Some details on Modern Architectures

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"**Foundation of HPC-basic" course**

DATA SCIENCE &
SCIENTIFIC COMPUTING

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This lecture presents the fundamental traits of the **single-core** modern architecture, in their historical developments and roots (assuming that the historical perspectives helps the understanding).

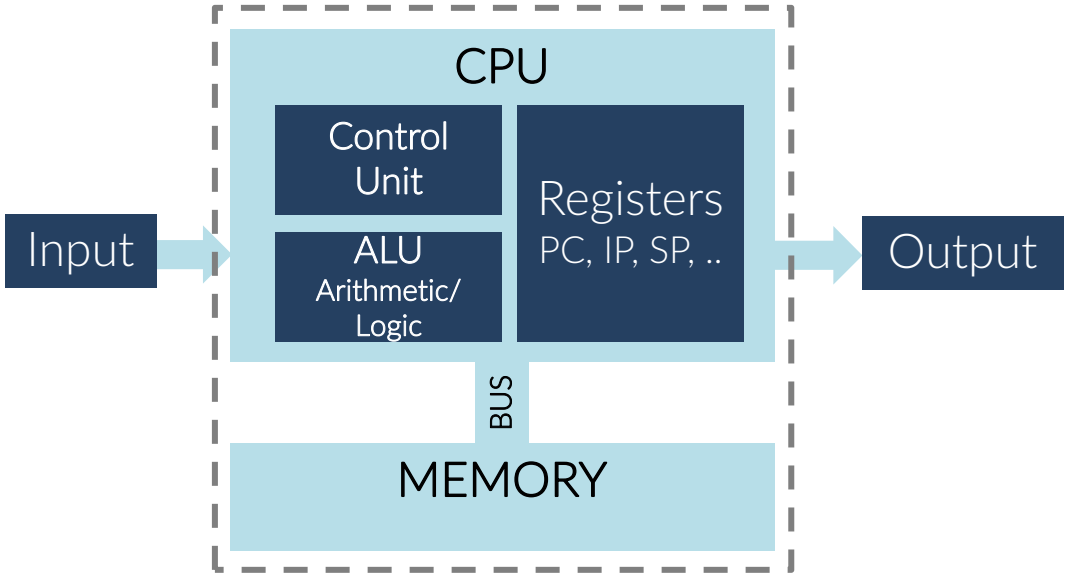
The aim is to show you why this knowledge is important in order to write efficient codes.

At a glance

CPUs become faster than memory	Accessing the central DRAM becomes a major bottleneck and a performance killer because if the memory access is not carefully designed the CPU is just waiting for the data most of the time (*data starvation*). A memory hierarchy is introduced to reduce the impact of this gap, and that introduces the key concept of *data locality*.
CPUs become super-scalar and acquire out-of-order capacilities	A modern core has more than one *port* that can perform the same type of operation (Arithmetic-logic, memory access, I/O, ...). That means that more than one operation can be performed in the same clock, if the code is suited to allow that, which is referred as Instruction-Level-Parallelism (ILP).
Operations are broken down into smaller stages and pipelined	The expected throughput is larger, at the condition that the pipelines are always as full as possible and do not stall due to data and control hazards (we'll see that later)
Branch predictors are an important part of the fron-end	Branches play a major role in causing stalls in the pipelines and in the execution flow. Dealing with this is a key factor to increase the code's performance.
CPUs acquire vector capabilities	Special registers in the CPU have the capacity of performing the same operation on multiple data (SIMD - Same Instruction Multiple Data). That is referred as Data-Level-Parallelism. Not all the loops are vectorizable, that depends on a number of factors.

Once upon a time..

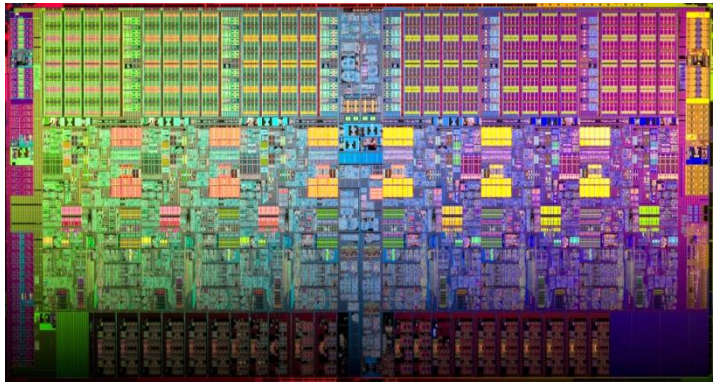
.. The computer architecture was much simpler than today.
In the lecture “The Free lunch is over”, we have seen the reasons why it was so – or, better, why nowadays it is much more complex.



In the **Von Neumann architecture** (still taught as the fundamental model)

- there is only 1 processing unit
- 1 instructions is executed at a time
- memory is “flat”:
  - access on any location has always the same cost
  - access to memory has the same cost than op execution

While today…



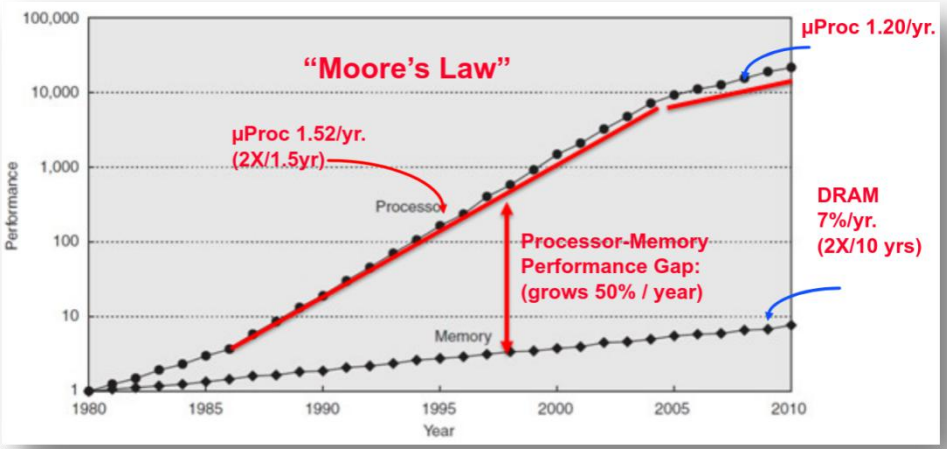
NOT an extreme example: 6-cores Intel Xeon e5600

(*) "cost" is in terms of the CPU-cycles currency

- there are *many* processing units
- many instructions can be executed at a time
- many data can be processed at a time
- "instructions" are internally broken down in many simpler µops that are pipelined
  - different instructions could have quite different cost(*)
- memory is strongly *not* "flat":
  - there is a strong memory hierarchy
  - access memory can have *very* different costs(*) depending on the location
  - accessing RAM is *way* more costly than performing a µop or reading an internal register

In the next slides we'll go through all this features in chronological order, as they developed in time

Early 90s: CPU becomes faster than memory



Processor	Alpha 21164	
Machine	AlphaServer 8200	
Clock Rate	300 MHz	
Memory Performance	Latency	Bandwidth
I Cache (8KB on chip)	6.7 ns (2 clocks)	4800 MB/sec
D Cache (8KB on chip)	6.7 ns (2 clocks)	4800 MB/sec
L2 Cache (96KB on chip)	20 ns (6 clocks)	4800 MB/sec
L3 Cache (4MB off chip)	26 ns (8 clocks)	960 MB/sec
Main Memory Subsystem	253 ns (76 clocks)	1200 MB/sec
Single DRAM component	≈60ns (18 clocks)	≈30–100 MB/sec

Taken from a 1997 paper

The CPU may spend more time waiting for data coming from RAM than executing ops.
That is part of the so called "memory wall".
What is the solution ?

A note about today

You certainly know that DDRAM memory frequency increased in the last year up to 3-4GHz

However, that alleviate the problem only partially

Figure taken from:
"Memory Bandwidth and Latency in HPC: System Requirements and Performance Impact"

Ph.D disserattion thesis, 2019, Dep.t of Computing Architectures, UPC

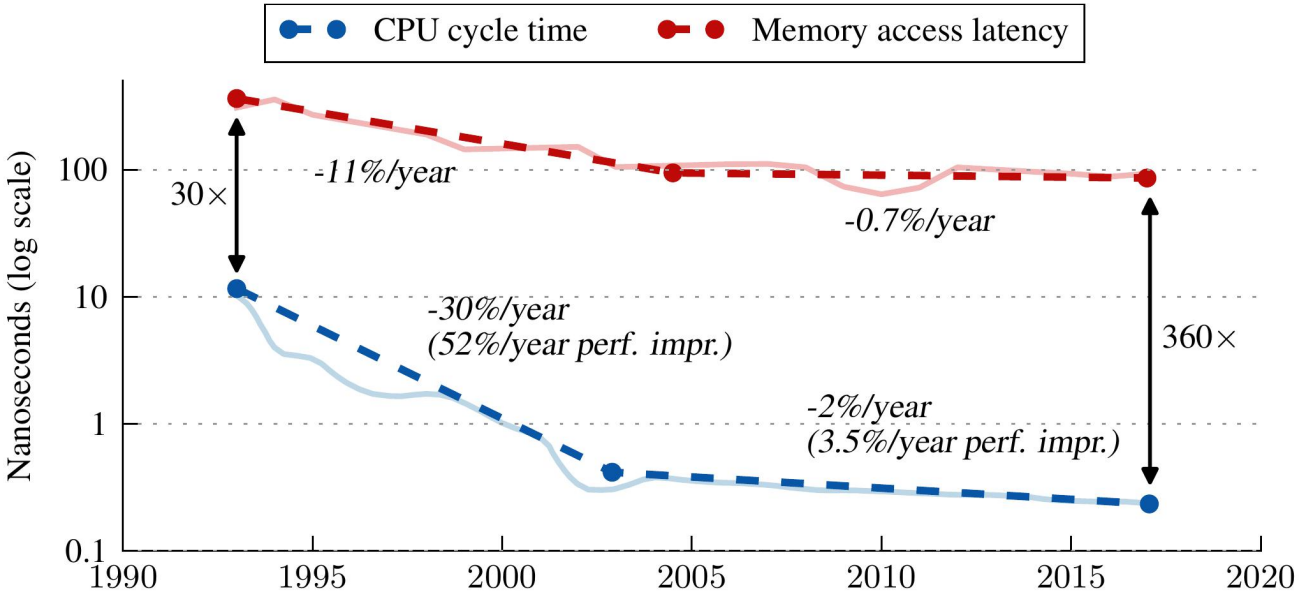


Figure 2.4: Increasing discrepancy between main memory access latency and CPU cycle time, for last 25 years. Recently the downtrend in CPU cycle time decreased to 2%, while single processor performance improves at 3.5% per year [52]. The decrement in memory access latency is less than 1%.

