
White Paper
**Intel® Multi-Core Processors**

# Intel® Multi-Core Processors

## Making the Move to Quad-Core and Beyond

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# Introduction

One constant in computing is that the world's hunger for faster performance is never satisfied. Every new performance advance in processors leads to another level of greater performance demands from businesses and consumers. Today these performance demands are not just for speed, but also for smaller, more powerful mobile devices, longer battery life, quieter desktop PCs, and—in the enterprise—better price/performance per watt and lower cooling costs. People want improvements in productivity, security, multitasking (running multiple applications simultaneously on your computer), data protection, game performance, and many other capabilities. There's also a growing demand for more convenient form factors for the home, office, data center, and on the go.

Through advances in silicon technology, microarchitecture, software, and platform technologies, Intel is on a fast-paced trajectory to continuously deliver new generations of multi-core processors with the superior performance and energy-efficiency necessary to meet these demands for years to come. A new cadence[1] in the microarchitecture arena (see sidebar next page), combined with Intel's ability to continue to extend Moore's Law, will enable Intel to bring new levels of performance, power savings, and computing capabilities year after year. In mid-2006, we reached new levels of energy-efficient performance with our Intel® Core™2 Duo processors and Dual-Core Intel® Xeon® processor 5100 series, both produced with our latest 65-nanometer (nm) silicon technology and microarchitecture (Intel® Core™ microarchitecture). Now we're ready to top that with the world's first mainstream quad-core processors for both desktop and mainstream servers—Intel® Core™2 Quad processors, Intel® Core™2 Extreme quad-core processors, and others.

This paper explains the advantages and challenges of multi-core processing, plus provides a glimpse into the upcoming Intel quad-core processors and the direction in which Intel is taking multi-core processors to the future. We discuss many of the benefits you will see as we continue to increase processor performance, energy efficiency, and capabilities.

## Redefining Performance

For years, Intel customers came to expect a doubling of performance every 18-24 months in accordance with Moore's Law. Most of these performance gains came from dramatic increases in frequency (from 5 MHz to 3 GHz in the years from 1983 to 2002) and through process technology advancements. Improvements also came from increases in instructions per cycle (IPC). By 2002, however, increasing power densities and the resultant heat began to reveal some limitations in using predominately frequency as a way of improving performance. So, while Moore's Law frequency increases, and IPC improvements continue to play an important role in performance increases, new thinking is also required.

The best example of this new thinking is multi-core processors. By putting multiple execution cores into a single processor (as well as continuing to increase clock frequency), Intel is able to provide even greater multiples of processing power. Using multi-core processors, Intel can dramatically increase a computer's capabilities and computing resources, providing better responsiveness, improving multithreaded throughput, and delivering the advantages of parallel computing to properly threaded mainstream applications.

### A New Cadence for Technological Advancement

Building on the foundation of Intel Core microarchitecture (introduced in 2006), Intel is establishing a new cadence that will speed up the delivery of products featuring superior performance and energy-efficiency for years to come. Intel plans to deliver a new, optimized energy-efficient performance microarchitecture approximately every two years that supports all its process technology advancements. For instance, in late 2007, Intel process technology will transition to 45 nm and effectively double the number of transistors in a given die size. In 2008 Intel will follow this gain with a new microarchitecture codenamed "Nehalem" expected to deliver new capabilities and several percentage-point improvements in performance and energy-efficiency. This cycle will then move on to 32 nm and another new microarchitecture targeted for 2010.

## A Fundamental Theorem of Multi-Core Processors

Multi-core processors take advantage of a fundamental relationship between power and frequency. By incorporating multiple cores, each core is able to run at a lower frequency, dividing among them the power normally given to a single core. The result is a big performance increase over a single-core processor. The following illustration—based on our lab experiments with commonly used workloads—illustrates this key advantage.

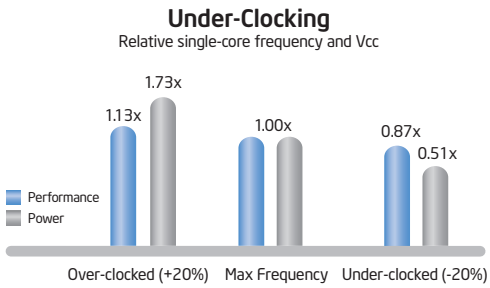



**Figure 1.** Increasing clock frequency by 20 percent to a single core delivers a 13 percent performance gain, but requires 73 percent greater power. Conversely, decreasing clock frequency by 20 percent reduces power usage by 49 percent, but results in just a 13 percent performance loss.

