Intel Multi-core Processors
Leading the Next Digital Revolution

Introduction

The “big bang” that began with the invention of the microprocessor has anything but abated. In the past 10 years, rapid advances in digital technologies have continued to have enormous impact on how we live, amuse ourselves, work, socialize, and communicate. Business users and corporations have hit new levels of productivity as they’re able to tap, store, process, and exchange knowledge in the form of data that was once beyond the reach of imagination. In our homes, computers have become necessities for everything from delivering the wonders of the Internet to our doors to storing our memories, instant messaging our friends, and—through immersive 3D games—engaging our fantasies.

Unlike the original Big Bang, this has been no accident. It’s been part of a roadmap of computing advances focused on using increasing processing performance to fulfill real needs, wants, and desires.

Continual increases in processor clock frequency have made many of these advancements possible. Yet the next wave of advances will have a much different source. Going beyond increases in clock frequency, Intel is now putting multiple execution cores (or “computational engines”) into a single processor. This will provide even greater multiples of processing power. And it will be part of an entire platform (the Intel® multi-core platform) providing an integrated set of “ingredients” designed to seamlessly work together to maximize performance and power efficiency.

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Multi-core processors are the next innovation in Intel's continuing commitment to enhancing computing architectures and platforms based on extensive research on what people want and how they use technology. Through this research, Intel deeply understands user requirements in each market segment and how to create compelling multi-core platform solutions to meet those values.

Intel multi-core platforms will enhance the computing experience by:

- Improving the performance of today's existing multi-threaded applications
- Boosting overall system performance while remaining within acceptable power and thermal envelopes
- Increasing the responsiveness of applications in multi-tasking environments
- Enabling new applications and humanlike intelligence in desktop, laptop, and other small form factors that may require high performance computing-like performance
- Improving ease-of-use with more humanlike interfaces
- Expanding the ways we can use our computers to mine and synthesize information, as well as create, innovate, and communicate

Intel plans on bringing the benefits of its multi-core platforms to all its targeted segments: desktop and mobile PCs as well as servers and workstations. A fast ramp up in 2005 and 2006 will enable people in all these segments to experience the wonders of multi-core in expanding the digital universe all around us. And by developing the processors with the full platform in mind, the full benefits of this new technology can be delivered to consumers.

A multi-core processor has two or more "execution cores" within a single processor. It plugs directly into a single processor socket, but the operating system perceives each of its execution cores as a discrete processor with a full set of execution resources. Dual-core processors, for example, are a multi-core processor implementation with two execution cores.

Bringing High Performance Computing Technology to the Mainstream in Volume

Hyper-Threading Technology (HT Technology) and multi-core processors from Intel represent an evolutionary shift in mainstream computing. These technologies deliver the same parallel processing techniques used in high performance computing (HPC) to computer users everywhere. Such massive performance capabilities are necessary as the world's data continues to increase at an astonishing rate, doubling every 24 months. Even more astonishing is what we could do with our computers and this data if we all had more processing power to mine and synthesize it for our own uses. In the enterprise, digital office, and digital home—and on the road—this greater processing power will come from Intel® multi-core platforms. Imagine being able to run software similar in power and scope to the high performance applications used in academic, industry, and research environments.

Three important considerations in bringing such applications to the mainstream are the performance, power, and space requirements of the computer. Obviously, clustering hundreds of individual processors like HPC systems do is impractical for mainstream PCs. All the additional processor sockets, processors, associated chips, and circuitry would be too expensive

and require too much space. But the advantages of parallel processing are too big to ignore, which is why Intel is now leading the charge to develop a multi-core platform designed to bring HPC power to mainstream computing.

Intel has more than 15 multi-core processor-based platform designs underway and is on the fast track to deliver multi-core processors in high volume across all its platform families. Intel's multi-core architecture could eventually feature dozens or even hundreds of processor cores on a single die. In addition to general-purpose cores, Intel multi-core processors will eventually include specialized cores for processing graphics, speech recognition algorithms, communication protocols, and more.