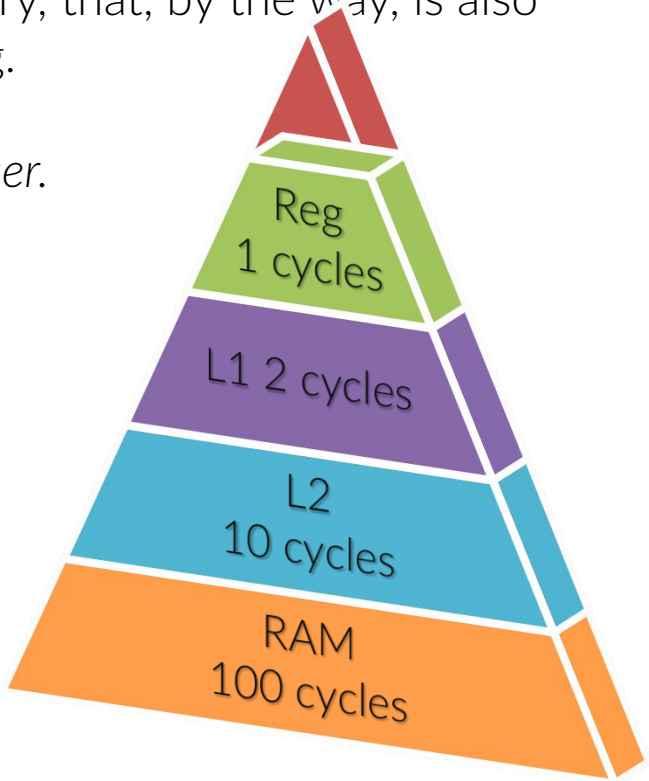
The cache memory

The solution is to equip your CPU with a *faster* memory, that, by the way, is also *way* more expensive and *way* more energy consuming.

Furthermore, to be faster it ought to be *extremely closer*.
All in all, the new memory that will be called ***cache***,
will be much *smaller* than RAM.

The cache itself has a hierarchy:

- *Level-I* is inside each core.
- *Level-II* is also inside the core, or may be shared by more cores.
- *Level-III* is inside the CPU, shared by many cores.



Just a quick curiosity: the origin of the word “*cache*” is linked to winery.

While you have the bulk of your precious wines in the basement cellar, it may be uncomfortable to get back and forth while you are dining with friends..

Just a quick curiosity: the origin of the word “*cache*” is linked to winery.

That’s why you are backing up with your ***cache***, which you did fill pre-emptively with the most suited wines !

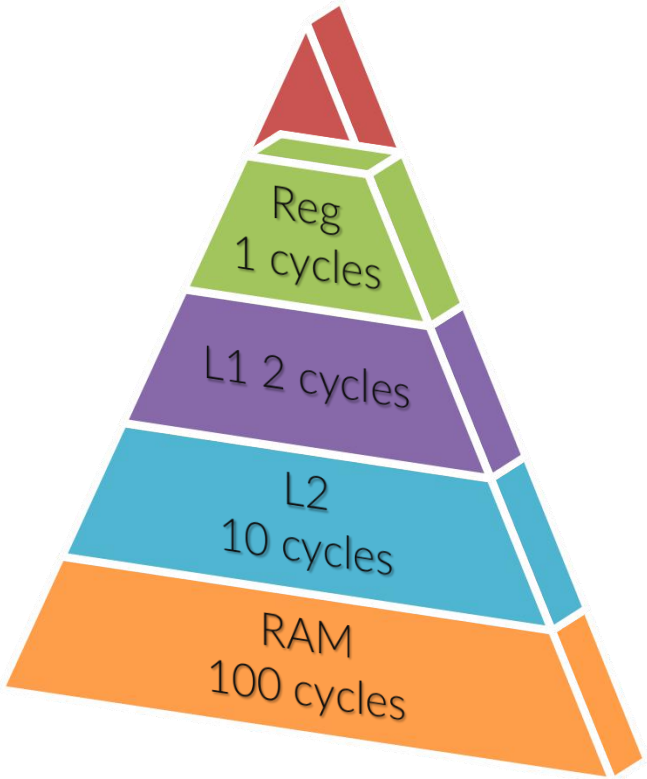
The cache memory

L1 cache + RAM

$L_{1cost} + Miss_1 \times RAM_{cost}$

- 100% L1 hit → 2 cycles
- 99% L1 hit → 3 cycles
- 97% L1 hit → 5 cycles

} 50% to 150% slower



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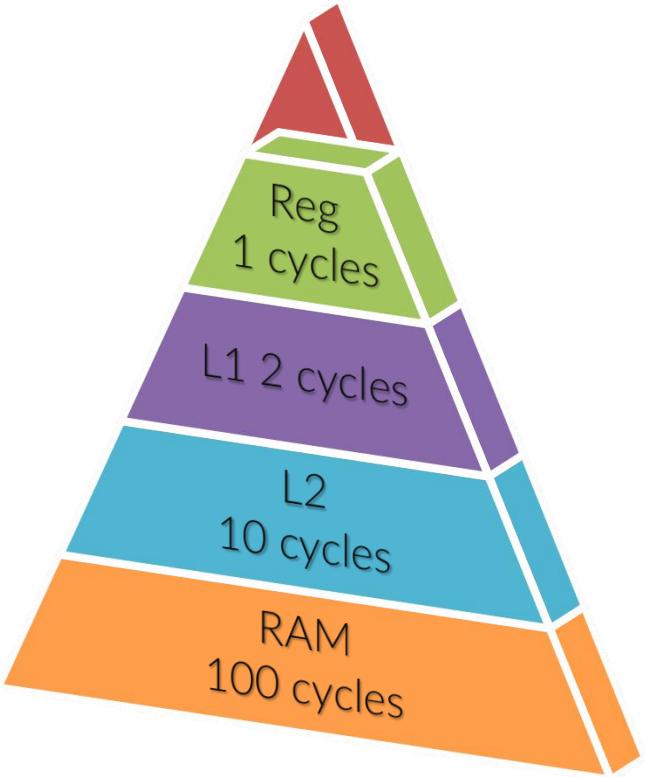
- 97% L1 hit → 5 cycles

L1 cache + L2 cache + RAM

$L_{1cost} + Miss_1 \times (L2_{cost} + Miss_2 \times RAM_{cost})$

- 100% L1 hit → 2 cycles
- 99% L1 hit, 100% L2 hit → 2.1cycles
- 97% L1 hit, 100% L2 hit → 2.3 cycles
- 90% L1 hit, 97% L2 hit → 3.3 cycles



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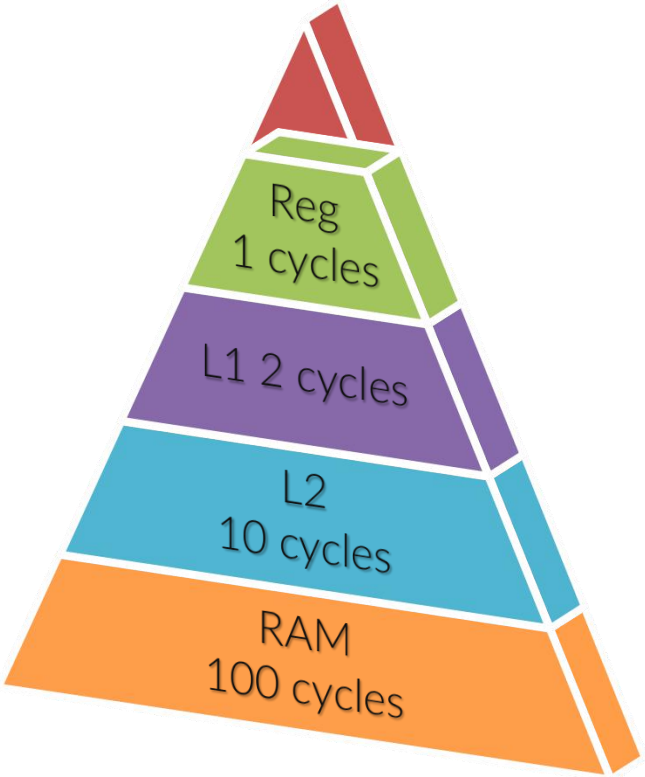


