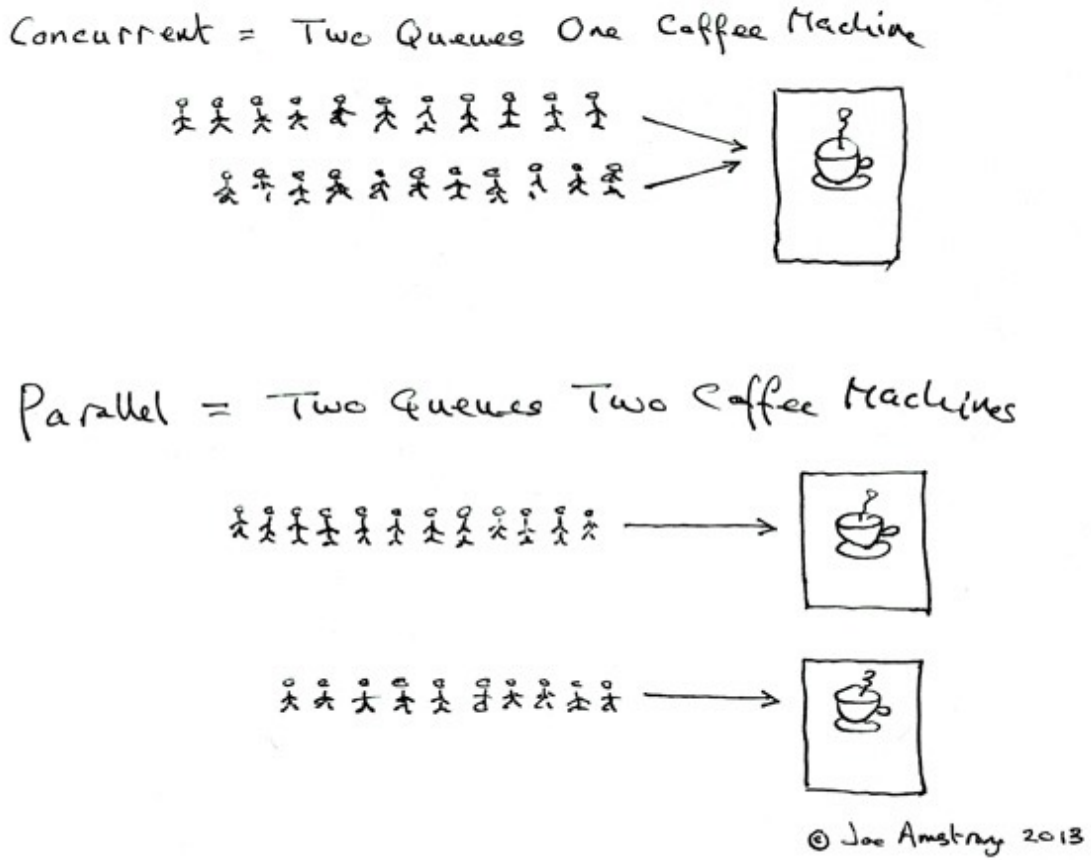
Introduction to Parallel and Distributed Systems

Definitions

- Sequential execution : one or more tasks are executed one after the other.
  - “Usual” mode of execution of most programs
  - Tasks can be instructions, methods/functions…
- Parallel execution : one or more tasks are executed simultaneously.
  - Becoming the norm now
  - Requires special hardware
- Concurrent execution : one or more tasks are in progress at the same time
  - They don’t necessarily execute at the same time
  - From an outsider point of view, they progress
  - Usually implemented in programming languages and libraries



http://joearms.github.io/2013/04/05/concurrent-and-parallel-programming.html

What is parallelism useful for?

- Going faster
  - Straightforward application of the definitions
  - Speed-up the execution
- Going larger
  - Manage much larger datasets
- Not necessarily the same techniques/tools for both

Hardware support

Flynn’s taxonomy

Flynn’s taxonomy (1966)

- Based on the 2 objectives of parallelism
- From a computer/program point of view, what does faster or larger mean?
  - Faster : more instructions per unit of time
  - Larger : processing more data per unit of time

Flynn's taxonomy

not parallel!

	Single Instruction	Multiple Instructions
Single Data	SISD	MISD
Multiple Data	SIMD	MIMD

- There are 4 types of parallel machines
  - Depends on how the manage instructions and data

SISD

- Single Instruction, Single Data
- Takes
  - 1 instruction from memory
  - 1 data (a variable, a memory address…)
- Executes, then do it again
- Example :
  - Very basic processor

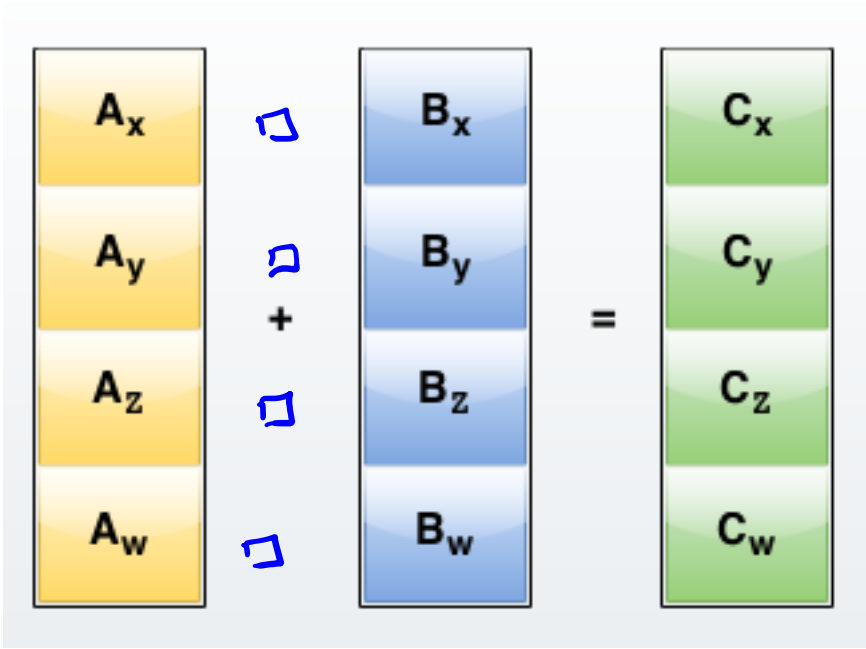
SIMD

on a SISD : 4 steps

on a SIMD with multiple cores: 1

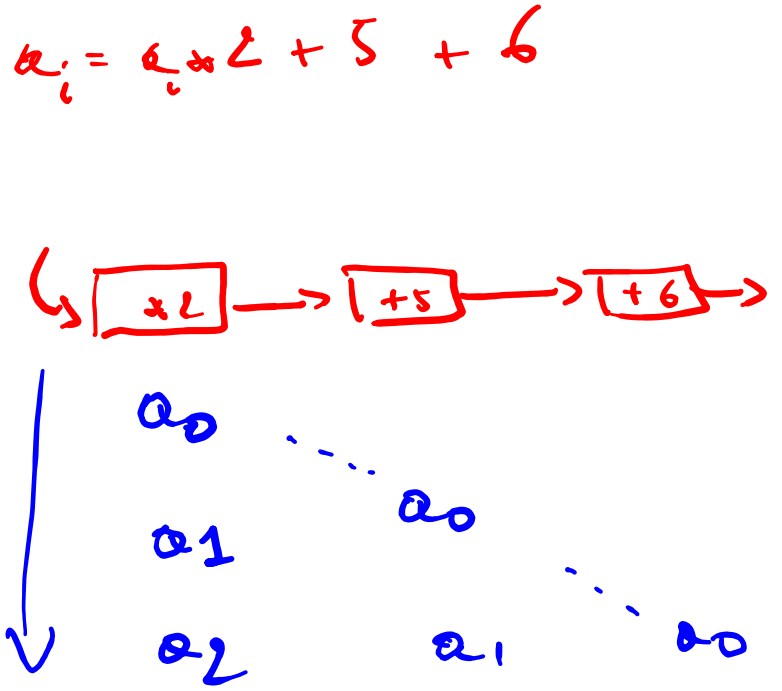
- Single Instruction, Multiple Data
- Takes
  - 1 instruction from memory
  - Multiple data
- Benefits
  - Instruction is decoded only once (costly)
  - Data
    - Can be organized nicely in memory
    - Loaded at once
  - Overall cache friendly
- Example:
  - Vector processors
  - Vector instructions in processors

