

HELP US ALL STAY HEALTHY

SIX SIMPLE TIPS



IF YOU ARE UNWELL AND WORRIED ABOUT COVID-19:

- Call the National Coronavirus Helpline: 1800 020 080
- Call your usual GP for advice
- Call the UWA Medical Centre for advice: 6488 2118

UWA FAQs:
uwa.edu.au/coronavirus

Report COVID-19 hazards and suspected/confirmed cases via RiskWare:
uwa.edu.au/riskware



DCS507757531

High-Performance Comput



Lecture 1 Introduction to Computer Architecture

Acknowledgement: The lecture slides are adapted from many online sources.

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Teaching Staff Information



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 - Consultation**
 - 10:00 am to 11:00 am Tuesdays
 - Discussion forum for not personal questions in nature**
- Lab Facilitators
 - Amitava Datta, TBA**
 - Monday 4-6 pm
 - Wednesday 12-2 pm
- More information
 - ✓ <https://research-repository.uwa.edu.au/en/persons/amitava-datta>

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Assessments, Lectures and Labs



- Two programming projects: 50%**
 - Each project contributes 25%.
 - Project specifications will be available on the LMS page.
- Final examination: 50%**
- Lectures**
 - Face to face + recorded
- Laboratories**
 - Lab sessions start from Week 3.
- C/C++** will be used in this unit

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Textbooks and Recommended Readings



- No textbook needed for this unit.

Recommended Readings

- Using OpenMP: Portable Shared Memory Parallel Programming, by B. Chapman, G. Jost and R. van der Paas, MIT Press, 2008.
- Parallel Programming in OpenMP, by Rohit Chandra et al., Morgan Kaufmann, 2000.
- MPI – The Complete Reference, by Snir et al., MIT Press, 1996.
- MPI Tutorial: <https://mpitutorial.com/tutorials/>

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Should I Study CITS5507?



- This is a “programming” unit.
- You should study this unit, if
 - you enjoy programming,
 - it is a core unit for your degree
- It opens a new door for programming
 - parallel and distributed computing

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Outline of Today's Lecture



- What and why we are studying
- Computer architecture
 - ✓ Processor
 - ✓ Process and thread
 - ✓ Memory hierarchy
 - An example on cache line

Note: we will sometime call a computer as a machine.

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Why High-Performance Computing



- Most of the programs that you write, run almost instantaneously.
- There are programs that take a long time to run.
- People are solving larger and larger problems as computers are becoming faster and faster.
- Some programs never complete execution, e.g. weather simulation (and forecasting) programs.
- The speed of hardware can never keep up with the demands of faster execution of programs.

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- **What is meant by high-performance computing?**
 - ✓ The practice of aggregating computing power to deliver much higher performance than one could get out of a typical desktop computer or workstation.
 - ✓ To solve large problems in science, engineering or business.
- **High-performance computing**
 - ✓ Computations done on multiple machines, or a single machine with multiple/many cores.
 - ✓ About using all the compute resources when possible

- **Single machine is getting faster and cheaper**
 - ✓ Graphics Processing Units (GPUs)
 - ✓ Multi/Many core CPUs
 - ✓ AI Accelerators (e.g. Google TPUs)
- **HPC cluster with multiple machines**
 - ✓ Enormous data sizes
 - ✓ On-demand HPC infrastructure
 - ✓ Much faster networking capabilities



CPU vs TPU vs GPU



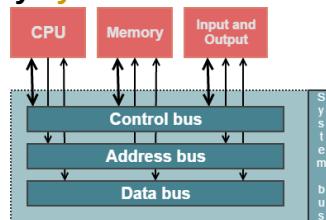
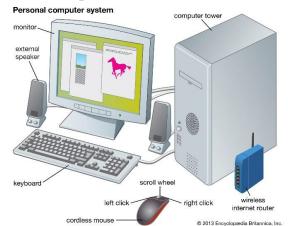
- Electronic computers were invented to perform computation, but we still need to design programs.
- Learning to write scalable code is something difficult to learn by yourself in a short time.
- Writing fast, reliable code will never go out of style.
 - ✓ Someone has to build the efficient tools
 - ✓ Large, numerical computations always exist
 - ✓ Most of the tools used in data-science, AI, etc. (e.g. Sklearn) are all high-performance codes.