The principle of locality

We are quite naturally led to the “principle of locality”:

> Data are defined “local” when they reside in a “small”portion of the address space that is accessed in some “short” period of time
>
> → local data are likely to be in the cache

Temporal locality	if an address is referenced, it is likely to be referenced again soon
Spatial locality	if an address is referenced, close addresses are likely to be referenced soon

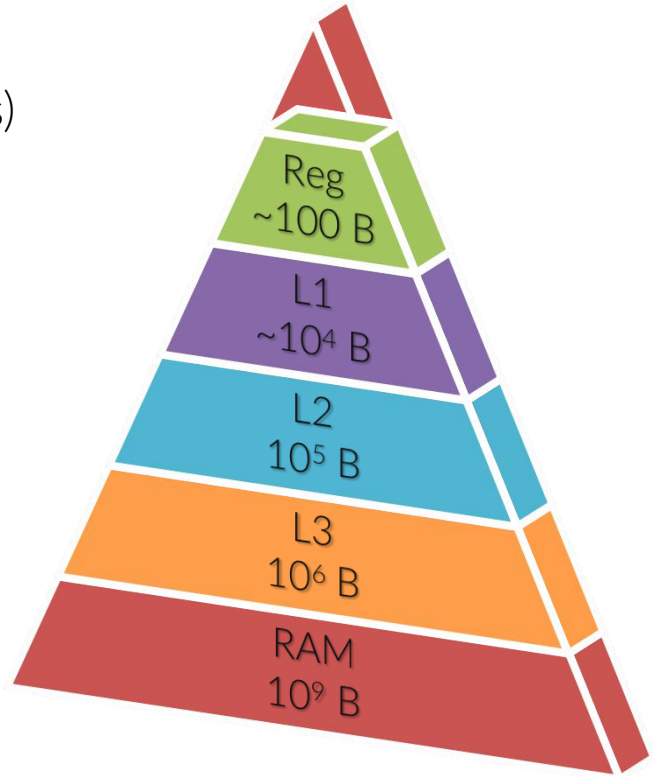
Cache mapping

Question:
The RAM contains ~10^9 bytes, while L1 contains ~10^4 bytes (32KB for data and 32KB for instructions)

So, how do you map the RAM in to a given level of cache, for instance L1, in an effective way?
The main problems are:

- *Where* to map an address
- *What if* the location in L1 is already occupied?

…we'll see that in the next lecture



Cache recap in two slides

3C for the foes

- **Compulsory misses**
  Unavoidable misses when data are read for the first time
- **Capacity misses**
  - Not enough space to hold all data
  - Too much data accessed in between successive use
- **Conflict misses**
  Cache trashing due to data mapping to same cache lines

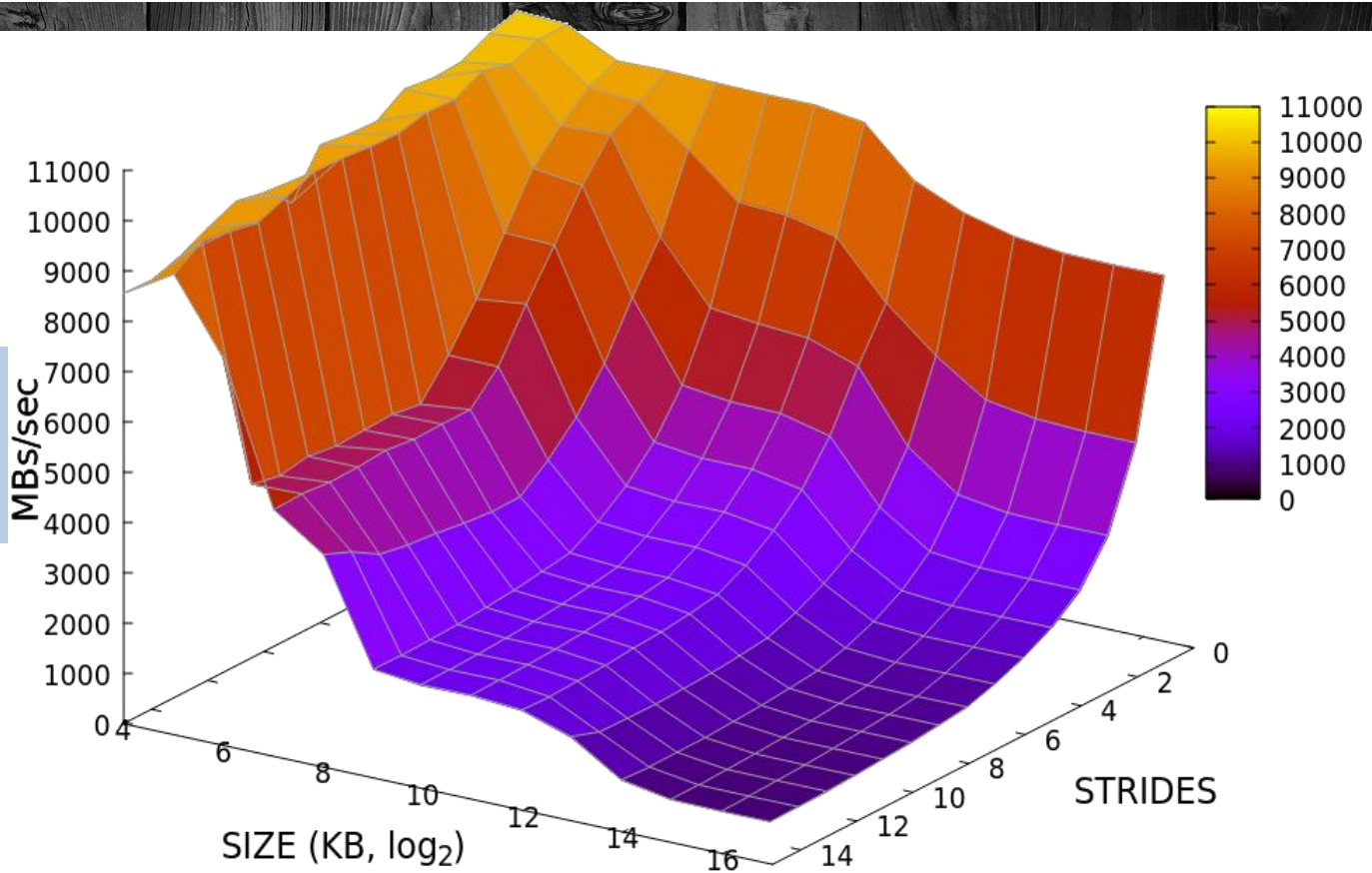
Cache recap in two slides

3R for the friends

- **Rearrange (code & data)**
  Design layout to improve temporal & spatial locality
- **Reduce (size)**
  - Smaller data size – smaller chunks accessed
  - Fewer instructions
- **Reuse (cache lines)**
  Increase spatial & temporal locality – keep resident data for more operations

Preview: The memory access pattern

The result is..
the memory mountain



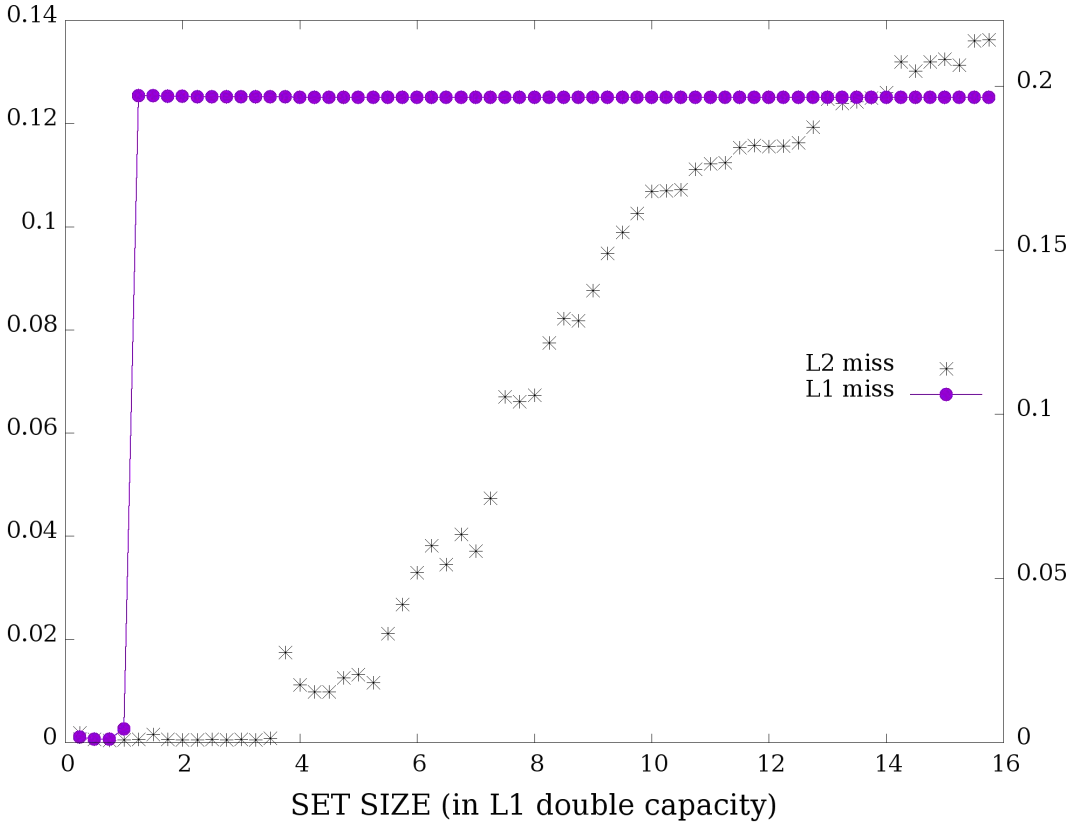
Just a preview;
more details in the next lecture

