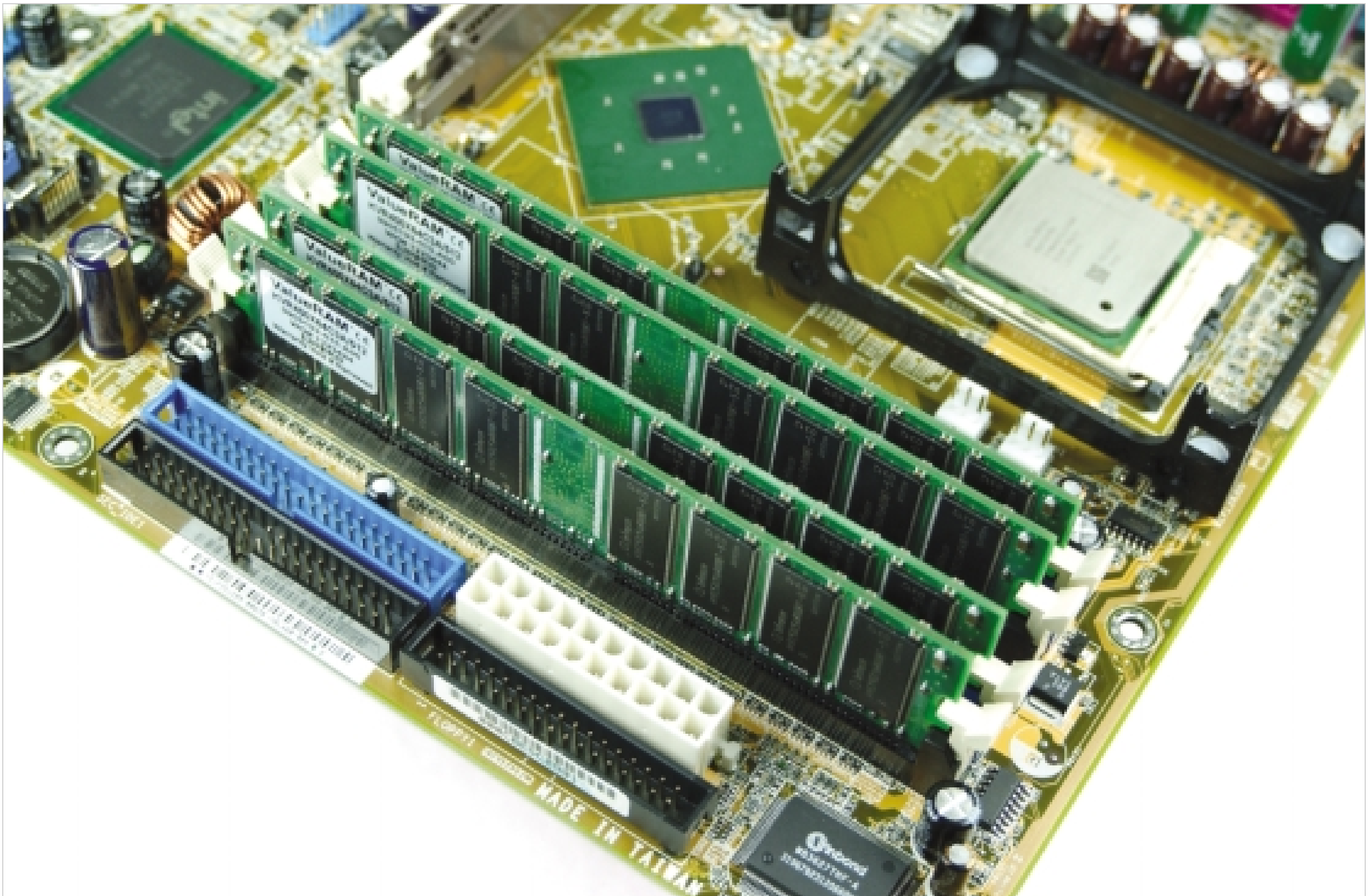

Intel Dual-Channel DDR Memory Architecture White Paper

INTRODUCTION

Today, buying a computer is becoming a more complicated process where potential buyers are inundated with technical terms like: GHz, DDR, FSB, Dual-Channel, and Hyper-Threading®, just to name a few. Traditionally, the GHz (Gigahertz) number, indicating processor speeds, has always been one of the key factors in any computer purchase. As the GHz number increases, so does the performance of the computer.