→ understanding the instruction



Source: http://man.hubwiz.com/ JavaScript SIMD API

MISD



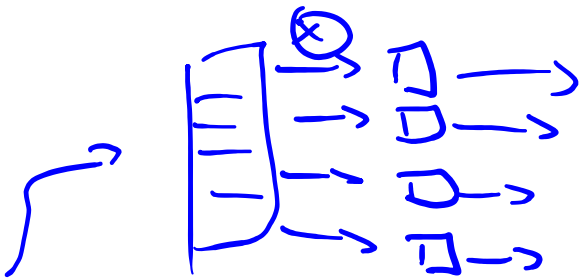
- Multiple Instructions, Single Data
- Principle
  - 1 data from memory
  - Apply multiple instructions on it
- The data “travels” from one instruction to another
  - It’s a pipeline
- Example:
  - Any modern processor has a pipeline for instructions (Fetch-Decode-Execute-Write back)
    - An instruction is processed in steps by a pipeline

MIMD

- Multiple Instructions, Multiple Data
- Basically multiple programs working on different data
- Examples:
  - Multiple computers
  - Multiple processors
  - Multi-cores

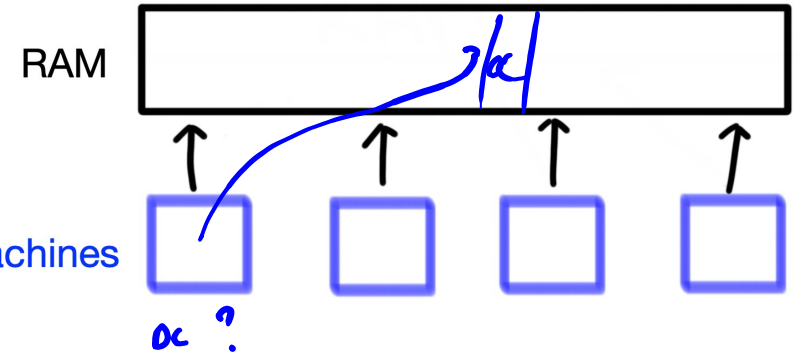
Flynn’s taxonomy and parallelism

- SISD: Not a parallel machine
- SIMD :
  - Process each data with a different processing unit
- MISD :
  - As soon as an instruction is finished, load next data
- MIMD : Naturally parallel

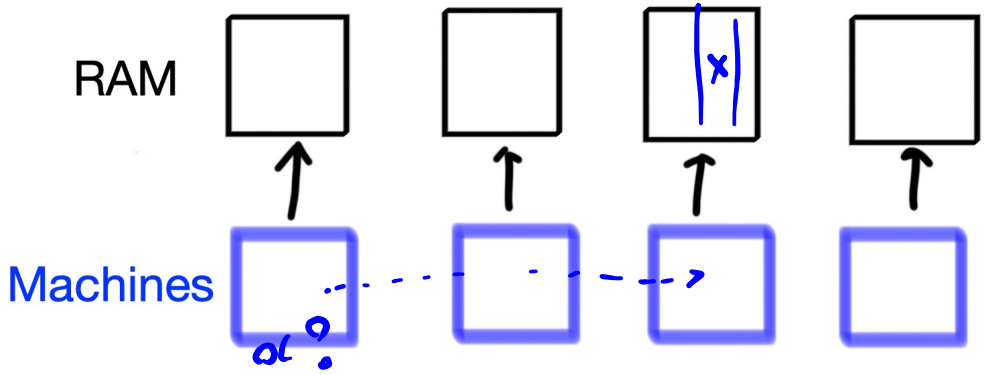


Other taxonomy

- Based on how memory is shared among processing units
- Shared memory
  - All processing units can access the same memory



- Private memory (aka Distributed Systems)
  - Each processing unit has some private memory invisible to others

