

# Parallel Computer Architecture

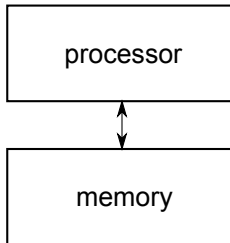
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February 4, 2022

# Architecture

- Multiprocessor
- Multicomputer
- Flynn's Taxonomy

# Uniprocessor



- This is how we think of a computer.

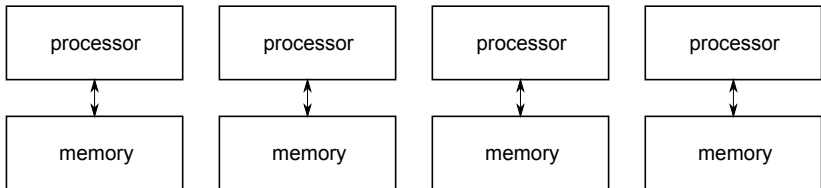
# Uniprocessor

- It has a single processor for computation.
- It has a single memory for storing instructions and data.
- The CPU fetches instructions from memory, executes the instructions, updates the contents of registers and possibly data in the memory, and then repeats.
- Intel 486, Pentium, etc.

# Multiple Uniprocessors

- It is intuitive to have multiple uniprocessors working together to have high performance.
- We believe that we can solve the problem faster if we have more processors working together.
- How do they work *together*?

# Work Together?

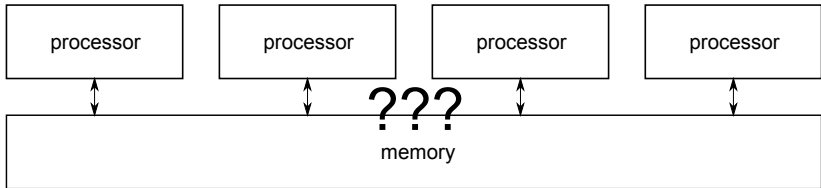


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# Communication

Processors must communicate to coordinate their actions, and exchange data if necessary.

# Work Together?



- We cannot simply connect all processors to a memory.
- The memory will be in an *inconsistent* state.



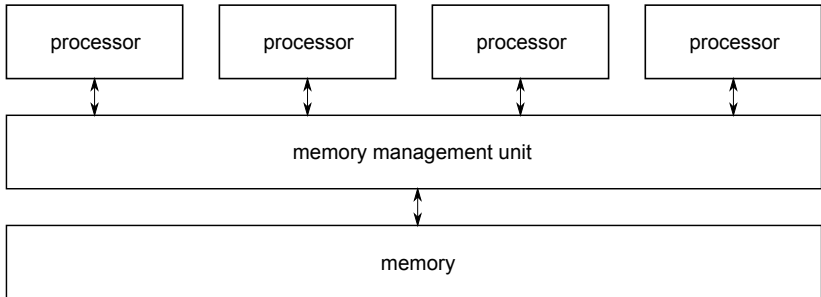
# Race Condition

- Suppose two processors want to add 1 to the same counter.
- The first processor fetches the old contents of the counter and adds 1 to it.
- Before the first processor can store the new content, and the second processor fetches the old content.
- The first processor now stores its new content to memory.
- The second processor adds 1 to the old content and stores the new content back to memory.
- The counter only increases by 1, which is *incorrect*.
- More details later.

# Multiple Uniprocessors

- We put a *memory management/arbitration unit* between the processors and the memory so that every processor can access memory.
- This memory management unit must be very efficient in providing *point-to-point* data transfer so as to provide fast memory access for every processor.

# Multiprocessor



# Discussion

- What could happen if three processors want to add 1, 2, and 4 into a memory with an initialized value 0?