In 2003, Intel® Corporation decided to launch a new motherboard architecture utilizing dual-channel memory into the mainstream computer market. Up until this point, all Intel-based mainstream computers were only available with single-channel memory. The number of memory channels has a significant effect on a computer's overall performance. The GHz number is no longer the sole criterion for determining system performance. Dual-channel memory has been used for many years in higher-performing systems such as servers and workstations and is quickly becoming a part of mainstream computing.

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Authored by Infineon Technologies North America Corporation and Kingston Technology Company, Inc.

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Jointly produced by Infineon® Technologies and Kingston® Technology, this white paper will explain the general architecture of Intel's dual-channel DDR desktop platforms launched in 2003 and its impact on system performance.

1.0 Computer Memory

The speed of system memory is another determining factor for computing performance. The most common form of memory installed today is Synchronous Dynamic Random Access Memory (SDRAM). A computer's memory is a temporary storage area for data that needs to be available for programs to run efficiently. The faster the memory can provide data, the more work the processor can perform. Increased data "throughput" translates directly into better system performance.

Since 1997, there have been several major transitions in SDRAM memory speed and technology. SDRAM started with a memory speed of 66 MHz (PC66) and progressed to 100MHz (PC100) and then to 133MHz (PC133). In 2002, standard SDRAM began to be replaced with the faster Double Data Rate (DDR) SDRAM memory technology. DDR memory started with 200MHz DDR (or DDR200) and is now available in DDR266, DDR333, and DDR400 speeds for mainstream PCs.

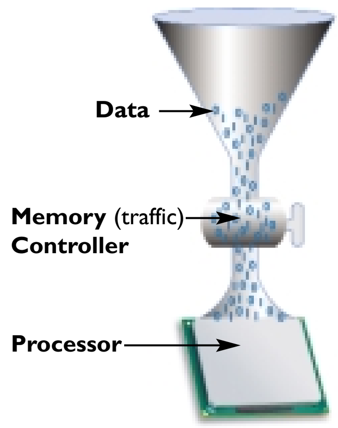
In the past, memory speeds were able to keep up with the processor's requirements. However, when we reached the point where the processor's ability to process data was accelerating faster than current memory technologies could support, memory became a major limitation in system performance. Simply put, memory speeds could no longer keep up with advances in processor speeds and data throughput. A new method to get more data to the processor in mainstream computers was needed – without relying solely on memory speed.

Intel and many system architects decided that the solution was to add a second channel of memory – called the "dual channel" memory layout.

2.0 Dual-Channel Memory

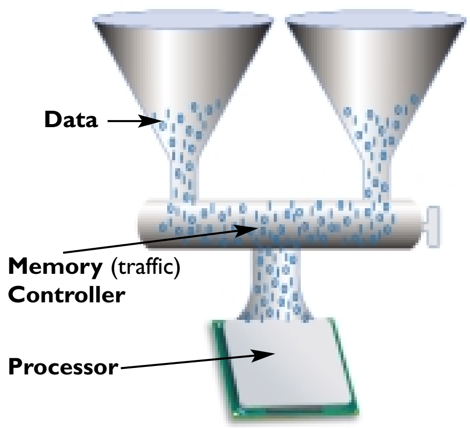
A processor in a computer is like the engine of a car. A car needs gasoline to fuel its engine. Similarly, a computer processor needs memory storage to process its data. Data (in bits which are zeros and ones) must be stored in memory first, before being delivered to the processor. When more data can be delivered to the processor via memory at faster speeds, the processor can manipulate instructions and data more efficiently and ultimately, the requested task can be accomplished in less time.

To illustrate the difference between single- and dual-channel memory, let's extend the analogy above. Data is filled into a funnel (memory); the funnel then "channels" the data through its pipe to the processor's input:

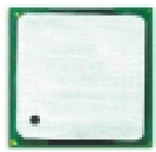


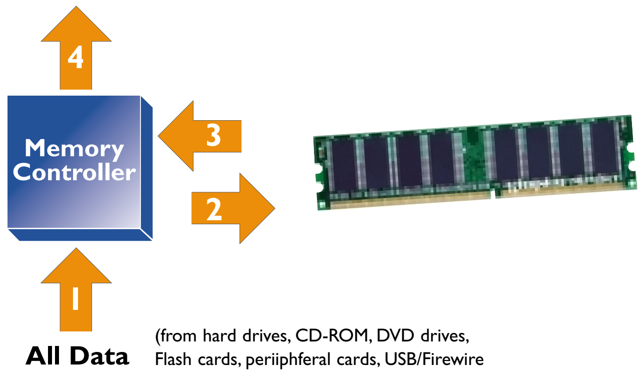
In this illustration, single-channel memory is like a funnel that feeds data to the processor engine through a single pipe. Data is transferred 64 bits at a time.