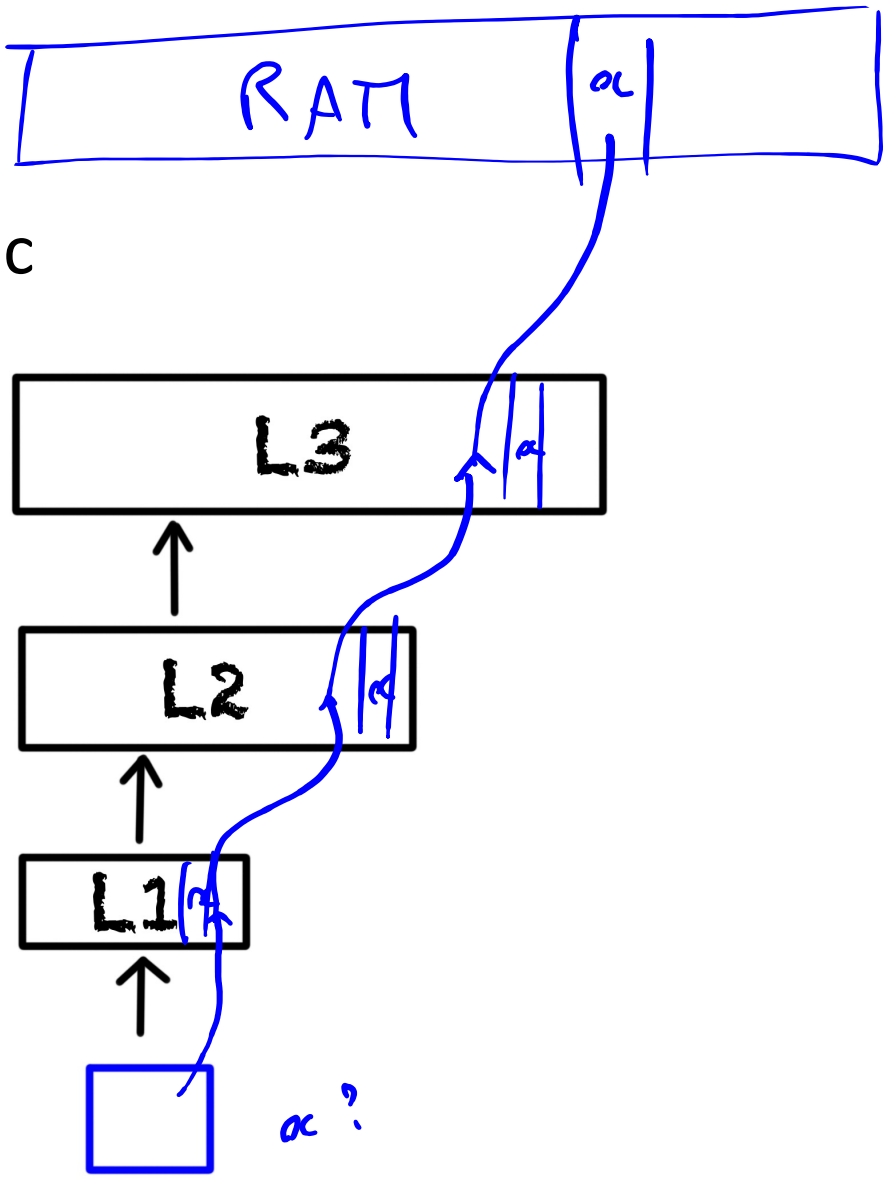


Hardware support

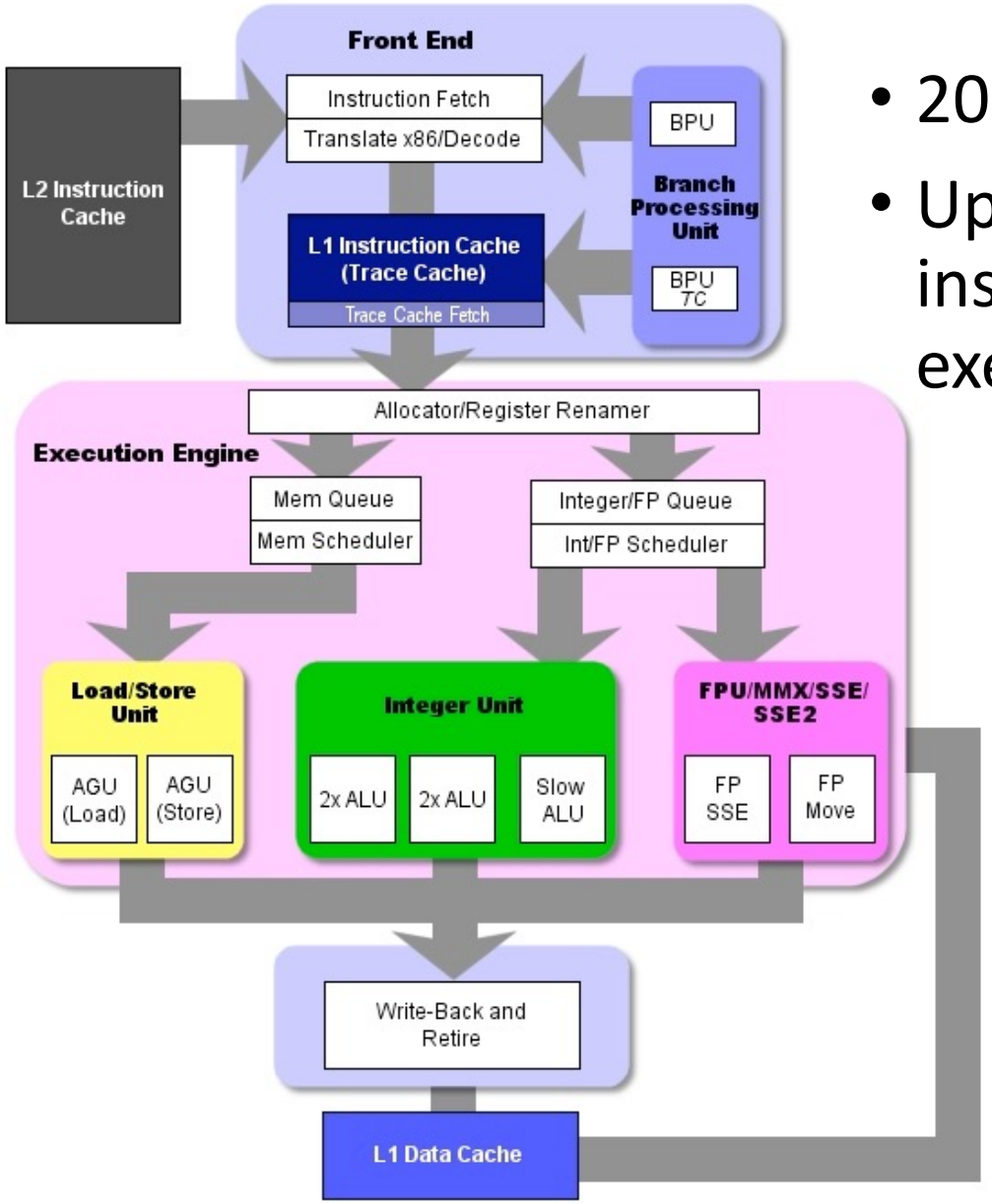
From single core to multicores

Inside processors

- Processors are complex and not monolithic
- Many different functional units
  - Integer computation, floating point…
- Complex memory hierarchy
  - Different cache levels (L1, L2, L3)
  - Fast caches are small



Pentium 4



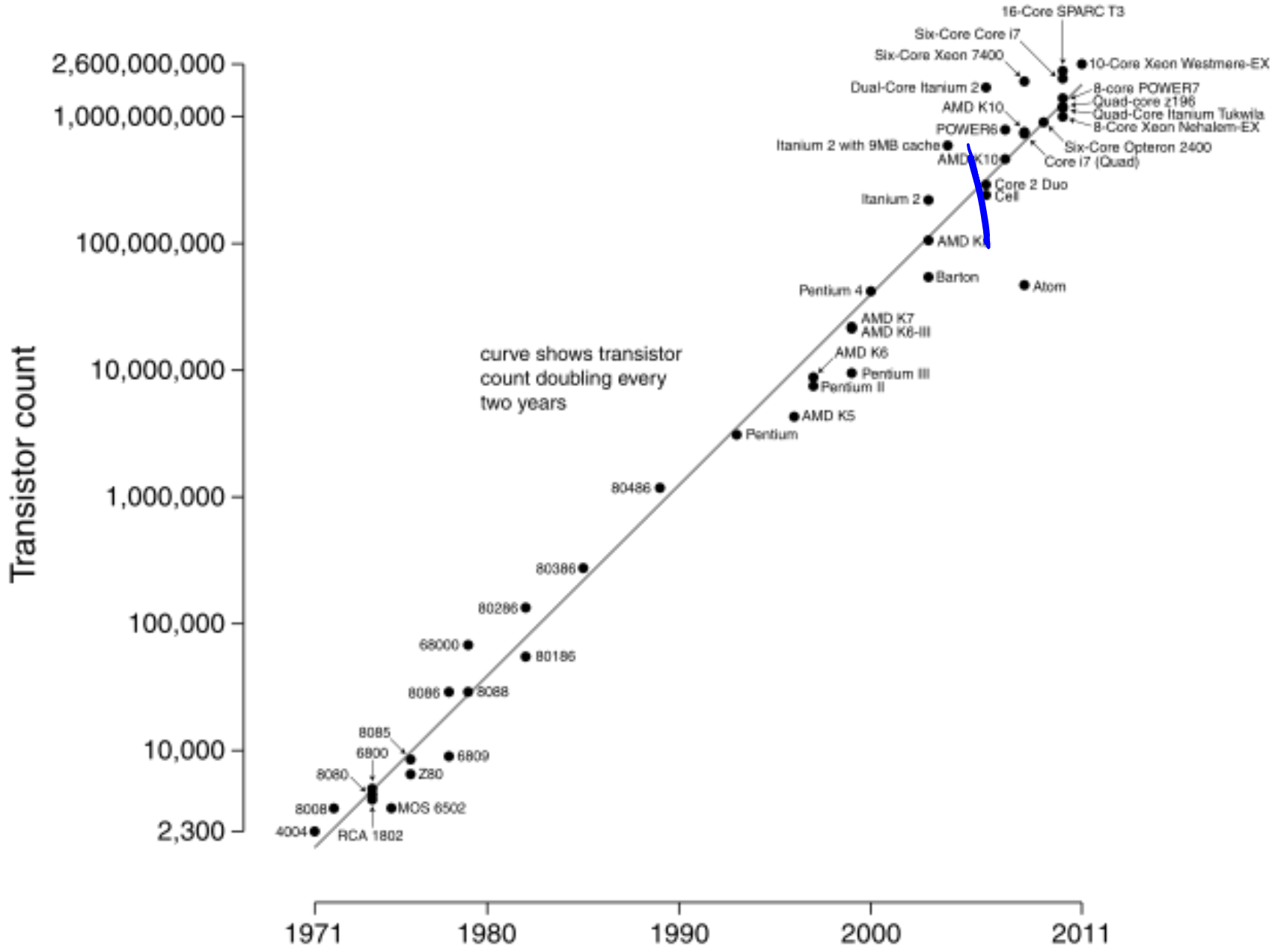
- 20 stages pipeline
- Up to 126 instructions executed in parallel

arstechnica.com

Free speedup

- Moore's Law (1975):
  - Every 24 months, the number of transistors in a CPU can be doubled
- Number of transistors approximates performance
- If you have a program to run faster, just wait for next generation
  - It's free!