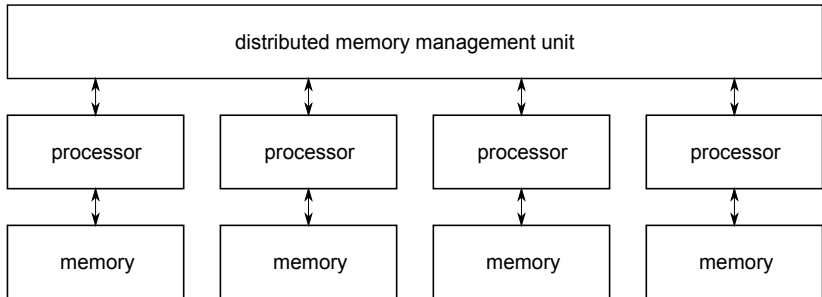
# Shared Memory

- Logically we do not care about the memory management unit – we simply believe that every processor can access this *shared memory*.
- This shared memory provides a *shared addressing space* for all processors.
- This *shared* memory is also a *global memory*.
- The cost for every processor to access every part of the memory is the same, and then we have Uniform Memory Access (UMA).

# Distributed Shared Memory

- It is a distributed version of shared memory.
- Every processor has local memory, and the collection of the local memory forms a global memory.
- We connect the processors to a memory management unit, which determines the address is local or remote.

# Multiprocessor



# Distributed Multiprocessor

- If the address is local, then it is retrieved from the local memory.
- If the address is remote, it is retrieved from someone else's local memory.
- The cost for every processor to access every part of the memory is *not* the same, then we have Non-Uniform Memory Access (NUMA).



# Discussion

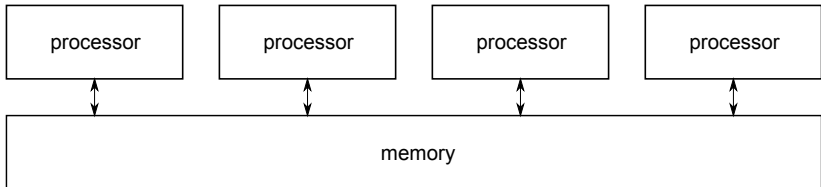
- Describe the difference between NUMA and UMA.

# Multiprocessor

- Logically we do not care about the memory management unit – we simply believe that every processor can access this *shared memory*.
- This shared memory provides a *shared addressing space* for all processors.
- This *shared* memory is also a *global memory*.

# A Logical View

- In summary, we can think of our multiprocessor is like this.



# Multiprocessor

- Conceptually multiple processors are connected by a shared memory – that is all we need to know in terms of programming.
- In some programming models, we still need to consider the possibility of race condition and use the construct provided by the programming model to avoid it.

# Functions

- Every processor has its computing resource, like ALU, registers, etc., so you can run multiple processes on them simultaneously.
- Every processor works on its assigned tasks using its computing resource.
- Every processor can read and write the shared memory to communicate or synchronize with other processors.

# Synchronization

- Processor can synchronize with each other by shared memory.
- For example, in a barrier synchronization, a processor cannot proceed until all others have reached the same conclusion.
- We can set a shared variable count. Every finished processor adds 1 to count. When the value of count reaches the number of processors, then every processor knows that it has synchronized with everyone.

# Discussion

- Describe the dependency graph using *functions* and *synchronization*.

# Memory Conflict

- Multiple processors can access the memory at the same time, causing conflicts.
- When a computation has different outcome due to different execution order, we have a *race condition*.



# An Example

- Suppose two processors want to add their variable  $n$  together into a global variable  $sum$ .
- Processor 1 has  $n = 3$  and processor 2 has  $n = 4$ .
- The computation consists of the following.
  - Load  $sum$  into a register  $r1$ .
  - Add your  $n$  into  $r1$ .
  - Store register  $r1$  back to  $sum$ .

# Race Condition

- Now imagine what will happen when P1 and P2 are doing this simultaneously.
- How many different outcomes could there be? Please try to enumerate them.

# Software Solution

- Programming environment must provide mechanism that prevents race condition.
- Critical section, lock, synchronization, etc.
- More specific details will be provided when we discuss parallel programming.

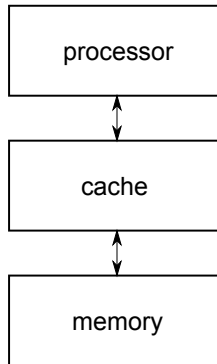
# Discussion

- Describe the concept “critical section”.