Preview: The cache-miss signature

Let's find out our cache size

```
for (j=0; j < size; j++)
   array[j] =
     2.3*array[j]+1.2;
```

Just a preview;
more details in the next lecture



Preview: The cache-miss signature

And the effect on cycles-per-operation metrics

```
for (j=0; j<size; j++)
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```

Just a preview;
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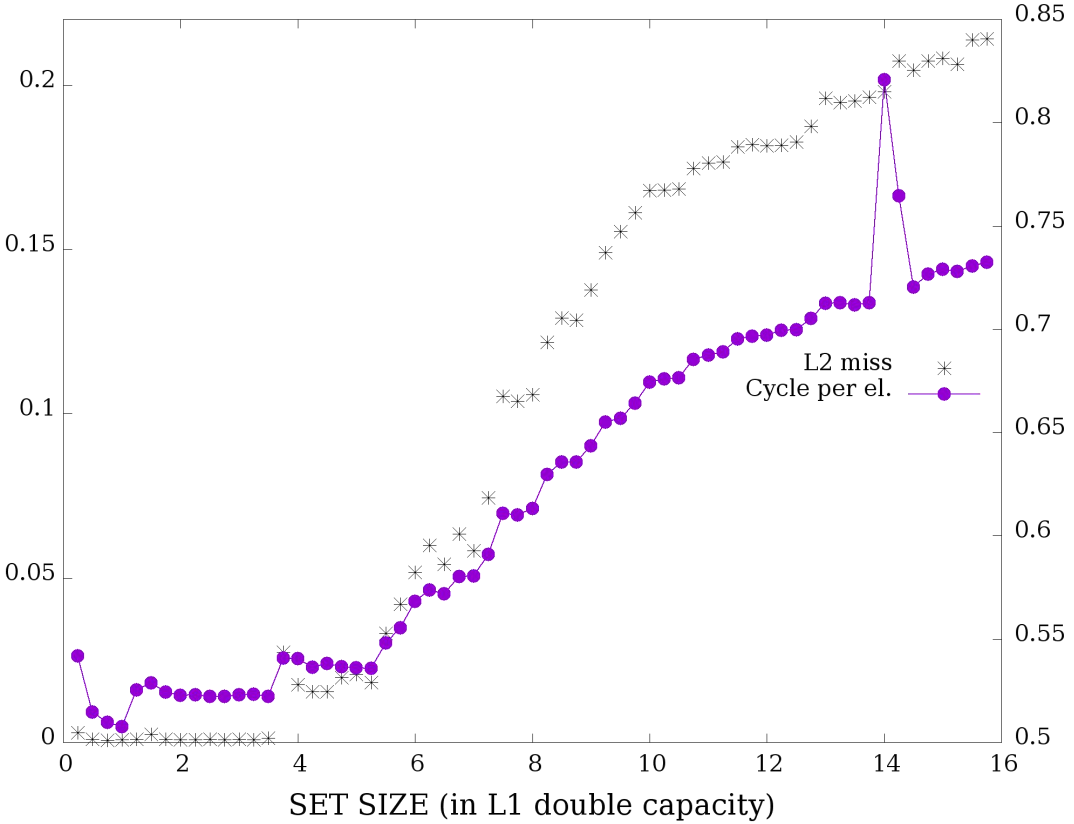
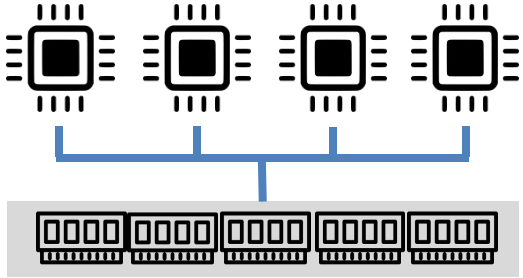
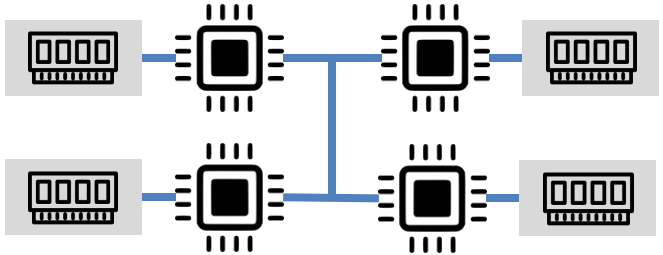


A coherency problem

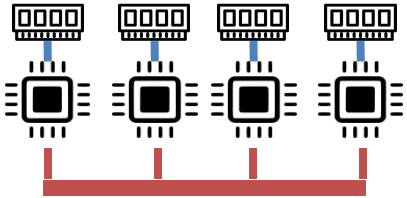
You already know the difference between

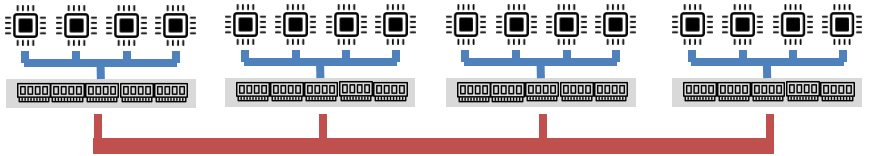
SMP





Disitributed NUMA

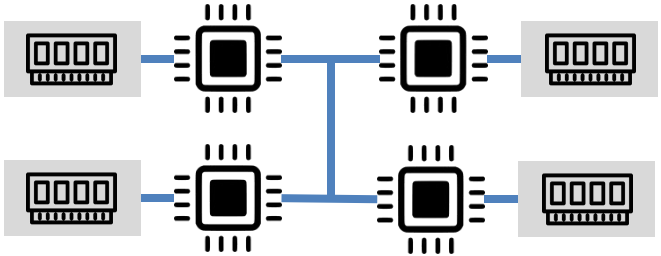




A coherency problem

Consider an SMP node, with tens of sockets interconnected by a bus

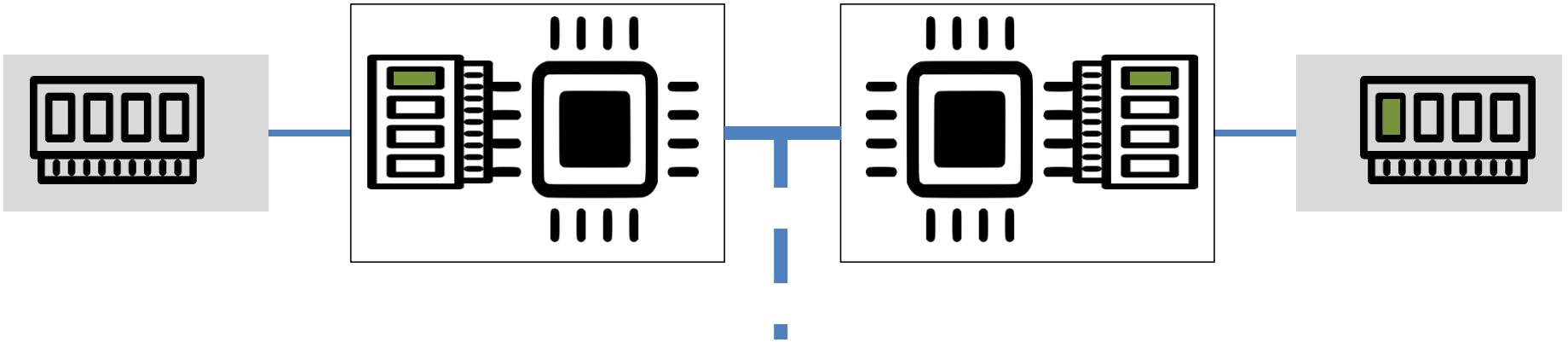
*(remind: a **bus** is a "collective" interconnect in which the messages are broadcasted and everyone is listening for a message dedicated to itself)*



The memory is *shared*, and everybody sees the whole amount of RAM

A coherency problem

Let's say that the CPUs have caches and some data are loaded in more than one cache



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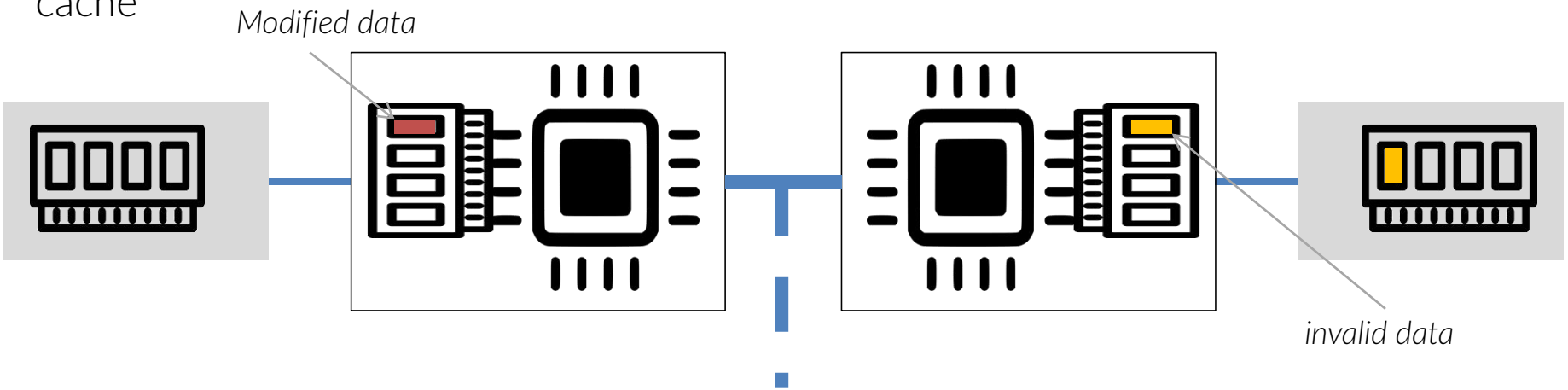


What happens to all the caches and "actual" data in memory when one CPU modifies the data?