Microprocessor Transistor Counts 1971-2011 & Moore's Law



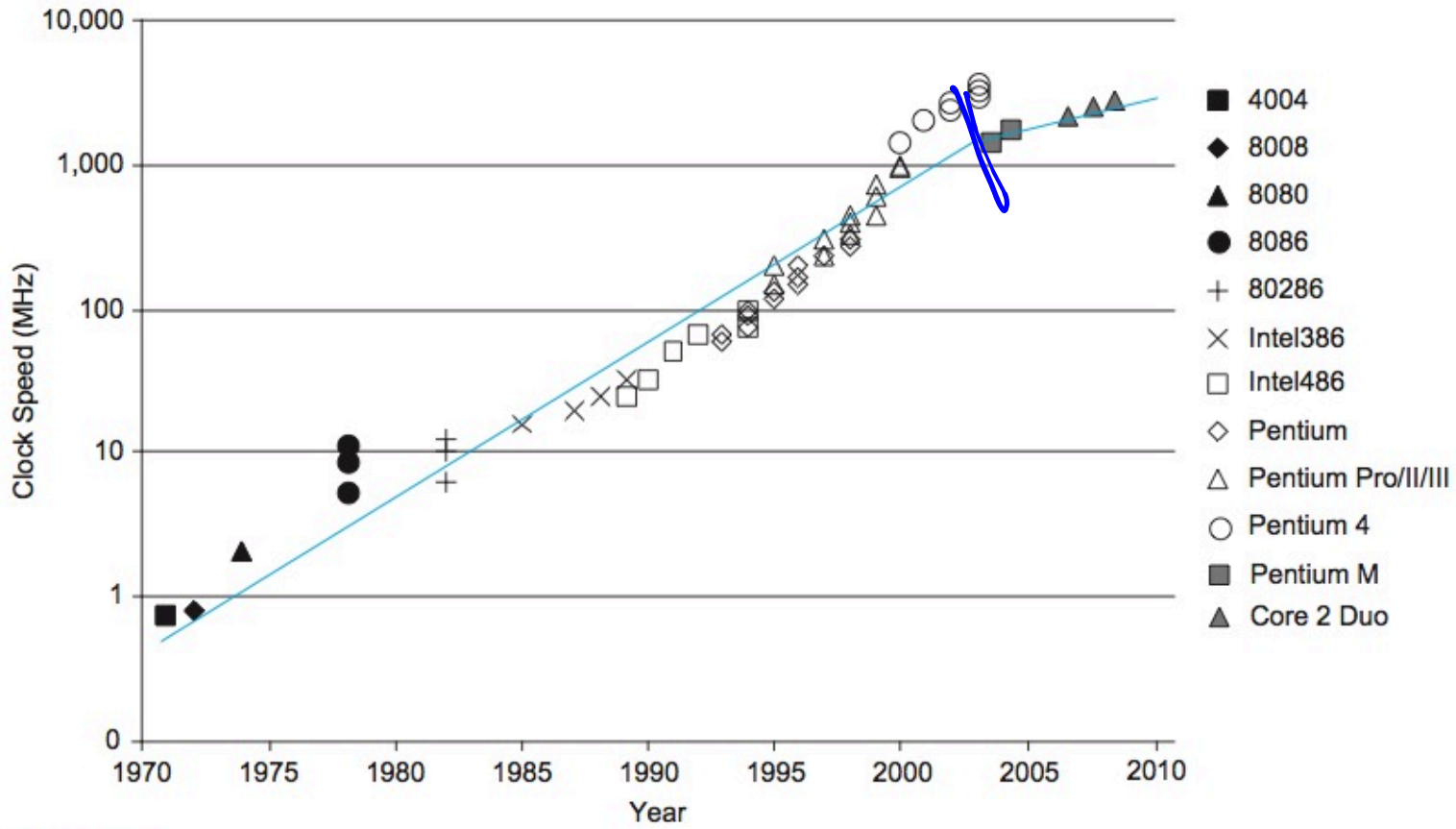
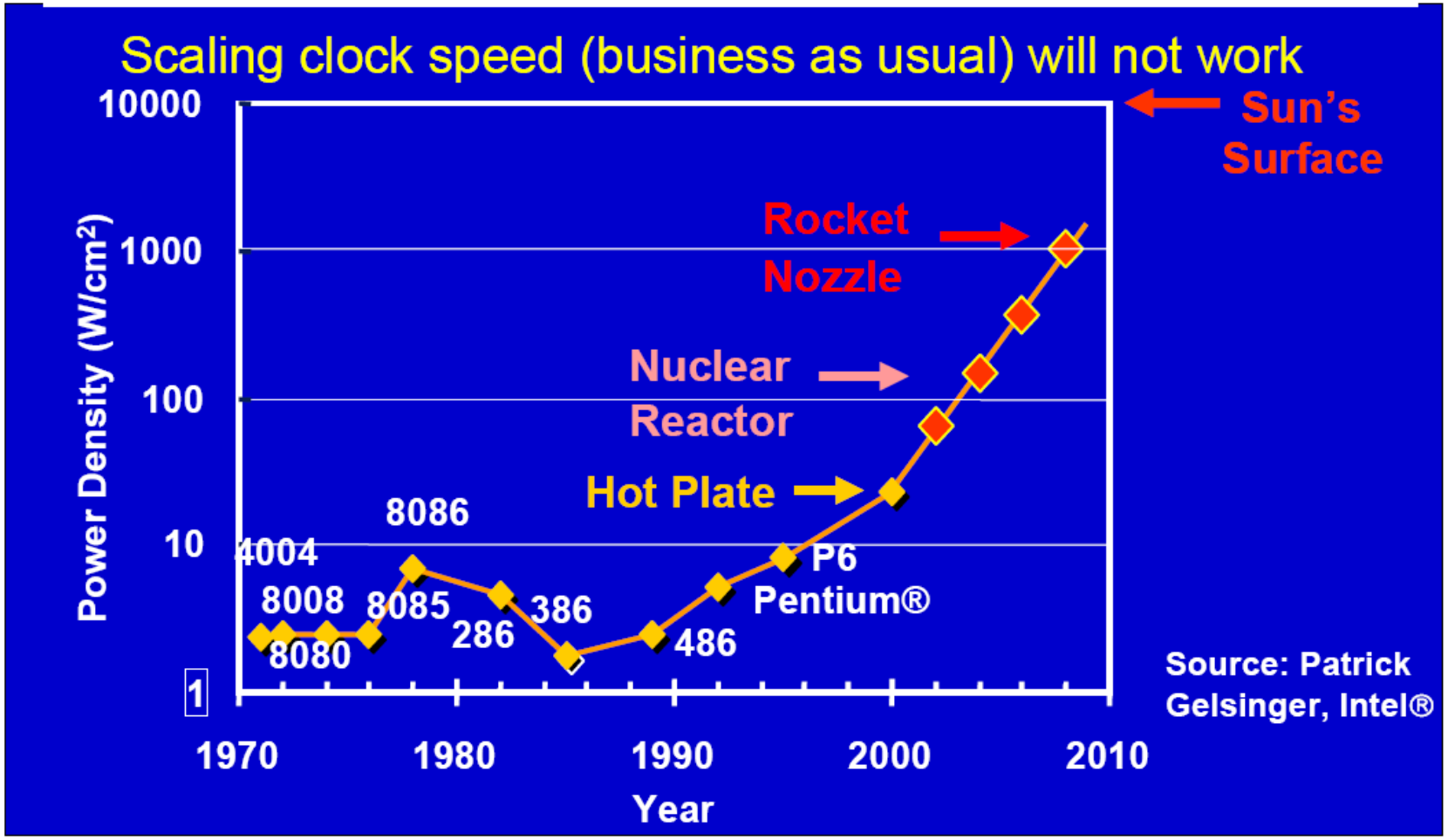


FIGURE 1.5 Clock frequencies of Intel microprocessors

From : **CMOS VLSI Design,** Weste and Harris.

