INTEL® EXTENDED MEMORY 64 TECHNOLOGY (EM64T)

Ramesh Radhakrishnan, PhD., Server and Storage Performance
Jimmy Pike, Director/Distinguished Engineer, Enterprise Architecture
Skipper Smith, Technologist, Client Architecture

Recent industry developments mark a milestone in the evolution of 64-bit computing. 64-bit computing has been around for a long time in mainframe, reduced instruction set computers (RISC), and, more recently, in Intel IA-64 Itanium® architectures. Now, 64-bit computing is being standardized and driven into volume markets by AMD and Intel in processors that are based on the mainstream *x*86 architecture, and by software companies such as Microsoft, Red Hat, SUSE, and Oracle with commercial off-the-shelf software. Both the hardware and software include 64-bit extensions that provide many of the benefits of full 64-bit computing. The new technology allows both 32- and 64-bit applications to run simultaneously on a system with a 64-bit operating system.

This white paper focuses on Intel's 64-bit extensions to the IA-32 platform. Intel announced the new extensions at the spring 2004 Intel Developer Forum (IDF) held in San Francisco. Previously code-named Clackamas Technology (CT), the official name of the new technology is Extended Memory 64 Technology (EM64T). Compatible with the AMD64 platform, EM64T provides an alternative to Intel's high-end 64-bit Itanium architecture. Dell has already introduced its first systems based on the new processor technology—the Dell Precision™ Workstation 470 and 670 and the PowerEdge™ 1800, 1850, 2800, and 2850 servers.

EM64T extends virtual and physical memory addressing[1] beyond the 4-GB limit of current IA-32 architectures. Drivers, operating systems, and applications must be appropriately changed to take advantage of the EM64T architecture. EM64T also adds enhanced Streaming SIMD Extensions (SSE) instructions and general-purpose registers. These new capabilities can improve performance on applications that can take advantage of the additional memory addressing or the larger 64-bit integers. They can also enable new functionality as applications are ported to take advantage of the new features. EM64T appeared first in the Xeon™ processor code-named "Nocona" and P4 processor code-named "Prescott." The new technology is expected to appear later in the Xeon MP processor code-named "Cranford," followed by the "Potomac" processor.

This white paper describes the characteristics and advantages of 64-bit computing. The paper then discusses the main features of EM64T, briefly compares it to the Intel Itanium architecture, and presents the operating system and chip set support required for EM64T. The paper closes with the impact of EM64T on Dell™ server and workstation products.

What is 64-bit Computing?

In part, the terms, "64-bit" and "32-bit," refer to the number of bits that each of a processor's general-purpose registers (GPRs) can hold. The term, "64-bit processor," is used to indicate a processor whose register width is 64 bits. Along the same lines, a "64-bit instruction" is an instruction that operates on 64-bit data. When applied to a microprocessor, the bits characterize the processor's data stream. Simply put, a 64-bit processor has 64-bit register widths and can perform operations on 64 bits of data at a time.

Two data types that are generally stored in GPRs are integer data and address data (or memory pointers). In addition, Intel IA-32 processors support floating-point and multimedia data (MMX, SSE, or SSE2 instructions). Each of these data types has its own set of registers and execution units. Table 1 compares the four data types in Intel's 32-bit and 64-bit *x*86 processors. The table shows that these processors differ in the integer and address hardware. The floating-point and multimedia register widths do not change. The potential perfor-

---

1. Virtual memory addresses are used by software and operating systems. Physical memory addresses are used by physical memory. The two addressing schemes are mapped to each other by the processor's memory management unit (MMU).

