types

Five standard memory types are defined by the AMD Athlon processor: writethrough (WT), writeback (WB), write-protect (WP), write-combining (WC), and uncacheable (UC). These are described in Table 12 on page 174.

Table 12. Memory Type Encodings

Type Number	Type Name	Type Description
00h	UC—Uncacheable	Uncacheable for reads or writes. Cannot be combined. Must be non-speculative for reads or writes.
01h	WC—Write-Combining	Uncacheable for reads or writes. Can be combined. Can be speculative for reads. Writes can never be speculative.
04h	WT—Writethrough	Reads allocate on a miss, but only to the S-state. Writes do not allocate on a miss and, for a hit, writes update the cached entry and main memory.
05h	WP—Write-Protect	WP is functionally the same as the WT memory type, except stores do not actually modify cached data and do not cause an exception.
06h	WB—Writeback	Reads will allocate on a miss, and will allocate to: S state if returned with a ReadDataShared command. M state if returned with a ReadDataDirty command. Writes allocate to the M state, if the read allows the line to be marked E.

MTRR Capability Register Format

The MTRR capability register is a read-only register that defines the specific MTRR capability of the processor and is defined as follows.

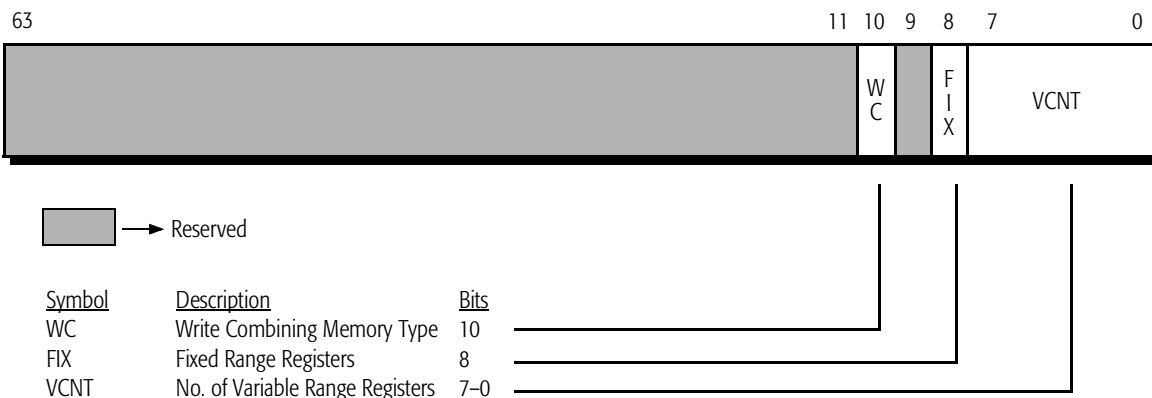


Figure 13. MTRR Capability Register Format

For the AMD Athlon processor, the MTRR capability register should contain 0508h (write-combining, fixed MTRRs supported, and eight variable MTRRs defined).

MTRR Default Type Register Format. The MTRR default type register is defined as follows.

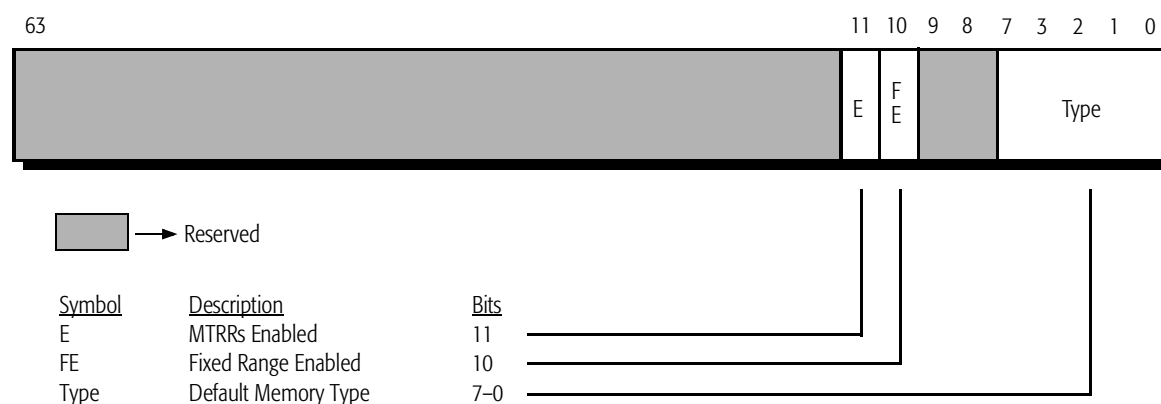


Figure 14. MTRR Default Type Register Format

- E** MTRRs are enabled when set. All MTRRs (both fixed and variable range) are disabled when clear, and all of physical memory is mapped as uncacheable memory (reset state = 0).
- FE** Fixed-range MTRRs are enabled when set. All MTRRs are disabled when clear. When the fixed-range MTRRs are enabled and an overlap occurs with a variable-range MTRR, the fixed-range MTRR takes priority (reset state = 0).
- Type** Defines the default memory type (reset state = 0). See Table 13 for more details.

Table 13. Standard MTRR Types and Properties

Memory Type	Encoding in MTRR	Internally Cacheable	Writeback Cacheable	Allows Speculative Reads	Memory Ordering Model
Uncacheable (UC)	0	No	No	No	Strong ordering
Write Combining (WC)	1	No	No	Yes	Weak ordering
Reserved	2	-	-	-	-
Reserved	3	-	-	-	-
Writethrough (WT)	4	Yes	No	Yes	Speculative ordering
Write Protected (WP)	5	Yes, reads No, Writes	No	Yes	Speculative ordering
Writeback (WB)	6	Yes	Yes	Yes	Speculative ordering
Reserved	7-255	-	-	-	-

Note that if two or more variable memory ranges match then the interactions are defined as follows:

1. If the memory types are identical, then that memory type is used.
2. If one or more of the memory types is UC, the UC memory type is used.
3. If one or more of the memory types is WT and the only other matching memory type is WB then the WT memory type is used.
4. Otherwise, if the combination of memory types is not listed above then the behavior of the processor is undefined.

MTRR Overlapping

The Intel documentation (P6/PII) states that the mapping of large pages into regions that are mapped with differing memory types can result in undefined behavior. However, testing shows that these processors decompose these large pages into 4-Kbyte pages.

When a large page (2 Mbytes/4 Mbytes) mapping covers a region that contains more than one memory type (as mapped by the MTRRs), the AMD Athlon processor does not suppress the caching of that large page mapping and only caches the mapping for just that 4-Kbyte piece in the 4-Kbyte TLB. Therefore, the AMD Athlon processor does not decompose large pages under these conditions. The fixed range MTRRs are

not affected by this issue, only the variable range (and MTRR DefType) registers are affected.

Page Attribute Table (PAT)

The Page Attribute Table (PAT) is an extension of the page table entry format, which allows the specification of memory types to regions of physical memory based on the linear address. The PAT provides the same functionality as MTRRs with the flexibility of the page tables. It provides the operating systems and applications to determine the desired memory type for optimal performance. PAT support is detected in the feature flags (bit 16) of the CPUID instruction.

MSR Access

The PAT is located in a 64-bit MSR at location 277h. It is illustrated in Figure 15. Each of the eight PA_n fields can contain the memory type encodings as described in Table 12 on page 174. An attempt to write an undefined memory type encoding into the PAT will generate a GP fault.

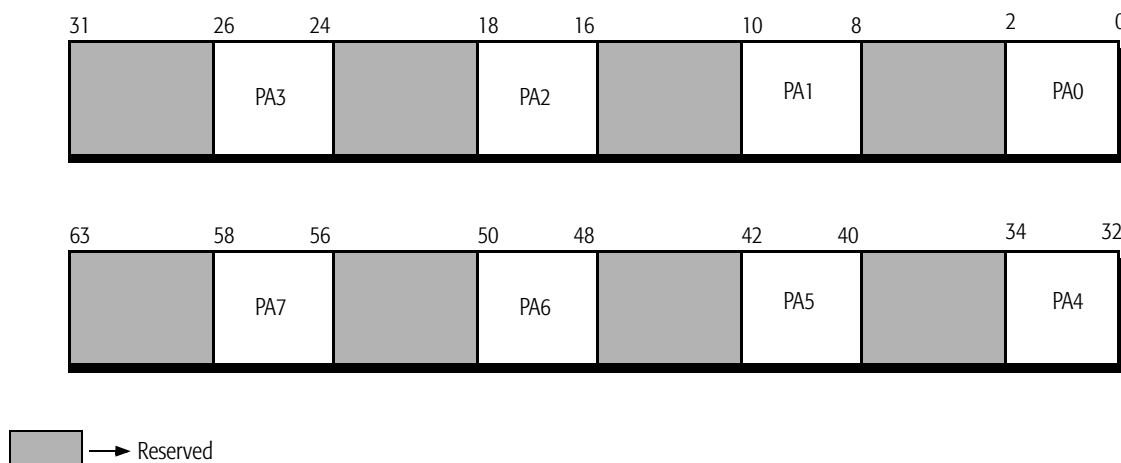


Figure 15. Page Attribute Table (MSR 277h)

Accessing the PAT

A 3-bit index consisting of the PATi, PCD, and PWT bits of the page table entry, is used to select one of the seven PAT register fields to acquire the memory type for the desired page (PATi is defined as bit 7 for 4-Kbyte PTEs and bit 12 for PDEs which map to 2-Mbyte or 4-Mbyte pages). The memory type from the PAT is used instead of the PCD and PWT for the effective memory type.

A 2-bit index consisting of PCD and PWT bits of the page table entry, is used to select one of four PAT register fields when PAE (page address extensions) is enabled, or when the PDE doesn't describe a large page. In the latter case, the PATi bit for a PTE (bit 7) corresponds to the page size bit in a PDE. Therefore, the OS should only use PA0-3 when setting the memory type for a page table that is also used as a page directory. See Table 14 on page 178.

Table 14. PATi 3-Bit Encodings

PATi	PCD	PWT	PAT Entry	Reset Value
0	0	0	0	
0	0	1	1	
0	1	0	2	
0	1	1	3	
1	0	0	4	
1	0	1	5	
1	1	0	6	
1	1	1	7	

MTRRs and PAT

The processor contains MTRRs as described earlier which provide a limited way of assigning memory types to specific regions. However, the page tables allow memory types to be assigned to the pages used for linear to physical translation.

The memory type as defined by PAT and MTRRs are combined to determine the effective memory type as listed in Table 15 and Table 16. Shaded areas indicated reserved settings.

Table 15. Effective Memory Type Based on PAT and MTRRs

PAT Memory Type	MTRR Memory Type	Effective Memory Type
UC-	WB, WT, WP, WC	UC-Page
	UC	UC-MTRR
WC	x	WC
WT	WB, WT	WT
	UC	UC
	WC	CD
	WP	CD
WP	WB, WP	WP
	UC	UC-MTRR
	WC, WT	CD
WB	WB	WB
	UC	UC
	WC	WC
	WT	WT
	WP	WP

Notes:

1. UC-MTRR indicates that the UC attribute came from the MTRRs and that the processor caches should not be probed for performance reasons.
2. UC-Page indicates that the UC attribute came from the page tables and that the processor caches must be probed due to page aliasing.
3. All reserved combinations default to CD.

Table 16. Final Output Memory Types

Input Memory Type				Output Memory Type			Note
RdMem	WrMem	Effective. MType	forceCD ⁵	AMD-751			
				RdMem	WrMem	MemType	
•	•	UC	-	•	•	UC	1
•	•	CD	-	•	•	CD	1
•	•	WC	-	•	•	WC	1
•	•	WT	-	•	•	WT	1
•	•	WP	-	•	•	WP	1
•	•	WB	-	•	•	WB	
•	•	-	•	•	•	CD	1, 2
•		UC	-	•		UC	
•		CD	-	•		CD	
•		WC	-	•		WC	
•		WT	-	•		CD	3
•		WP	-	•		WP	1
•		WB	-	•		CD	3
•		-	•	•		CD	2
	•	UC	-		•	UC	
	•	CD	-		•	CD	
	•	WC	-		•	WC	
	•	WT	-		•	CD	6
	•	WP	-		•	CD	6
	•	WB	-		•	CD	6
	•	-	•		•	CD	2
•	•	UC	-		•	UC	

Table 16. Final Output Memory Types (Continued)

Input Memory Type				Output Memory Type			Note
RdMem	WrMem	Effective. MType	forceCD ⁵	AMD-751			
				RdMem	WrMem	MemType	
●	●	CD	-	●	●	CD	
●	●	WC	-	●	●	WC	
●	●	WT	-	●	●	WT	
●	●	WP	-	●	●	WP	
●	●	WB	-	●	●	WT	4
●	●	-	●	●	●	CD	2

Notes:

- WP is not functional for RdMem/WrMem.*
- ForceCD must cause the MTRR memory type to be ignored in order to avoid x's.*
- D-I should always be WP because the BIOS will only program RdMem-WrIO for WP. CD is forced to preserve the write-protect intent.*
- Since cached IO lines cannot be copied back to IO, the processor forces WB to WT to prevent cached IO from going dirty.*
- ForceCD. The memory type is forced CD due to (1) CR0[CD]=1, (2) memory type is for the ITLB and the I-Cache is disabled or for the DTLB and the D-Cache is disabled, (3) when clean victims must be written back and RdIO and WrIO and WT, WB, or WP, or (4) access to Local APIC space.*
- The processor does not support this memory type.*

MTRR Fixed-Range Register Format

The memory types defined for memory segments defined in each of the MTRR fixed-range registers are defined in Table 17 (Also See “Standard MTRR Types and Properties” on page 176.).

Table 17. MTRR Fixed Range Register Format

Address Range (in hexadecimal)								Register
63:56	55:48	47:40	39:32	31:24	23:16	15:8	7:0	
7000-7FFF	6000-6FFF	5000-5FFF	4000-4FFF	3000-3FFF	2000-2FFF	1000-1FFF	0000-0FFF	MTRR_fix64K_00000
9C000-9FFFF	98000-9BFFF	94000-97FFF	90000-93FFF	8C000-8FFFF	88000-8BFFF	84000-87FFF	80000-83FFF	MTRR_fix16K_80000
BC000-BFFFF	B8000-BBFFF	B4000-B7FFF	B0000-B3FFF	AC000-AFFFF	A8000-ABFFF	A4000-A7FFF	A0000-A3FFF	MTRR_fix16K_A0000
C7000-C7FFF	C6000-C6FFF	C5000-C5FFF	C4000-C4FFF	C3000-C3FFF	C2000-C2FFF	C1000-C1FFF	C0000-C0FFF	MTRR_fix4K_C0000
CF000C-FFFF	CE000-CEFFF	CD000-CDFFF	CC000-CCFFF	CB000-CBFFF	CA000-CAFFF	C9000-C9FFF	C8000-C8FFF	MTRR_fix4K_C8000
D7000-D7FFF	D6000-D6FFF	D5000-D5FFF	D4000-D4FFF	D3000-D3FFF	D2000-D2FFF	D1000-D1FFF	D0000-D0FFF	MTRR_fix4K_D0000
DF000-DFFFF	DE000-DEFFF	DD000-DDFFF	DC000-DCFFF	DB000-DBFFF	DA000-DAFFF	D9000-D9FFF	D8000-D8FFF	MTRR_fix4K_D8000
E7000-E7FFF	E6000-E6FFF	E5000-E5FFF	E4000-E4FFF	E3000-E3FFF	E2000-E2FFF	E1000-E1FFF	E0000-E0FFF	MTRR_fix4K_E0000
EF000-EFFFF	EE000-EEFFF	ED000-EDFFF	EC000-ECFFF	EB000-EBFFF	EA000-EAFFF	E9000-E9FFF	E8000-E8FFF	MTRR_fix4K_E8000
F7000-F7FFF	F6000-F6FFF	F5000-F5FFF	F4000-F4FFF	F3000-F3FFF	F2000-F2FFF	F1000-F1FFF	F0000-F0FFF	MTRR_fix4K_F0000
FF000-FFFF	FE000-FEFFF	FD000-FDFFF	FC000-FCFFF	FB000-FBFFF	FA000-FAFFF	F9000-F9FFF	F8000-F8FFF	MTRR_fix4K_F8000

Variable-Range MTRRs

A variable MTRR can be programmed to start at address 0000_0000h because the fixed MTRRs always override the variable ones. However, it is recommended not to create an overlap.

The upper two variable MTRRs should not be used by the BIOS and are reserved for operating system use.

Variable-Range MTRR Register Format

The variable address range is power of 2 sized and aligned. The range of supported sizes is from 2¹² to 2³⁶ in powers of 2. The AMD Athlon processor does not implement A[35:32].

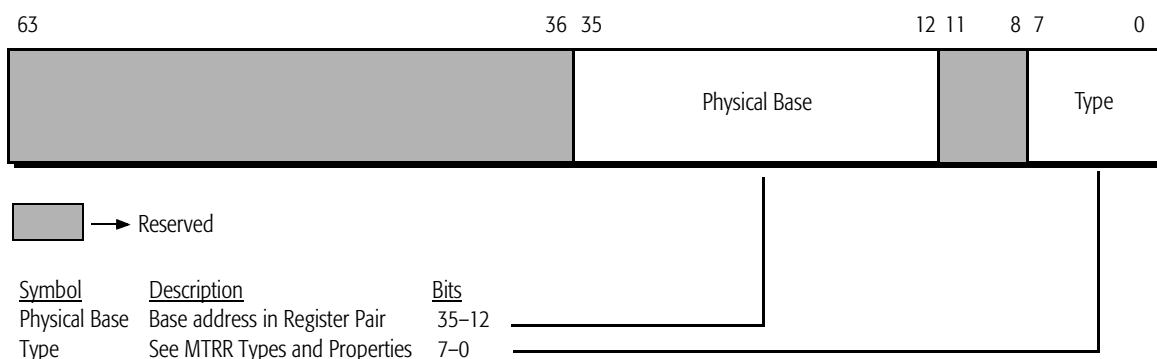


Figure 16. MTRRphysBase Register Format

Note: A software attempt to write to reserved bits will generate a general protection exception.