# Cache

- To make the case even worst, we need to deal with the cache.
- Cache is fast memory, usually small and expensive.
- To improve performance, we put often-used data/instructions in a cache. If we need the data/instructions again, we can access them in the fast cache instead of the slow main memory.

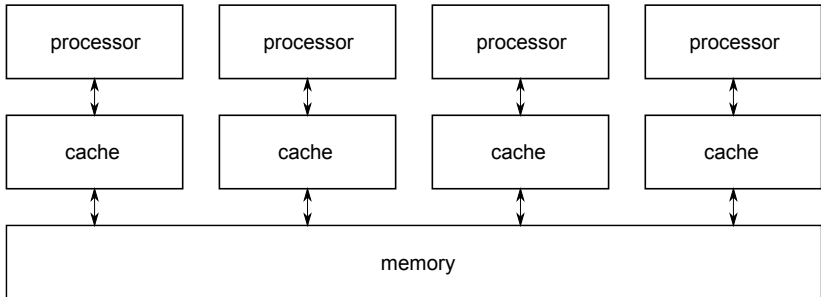
# Cache for Uniprocessor



# Race Condition

- Now every processor has a cache, and it can take data from its cache, not the main memory.
- Suppose one processor changes the content of the memory, what should happen to the cached data in some processor's cache?
- If one processor changes the data in its cache, would other processor be able to notice this change?

# Cache





# Hardware Solution

- The hardware must guarantee that the memory and cache are in a consistent state. There are various levels of guarantees.
- If one processor changes the content of the memory, the hardware should invalidate data that other processors have cached.
- If one processor changes the data in its cache, other processors should be able to see it.

# Writing Policy

**Write-through** Write is done synchronously both to the cache and to the backing store.

**Write-back** Initially, writing is done only to the cache. The write to the backing store is postponed until the cache blocks containing the data are about to be accessed by others.

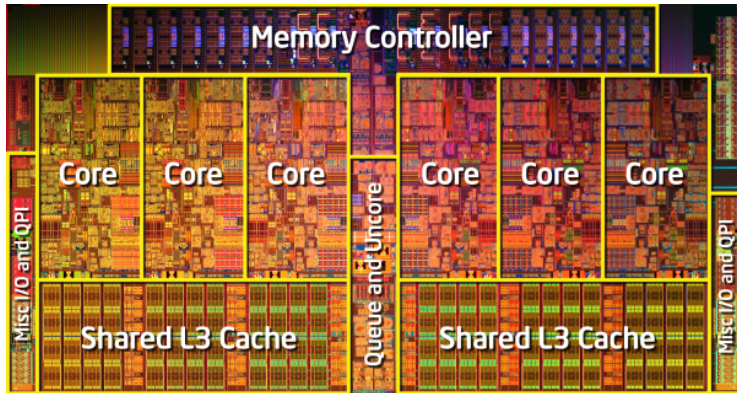
# Discussion

- Describe the difference between “Write-through” and “Write-back” caching.

# Intel Gulftown CPU

- Core i7-9xx
- 6 cores
- 32nm
- 12MB L3 cache
- Introduced January 2011.

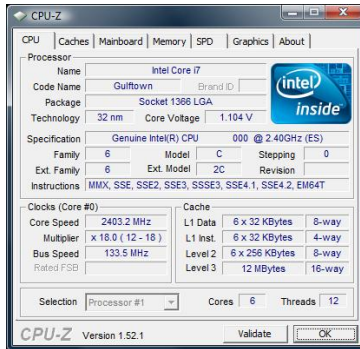
# Gulftown



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<sup>1</sup><http://gizmodo.com/5491045/intels-6+core-gulftown-gets-tested-blows-us-away>

# Gulftown



2

<sup>2</sup><http://global.hkepc.com/database/images/2009/08/source/1015564707405292968.jpg>

# Gulftown

- The memory controller controls and coordinates the access to a shared memory.
- Cores can communicate with the queue.
- Three cores share two L3 caches.
  - Shared L3 cache indicates that if we place wrong processes/threads into the cores that share the L3 cache, the performance will suffer.