The User Benefits of the Intel® Multi-core Processor-based Platforms

Like any innovation, the first question that comes to mind concerning multi-core processors is what will it do for me? How will it change my life? What will I be able to do with it that I can't now? Why should I get excited about it?

Intel sought answers to these questions by sending ethnographic and market researchers out to do extensive research worldwide on how people are actually using computers today and might use them in the future. From this research, Intel discovered people were going to need systems with more processing capacity in a variety of form factors. These gains in processing capacity, while still maintaining reasonable platform implementations, were only achievable through multi-core processor-based platforms. Intel also uncovered many of the ways this extra capacity might be used to solve today's computing challenges and fulfill the aspirations society has for computing and our interactions with computing devices in the future. In this section, we will briefly cover some of the more concrete advantages people can expect to experience in the digital enterprise (servers and workstations), digital office (desktop, mobile), digital home (desktop, mobile, and other form factors), and on the go (mobile uses) from Intel® multi-core platforms.

Multi-core Platform Advantages in the Digital Enterprise

IT managers are continually faced with providing more services to more users, meeting higher performance expectations, storing and managing ever-growing amounts of data, maintaining availability and stability, and improving security. To meet many of these challenges, they've turned to Intel® Itanium® 2 processors and Intel® Xeon™ processors. And now a transformative technology such as the Intel® multi-core processor-based platform has come along to dramatically push performance to a new level, solve pressing challenges, and provide new avenues for innovation. Today's multi-core server processors are a critical industry inflection point. By the end of the decade, Intel envisions them delivering a 10X performance gain.

Server Density

For years Intel® processor designs have enabled servers to continue delivering increased performance for the powerful applications that support rapid business growth and efficiency. Yet this increased performance has come at a price: a corresponding increase in platform power consumption and thermal and space requirements. Today the steady increase in the density of systems in data centers is creating power and cooling challenges for many IT organizations.

Part of the answer will be Intel® multi-core server platforms. By enabling a single processor form factor to serve multiple processor cores, these platforms will provide superior performance and scalability while remaining relatively constant in power consumption, heat and space requirements. As a result, more processing capacity can be concentrated into fewer servers. This means greater density and fewer servers to manage. Bottom line: Multi-core platforms give more value by enabling more to be done with less.

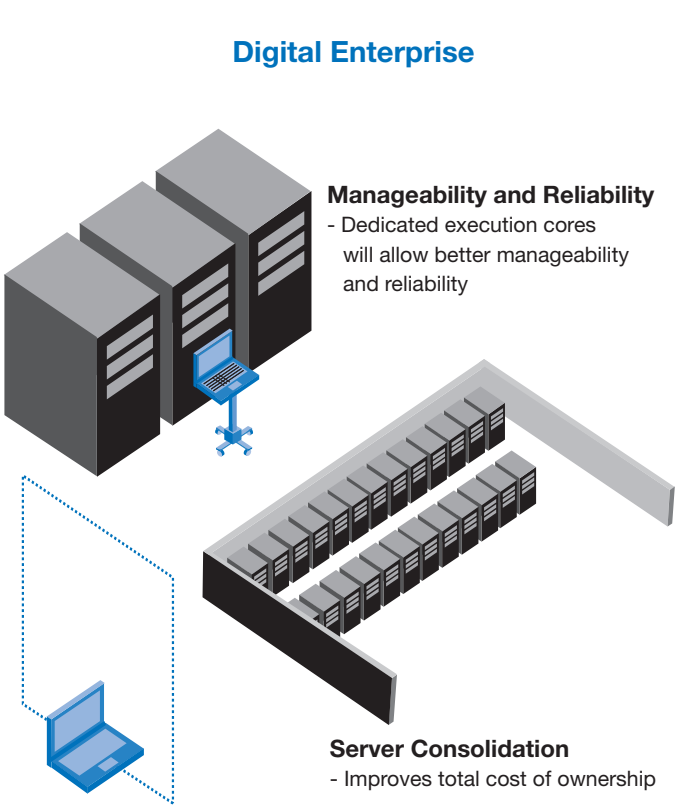
Multi-core processors are essential to maintaining the performance gains we've grown accustomed to from computers as we continually ask them to do more for us. An Intel-sponsored Harris Interactive survey found that nine out of 10 users reported problems while trying to perform multiple processor-intensive tasks. Problems include computer freezes, time lags, function shut-downs, chopping off screens, and audio distortion. For home users, waits are boring and problems disconcerting. For businesses, a few seconds here and a few seconds there in a day, week, month, year, spread over hundreds or thousands of employee, has a significant impact on productivity and the bottom line.