- Physical Base** Specifies a 24-bit value which is extended by 12 bits to form the base address of the region defined in the register pair.
- Type** See “Standard MTRR Types and Properties” on page 176.

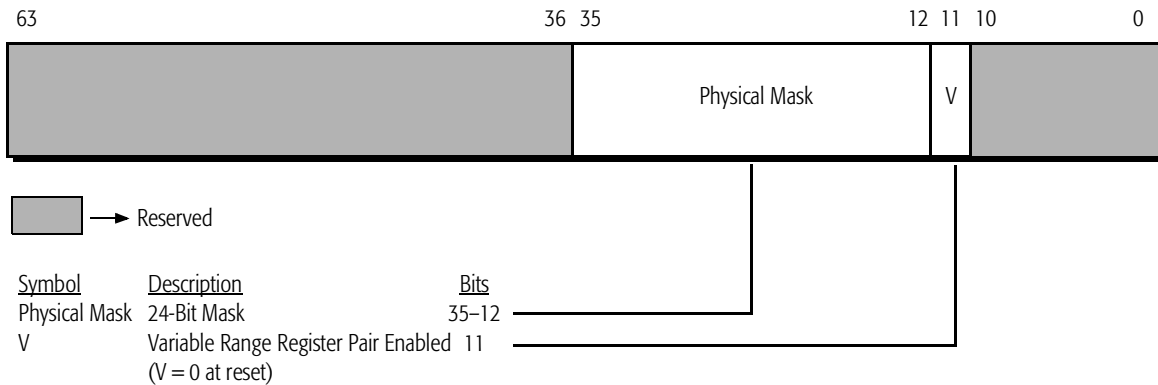


Figure 17. MTRRphysMaskn Register Format

Note: A software attempt to write to reserved bits will generate a general protection exception.

Physical Mask Specifies a 24-bit mask to determine the range of the region defined in the register pair.

V Enables the register pair when set (V = 0 at reset).

Mask values can represent discontinuous ranges (when the mask defines a lower significant bit as zero and a higher significant bit as one). In a discontinuous range, the memory area not mapped by the mask value is set to the default type. Discontinuous ranges should not be used.

The range that is mapped by the variable-range MTRR register pair must meet the following range size and alignment rule:

- Each defined memory range must have a size equal to 2^n ($11 < n < 36$).
- The base address for the address pair must be aligned to a similar 2^n boundary.

An example of a variable MTRR pair is as follows:

To map the address range from 8 Mbytes (0080_0000h) to 16 Mbytes (00FF_FFFFh) as writeback memory, the base register should be loaded with 80_0006h, and the mask should be loaded with FFF8_00800h.

MTRR MSR Format

This table defines the model-specific registers related to the memory type range register implementation. All MTRRs are defined to be 64 bits.

Table 18. MTRR-Related Model-Specific Register (MSR) Map

Register Address	Register Name	Description	
0FEh	MTRRcap	See “MTRR Capability Register Format” on page 174.	
200h	MTRR Base0	See “MTRRphysBasen Register Format” on page 183.	
201h	MTRR Mask0	See “MTRRphysMaskn Register Format” on page 184.	
202h	MTRR Base1		
203h	MTRR Mask1		
204h	MTRR Base2		
205h	MTRR Mask2		
206h	MTRR Base3		
207h	MTRR Mask3		
208h	MTRR Base4		
209h	MTRR Mask4		
20Ah	MTRR Base5		
20Bh	MTRR Mask5		
20Ch	MTRR Base6		
20Dh	MTRR Mask6		
20Eh	MTRR Base7		
20Fh	MTRR Mask7		
250h	MTRRFIX64k_00000	See “MTRR Fixed-Range Register Format” on page 182.	
258h	MTRRFIX16k_80000		
259h	MTRRFIX16k_A0000		
268h	MTRRFIX4k_C0000		
269h	MTRRFIX4k_C8000		
26Ah	MTRRFIX4k_D0000		
26Bh	MTRRFIX4k_D8000		
26Ch	MTRRFIX4k_E0000		
26Dh	MTRRFIX4k_E8000		
26Eh	MTRRFIX4k_F0000		
26Fh	MTRRFIX4k_F8000		
2FFh	MTRRdefType		See “MTRR Default Type Register Format” on page 175.

Appendix F

Instruction Dispatch and Execution Resources

This chapter describes the MacroOPs generated by each decoded instruction, along with the relative static execution latencies of these groups of operations. Tables 19 through 24 starting on page 188 define the integer, MMX™, MMX extensions, floating-point, 3DNow!™, and 3DNow! extensions instructions, respectively.

The first column in these tables indicates the instruction mnemonic and operand types with the following notations:

- *reg8*—byte integer register defined by instruction byte(s) or bits 5, 4, and 3 of the modR/M byte
- *mreg8*—byte integer register defined by bits 2, 1, and 0 of the modR/M byte
- *reg16/32*—word and doubleword integer register defined by instruction byte(s) or bits 5, 4, and 3 of the modR/M byte
- *mreg16/32*—word and doubleword integer register defined by bits 2, 1, and 0 of the modR/M byte
- *mem8*—byte memory location
- *mem16/32*—word or doubleword memory location
- *mem32/48*—doubleword or 6-byte memory location
- *mem48*—48-bit integer value in memory
- *mem64*—64-bit value in memory
- *imm8/16/32*—8-bit, 16-bit or 32-bit immediate value
- *disp8*—8-bit displacement value

- *disp16/32*—16-bit or 32-bit displacement value
- *disp32/48*—32-bit or 48-bit displacement value
- *eXX*—register width depending on the operand size
- *mem32real*—32-bit floating-point value in memory
- *mem64real*—64-bit floating-point value in memory
- *mem80real*—80-bit floating-point value in memory
- *mmreg*—MMX/3DNow! register
- *mmreg1*—MMX/3DNow! register defined by bits 5, 4, and 3 of the modR/M byte
- *mmreg2*—MMX/3DNow! register defined by bits 2, 1, and 0 of the modR/M byte

The second and third columns list all applicable encoding opcode bytes.

The fourth column lists the modR/M byte used by the instruction. The modR/M byte defines the instruction as register or memory form. If mod bits 7 and 6 are documented as mm (memory form), mm can only be 10b, 01b, or 00b.

The fifth column lists the type of instruction decode—DirectPath or VectorPath (see “DirectPath Decoder” on page 133 and “VectorPath Decoder” on page 133 for more information). The AMD Athlon™ processor enhanced decode logic can process three instructions per clock.

The FPU, MMX, and 3DNow! instruction tables have an additional column that lists the possible FPU execution pipelines available for use by any particular DirectPath decoded operation. Typically, VectorPath instructions require more than one execution pipe resource.