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What is a Computer



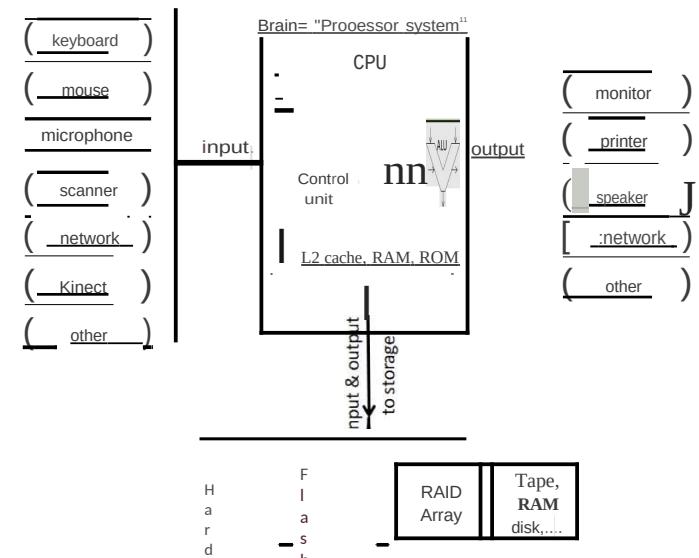
- A computer has three parts:**
 - ✓ the Central Processing Unit (CPU) or processor,
 - ✓ the memory, and some input/output (I/O) devices.
- The parts are connected by system bus.**



- For executing a program, it has to be first stored in the memory and then executed on the CPU.
- This is the '**von Neumann**' architecture used in all forms of computers today. It was first proposed John von Neumann.

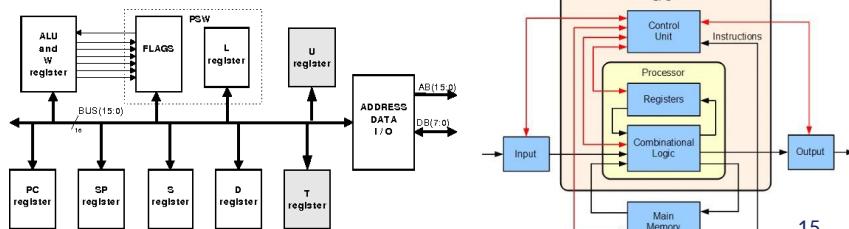
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What is a Computer (continued)



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A CPU

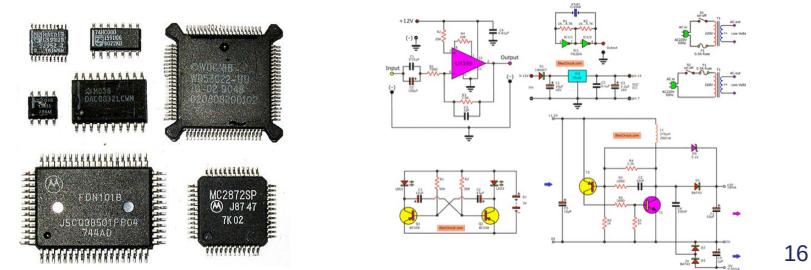


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Evolution of Processors



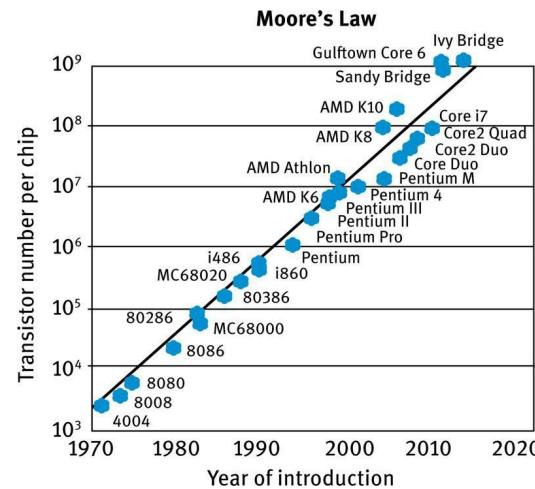
- Every computer (e.g. desktop/laptop and mobile) has a processor (usually an electronic chip).
- Processors become more and more powerful.
 - By packing **more and more** electronic circuits within a small chip area.