Moore's Law limitations



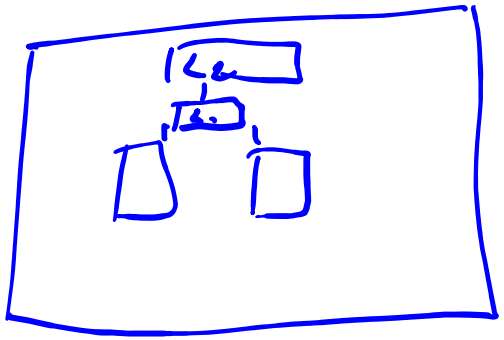
Source, cours CS194 U.Berkeley

Limits to Moore's Law

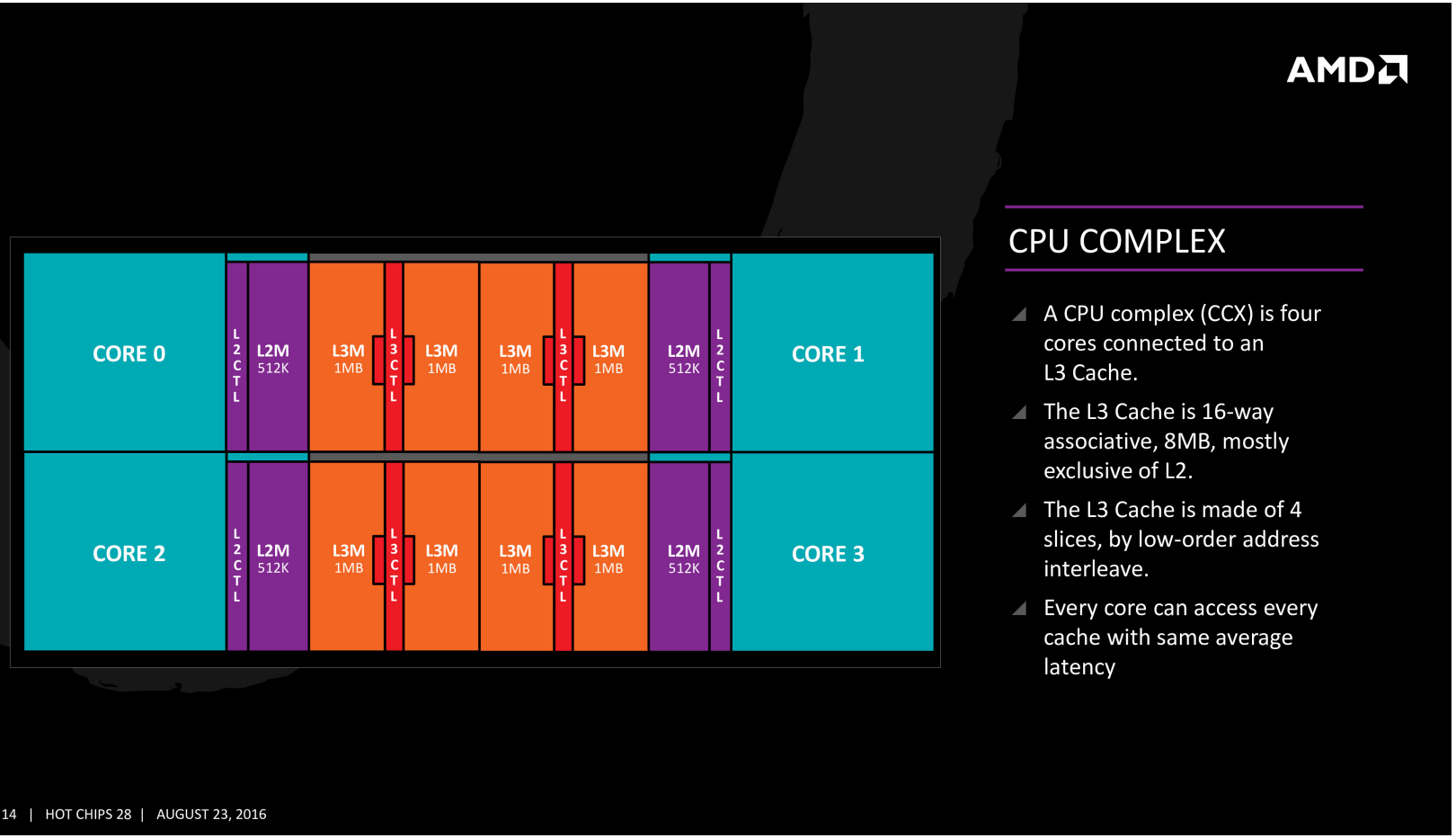
- Moore's Law is still valid
  - But no more free lunch
- What went wrong?
  - Physics did
- Limits on single-core
  - Smaller transistors
  - Or larger die
- Need to pack more CPUs together
  - Multi-core

Multi-core CPUs

- Multiple Processing Units (core) on the same die
  - Share some cache level
  - Have priority access to part of the physical memory
    - NUMA : Non Uniform Memory Access
- Core can be simple or complex
  - Complex cores form an MIMD machine
  - Simple cores usually SIMD



AMD Ryzen 1 & 2



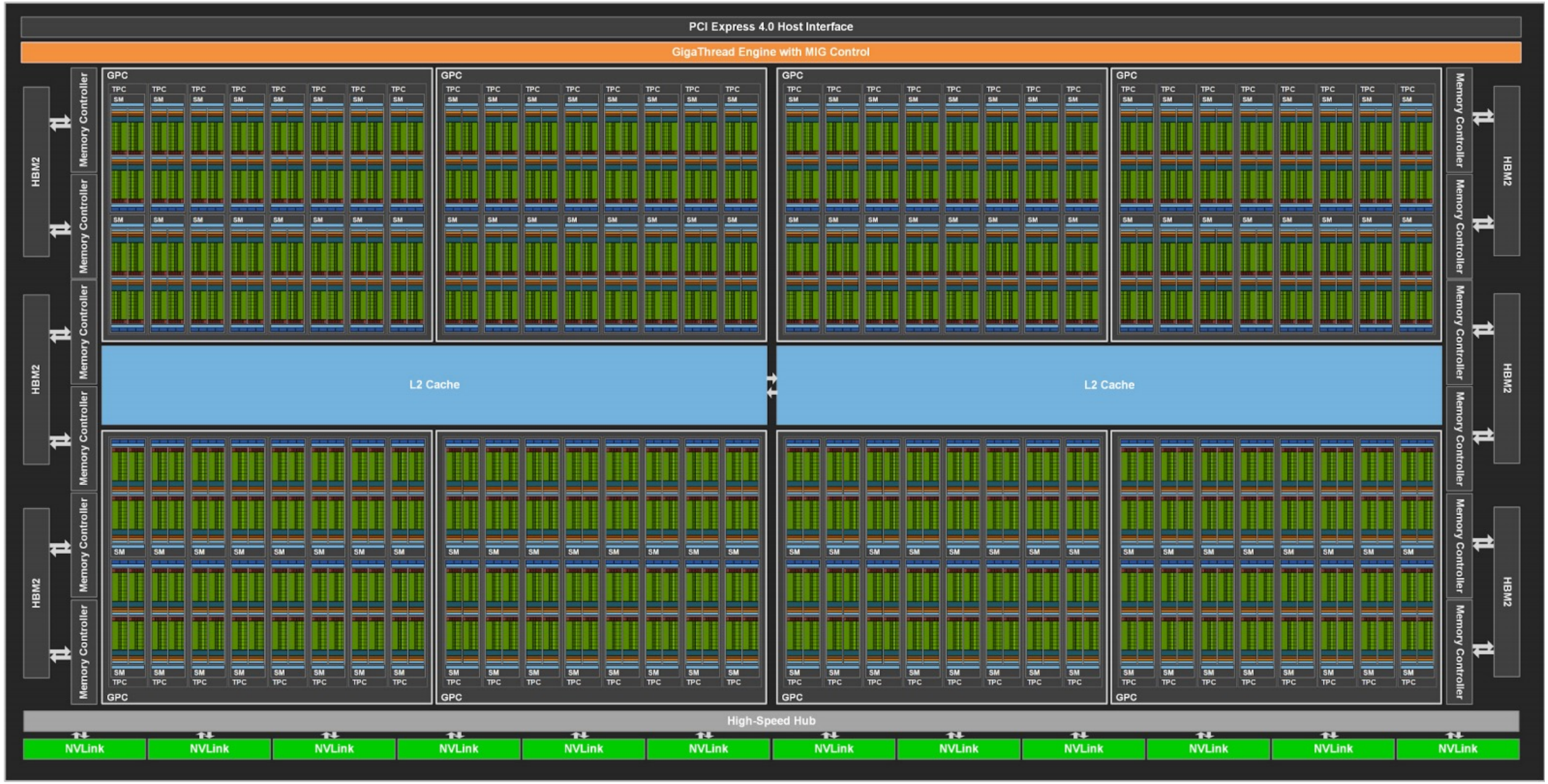
- Cores are grouped by 4 in a CCX
- Two CCX are grouped a CCD (Core Chiplet Die)
- Very modular architecture, increase CCD to have more cores
- Overall a MIMD

GPGPU

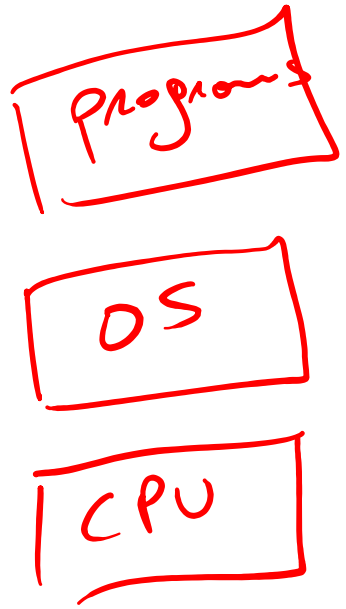
- General Purpose Graphics Processing Unit (GPGPU)
  - Very efficient for FP computations
  - Massively parallel
- Hierarchical organization (NVIDIA)
  - GPU Processing Clusters
    - Streaming Multiprocessors
      - CUDA Cores
- Hybrid model
  - MIMD (Overall) & SIMD (SM)