Table 19. Integer Instructions

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
AAA	37h			VectorPath
AAD	D5h	0Ah		VectorPath
AAM	D4h	0Ah		VectorPath
AAS	3Fh			VectorPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
ADC mreg8, reg8	10h		11-xxx-xxx	DirectPath
ADC mem8, reg8	10h		mm-xxx-xxx	DirectPath
ADC mreg16/32, reg16/32	11h		11-xxx-xxx	DirectPath
ADC mem16/32, reg16/32	11h		mm-xxx-xxx	DirectPath
ADC reg8, mreg8	12h		11-xxx-xxx	DirectPath
ADC reg8, mem8	12h		mm-xxx-xxx	DirectPath
ADC reg16/32, mreg16/32	13h		11-xxx-xxx	DirectPath
ADC reg16/32, mem16/32	13h		mm-xxx-xxx	DirectPath
ADC AL, imm8	14h			DirectPath
ADC EAX, imm16/32	15h			DirectPath
ADC mreg8, imm8	80h		11-010-xxx	DirectPath
ADC mem8, imm8	80h		mm-010-xxx	DirectPath
ADC mreg16/32, imm16/32	81h		11-010-xxx	DirectPath
ADC mem16/32, imm16/32	81h		mm-010-xxx	DirectPath
ADC mreg16/32, imm8 (sign extended)	83h		11-010-xxx	DirectPath
ADC mem16/32, imm8 (sign extended)	83h		mm-010-xxx	DirectPath
ADD mreg8, reg8	00h		11-xxx-xxx	DirectPath
ADD mem8, reg8	00h		mm-xxx-xxx	DirectPath
ADD mreg16/32, reg16/32	01h		11-xxx-xxx	DirectPath
ADD mem16/32, reg16/32	01h		mm-xxx-xxx	DirectPath
ADD reg8, mreg8	02h		11-xxx-xxx	DirectPath
ADD reg8, mem8	02h		mm-xxx-xxx	DirectPath
ADD reg16/32, mreg16/32	03h		11-xxx-xxx	DirectPath
ADD reg16/32, mem16/32	03h		mm-xxx-xxx	DirectPath
ADD AL, imm8	04h			DirectPath
ADD EAX, imm16/32	05h			DirectPath
ADD mreg8, imm8	80h		11-000-xxx	DirectPath
ADD mem8, imm8	80h		mm-000-xxx	DirectPath
ADD mreg16/32, imm16/32	81h		11-000-xxx	DirectPath
ADD mem16/32, imm16/32	81h		mm-000-xxx	DirectPath
ADD mreg16/32, imm8 (sign extended)	83h		11-000-xxx	DirectPath
ADD mem16/32, imm8 (sign extended)	83h		mm-000-xxx	DirectPath
AND mreg8, reg8	20h		11-xxx-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
AND mem8, reg8	20h		mm-xxx-xxx	DirectPath
AND mreg16/32, reg16/32	21h		11-xxx-xxx	DirectPath
AND mem16/32, reg16/32	21h		mm-xxx-xxx	DirectPath
AND reg8, mreg8	22h		11-xxx-xxx	DirectPath
AND reg8, mem8	22h		mm-xxx-xxx	DirectPath
AND reg16/32, mreg16/32	23h		11-xxx-xxx	DirectPath
AND reg16/32, mem16/32	23h		mm-xxx-xxx	DirectPath
AND AL, imm8	24h			DirectPath
AND EAX, imm16/32	25h			DirectPath
AND mreg8, imm8	80h		11-100-xxx	DirectPath
AND mem8, imm8	80h		mm-100-xxx	DirectPath
AND mreg16/32, imm16/32	81h		11-100-xxx	DirectPath
AND mem16/32, imm16/32	81h		mm-100-xxx	DirectPath
AND mreg16/32, imm8 (sign extended)	83h		11-100-xxx	DirectPath
AND mem16/32, imm8 (sign extended)	83h		mm-100-xxx	DirectPath
ARPL mreg16, reg16	63h		11-xxx-xxx	VectorPath
ARPL mem16, reg16	63h		mm-xxx-xxx	VectorPath
BOUND	62h			VectorPath
BSF reg16/32, mreg16/32	0Fh	BCh	11-xxx-xxx	VectorPath
BSF reg16/32, mem16/32	0Fh	BCh	mm-xxx-xxx	VectorPath
BSR reg16/32, mreg16/32	0Fh	BDh	11-xxx-xxx	VectorPath
BSR reg16/32, mem16/32	0Fh	BDh	mm-xxx-xxx	VectorPath
BSWAP EAX	0Fh	C8h		DirectPath
BSWAP ECX	0Fh	C9h		DirectPath
BSWAP EDX	0Fh	CAh		DirectPath
BSWAP EBX	0Fh	CBh		DirectPath
BSWAP ESP	0Fh	CCh		DirectPath
BSWAP EBP	0Fh	CDh		DirectPath
BSWAP ESI	0Fh	CEh		DirectPath
BSWAP EDI	0Fh	CFh		DirectPath
BT mreg16/32, reg16/32	0Fh	A3h	11-xxx-xxx	DirectPath
BT mem16/32, reg16/32	0Fh	A3h	mm-xxx-xxx	VectorPath
BT mreg16/32, imm8	0Fh	BAh	11-100-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
BT mem16/32, imm8	0Fh	BAh	mm-100-xxx	DirectPath
BTC mreg16/32, reg16/32	0Fh	BBh	11-xxx-xxx	VectorPath
BTC mem16/32, reg16/32	0Fh	BBh	mm-xxx-xxx	VectorPath
BTC mreg16/32, imm8	0Fh	BAh	11-111-xxx	VectorPath
BTC mem16/32, imm8	0Fh	BAh	mm-111-xxx	VectorPath
BTR mreg16/32, reg16/32	0Fh	B3h	11-xxx-xxx	VectorPath
BTR mem16/32, reg16/32	0Fh	B3h	mm-xxx-xxx	VectorPath
BTR mreg16/32, imm8	0Fh	BAh	11-110-xxx	VectorPath
BTR mem16/32, imm8	0Fh	BAh	mm-110-xxx	VectorPath
BTS mreg16/32, reg16/32	0Fh	ABh	11-xxx-xxx	VectorPath
BTS mem16/32, reg16/32	0Fh	ABh	mm-xxx-xxx	VectorPath
BTS mreg16/32, imm8	0Fh	BAh	11-101-xxx	VectorPath
BTS mem16/32, imm8	0Fh	BAh	mm-101-xxx	VectorPath
CALL full pointer	9Ah			VectorPath
CALL near imm16/32	E8h			VectorPath
CALL mem16:16/32	FFh		11-011-xxx	VectorPath
CALL near mreg32 (indirect)	FFh		11-010-xxx	VectorPath
CALL near mem32 (indirect)	FFh		mm-010-xxx	VectorPath
CBW/CWDE	98h			DirectPath
CLC	F8h			DirectPath
CLD	FCh			VectorPath
CLI	FAh			VectorPath
CLTS	0Fh	06h		VectorPath
CMC	F5h			DirectPath
CMOVA/CMOVNBE reg16/32, reg16/32	0Fh	47h	11-xxx-xxx	DirectPath
CMOVA/CMOVNBE reg16/32, mem16/32	0Fh	47h	mm-xxx-xxx	DirectPath
CMOVAE/CMOVNB/CMOVNC reg16/32, mem16/32	0Fh	43h	11-xxx-xxx	DirectPath
CMOVAE/CMOVNB/CMOVNC mem16/32, mem16/32	0Fh	43h	mm-xxx-xxx	DirectPath
CMOVB/CMOVC/CMOVNAE reg16/32, reg16/32	0Fh	42h	11-xxx-xxx	DirectPath
CMOVB/CMOVC/CMOVNAE mem16/32, reg16/32	0Fh	42h	mm-xxx-xxx	DirectPath
CMOVBE/CMOVNA reg16/32, reg16/32	0Fh	46h	11-xxx-xxx	DirectPath
CMOVBE/CMOVNA reg16/32, mem16/32	0Fh	46h	mm-xxx-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
CMOVE/CMOVZ reg16/32, reg16/32	0Fh	44h	11-xxx-xxx	DirectPath
CMOVE/CMOVZ reg16/32, mem16/32	0Fh	44h	mm-xxx-xxx	DirectPath
CMOVG/CMOVNLE reg16/32, reg16/32	0Fh	4Fh	11-xxx-xxx	DirectPath
CMOVG/CMOVNLE reg16/32, mem16/32	0Fh	4Fh	mm-xxx-xxx	DirectPath
CMOVGE/CMOVNLE reg16/32, reg16/32	0Fh	4Dh	11-xxx-xxx	DirectPath
CMOVGE/CMOVNLE reg16/32, mem16/32	0Fh	4Dh	mm-xxx-xxx	DirectPath
CMOVL/CMOVNGE reg16/32, reg16/32	0Fh	4Ch	11-xxx-xxx	DirectPath
CMOVL/CMOVNGE reg16/32, mem16/32	0Fh	4Ch	mm-xxx-xxx	DirectPath
CMOVLE/CMOVNG reg16/32, reg16/32	0Fh	4Eh	11-xxx-xxx	DirectPath
CMOVLE/CMOVNG reg16/32, mem16/32	0Fh	4Eh	mm-xxx-xxx	DirectPath
CMOVNE/CMOVNZ reg16/32, reg16/32	0Fh	45h	11-xxx-xxx	DirectPath
CMOVNE/CMOVNZ reg16/32, mem16/32	0Fh	45h	mm-xxx-xxx	DirectPath
CMOVNO reg16/32, reg16/32	0Fh	41h	11-xxx-xxx	DirectPath
CMOVNO reg16/32, mem16/32	0Fh	41h	mm-xxx-xxx	DirectPath
CMOVNP/CMOVPO reg16/32, reg16/32	0Fh	4Bh	11-xxx-xxx	DirectPath
CMOVNP/CMOVPO reg16/32, mem16/32	0Fh	4Bh	mm-xxx-xxx	DirectPath
CMOVNS reg16/32, reg16/32	0Fh	49h	11-xxx-xxx	DirectPath
CMOVNS reg16/32, mem16/32	0Fh	49h	mm-xxx-xxx	DirectPath
CMOVO reg16/32, reg16/32	0Fh	40h	11-xxx-xxx	DirectPath
CMOVO reg16/32, mem16/32	0Fh	40h	mm-xxx-xxx	DirectPath
CMOVPE/CMOVPE reg16/32, reg16/32	0Fh	4Ah	11-xxx-xxx	DirectPath
CMOVPE/CMOVPE reg16/32, mem16/32	0Fh	4Ah	mm-xxx-xxx	DirectPath
CMOVS reg16/32, reg16/32	0Fh	48h	11-xxx-xxx	DirectPath
CMOVS reg16/32, mem16/32	0Fh	48h	mm-xxx-xxx	DirectPath
CMP mreg8, reg8	38h		11-xxx-xxx	DirectPath
CMP mem8, reg8	38h		mm-xxx-xxx	DirectPath
CMP mreg16/32, reg16/32	39h		11-xxx-xxx	DirectPath
CMP mem16/32, reg16/32	39h		mm-xxx-xxx	DirectPath
CMP reg8, mreg8	3Ah		11-xxx-xxx	DirectPath
CMP reg8, mem8	3Ah		mm-xxx-xxx	DirectPath
CMP reg16/32, mreg16/32	3Bh		11-xxx-xxx	DirectPath
CMP reg16/32, mem16/32	3Bh		mm-xxx-xxx	DirectPath
CMP AL, imm8	3Ch			DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
CMP EAX, imm16/32	3Dh			DirectPath
CMP mreg8, imm8	80h		11-111-xxx	DirectPath
CMP mem8, imm8	80h		mm-111-xxx	DirectPath
CMP mreg16/32, imm16/32	81h		11-111-xxx	DirectPath
CMP mem16/32, imm16/32	81h		mm-111-xxx	DirectPath
CMP mreg16/32, imm8 (sign extended)	83h		11-111-xxx	DirectPath
CMP mem16/32, imm8 (sign extended)	83h		mm-111-xxx	DirectPath
CMPSB mem8, mem8	A6h			VectorPath
CMPSW mem16, mem32	A7h			VectorPath
CMPSD mem32, mem32	A7h			VectorPath
CMPXCHG mreg8, reg8	0Fh	B0h	11-xxx-xxx	VectorPath
CMPXCHG mem8, reg8	0Fh	B0h	mm-xxx-xxx	VectorPath
CMPXCHG mreg16/32, reg16/32	0Fh	B1h	11-xxx-xxx	VectorPath
CMPXCHG mem16/32, reg16/32	0Fh	B1h	mm-xxx-xxx	VectorPath
CMPXCHG8B mem64	0Fh	C7h	mm-xxx-xxx	VectorPath
CPUID	0Fh	A2h		VectorPath
CWD/CDQ	99h			DirectPath
DAA	27h			VectorPath
DAS	2Fh			VectorPath
DEC EAX	48h			DirectPath
DEC ECX	49h			DirectPath
DEC EDX	4Ah			DirectPath
DEC EBX	4Bh			DirectPath
DEC ESP	4Ch			DirectPath
DEC EBP	4Dh			DirectPath
DEC ESI	4Eh			DirectPath
DEC EDI	4Fh			DirectPath
DEC mreg8	FEh		11-001-xxx	DirectPath
DEC mem8	FEh		mm-001-xxx	DirectPath
DEC mreg16/32	FFh		11-001-xxx	DirectPath
DEC mem16/32	FFh		mm-001-xxx	DirectPath
DIV AL, mreg8	F6h		11-110-xxx	VectorPath
DIV AL, mem8	F6h		mm-110-xxx	VectorPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
DIV EAX, mreg16/32	F7h		11-110-xxx	VectorPath
DIV EAX, mem16/32	F7h		mm-110-xxx	VectorPath
ENTER	C8			VectorPath
IDIV mreg8	F6h		11-111-xxx	VectorPath
IDIV mem8	F6h		mm-111-xxx	VectorPath
IDIV EAX, mreg16/32	F7h		11-111-xxx	VectorPath
IDIV EAX, mem16/32	F7h		mm-111-xxx	VectorPath
IMUL reg16/32, imm16/32	69h		11-xxx-xxx	VectorPath
IMUL reg16/32, mreg16/32, imm16/32	69h		11-xxx-xxx	VectorPath
IMUL reg16/32, mem16/32, imm16/32	69h		mm-xxx-xxx	VectorPath
IMUL reg16/32, imm8 (sign extended)	6Bh		11-xxx-xxx	VectorPath
IMUL reg16/32, mreg16/32, imm8 (signed)	6Bh		11-xxx-xxx	VectorPath
IMUL reg16/32, mem16/32, imm8 (signed)	6Bh		mm-xxx-xxx	VectorPath
IMUL AX, AL, mreg8	F6h		11-101-xxx	VectorPath
IMUL AX, AL, mem8	F6h		mm-101-xxx	VectorPath
IMUL EDX:EAX, EAX, mreg16/32	F7h		11-101-xxx	VectorPath
IMUL EDX:EAX, EAX, mem16/32	F7h		mm-101-xxx	VectorPath
IMUL reg16/32, mreg16/32	0Fh	AFh	11-xxx-xxx	VectorPath
IMUL reg16/32, mem16/32	0Fh	AFh	mm-xxx-xxx	VectorPath
IN AL, imm8	E4h			VectorPath
IN AX, imm8	E5h			VectorPath
IN EAX, imm8	E5h			VectorPath
IN AL, DX	ECh			VectorPath
IN AX, DX	EDh			VectorPath
IN EAX, DX	EDh			VectorPath
INC EAX	40h			DirectPath
INC ECX	41h			DirectPath
INC EDX	42h			DirectPath
INC EBX	43h			DirectPath
INC ESP	44h			DirectPath
INC EBP	45h			DirectPath
INC ESI	46h			DirectPath
INC EDI	47h			DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
INC mreg8	FEh		11-000-xxx	DirectPath
INC mem8	FEh		mm-000-xxx	DirectPath
INC mreg16/32	FFh		11-000-xxx	DirectPath
INC mem16/32	FFh		mm-000-xxx	DirectPath
INVD	0Fh	08h		VectorPath
INVLPG	0Fh	01h	mm-111-xxx	VectorPath
JO short disp8	70h			DirectPath
JNO short disp8	71h			DirectPath
JB/JNAE/JC short disp8	72h			DirectPath
JNB/JAE/JNC short disp8	73h			DirectPath
JZ/JE short disp8	74h			DirectPath
JNZ/JNE short disp8	75h			DirectPath
JBE/JNA short disp8	76h			DirectPath
JNBE/JA short disp8	77h			DirectPath
JS short disp8	78h			DirectPath
JNS short disp8	79h			DirectPath
JP/JPE short disp8	7Ah			DirectPath
JNP/JPO short disp8	7Bh			DirectPath
JL/JNGE short disp8	7Ch			DirectPath
JNL/JGE short disp8	7Dh			DirectPath
JLE/JNG short disp8	7Eh			DirectPath
JNLE/JG short disp8	7Fh			DirectPath
JCXZ/JEC short disp8	E3h			VectorPath
JO near disp16/32	0Fh	80h		DirectPath
JNO near disp16/32	0Fh	81h		DirectPath
JB/JNAE near disp16/32	0Fh	82h		DirectPath
JNB/JAE near disp16/32	0Fh	83h		DirectPath
JZ/JE near disp16/32	0Fh	84h		DirectPath
JNZ/JNE near disp16/32	0Fh	85h		DirectPath
JBE/JNA near disp16/32	0Fh	86h		DirectPath
JNBE/JA near disp16/32	0Fh	87h		DirectPath
JS near disp16/32	0Fh	88h		DirectPath
JNS near disp16/32	0Fh	89h		DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
JP/JPE near disp16/32	0Fh	8Ah		DirectPath
JNP/JPO near disp16/32	0Fh	8Bh		DirectPath
JL/JNGE near disp16/32	0Fh	8Ch		DirectPath
JNL/JGE near disp16/32	0Fh	8Dh		DirectPath
JLE/JNG near disp16/32	0Fh	8Eh		DirectPath
JNLE/JG near disp16/32	0Fh	8Fh		DirectPath
JMP near disp16/32 (direct)	E9h			DirectPath
JMP far disp32/48 (direct)	EAh			VectorPath
JMP disp8 (short)	EBh			DirectPath
JMP far mem32 (indirect)	EFh		mm-101-xxx	VectorPath
JMP far mreg32 (indirect)	FFh		mm-101-xxx	VectorPath
JMP near mreg16/32 (indirect)	FFh		11-100-xxx	DirectPath
JMP near mem16/32 (indirect)	FFh		mm-100-xxx	DirectPath
LAHF	9Fh			VectorPath
LAR reg16/32, mreg16/32	0Fh	02h	11-xxx-xxx	VectorPath
LAR reg16/32, mem16/32	0Fh	02h	mm-xxx-xxx	VectorPath
LDS reg16/32, mem32/48	C5h		mm-xxx-xxx	VectorPath
LEA reg16, mem16/32	8Dh		mm-xxx-xxx	VectorPath
LEA reg32, mem16/32	8Dh		mm-xxx-xxx	DirectPath
LEAVE	C9h			VectorPath
LES reg16/32, mem32/48	C4h		mm-xxx-xxx	VectorPath
LFS reg16/32, mem32/48	0Fh	B4h		VectorPath
LGDT mem48	0Fh	01h	mm-010-xxx	VectorPath
LGS reg16/32, mem32/48	0Fh	B5h		VectorPath
LIDT mem48	0Fh	01h	mm-011-xxx	VectorPath
LLDT mreg16	0Fh	00h	11-010-xxx	VectorPath
LLDT mem16	0Fh	00h	mm-010-xxx	VectorPath
LMSW mreg16	0Fh	01h	11-100-xxx	VectorPath
LMSW mem16	0Fh	01h	mm-100-xxx	VectorPath
LODSB AL, mem8	ACh			VectorPath
LODSW AX, mem16	ADh			VectorPath
LOSD EAX, mem32	ADh			VectorPath
LOOP disp8	E2h			VectorPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
LOOPE/LOOPZ disp8	E1h			VectorPath
LOOPNE/LOOPNZ disp8	E0h			VectorPath
LSL reg16/32, mreg16/32	0Fh	03h	11-xxx-xxx	VectorPath
LSL reg16/32, mem16/32	0Fh	03h	mm-xxx-xxx	VectorPath
LSS reg16/32, mem32/48	0Fh	B2h	mm-xxx-xxx	VectorPath
LTR mreg16	0Fh	00h	11-011-xxx	VectorPath
LTR mem16	0Fh	00h	mm-011-xxx	VectorPath
MOV mreg8, reg8	88h		11-xxx-xxx	DirectPath
MOV mem8, reg8	88h		mm-xxx-xxx	DirectPath
MOV mreg16/32, reg16/32	89h		11-xxx-xxx	DirectPath
MOV mem16/32, reg16/32	89h		mm-xxx-xxx	DirectPath
MOV reg8, mreg8	8Ah		11-xxx-xxx	DirectPath
MOV reg8, mem8	8Ah		mm-xxx-xxx	DirectPath
MOV reg16/32, mreg16/32	8Bh		11-xxx-xxx	DirectPath
MOV reg16/32, mem16/32	8Bh		mm-xxx-xxx	DirectPath
MOV mreg16, segment reg	8Ch		11-xxx-xxx	VectorPath
MOV mem16, segment reg	8Ch		mm-xxx-xxx	VectorPath
MOV segment reg, mreg16	8Eh		11-xxx-xxx	VectorPath
MOV segment reg, mem16	8Eh		mm-xxx-xxx	VectorPath
MOV AL, mem8	A0h			DirectPath
MOV EAX, mem16/32	A1h			DirectPath
MOV mem8, AL	A2h			DirectPath
MOV mem16/32, EAX	A3h			DirectPath
MOV AL, imm8	B0h			DirectPath
MOV CL, imm8	B1h			DirectPath
MOV DL, imm8	B2h			DirectPath
MOV BL, imm8	B3h			DirectPath
MOV AH, imm8	B4h			DirectPath
MOV CH, imm8	B5h			DirectPath
MOV DH, imm8	B6h			DirectPath
MOV BH, imm8	B7h			DirectPath
MOV EAX, imm16/32	B8h			DirectPath
MOV ECX, imm16/32	B9h			DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
MOV EDX, imm16/32	BAh			DirectPath
MOV EBX, imm16/32	BBh			DirectPath
MOV ESP, imm16/32	BCh			DirectPath
MOV EBP, imm16/32	BDh			DirectPath
MOV ESI, imm16/32	BEh			DirectPath
MOV EDI, imm16/32	BFh			DirectPath
MOV mreg8, imm8	C6h		11-000-xxx	DirectPath
MOV mem8, imm8	C6h		mm-000-xxx	DirectPath
MOV mreg16/32, imm16/32	C7h		11-000-xxx	DirectPath
MOV mem16/32, imm16/32	C7h		mm-000-xxx	DirectPath
MOVSb mem8, mem8	A4h			VectorPath
MOVSD mem16, mem16	A5h			VectorPath
MOVSW mem32, mem32	A5h			VectorPath
MOVSX reg16/32, mreg8	0Fh	BEh	11-xxx-xxx	DirectPath
MOVSX reg16/32, mem8	0Fh	BEh	mm-xxx-xxx	DirectPath
MOVSX reg32, mreg16	0Fh	BFh	11-xxx-xxx	DirectPath
MOVSX reg32, mem16	0Fh	BFh	mm-xxx-xxx	DirectPath
MOVZX reg16/32, mreg8	0Fh	B6h	11-xxx-xxx	DirectPath
MOVZX reg16/32, mem8	0Fh	B6h	mm-xxx-xxx	DirectPath
MOVZX reg32, mreg16	0Fh	B7h	11-xxx-xxx	DirectPath
MOVZX reg32, mem16	0Fh	B7h	mm-xxx-xxx	DirectPath
MUL AL, mreg8	F6h		11-100-xxx	VectorPath
MUL AL, mem8	F6h		mm-100-xx	VectorPath
MUL AX, mreg16	F7h		11-100-xxx	VectorPath
MUL AX, mem16	F7h		mm-100-xxx	VectorPath
MUL EAX, mreg32	F7h		11-100-xxx	VectorPath
MUL EAX, mem32	F7h		mm-100-xx	VectorPath
NEG mreg8	F6h		11-011-xxx	DirectPath
NEG mem8	F6h		mm-011-xx	DirectPath
NEG mreg16/32	F7h		11-011-xxx	DirectPath
NEG mem16/32	F7h		mm-011-xx	DirectPath
NOP (XCHG EAX, EAX)	90h			DirectPath
NOT mreg8	F6h		11-010-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
NOT mem8	F6h		mm-010-xx	DirectPath
NOT mreg16/32	F7h		11-010-xxx	DirectPath
NOT mem16/32	F7h		mm-010-xx	DirectPath
OR mreg8, reg8	08h		11-xxx-xxx	DirectPath
OR mem8, reg8	08h		mm-xxx-xxx	DirectPath
OR mreg16/32, reg16/32	09h		11-xxx-xxx	DirectPath
OR mem16/32, reg16/32	09h		mm-xxx-xxx	DirectPath
OR reg8, mreg8	0Ah		11-xxx-xxx	DirectPath
OR reg8, mem8	0Ah		mm-xxx-xxx	DirectPath
OR reg16/32, mreg16/32	0Bh		11-xxx-xxx	DirectPath
OR reg16/32, mem16/32	0Bh		mm-xxx-xxx	DirectPath
OR AL, imm8	0Ch			DirectPath
OR EAX, imm16/32	0Dh			DirectPath
OR mreg8, imm8	80h		11-001-xxx	DirectPath
OR mem8, imm8	80h		mm-001-xxx	DirectPath
OR mreg16/32, imm16/32	81h		11-001-xxx	DirectPath
OR mem16/32, imm16/32	81h		mm-001-xxx	DirectPath
OR mreg16/32, imm8 (sign extended)	83h		11-001-xxx	DirectPath
OR mem16/32, imm8 (sign extended)	83h		mm-001-xxx	DirectPath
OUT imm8, AL	E6h			VectorPath
OUT imm8, AX	E7h			VectorPath
OUT imm8, EAX	E7h			VectorPath
OUT DX, AL	EEh			VectorPath
OUT DX, AX	EFh			VectorPath
OUT DX, EAX	EFh			VectorPath
POP ES	07h			VectorPath
POP SS	17h			VectorPath
POP DS	1Fh			VectorPath
POP FS	0Fh	A1h		VectorPath
POP GS	0Fh	A9h		VectorPath
POP EAX	58h			VectorPath
POP ECX	59h			VectorPath
POP EDX	5Ah			VectorPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
POP EBX	5Bh			VectorPath
POP ESP	5Ch			VectorPath
POP EBP	5Dh			VectorPath
POP ESI	5Eh			VectorPath
POP EDI	5Fh			VectorPath
POP mreg 16/32	8Fh		11-000-xxx	VectorPath
POP mem 16/32	8Fh		mm-000-xxx	VectorPath
POPA/POPAD	61h			VectorPath
POPF/POPPD	9Dh			VectorPath
PUSH ES	06h			VectorPath
PUSH CS	0Eh			VectorPath
PUSH FS	0Fh	A0h		VectorPath
PUSH GS	0Fh	A8h		VectorPath
PUSH SS	16h			VectorPath
PUSH DS	1Eh			VectorPath
PUSH EAX	50h			DirectPath
PUSH ECX	51h			DirectPath
PUSH EDX	52h			DirectPath
PUSH EBX	53h			DirectPath
PUSH ESP	54h			DirectPath
PUSH EBP	55h			DirectPath
PUSH ESI	56h			DirectPath
PUSH EDI	57h			DirectPath
PUSH imm8	6Ah			DirectPath
PUSH imm16/32	68h			DirectPath
PUSH mreg16/32	FFh		11-110-xxx	VectorPath
PUSH mem16/32	FFh		mm-110-xxx	VectorPath
PUSHA/PUSHAD	60h			VectorPath
PUSHF/PUSHFD	9Ch			VectorPath
RCL mreg8, imm8	C0h		11-010-xxx	DirectPath
RCL mem8, imm8	C0h		mm-010-xxx	VectorPath
RCL mreg16/32, imm8	C1h		11-010-xxx	DirectPath
RCL mem16/32, imm8	C1h		mm-010-xxx	VectorPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
RCL mreg8, 1	D0h		11-010-xxx	DirectPath
RCL mem8, 1	D0h		mm-010-xxx	DirectPath
RCL mreg16/32, 1	D1h		11-010-xxx	DirectPath
RCL mem16/32, 1	D1h		mm-010-xxx	DirectPath
RCL mreg8, CL	D2h		11-010-xxx	DirectPath
RCL mem8, CL	D2h		mm-010-xxx	VectorPath
RCL mreg16/32, CL	D3h		11-010-xxx	DirectPath
RCL mem16/32, CL	D3h		mm-010-xxx	VectorPath
RCR mreg8, imm8	C0h		11-011-xxx	DirectPath
RCR mem8, imm8	C0h		mm-011-xxx	VectorPath
RCR mreg16/32, imm8	C1h		11-011-xxx	DirectPath
RCR mem16/32, imm8	C1h		mm-011-xxx	VectorPath
RCR mreg8, 1	D0h		11-011-xxx	DirectPath
RCR mem8, 1	D0h		mm-011-xxx	DirectPath
RCR mreg16/32, 1	D1h		11-011-xxx	DirectPath
RCR mem16/32, 1	D1h		mm-011-xxx	DirectPath
RCR mreg8, CL	D2h		11-011-xxx	DirectPath
RCR mem8, CL	D2h		mm-011-xxx	VectorPath
RCR mreg16/32, CL	D3h		11-011-xxx	DirectPath
RCR mem16/32, CL	D3h		mm-011-xxx	VectorPath
RDMSR	0Fh	32h		VectorPath
RDPMC	0Fh	33h		VectorPath
RDTSC	0Fh	31h		VectorPath
RET near imm16	C2h			VectorPath
RET near	C3h			VectorPath
RET far imm16	CAh			VectorPath
RET far	CBh			VectorPath
ROL mreg8, imm8	C0h		11-000-xxx	DirectPath
ROL mem8, imm8	C0h		mm-000-xxx	DirectPath
ROL mreg16/32, imm8	C1h		11-000-xxx	DirectPath
ROL mem16/32, imm8	C1h		mm-000-xxx	DirectPath
ROL mreg8, 1	D0h		11-000-xxx	DirectPath
ROL mem8, 1	D0h		mm-000-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
ROL mreg16/32, 1	D1h		11-000-xxx	DirectPath
ROL mem16/32, 1	D1h		mm-000-xxx	DirectPath
ROL mreg8, CL	D2h		11-000-xxx	DirectPath
ROL mem8, CL	D2h		mm-000-xxx	DirectPath
ROL mreg16/32, CL	D3h		11-000-xxx	DirectPath
ROL mem16/32, CL	D3h		mm-000-xxx	DirectPath
ROR mreg8, imm8	C0h		11-001-xxx	DirectPath
ROR mem8, imm8	C0h		mm-001-xxx	DirectPath
ROR mreg16/32, imm8	C1h		11-001-xxx	DirectPath
ROR mem16/32, imm8	C1h		mm-001-xxx	DirectPath
ROR mreg8, 1	D0h		11-001-xxx	DirectPath
ROR mem8, 1	D0h		mm-001-xxx	DirectPath
ROR mreg16/32, 1	D1h		11-001-xxx	DirectPath
ROR mem16/32, 1	D1h		mm-001-xxx	DirectPath
ROR mreg8, CL	D2h		11-001-xxx	DirectPath
ROR mem8, CL	D2h		mm-001-xxx	DirectPath
ROR mreg16/32, CL	D3h		11-001-xxx	DirectPath
ROR mem16/32, CL	D3h		mm-001-xxx	DirectPath
SAHF	9Eh			VectorPath
SAR mreg8, imm8	C0h		11-111-xxx	DirectPath
SAR mem8, imm8	C0h		mm-111-xxx	DirectPath
SAR mreg16/32, imm8	C1h		11-111-xxx	DirectPath
SAR mem16/32, imm8	C1h		mm-111-xxx	DirectPath
SAR mreg8, 1	D0h		11-111-xxx	DirectPath
SAR mem8, 1	D0h		mm-111-xxx	DirectPath
SAR mreg16/32, 1	D1h		11-111-xxx	DirectPath
SAR mem16/32, 1	D1h		mm-111-xxx	DirectPath
SAR mreg8, CL	D2h		11-111-xxx	DirectPath
SAR mem8, CL	D2h		mm-111-xxx	DirectPath
SAR mreg16/32, CL	D3h		11-111-xxx	DirectPath
SAR mem16/32, CL	D3h		mm-111-xxx	DirectPath
SBB mreg8, reg8	18h		11-xxx-xxx	DirectPath
SBB mem8, reg8	18h		mm-xxx-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
SBB mreg16/32, reg16/32	19h		11-xxx-xxx	DirectPath
SBB mem16/32, reg16/32	19h		mm-xxx-xxx	DirectPath
SBB reg8, mreg8	1Ah		11-xxx-xxx	DirectPath
SBB reg8, mem8	1Ah		mm-xxx-xxx	DirectPath
SBB reg16/32, mreg16/32	1Bh		11-xxx-xxx	DirectPath
SBB reg16/32, mem16/32	1Bh		mm-xxx-xxx	DirectPath
SBB AL, imm8	1Ch			DirectPath
SBB EAX, imm16/32	1Dh			DirectPath
SBB mreg8, imm8	80h		11-011-xxx	DirectPath
SBB mem8, imm8	80h		mm-011-xxx	DirectPath
SBB mreg16/32, imm16/32	81h		11-011-xxx	DirectPath
SBB mem16/32, imm16/32	81h		mm-011-xxx	DirectPath
SBB mreg16/32, imm8 (sign extended)	83h		11-011-xxx	DirectPath
SBB mem16/32, imm8 (sign extended)	83h		mm-011-xxx	DirectPath
SCASB AL, mem8	A Eh			VectorPath
SCASW AX, mem16	A Fh			VectorPath
SCASD EAX, mem32	A Fh			VectorPath
SETO mreg8	0Fh	90h	11-xxx-xxx	DirectPath
SETO mem8	0Fh	90h	mm-xxx-xxx	DirectPath
SETNO mreg8	0Fh	91h	11-xxx-xxx	DirectPath
SETNO mem8	0Fh	91h	mm-xxx-xxx	DirectPath
SETB/SETC/SETNAE mreg8	0Fh	92h	11-xxx-xxx	DirectPath
SETB/SETC/SETNAE mem8	0Fh	92h	mm-xxx-xxx	DirectPath
SETAE/SETNB/SETNC mreg8	0Fh	93h	11-xxx-xxx	DirectPath
SETAE/SETNB/SETNC mem8	0Fh	93h	mm-xxx-xxx	DirectPath
SETE/SETZ mreg8	0Fh	94h	11-xxx-xxx	DirectPath
SETE/SETZ mem8	0Fh	94h	mm-xxx-xxx	DirectPath
SETNE/SETNZ mreg8	0Fh	95h	11-xxx-xxx	DirectPath
SETNE/SETNZ mem8	0Fh	95h	mm-xxx-xxx	DirectPath
SETBE/SETNA mreg8	0Fh	96h	11-xxx-xxx	DirectPath
SETBE/SETNA mem8	0Fh	96h	mm-xxx-xxx	DirectPath
SETA/SETNBE mreg8	0Fh	97h	11-xxx-xxx	DirectPath
SETA/SETNBE mem8	0Fh	97h	mm-xxx-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
SETS mreg8	0Fh	98h	11-xxx-xxx	DirectPath
SETS mem8	0Fh	98h	mm-xxx-xxx	DirectPath
SETNS mreg8	0Fh	99h	11-xxx-xxx	DirectPath
SETNS mem8	0Fh	99h	mm-xxx-xxx	DirectPath
SETP/SETPE mreg8	0Fh	9Ah	11-xxx-xxx	DirectPath
SETP/SETPE mem8	0Fh	9Ah	mm-xxx-xxx	DirectPath
SETNP/SETPO mreg8	0Fh	9Bh	11-xxx-xxx	DirectPath
SETNP/SETPO mem8	0Fh	9Bh	mm-xxx-xxx	DirectPath
SETL/SETNGE mreg8	0Fh	9Ch	11-xxx-xxx	DirectPath
SETL/SETNGE mem8	0Fh	9Ch	mm-xxx-xxx	DirectPath
SETGE/SETNL mreg8	0Fh	9Dh	11-xxx-xxx	DirectPath
SETGE/SETNL mem8	0Fh	9Dh	mm-xxx-xxx	DirectPath
SETLE/SETNG mreg8	0Fh	9Eh	11-xxx-xxx	DirectPath
SETLE/SETNG mem8	0Fh	9Eh	mm-xxx-xxx	DirectPath
SETG/SETNLE mreg8	0Fh	9Fh	11-xxx-xxx	DirectPath
SETG/SETNLE mem8	0Fh	9Fh	mm-xxx-xxx	DirectPath
SGDT mem48	0Fh	01h	mm-000-xxx	VectorPath
SIDT mem48	0Fh	01h	mm-001-xxx	VectorPath
SHL/SAL mreg8, imm8	C0h		11-100-xxx	DirectPath
SHL/SAL mem8, imm8	C0h		mm-100-xxx	DirectPath
SHL/SAL mreg16/32, imm8	C1h		11-100-xxx	DirectPath
SHL/SAL mem16/32, imm8	C1h		mm-100-xxx	DirectPath
SHL/SAL mreg8, 1	D0h		11-100-xxx	DirectPath
SHL/SAL mem8, 1	D0h		mm-100-xxx	DirectPath
SHL/SAL mreg16/32, 1	D1h		11-100-xxx	DirectPath
SHL/SAL mem16/32, 1	D1h		mm-100-xxx	DirectPath
SHL/SAL mreg8, CL	D2h		11-100-xxx	DirectPath
SHL/SAL mem8, CL	D2h		mm-100-xxx	DirectPath
SHL/SAL mreg16/32, CL	D3h		11-100-xxx	DirectPath
SHL/SAL mem16/32, CL	D3h		mm-100-xxx	DirectPath
SHR mreg8, imm8	C0h		11-101-xxx	DirectPath
SHR mem8, imm8	C0h		mm-101-xxx	DirectPath
SHR mreg16/32, imm8	C1h		11-101-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
SHR mem16/32, imm8	C1h		mm-101-xxx	DirectPath
SHR mreg8, 1	D0h		11-101-xxx	DirectPath
SHR mem8, 1	D0h		mm-101-xxx	DirectPath
SHR mreg16/32, 1	D1h		11-101-xxx	DirectPath
SHR mem16/32, 1	D1h		mm-101-xxx	DirectPath
SHR mreg8, CL	D2h		11-101-xxx	DirectPath
SHR mem8, CL	D2h		mm-101-xxx	DirectPath
SHR mreg16/32, CL	D3h		11-101-xxx	DirectPath
SHR mem16/32, CL	D3h		mm-101-xxx	DirectPath
SHLD mreg16/32, reg16/32, imm8	0Fh	A4h	11-xxx-xxx	VectorPath
SHLD mem16/32, reg16/32, imm8	0Fh	A4h	mm-xxx-xxx	VectorPath
SHLD mreg16/32, reg16/32, CL	0Fh	A5h	11-xxx-xxx	VectorPath
SHLD mem16/32, reg16/32, CL	0Fh	A5h	mm-xxx-xxx	VectorPath
SHRD mreg16/32, reg16/32, imm8	0Fh	ACh	11-xxx-xxx	VectorPath
SHRD mem16/32, reg16/32, imm8	0Fh	ACh	mm-xxx-xxx	VectorPath
SHRD mreg16/32, reg16/32, CL	0Fh	ADh	11-xxx-xxx	VectorPath
SHRD mem16/32, reg16/32, CL	0Fh	ADh	mm-xxx-xxx	VectorPath
SLDT mreg16	0Fh	00h	11-000-xxx	VectorPath
SLDT mem16	0Fh	00h	mm-000-xxx	VectorPath
SMSW mreg16	0Fh	01h	11-100-xxx	VectorPath
SMSW mem16	0Fh	01h	mm-100-xxx	VectorPath
STC	F9h			DirectPath
STD	FDh			VectorPath
STI	FBh			VectorPath
STOSB mem8, AL	AAh			VectorPath
STOSW mem16, AX	ABh			VectorPath
STOSD mem32, EAX	ABh			VectorPath
STR mreg16	0Fh	00h	11-001-xxx	VectorPath
STR mem16	0Fh	00h	mm-001-xxx	VectorPath
SUB mreg8, reg8	28h		11-xxx-xxx	DirectPath
SUB mem8, reg8	28h		mm-xxx-xxx	DirectPath
SUB mreg16/32, reg16/32	29h		11-xxx-xxx	DirectPath
SUB mem16/32, reg16/32	29h		mm-xxx-xxx	DirectPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
SUB reg8, mreg8	2Ah		11-xxx-xxx	DirectPath
SUB reg8, mem8	2Ah		mm-xxx-xxx	DirectPath
SUB reg16/32, mreg16/32	2Bh		11-xxx-xxx	DirectPath
SUB reg16/32, mem16/32	2Bh		mm-xxx-xxx	DirectPath
SUB AL, imm8	2Ch			DirectPath
SUB EAX, imm16/32	2Dh			DirectPath
SUB mreg8, imm8	80h		11-101-xxx	DirectPath
SUB mem8, imm8	80h		mm-101-xxx	DirectPath
SUB mreg16/32, imm16/32	81h		11-101-xxx	DirectPath
SUB mem16/32, imm16/32	81h		mm-101-xxx	DirectPath
SUB mreg16/32, imm8 (sign extended)	83h		11-101-xxx	DirectPath
SUB mem16/32, imm8 (sign extended)	83h		mm-101-xxx	DirectPath
SYSCALL	0Fh	05h		VectorPath
SYSENTER	0Fh	34h		VectorPath
SYSEXIT	0Fh	35h		VectorPath
SYSRET	0Fh	07h		VectorPath
TEST mreg8, reg8	84h		11-xxx-xxx	DirectPath
TEST mem8, reg8	84h		mm-xxx-xxx	DirectPath
TEST mreg16/32, reg16/32	85h		11-xxx-xxx	DirectPath
TEST mem16/32, reg16/32	85h		mm-xxx-xxx	DirectPath
TEST AL, imm8	A8h			DirectPath
TEST EAX, imm16/32	A9h			DirectPath
TEST mreg8, imm8	F6h		11-000-xxx	DirectPath
TEST mem8, imm8	F6h		mm-000-xxx	DirectPath
TEST mreg8, imm16/32	F7h		11-000-xxx	DirectPath
TEST mem8, imm16/32	F7h		mm-000-xxx	DirectPath
VERR mreg16	0Fh	00h	11-100-xxx	VectorPath
VERR mem16	0Fh	00h	mm-100-xxx	VectorPath
VERW mreg16	0Fh	00h	11-101-xxx	VectorPath
VERW mem16	0Fh	00h	mm-101-xxx	VectorPath
WAIT	9Bh			DirectPath
WBINVD	0Fh	09h		VectorPath
WRMSR	0Fh	30h		VectorPath

