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BACKGROUNDER

INTEL MULTI-CORE PROCESSOR ARCHITECTURE DEVELOPMENT

A New Path Toward an Enhanced User Experience, Better Platform Efficiency

In the October 1989 issue of IEEE Spectrum, an article titled "Microprocessors Circa 2000" predicted that multi-core processors could come to market soon after the turn of the century. The paper was the work of four Intel Corporation technologists — including Pat Gelsinger, vice president and general manager of the Digital Enterprise Group, who envisioned the future through the lens of Moore's Law.

Fifteen years later, their predictions are proving true, and multi-core processor and platform capability development has become one of Intel's top business and product initiatives.

Intel continues to focus its near- and long-term efforts on enhancing the overall computing platform to deliver greater value and functionality to PC users. Three years ago Intel sharpened its continued focus on platform-level improvements and began providing fundamental technologies and features in a move to bring more benefits to users. Intel's vision of a balanced platform is moving beyond gigahertz (GHz) and expanding the company's focus on the fundamental technologies and features for delivering greater value and functionality. Intel has realigned its strategy and moved resources away from pure GHz-oriented projects, to shift to platforms with multi-core architectures. Intel also continued to invest in its manufacturing capacity during the 2000 economic downturn to ensure that it has the capacity to deliver processors, including multi-core processors, in high volume and at affordable price points.

Multi-core processor capability is central to Intel's platform-centric approach. By enabling enhanced performance, reduced power consumption and more efficient simultaneous processing of multiple tasks, multi-core processors promise to improve the user experience in home and business environments.

Understanding Multi-Core Processor Architecture

Explained most simply, multi-core processor architecture entails silicon design engineers placing two or more Intel processor "execution cores," or computational engines, within a single processor. This multi-core processor plugs directly into a single processor socket, but the operating system perceives each of its execution cores as a discrete logical processor, with all the associated execution resources.

The idea behind this implementation of the chip's internal architecture is in essence a "divide and conquer" strategy. In other words, by divvying up the computational work performed by the single processor execution core in traditional microprocessors and spreading it over multiple processor execution cores, a multi-core processor can perform more work within a given clock cycle. Thus, it is designed to deliver a better overall user experience. To enable this improvement, the software running on the platform must be written such that it can spread its workload across multiple execution cores. This functionality is called thread-level parallelism or "threading," and applications and operating systems (such as Microsoft Windows* XP) that are written to support it are referred to as "threaded" or "multi-threaded."

A processor equipped with hardware thread-level parallelism can execute completely separate threads of code simultaneously. This can mean one thread running from an application and a second thread running from an operating system, or parallel threads running from within a single application. (Multimedia applications are especially conducive to thread-level parallelism because many of their operations can run in parallel.)

As software developers continue to design more threaded applications that capitalize on this architecture, multi-core processors can be expected to provide new and innovative benefits for PC users, at home and at work. Multi-core capability can also enhance the user experience in multitasking environments, namely, where a number of foreground applications run concurrently with a number of background applications such as virus protection and security, wireless, management, compression, encryption and synchronization.

Like other hardware-enhanced threaded capabilities advanced at Intel, multi-core capability reflects a shift to parallel processing — a concept originally conceived in the supercomputing world. For example, Hyper-Threading (HT) Technology, introduced by Intel in 2002 enables processors to execute tasks in parallel by weaving together multiple "threads" in a single-core processor. But whereas HT Technology is limited to a single core's using existing

execution resources more efficiently to better enable threading, multi-core capability provides two or more complete sets of execution resources to increase overall compute throughput.

In a technical nutshell, Intel believes multi-core processing will support several key capabilities that can enhance the user experience, including the number of PC tasks a user can do at one time, and the ability to do multiple bandwidth-intensive activities and increase the number of users utilizing the same PC at the same time.

Benefits Spanning the Digital Home and the Enterprise

Intel expects most applications that benefit from being threaded today will show excellent performance scalability when running on a multi-core processor. Software in this category includes multimedia applications (namely content creation, editing and local and streaming playback), scientific applications and CAD/CAM packages.

On the multitasking side, the performance boost of multi-core processing can improve PC responsiveness in any environment where users are actively working in two or more applications, or when background processes "compete" with each other and with multiple 'foreground' user applications.

In a 2002 Intel-sponsored Harris Interactive survey, 76 percent of computer users said they multitask at least occasionally or frequently on the PC, and nine out of 10 users reported that they've experienced problems while trying to perform multiple processor-intensive tasks on a PC. Problems include computer freezes, time lags, function shut-downs, choppy screens and audio distortion. Nearly 60 percent of survey respondents said they feel bored when a computer function makes them wait, so they do something else on the computer at the same time.

A multitasking scenario can be as simple as a home user photo editing while recording a TV show through a digital video recorder. In a business setting, a user can browse the Internet while downloading a large software program as the system also runs a virus software application in the background.