Dual-channel memory utilizes two funnels (and thus two pipes) to feed data to the processor, thereby being able to deliver up to twice the data of the single funnel. With two funnels or channels, data is transferred 128 bits at a time. The process works the same way when data is "emptied" from the processor by reversing the flow of data. To prevent the funnel from being over-filled with data or to reverse the flow of data through the funnel, there is a "traffic" controller shown as a valve on the funnel's pipe. In computers, there is a special chip called the "Memory Controller" that handles all data transfers involving the memory modules and the processor.

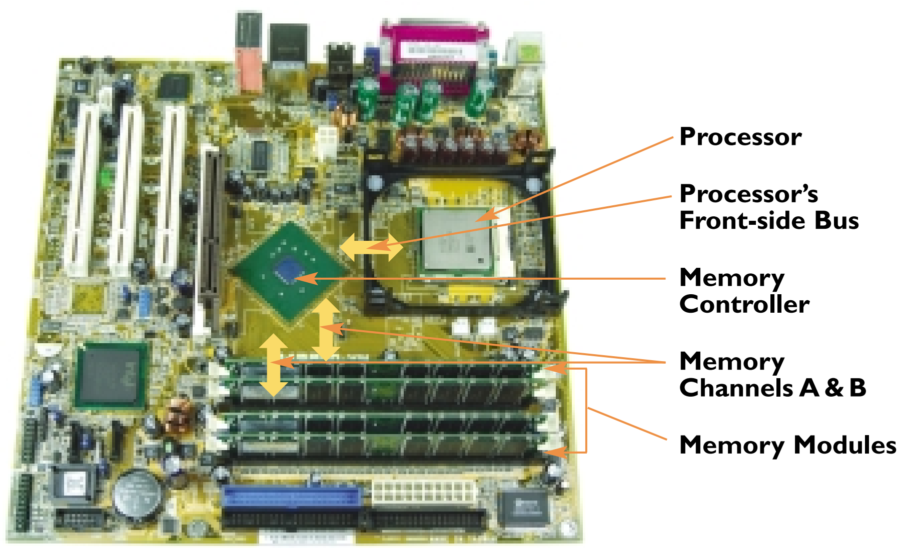


The Memory Controller manages all movement of data between the processor and the memory modules. Data is sent to the Memory Controller (which is part of a computer motherboard's "chipset"). The Memory Controller is like a traffic signal that regulates data transfer either to memory modules for storage, or to the processor for data manipulation or "crunching". Graphically, this architecture is pictured below:

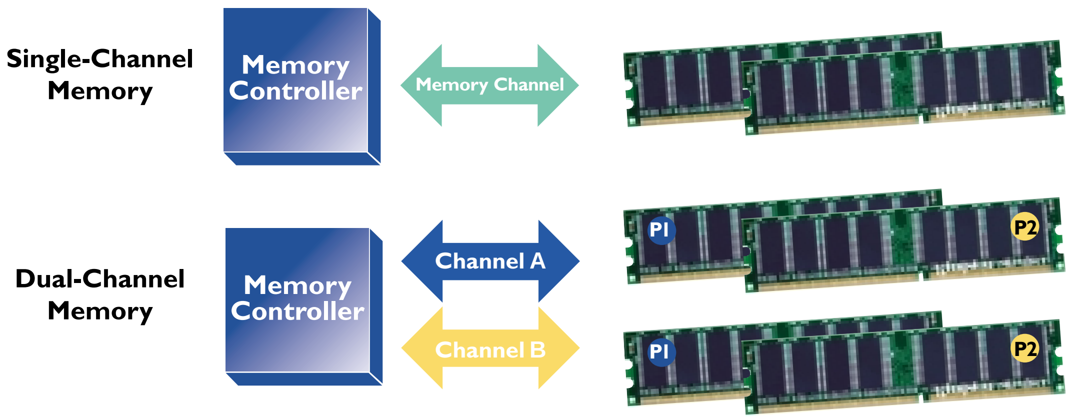




Data moves through the funnel's pipe in one direction at a time (just like a one-lane bridge that can be used in both directions, but only one car can cross it at a time). The memory controller acts like a traffic signal that directs the movement of data across the memory channel. For example, data arriving to the Memory Controller is first stored in the memory modules (2), then is re-read (3) and finally transferred to the processor (4). On a typical motherboard, these same components can be easily identified:



Dual-channel memory, as pictured below, doubles the maximum amount of data that can be transferred between the processor and the memory modules.



With dual-channel memory, the memory controller is able to move double the peak amount of data that it could normally move with single-channel memory. That's because it is sending or receiving data from two memory module pairs at the same time (shown as module pairs "P1" and "P2" in the graphic above).

The memory industry generally describes memory performance in Peak Data Bandwidth or simply, Peak Bandwidth in seconds.

3.0 Peak Bandwidth

One way to describe the maximum data throughput of memory is to calculate its Peak Bandwidth. This calculation, expressed in number of Bytes per second (1 Byte = 8 bits where bits, represent either a '0' or a '1', are the smallest unit of data a computer uses), gives a general idea of the performance of the memory (which we will later compare to the processor's bandwidth).

The table on the next page shows the Peak Bandwidth of DDR memory technologies available today. In single-channel mode, the Memory Controller moves 64 bits of data at a time whereas in dual-channel mode, it can move double that amount or 128 bits of data. In our "funnel" analogy, this is equivalent to a single funnel transferring 64 bits to the processor while having two funnels allows us to transfer 128 bits to the processor during the same timeframe.

PEAK BANDWIDTH	DATA BITS ACCESSED	PC-133	PC2100 DDR266	PC2700 DDR333	PC3200 DDR400
Single-Channel	64	1.1GB/s	2.1GB/s	2.7GB/s	3.2GB/s
Dual-Channel	128		4.2GB/s	5.4GB/s	6.4GB/s

Peak Bandwidth is calculated as:

Memory Speed x Number of bytes transferred per channel x Number of Channels
(its data rate) (8 Bytes or 64 bits) (one or two)

For PC3200, also known as DDR400, modules on a dual-channel motherboard,

Peak Bandwidth = (400 MHz) x (8 Bytes) x (2 Channels)
= 6400 Megabytes per second (MB/s)
or 6.4 Gigabytes per second (GB/s)

4.0 Looking at the Processor's Front-Side Bus

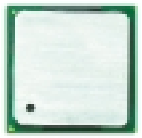
A processor's link to the memory controller is called the processor's front-side bus (FSB). The FSB is the "high-speed highway" that interfaces to the processor.

The front-side bus determines how fast the processor can obtain data from the memory controller. The speeds of the newest processors are now so fast that there are times when the processor remains idle, waiting for more data from memory. To increase efficiency, the memory controller needs to send data as fast as the processor can receive it (and store it back into memory modules as fast as the processor can "pump" the data out). Peak efficiency is only reached when the data throughput from the processor's front-side bus matches the memory modules' throughput.

Intel's newest Pentium4 processors have front-side bus architectures operating at data speeds of 533MHz and 800MHz. This translates to a peak data bandwidth of 4.2GB/s (533MHz x 8 Bytes) and 6.4GB/s (800MHz x 8 Bytes) respectively.

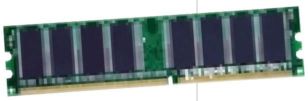
The following chart illustrates the Peak Bandwidth of the processor and memory:

P4 Front-Side Bus (FSB) Speed and Peak Bandwidth



P4/400 Being phased out	P4/533	P4/800 New for 2003	Faster FSB
3.2GB/s	4.2GB/s	6.4GB/s	

Best Memory Match*



PEAK PLATFORM BANDWIDTH	PC-133	PC2100 DDR266	PC2700 DDR333	PC3200 DDR400
Single-Channel	1.1GB/s	2.1GB/s	2.7GB/s	3.2GB/s
Dual-Channel		4.2GB/s	5.4GB/s	6.4GB/s

**Best match based upon system memory having a peak bandwidth equal to or greater than the processor's*

As this table shows, current P4 processors with 533MHz and 800MHz front-side bus speeds (also represented as "P4/533" and "P4/800") require dual-channel memory architecture for best performance and performance headroom – the ability to provide more performance for future applications.