# Intel CPU's

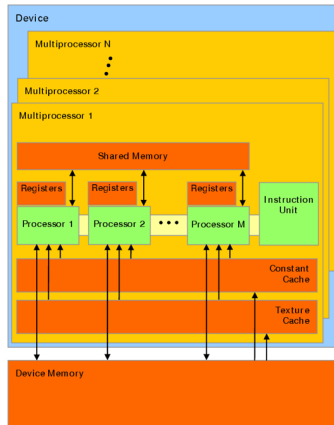
- You can find all the facts of Intel CPU here.
- <http://www.intel.com/pressroom/kits/quickreffam.htm>



# Nvidia Tesla

- The Tesla graphics processing unit (GPU) is Nvidia's third brand of GPUs.
- Tesla is based on high-end GPUs from the G80 (and on), as well as the Quadro lineup.
- Tesla is Nvidia's first dedicated *General Purpose GPU* (GPGPU).
- [http://en.wikipedia.org/wiki/Nvidia\\_Tesla](http://en.wikipedia.org/wiki/Nvidia_Tesla)

# GPU Architecture



A set of SMT multiprocessors with on-chip shared memory.

Figure 3-1. Hardware Model

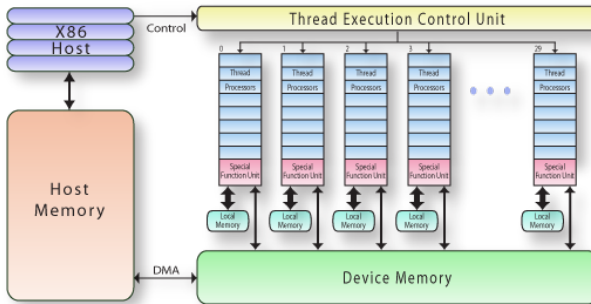
# Nvidia Tesla



# C1060

- 240 processors at 1.30 GHz.
- 4096 MB of GDDR3 memory.
- 102.4 GB/s memory bandwidth.
- 933.12 GFLOPs single precision, 77.76 GFLOPs double precision.

# Tesla Architecture



# Characteristics

- A GPU is a device that needs a host to provide data and instructions.
- A GPU has many cores – usually much more than a CPU.
- CPU cores receive instructions from the host for execution, which means they must run the same set of instructions.
- GPU cores have their local memory and share a device memory.
- More details in the “OpenCL” lectures.

# Discussion

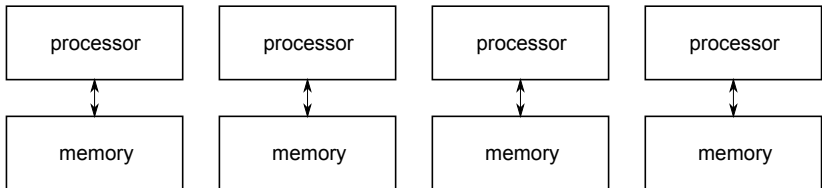
- Describe the difference between CPU and GPU.

# Multiple Uniprocessor

- It is intuitive to have multiple uniprocessors working together to have high performance.
- How do they work *together*?



# Work Together

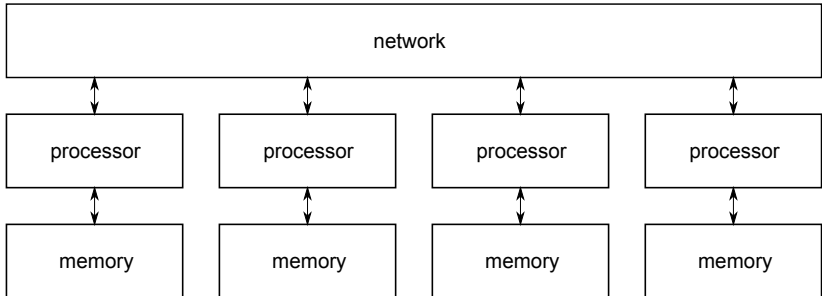


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# Multiple Uniprocessor

- We connect all the computers with a *network*, so they can send *messages* to each other.
- This network could be very slow or fast, depending on the applications.
- The network must provide *point-to-point* data transfer to move data from one processor to another.
- Processors can only synchronize themselves via the network, which is a difficult task.