Table 19. Integer Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type
XADD mreg8, reg8	0Fh	C0h	11-100-xxx	VectorPath
XADD mem8, reg8	0Fh	C0h	mm-100-xxx	VectorPath
XADD mreg16/32, reg16/32	0Fh	C1h	11-101-xxx	VectorPath
XADD mem16/32, reg16/32	0Fh	C1h	mm-101-xxx	VectorPath
XCHG reg8, mreg8	86h		11-xxx-xxx	VectorPath
XCHG reg8, mem8	86h		mm-xxx-xxx	VectorPath
XCHG reg16/32, mreg16/32	87h		11-xxx-xxx	VectorPath
XCHG reg16/32, mem16/32	87h		mm-xxx-xxx	VectorPath
XCHG EAX, EAX	90h			DirectPath
XCHG EAX, ECX	91h			VectorPath
XCHG EAX, EDX	92h			VectorPath
XCHG EAX, EBX	93h			VectorPath
XCHG EAX, ESP	94h			VectorPath
XCHG EAX, EBP	95h			VectorPath
XCHG EAX, ESI	96h			VectorPath
XCHG EAX, EDI	97h			VectorPath
XLAT	D7h			VectorPath
XOR mreg8, reg8	30h		11-xxx-xxx	DirectPath
XOR mem8, reg8	30h		mm-xxx-xxx	DirectPath
XOR mreg16/32, reg16/32	31h		11-xxx-xxx	DirectPath
XOR mem16/32, reg16/32	31h		mm-xxx-xxx	DirectPath
XOR reg8, mreg8	32h		11-xxx-xxx	DirectPath
XOR reg8, mem8	32h		mm-xxx-xxx	DirectPath
XOR reg16/32, mreg16/32	33h		11-xxx-xxx	DirectPath
XOR reg16/32, mem16/32	33h		mm-xxx-xxx	DirectPath
XOR AL, imm8	34h			DirectPath
XOR EAX, imm16/32	35h			DirectPath
XOR mreg8, imm8	80h		11-110-xxx	DirectPath
XOR mem8, imm8	80h		mm-110-xxx	DirectPath
XOR mreg16/32, imm16/32	81h		11-110-xxx	DirectPath
XOR mem16/32, imm16/32	81h		mm-110-xxx	DirectPath
XOR mreg16/32, imm8 (sign extended)	83h		11-110-xxx	DirectPath
XOR mem16/32, imm8 (sign extended)	83h		mm-110-xxx	DirectPath