- NVIDIA Ampere (GA100)
  - 128 Streaming Multiprocessors
  - 8192 Cuda Cores
  - 512 Tensor Cores

https://www.nvidia.com/content/dam/en-zz/Solutions/Data-Center/nvidia-ampere-architecture-whitepaper.pdf



https://www.nvidia.com/content/dam/en-zz/Solutions/Data-Center/nvidia-ampere-architecture-whitepaper.pdf

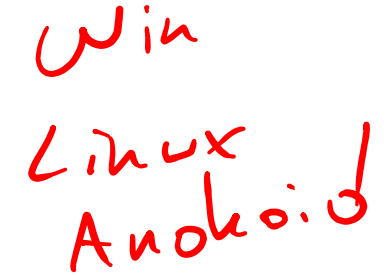


Software support

Processes and threads

Processes

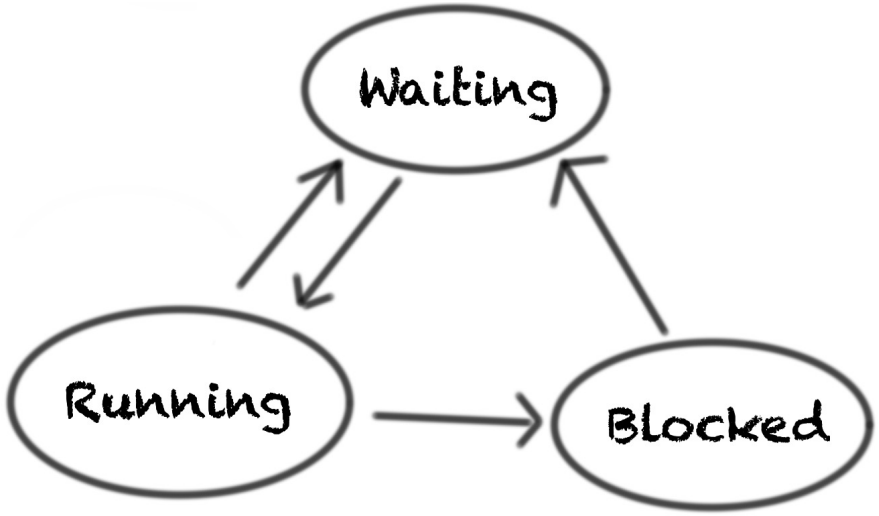
- A process is a program being executed
- Created by the operating system (OS)
- Contains all necessary information
  - Memory addresses used
  - Open files
  - Current instructions
- Provides isolation
  - Cannot see the memory of another process (SEGFAULT)
  - Sharing info between processes is a service of the OS
    - Inter Process Communication (IPC) through shared memory



Multi-tasking

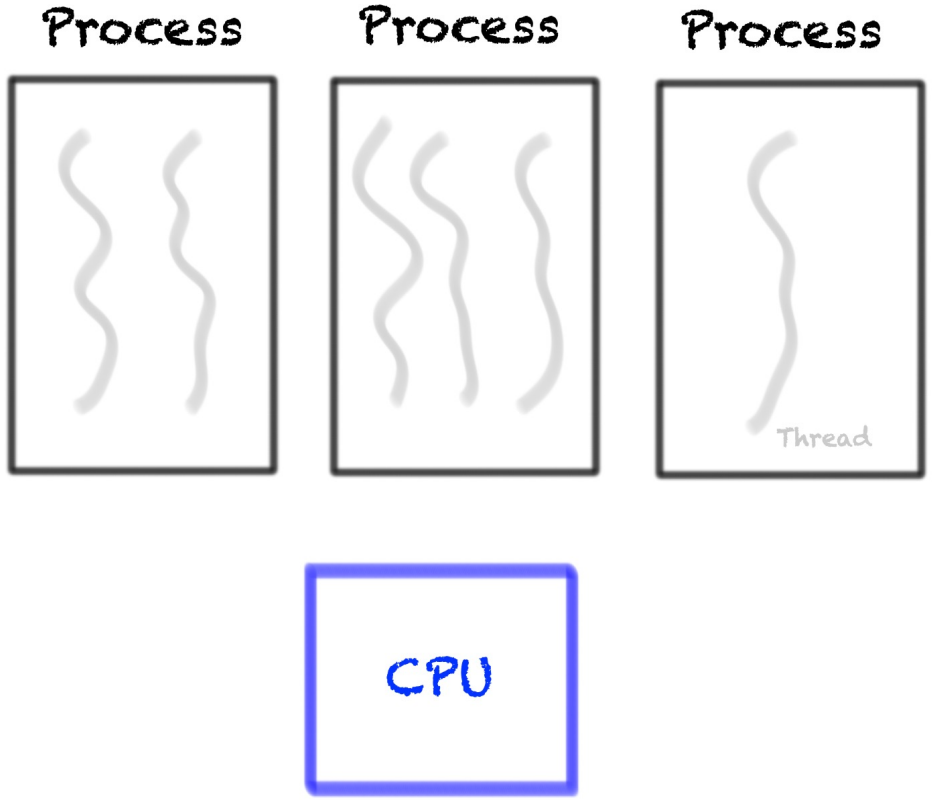
cooperative multi task
vs
preemptive multi task

- Processes share the CPU
  - The OS also needs the CPU
- Each process is given a timeslice (5-15ms)
  - Maximum duration on CPU
- A process loses the CPU if
  - It runs for the whole timeslice (waiting)
  - It does an I/O (blocked)
- The OS replaces the process on the CPU
  - Decides which process to run next (Scheduling)
  - Use of a queue with priority



Context switch

- Changing which process runs is called context switch
- Context switches are costly
  - Lots of CPU register to change
  - Possible invalidation of caches
  - Execution of OS' scheduler
- Needs for a lighter alternative
  - Threads, aka lightweight processes.



Threads

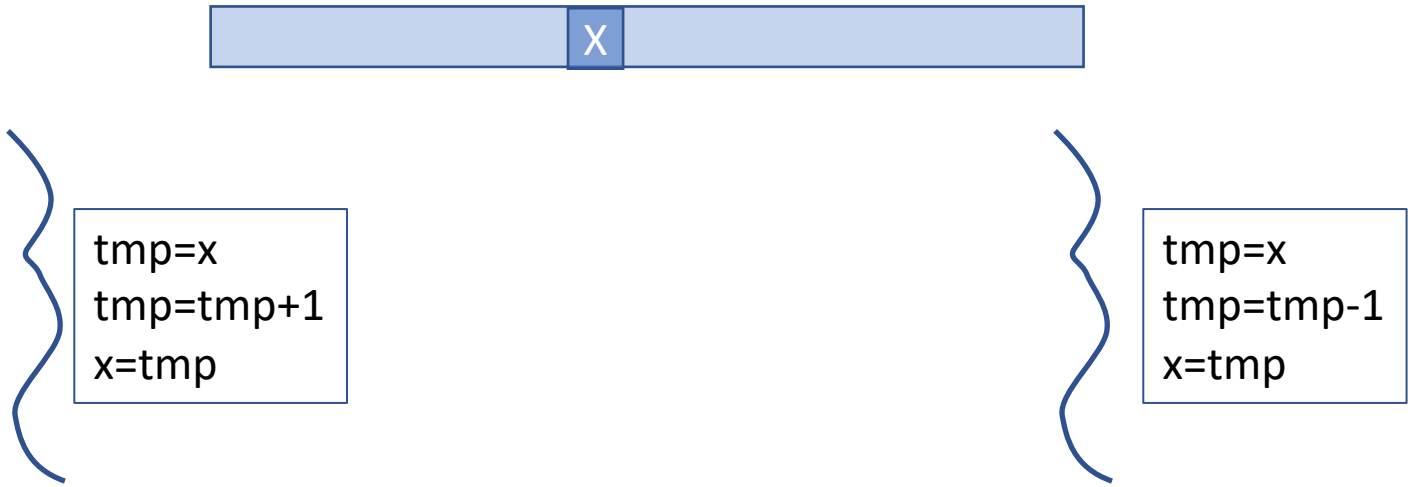
- A process contains multiple threads
- Threads of the same process share everything
  - Memory, open files…
  - Can have local (private) variables
- Scheduling another thread of the same process has very little cost
- Threads are provided by the OS
  - Usually accessible through APIs (pthreads in C, Thread in Java, threading in Python)