Data Type/Characteristic	Integer	Pointer	Floating Point	Multimedia
Register	GPR	GPR	Floating point register (FPR)	Multimedia Extensions (MMX)/Extended Multimedia (XMM)
Execution unit	Arithmetic logic unit (ALU)	ALU/Address generation unit (AGU)	Floating point unit (FPU)	FPU
Width (32-bit system)	32	32	64 (80)*	64/128
Width (64-bit system)	64	64	64 (80)*	64/128

*The x86 processor uses 80-bit registers to do double-precision floating-point operations. The floating-point operations are 64-bit, but the processor converts them to an internal, 80-bit format for increased precision when doing computations. Single-precision operations use 64 bits of the floating-point registers.

Table 1. Comparison of Intel 32- and 64-bit _x_86 Processors

mance benefits of 64-bit computing are, therefore, tied mainly to the integer and memory addressing components of an application.

Advantages of 64-Bit Computing

There are two main advantages of 64-bit computing:

- Higher range of integer values
- Larger memory support

Higher Range of Integer Values

A wider integer provides an increased range or representation of integer values. The general formula used to compute the number of integers that can be represented with an _n_-digit number is:

Range = 2^n, where _n_ is the number of bits or digits

Using this formula, a 32-bit integer can express 2^{32} or 4 GB of possible values and a 64-bit integer can express 2^{64} or 16 exabytes of possible values.

Applications that rely on 64-bit integers may gain a performance increase on 64-bit hardware that is due solely to the wider registers and increased range. Scientific computing and simulations applications that compute 64-bit or larger integer results will require fewer calculations to generate their results. Cryptography applications will also benefit from 64-bit integers, because decryption algorithms can take advantage of the 64-bit registers to process twice as much data simultaneously as is possible with 32-bit registers.

Larger Memory Support

Another advantage that 64-bit systems offer is 64-bit memory addressing. Because memory addresses are integers, an ALU and register combination that can han-

dle more possible integer values can handle many more addresses. Therefore, a 32-bit processor can address no more than 4 GB of memory (2^{32} bytes), while a 64-bit architecture can theoretically address up to 16 exabytes of memory (2^{64} bytes).

The actual size of the virtual and physical address spaces that a 64-bit architecture supports depends on the processor implementation. For example, in the initial EM64T processor implementations—Nocona and Prescott—the virtual address space is 48 bits and the physical address space is 36 bits.

Legacy PAE Mode

Current IA-32 systems that use more than 4 GB of physical memory do so by using Physical Addressing Extensions (PAE). This is a segmented memory model that requires the use of Address Windowing Extensions (AWE) to manipulate data above the 4-GB limit. This approach has associated overhead because the memory beyond 4 GB is swapped in and out of an AWE "window," which exists in the first 4 GB of memory. Such software memory management schemes are expensive and are not as straightforward as 64-bit addressing.

The ability to address more than 4 GB of virtual memory can improve the performance of database server workloads by allowing larger portions of the databases to be cached in memory. On workstation and server platforms, simulation and CAD/CAM applications that work with large data sets could also benefit from the additional memory.

What is EM64T?

EM64T is an enhancement to Intel's IA-32 architecture that allows the processor to run 64-bit code that has been compiled for the EM64T architecture, access larger amounts of memory, and take advantage of an increased range of integer values. These capabilities require driver and chip set support, as well as a 64-bit

operating system. The new EM64T technology consists of the following features:

- **Extended memory addressing using 64-bit registers and memory pointers.** A new 64-bit instruction pointer register is added that allows for 64-bit memory addressing. However, the size of virtual and physical address spaces is processor-specific as summarized in Table 2.

Processor	Virtual Address Space	Physical Address Space	Physical Memory Support
Prescott (P4)	48-bit	36-bit*	64 GB
Nocona (Xeon)	48-bit	36-bit*	64 GB
Cranford (Xeon MP)	48-bit	Not available	Not available
Potomac (Xeon MP)	48-bit	Not available	Not available

*This is the physical address space supported by the processor. The accompanying chip set governs the actual physical address space supported in a particular processor/chip set implementation. See "Chip Set Support" for more information.