# A Network



# Functions

- Every processor works on the tasks assigned to it, using its own computing resource.
- Every processor can send message to each other, so as to communicate or synchronize with other processors.

# Multicomputer

- Sometimes we use the term “node”, since these processors are by themselves “computers”.
  - Remember the 16,000 nodes in the Tianhe 2 cluster.
- Each node has its own CPU's, memory, even I/O devices.
- The nodes can communicate with each other by the network, usually through standard TCP/IP protocol.

# Memory

- There is no *shared addressing space* for all processors – each processor use its own memory.
- The memory of every processor is called *local memory*.
- Since a memory is accessed by only one processor, we do *not* have memory conflict.

# Synchronization

- Processor can synchronize with each other by messages.
- In a barrier synchronization, a processor cannot proceed until all others have reached the same conclusion.
- Every processor sends a message to a master after finishing its work.
- When the master receives a message from every processor, he knows everybody has finished.
- The master sends a message to everyone that it can continue.

# Discussion


- Compare the way multicomputer and multiprocessor does a barrier synchronization.



# Network

- We do care about the network – a fast network provide better connectivity.<sup>3</sup>
  - Ethernet 10Mbit/s
  - Fast Ethernet 100Mbit/s
  - Gigabit Ethernet 1 Gbit/s
  - 10 Gigabit Ethernet 10 Gbit/s
  - Myrinet 10 Gbit/s
  - 100 Gigabit Ethernet 100 Gbit/s
  - InfiniBand (12X EDR) 300 Gbit/s

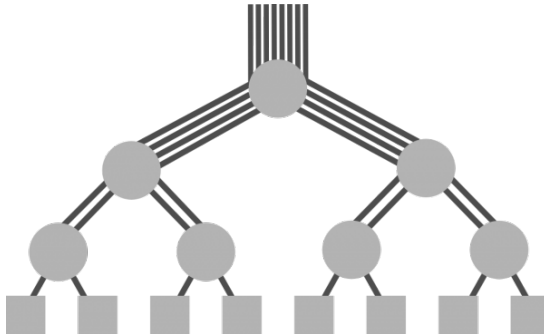
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<sup>3</sup>[http://en.wikipedia.org/wiki/Network\\_bandwidth](http://en.wikipedia.org/wiki/Network_bandwidth) 

# Topology

- We cannot connect a large number of nodes to a single switch, so the topology of the network becomes important.
  - Ring
  - Tree and fat tree
  - Two or higher dimensional mesh and torus
  - Hypercube
  - FFT (butterfly)

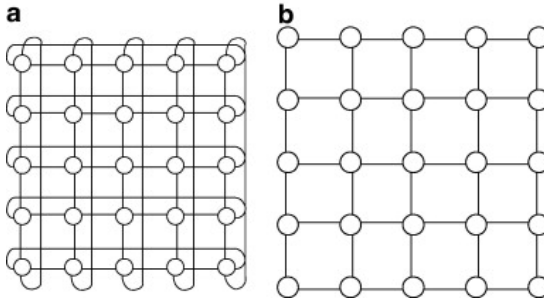
# Fat Tree



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<sup>4</sup>[http://clusterdesign.org/wp-content/uploads/2012/02/fat\\_tree\\_varying\\_ports-600x365.png](http://clusterdesign.org/wp-content/uploads/2012/02/fat_tree_varying_ports-600x365.png)