Threads

- When and why use threads?
- Computational intensive application
  - Each thread computes part of the result
  - Use as many threads as core
  - Depends on the API used : not working in Python
- Applications with I/O
  - Use threads for performing I/O
  - Eg : app with GUI

Race conditions

- Data can be shared between processes (IPC) or threads
  - What could go wrong?
- Example :
  - 2 threads using the same variable
  - 1 thread increasing it, the other decreasing it



Protection against race conditions

- Avoid sharing!
  - Depends on your algorithm/problem
  - Easier with some programing models
- Protect the shared data
  - Notion of critical section (no 2 threads in this part of the code)
  - Test & set instructions
  - Low level tools : semaphores, monitors…

Software support

Middleware and libraries

Low level vs High level

- Low vs High
  - Usually how close you are to the hardware
- Example : C (low) vs Python (High)
- In parallel/distributed systems
  - Low : you manage threads, semaphores, sockets…
  - High : abstractions hide the low level details
- As data scientists
  - Know that low level exists
  - Focus on high level

Libraries

- Libraries are high level tools
  - Provide function, methods to use in your code
- Example :
  - TensorFlow, Pandas
  - PyTorch : scientific computing with or without GPGPU

```
if torch.cuda.is_available():
  dev = "cuda:0"
else:
  dev = "cpu"

device = torch.device(dev)
a = torch.zeros(4,3)
a = a.to(device)
```

https://medium.com/ai%C2%B3-theory-practice-business/use-gpu-in-your-pytorch-code-676a67faed09

Frameworks

- Frameworks are also high level
  - Provides some default functionalities
  - Your code adds/modifies functionalities
  - The framework uses your code
- Example :
  - Hadoop, Spark, Flink…
- Frameworks are very common in distributed systems

Concepts of Distributed Systems

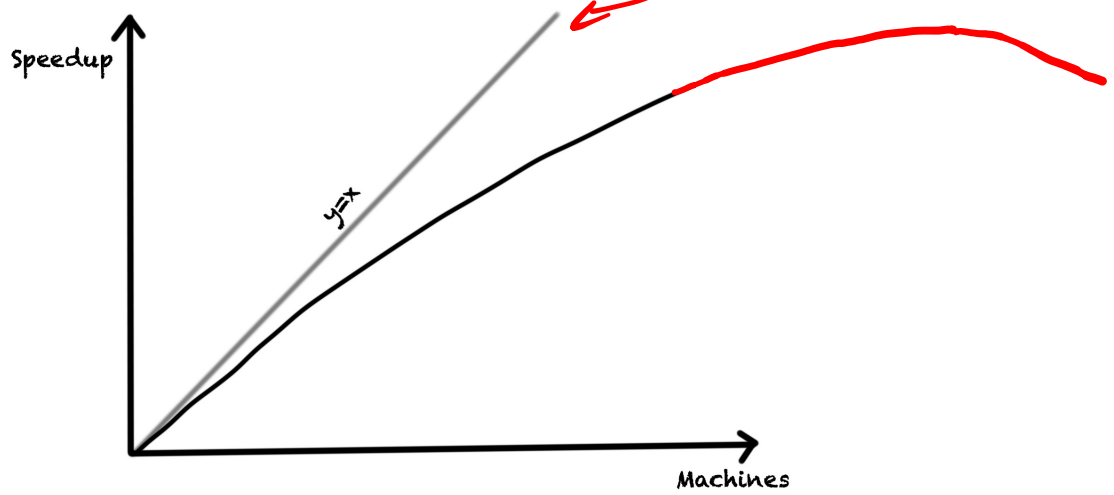
Scalability

Speedup

- Measure of the relative performance
  - Sequential vs parallel
- Example
  - Ts = 200 seconds
  - Tp = 100 seconds on 2 cores/machines
  - Speedup = 2 (i.e the parallel version is twice as fast as the sequential one)
- Speedup varies
  - With the problem
  - With the number of resources

200/100 = 2

ideal



Scalability

- Capacity of a system to manage varying load through adaptation
  - Add (resp. remove) resources when load increases (resp. decreases)
- Scaling up (resp. down)
  - Increase the resources of a single machine
    - Add memory, increase CPU frequency…
  - Limited and complicated but transparent to the application
- Scaling out (resp. in)
  - Add more machines
  - Easy if the application is stateless.

Auto vs Manual scaling

- Manual scaling
  - Decided by the user or administrator
  - Could be based on expected load (e.g. time of day)
  - Slow, error prone
- Auto scaling
  - The application (framework) decides based on measured metrics
  - Fast but can have unexpected results

Concepts of Distributed Systems

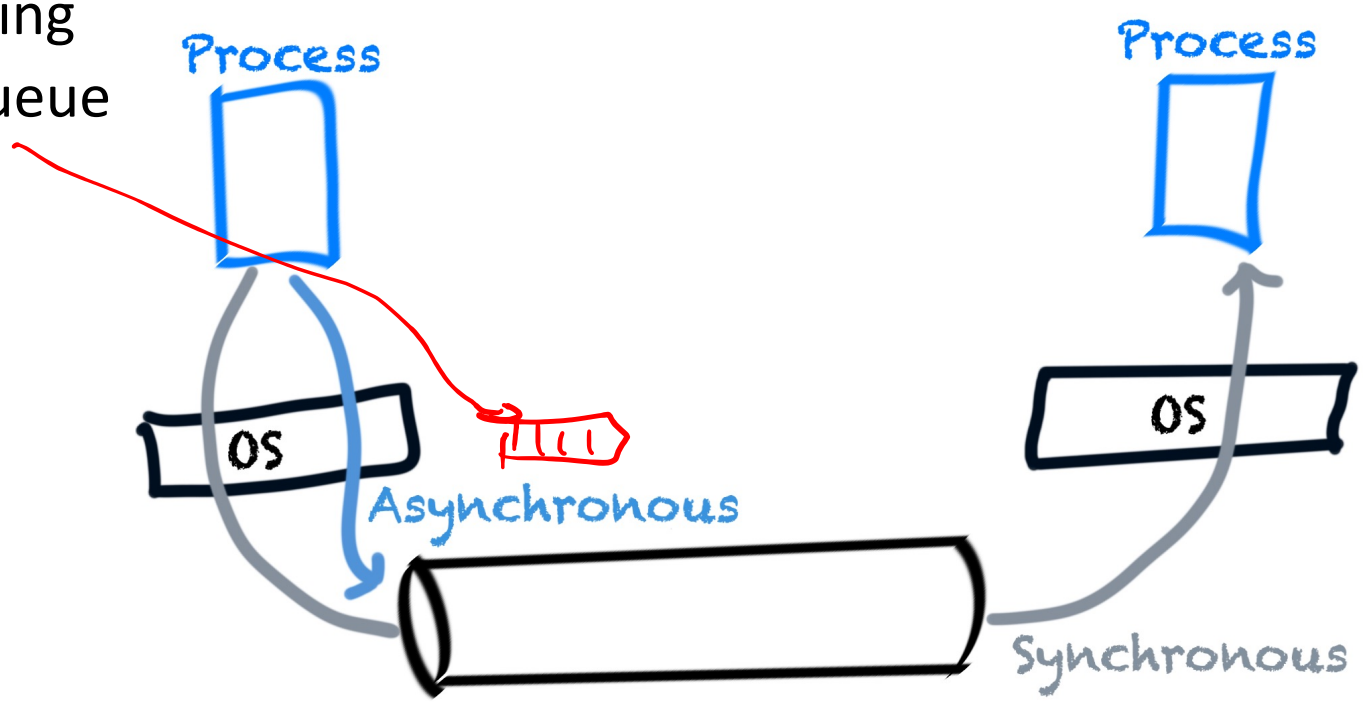
Communications

Communication

- Low level : sockets
- End points for sending/receiving data
  - FIFO, handle bytes
- Needs IP address and port of remote machine
  - Lack of transparency
- Sending complex data structures requires transformation
  - Serialization/Deserialization
- High level : messages, Remote Procedure Call (RPC)

