INTRODUCTION TO PARALLEL PROGRAMMING

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Goals

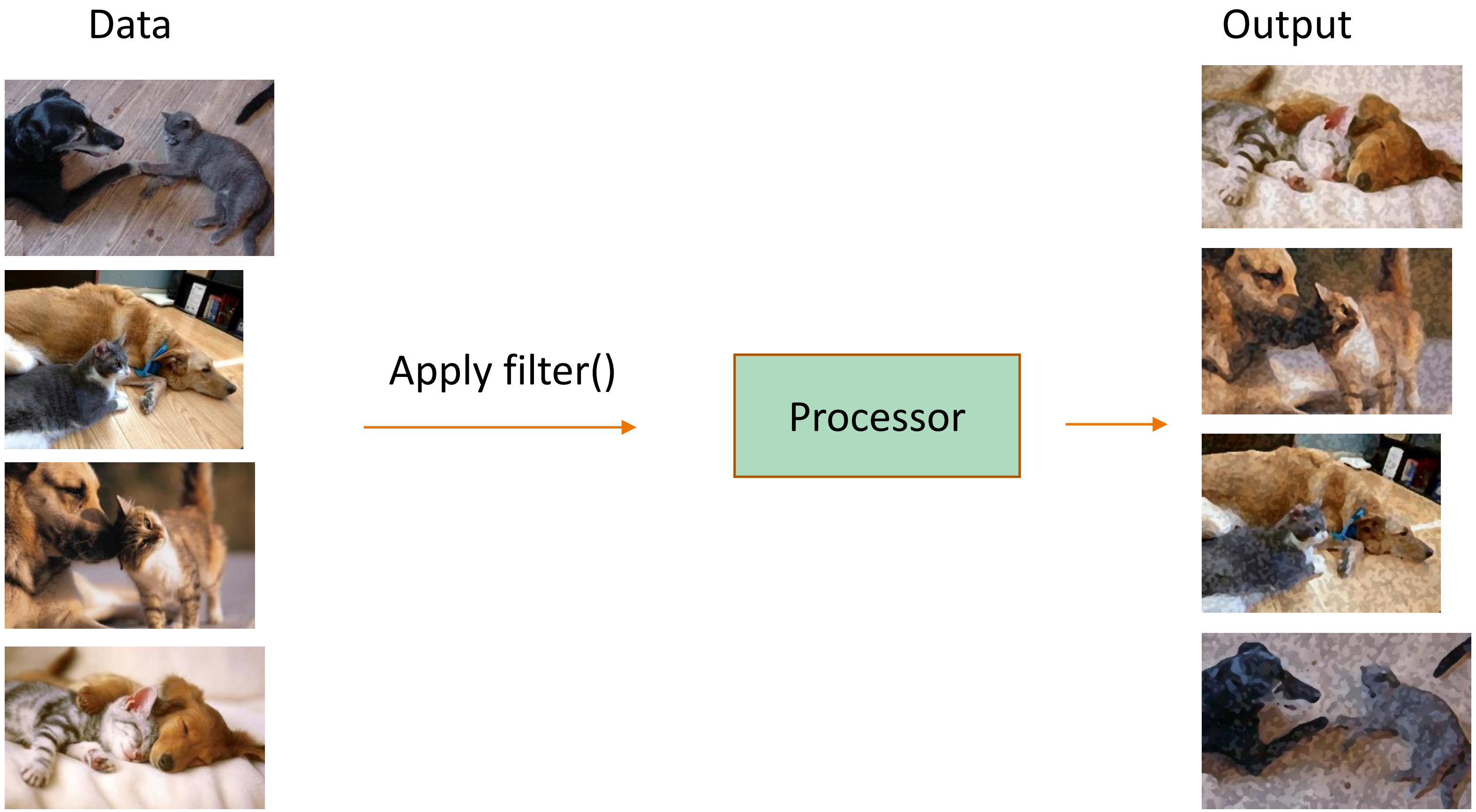
- The goal is to understand:
  - Merits and limits of parallel computing
  - Parallel programming models (task / data parallelism)
  - Differences between shared and distributed memory systems