For example, a single channel of PC3200 memory provides one-half the required bandwidth capacity for the P4/800 processor. For demanding applications, in the single channel mode, the processor will be "starved" for data.

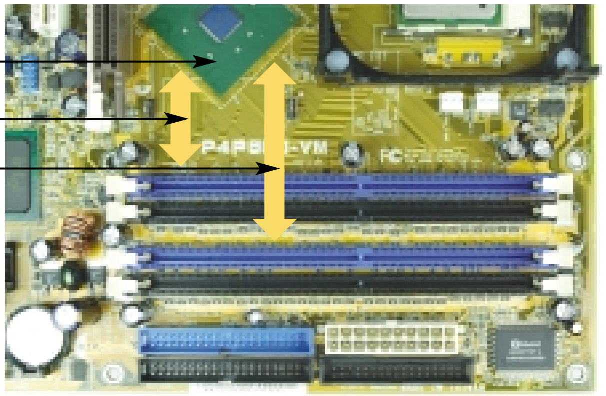
As front-side bus bandwidth of future processors increases, memory performance will need to exceed what is currently offered by dual-channel PC3200 platforms.

5.0 Enabling Dual-Channel Memory

The majority of systems supporting dual-channel memory can be configured in either single-channel or dual-channel memory mode. An important fact to keep in mind is that even if a new computer or motherboard supports dual-channel DDR memory, this does not necessarily guarantee that both memory channels are being utilized in dual-channel mode.

It is not sufficient to just plug multiple memory modules into their sockets to get dual-channel memory operation–computer users need to follow specific rules when adding memory modules to ensure that they get dual-channel memory performance. Otherwise, their system may fall back to single-channel memory mode. Why pay for a Ferrari and limit yourself to only using first gear?

Most dual-channel systems will have four memory DIMM sockets. Two sockets belong to channel A and the other two sockets to channel B.