Synchronous vs Asynchronous

- Synchronous
  - Sender is blocked until message is processed by receiver
- Asynchronous
  - Sender is blocked during sending
  - Usually relies on a message queue



Latency

- Any communication takes time
  - Base latency + bandwidth from network
  - Multiple software layers
- Avoid them if possible
  - But latency does not come only from network
  - Even memory access add latency

Latency Comparison Numbers

```
L1 cache reference ......................... 0.5 ns
Branch mispredict ............................ 5 ns
L2 cache reference ........................... 7 ns
Mutex lock/unlock ........................... 25 ns
Main memory reference ...................... 100 ns
Compress 1K bytes with Zippy ............. 3,000 ns  =   3 µs
Send 2K bytes over 1 Gbps network ....... 20,000 ns  =  20 µs
SSD random read ........................ 150,000 ns  = 150 µs
Read 1 MB sequentially from memory ..... 250,000 ns  = 250 µs
Round trip within same datacenter ...... 500,000 ns  = 0.5 ms
Read 1 MB sequentially from SSD* ..... 1,000,000 ns  =   1 ms
Disk seek ........................... 10,000,000 ns  =  10 ms
Read 1 MB sequentially from disk .... 20,000,000 ns  =  20 ms
Send packet CA->Netherlands->CA .... 150,000,000 ns  = 150 ms
```

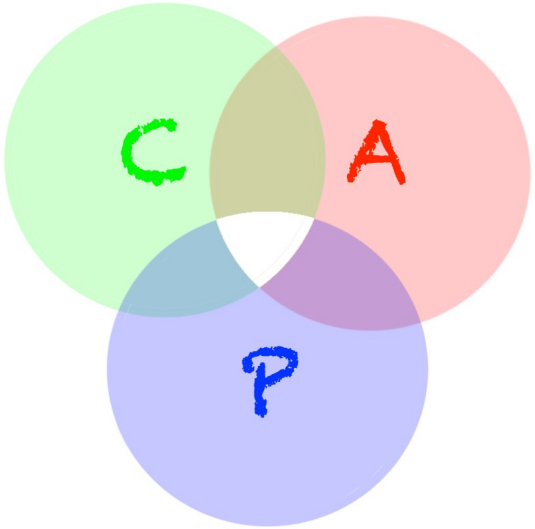
https://gist.github.com/hellerbarde/2843375

Concepts of Distributed Systems

Limits to distributed systems

CAP theorem

- Theorem from Eric Brewer (2000)
- A distributed system with read/write cannot provide more than 2 of the following guarantees
  - Consistency
  - Availability
  - Partition Tolerance



CAP theorem

- Consistency : a read returns the most recent write
- Availability : every request to any node returns a result (not necessarily correct)
- Partition Tolerance : the system still works in presence of network failures.
- In practice, the network is NOT reliable
  - Partitions WILL occur

CAP theorem

- So CAP theorem can be rephrased
  - In presence of network failure, you have to choose between Availability and Consistency
- A-P : When there is a partition, the system continues to work but might answer outdated/inconsistent results.
- C-P : When there is partition, some nodes might stop answering.

CAP in the wild

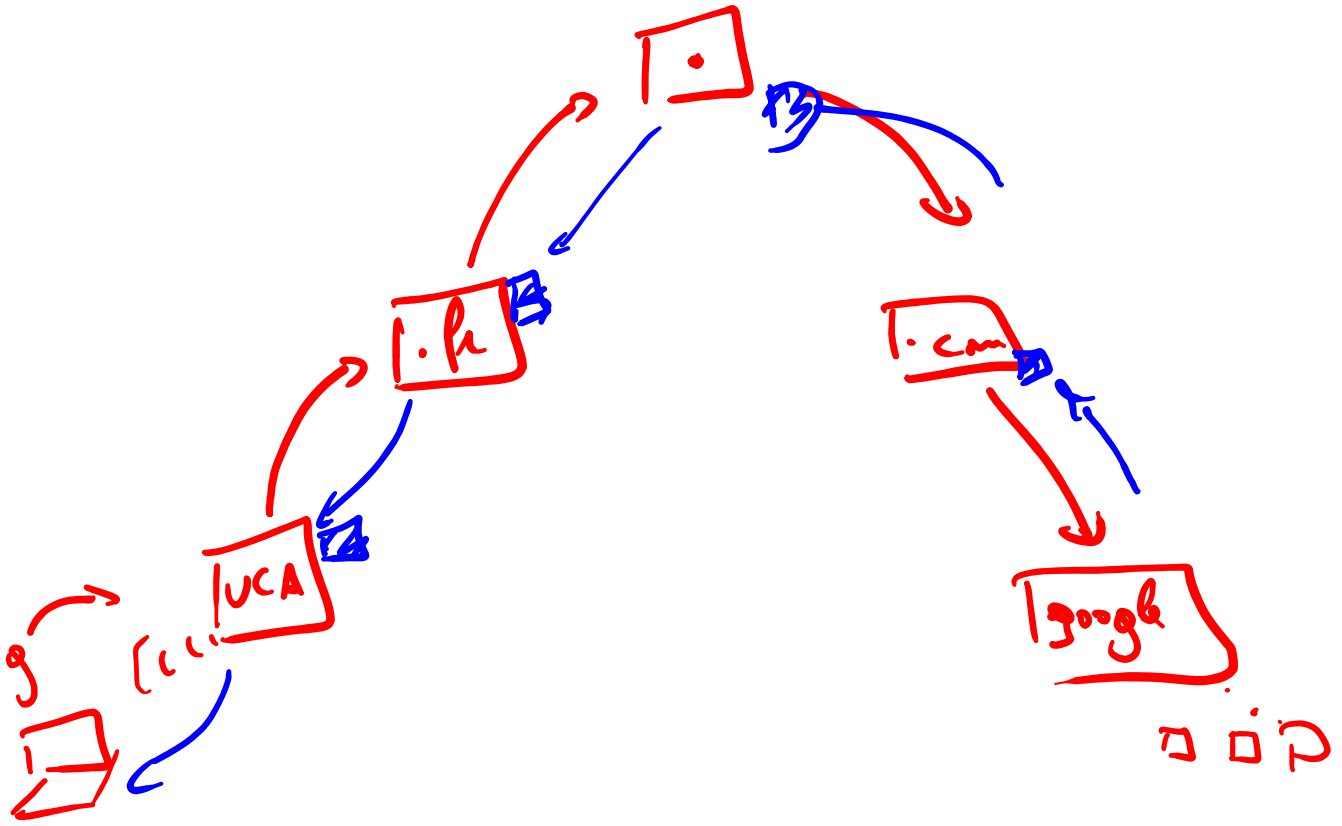
- A distributed DB on a single cluster
  - C-A
- Domain Name Server
  - A – P
- A multi-site distributed DB
  - C - P

DNS

www.google.com

IP?

DNS



Failures

- Software can crash
- The network is not reliable
- But so are the machines!
  - A single machine can be reliable
  - But 10s of them?

Typical first year for a new google cluster

- ~0.5 overheating (power down most machines in <5 mins, ~1-2 days to recover)
- ~1 PDU failure (~500-1000 machines suddenly disappear, ~6 hours to come back)
- ~1 rack-move (plenty of warning, ~500-1000 machines powered down, ~6 hours)
- ~1 network rewiring (rolling ~5% of machines down over 2-day span)
- ~20 rack failures (40-80 machines instantly disappear, 1-6 hours to get back)
- ~5 racks go wonky (40-80 machines see 50% packetloss)
- ~8 network maintenances (4 might cause ~30-minute random connectivity losses)
- ~12 router reloads (takes out DNS and external vips for a couple minutes)
- ~3 router failures (have to immediately pull traffic for an hour)
- ~dozens of minor 30-second blips for dns
- ~1000 individual machine failures
- ~thousands of hard drive failures
- slow disks, bad memory, misconfigured machines, flaky machines, etc.
- Long distance links: wild dogs, sharks, dead horses, drunken hunters, etc.

https://static.googleusercontent.com/media/research.google.com/en//pubs/archive/44922.pdf

Conclusion

Take home message

Conclusion

- Parallelism requires specific hardware
- Modern hardware is parallel
  - Multicore
  - GPGPUs
- High level libraries/frameworks hide the complexity