Content

- What is parallel computing?
- Parallel programming models
- Different types of systems

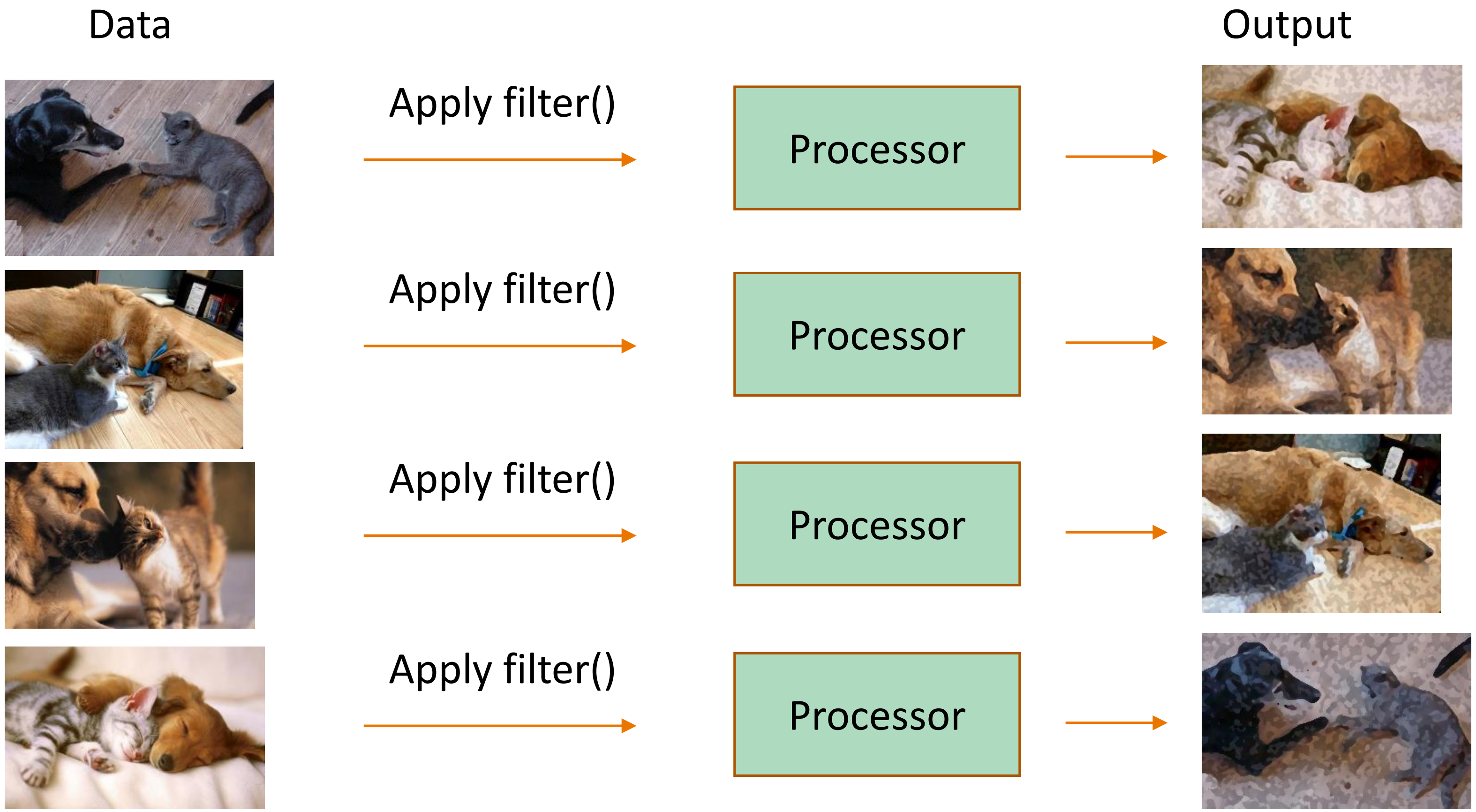
What is parallel computing?