Table 20. MMX™ Instructions

Instruction Mnemonic	Prefix Byte(s)	First Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Notes
EMMS	0Fh	77h		DirectPath	FADD/FMUL/FSTORE	
MOVD mmreg, reg32	0Fh	6Eh	11-xxx-xxx	VectorPath		1
MOVD mmreg, mem32	0Fh	6Eh	mm-xxx-xxx	DirectPath	FADD/FMUL/FSTORE	
MOVD reg32, mmreg	0Fh	7Eh	11-xxx-xxx	VectorPath		1
MOVD mem32, mmreg	0Fh	7Eh	mm-xxx-xxx	DirectPath	FSTORE	
MOVQ mmreg1, mmreg2	0Fh	6Fh	11-xxx-xxx	DirectPath	FADD/FMUL	
MOVQ mmreg, mem64	0Fh	6Fh	mm-xxx-xxx	DirectPath	FADD/FMUL/FSTORE	
MOVQ mmreg2, mmreg1	0Fh	7Fh	11-xxx-xxx	DirectPath	FADD/FMUL	
MOVQ mem64, mmreg	0Fh	7Fh	mm-xxx-xxx	DirectPath	FSTORE	
PACKSSDW mmreg1, mmreg2	0Fh	6Bh	11-xxx-xxx	DirectPath	FADD/FMUL	
PACKSSDW mmreg, mem64	0Fh	6Bh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PACKSSWB mmreg1, mmreg2	0Fh	63h	11-xxx-xxx	DirectPath	FADD/FMUL	
PACKSSWB mmreg, mem64	0Fh	63h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PACKUSWB mmreg1, mmreg2	0Fh	67h	11-xxx-xxx	DirectPath	FADD/FMUL	
PACKUSWB mmreg, mem64	0Fh	67h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PADDB mmreg1, mmreg2	0Fh	FCh	11-xxx-xxx	DirectPath	FADD/FMUL	
PADDB mmreg, mem64	0Fh	FCh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PADDD mmreg1, mmreg2	0Fh	FEh	11-xxx-xxx	DirectPath	FADD/FMUL	
PADDD mmreg, mem64	0Fh	FEh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PADDSB mmreg1, mmreg2	0Fh	ECh	11-xxx-xxx	DirectPath	FADD/FMUL	
PADDSB mmreg, mem64	0Fh	ECh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PADDSW mmreg1, mmreg2	0Fh	EDh	11-xxx-xxx	DirectPath	FADD/FMUL	
PADDSW mmreg, mem64	0Fh	EDh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PADDUSB mmreg1, mmreg2	0Fh	DCh	11-xxx-xxx	DirectPath	FADD/FMUL	
PADDUSB mmreg, mem64	0Fh	DCh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PADDUSW mmreg1, mmreg2	0Fh	DDh	11-xxx-xxx	DirectPath	FADD/FMUL	
PADDUSW mmreg, mem64	0Fh	DDh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PADDW mmreg1, mmreg2	0Fh	FDh	11-xxx-xxx	DirectPath	FADD/FMUL	
PADDW mmreg, mem64	0Fh	FDh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PAND mmreg1, mmreg2	0Fh	DBh	11-xxx-xxx	DirectPath	FADD/FMUL	
PAND mmreg, mem64	0Fh	DBh	mm-xxx-xxx	DirectPath	FADD/FMUL	

Notes:

1. Bits 2, 1, and 0 of the modR/M byte select the integer register.

Table 20. MMX™ Instructions (Continued)

Instruction Mnemonic	Prefix Byte(s)	First Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Notes
PANDN mmreg1, mmreg2	0Fh	DFh	11-xxx-xxx	DirectPath	FADD/FMUL	
PANDN mmreg, mem64	0Fh	DFh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PCMPEQB mmreg1, mmreg2	0Fh	74h	11-xxx-xxx	DirectPath	FADD/FMUL	
PCMPEQB mmreg, mem64	0Fh	74h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PCMPEQD mmreg1, mmreg2	0Fh	76h	11-xxx-xxx	DirectPath	FADD/FMUL	
PCMPEQD mmreg, mem64	0Fh	76h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PCMPEQW mmreg1, mmreg2	0Fh	75h	11-xxx-xxx	DirectPath	FADD/FMUL	
PCMPEQW mmreg, mem64	0Fh	75h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PCMPGTB mmreg1, mmreg2	0Fh	64h	11-xxx-xxx	DirectPath	FADD/FMUL	
PCMPGTB mmreg, mem64	0Fh	64h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PCMPGTD mmreg1, mmreg2	0Fh	66h	11-xxx-xxx	DirectPath	FADD/FMUL	
PCMPGTD mmreg, mem64	0Fh	66h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PCMPGTW mmreg1, mmreg2	0Fh	65h	11-xxx-xxx	DirectPath	FADD/FMUL	
PCMPGTW mmreg, mem64	0Fh	65h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PMADDWD mmreg1, mmreg2	0Fh	F5h	11-xxx-xxx	DirectPath	FMUL	
PMADDWD mmreg, mem64	0Fh	F5h	mm-xxx-xxx	DirectPath	FMUL	
PMULHW mmreg1, mmreg2	0Fh	E5h	11-xxx-xxx	DirectPath	FMUL	
PMULHW mmreg, mem64	0Fh	E5h	mm-xxx-xxx	DirectPath	FMUL	
PMULLW mmreg1, mmreg2	0Fh	D5h	11-xxx-xxx	DirectPath	FMUL	
PMULLW mmreg, mem64	0Fh	D5h	mm-xxx-xxx	DirectPath	FMUL	
POR mmreg1, mmreg2	0Fh	EBh	11-xxx-xxx	DirectPath	FADD/FMUL	
POR mmreg, mem64	0Fh	EBh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSLLD mmreg1, mmreg2	0Fh	F2h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSLLD mmreg, mem64	0Fh	F2h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSLLD mmreg, imm8	0Fh	72h	11-110-xxx	DirectPath	FADD/FMUL	
PSLLQ mmreg1, mmreg2	0Fh	F3h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSLLQ mmreg, mem64	0Fh	F3h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSLLQ mmreg, imm8	0Fh	73h	11-110-xxx	DirectPath	FADD/FMUL	
PSLLW mmreg1, mmreg2	0Fh	F1h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSLLW mmreg, mem64	0Fh	F1h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSLLW mmreg, imm8	0Fh	71h	11-110-xxx	DirectPath	FADD/FMUL	
Notes:						
1. Bits 2, 1, and 0 of the modR/M byte select the integer register.						

Table 20. MMX™ Instructions (Continued)

Instruction Mnemonic	Prefix Byte(s)	First Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Notes
PSRAW mmreg1, mmreg2	0Fh	E1h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSRAW mmreg, mem64	0Fh	E1h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSRAW mmreg, imm8	0Fh	71h	11-100-xxx	DirectPath	FADD/FMUL	
PSRAD mmreg1, mmreg2	0Fh	E2h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSRAD mmreg, mem64	0Fh	E2h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSRAD mmreg, imm8	0Fh	72h	11-100-xxx	DirectPath	FADD/FMUL	
PSRLD mmreg1, mmreg2	0Fh	D2h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSRLD mmreg, mem64	0Fh	D2h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSRLD mmreg, imm8	0Fh	72h	11-010-xxx	DirectPath	FADD/FMUL	
PSRLQ mmreg1, mmreg2	0Fh	D3h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSRLQ mmreg, mem64	0Fh	D3h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSRLQ mmreg, imm8	0Fh	73h	11-010-xxx	DirectPath	FADD/FMUL	
PSRLW mmreg1, mmreg2	0Fh	D1h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSRLW mmreg, mem64	0Fh	D1h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSRLW mmreg, imm8	0Fh	71h	11-010-xxx	DirectPath	FADD/FMUL	
PSUBB mmreg1, mmreg2	0Fh	F8h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSUBB mmreg, mem64	0Fh	F8h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSUBD mmreg1, mmreg2	0Fh	FAh	11-xxx-xxx	DirectPath	FADD/FMUL	
PSUBD mmreg, mem64	0Fh	FAh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSUBSB mmreg1, mmreg2	0Fh	E8h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSUBSB mmreg, mem64	0Fh	E8h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSUBSW mmreg1, mmreg2	0Fh	E9h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSUBSW mmreg, mem64	0Fh	E9h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSUBUSB mmreg1, mmreg2	0Fh	D8h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSUBUSB mmreg, mem64	0Fh	D8h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSUBUSW mmreg1, mmreg2	0Fh	D9h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSUBUSW mmreg, mem64	0Fh	D9h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PSUBW mmreg1, mmreg2	0Fh	F9h	11-xxx-xxx	DirectPath	FADD/FMUL	
PSUBW mmreg, mem64	0Fh	F9h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKHBW mmreg1, mmreg2	0Fh	68h	11-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKHBW mmreg, mem64	0Fh	68h	mm-xxx-xxx	DirectPath	FADD/FMUL	

Notes:

- Bits 2, 1, and 0 of the modR/M byte select the integer register.

Table 20. MMX™ Instructions (Continued)

Instruction Mnemonic	Prefix Byte(s)	First Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Notes
PUNPCKHDQ mmreg1, mmreg2	0Fh	6Ah	11-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKHDQ mmreg, mem64	0Fh	6Ah	mm-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKHWD mmreg1, mmreg2	0Fh	69h	11-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKHWD mmreg, mem64	0Fh	69h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKLBW mmreg1, mmreg2	0Fh	60h	11-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKLBW mmreg, mem64	0Fh	60h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKLDQ mmreg1, mmreg2	0Fh	62h	11-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKLDQ mmreg, mem64	0Fh	62h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKLWD mmreg1, mmreg2	0Fh	61h	11-xxx-xxx	DirectPath	FADD/FMUL	
PUNPCKLWD mmreg, mem64	0Fh	61h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PXOR mmreg1, mmreg2	0Fh	EFh	11-xxx-xxx	DirectPath	FADD/FMUL	
PXOR mmreg, mem64	0Fh	EFh	mm-xxx-xxx	DirectPath	FADD/FMUL	

Notes:

1. Bits 2, 1, and 0 of the modR/M byte select the integer register.

Table 21. MMX™ Extensions

Instruction Mnemonic	Prefix Byte(s)	First Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Notes
MASKMOVQ mmreg1, mmreg2	0Fh	F7h		VectorPath	FADD/FMUL/FSTORE	
MOVNTQ mem64, mmreg	0Fh	E7h		DirectPath	FSTORE	
PAVGB mmreg1, mmreg2	0Fh	E0h	11-xxx-xxx	DirectPath	FADD/FMUL	
PAVGB mmreg, mem64	0Fh	E0h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PAVGW mmreg1, mmreg2	0Fh	E3h	11-xxx-xxx	DirectPath	FADD/FMUL	
PAVGW mmreg, mem64	0Fh	E3h	mm-xxx-xxx	DirectPath	FADD/FMUL	
PEXTRW reg32, mmreg, imm8	0Fh	C5h		VectorPath		
PINSRW mmreg, reg32, imm8	0Fh	C4h		VectorPath		
PINSRW mmreg, mem16, imm8	0Fh	C4h		VectorPath		
PMAXSW mmreg1, mmreg2	0Fh	EEh	11-xxx-xxx	DirectPath	FADD/FMUL	
PMAXSW mmreg, mem64	0Fh	EEh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PMAXUB mmreg1, mmreg2	0Fh	DEh	11-xxx-xxx	DirectPath	FADD/FMUL	
PMAXUB mmreg, mem64	0Fh	DEh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PMINSW mmreg1, mmreg2	0Fh	EAh	11-xxx-xxx	DirectPath	FADD/FMUL	

Notes:

1. For the PREFETCHNTA/T0/T1/T2 instructions, the mem8 value refers to an address in the 64-byte line that will be prefetched.

Table 21. MMX™ Extensions (Continued)

Instruction Mnemonic	Prefix Byte(s)	First Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Notes
PMINSW mmreg, mem64	0Fh	EAh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PMINUB mmreg1, mmreg2	0Fh	DAh	11-xxx-xxx	DirectPath	FADD/FMUL	
PMINUB mmreg, mem64	0Fh	DAh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PMOVMKB reg32, mmreg	0Fh	D7h		VectorPath		
PMULHUW mmreg1, mmreg2	0Fh	E4h	11-xxx-xxx	DirectPath	FMUL	
PMULHUW mmreg, mem64	0Fh	E4h	mm-xxx-xxx	DirectPath	FMUL	
PSADBW mmreg1, mmreg2	0Fh	F6h	11-xxx-xxx	DirectPath	FADD	
PSADBW mmreg, mem64	0Fh	F6h	mm-xxx-xxx	DirectPath	FADD	
PSHUFW mmreg1, mmreg2, imm8	0Fh	70h		DirectPath	FADD/FMUL	
PSHUFW mmreg, mem64, imm8	0Fh	70h		DirectPath	FADD/FMUL	
PREFETCHNTA mem8	0Fh	18h		DirectPath	-	1
PREFETCHT0 mem8	0Fh	18h		DirectPath	-	1
PREFETCHT1 mem8	0Fh	18h		DirectPath	-	1
PREFETCHT2 mem8	0Fh	18h		DirectPath	-	1
SFENCE	0Fh	AEh		VectorPath	-	

Notes:
 1. For the PREFETCHNTA/T0/T1/T2 instructions, the mem8 value refers to an address in the 64-byte line that will be prefetched.

Table 22. Floating-Point Instructions

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
F2XM1	D9h	F0h		VectorPath		
FABS	D9h	E1h		DirectPath	FMUL	
FADD ST, ST(i)	D8h		11-000-xxx	DirectPath	FADD	1
FADD [mem32real]	D8h		mm-000-xxx	DirectPath	FADD	
FADD ST(i), ST	DCh		11-000-xxx	DirectPath	FADD	1
FADD [mem64real]	DCh		mm-000-xxx	DirectPath	FADD	
FADDP ST(i), ST	DEh		11-000-xxx	DirectPath	FADD	1
FBLD [mem80]	DFh		mm-100-xxx	VectorPath		
FBSTP [mem80]	DFh		mm-110-xxx	VectorPath		
FCHS	D9h	E0h		DirectPath	FMUL	
FCLEX	DBh	E2h		VectorPath		

Notes:
 1. The last three bits of the modR/M byte select the stack entry ST(i).

Table 22. Floating-Point Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
FCMOVB ST(0), ST(i)	DAh	C0-C7h		VectorPath		
FCMOVE ST(0), ST(i)	DAh	C8-CFh		VectorPath		
FCMOVBE ST(0), ST(i)	DAh	D0-D7h		VectorPath		
FCMOVU ST(0), ST(i)	DAh	D8-DFh		VectorPath		
FCMOVNB ST(0), ST(i)	DBh	C0-C7h		VectorPath		
FCMOVNE ST(0), ST(i)	DBh	C8-CFh		VectorPath		
FCMOVNBE ST(0), ST(i)	DBh	D0-D7h		VectorPath		
FCMOVNU ST(0), ST(i)	DBh	D8-DFh		VectorPath		
FCOM ST(i)	D8h		11-010-xxx	DirectPath	FADD	1
FCOMP ST(i)	D8h		11-011-xxx	DirectPath	FADD	1
FCOM [mem32real]	D8h		mm-010-xxx	DirectPath	FADD	
FCOM [mem64real]	DCh		mm-010-xxx	DirectPath	FADD	
FCOMI ST, ST(i)	DBh	F0-F7h		VectorPath	FADD	
FCOMIP ST, ST(i)	DFh	F0-F7h		VectorPath	FADD	
FCOMP [mem32real]	D8h		mm-011-xxx	DirectPath	FADD	
FCOMP [mem64real]	DCh		mm-011-xxx	DirectPath	FADD	
FCOMPP	DEh	D9h	11-011-001	DirectPath	FADD	
FCOS	D9h	FFh		VectorPath		
FDECSTP	D9h	F6h		DirectPath	FADD/FMUL/FSTORE	
FDIV ST, ST(i)	D8h		11-110-xxx	DirectPath	FMUL	1
FDIV ST(i), ST	DCh		11-111-xxx	DirectPath	FMUL	1
FDIV [mem32real]	D8h		mm-110-xxx	DirectPath	FMUL	
FDIV [mem64real]	DCh		mm-110-xxx	DirectPath	FMUL	
FDIVP ST, ST(i)	DEh		11-111-xxx	DirectPath	FMUL	1
FDIVR ST, ST(i)	D8h		11-110-xxx	DirectPath	FMUL	1
FDIVR ST(i), ST	DCh		11-111-xxx	DirectPath	FMUL	1
FDIVR [mem32real]	D8h		mm-111-xxx	DirectPath	FMUL	
FDIVR [mem64real]	DCh		mm-111-xxx	DirectPath	FMUL	
FDIVRP ST(i), ST	DEh		11-110-xxx	DirectPath	FMUL	1
FFREE ST(i)	DDh		11-000-xxx	DirectPath	FADD/FMUL/FSTORE	1
FFREEP ST(i)	DFh	C0-C7h		DirectPath	FADD/FMUL/FSTORE	1
Notes:						
1. The last three bits of the modR/M byte select the stack entry ST(i).						