Manageability and Security

Intel® multi-core processors in combination with other platform capabilities offer the ability to enhance manageability and security. Different cores can be assigned different tasks having to do with managing the asset or providing security, while other cores work on primary processing functions. IT will be able to use these capabilities to tailor and enhance service levels to multiple applications and complex workloads. Having "dedicated" execution cores will allow manageability and security solutions to be more robust and independent from other processing operations going on at any specific time. As a result, servers and clients will maintain responsiveness while concurrently running multiple enterprise management and productivity applications like virus scans, software updates, configuration checks, and inventory requests. IT will even be able to run different instances of an operating system on the same system simultaneously without any performance degradation.

Intel Leads the Way in Bringing Multi-threading and Parallelism to Mainstream Computing

Multi-core processing is a long-term strategy for Intel that began more than a decade ago. In 1994 Intel introduced instruction-level parallelism in mainstream computing through the Intel® Pentium® processor. In instruction-level parallelism, the instructions in a single thread of code are extracted, executed in parallel, and then recombined in the same order. In 2002, Hyper-Threading Technology (HT Technology) introduced thread-level parallelism by enabling multi-threaded software applications to execute threads in parallel on a single-core processor. Intel benchmarks showed that some applications could see improvements of up to 30 percent on processors with HT Technology. Now with multi-core platforms, Intel leads the way in bringing parallelism to mainstream PCs by enabling full parallel processing of threads by multiple executional cores within a single processor.



Transitioning to a Service-Oriented Enterprise

To take advantage of global collaboration, real-time business responsiveness, and the productivity gains of more mobile work forces, enterprises need to move to a Service-Oriented Enterprise approach. That means changing the focus from managing individual resources—devices, programs, and datasets—to instead orchestrating services and workflows that define your business and ultimately deliver value to your customers or end users. Achieving this requires shifting to an innovative set of business processes supported by a very modular, manageable IT infrastructure based on industry standard hardware and software building blocks, and delivered as complementary, interoperable services interacting via standard Web protocols. Intel multi-core processors will be a key building block in making this transition. They will supply the fast throughput required for multiple, simultaneous transactions and improving service responsiveness in everything from real-time business interactions to automated asset tracking. For more on the Service-Oriented Enterprise, see **www.intel.com/business/bss/technologies/soe/soe_backgrounder.pdf**.

Multi-core Platform Advantages for the Digital Office, Digital Home and Mobile Users

Consider what you can do today with computers that you couldn't do a decade ago in everything from video and photography to games and music. Intel® Pentium® processors and Intel® Centrino™ mobile technology have enabled a new generation of rich applications and computer experiences. But incredible new digital technologies in areas like healthcare are on the horizon, and other digital devices also need to keep advancing. Multi-core processors are key components of these breakthrough new technical platforms.

Pervasive Connectivity

As new wireless communication technologies such as Voice over Internet Protocol (VoIP) and WiMAX enter the office and home, and as network bandwidth keeps increasing, processing the massive data packets needs to be handled separately without affecting the performance of the main application. Multi-core processors will enable the burden of handling these communications to be dedicated to one or more cores of the processor while the other cores remain dedicated to the primary tasks. The result will be better background performance for your communications and greater responsiveness for your work at hand.