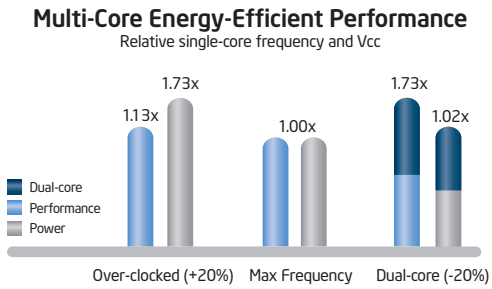



**Figure 2.** Here we add a second core on the underclocked example in Figure 1. This results in a dual-core processor that at 20 percent reduced clock frequency effectively delivers 73 percent more performance while using approximately the same power as a single-core processor at maximum frequency.

This fundamental relationship between power and frequency can be effectively used to multiply the number of cores from two to four, and then eightand more, to deliver continuous increases in performance without increasing power usage. To do this though, there are many advancements that must be made that are only achievable by a company like Intel.

These include:

- **Continuous advances in silicon process technology** from 65 nm to 45 nm and to 32 nm) to increase transistor density. In addition, Intel is committed to continuing to deliver superior energy-efficient performance transistors.
- **Enhancing the performance of each core and optimizing it for multi-core** through the introduction of new advanced microarchitectures about every two years.
- **Improving the memory subsystem and optimizing data access** in ways that ensure data can be used as fast as possible among all cores. This minimizes latency and improves efficiency and speed.
- **Optimizing the interconnect fabric** that connects the cores to improve performance between cores and memory units.
- **Optimizing and expanding the instruction set** to enhance the capabilities of Intel® architecture and enable the industry to deliver advanced applications with greater performance and lower power requirements. Some of these instructions can effectively dedicate a core to deliver specific capabilities.
- **Continuing to grow Intel's commitment to developing multi-core software tools and programs** by working closely with developers, independent software vendors (ISVs), operating system vendors (OSVs) and academia. Through these efforts, Intel enables the industry to develop software that runs faster and better on our energy-efficient performance multi-core platforms.

## Extending the World's Most Popular Processor Architecture with New Instructions

From the original Intel® 8086 to the recent addition of Supplemental Streaming SIMD Extensions 3 (Supplemental SSE3) found in Intel® Core™2 Duo processors, Intel has led the charge in expanding the capabilities of the world's most popular and broadly used computer architecture—Intel® architecture. Intel will soon add new instructions enabling our microprocessors across all volume market segments to deliver even greater performance and energy efficiency to a broad range of 32-bit and 64-bit applications.

## Best Energy-Efficient Performance Processor Transistors in Volume

- Intel Second Generation Strained Silicon Technology increases transistor performance 10 to 15 percent without increasing leakage.
- Compared to 90 nm transistor technology, Intel's enhanced energy-efficient performance 65 nm transistors provide over 20% improvement in transistor switching speed and over 30% reduction in transistor switching power
- We announced and demonstrated 45 nm process technology first. We are on track to deliver 45 nm products in 2007.

## Intel Achievements in Dual-Core Processing

Intel first implemented multi-core processing through dual-core processors across all key sectors (desktop, workstation, mobile, and mainstream server). In accordance with our new cadence for process technology and microarchitecture, Intel's second generation of dual-core processors, released in the third quarter of 2006, uses the new Intel Core microarchitecture. These products include Intel® Core™2 Duo desktop and mobile processors, and Dual-Core Intel® Xeon® 5100 processor 5100 series for dual-processor servers. By transitioning the majority of our volume products to Intel Core microarchitecture-based dual-core processors, Intel took the lead in performance and energy efficiency in most of these product segments.

According to benchmark tests:

- **The Dual-Core Intel Xeon 5100 server processor** delivers up to 135 percent performance improvements[2] and up to a 40 percent reduction[3] in energy consumption over previous Intel server products.
- **The Intel Core 2 Duo desktop processor** delivers up to a 40 percent improvement in performance and up to a 40 percent reduction in power as compared to today's high-end Intel® Pentium® D processor 960.[4]
- **The Intel Core 2 Duo mobile processor** delivers greater than 2X CPU performance[5] and up to a 28 percent power reduction[6] with new Intel® Centrino® Duo mobile technology laptops based on the Intel Core 2 Duo processor as compared to previous-generation Intel® Centrino® mobile technology-based laptops.