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Evolution of Processors—Moore's Law

- In 1965, Intel co-founder Gordon Moore predicted that semiconductor density would double every 18 months.
- Since the 2000s, there has been an ongoing debate about whether Moore's Law is still alive or dead.



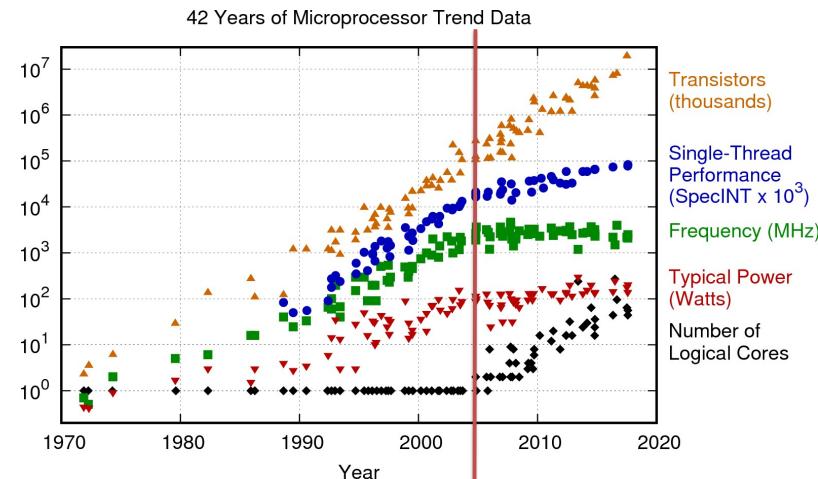
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Evolution of Processors

- Every computer (e.g. desktop/laptop and mobile) has a processor (usually an electronic chip).
- Processors become more and more powerful.
 - By packing **more and more** electronic circuits within a small chip area.
- Processors have almost reached the limits.
 - Physical limit:** how small the electronic circuit elements can be.
 - Thermal limit:** electronic circuits **generate heat** during their operations. Processors must be cooled.

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Evolution of Processors (continued)



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Multi-Core Processors

- The new trend has been
 - not to have a **single** core powerful processor,
 - but to have **several** less powerful cores in a processor (i.e. multi-core processor)
- The challenge is to make use of multi-core processors for executing programs faster.
 - We will learn techniques to make use of them.
- There are two related, but slightly different issues regarding this, **concurrency and parallelism**.

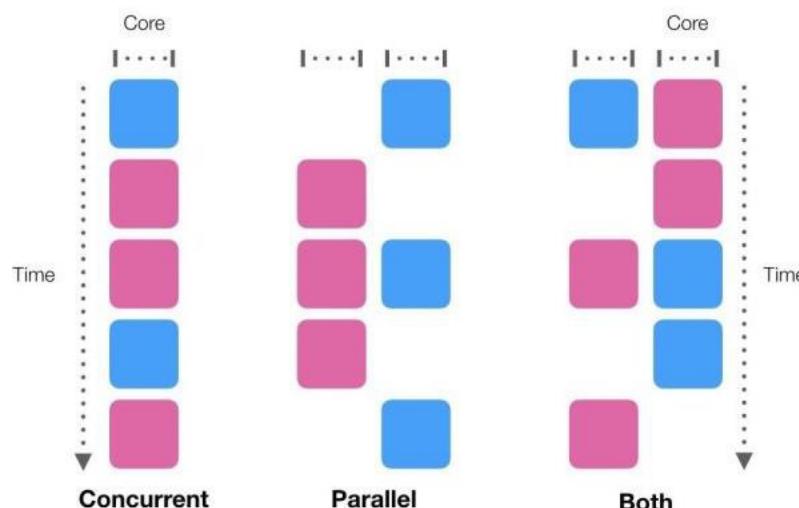
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- **Concurrency:**
 - ✓ simultaneous execution of **multiple tasks**.
 - ✓ E.g. at the **same time** on a laptop, you could be
 - browsing the internet,
 - writing a program and
 - listening to music.
- **Concurrency could be logical or physical.**
 - ✓ Individual tasks can be executed on the same processor giving a **logical** concurrency,
 - ✓ or each task may run on a different processor, giving **physical** concurrency.