That is called *cache coherency* and the overwhelming difficulty and cost to manage it on too large SMP nodes is the main limit to their size.

Early 90s: CPU becomes faster than memory

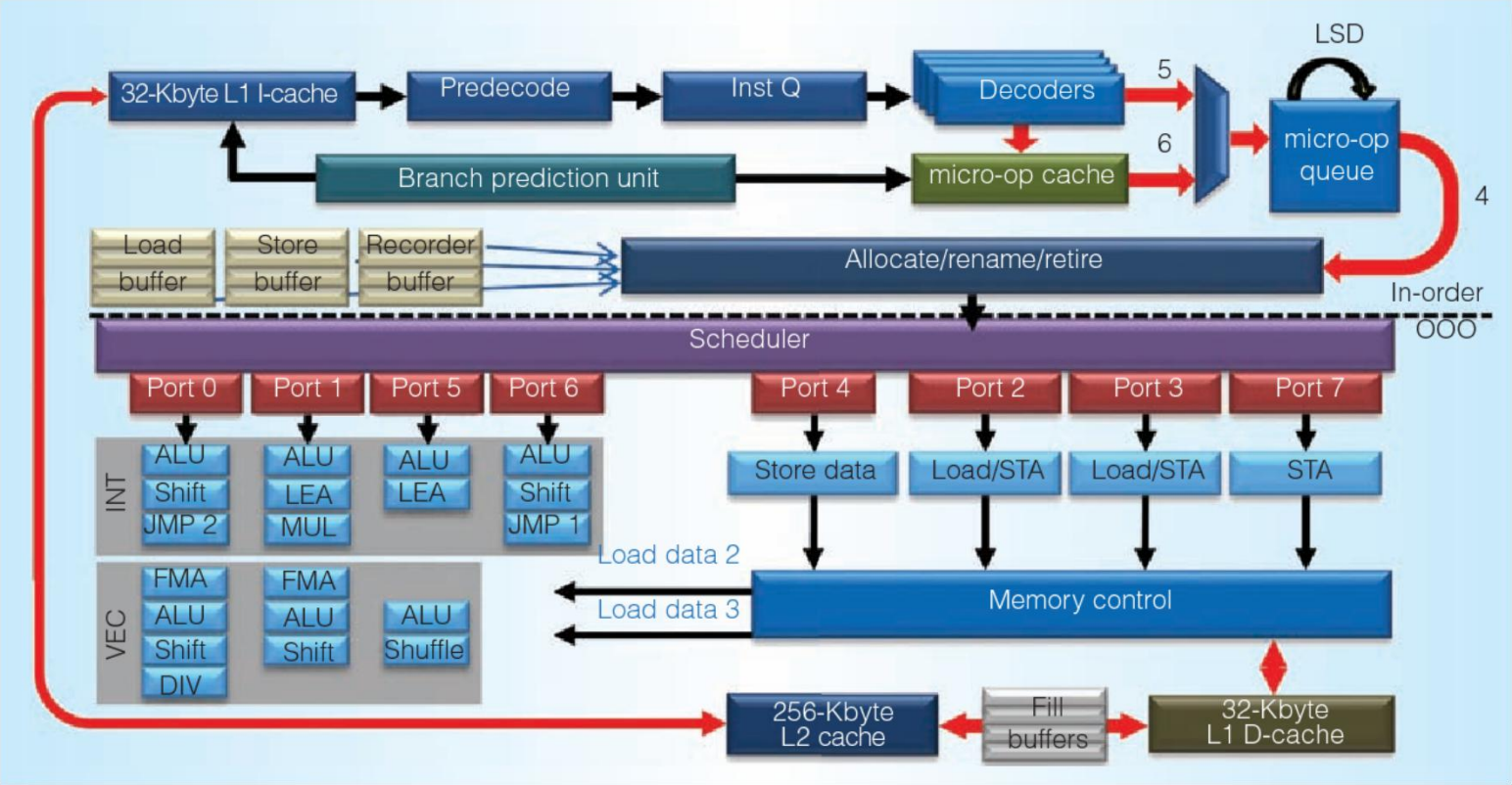
So, after having introduced the hierarchy of cache memories, you have to deal with a strong memory hierarchy and the fact that your CPU is much faster than the central memory.

Even if you are very good in designing the data model and the workflow of your code, that complexity may result in a real performance disaster: for instance because your CPU is stuck doing nothing while waiting for some data or for some operation to end.

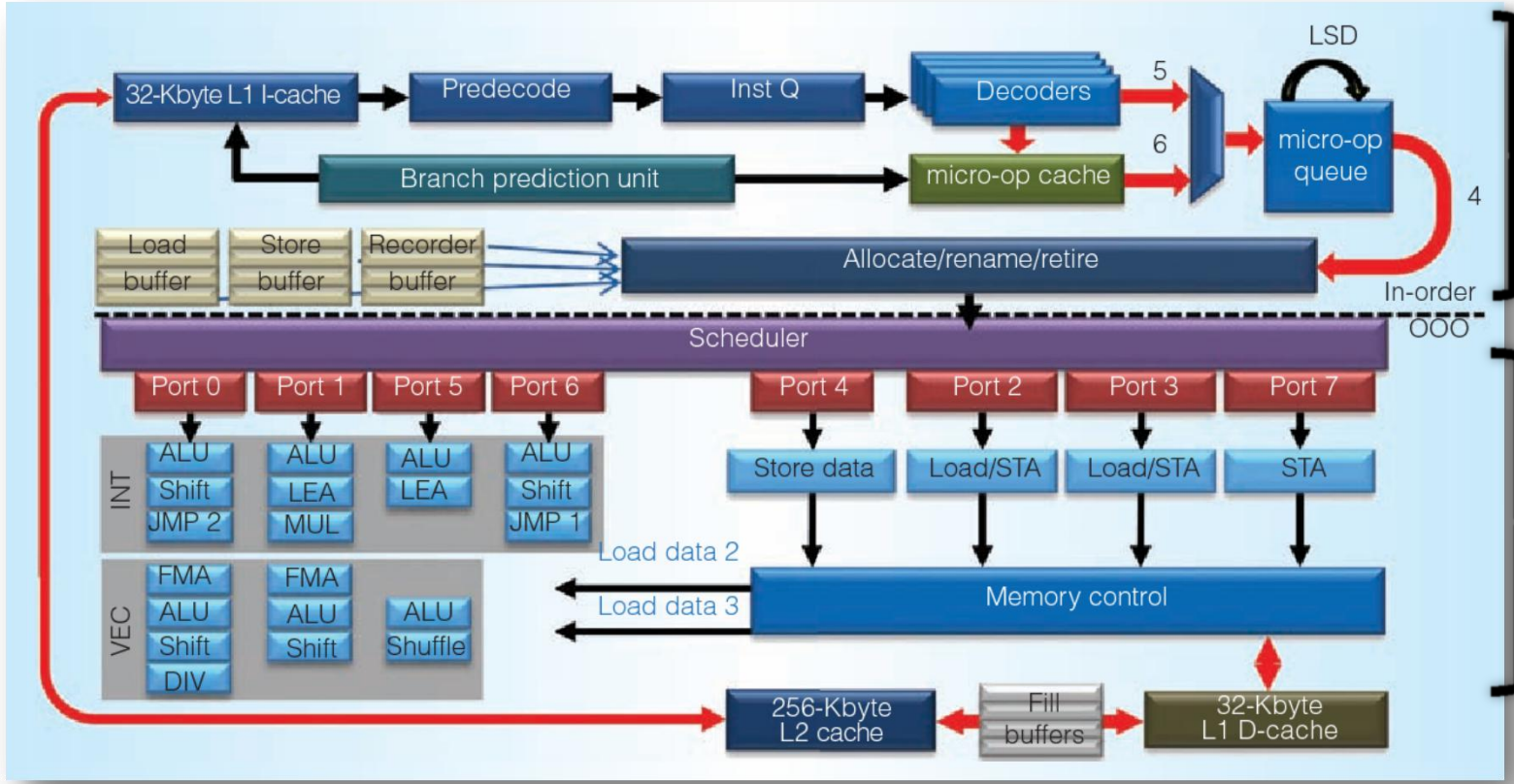
This leads us to some more improvements.

Mid 90s: superscalar and out-of-order CPUs

6th generation SkyLake micro-arch.

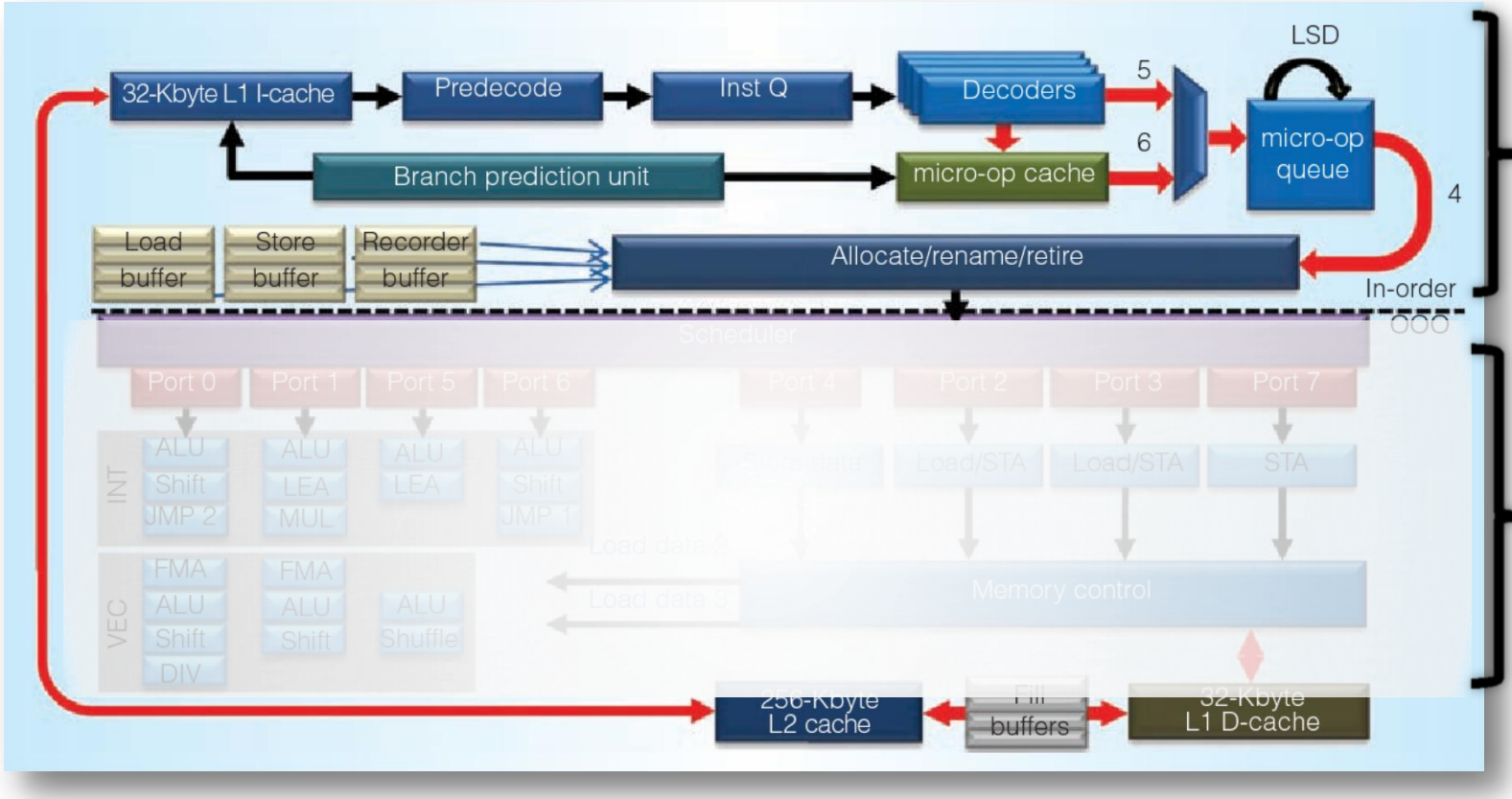


More than 1 *port* is available to execute CPU instructions, although different units have different specializations (ALU, LEA, SHIFT, FMA, …) : that is superscalar capacity, i.e. the capacity of executing more than 1 instructions per cycle.



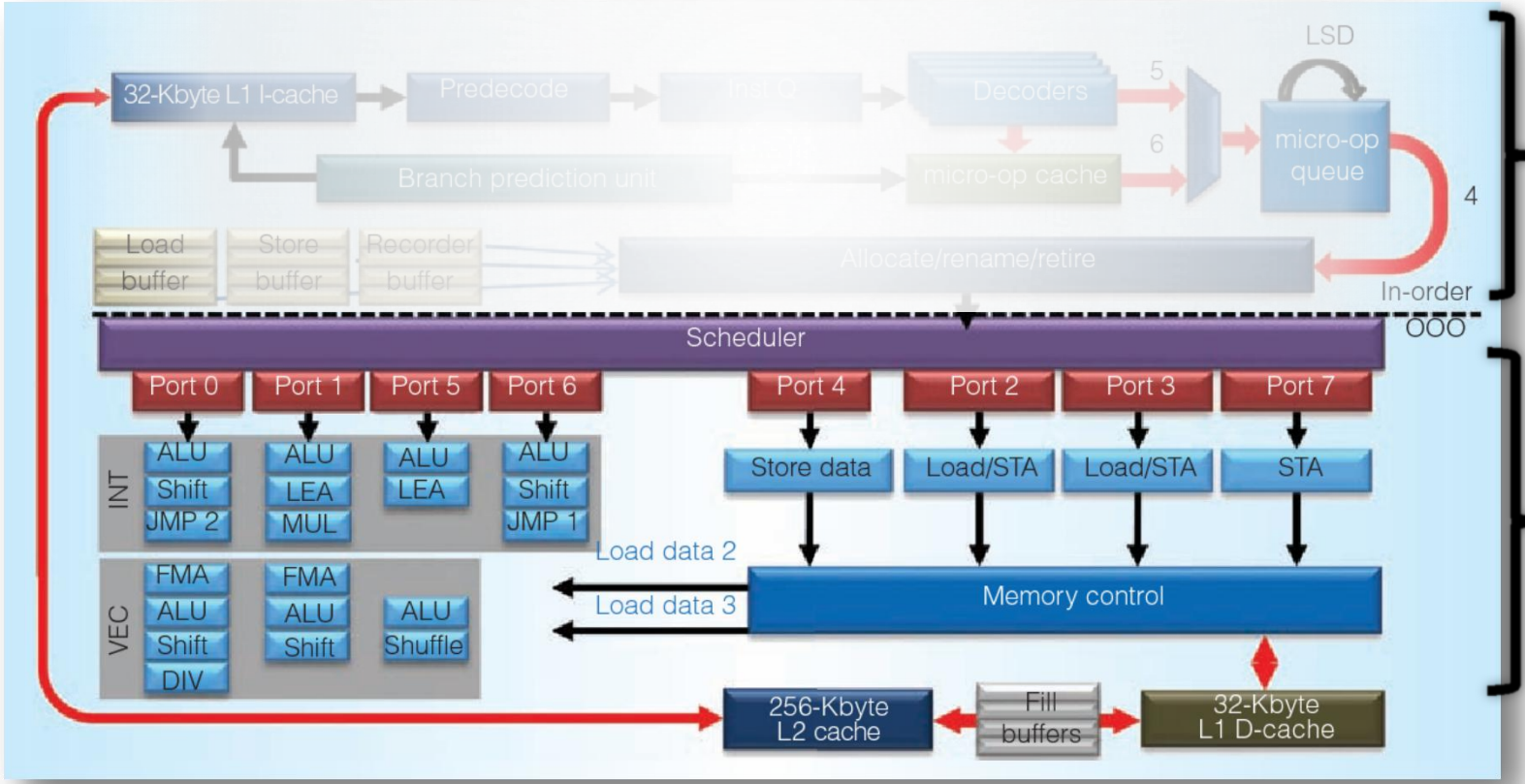
6th generation SkyLake micro-arch.

The *Front-End* basically fetches instructions and the data they operate on from instruction and data caches, decodes instructions, predicts branches and dispatches the instructions to different ports