# Mesh and Torus



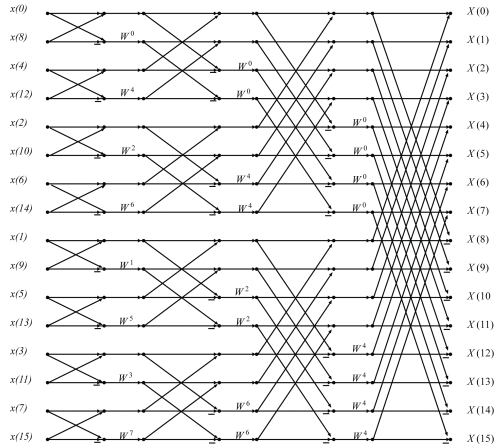
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<sup>5</sup>[http:](http://ars.els-cdn.com/content/image/1-s2.0-S1383762107000495-gr2.jpg)

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# FFT



# Trend

- The most popular topology appears to be fat tree.
  - For example, the Tianhe 2 cluster connects all its processors with 13 switches as fat tree.
- Two or higher dimension torus are also popular.
  - The Tofu network of K-computer is a six dimensional torus.

# Discussion

- What is the difference between torus and a mesh?

# Massively Parallel Computer

- A computer cluster consists of a set of *tightly* connected *high performance* computers that work together so that in many respects they can be viewed as a single system.
- Tightly connected means they connected by *fast* network.
- The performance is paramount and usually achieved by aggregation of a large number of processors.



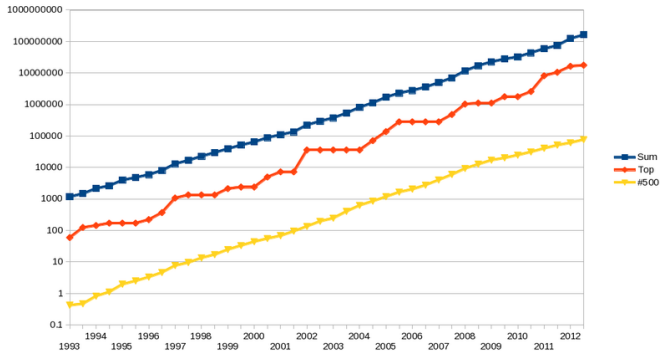
# Top 500

- The TOP500 project ranks and details the 500 most powerful (non-distributed) computer systems in the world.
- The project aims to provide a reliable basis for tracking and detecting trends in high-performance computing and bases rankings on HPL, a portable implementation of the High-Performance LINPACK benchmark written in Fortran for distributed-memory computers.<sup>7</sup>

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<sup>7</sup><http://top500.org/>

# Top 500



- Exponential growth of supercomputers performance, based on data from top500.org<sup>8</sup>.

<sup>8</sup><http://en.wikipedia.org/wiki/File:Supercomputers.png>

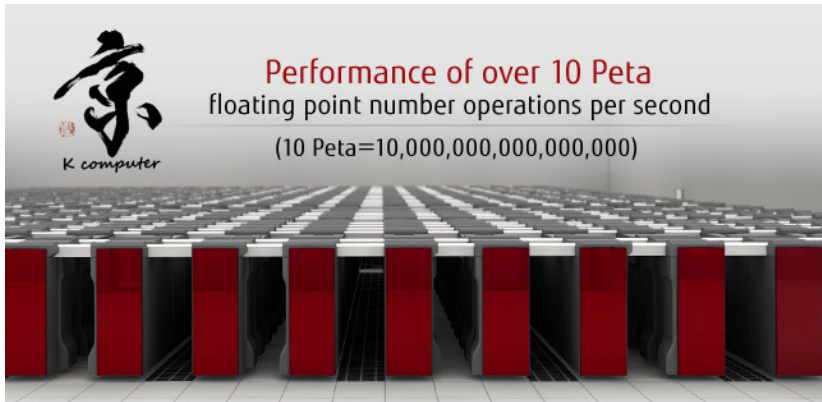
# K computer

- The K computer – named for the Japanese word “kei” (京), meaning ten quadrillions ( $10^{16}$ ).
- A supercomputer manufactured by Fujitsu, currently installed at the RIKEN Advanced Institute for Computational Science campus in Kobe, Japan.
- In June 2011, TOP500 ranked K the world's fastest supercomputer, with a rating of over eight petaflops, and in November 2011, K became the first computer to top 10 petaflops.<sup>9</sup>