Increased Productivity

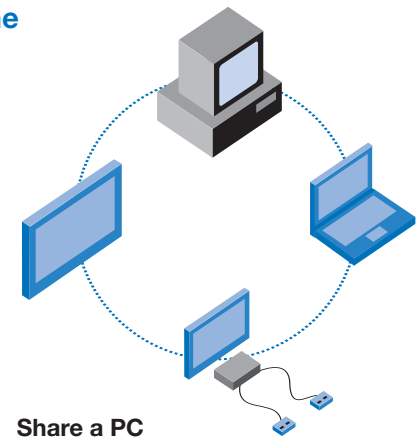
Multi-core processors hold the promise of continuing the enormous increases in the performance seen in computers over the last quarter century while holding corresponding increases in power requirements in check. What will this performance mean for productivity? Consider a graphic designer using Adobe PhotoShop* or Illustrator.* Saving a few seconds here and a few minutes there on each procedure can rapidly add up when a deadline looms and you need time to try out new ideas. Greater responsiveness also translates into less waiting and frustration as you run through a series of tasks or operations. For people like stockbrokers this could literally mean dollars as their computers process information in nanoseconds and enable them to make faster, smarter investment decisions and fast trades.

Improved Multitasking

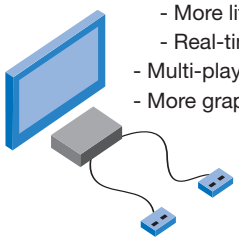
Today the responsiveness of our computers suffers when we try to do too many processing-intensive tasks. Try switching over to word processing while you're in the middle of a virus scan for instance, and you may type a few letters and see nothing immediately appear. An instant later, the letters finally make their way on-screen. Those minor stalls, the fits and starts of day-to-day multitasking, are the price we pay for the burden of all the background tasks (virus scans, spam quarantining, software updates, driver updates, background files

Digital Home

Pervasive Connectivity
- Capability to handle new communications technologies more efficiently



Gaming
- New levels of realism
  - More life-like artificial intelligence
  - Real-time physics simulations
- Multi-player collaborative environments
- More graphics-intensive games



Share a PC
- A media processing system will deliver content in parallel to extenders or other devices in a home network
- Multiple users on one system in parallel

Creativity
- Produce high-definition videos with complex special effects
- Produce music/audio with more tracks, more real-time digital effects, and better quality
- Create and share art/photographic images with higher resolutions

saves, automatic e-mail checks, and so on) we ask our computers to do. Throw in a really processing-intensive activity like video rendering or gaming and today's machines are noticeably taxed. Then there are some tasks, such as burning a DVD, that ask us to not use our PCs at all while they're doing their work.

As more software is written for multi-core processing and as multi-core platforms become common, these performance hiccups will vanish. What's more, performance gains will make much more ambitious forms of multitasking possible. For instance, two people in different rooms can share the same PC located in an entirely different room. One might play an action-intensive game. The other might download video from a digital camcorder and begin editing scenes from a recent vacation.

As more and more devices in the home become digital, the demands on an operating system in a computer managing the devices or communicating with them will continue to grow. The boundaries of what a typical entertainment PC can do—control and exchange media—will have to greatly expand. This means the digital home will increasingly depend on the multitasking capabilities of multi-core processors to handle the demands of orchestrating all the different networked TVs, stereos, cameras, and other devices and appliances in the household.

Gaming So Real It's Unreal

Multi-core processors will allow game developers to separate tasks between the different cores. The added processing power will give designers the freedom to create more rigorous graphics, physics, and artificial intelligence. For example, a photorealistic graphics algorithm needing extensive processing power could use one or more dedicated cores to render on the fly.