## Introducing Intel® Quad-Core Technology

The next milestone in multi-core processor design and performance will be Intel's unveiling of the industry's first quad-core processors for desktops, workstations and volume servers. Intel is the only company with the manufacturing resources to take this next step so quickly. Intel's implementation of quad-core takes advantage of our rich history of engineering expertise, along with our industry-leading manufacturing technologies and capabilities. This translates into excellent volume pricing and consistent supply. The industry will be able to make a fast transition as well—these quad-core processors are designed to plug into current motherboards meeting the proper thermal and electrical specifications.[7]

### Intel® Core™ Microarchitecture

Intel® Core™ microarchitecture is the foundation for new Intel® architecture-based desktop, mobile and mainstream server multi-core processors. This state-of-the-art, multi-core optimized microarchitecture delivers a number of new and innovative features that have set new standards for energy-efficient performance. Two of these features accelerate the execution of memory-related instructions.

### Intel® Advanced Smart Cache

Intel® Advanced Smart Cache is multi-core optimized cache that improves performance and efficiency by increasing the probability that each core of a multi-core processor can access data from a higher-performance, more-efficient cache subsystem. Intel Advanced Smart Cache works by sharing the Level 2 (L2) cache among cores so that data is stored in one place that each core can access. Sharing L2 cache enables each core to dynamically use up to 100 percent of available L2 cache, thus optimizing cache resources.

### Intel® Smart Memory Access

Intel® Smart Memory Access improves system performance by optimizing available data bandwidth from the memory subsystem and hiding the latency of memory accesses through two techniques: a new capability called memory disambiguation, and an instruction pointer-based prefetcher that fetches memory contents before they are requested.

### The Race is On

Intel plans to ship millions of multi-core processors in 2006 and expects to exit the year shipping dual-core and quad-core processors at a rate of more than 75 percent for its performance and mainstream desktop, 90 percent for its performance mobile processor families, and 85 percent for its servers. Intel expects to exit 2007 shipping multi-core processors at a rate of 90 percent for its performance desktop and mobile families and close to 100 percent for its servers.

## The Quad-Core Line Up

First up are the Intel® Core™2 Extreme quad-core processor QX6700 and the new Quad-Core Intel® Xeon® 5300 processor for servers. Slated for introduction in late 2006, these 65 nm quad-core processors feature four complete execution cores within a single processor and are based upon the revolutionary and proven Intel® Core™ microarchitecture.

- **Intel® Core™2 Extreme Quad-Core Processor—World's First Quad-Core for the Desktop.** This quad-core desktop processor will be the ultimate gaming machine and multimedia processing engine for today's growing list of threaded applications. In addition to being excellent for intensive multitasking, the Intel Core 2 Extreme quad-core processor will provide impressive gaming performance, offering plenty of headroom for tomorrow's thread-intensive games. Gamers can expect a smoother, more exciting gaming experience through the distribution of artificial intelligence (AI), physics and rendering across four hardware threads. Ideal for processor-intensive, highly threaded applications, the Intel Core 2 Extreme quad-core processor will be the top choice for multimedia enthusiasts, gamers, and workers in demanding multitasking environments. It will feature 2.66 GHz core speed and 1066 MHz front side bus speed.

### Coming in Q1 2007

**Intel® Core™2 Quad processor Q6600**

- Multimedia powerhouse for demanding entertainment applications
- Ideal choice for processor intensive, highly-threaded applications
- 2.40 GHz core speed, 1066 MHz bus speed

**Quad Core Intel® Xeon® processor L5310**

- Low Power version of 5300
- 50 watt thermal design point
- 1.6 GHz core speed, 1066 MHz bus speed

**Quad Core Intel® Xeon® processor 3200**

- For single-processor servers and workstation systems

- **Intel® Xeon 5300 Processor—Breakthrough Performance from the Industry's First Quad-Core Standard High-Volume Processor.** This new quad-core processor will enable server customers to turbo boost their general purpose servers with breakthrough energy-efficient performance, greater density and fewer cooling challenges. The Quad-Core Intel Xeon 5300 processor provides up to 50 percent better performance[8] (SPECintRate) than dual-core 2-way Intel Xeon processors on certain applications. The additional threads from quad-core technology and key Intel platform-level innovations deliver the most headroom for running multiple applications simultaneously and virtualized environments on a two-way server.

The Quad-Core Intel Xeon 5300 series will feature 2.66 GHz to 1.60 GHz cores speeds, 1333 to 1066 MHz bus speeds, and a 105 watt thermal design point (TDP). A low power version (L5310) with a 50 watt TDP will be available in the first quarter of 2007. Another version will be available for single-processor servers and workstations in the same time frame.