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- Parallelism is
 - ✓ **breaking** up a task into smaller tasks and
 - ✓ **solving** these smaller tasks **simultaneously**.
- The smaller tasks will give only partial results and we have to **combine** these partial results to get the final result.
- Suppose you want to add 1000 numbers.
 - ✓ You can ask **10** friends each of whom adds **100** numbers at the same time.
 - ✓ You add these partial sums to get the final sum.
 - ✓ You can complete the task ~10 times faster than adding the 1000 numbers by yourself.

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- Our aim in this unit is to study parallelism on machines that have multicore processors.
- There are many such machines including
 - ✓ laptop, desktop, mobile phone, supercomputers.
- We will study two kinds of machines in this unit,
 - ✓ multicore processors
 - available in your desktop/laptop computer.
 - ✓ cluster of workstations
 - The cluster is called a '[distributed memory](#)' architecture
 - We will have access to a cluster in UWA.

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Programs that Computers Can Execute



- Though you write programs in many languages, e.g. C and Python, a particular computer can execute programs that are written in one particular language.
 - ✓ called the **machine language**.
- A special program called a **compiler** translates a program written in a higher level language like C or Python into a machine language program.
 - ✓ The machine language program is stored in **RAM** and executed by CPUs, instruction by instruction.
- An example machine language program A=A+B:
 - ✓ MOV A, R1
 - ✓ MOV B, R2
 - ✓ ADD R1,R2
 - ✗ MOV R1,

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MPI uses processes; OpenMP uses threads

Outline of Today's Lecture



- **What and why we are studying**
- **Computer architecture**
 - ✓ Processor
 - ✓ **Process and thread**
 - ✓ Memory hierarchy
 - An example on cache line

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What is a Process?



- A program is the **code**, or the machine code after it has been translated into machine language.
- A process is **a program in execution**.
- A process requires resources for its execution.
 - ✓ The operating system (OS) allocates **memory**, and allows the process to make system calls for performing **input/output (I/O) operations**.
 - ✓ A process can access memory that is allocated to it by the operating system (OS).
 - The OS usually terminates a process if the process tries to access memory that is not allocated to it (e.g. Segmentation Fault).

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How a Process is Executed?



- A processor usually executes processes in a **round-robin** fashion.
 - ✓ Many processes wait for execution in a queue.
- The operating system gives a fixed time for the process at the head of the queue.
 - ✓ If the process does not complete execution, it is suspended and the next process is given time.
 - ✓ The suspended process goes to the back of the queue and gets scheduled to execute later.

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Round-Robin Process Execution



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How a Process is Executed?



- The operating system gives a fixed time for the process at the head of the queue.
 - ✓ If the process does not complete execution, it is suspended and the next process is given time.
 - ✓ The suspended process goes to the back of the queue and gets scheduled to execute later.
 - ✓ The operating system stores the **execution status** of a process for resuming it later.

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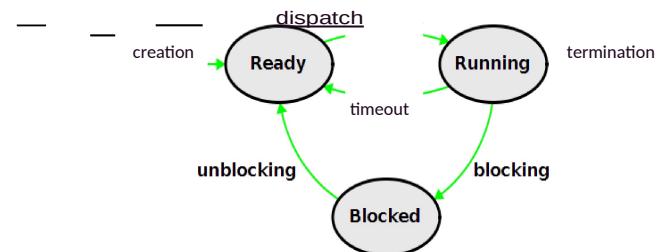
A Gantt chart titled "Round Robin" showing the execution of five processes (P1-P5) over time. The x-axis represents Time in seconds (0 to 15), and the y-axis represents Process Number (1 to 5). Each process is represented by a colored bar indicating its execution interval. The chart shows a repeating cycle of 1-second time slices for each process.

Time (s)	P1	P2	P3	P4	P5
0-1	Red				
2-3		Orange			
4-5			Blue		Green
6-7				Orange	
8-9					Green
10-11				Orange	Green
12-13					Green
14-15				Orange	Green

- A processor usually executes processes in a **round-robin** fashion.
 - ✓ Many processes wait for execution in a queue.

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Process states



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Process and Thread



- A process can be considered as an **independent** execution environment in a computer system.
- There are usually many processes in a system at any time, each with **its own memory space**.
- Each process executes a sequence of instructions (the machine language program).
- Threads are also **independent** execution environments, but with **a shared memory space** (or address space).