6th generation SkyLake micro-arch.

The *Back-End* is responsible for the actual instructions execution and for the back-writing of results in memory locations. It is responsible also for orchestrating out-of-order ops execution depending on their instructions/data dependencies.

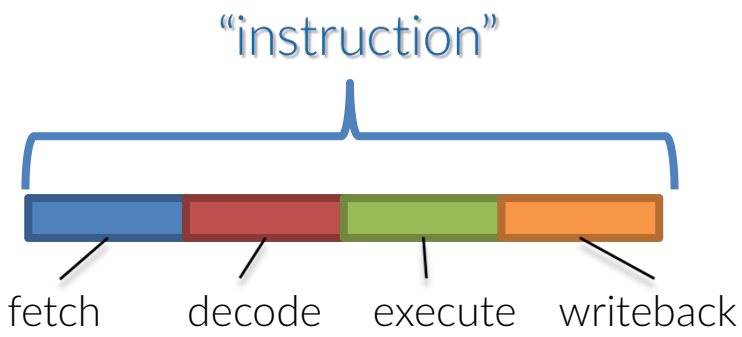


6th generation SkyLake micro-arch.

Pipelines

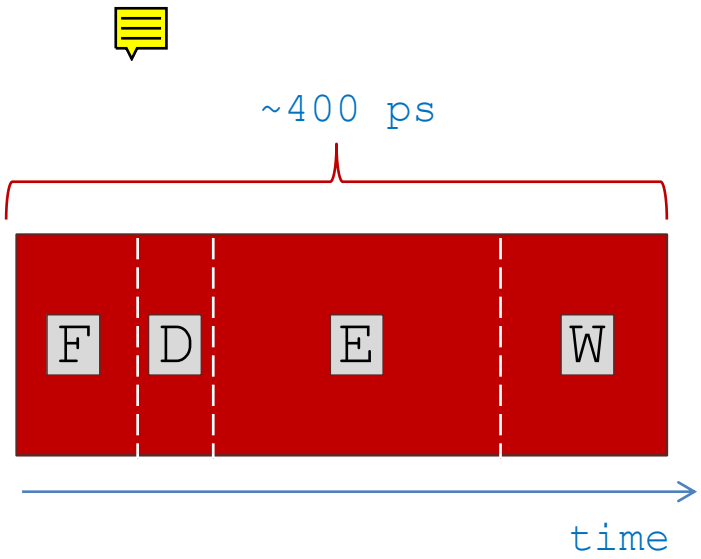
It would be obvious to think that an “instruction” is a kind of *atomic* operation that the CPU perform as a whole. Indeed that was true until the mid of the 80s.

If you think carefully about it, it is easy to understand that actually an “instruction” involves at least the following ***independent*** steps:



1. *Fetching*
   it must be recalled from memory/Icache
2. *Deconding:*
   it must be “understood and interpreted”
3. *Execution*
4. *Writeback :*
   the result must be accounted in memory ()

Pipelines

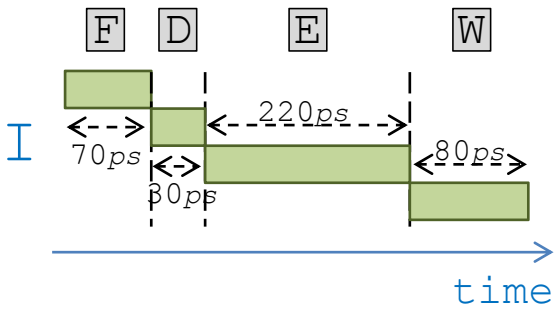


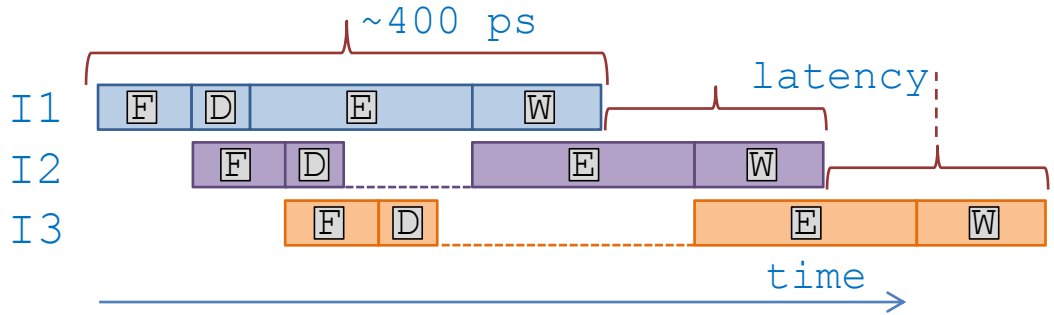
If all the four stages take ~400ps, we then would obtain a **throughput** of 2.5GIPS (giga-instructions per second).
400ps is also the total time required to get a result from an instruction, and so it is the **latency** of the instruction.

However, if we were able to "detach" the four stages, we could organize things differently, like in a car-building chain, or even at the mensa of the university.