- Parallel computing
  - Multiple processors or computers working on a single computational problem



What is parallel computing?

- Parallel computing
  - Multiple processors or computers working on a single computational problem

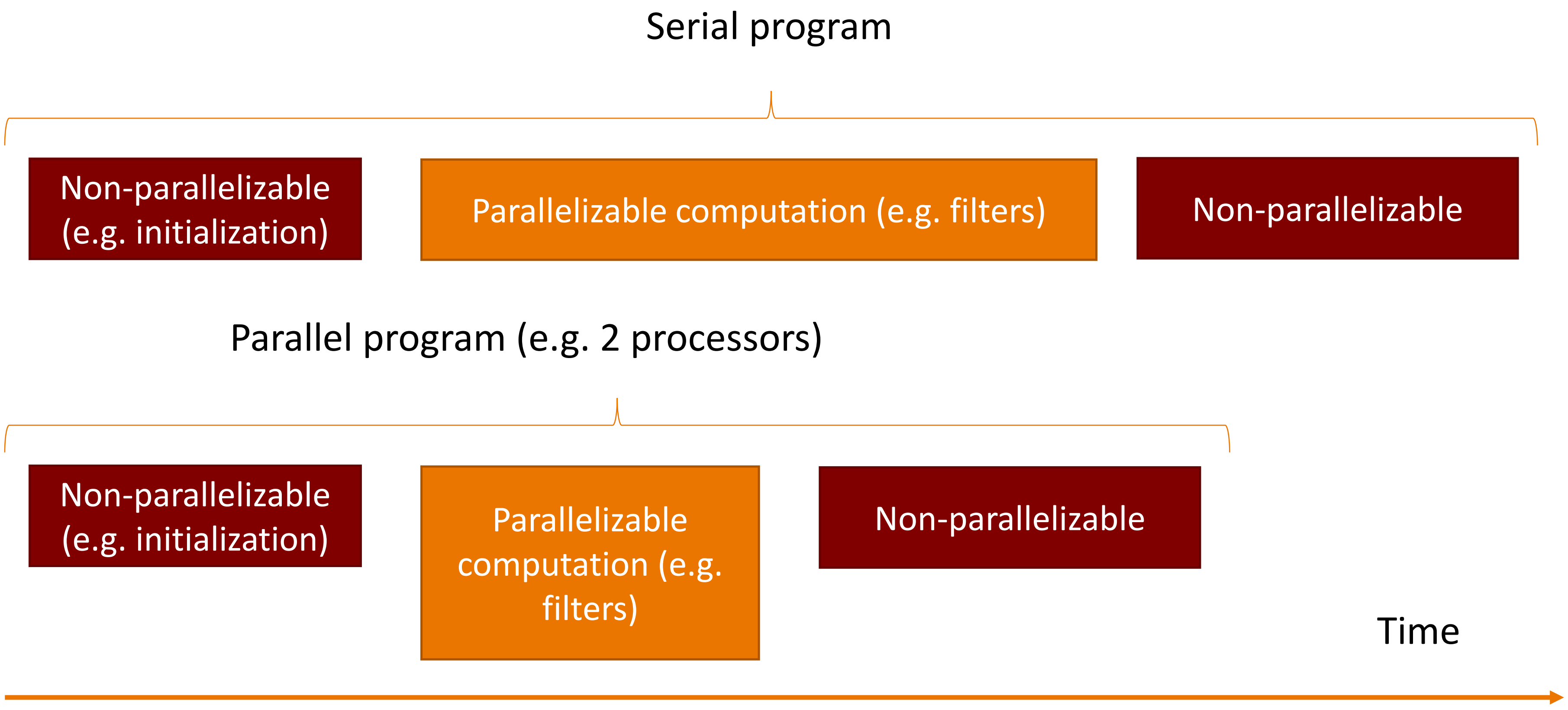


Parallel computing: benefits

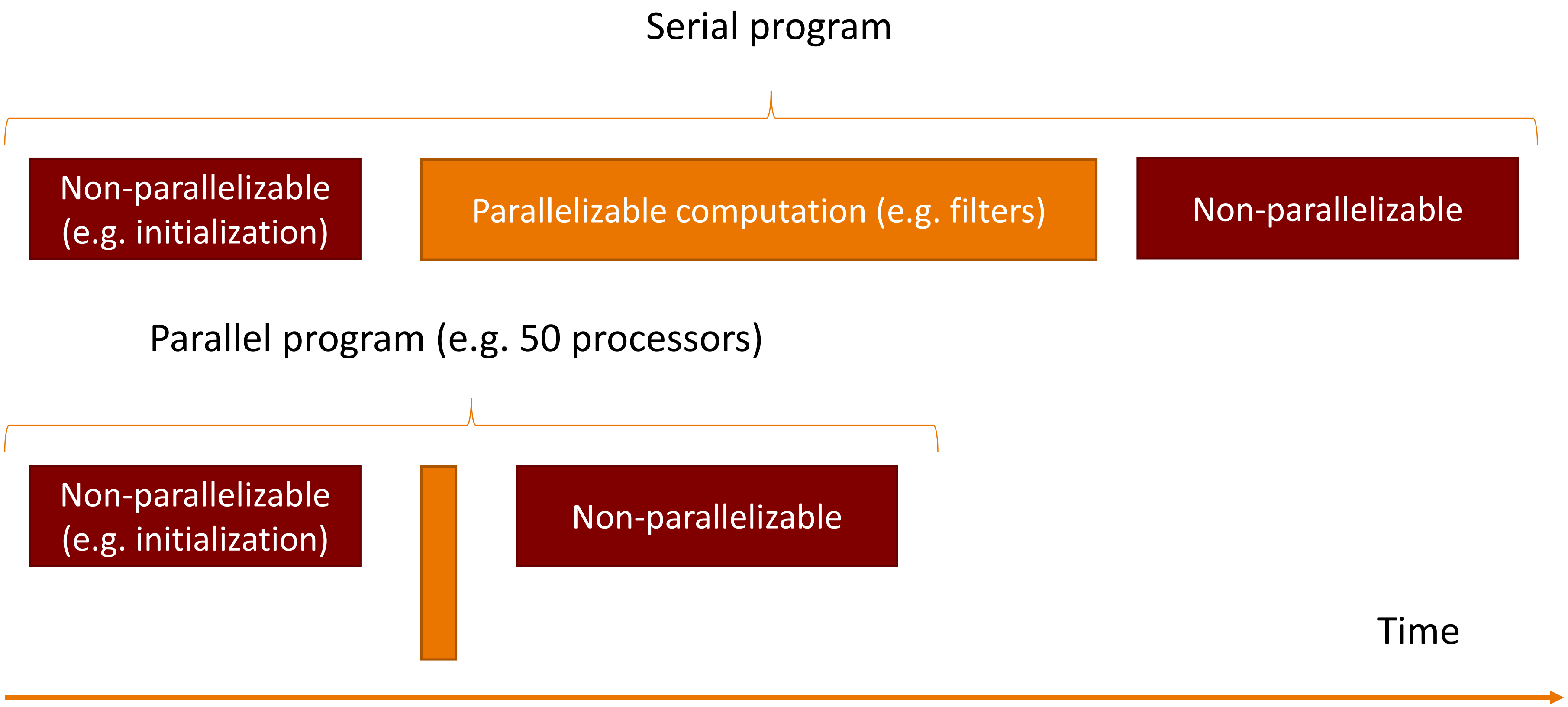
- Benefits
  - Solve computationally intensive problems (speedup)
  - Solve problems that don’t fit a single memory (multiple computers)