A Long-Term Strategy Within Intel

Intel has a long history with the concept of parallelism and the development of hardware-enhanced threading capabilities with some of the more public discussions initially taking place in the 1989 paper authored by Intel architects Gelsinger, Dr. Paolo Gargini, Gerhard Parker and Albert Yu [www.intel.com/research/silicon/ieee/circa2000.pdf]. Although Intel's research in this

arena began earlier, the paper's publication marked the first time that Intel discussed the concept of more mainstream multi-core processors publicly.

Today, Intel has been delivering threading-capable products for more than a decade. By 1994, the Intel Pentium processor already featured instruction-level parallelism, an architectural feature whereby the instructions in a single thread of code are extracted, executed in parallel and then recombined in the same order. That same year, Intel added "glue-less" dual-processing capability — two full processors that plugged into two board sockets — to provide a hardware enhanced threaded environment for servers and workstations. The company expanded its efforts in 1995, providing "glue-less" multi-processing capability with the introduction of the Intel Pentium Pro processor. The Intel Pentium Pro processor enabled the seamless connection of as many as four processors on a single board, providing servers and workstation-class products with the means to attain higher compute throughput in threaded software environments.

These efforts provided a springboard for delivering higher degrees of thread-level parallelism in a single processor on the volume mainstream platforms. Early in the 2000 decade, Intel introduced HT Technology into its Intel NetBurst® micro-architecture (for Intel Pentium 4 and Intel Xeon™ processors) as an innovative means to deliver higher thread-level parallelism on volume implementations.

Intel recognized that HT Technology would naturally lead to higher degrees of parallelism with multi-core products. And although the 1989 predictions of Intel's current CTO Gelsinger were slightly off the mark, multi-core Intel processors will become reality in 2005.

Intel's development of threaded technologies, including multi-core capability, has also been guided by Moore's Law. Proposed by Intel founder Gordon Moore in 1965, the law has been inaccurately paraphrased in various ways for over 40 years, but essentially it predicts that about every 18 to 24 months, semiconductor manufacturers will have twice the number of transistors at their disposal. Intel continues to innovate around and drive Moore's Law with 18 to 24-month cycles, and plans to keep doing so by focusing on "balanced platforms" that move beyond the traditional megahertz and gigahertz and towards features delivering greater end user value.

The "Balanced Platform" Imperative

Intel has long been committed to enhancing the user experience by advancing the compute platform. Although improvements such as hardware-enhanced threading are extremely important to this objective, Intel has sharpened its continued focus on delivering platform-level

features and capabilities that will help the company offer an optimal solution to PC users. Intel calls this a "balanced platform." In a balanced platform, all elements are enhanced in concert, and the integrated features and capabilities help contribute to a more ideal user experience.

Intel has focused on moving the platform forward for well over a decade. Examples include its leadership in the development of the PCI specification and its volume chipset implementation of PCI in the early to mid 1990s. Over the past 10 years, Intel has continued to drive key advancements into the platform, most recently with Intel® Centrino™ Mobile Technology, announced in 2003 as the company's first set of integrated computing technologies for wireless laptops; and new in 2004, the Intel 915 Express desktop chipset, which includes innovations such as better audio and graphics and higher-bandwidth (DDR-2) memory, PCI Express* and RAID (Redundant array of independent disks).

Intel® Extended Memory 64 Technology (EM64T), which enables 64-bit computing, is shipping today for server, workstations and desktop clients. Intel expects to deliver several new platform-based technologies within the next several years. For example, a set of hardware components, codenamed "LaGrande Technology," is being developed to enhance the PC's security capabilities. Intel also plans to provide hardware based virtualization technology, called Intel Virtualization Technology (formerly codenamed "Vanderpool Technology") that will enable computers to run multiple operating environments simultaneously to potentially significantly improve system reliability, flexibility, responsiveness and efficiency.

Intel believes that these and other technology building blocks, in combination with multi-core processing, will enable many novel usage models and new user experiences in server, desktop and mobile computing environments.

Leading the Way to Multi-Core Platforms

The two key requirements for successfully delivering multi-core processing capability to a wide industry are process technology and the ability to architect and deliver multi-core processors in a die size that can be manufactured in volume.

Intel brings unique assets to the table in this regard: second-to-none process technology and the capacity to drive — in this initial instance — dual-core processor manufacturing in volume throughout each of its product segments. Intel forecasts that more than 85 percent of its server processors and more than 70 percent of its mobile and desktop Pentium family processors shipments will be dual-core-based exiting 2006.

Intel's strategic decision to invest $28 billion in R&D and new capacity between 2001 and 2003 helps make this goal achievable. As Intel moves from one execution core per product to two or more execution cores per product, advantages such as 300mm wafers, 90nm and 65nm process technology and a large number of fabrication facilities are sure to prove the investment worthwhile.

With its heightened manufacturing capability, Intel is in an ideal position to produce a variety of processors for a wide range of customer needs. The company today has four 300mm factories in operation and a fifth in progress.