Pipelines

Note: all the timing estimates are hypothetical for the purpose of discussing the concepts



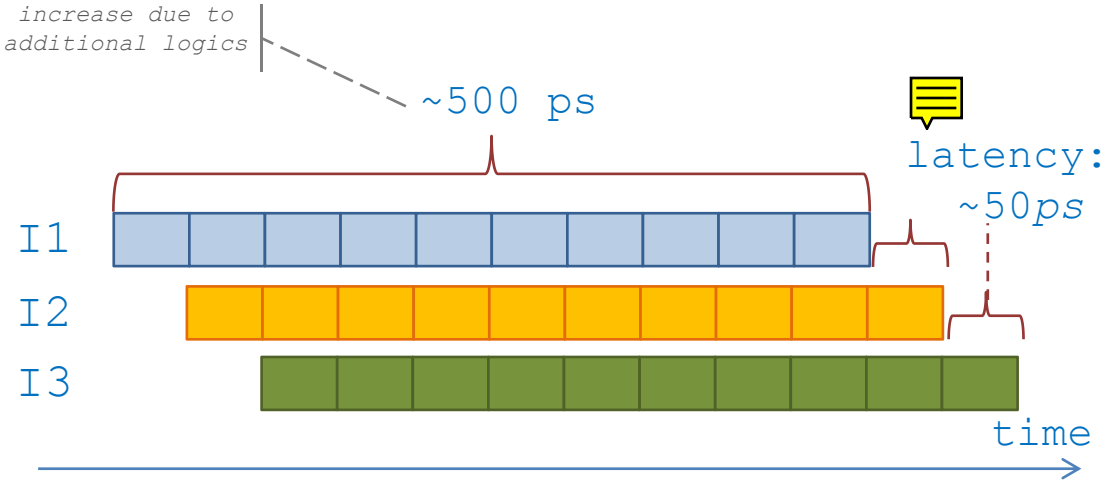


If many independent logical units exist to perform each step, they could operate subsequently on **different instructions**:

If the stage delays are not uniform, the throughput is limited by the latency `F+(D+E)-(F+D) = E` ~ 220*ps*, which means we have a throughput of ~**4.5GIPS** just because of logic units separation.

Pipelines

Therefore, introducing the instructions pipelining, we can increase the **throughput** of our system by a large factor.
However, the efficiency of the pipelines is limited by its longest stage: the better option would be to have all equal stages, for instance further subdividing each stage – especially the most demanding ones (*).



Now the throughput of our system has increased to 1 instruction retired every 50*ps*, i.e. 20GIPS

(*) this is called *superpipelining*: modern CPUs may have 10-20 stages per pipeline.

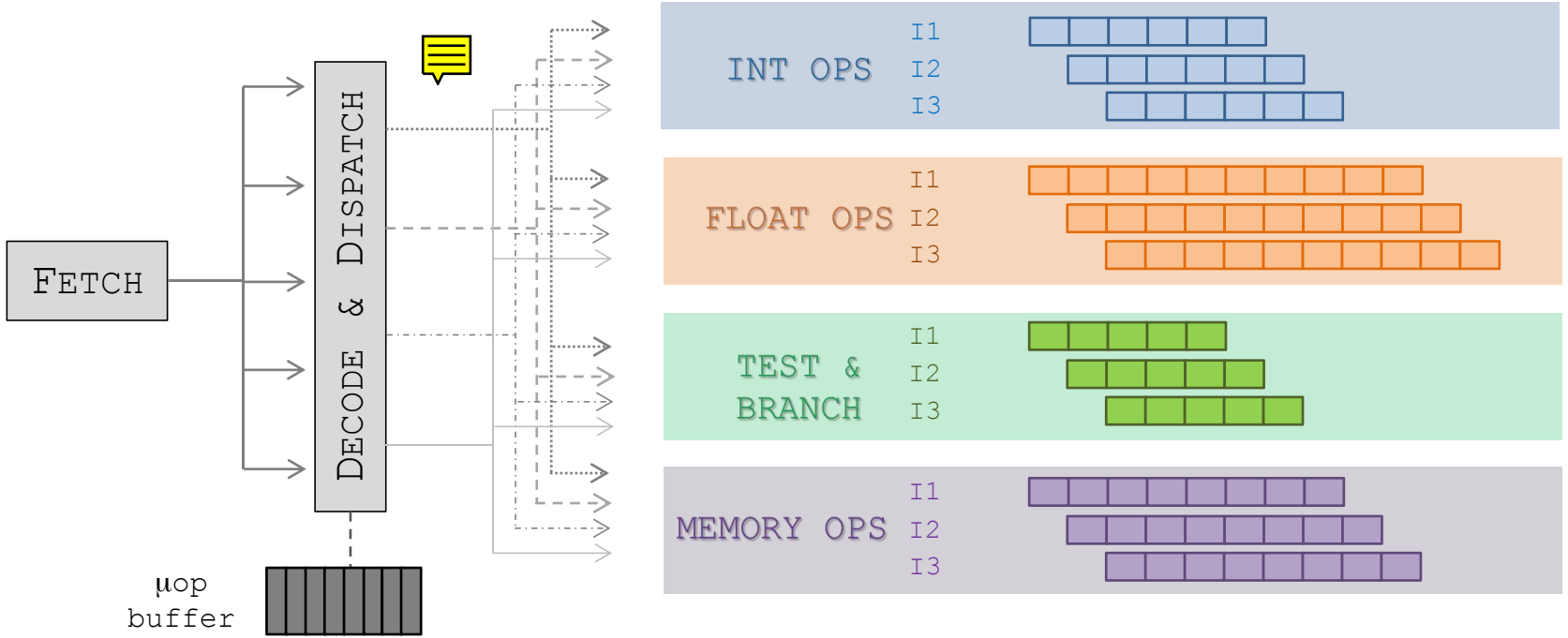
Pipelines are about throughput

Pipelining is then about increasing the throughput of a system, and as we have seen it could be really effective.

However, there is more that can be done working on the **execution stage** that, of course, encompasses a large number of different ***functional units***, performing a **different and independent tasks**.