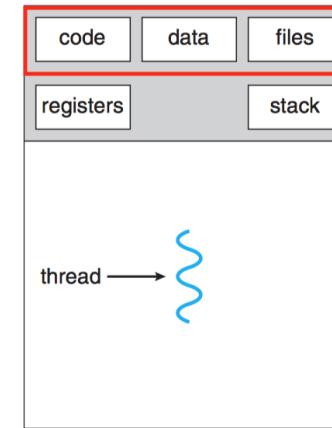
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What is a Thread

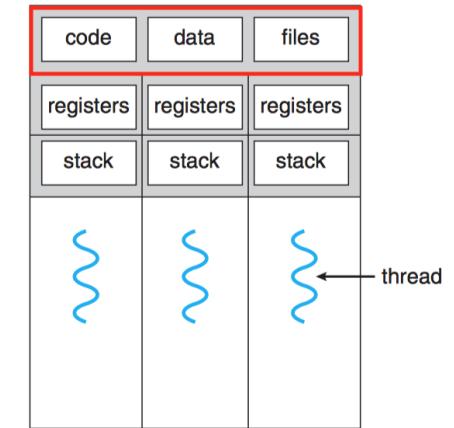
- Threads are also independent execution environments, but with a shared memory space (or address space).
- Each thread executes its own sequence of instructions (or machine language code), but they can access a set of common memory locations.
- Usually **a process creates multiple threads** and these threads **share** the address space of the parent process.

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Single and Multiple Threads in a Process



single-threaded process



multithreaded process

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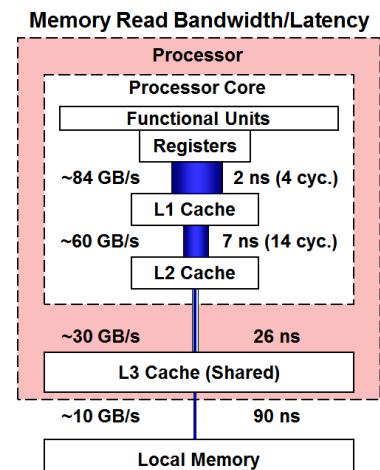
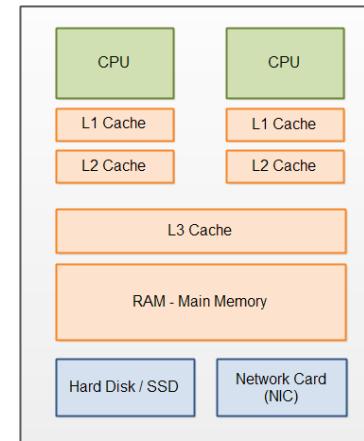
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Memory Hierarchy



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The Memory Hierarchy



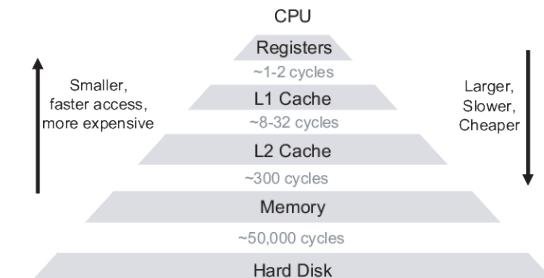
- Most computers have **caches**.
 - ✓ The access time for the cache memory is orders of magnitude faster than RAM or hard disks.
 - ✓ Registers < caches < RAM < hard disks
- When the CPU needs an instruction or data from the RAM, the cache is looked up first.
 - ✓ If the item is present in cache, the memory access is very fast.
- How fast a process will run depends on how much of the memory access is in the cache.

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The Memory Hierarchy



- Why not build computers entirely with fast memories like the cache?
 - ✓ The cost will be high, consumer hardware will not be competitively priced.
 - ✓ The cost is in manufacturing hardware, caches are usually "on-chip" with the processor.



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Multi-Level Cache



- Multi-core processors usually have multiple levels of cache, e.g. L1, L2 and L3.
 - ✓ Generally, the L1 cache is private for each core, each pair of cores share an L2 cache and all cores share the L3 cache.
 - ✓ L1 cache is the smallest, the L2 cache is larger than the L1 cache but smaller than L3.
- The memory access pattern is,
 - i. first look-up the L1 cache,
 - ii. then the L2 cache if L1 doesn't have the data,
 - iii. then the L3 cache if L2 doesn't have the data,
 - iv. and finally RAM if the caches don't have the data.