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<sup>9</sup>[http://en.wikipedia.org/wiki/K\\_computer](http://en.wikipedia.org/wiki/K_computer)

# K Computer



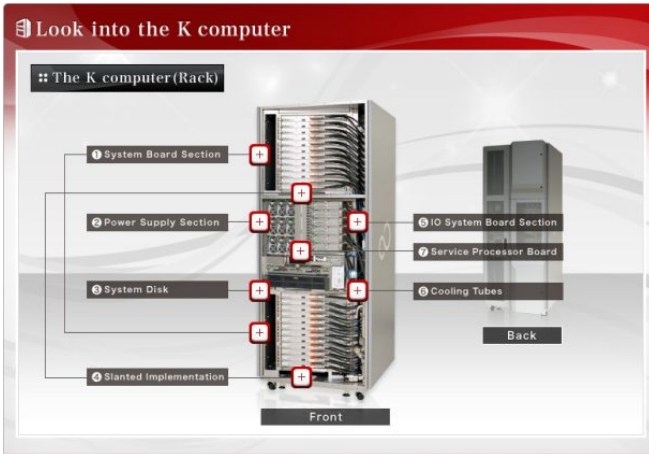
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<sup>10</sup>[http://cdn0.sbnation.com/entry\\_photo\\_images/2197300/k-computer\\_large\\_verge\\_medium\\_landscape.jpg](http://cdn0.sbnation.com/entry_photo_images/2197300/k-computer_large_verge_medium_landscape.jpg)

# Configuration

- 864 cabinets, 88,128 SPARC64 VIIIfx processors, over 640,000 cores.
- A proprietary six-dimensional torus interconnect called Tofu.
- A two-level local/global file system with parallel/distributed functions, which provides users with an automatic staging function for moving files between global and local file systems.
- Linux operating system.
- 9.89 MW – the equivalent of almost 10,000 suburban homes.

# K Computer



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<sup>11</sup><http://cdn-static.zdnet.com/i/story/30/40/093162/k-computer-riken-4.jpg>

# Discussion

- What is the difference between K-computer and Tianhe 2?

# Cluster

- A computer cluster consists of a set of *loosely* connected computers that work together so that in many respects they can be viewed as a single system.
- Loosely connected means they are *not* connected by fast network.
- An economical alternative to those who cannot afford expensive parallel computers.



# TrendMicro Cluster

- A cluster donated by TrendMicro for the Cloud Computing Program.
- Loosely connected means they are not connected by fast network.
- A economical alternative to those who cannot afford expensive parallel computers.

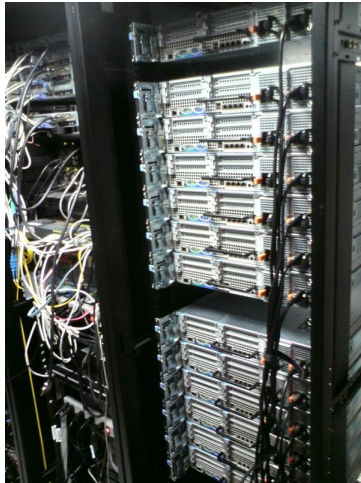
# Configuration

- 1 cabinet, 15 Intel X5570 quad-core processors, 120 cores.
- A standard Ethernet switch.
- Gluster file system.
- Roystonea operating system, developed by the Parallel and Distributed Processing Laboratory, Department of Computer Science and Information Engineering, National Taiwan University.
- Never made it to top 500.

# TrendMicro Cluster



# TrendMicro Cluster



- We (the Parallel and Distributed Processing Laboratory) learn many things in building Roystonea for the Trend cluster.
- We learned network virtual machine management, virtual machines deployment, network management for the cluster, distributed file system for the cluster, distributed database, and NoSQL database for a cloud system.
- We built a cloud OS called “Roystonea” to manage the Trend cluster.
- These experiences later enable us to take on more ambitious projects, like optimizing the billing system of Chunghwa Telecommunication.