Table 22. Floating-Point Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
FIADD [mem32int]	DAh		mm-000-xxx	VectorPath		
FIADD [mem16int]	DEh		mm-000-xxx	VectorPath		
FICOM [mem32int]	DAh		mm-010-xxx	VectorPath		
FICOM [mem16int]	DEh		mm-010-xxx	VectorPath		
FICOMP [mem32int]	DAh		mm-011-xxx	VectorPath		
FICOMP [mem16int]	DEh		mm-011-xxx	VectorPath		
FIDIV [mem32int]	DAh		mm-110-xxx	VectorPath		
FIDIV [mem16int]	DEh		mm-110-xxx	VectorPath		
FIDIVR [mem32int]	DAh		mm-111-xxx	VectorPath		
FIDIVR [mem16int]	DEh		mm-111-xxx	VectorPath		
FILD [mem16int]	DFh		mm-000-xxx	DirectPath	FSTORE	
FILD [mem32int]	DBh		mm-000-xxx	DirectPath	FSTORE	
FILD [mem64int]	DFh		mm-101-xxx	DirectPath	FSTORE	
FIMUL [mem32int]	DAh		mm-001-xxx	VectorPath		
FIMUL [mem16int]	DEh		mm-001-xxx	VectorPath		
FINCSTP	D9h	F7h		DirectPath	FADD/FMUL/FSTORE	
FINIT	DBh	E3h		VectorPath		
FIST [mem16int]	DFh		mm-010-xxx	DirectPath	FSTORE	
FIST [mem32int]	DBh		mm-010-xxx	DirectPath	FSTORE	
FISTP [mem16int]	DFh		mm-011-xxx	DirectPath	FSTORE	
FISTP [mem32int]	DBh		mm-011-xxx	DirectPath	FSTORE	
FISTP [mem64int]	DFh		mm-111-xxx	DirectPath	FSTORE	
FISUB [mem32int]	DAh		mm-100-xxx	VectorPath		
FISUB [mem16int]	DEh		mm-100-xxx	VectorPath		
FISUBR [mem32int]	DAh		mm-101-xxx	VectorPath		
FISUBR [mem16int]	DEh		mm-101-xxx	VectorPath		
FLD ST(i)	D9h		11-000-xxx	DirectPath	FADD/FMUL	1
FLD [mem32real]	D9h		mm-000-xxx	DirectPath	FADD/FMUL/FSTORE	
FLD [mem64real]	DDh		mm-000-xxx	DirectPath	FADD/FMUL/FSTORE	
FLD [mem80real]	DBh		mm-101-xxx	VectorPath		
FLD1	D9h	E8h		DirectPath	FSTORE	
Notes:						
1. The last three bits of the modR/M byte select the stack entry ST(i).						

Table 22. Floating-Point Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
FLDCW [mem16]	D9h		mm-101-xxx	VectorPath		
FLDENV [mem14byte]	D9h		mm-100-xxx	VectorPath		
FLDENV [mem28byte]	D9h		mm-100-xxx	VectorPath		
FLDL2E	D9h	EAh		DirectPath	FSTORE	
FLDL2T	D9h	E9h		DirectPath	FSTORE	
FLDLG2	D9h	ECh		DirectPath	FSTORE	
FLDLN2	D9h	EDh		DirectPath	FSTORE	
FLDPI	D9h	EBh		DirectPath	FSTORE	
FLDZ	D9h	EEh		DirectPath	FSTORE	
FMUL ST, ST(i)	D8h		11-001-xxx	DirectPath	FMUL	1
FMUL ST(i), ST	DCh		11-001-xxx	DirectPath	FMUL	1
FMUL [mem32real]	D8h		mm-001-xxx	DirectPath	FMUL	
FMUL [mem64real]	DCh		mm-001-xxx	DirectPath	FMUL	
FMULP ST, ST(i)	DEh		11-001-xxx	DirectPath	FMUL	1
FNOP	D9h	D0h		DirectPath	FADD/FMUL/FSTORE	
FPTAN	D9h	F2h		VectorPath		
FPATAN	D9h	F3h		VectorPath		
FPREM	D9h	F8h		DirectPath	FMUL	
FPREM1	D9h	F5h		DirectPath	FMUL	
FRNDINT	D9h	FCh		VectorPath		
FRSTOR [mem94byte]	DDh		mm-100-xxx	VectorPath		
FRSTOR [mem108byte]	DDh		mm-100-xxx	VectorPath		
FSAVE [mem94byte]	DDh		mm-110-xxx	VectorPath		
FSAVE [mem108byte]	DDh		mm-110-xxx	VectorPath		
FSCALE	D9h	FDh		VectorPath		
FSIN	D9h	FEh		VectorPath		
FSINCOS	D9h	FBh		VectorPath		
FSQRT	D9h	FAh		DirectPath	FMUL	
FST [mem32real]	D9h		mm-010-xxx	DirectPath	FSTORE	
FST [mem64real]	DDh		mm-010-xxx	DirectPath	FSTORE	
FST ST(i)	DDh		11-010xxx	DirectPath	FADD/FMUL	
Notes:						
1. The last three bits of the modR/M byte select the stack entry ST(i).						

Table 22. Floating-Point Instructions (Continued)

Instruction Mnemonic	First Byte	Second Byte	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
FSTCW [mem16]	D9h		mm-111-xxx	VectorPath		
FSTENV [mem14byte]	D9h		mm-110-xxx	VectorPath		
FSTENV [mem28byte]	D9h		mm-110-xxx	VectorPath		
FSTP [mem32real]	D9h		mm-011-xxx	DirectPath	FADD/FMUL	
FSTP [mem64real]	DDh		mm-011-xxx	DirectPath	FADD/FMUL	
FSTP [mem80real]	D9h		mm-111-xxx	VectorPath		
FSTP ST(i)	DDh		11-011-xxx	DirectPath	FADD/FMUL	
FSTSW AX	DFh	E0h		VectorPath		
FSTSW [mem16]	DDh		mm-111-xxx	VectorPath	FSTORE	
FSUB [mem32real]	D8h		mm-100-xxx	DirectPath	FADD	
FSUB [mem64real]	DCh		mm-100-xxx	DirectPath	FADD	
FSUB ST, ST(i)	D8h		11-100-xxx	DirectPath	FADD	1
FSUB ST(i), ST	DCh		11-101-xxx	DirectPath	FADD	1
FSUBP ST, ST(i)	DEh		11-101-xxx	DirectPath	FADD	1
FSUBR [mem32real]	D8h		mm-101-xxx	DirectPath	FADD	
FSUBR [mem64real]	DCh		mm-101-xxx	DirectPath	FADD	
FSUBR ST, ST(i)	D8h		11-100-xxx	DirectPath	FADD	1
FSUBR ST(i), ST	DCh		11-101-xxx	DirectPath	FADD	1
FSUBRP ST(i), ST	DEh		11-100-xxx	DirectPath	FADD	1
FTST	D9h	E4h		DirectPath	FADD	
FUCOM	DDh		11-100-xxx	DirectPath	FADD	
FUCOMI ST, ST(i)	DB	E8-EFh		VectorPath	FADD	
FUCOMIP ST, ST(i)	DF	E8-EFh		VectorPath	FADD	
FUCOMP	DDh		11-101-xxx	DirectPath	FADD	
FUCOMPP	DAh	E9h		DirectPath	FADD	
FWAIT	9Bh			DirectPath		
FXAM	D9h	E5h		VectorPath		
FXCH	D9h		11-001-xxx	DirectPath	FADD/FMUL/FSTORE	
EXTRACT	D9h	F4h		VectorPath		
FYL2X	D9h	F1h		VectorPath		
FYL2XP1	D9h	F9h		VectorPath		

Notes:

- The last three bits of the modR/M byte select the stack entry ST(i).

Table 23. 3DNow!™ Instructions

Instruction Mnemonic	Prefix Byte(s)	imm8	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
FEMMS	0Fh	0Eh		DirectPath	FADD/FMUL/FSTORE	2
PAVGUSB mmreg1, mmreg2	0Fh, 0Fh	BFh	11-xxx-xxx	DirectPath	FADD/FMUL	
PAVGUSB mmreg, mem64	0Fh, 0Fh	BFh	mm-xxx-xxx	DirectPath	FADD/FMUL	
PF2ID mmreg1, mmreg2	0Fh, 0Fh	1Dh	11-xxx-xxx	DirectPath	FADD	
PF2ID mmreg, mem64	0Fh, 0Fh	1Dh	mm-xxx-xxx	DirectPath	FADD	
PFACC mmreg1, mmreg2	0Fh, 0Fh	AEh	11-xxx-xxx	DirectPath	FADD	
PFACC mmreg, mem64	0Fh, 0Fh	AEh	mm-xxx-xxx	DirectPath	FADD	
PFADD mmreg1, mmreg2	0Fh, 0Fh	9Eh	11-xxx-xxx	DirectPath	FADD	
PFADD mmreg, mem64	0Fh, 0Fh	9Eh	mm-xxx-xxx	DirectPath	FADD	
PFCMPEQ mmreg1, mmreg2	0Fh, 0Fh	B0h	11-xxx-xxx	DirectPath	FADD	
PFCMPEQ mmreg, mem64	0Fh, 0Fh	B0h	mm-xxx-xxx	DirectPath	FADD	
PFCMPGE mmreg1, mmreg2	0Fh, 0Fh	90h	11-xxx-xxx	DirectPath	FADD	
PFCMPGE mmreg, mem64	0Fh, 0Fh	90h	mm-xxx-xxx	DirectPath	FADD	
PFCMPGT mmreg1, mmreg2	0Fh, 0Fh	A0h	11-xxx-xxx	DirectPath	FADD	
PFCMPGT mmreg, mem64	0Fh, 0Fh	A0h	mm-xxx-xxx	DirectPath	FADD	
PFMAX mmreg1, mmreg2	0Fh, 0Fh	A4h	11-xxx-xxx	DirectPath	FADD	
PFMAX mmreg, mem64	0Fh, 0Fh	A4h	mm-xxx-xxx	DirectPath	FADD	
PFMIN mmreg1, mmreg2	0Fh, 0Fh	94h	11-xxx-xxx	DirectPath	FADD	
PFMIN mmreg, mem64	0Fh, 0Fh	94h	mm-xxx-xxx	DirectPath	FADD	
PFMUL mmreg1, mmreg2	0Fh, 0Fh	B4h	11-xxx-xxx	DirectPath	FMUL	
PFMUL mmreg, mem64	0Fh, 0Fh	B4h	mm-xxx-xxx	DirectPath	FMUL	
PFRCP mmreg1, mmreg2	0Fh, 0Fh	96h	11-xxx-xxx	DirectPath	FMUL	
PFRCP mmreg, mem64	0Fh, 0Fh	96h	mm-xxx-xxx	DirectPath	FMUL	
PFRCPIT1 mmreg1, mmreg2	0Fh, 0Fh	A6h	11-xxx-xxx	DirectPath	FMUL	
PFRCPIT1 mmreg, mem64	0Fh, 0Fh	A6h	mm-xxx-xxx	DirectPath	FMUL	
PFRCPIT2 mmreg1, mmreg2	0Fh, 0Fh	B6h	11-xxx-xxx	DirectPath	FMUL	
PFRCPIT2 mmreg, mem64	0Fh, 0Fh	B6h	mm-xxx-xxx	DirectPath	FMUL	
PFRSQIT1 mmreg1, mmreg2	0Fh, 0Fh	A7h	11-xxx-xxx	DirectPath	FMUL	
PFRSQIT1 mmreg, mem64	0Fh, 0Fh	A7h	mm-xxx-xxx	DirectPath	FMUL	
PFRSQRT mmreg1, mmreg2	0Fh, 0Fh	97h	11-xxx-xxx	DirectPath	FMUL	

Notes:

1. For the PREFETCH and PREFETCHW instructions, the mem8 value refers to an address in the 64-byte line that will be prefetched.
2. The byte listed in the column titled 'imm8' is actually the opcode byte.

Table 23. 3DNow!™ Instructions (Continued)

Instruction Mnemonic	Prefix Byte(s)	imm8	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
PFRSqrt mmreg, mem64	0Fh, 0Fh	97h	mm-xxx-xxx	DirectPath	FMUL	
PFSUB mmreg1, mmreg2	0Fh, 0Fh	9Ah	11-xxx-xxx	DirectPath	FADD	
PFSUB mmreg, mem64	0Fh, 0Fh	9Ah	mm-xxx-xxx	DirectPath	FADD	
PFSUBR mmreg1, mmreg2	0Fh, 0Fh	AAh	11-xxx-xxx	DirectPath	FADD	
PFSUBR mmreg, mem64	0Fh, 0Fh	AAh	mm-xxx-xxx	DirectPath	FADD	
PI2FD mmreg1, mmreg2	0Fh, 0Fh	0Dh	11-xxx-xxx	DirectPath	FADD	
PI2FD mmreg, mem64	0Fh, 0Fh	0Dh	mm-xxx-xxx	DirectPath	FADD	
PMULHRW mmreg1, mmreg2	0Fh, 0Fh	B7h	11-xxx-xxx	DirectPath	FMUL	
PMULHRW mmreg1, mem64	0Fh, 0Fh	B7h	mm-xxx-xxx	DirectPath	FMUL	
PREFETCH mem8	0Fh	0Dh	mm-000-xxx	DirectPath	-	1, 2
PREFETCHW mem8	0Fh	0Dh	mm-001-xxx	DirectPath	-	1, 2

Notes:

- For the PREFETCH and PREFETCHW instructions, the mem8 value refers to an address in the 64-byte line that will be prefetched.
- The byte listed in the column titled 'imm8' is actually the opcode byte.

Table 24. 3DNow!™ Extensions

Instruction Mnemonic	Prefix Byte(s)	imm8	ModR/M Byte	Decode Type	FPU Pipe(s)	Note
PF2IW mmreg1, mmreg2	0Fh, 0Fh	1Ch	11-xxx-xxx	DirectPath	FADD	
PF2IW mmreg, mem64	0Fh, 0Fh	1Ch	mm-xxx-xxx	DirectPath	FADD	
PFNACC mmreg1, mmreg2	0Fh, 0Fh	8Ah	11-xxx-xxx	DirectPath	FADD	
PFNACC mmreg, mem64	0Fh, 0Fh	8Ah	mm-xxx-xxx	DirectPath	FADD	
PFPNACC mmreg1, mmreg2	0Fh, 0Fh	8Eh	11-xxx-xxx	DirectPath	FADD	
PFPNACC mmreg, mem64	0Fh, 0Fh	8Eh	mm-xxx-xxx	DirectPath	FADD	
PI2FW mmreg1, mmreg2	0Fh, 0Fh	0Ch	11-xxx-xxx	DirectPath	FADD	
PI2FW mmreg, mem64	0Fh, 0Fh	0Ch	mm-xxx-xxx	DirectPath	FADD	
PSWAPD mmreg1, mmreg2	0Fh, 0Fh	BBh	11-xxx-xxx	DirectPath	FADD/FMUL	
PSWAPD mmreg, mem64	0Fh, 0Fh	BBh	mm-xxx-xxx	DirectPath	FADD/FMUL	

Appendix G

DirectPath versus VectorPath Instructions

Select DirectPath Over VectorPath Instructions

Use **DirectPath** instructions rather than **VectorPath** instructions. DirectPath instructions are optimized for decode and execute efficiently by minimizing the number of operations per x86 instruction, which includes ‘register←register op memory’ as well as ‘register←register op register’ forms of instructions.

DirectPath Instructions

The following tables contain DirectPath instructions, which should be used in the AMD Athlon processor wherever possible:

- Table 25, “DirectPath Integer Instructions,” on page 220
- Table 26, “DirectPath MMX™ Instructions,” on page 227 and Table 27, “DirectPath MMX™ Extensions,” on page 228
- Table 28, “DirectPath Floating-Point Instructions,” on page 229
- All 3DNow! instructions, including the 3DNow! Extensions, are DirectPath and are listed in Table 23, “3DNow!™ Instructions,” on page 217 and Table 24, “3DNow!™ Extensions,” on page 218.