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Multi-Core and Multi-Threading



- The purpose of multi-core, multi-threaded programming is to make processes run faster.
- We partition the work so that multiple threads can share the work.
 - ✓ More on this later, the entire unit is about this.
- The performance improvement:
 - ✗ if multiple threads run on the same CPU core, they will just get round-robin access to the CPU;
 - ✓ if multiple threads run on multiple CPU cores, they will run simultaneously in parallel.

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Cache Hit and Cache Miss



- Suppose a machine only has a cache and RAM.
- It is a **cache hit** if the required information is found in the cache, and a **cache miss** if it is not found in the cache.
- When cache miss, perform the following steps.
 - ✓ The memory access request goes to RAM.
 - ✓ Then, the cache is filled with a block of instructions or data (called a **cache line**) from RAM. This is a contiguous block of instructions or data adjacent to the request that the CPU made.
 - ✓ The previous block of instructions or data in the cache is over-written (and lost).

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Cache Hit and Cache Miss (Analogy)



- A customer orders meal in KFC—require for information
 - o The ordered boxed meal is already in a tray—**cache hit**
 - o The customer gets the boxed meal fast
- A customer orders meal in KFC—require for information
 - o The ordered boxed meal isn't in a tray—**cache miss**
 - o The order goes to the kitchen—goes to **RAM**
 - o The ordered boxed meal is put in a tray
- When frying chips, they fry 1kg at a time
 - o **cache line**



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Principle of Locality



- Ideally, the process will need instructions and data **adjacent** to the instruction or data that caused the cache miss.
 - This is based on the principle of locality.
- Process execution is mostly localised in code—machine instructions are mostly executed one after another.
 - The exceptions are conditional statements like **if** and **function or procedure calls**, where jumps in process code occur.
 - But these jumps are infrequent.
- Data used by a process is often sequential.

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Principle of Locality (continued)



- Instructions and data are not accessed randomly.
- **Temporal locality**
 - ✓ Recently accessed items will be accessed in the near future (e.g. code in loops, top of stack)
- **Spatial locality**
 - ✓ Items at addresses close to the addresses of recently accessed items will be accessed in the near future (sequential code, elements of arrays)

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Multi-Threading Performance



- When cache access results in a **cache-hit**, the higher level caches will be filled up.
 - E.g. if there is a cache-hit in the L3 cache, the L2 and L1 caches will be filled up with blocks from the L3 cache, depending on their capacities.
- The performance of multi-threaded programs notably impacts by how they utilise the caches.
- Multi-threaded programs may run **slower** than single-threaded (or sequential) programs if the **programs are not carefully written or data structures are not carefully designed**.

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Outline of Today's Lecture

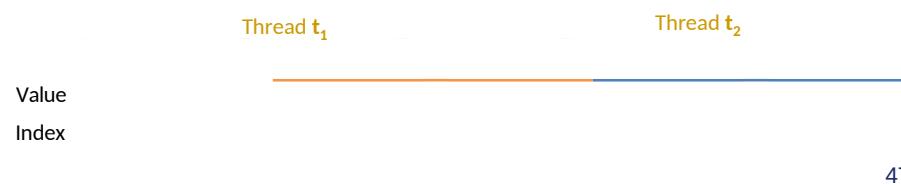


- **What and why we are studying**
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A	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51
	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63

- Consider a simple example of adding the numbers stored in an array.
- Suppose the array is: `int a[64]`
 - Change **64** to a large number (e.g. 100,000) in your code to observe more significant differences.
- A natural way of adding the elements in this array is to use two threads, t_1 and t_2 . Thread t_1 will add the elements $a[0...31]$ and t_2 the elements $a[32...63]$



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An Intuitive Example



- Consider a simple example of adding the numbers stored in an array.
- Suppose the array is: `int a[64]`
 - Change **64** to a large number (e.g. 100,000) in your code to observe more significant differences.
- A natural way of adding the elements in this array is to use two threads, t_1 and t_2 . Thread t_1 will add the elements $a[0...31]$ and t_2 the elements $a[32...63]$
- The program **should run nearly twice faster**, as the work is halved between the two threads.
- So we write a program where the two threads run on two cores that share an L2 cache.