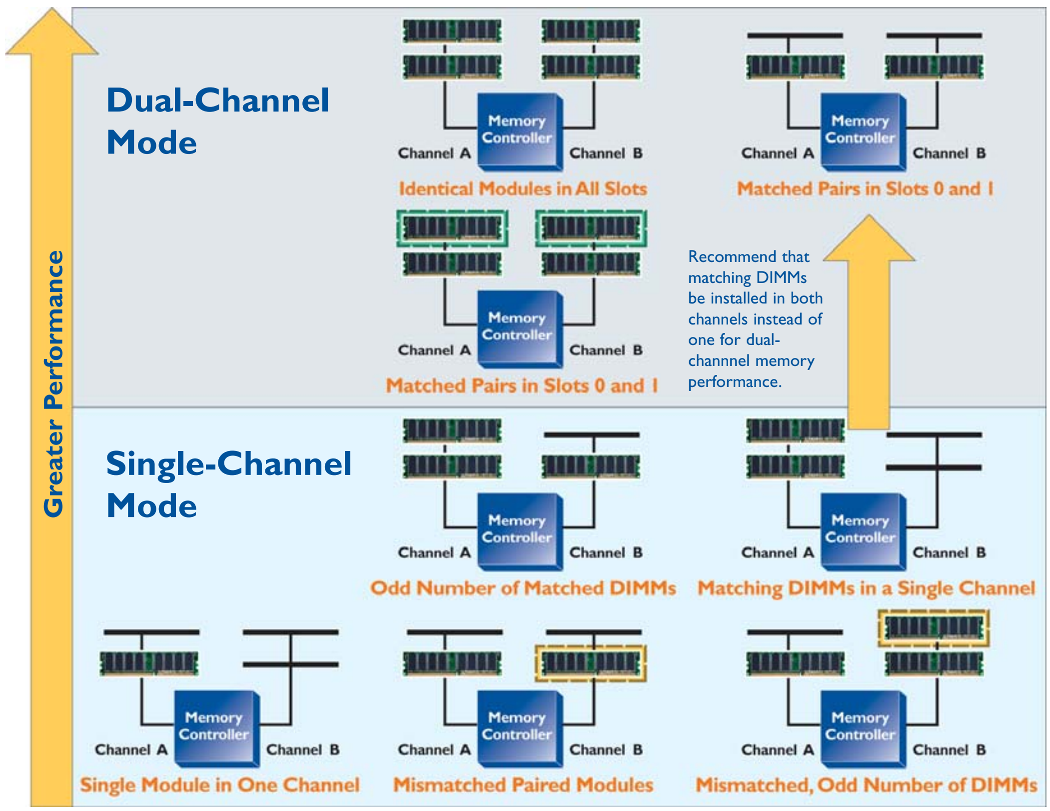


For the best dual-channel memory performance on motherboards with the Intel dual-channel DDR chipsets, you must use identically paired memory modules in DIMM sockets 0 of channel A and B. Identically paired memory modules must also be used when populating DIMM sockets 1 of channel A and B. One can, for example, plug in matching 256MB DIMMs in both DIMM 0 slots, and plug in matching 512MB DIMMs in both DIMM 1 slots.

In this context, "matching" modules means:

1. Both modules are the same capacity (e.g. both are 256MB, or 512MB)
2. Both modules are the same speed (e.g. both are PC2700 or PC3200)
3. Both have the same number of chips and module sides (e.g. both have the same number of chips on the module, and both are either single-sided or double-sided).

For the Intel platforms based upon the Intel 865 or 875 chipsets, the rules can be summarized as follows:

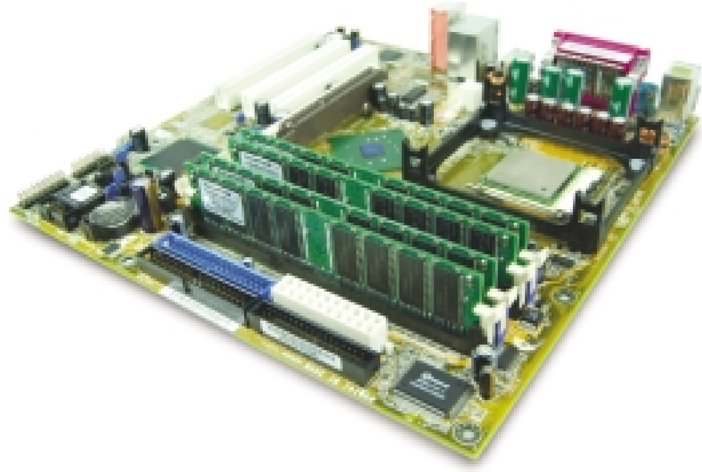


Ideally, with each channel limited to two DIMM sockets, a minimum of two 256MB memory modules should be used for a total memory capacity of 512MB. Only low-end, low-cost systems typically come with a pair of 128MB modules. These 128MB modules are gradually being phased out and will become harder to find as the memory "sweet spot" today is 256MB DIMMs (the "sweet spot" corresponds to the majority of modules shipped in the industry and also offer the best performance to price ratio).

6.0 Performance Benchmarking

Infineon Technologies has conducted benchmark testing to provide computer users with comparisons between memory speed and single- vs. dual-channel memory architectures.

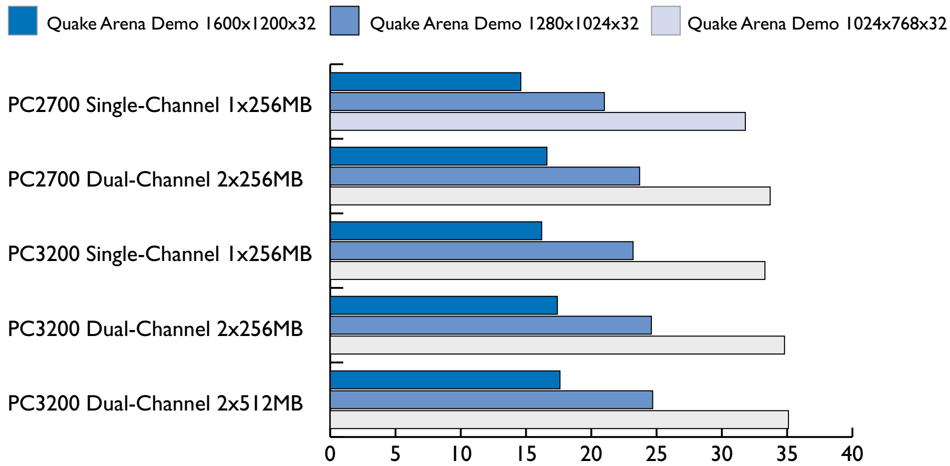
Infineon's benchmark used an Asus® P4P800-VM motherboard, which incorporates the Intel 865G chipset (code-named "Springdale"). The memory modules used in the benchmarking were Kingston DDR400 KVR400X64C25/256 and /512 memory modules, and DDR333 KVR333X64C25/256 and /512 memory modules utilizing Infineon's DDR DRAM chips.