Enhancements in artificial intelligence will also increase what the game can do rather than just the quality of the images. For example, enemy artificial intelligence in games today has limited path-finding abilities. It's smart enough to move around objects from one point to another, but it can't achieve the intelligence you expect from a clever opponent. In the future, a game designed to take advantage of multiple cores could dedicate one or more cores to graphics duties while several other cores handle AI tasks, allowing a more realistic game experience.

Though it will take time for game developers to fully take advantage of the multitude of cores and threads, major developers (including Epic Games, Lionhead Studios, BioWare, and Ubisoft) are already working on it for future titles.

Multi-core will also make multiparty gaming ubiquitous. Tomorrow's computers will be powerful enough to run multi-party gaming and collaboration on their own. No longer will these games have to be housed in huge servers—but they will be distributed across the Internet. That should enable greater proliferation and access, plus inspire new forms of games and collaboration. Gaming competitions will be less expensive and easier to set up.

Thinking beyond the Processor: The Intel® Platform Advantage

Multi-core processing isn't simply about a new generation in processors. It's an enormous technological leap that will influence computing for years to come. But the full benefits of multi-core processing won't be realized with multi-core processors alone. To make the most of this leap requires a platform approach driving new developments in chipsets, components, companion technologies, software, and the industry ecosystem influenced at every stage by user requirements. Intel's platform approach seeks to enhance all these platform elements in concert for the best user experiences.

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

An Evolutionary Step in Multitasking

Today's operating systems multitask by briefly suspending one thread, working on another, and then going back to the original thread or yet another. At any point in time, the processor is running just a single thread. The tradeoff for multitasking is slower performance for all the applications being multitasked than if they were the only application running. Intel® HT Technology improved multitasking by enabling multi-threaded software applications to execute threads in parallel on a single-core processor. Dual-core takes this a step further by running parallel threads through two separate execution cores in the same processor. Multi-core processors will eventually eliminate the tradeoffs in multitasking by having enough cores to give each thread its own execution pipeline and core without blocking resources needed by other running software threads. This "divide and conquer" strategy (thread-level parallelism) will radically improve multitasking performance as more applications are written to take advantage of thread-level parallelism.

Moore's Law, Multi-core, and Silicon Innovation

Gordon Moore, one of Intel's founders, observed in 1965 that innovations in technology would allow a doubling of the number of transistors in a given space every year (in an update article in 1975, Moore adjusted the rate to every two years to account for the growing complexity of chips), and that the speed of those transistors would increase. Moore also stated that manufacturing costs would dramatically drop as the technology advanced.

For nearly four decades Intel has proved Moore right. Today, continuing to deliver innovation to make the predictions of Moore's Law a reality means shrinking the nominal size of the devices that populate the silicon. The difficulty is that researchers now are coming up against the physical limits of atomic structure for scaling transistors while still managing power and thermals. This issue—as well as other factors—creates a significant and continuous challenge for the entire silicon industry.

In response to this challenge, Intel is aggressively pursuing research into both conventional and unconventional technologies. This includes introducing many new and exciting technologies and innovations in materials, design, and packaging. Multi-core processors are a key technology in these efforts.

What are some of the others? At the process level, Intel's roadmap for researching and developing new process technologies addresses every variable and manufacturing aspect that affects the power equation. It encompasses technologies from conventional CMOS processes to research in unconventional materials, such as carbon nanotubes or carbon nanowires.

Progress is fast and Intel remains ahead of its competitors in process technology life cycle by two years. In 2003 Intel developed and deployed the first high-volume production 90-nm process technology using strained silicon, reducing the current leakage from transistors by a factor of five (or more, actually) without reducing on-current performance. Intel is already readying its shift to 65-nm process technology, with improved, second-generation strained silicon, and transistors whose gate length is just 35 nm—so tiny that about 100 of these gates could fit inside the diameter of a human red blood cell. And beyond that? Intel is already researching 45-nm, 32-nm, and 22-nm process technologies.