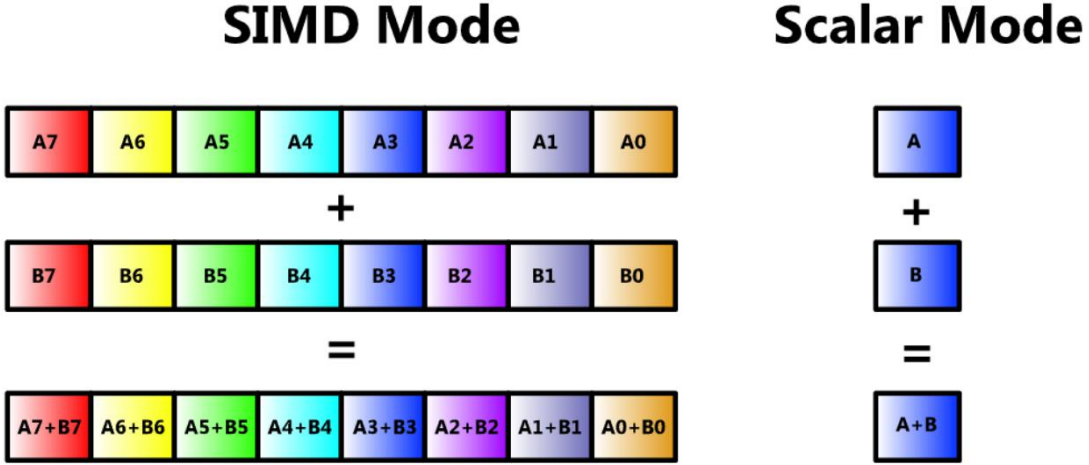
With an enhancement of the decode/dispatch stage, we can address multiple pipelines that can be active at the same time:

Multiple pipelines



Late 90s: vector capabilities become mainstream

https://software.intel.com/sites/default/files/m/d/4/1/d/8/Intro_to_Intel_AVX.pdf

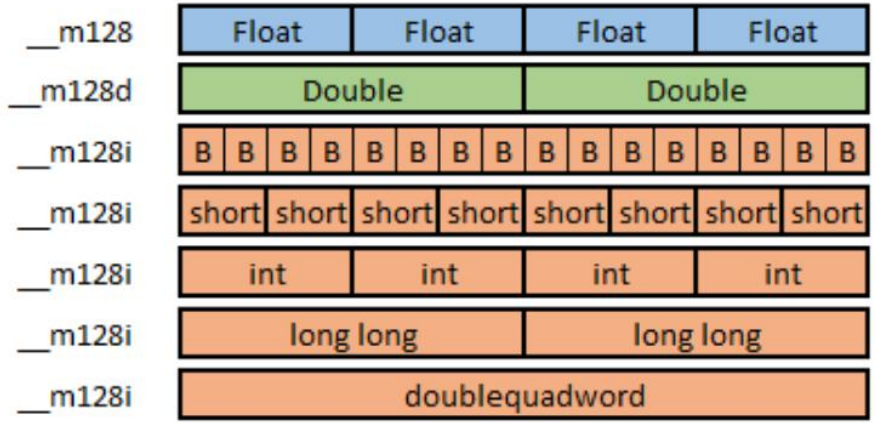


Vector registers are large special registers in the CPU that can be considered subdivided in smaller independent chunks over which the same operation can be performed:

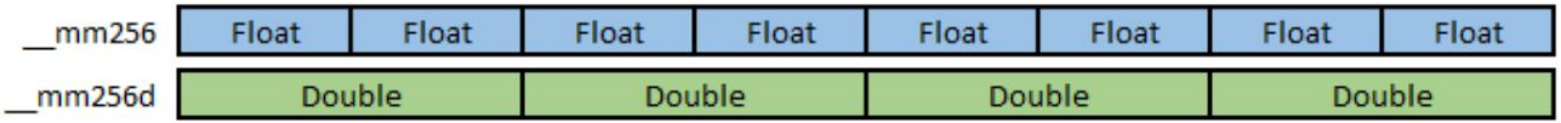
SIMD: Single Instruction
Multiple Data

Vector registers size

SSE Data Types (16 XMM Registers)



AVX Data Types (16 YMM Registers)



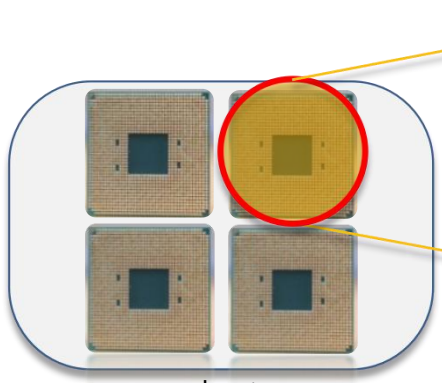
__mm256i *256-bit Integer registers. It behaves similarly to __m128i.Out of scope in AVX, useful on AVX2*

Early oos: multi-core becomes mainstream

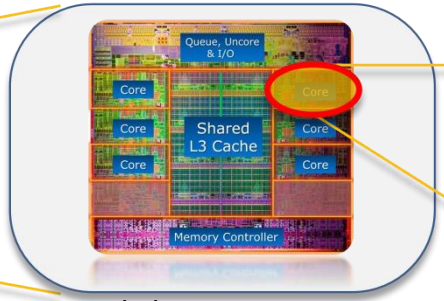
Late 00s : accelerators become mainstream
Early 10s: many-cores + heterogeneous computation becomes mainstream

That is the focus of the course on OpenMP/MPI

A final sketch

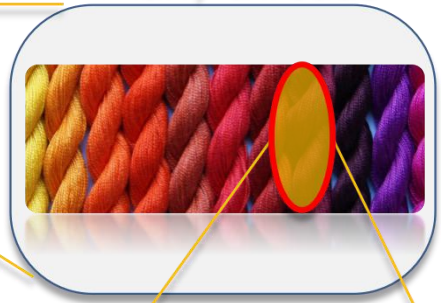


sockets



Many cores per socket

Many threads

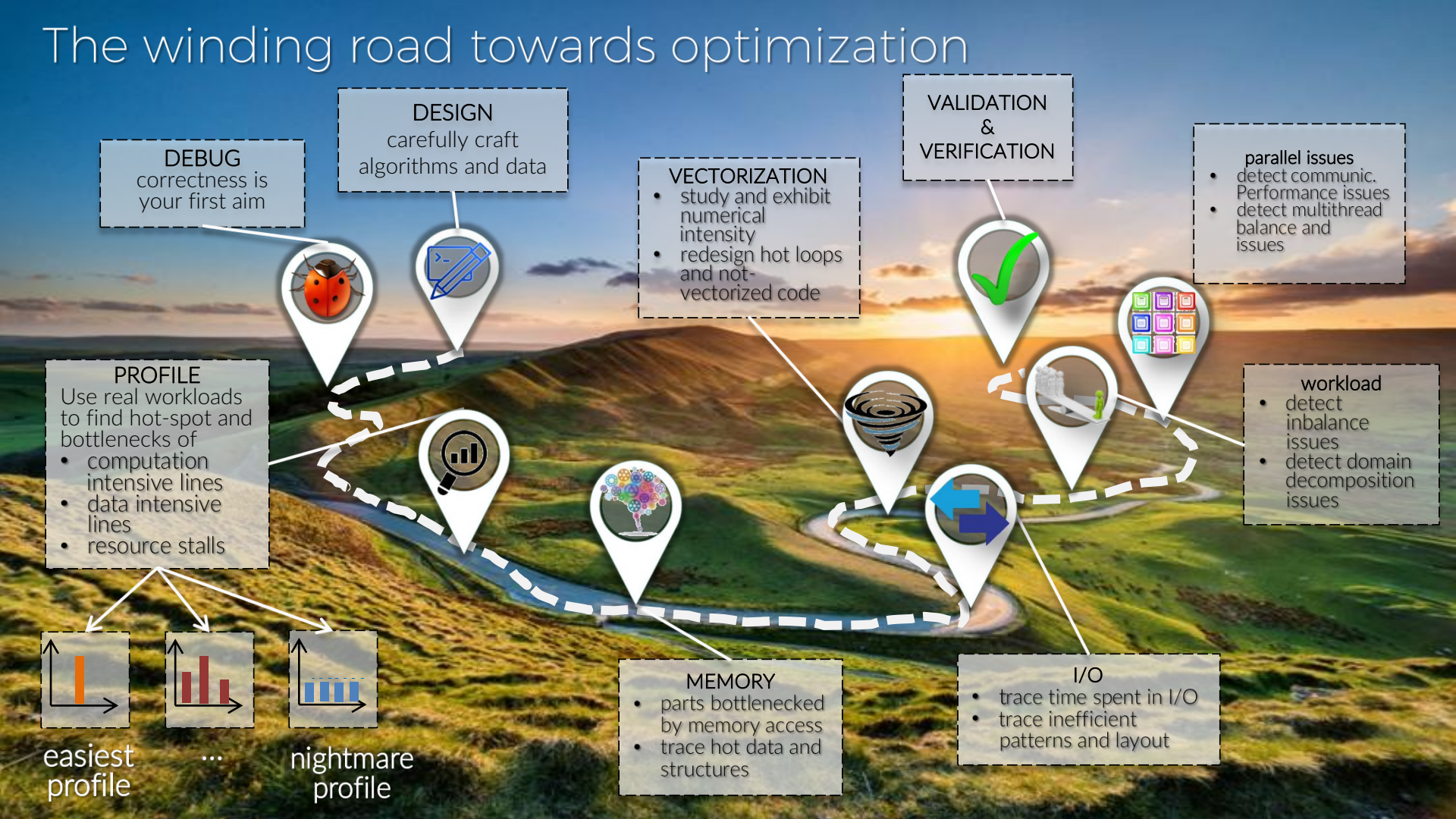


Vectorisation

Pipelining

Superscalarity

The winding road towards optimization



that's all, have fun