Table 25. DirectPath Integer Instructions

Instruction Mnemonic	Instruction Mnemonic
ADC mreg8, reg8	AND mreg16/32, reg16/32
ADC mem8, reg8	AND mem16/32, reg16/32
ADC mreg16/32, reg16/32	AND reg8, mreg8
ADC mem16/32, reg16/32	AND reg8, mem8
ADC reg8, mreg8	AND reg16/32, mreg16/32
ADC reg8, mem8	AND reg16/32, mem16/32
ADC reg16/32, mreg16/32	AND AL, imm8
ADC reg16/32, mem16/32	AND EAX, imm16/32
ADC AL, imm8	AND mreg8, imm8
ADC EAX, imm16/32	AND mem8, imm8
ADC mreg8, imm8	AND mreg16/32, imm16/32
ADC mem8, imm8	AND mem16/32, imm16/32
ADC mreg16/32, imm16/32	AND mreg16/32, imm8 (sign extended)
ADC mem16/32, imm16/32	AND mem16/32, imm8 (sign extended)
ADC mreg16/32, imm8 (sign extended)	BSWAP EAX
ADC mem16/32, imm8 (sign extended)	BSWAP ECX
ADD mreg8, reg8	BSWAP EDX
ADD mem8, reg8	BSWAP EBX
ADD mreg16/32, reg16/32	BSWAP ESP
ADD mem16/32, reg16/32	BSWAP EBP
ADD reg8, mreg8	BSWAP ESI
ADD reg8, mem8	BSWAP EDI
ADD reg16/32, mreg16/32	BT mreg16/32, reg16/32
ADD reg16/32, mem16/32	BT mreg16/32, imm8
ADD AL, imm8	BT mem16/32, imm8
ADD EAX, imm16/32	CBW/CWDE
ADD mreg8, imm8	CLC
ADD mem8, imm8	CMC
ADD mreg16/32, imm16/32	CMOVA/CMOVBE reg16/32, reg16/32
ADD mem16/32, imm16/32	CMOVA/CMOVBE reg16/32, mem16/32
ADD mreg16/32, imm8 (sign extended)	CMOVAE/CMOVNB/CMOVNC reg16/32, mem16/32
ADD mem16/32, imm8 (sign extended)	CMOVAE/CMOVNB/CMOVNC mem16/32, mem16/32
AND mreg8, reg8	CMOVB/CMOVC/CMOVNAE reg16/32, reg16/32
AND mem8, reg8	CMOVB/CMOVC/CMOVNAE mem16/32, reg16/32

Table 25. DirectPath Integer Instructions (Continued)

Instruction Mnemonic	Instruction Mnemonic
CMOVBE/CMOVNA reg16/32, reg16/32	CMP AL, imm8
CMOVBE/CMOVNA reg16/32, mem16/32	CMP EAX, imm16/32
CMOVE/CMOVZ reg16/32, reg16/32	CMP mreg8, imm8
CMOVE/CMOVZ reg16/32, mem16/32	CMP mem8, imm8
CMOVB/CMOVNB reg16/32, reg16/32	CMP mreg16/32, imm16/32
CMOVB/CMOVNB reg16/32, mem16/32	CMP mem16/32, imm16/32
CMOVGE/CMOVNL reg16/32, reg16/32	CMP mreg16/32, imm8 (sign extended)
CMOVGE/CMOVNL reg16/32, mem16/32	CMP mem16/32, imm8 (sign extended)
CMOVL/CMOVNGE reg16/32, reg16/32	CWD/CDQ
CMOVL/CMOVNGE reg16/32, mem16/32	DEC EAX
CMOVLE/CMOVNG reg16/32, reg16/32	DEC ECX
CMOVLE/CMOVNG reg16/32, mem16/32	DEC EDX
CMOVNE/CMOVNZ reg16/32, reg16/32	DEC EBX
CMOVNE/CMOVNZ reg16/32, mem16/32	DEC ESP
CMOVNO reg16/32, reg16/32	DEC EBP
CMOVNO reg16/32, mem16/32	DEC ESI
CMOVNP/CMOVPO reg16/32, reg16/32	DEC EDI
CMOVNP/CMOVPO reg16/32, mem16/32	DEC mreg8
CMOVNS reg16/32, reg16/32	DEC mem8
CMOVNS reg16/32, mem16/32	DEC mreg16/32
CMOVO reg16/32, reg16/32	DEC mem16/32
CMOVO reg16/32, mem16/32	INC EAX
CMOVP/CMOVPE reg16/32, reg16/32	INC ECX
CMOVP/CMOVPE reg16/32, mem16/32	INC EDX
CMOVS reg16/32, reg16/32	INC EBX
CMOVS reg16/32, mem16/32	INC ESP
CMP mreg8, reg8	INC EBP
CMP mem8, reg8	INC ESI
CMP mreg16/32, reg16/32	INC EDI
CMP mem16/32, reg16/32	INC mreg8
CMP reg8, mreg8	INC mem8
CMP reg8, mem8	INC mreg16/32
CMP reg16/32, mreg16/32	INC mem16/32
CMP reg16/32, mem16/32	JO short disp8

Table 25. DirectPath Integer Instructions (Continued)

Instruction Mnemonic	Instruction Mnemonic
JNO short disp8	JMP near mreg16/32 (indirect)
JB/JNAE short disp8	JMP near mem16/32 (indirect)
JNB/JAE short disp8	LEA reg32, mem16/32
JZ/JE short disp8	MOV mreg8, reg8
JNZ/JNE short disp8	MOV mem8, reg8
JBE/JNA short disp8	MOV mreg16/32, reg16/32
JNBE/JA short disp8	MOV mem16/32, reg16/32
JS short disp8	MOV reg8, mreg8
JNS short disp8	MOV reg8, mem8
JP/JPE short disp8	MOV reg16/32, mreg16/32
JNP/JPO short disp8	MOV reg16/32, mem16/32
JL/JNGE short disp8	MOV AL, mem8
JNL/JGE short disp8	MOV EAX, mem16/32
JLE/JNG short disp8	MOV mem8, AL
JNLE/JG short disp8	MOV mem16/32, EAX
JO near disp16/32	MOV AL, imm8
JNO near disp16/32	MOV CL, imm8
JB/JNAE near disp16/32	MOV DL, imm8
JNB/JAE near disp16/32	MOV BL, imm8
JZ/JE near disp16/32	MOV AH, imm8
JNZ/JNE near disp16/32	MOV CH, imm8
JBE/JNA near disp16/32	MOV DH, imm8
JNBE/JA near disp16/32	MOV BH, imm8
JS near disp16/32	MOV EAX, imm16/32
JNS near disp16/32	MOV ECX, imm16/32
JP/JPE near disp16/32	MOV EDX, imm16/32
JNP/JPO near disp16/32	MOV EBX, imm16/32
JL/JNGE near disp16/32	MOV ESP, imm16/32
JNL/JGE near disp16/32	MOV EBP, imm16/32
JLE/JNG near disp16/32	MOV ESI, imm16/32
JNLE/JG near disp16/32	MOV EDI, imm16/32
JMP near disp16/32 (direct)	MOV mreg8, imm8
JMP far disp32/48 (direct)	MOV mem8, imm8
JMP disp8 (short)	MOV mreg16/32, imm16/32

Table 25. DirectPath Integer Instructions (Continued)

Instruction Mnemonic	Instruction Mnemonic
MOV mem16/32, imm16/32	PUSH EAX
MOVSX reg16/32, mreg8	PUSH ECX
MOVSX reg16/32, mem8	PUSH EDX
MOVSX reg32, mreg16	PUSH EBX
MOVSX reg32, mem16	PUSH ESP
MOVZX reg16/32, mreg8	PUSH EBP
MOVZX reg16/32, mem8	PUSH ESI
MOVZX reg32, mreg16	PUSH EDI
MOVZX reg32, mem16	PUSH imm8
NEG mreg8	PUSH imm16/32
NEG mem8	RCL mreg8, imm8
NEG mreg16/32	RCL mreg16/32, imm8
NEG mem16/32	RCL mreg8, 1
NOP (XCHG EAX, EAX)	RCL mem8, 1
NOT mreg8	RCL mreg16/32, 1
NOT mem8	RCL mem16/32, 1
NOT mreg16/32	RCL mreg8, CL
NOT mem16/32	RCL mreg16/32, CL
OR mreg8, reg8	RCR mreg8, imm8
OR mem8, reg8	RCR mreg16/32, imm8
OR mreg16/32, reg16/32	RCR mreg8, 1
OR mem16/32, reg16/32	RCR mem8, 1
OR reg8, mreg8	RCR mreg16/32, 1
OR reg8, mem8	RCR mem16/32, 1
OR reg16/32, mreg16/32	RCR mreg8, CL
OR reg16/32, mem16/32	RCR mreg16/32, CL
OR AL, imm8	ROL mreg8, imm8
OR EAX, imm16/32	ROL mem8, imm8
OR mreg8, imm8	ROL mreg16/32, imm8
OR mem8, imm8	ROL mem16/32, imm8
OR mreg16/32, imm16/32	ROL mreg8, 1
OR mem16/32, imm16/32	ROL mem8, 1
OR mreg16/32, imm8 (sign extended)	ROL mreg16/32, 1
OR mem16/32, imm8 (sign extended)	ROL mem16/32, 1

Table 25. DirectPath Integer Instructions (Continued)

Instruction Mnemonic
ROL mreg8, CL
ROL mem8, CL
ROL mreg16/32, CL
ROL mem16/32, CL
ROR mreg8, imm8
ROR mem8, imm8
ROR mreg16/32, imm8
ROR mem16/32, imm8
ROR mreg8, 1
ROR mem8, 1
ROR mreg16/32, 1
ROR mem16/32, 1
ROR mreg8, CL
ROR mem8, CL
ROR mreg16/32, CL
ROR mem16/32, CL
SAR mreg8, imm8
SAR mem8, imm8
SAR mreg16/32, imm8
SAR mem16/32, imm8
SAR mreg8, 1
SAR mem8, 1
SAR mreg16/32, 1
SAR mem16/32, 1
SAR mreg8, CL
SAR mem8, CL
SAR mreg16/32, CL
SAR mem16/32, CL
SBB mreg8, reg8
SBB mem8, reg8
SBB mreg16/32, reg16/32
SBB mem16/32, reg16/32
SBB reg8, mreg8
SBB reg8, mem8

Instruction Mnemonic
SBB reg16/32, mreg16/32
SBB reg16/32, mem16/32
SBB AL, imm8
SBB EAX, imm16/32
SBB mreg8, imm8
SBB mem8, imm8
SBB mreg16/32, imm16/32
SBB mem16/32, imm16/32
SBB mreg16/32, imm8 (sign extended)
SBB mem16/32, imm8 (sign extended)
SETO mreg8
SETO mem8
SETNO mreg8
SETNO mem8
SETB/SETC/SETNAE mreg8
SETB/SETC/SETNAE mem8
SETAE/SETNB/SETNC mreg8
SETAE/SETNB/SETNC mem8
SETE/SETZ mreg8
SETE/SETZ mem8
SETNE/SETNZ mreg8
SETNE/SETNZ mem8
SETBE/SETNA mreg8
SETBE/SETNA mem8
SETA/SETNBE mreg8
SETA/SETNBE mem8
SETS mreg8
SETS mem8
SETNS mreg8
SETNS mem8
SETP/SETPE mreg8
SETP/SETPE mem8
SETNP/SETPO mreg8
SETNP/SETPO mem8

Table 25. DirectPath Integer Instructions (Continued)

Instruction Mnemonic	Instruction Mnemonic
SETL/SETNGE mreg8	SUB mem8, reg8
SETL/SETNGE mem8	SUB mreg16/32, reg16/32
SETGE/SETNL mreg8	SUB mem16/32, reg16/32
SETGE/SETNL mem8	SUB reg8, mreg8
SETLE/SETNG mreg8	SUB reg8, mem8
SETLE/SETNG mem8	SUB reg16/32, mreg16/32
SETG/SETNLE mreg8	SUB reg16/32, mem16/32
SETG/SETNLE mem8	SUB AL, imm8
SHL/SAL mreg8, imm8	SUB EAX, imm16/32
SHL/SAL mem8, imm8	SUB mreg8, imm8
SHL/SAL mreg16/32, imm8	SUB mem8, imm8
SHL/SAL mem16/32, imm8	SUB mreg16/32, imm16/32
SHL/SAL mreg8, 1	SUB mem16/32, imm16/32
SHL/SAL mem8, 1	SUB mreg16/32, imm8 (sign extended)
SHL/SAL mreg16/32, 1	SUB mem16/32, imm8 (sign extended)
SHL/SAL mem16/32, 1	TEST mreg8, reg8
SHL/SAL mreg8, CL	TEST mem8, reg8
SHL/SAL mem8, CL	TEST mreg16/32, reg16/32
SHL/SAL mreg16/32, CL	TEST mem16/32, reg16/32
SHL/SAL mem16/32, CL	TEST AL, imm8
SHR mreg8, imm8	TEST EAX, imm16/32
SHR mem8, imm8	TEST mreg8, imm8
SHR mreg16/32, imm8	TEST mem8, imm8
SHR mem16/32, imm8	TEST mreg8, imm16/32
SHR mreg8, 1	TEST mem8, imm16/32
SHR mem8, 1	WAIT
SHR mreg16/32, 1	XCHG EAX, EAX
SHR mem16/32, 1	XOR mreg8, reg8
SHR mreg8, CL	XOR mem8, reg8
SHR mem8, CL	XOR mreg16/32, reg16/32
SHR mreg16/32, CL	XOR mem16/32, reg16/32
SHR mem16/32, CL	XOR reg8, mreg8
STC	XOR reg8, mem8
SUB mreg8, reg8	XOR reg16/32, mreg16/32

Table 25. DirectPath Integer Instructions (Continued)

Instruction Mnemonic
XOR reg16/32, mem16/32
XOR AL, imm8
XOR EAX, imm16/32
XOR mreg8, imm8
XOR mem8, imm8
XOR mreg16/32, imm16/32
XOR mem16/32, imm16/32
XOR mreg16/32, imm8 (sign extended)
XOR mem16/32, imm8 (sign extended)

Table 26. DirectPath MMX™ Instructions

Instruction Mnemonic
EMMS
MOVD mmreg, mem32
MOVD mem32, mmreg
MOVQ mmreg1, mmreg2
MOVQ mmreg, mem64
MOVQ mmreg2, mmreg1
MOVQ mem64, mmreg
PACKSSDW mmreg1, mmreg2
PACKSSDW mmreg, mem64
PACKSSWB mmreg1, mmreg2
PACKSSWB mmreg, mem64
PACKUSWB mmreg1, mmreg2
PACKUSWB mmreg, mem64
PADDB mmreg1, mmreg2
PADDB mmreg, mem64
PADD mmreg1, mmreg2
PADD mmreg, mem64
PADDSB mmreg1, mmreg2
PADDSB mmreg, mem64
PADDSW mmreg1, mmreg2
PADDSW mmreg, mem64
PADDUSB mmreg1, mmreg2
PADDUSB mmreg, mem64
PADDUSW mmreg1, mmreg2
PADDUSW mmreg, mem64
PADDW mmreg1, mmreg2
PADDW mmreg, mem64
PAND mmreg1, mmreg2
PAND mmreg, mem64
PANDN mmreg1, mmreg2
PANDN mmreg, mem64
PCMPEQB mmreg1, mmreg2
PCMPEQB mmreg, mem64
PCMPEQD mmreg1, mmreg2

Instruction Mnemonic
PCMPEQD mmreg, mem64
PCMPEQW mmreg1, mmreg2
PCMPEQW mmreg, mem64
PCMPGTB mmreg1, mmreg2
PCMPGTB mmreg, mem64
PCMPGTD mmreg1, mmreg2
PCMPGTD mmreg, mem64
PCMPGTW mmreg1, mmreg2
PCMPGTW mmreg, mem64
PMADDWD mmreg1, mmreg2
PMADDWD mmreg, mem64
PMULHW mmreg1, mmreg2
PMULHW mmreg, mem64
PMULLW mmreg1, mmreg2
PMULLW mmreg, mem64
POR mmreg1, mmreg2
POR mmreg, mem64
PSLLD mmreg1, mmreg2
PSLLD mmreg, mem64
PSLLD mmreg, imm8
PSLLQ mmreg1, mmreg2
PSLLQ mmreg, mem64
PSLLQ mmreg, imm8
PSLLW mmreg1, mmreg2
PSLLW mmreg, mem64
PSLLW mmreg, imm8
PSRAW mmreg1, mmreg2
PSRAW mmreg, mem64
PSRAW mmreg, imm8
PSRAD mmreg1, mmreg2
PSRAD mmreg, mem64
PSRAD mmreg, imm8
PSRLD mmreg1, mmreg2
PSRLD mmreg, mem64

Table 26. DirectPath MMX™ Instructions (Continued)

Instruction Mnemonic
PSRLD mmreg, imm8
PSRLQ mmreg1, mmreg2
PSRLQ mmreg, mem64
PSRLQ mmreg, imm8
PSRLW mmreg1, mmreg2
PSRLW mmreg, mem64
PSRLW mmreg, imm8
PSUBB mmreg1, mmreg2
PSUBB mmreg, mem64
PSUBD mmreg1, mmreg2
PSUBD mmreg, mem64
PSUBSB mmreg1, mmreg2
PSUBSB mmreg, mem64
PSUBSW mmreg1, mmreg2
PSUBSW mmreg, mem64
PSUBUSB mmreg1, mmreg2
PSUBUSB mmreg, mem64
PSUBUSW mmreg1, mmreg2
PSUBUSW mmreg, mem64
PSUBW mmreg1, mmreg2
PSUBW mmreg, mem64
PUNPCKHBW mmreg1, mmreg2
PUNPCKHBW mmreg, mem64
PUNPCKHDQ mmreg1, mmreg2
PUNPCKHDQ mmreg, mem64
PUNPCKHWD mmreg1, mmreg2
PUNPCKHWD mmreg, mem64
PUNPCKLBW mmreg1, mmreg2
PUNPCKLBW mmreg, mem64
PUNPCKLDQ mmreg1, mmreg2
PUNPCKLDQ mmreg, mem64
PUNPCKLWD mmreg1, mmreg2
PUNPCKLWD mmreg, mem64
PXOR mmreg1, mmreg2

Instruction Mnemonic
PXOR mmreg, mem64

Table 27. DirectPath MMX™ Extensions

Instruction Mnemonic
MOVNTQ mem64, mmreg
PAVGB mmreg1, mmreg2
PAVGB mmreg, mem64
PAVGW mmreg1, mmreg2
PAVGW mmreg, mem64
PMAXSW mmreg1, mmreg2
PMAXSW mmreg, mem64
PMAXUB mmreg1, mmreg2
PMAXUB mmreg, mem64
PMINSW mmreg1, mmreg2
PMINSW mmreg, mem64
PMINUB mmreg1, mmreg2
PMINUB mmreg, mem64
PMULHUW mmreg1, mmreg2
PMULHUW mmreg, mem64
PSADBW mmreg1, mmreg2
PSADBW mmreg, mem64
PSHUFW mmreg1, mmreg2, imm8
PSHUFW mmreg, mem64, imm8
PREFETCHNTA mem8
PREFETCHT0 mem8
PREFETCHT1 mem8
PREFETCHT2 mem8