Quad-Core Intel Xeon 5300 processor platforms also include several advanced capabilities:

- **Intel® Virtualization Technology (Intel® VT).** This is the industry's first hardware-assisted technology supporting today's industry-leading virtualization software.
- **Fully-buffered DIMM Technology**. The latest in memory technology, fully-buffered DIMM technology provides significantly greater performance and capacity while improving memory reliability.
- **Intel® I/O Acceleration Technology.** This unique Intel technology moves network data more efficiently through Intel Xeon processor-based servers for fast, scaleable, and reliable networking.

## Beyond Quad-Core: Tera-Scale Computing

Spurred by increasing globalization, growing device intelligence, and the explosion of digital data, Intel believes the next decade's applications will be much more computationally intensive than anything we've seen to date. This will be the "tera era"—an age when people need teraflops (a trillion floating point operations per second) of computing power, terabits (a trillion bits per second of communications bandwidth), and terabytes (1,024 gigabytes) of data storage to handle the information all around them.

With the tera era in mind, Intel researchers are today working to shape future Intel microprocessors through the Intel® Tera-scale Computing Research Program. Intel has over 100 R&D projects worldwide in the tera-scale area. Our researchers are addressing the hardware and software challenges of building and programming systems with dozens (even hundreds) of energy-efficient cores with sophisticated memory hierarchies to deliver the performance and capabilities needed by these systems.

## Transitioning the Industry to Multi-Core Processing

One immediate benefit of multi-core processors is how they improve an operating system's ability to multitask applications. For instance, say you have a virus scan running in the background while you're working on your word-processing application. This often degrades responsiveness so much that when you strike a key, there can be a delay before the letter actually appears on the screen. On multi-core processors, the operating system can schedule the tasks in different cores so that each task runs at full performance.

Another major multi-core benefit comes from individual applications optimized for multi-core processors. These applications, when properly programmed, can split a task into multiple smaller tasks and run them in separate threads. For instance, a word processor can have "find and replace" run as a separate thread so doing a "find and replace" on a big document doesn't have to keep you from continuing to write or edit. In a game, a graphics algorithm needing extensive processing power could be one thread, rendering the next scene on the fly, while another thread responds to your commands for a character's movements.

The critical element in multi-core computing is the software. The throughput, energy efficiency, and multitasking performance of multi-core processors will all be more fully realized when application code is threaded and multi-core ready. Intel provides extensive partner programs with software developers, operating system vendors, ISVs, and academia to accelerate the delivery of dual-core and quad-core products. Intel has recently updated the Intel® Threading Building Blocks, Intel® Thread Profiler, and Intel® Thread Checker tools to support our quad-core products.

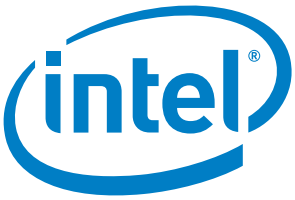
Intel's software products and programs include:

- Intel® Software Development Products—These products and tools embrace multi-core programming best practices, facilitate threading applications, and help developers shorten the time to market. Products include Intel® Compilers, Intel® Performance Libraries, Intel® VTune™ Performance Analyzers, Intel® Threading Tools, and Intel® Cluster Tools. Intel also offers software platform products such as Intel® Platform Administration Technology, Intel® Innovation Framework for EFI, and Intel® Media Codecs to help speed value delivery in the platforms.

- Software Programs and Services—Beyond software products, Intel works with leading software vendors to provide tools, resources, expertise and relationships to drive thread optimization across a wide range of applications. Through deep technical onsite collaborations with operating system (OS), firmware and database vendors, we enable them to fully utilize the multi-core platforms prior to launch. Intel also works with industry groups like ODSL and Eclipse to shape the direction of the open source community. In addition, Intel works with thousands of ISVs to help them prepare and optimize their solutions for new platform technologies and with academia in developing multi-core curriculum. Intel software programs and services include the Intel® Early Access Program, Threading Immersion Program, Intel Competency Centers, Intel® Software College, Intel® Software Network, Intel® Solution Services, and Intel Capital.

Progress has been fast. Microsoft Windows XP,* Windows Server,* Microsoft Vista,* some applications in Microsoft Office 2007,* various Linux* vendor offerings, and others are already threaded for better performance with Intel multi-core processors. In addition, Intel's Software and Solutions Group (SSG) has worked with hundreds of independent software vendors (ISVs) in enabling their applications to achieve greater performance running on Intel multi-core processors.