# Discussion

- What does the name “Roystonea” come from?

# Flynn's Taxonomy

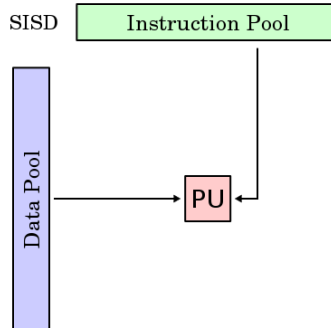
- Single instruction stream and multiple instruction stream.
- Single data stream and multiple data stream.
- We have four combinations – SISD, SIMD, MISD, and MIMD.

# SISD

- SISD (single instruction, single data)
- A computer architecture in which a single uniprocessor executes a single instruction stream to operate on a data stream.
- Standard von Neumann architecture.



# SISD



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<sup>12</sup><http://en.wikipedia.org/wiki/SISD>

# Old School

- This is how we have been doing – sequential programming.
- The compiler for sequential programming is quite mature and can transform source program into efficient binaries.
- System support for sequential programming, e.g., system call, user library, debugging are also very useful.

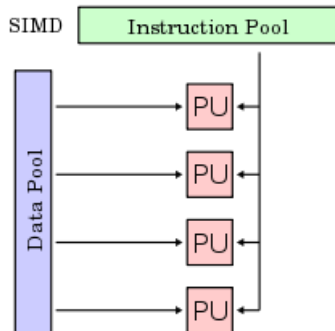
# Discussion

- Give an example of SISD machine.

# SIMD

- Single instruction, multiple data (SIMD)
- A computer architecture in which multiple processors execute a single instruction stream to operate on multiple data streams.

# SIMD



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<sup>13</sup><http://en.wikipedia.org/wiki/SIMD>

# SIMD

- SIMD is strongly related to data-parallel programming since it applies the same instruction to different data and achieves high performance by data parallelism.
- The architecture of GPUs follows the SIMD model – the host issues the same command to all processors to process a large amount of data simultaneously.

# Discussion

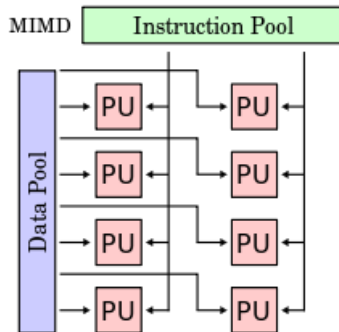
- Give an example of SIMD machine.

# MIMD

- Multiple instruction, multiple data (MIMD)
- A computer architecture in which multiple processors execute multiple instruction streams to operate on multiple data streams.



# MIMD



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<sup>14</sup><http://en.wikipedia.org/wiki/MIMD>

# MIMD

- Strongly related to functional parallelism since different processors execute different instructions on different data.
- The instructions are different because they are from different tasks in a wavefront, i.e., tasks that can run in parallel.
- The data are different because they are for different tasks.
- Most multicomputers support the MIMD computation model – computers work independently and synchronize themselves when necessary.

# Discussion

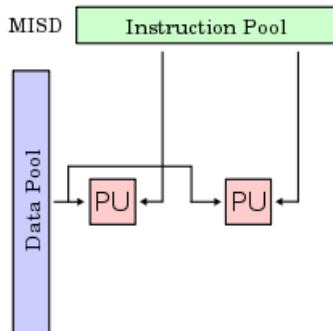
- Give an example of MIMD machine.

# Wait! You forgot MISD!

# MISD

- Multiple instruction, single data (MISD)
- A computer architecture in which multiple processors execute multiple instruction streams to operate on a single data stream.
- Does it make sense to you?

# MISD



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<sup>15</sup><http://en.wikipedia.org/wiki/MISD>

# Fault Tolerance

- If we consider MISD as multiple copies of SISD, it can tolerate faults.
- The same computation is repeated multiple times by different processors so that at least they can deliver the results even if some of them fail.
- For example, in Google MapReduce computation, certain tasks are duplicated exactly for fault tolerance and performance improvement.

# Discussion

- Give an example of MIMD machine.