Table 28. DirectPath Floating-Point Instructions

Instruction Mnemonic
FABS
FADD ST, ST(i)
FADD [mem32real]
FADD ST(i), ST
FADD [mem64real]
FADDP ST(i), ST
FCBS
FCOM ST(i)
FCOMP ST(i)
FCOM [mem32real]
FCOM [mem64real]
FCOMP [mem32real]
FCOMP [mem64real]
FCOMPP
FDECSTP
FDIV ST, ST(i)
FDIV ST(i), ST
FDIV [mem32real]
FDIV [mem64real]
FDIVP ST, ST(i)
FDIVR ST, ST(i)
FDIVR ST(i), ST
FDIVR [mem32real]
FDIVR [mem64real]
FDIVRP ST(i), ST
FFREE ST(i)
FFREEP ST(i)
FILD [mem16int]
FILD [mem32int]
FILD [mem64int]
FIMUL [mem32int]
FIMUL [mem16int]
FINCSTP
FIST [mem16int]

Instruction Mnemonic
FIST [mem32int]
FISTP [mem16int]
FISTP [mem32int]
FISTP [mem64int]
FLD ST(i)
FLD [mem32real]
FLD [mem64real]
FLD [mem80real]
FLD1
FLDL2E
FLDL2T
FLDLG2
FLDLN2
FLDPI
FLDZ
FMUL ST, ST(i)
FMUL ST(i), ST
FMUL [mem32real]
FMUL [mem64real]
FMULP ST, ST(i)
FNOP
FPREM
FPREM1
FSQRT
FST [mem32real]
FST [mem64real]
FST ST(i)
FSTP [mem32real]
FSTP [mem64real]
FSTP [mem80real]
FSTP ST(i)
FSUB [mem32real]
FSUB [mem64real]
FSUB ST, ST(i)

Table 28. DirectPath Floating-Point Instructions

Instruction Mnemonic
FSUB ST(i), ST
FSUBP ST, ST(i)
FSUBR [mem32real]
FSUBR [mem64real]
FSUBR ST, ST(i)
FSUBR ST(i), ST
FSUBRP ST(i), ST
FTST
FUCOM
FUCOMP
FUCOMPP
FWAIT
FXCH

VectorPath Instructions

The following tables contain **VectorPath** instructions, which should be **avoided** in the AMD Athlon processor:

- Table 29, “VectorPath Integer Instructions,” on page 231
- Table 30, “VectorPath MMX™ Instructions,” on page 234 and Table 31, “VectorPath MMX™ Extensions,” on page 234
- Table 32, “VectorPath Floating-Point Instructions,” on page 235

Table 29. VectorPath Integer Instructions

Instruction Mnemonic
AAA
AAD
AAM
AAS
ARPL mreg16, reg16
ARPL mem16, reg16
BOUND
BSF reg16/32, mreg16/32
BSF reg16/32, mem16/32
BSR reg16/32, mreg16/32
BSR reg16/32, mem16/32
BT mem16/32, reg16/32
BTC mreg16/32, reg16/32
BTC mem16/32, reg16/32
BTC mreg16/32, imm8
BTC mem16/32, imm8
BTR mreg16/32, reg16/32
BTR mem16/32, reg16/32
BTR mreg16/32, imm8
BTR mem16/32, imm8
BTS mreg16/32, reg16/32
BTS mem16/32, reg16/32
BTS mreg16/32, imm8

Instruction Mnemonic
BTS mem16/32, imm8
CALL full pointer
CALL near imm16/32
CALL mem16:16/32
CALL near mreg32 (indirect)
CALL near mem32 (indirect)
CLD
CLI
CLTS
CMPSB mem8, mem8
CMP SW mem16, mem32
CMP SD mem32, mem32
CMPXCHG mreg8, reg8
CMPXCHG mem8, reg8
CMPXCHG mreg16/32, reg16/32
CMPXCHG mem16/32, reg16/32
CMPXCHG8B mem64
CPUID
DAA
DAS
DIV AL, mreg8
DIV AL, mem8
DIV EAX, mreg16/32

Table 29. VectorPath Integer Instructions (Continued)

Instruction Mnemonic	Instruction Mnemonic
DIV EAX, mem16/32	LEA reg16, mem16/32
ENTER	LEAVE
IDIV mreg8	LES reg16/32, mem32/48
IDIV mem8	LFS reg16/32, mem32/48
IDIV EAX, mreg16/32	LGDT mem48
IDIV EAX, mem16/32	LGS reg16/32, mem32/48
IMUL reg16/32, imm16/32	LIDT mem48
IMUL reg16/32, mreg16/32, imm16/32	LLDT mreg16
IMUL reg16/32, mem16/32, imm16/32	LLDT mem16
IMUL reg16/32, imm8 (sign extended)	LMSW mreg16
IMUL reg16/32, mreg16/32, imm8 (signed)	LMSW mem16
IMUL reg16/32, mem16/32, imm8 (signed)	LODSB AL, mem8
IMUL AX, AL, mreg8	LODSW AX, mem16
IMUL AX, AL, mem8	LODSD EAX, mem32
IMUL EDX:EAX, EAX, mreg16/32	LOOP disp8
IMUL EDX:EAX, EAX, mem16/32	LOOPE/LOOPZ disp8
IMUL reg16/32, mreg16/32	LOOPNE/LOOPNZ disp8
IMUL reg16/32, mem16/32	LSL reg16/32, mreg16/32
IN AL, imm8	LSL reg16/32, mem16/32
IN AX, imm8	LSS reg16/32, mem32/48
IN EAX, imm8	LTR mreg16
IN AL, DX	LTR mem16
IN AX, DX	MOV mreg16, segment reg
IN EAX, DX	MOV mem16, segment reg
INVD	MOV segment reg, mreg16
INVLPG	MOV segment reg, mem16
JCXZ/JEC short disp8	MOVSB mem8,mem8
JMP far disp32/48 (direct)	MOVSD mem16, mem16
JMP far mem32 (indirect)	MOVSW mem32, mem32
JMP far mreg32 (indirect)	MUL AL, mreg8
LAHF	MUL AL, mem8
LAR reg16/32, mreg16/32	MUL AX, mreg16
LAR reg16/32, mem16/32	MUL AX, mem16
LDS reg16/32, mem32/48	MUL EAX, mreg32

Table 29. VectorPath Integer Instructions (Continued)

Instruction Mnemonic	Instruction Mnemonic
MUL EAX, mem32	RCL mem8, imm8
OUT imm8, AL	RCL mem16/32, imm8
OUT imm8, AX	RCL mem8, CL
OUT imm8, EAX	RCL mem16/32, CL
OUT DX, AL	RCR mem8, imm8
OUT DX, AX	RCR mem16/32, imm8
OUT DX, EAX	RCR mem8, CL
POP ES	RCR mem16/32, CL
POP SS	RDMSR
POP DS	RDPMC
POP FS	RDTSR
POP GS	RET near imm16
POP EAX	RET near
POP ECX	RET far imm16
POP EDX	RET far
POP EBX	SAHF
POP ESP	SCASB AL, mem8
POP EBP	SCASW AX, mem16
POP ESI	SCASD EAX, mem32
POP EDI	SGDT mem48
POP mreg 16/32	SIDT mem48
POP mem 16/32	SHLD mreg16/32, reg16/32, imm8
POPA/POPAD	SHLD mem16/32, reg16/32, imm8
POPF/POPPD	SHLD mreg16/32, reg16/32, CL
PUSH ES	SHLD mem16/32, reg16/32, CL
PUSH CS	SHRD mreg16/32, reg16/32, imm8
PUSH FS	SHRD mem16/32, reg16/32, imm8
PUSH GS	SHRD mreg16/32, reg16/32, CL
PUSH SS	SHRD mem16/32, reg16/32, CL
PUSH DS	SLDT mreg16
PUSH mreg16/32	SLDT mem16
PUSH mem16/32	SMSW mreg16
PUSHA/PUSHAD	SMSW mem16
PUSHF/PUSHFD	STD

Table 29. VectorPath Integer Instructions (Continued)

Instruction Mnemonic
STI
STOSB mem8, AL
STOSW mem16, AX
STOSD mem32, EAX
STR mreg16
STR mem16
SYSCALL
SYSENTER
SYSEXIT
SYSRET
VERR mreg16
VERR mem16
VERW mreg16
VERW mem16
WBINVD
WRMSR
XADD mreg8, reg8
XADD mem8, reg8
XADD mreg16/32, reg16/32
XADD mem16/32, reg16/32
XCHG reg8, mreg8
XCHG reg8, mem8
XCHG reg16/32, mreg16/32
XCHG reg16/32, mem16/32
XCHG EAX, ECX
XCHG EAX, EDX
XCHG EAX, EBX
XCHG EAX, ESP
XCHG EAX, EBP
XCHG EAX, ESI
XCHG EAX, EDI
XLAT

Table 30. VectorPath MMX™ Instructions

Instruction Mnemonic
MOVD mmreg, mreg32
MOVD mreg32, mmreg

Table 31. VectorPath MMX™ Extensions

Instruction Mnemonic
MASKMOVQ mmreg1, mmreg2
PEXTRW reg32, mmreg, imm8
PINSRW mmreg, reg32, imm8
PINSRW mmreg, mem16, imm8
PMOVMKB reg32, mmreg
SFENCE

Table 32. VectorPath Floating-Point Instructions

Instruction Mnemonic
F2XM1
FBLD [mem80]
FBSTP [mem80]
FCLEX
FCMOVB ST(0), ST(i)
FCMOVE ST(0), ST(i)
FCMOVBE ST(0), ST(i)
FCMOVU ST(0), ST(i)
FCMOVNB ST(0), ST(i)
FCMOVNE ST(0), ST(i)
FCMOVNBE ST(0), ST(i)
FCMOVNU ST(0), ST(i)
FCOMI ST, ST(i)
FCOMIP ST, ST(i)
FCOS
FIADD [mem32int]
FIADD [mem16int]
FICOM [mem32int]
FICOM [mem16int]
FICOMP [mem32int]
FICOMP [mem16int]
FIDIV [mem32int]
FIDIV [mem16int]
FIDIVR [mem32int]
FIDIVR [mem16int]
FIMUL [mem32int]
FIMUL [mem16int]
FINIT
FISUB [mem32int]
FISUB [mem16int]
FISUBR [mem32int]
FISUBR [mem16int]
FLD [mem80real]
FLDCW [mem16]

Instruction Mnemonic
FLDENV [mem14byte]
FLDENV [mem28byte]
FPTAN
FPATAN
FRNDINT
FRSTOR [mem94byte]
FRSTOR [mem108byte]
FSAVE [mem94byte]
FSAVE [mem108byte]
FSCALE
FSIN
FSINCOS
FSTCW [mem16]
FSTENV [mem14byte]
FSTENV [mem28byte]
FSTP [mem80real]
FSTSW AX
FSTSW [mem16]
FUCOMI ST, ST(i)
FUCOMIP ST, ST(i)
FXAM
FXTRACT
FYL2X
FYL2XP1

Index

Numerics

3DNow!™ Instructions	10, 107
3DNow! and MMX™ Intra-Operand Swapping	112
Clipping	122
Fast Division	108
Fast Square Root and Reciprocal Square Root	110
FEMMS Instruction	107
PAVGUSB for MPEG-2 Motion Compensation	123
PFCMP Instruction	114
PFMUL Instruction	113–114
PI2FW Instruction	113
PREFETCH and PREFETCHW Instructions	8, 46–47, 49
PSWAPD Instruction	112, 126
Scalar Code Translated into 3DNow! Code	61–64

A

Address Generation Interlocks	72
AMD Athlon™ Processor	
Branch-Free Code	58
Code Padding	40
Family	3
Microarchitecture	4, 129–130
AMD Athlon™ System Bus	139

B

Blended Code, AMD-K6 and AMD Athlon Processors	
3DNow! and MMX Intra-Operand Swapping	112
Block Copies and Block Fills	115
Branch Examples	58
Code Padding	41
Signed Words to Floating-Point Example	113
Branches	
Align Branch Targets	36
Compound Branch Conditions	20
Dependent on Random Data	10, 57
Prediction	132
Replace with Computation in 3DNow! Code	60

C

C Language	13
Array-Style Over Pointer-Style Code	15
C Code to 3DNow! Code Examples	61–64
Structure Component Considerations	27, 55
Cache	4
64-Byte Cache Line	11, 50
Cache and Memory Optimizations	45
CALL and RETURN Instructions	59
Code Padding Using Neutral Code Fillers	39
Code Sample Analysis	152
Complex Number Arithmetic	126
Const Type Qualifier	22
Constant Control Code, Multiple	23

D

Data Cache	134
Decoding	33, 133
Dependencies	128
DirectPath	
Decoder	133
DirectPath Over VectorPath Instructions	9, 34, 219
Instructions	219
Displacements, 8-Bit Sign-Extended	39
Division	77–80, 93, 95
Replace Divides with Multiplies, Integer	31, 77
Using 3DNow! Instructions	108–109
Dynamic Memory Allocation Consideration	25

E

Event and Time-Stamp Monitoring Software	168
Execution Unit Resources	148
Extended-Precision Data	99

F

Far Control Transfer Instructions	65
Fetch and Decode Pipeline Stages	141
FFREEP Macro	98
Floating-Point	
Compare Instructions	98
Divides and Square Roots	29
Execution Unit	137
Optimizations	97
Pipeline Operations	150
Pipeline Stages	146
Scheduler	136
Subexpression Elimination	103
To Integer Conversions	100
Variables and Expressions are Type Float	13
FRNDINT Instruction	100
FSINCOS Instruction	105
FXCH Instruction	99, 103

G

Group I — Essential Optimizations	7–8
Group II — Secondary Optimizations	7, 9

I

If Statement	24
Immediates, 8-Bit Sign-Extended	38
Inline Functions	71, 72, 86
Inline REP String with Low Counts	85

Instruction		MOVZX and MOVSX Instructions	73
Cache	131	MSR Access	177
Control Unit	134	Multiplication	
Decoding	33	Alternative Code When Multiplying by a Constant	81
Dispatch and Execution Resources	187	Matrix	119
Short Forms	127	Multiplies over Divides, Floating Point	97
Short Lengths	36	Muxing Constructs	60
Integer	77		
Arithmetic, 64-Bit	86	N	
Division	31	Newton-Raphson Reciprocal	109
Execution Unit	135	Newton-Raphson Reciprocal Square Root	111
Operand, Consider Sign	14		
Pipeline Operations	149	O	
Pipeline Stages	144	Operands	148
Scheduler	135	Largest Possible Operand Size, Repeated String	84
Use 32-Bit Data Types for Integer Code	13	Optimization Star	8
L		P	
L2 Cache Controller	139	Page Attribute Table (PAT)	171, 177–178
LEA Instruction	38	Parallelism	25
Load/Store Pipeline Operations	151	PerfCtr MSR	167
Load-Execute Instructions	9, 34	PerfEvtSel MSR	162
Floating-Point Instructions	10, 35	Performance-Monitoring Counters	161, 168–169
Integer Instructions	34	Pipeline and Execution Unit Resources Overview	141
Load-Store Unit (LSU)	138	Pointers	
Local Functions	24	De-referenced Arguments	31
Local Variables	28, 31, 56	Use Array-Style Code Instead	15
Loop Instruction	65	Population Count Function	91
Loops		Predecode	132
Deriving Loop Control For Partially Unrolled	70	Prefetch	
Generic Loop Hoisting	22	Determining Distance	49
Minimize Pointer Arithmetic	73	Multiple	47
Partial Loop Unrolling	68	Prototypes	21
REP String with Low Variable Counts	85		
Unroll Small Loops	18	R	
Unrolling Loops	67	Recursive Functions	66
		Register Operands	128
M		Register Reads and Writes, Partial	37
Memory		REP Prefix	40, 84–85
Pushing Memory Data	75		
Size and Alignment Issues	8, 45	S	
Types	174	Scheduling	67
Memory Type Range Register (MTRR)	171	SHLD Instruction	38
Capability Register Format	174	SHR Instruction	38
Default Type Register Format	175	Signed Words to Floating-Point Conversion	113
Extensions	177	Square Root	110
Fixed-Range Register Format	182	Stack	
MSR Format	185	Alignment Considerations	54
MTRRs and PAT	178	Allocation	128
Overlapping	176	Store-to-Load Forwarding	18, 51, 53–54
Variable-Range MTRR Register Format	183	Stream of Packed Unsigned Bytes	125
MMX™ Instructions	107	String Instructions	84
Block Copies and Block Fills	115	Structure (Struct)	27–28, 56
Integer-Only Work	83	Subexpressions, Explicitly Extract Common	26
MOVQ Instruction	85	Superscalar Processor	130
PAND to Find Absolute Value in 3DNow! Code	119	Switch Statement	21, 24
PCMP Instead of 3DNow! PFCMP	114		
PCMPEQD to Set an MMX Register	119		
PMADDWD Instruction	111		
PREFETCHNTA/T0/T1/T2 Instruction	47		
PXOR Instruction	113, 118–119		

T

TBYTE Variables 55
Trigonometric Instructions 103

V

VectorPath Decoder 133
VectorPath Instructions 231

W

Write Combining 10, 50, 139, 155–157, 159

X

x86 Optimization Guidelines 127
XOR Instruction 86