Since different graphic cards can often skew benchmark results, a motherboard with a built-in graphics chipset was selected. Using the motherboard's built-in graphic capabilities may produce lower test scores in 3D graphic benchmarks, but will better match the expected results with systems sold to business and home users without a high-performance graphics card. When reading the benchmark test results, only the relative performance differences between the different memory configurations are meaningful.

6.1 FUTUREMARK'S 3DMARK2001 BENCHMARK:

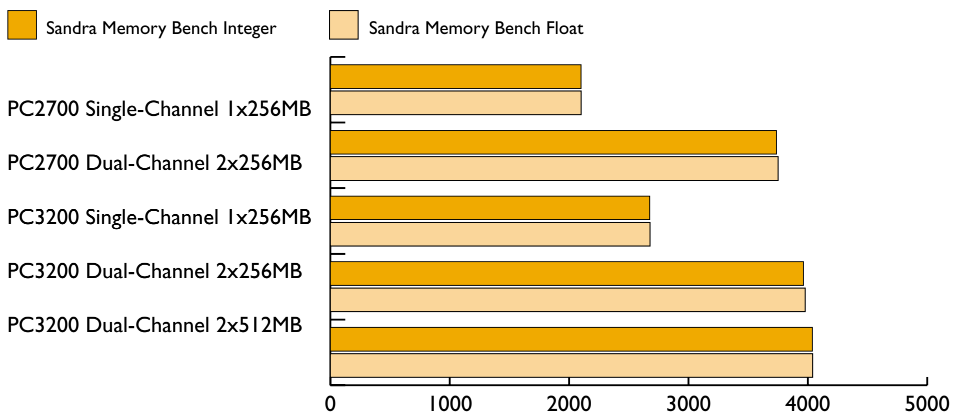
In this industry-standard benchmark showing 3D graphical performance, going from single- to dual-channel PC3200 memory increases system performance by over 15 percent. Going from single-channel PC2700 to dual-channel PC3200 increases performance by over 25 percent. In addition, system performance actually increased by nearly 5 percent when 1GB of total memory was used instead of 512MB.



6.2 idSOFTWARE'S QUAKE III BENCHMARK:

Another popular 3D benchmark, Quake3 Arena, was used to show the relative frames per second (FPS). Just as in the 3DMark benchmark, going from single-channel to dual-channel memory visibly increases system performance.

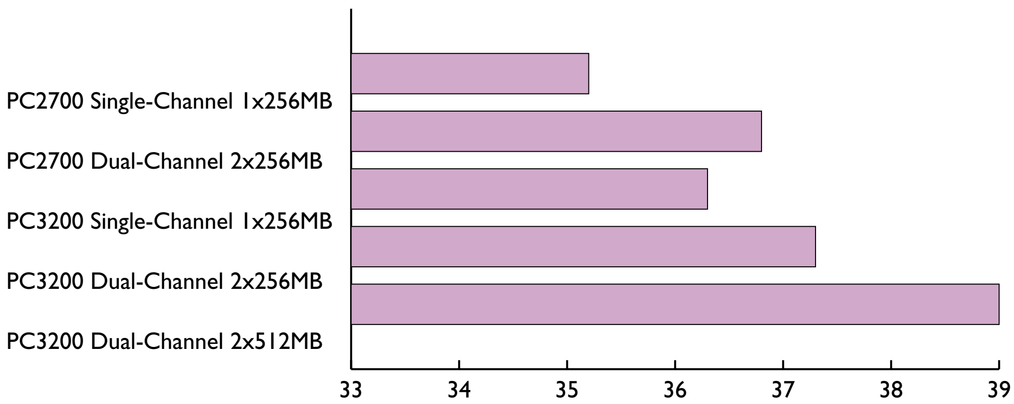
6.3 SISOFTWARE'S SANDRA STANDARD MEMORY BANDWIDTH BENCHMARK:



This benchmark measures the sustainable memory bandwidth (in MB/s).