Table 2. Address Space for Intel EM64T Processors

- **Enhanced SSE and GPRs.** EM64T extends all GPRs to 64 bits and adds eight new 64-bit GPRs (R8-R15) for integer operations. EM64T also adds eight new 128-bit SSE registers (XMM8-XMM15) for multimedia support.

EM64T Legacy and 64-bit Modes

Support for 64-bit extensions is controlled by bit 10 in the "extended feature enable register" (IA32_EFER) of the EM64T processor. Bit 10 is called "IA-32e mode active" or "long mode active" (LMA). When LMA = 0, the processor operates in "legacy mode" as a standard Intel 32-bit (IA-32) processor.

When LMA = 1, the processor operates in "IA-32e mode," which enables EM64T. To run in this mode, a system requires a 64-bit operating system and 64-bit EM64T device drivers. Applications can be run on this platform in compatibility mode or 64-bit mode. In compatibility mode, existing 16- and 32-bit applications can run natively on a 64-bit operating system that supports 16- and 32-bit applications. Virtual address space in this mode is limited to 4 GB.

In contrast, applications that have been recompiled for the EM64T architecture run in 64-bit mode. These appli-

cations can take advantage of 64-bit memory addressing, additional general-purpose and multimedia registers, and increased GPR widths. Both 32- and 64-bit applications can run simultaneously on the EM64T processor. Table 3 summarizes these modes.

Mode		IA-32e Mode		Legacy Mode
		64-bit	Compatibility	
Default Sizes	Address	64	32/16	32/16
	Operand	32	32/16	32/16
GPR width		64	32	32
Operating system required		64	64	32/16
Application recompile required?		Yes	No	No

Table 3. EM64T Legacy and 64-bit Modes

Intel EM64T vs. Itanium

The 64-bit Intel IA-64 processor family provides *x*86 compatibility using hardware support or software emulation. In contrast, EM64T is a true *x*86 processor that includes 64-bit addressing through register extensions. Itanium 2 is the current IA-64 processor implementation.

The following are some key differences between EM64T and Itanium 2 processors:

- EM64T is an extension of the *x*86 architecture, while IA-64 is completely different architecture.
- EM64T provides full 32-bit native support in hardware. In contrast, Itanium 2 uses software emulation to run IA-32 software.
- Itanium 2 supports larger cache sizes and wider system buses for more scalable systems.

The Itanium 2 processor is based on the Explicitly Parallel Instruction Computing (EPIC) model and supports high-instruction parallelism, large memory addressing, and excellent floating-point performance. A large number of execution registers allow the compiler to schedule code for parallel execution of up to six instructions in a single clock cycle. Itanium 2 processors are designed for applications that are floating-point intensive and/or require large physical memory support.

EM64T processors are based on the Intel NetBurst® microarchitecture introduced with the Pentium® 4 processor. The Intel NetBurst microarchitecture includes an execution trace cache and out-of-order core that processes simplified micro-operations generated by the

decode unit. Current EM64T processors include Intel's Hyper-Threading Technology that allows one physical processor to appear as two logical processors to the operating system.

Table 4 compares key Intel Itanium 2 and EM64T processor characteristics. Intel presents a detailed explanation of the positioning of the two platforms at **ftp://download.intel.com/technology/64bitextensions/ 4071_Intel_Xeon_rev3.pdf.**

	Intel Itanium 2	EM64T (Prescott/Nocona)
Architecture	In-order EPIC	Out-of-order execution engine
Frequency	1-1.5 GHz	> 3.0 GHz
Pipeline stages	8	31
Issue/retire	6 instructions per cycle	6 instructions per cycle
Register set	128 GPRs, 128 FPRs, 8 branch registers	16 GPRs and 16 SSE registers
Caches		
L1 - instruction	16 KB	12 KB trace cache
L1 - data	16 KB	16 KB
L2	256 KB	1 MB
L3	1.5, 3, 4, and 6 MB	Not applicable
Physical addressing	Up to 1,000 terabytes	Up to 64 GB

Table 4. High-Level Comparison of Intel IA-64 and EM64T Processors

Chip Set Support

Chip set support is required to take full advantage of the increased virtual address space of the EM64T processor. This additional virtual address space has immediate advantages for server and workstation systems based on the Nocona (Xeon) and Cranford (Xeon MP) processors. The Intel chip sets that accompany these processors will have native support for physical memory addressing beyond 4 GB. For these systems, EM64T offers a potential performance advantage over the legacy PAE mode currently used to address more than 4 GB of physical memory.