No one is in a better position to spearhead platform development than Intel. Intel's leadership in the industry, our commitment to investment in research and development, our understanding of all segments of the market, and our long history of collaboration with other industry leaders, puts us in a unique position to lead the charge for multi-core processor-based platforms.



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## Empowering the Ecosystem

Intel Capital, Intel's strategic investment program, is investing hundreds of millions of dollars in companies whose products and services supplement Intel's own product lines and capabilities. Other ecosystem development activities include Intel's sponsorship of the Intel Developer Forum (IDF), an annual series of worldwide conferences that provide insights into Intel's future technology directions and enable the developer community to share their knowledge, ideas, and products.

## Summary

Multi-core processors are the future of computing. As the wealth and complexity of the data around us grows, multi-core processors will become increasingly important for helping run businesses, governments, our homes, and our entertainment. Multi-core processors will empower the development of new usage models that will enable wide-ranging advances in everything from medicine to IT, as well as revolutionize the digital office, digital home, computing on the go, and computer gaming.

Think of a time a decade or so from now when the full power of high performance computing and parallel processing is available to computer users everywhere, and it might be possible to hold the power of a computer with hundreds of execution cores in the palm of your hand. Chances are, we'll look back and wonder how people ever managed with computers having just a single execution core in their processor. Intel® quad-core processors are the next step in this process.

## Learn More

Intel® Multi-Core
*www.intel.com/multi-core*

New Instructions
*www.intel.com/technology/architecture/new_instructions.htm*

Intel® Architecture
*www.intel.com/technology/architecture*

Tera-Scale Computing
*www.intel.com/technology/techresearch/terascale*

Silicon Technologies
*www.intel.com/technology/silicon*

Technology and Research at Intel
*www.intel.com/technology*

1. Intel CEO Paul Otellini in Spring 2006 Financial Analyst Forum
2. 135 percent Performance Claim based on published results on SPECjbb2005 benchmark as of June 26, 2006. Configuration details: Dual-Core Intel Xeon Processor 2.80 GHz based platform details: Fujitsu Siemens Computers PRIMERGY RX300 S2 server platform: Two Dual-Core Intel® Xeon® processors 2.80 GHz with 2x2MB L2 cache 800 MHz system bus, 4 GB DDR2, Microsoft Windows Server* 2003. Java HotSpot(TM) Server VM (build 1.5.0_06-b05). Referenced as published at 41986 bops and 41986 bops/jvm. For more information see www.spec.org/jbb2005/results/

   Dual-Core Intel Xeon Processor 5160 based platform details: Fujitsu Siemens BX620 S3 Server platform with two Dual-Core Intel Xeon Processor 5160, 3.00 GHz with 4M L2 Cache, 1333 MHz system bus, 8GB (8x1GB) FB-DIMM memory, Windows 2003 Enterprise Edition. BEA JRockit(R) 5.0 P26.4.0. Referenced as published at 100407 bops and 100407 bops/jvm. For more information see www.spec.org/jbb2005/results/
3. 40 percent reduction based on Processor TDP comparison between previous generation Dual-Core Intel Xeon Processor 2.80GHz and new Dual-Core Intel Xeon Processor 5160.
4. Performance based on SPECint*_rate_base2000 (2 copies) and energy efficiency based on Thermal Design Power (TDP), comparing Intel® Core™2 Duo E6700 to Intel® Pentium® D Processor 960. Actual performance may vary. See www.intel.com/performance for more information.
5. As measured by SPEC* CPU2000* (SPECfp*_rate_base2000 and SPECint*_rate_base2000) comparing Intel® Pentium® M Processor 780 and 750 with Intel® Core™2 Duo Processor T7600 and T5600. Actual performance may vary. See http://www.intel.com/performance/mobile/benchmarks.htm for important additional information. SPEC, SPECint, SPECfp, SPECrate, SPECweb, SPECjbb are trademarks of the Standard Performance Evaluation Corporation. See: http://www.spec.org for more information on the benchmarks.
6. Based on power utilization measured by average power of Intel components of pre-production Intel® Core™2 Duo processor-based laptop as compared to an Intel® Pentium® M processor-based notebook. Actual performance may vary. See http://www.intel.com/technology/eep/platforms.htm for important additional information.
7. Contract your motherboard vendor for more information.
8. Performance may vary. Please refer www.intel.com/performance for more details.

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