As expected, memory bandwidth increases by nearly 50 percent going from single-channel PC2700 to dual-channel PC3200. Once again, increasing total memory to 1GB also increases the memory bandwidth, albeit only by a few percentage points.

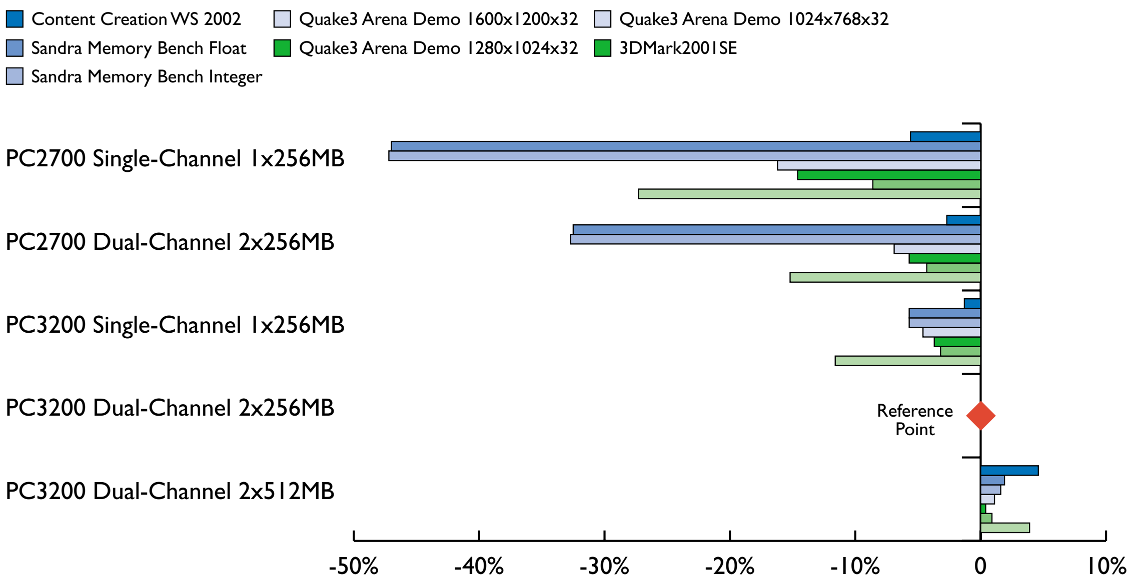
6.4 VERITEST® MULTIMEDIA CONTENT CREATION WINSTONE BENCHMARK:



This Multimedia Content Creation benchmark utilizes many real-world multimedia applications such as Adobe® Photoshop, Macromedia® Director, and Microsoft® Windows Media Encoder. Once again, the dual-channel PC3200 memory delivers the best performance. And just as in the 3D benchmarks, increasing the system memory from 512MB to 1GB also increases the performance in the area of content creation.

7.0 Benchmark Summary

If we combine all the benchmark results and use the performance of PC3200 DIMMs, 2x256MB modules as the baseline, we can look at the performance gains or losses by using slower memory modules and varying the number of channels.



8.0 Conclusion

Dual-channel DDR memory systems offer a new level in system performance. Considering the low memory prices enjoyed by computer customers in the last few years, combining faster memory speeds with dual-channel memory platforms creates a new price/performance value level as shown in the benchmarks.

Dual-channel memory performance is only realized when matched memory modules are added in pairs, and installed in the correct socket configurations. Otherwise, a system will revert to the lower-performing, single-channel memory mode.

Dual-channel memory is here to stay. As the next-generation DDR2 memory ramps up in 2004, we can expect to see more dual-channel memory platforms requiring even faster memory than those available today.

ABOUT INFINEON

Infineon Technologies AG, Munich, Germany, offers semiconductor and system solutions for the automotive and industrial sectors, for applications in the wired communications markets, secure mobile solutions as well as memory products. With a global presence, Infineon operates in the US from San Jose, CA, in the Asia-Pacific region from Singapore and in Japan from Tokyo. In fiscal year 2002 (ending September), the company achieved sales of Euro 5.21 billion with about 30,400 employees worldwide. Infineon is listed on the DAX index of the Frankfurt Stock Exchange and on the New York Stock Exchange (ticker symbol: IFX).

ABOUT KINGSTON

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