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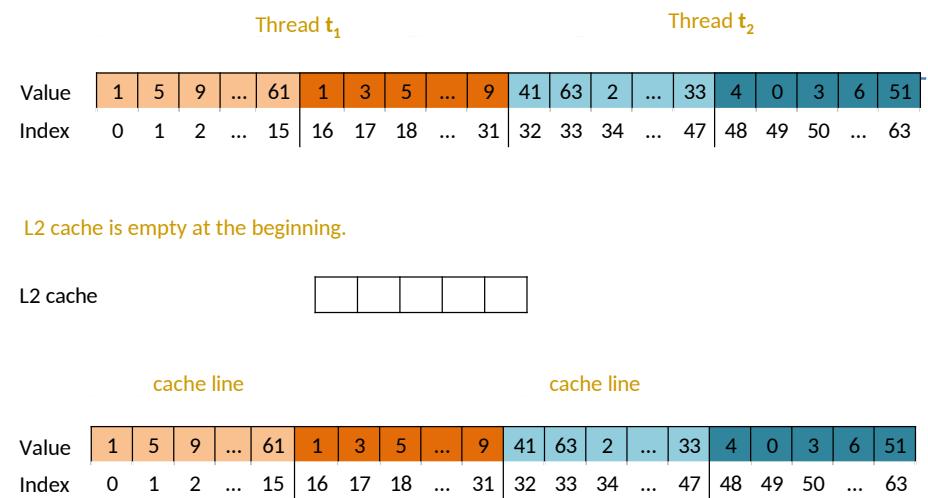
An Intuitive Example—Poor Performance



- Threads t_1 and t_2 execute different loops:
 - t_1 : `for(i=0;i<32;i++)`
`localSum1 = localSum1+a[i];`
 - t_2 : `for(i=32;i<64;i++)`
`localSum2=localSum2+a[i];`
- Finally, one of t_1 or t_2 computes the sum:
`sum=localSum1+localSum2;`
- Though it seems a beautiful partition of work between the two threads, this will result in **very poor performance**.
 - The program will run much slower compared to the sequential program (just one thread).

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An Intuitive Example—Cache Line



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An Intuitive Example—Cache Line



	Thread t_1															Thread t_2														
Value	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51										
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

Thread t_1 reads $a[0]$

	L2 cache															cache														
Value	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51										
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

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An Intuitive Example—Cache Line



	Thread t_1															Thread t_2														
Value	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51										
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

Thread t_2 reads $a[32]$

	L2 cache															cache														
Value	41	63	2	...	33	41	63	2	...	33	4	0	3	6	51															
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

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An Intuitive Example—Cache Line



	Thread t_1															Thread t_2														
Value	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51										
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

Thread t_1 reads $a[1]$

	L2 cache															cache														
Value	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51										
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

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An Intuitive Example—Cache Line



	Thread t_1															Thread t_2														
Value	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51										
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

Thread t_2 reads $a[33]$

	L2 cache															cache														
Value	41	63	2	...	33	41	63	2	...	33	4	0	3	6	51															
Index	0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63										

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An Intuitive Example



- When t_1 executes the first iteration of its loop, elements $a[0] \dots a[15]$ will be brought to the L2 cache.
- When t_2 executes the first iteration of its loop, elements $a[32] \dots a[47]$ will be brought to the L2 cache.
- This **ping-pong effect** continues and the cache is filled again and again by the elements each thread requires.
- In effect, almost every iteration of each thread's loop results in a cache-miss and the overall execution time is much longer compared to the sequential code.

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A	1	5	9	...	61	1	3	5	...	9	41	63	2	...	33	4	0	3	6	51
0	1	2	...	15	16	17	18	...	31	32	33	34	...	47	48	49	50	...	63	

- In a sequential program (a single thread):
 - ✓ Element $a[0]$ will be accessed in the first iteration of the loop.
 - ✓ However, this will be a cache-miss (as the cache is empty in the beginning) and hence elements $a[0] \dots a[15]$ will be brought to the L2 cache.
 - ✓ The next 15 elements can now be accessed from the L2 cache, i.e. there will be 15 consecutive cache-hits after this.
 - ✓ This will result in very fast execution of the sequential algorithm.

Thread t_1

Value
Index

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References



- Readings
 - [Moore's Law Visualisation \(1971 to 2019\)](#)
 - [Memory Hierarchy](#)
 - [Concurrency v.s. Parallelism](#)

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