In contrast, the initial chip sets that accompany the Prescott (Pentium 4) processor do not support physical memory addressing beyond 4 GB. As a result, the Prescott processor's increased virtual memory space will have limited value until accompanying chip sets support additional physical memory space.

- **Multiprocessor server** — The Cranford and Potomac (Xeon MP) processors will be paired with the chip set code-named "Twin Castle." The physical address space supported by these processors and the Twin Castle chip set has not been released.
- **Dual-processor servers and workstations** — The Intel chip sets code-named "Lindenhurst" and "Tumwater" are paired with the Nocona (Xeon) processor. All three support a physical address space of 36 bits.
- **Single-processor servers and workstations** — The Prescott (Pentium 4) processor is paired with Intel chip sets code-named "Alderwood" and "Copper River." While Prescott supports a 36-bit physical address space, the Alderwood and Copper River chip sets support 32 bits of physical address space or up to 4 GB of physical memory addressing.

The actual amount of physical memory supported by a particular platform is governed by additional factors such as chip set support, chassis size, memory interface used (DDR1, DDR2, and so forth), and available memory modules.

Software Requirements

To run an EM64T-capable server or client system in full 64-bit IA-32e mode, the entire software stack—including the operating system, drivers, and applications—must be written for EM64T. Today, Red Hat® Linux is the primary operating system available for EM64T systems. SUSE Linux and Microsoft server and client operating systems that support EM64T will be available later. Software compiled for the Intel IA-64 (Itanium) architecture will not run on EM64T systems.

Operating System and Application Support

When paired with a 64-bit operating system and application that has been rewritten or recompiled for EM64T, Intel's EM64T processors provide opportunities for performance gains on Dell workstation and server platforms. Microsoft and SUSE have announced plans for, and Red Hat has released, operating systems with support for 64-bit extensions.

- Microsoft® Windows® Server 2003 for 64-Bit Extended Systems and Windows XP 64-Bit Edition for 64-Bit Extended Systems are scheduled for release in the first half of 2005. Beta versions of these operating systems can be downloaded at **http://www.microsoft.com/windowsserver2003/64bit/ default.mspx**. The 32-bit versions of Microsoft operating systems will run on EM64T processors in legacy mode.
- SUSE Linux supports EM64T in SUSE Linux Enterprise Server 9. The beta version is currently available and the final version is expected in the second half of this year.
- Red Hat has released Red Hat Enterprise Linux 3, update 2.

Driver and application support will be somewhat limited in 2004. Most drivers for Windows 2003 for 64-Bit Extended Systems will be available when the operating system is released. Windows XP 64-Bit Edition for 64-Bit Extended Systems drivers will follow the release of the operating system. Pervasive support for EM64T is expected by the release of Microsoft's next major operating system, code-named "Longhorn."

Impact on Dell Precision Workstations and Servers

The 64-bit extensions appeared first in the Nocona (Xeon) and Prescott (P4) processors used in Dell server and workstation platforms. Single- and dual-processor Dell PowerEdge server and Precision Workstation platforms released in mid-2004 use these processors. EM64T will appear next in Cranford (Xeon MP) processors in 2005. Dell will release four-way PowerEdge servers with Cranford processors.

Intel plans to incorporate this technology on future desktop and mobile platforms, based on customer demand and software availability. For more information on EM64T, see **www.intel.com/technology/64bitextensions.**