Intel is also investigating novel structures of transistors (such as tri-gate transistors) and unique dielectric materials (such as the dielectric referred to as Hi-K material). Other Intel innovations, such as HT Technology, execution trace cache, and Enhanced Intel® SpeedStep® Technology, and of course, multi-core processors address the challenge at an architectural level, adding dramatic performance enhancements to Intel®-based platforms.

Intel believes the answer to the question of continuing on the trajectory predicted by Moore's Law lies in addressing power challenges at every level, from silicon to system. You can find out more at www.intel.com/technology.

second-to-none in process technology and the capacity to drive first dual-core, then multi-core processor manufacturing in volume through 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 Intel® Pentium family processor shipments will be dual-core by the end of 2006.

By incorporating innovative technologies and focusing on the entire platform, Intel will be able to deliver tomorrow's computing experiences to each segment at extraordinary value—as well as bring to life many of the novel usage models and new user experiences described in this paper.

In conjunction with multi-core, these new capabilities will be instrumental in helping computer users optimize value, reduce costs, and mitigate risk as they transition to multi-core architectures. These capabilities will also establish a flexible, standards-based foundation for ongoing platform, IT, and business innovation.

Enabling the Ecosystem

Intel has been working with leading software vendors and many other key players in the software industry to deliver applications that support multi-threaded code. As a result, Intel has established extensive tools, resources, expertise, and relationships that have helped drive thread-optimization across a wide range of business applications.

Intel continues to accelerate these efforts, working with leading developers and academia to enable their applications to make use of the power of Intel® multi-core platforms. New advanced tools, adaptive libraries, and other infrastructure will further speed industry progress in taking full advantage of evolving platform capabilities and the opportunity to run hundreds or even thousand of threads in future solutions.

Progress is already being made. Microsoft Windows* XP, Windows* Server, various Linux* vendor offerings, and others are already threaded to take advantage of HT and Intel® multi-core processors. In addition, Intel has worked with hundreds of independent software vendors (ISVs) in enabling their applications for HT and is continuing to work with them in making sure that those applications work efficiently in Intel multi-core platforms.

Intel has a dedicated division, the Software and Solutions Group (SSG), devoted to helping third-party software and solutions developers optimize their solutions for Intel multi-core platforms. SSG has developed Intel's Threading Immersion Program and a robust set of threading tools, compilers, and other performance-tuning kits that enable software developers to implement thread-level parallelism enhancements within their code. Intel has also invested heavily in Intel Solution Centers (currently there are 15 around the world) where applications vendors can work onsite to further optimize their offerings to the latest Intel technologies. Intel Software College and Intel's University Programs are also examples.

All this is vitally important work because to achieve the performance required for things people want, such as humanlike interfaces and natural speech recognition, developers will need help configuring all kinds of algorithms to solve problems in parallel. Intel is aggressively funding efforts within the company's research and product groups to address these challenges. Intel Capital, Intel's strategic investment program, is also 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 provides insights into Intel's future technology directions and enables the developer community to share their knowledge, ideas, and products.

Summary

Multi-core processor-based platforms are where Intel is heading. As the wealth and complexity of the data around us grows, these multi-core platforms will become increasingly important for helping run businesses, governments, our homes, and our entertainment. Multi-core platforms will empower the development of new applications that will enable wide-ranging advances in everything from medicine to IT, from the digital office to the digital home, from mobility solutions to the latest games.

Think of a time a decade or so from now when it might be possible to hold the power of a computer with hundreds of execution cores in the palm of your hand, when the power of high performance computing and parallel processing is available to computer users everywhere. What will you do with it? Maybe the better question is: What won't you do with it?

The first generation of dual-core processors is already here, and advancing the digital revolution at home and at work. Much greater advances are in store as Intel works with the industry in building the necessary platform elements, standards, and ecosystem to take multi-core platforms from early adopters to mainstream computer users.

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