However, the requirements for successfully delivering hardware-enhanced threading and multi-core processing capability go beyond critical silicon manufacturing capacity and technology. The promise of a better user experience also depends on software as well. With this in mind, Intel has been working with operating system and application vendors over the course of the past decade to optimize and enhance the threading capabilities of their software. This effort began in the server and workstation arena and then broadened to include desktop systems in the late 1990s, in anticipation of Hyper-Threading Technology on the desktop in 2002.

HT Technology, which as of September 2004 had shipped on more than 50 million Intel Pentium 4 products for desktops, servers and mobile PCs, offers new incentive for software developers to design applications capable of processing information in parallel for greater efficiency. To date, more than 150 client applications have been enabled for HT Technology, on top of the many hundreds of applications that have previously been threaded. These numbers continue to grow and demonstrate that many developers and design tools are already in place to capitalize on Intel multi-core capability.

Intel also recognizes that operating systems such as Windows XP*, Windows Server*, various Linux vendor offerings, and others are already threaded to take advantage of HT and multi-core technologies. In addition, Intel has strongly advocated that software vendors license their offerings based on socket, not the number of execution cores. Intel applauds Microsoft's recent announcement that it will license operating systems on a per-socket basis versus a per-core basis and hopes other industry vendors will follow suit.

Today, multiple groups at Intel are coming together to drive the multi-core initiative forward. Foremost among them is Intel's Software and Solutions Group (SSG), a large worldwide organization that works with third-party software and solution developers to help their designs get the full performance benefit of Intel architectures and ultimately deliver greater

value to end users. SSG has had a Threading Enabling Program in place since well before the introduction of Hyper-Threading Technology. This ongoing program provides software developers with access to HT Technology and dual core Intel-based development platforms. SSG also offers a robust set of threading tools, compilers and other performance-tuning tool kits and white papers that help enable software developers to implement thread-level parallelism enhancements within their code. Intel has also invested heavily in Intel Solution Centers — worldwide centers of expertise where application vendors can work on site to further optimize their offerings for the latest Intel technologies, including hardware-enhanced threading.

Other groups working inside Intel to advance the multi-core business initiative include the Solutions Development Marketing Group (SMDG), which focuses on bringing to market enterprise business solutions based on Intel Architecture; and Intel Capital, Intel's strategic investment program which invests in companies whose products and services supplement Intel's own product line and capabilities.

Intel's Roadmap for Multi-Core Processors

Intel is deploying multi-core processors across key product lines as a pivotal piece of its platform focus. Production of dual-core products for mobile, desktop and server platforms is scheduled to begin in 2005.

Intel's first dual-core processors for desktop platforms -- the Intel Pentium Processor Extreme Edition 840 and the Intel Pentium D processor (previously codenamed "Smithfield") are both slated to debut in of the second quarter of 2005. Intel plans to deliver additional dual-core desktop processors based on its 65nm process technology in 2006.

Initial plans for the server arena include shipping a dual-core Intel Itanium processor, codenamed "Montecito" and based on 90nm process technology, in the second half of 2005. In addition to its dual-core design, the next-generation "Montecito" chip will boast more than 1.7 billion transistors and a 24MB cache. In the first quarter of 2006, Intel intends to deliver two optimized Intel Xeon™ dual-core processors with Intel® EM64T designed for dual-processor and multi-processor platforms.

Intel expects to begin revenue shipments of its first mobile dual-core processor, code-named "Yonah," in 2005 and go into volume production in 2006. Based on a mobile-optimized microarchitecture and 65nm process technology, "Yonah" is designed to provide power management capabilities and enhanced performance for multiple demanding applications and multi-threaded applications.

Further on the horizon, Intel plans to deliver additional processors with two or more cores for mobile, desktop and server platforms. At present, the company has more than 15 dual-core and other multi-core projects in development.

Intel recognizes that the need for platforms with the right type of compute capability and performance will continue to escalate over time. Fifteen years hence, the capabilities that users expect of PCs are certain to change as dramatically as they have in the past 15 years. The evolution is likely to include magnitudes-better recognition applications and search functions that enable seamless mining of information and support knowledgeable, data-based decision-making, as well as much more realistic and natural ways to interact with the platform.

As these and other emerging consumer and business usage models go mainstream, they will require increasingly more compute capability. A comprehensive threading strategy that advances the platform — through Hyper-Threading Technology, dual-core processors and eventually other multi-core processors — is crucial to delivering this need. Going forward, Intel will continue to focus its research, development and marketing efforts on technologies that help make the balanced platform a reality, thereby delivering benefits to users in all market segments.

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* Hyper-Threading Technology requires a computer system with an Intel® Pentium® 4 processor with Hyper-Threading Technology and a HT Technology enabled chipset, BIOS and operating system. Performance will vary depending on the specific hardware and software you use. Visit www.intel.com/info/hyperthreading for more information, including details on which processors support HT Technology.