- Requirements:
  - Problem should be divisible in smaller tasks

Real problem: often partly parallelizable



Real problem: often partly parallelizable

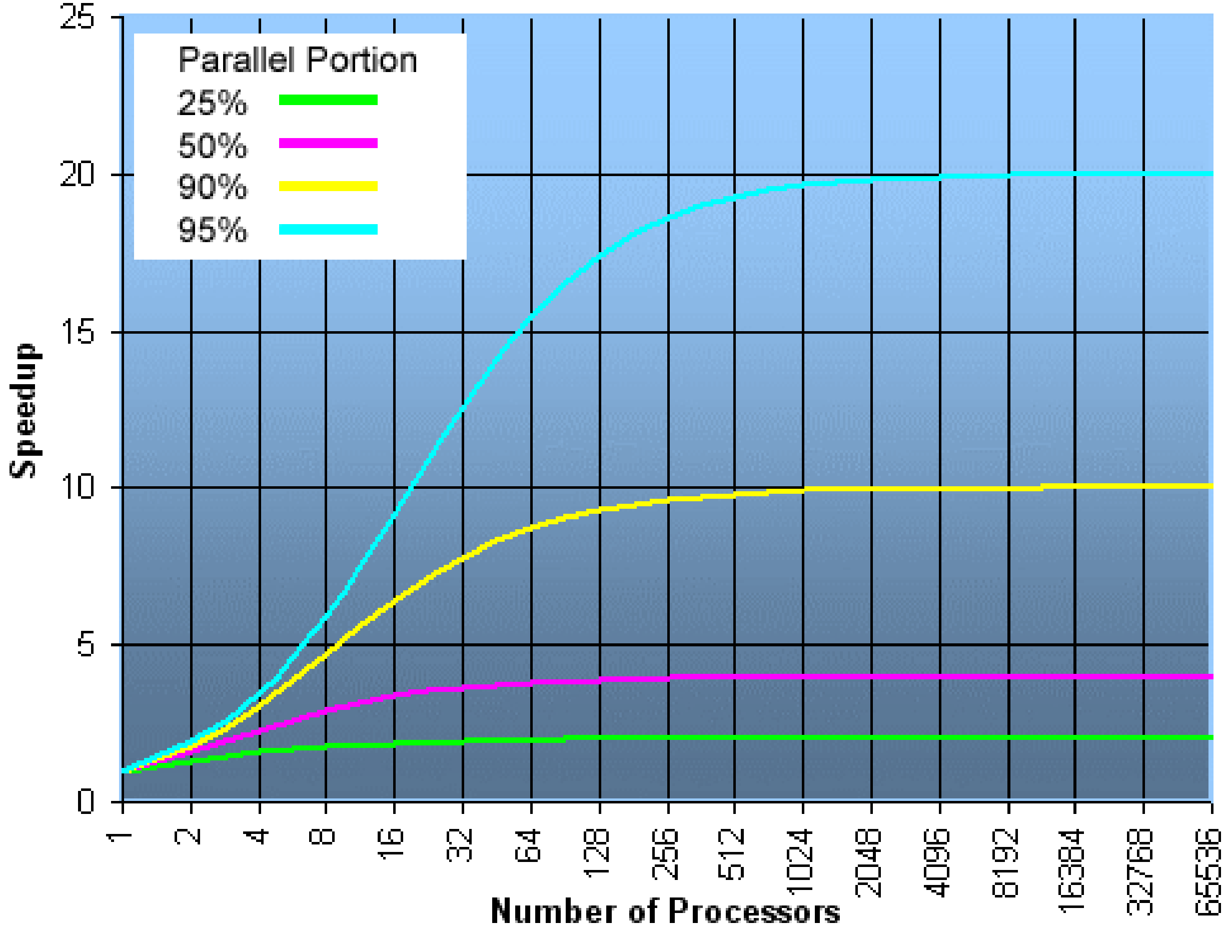


Amdahl's Law

$$Speedup = \frac{1}{(1-p)+\frac{p}{N}}$$

N = number of processors

p = parallel fraction



Amdahl's law describes *strong scaling*

- Strong scaling
  - Variation of solution time with #processors for fixed *total* problem size
  - Possibilities to run the same problem in shorter time

Apply filter()

Processor

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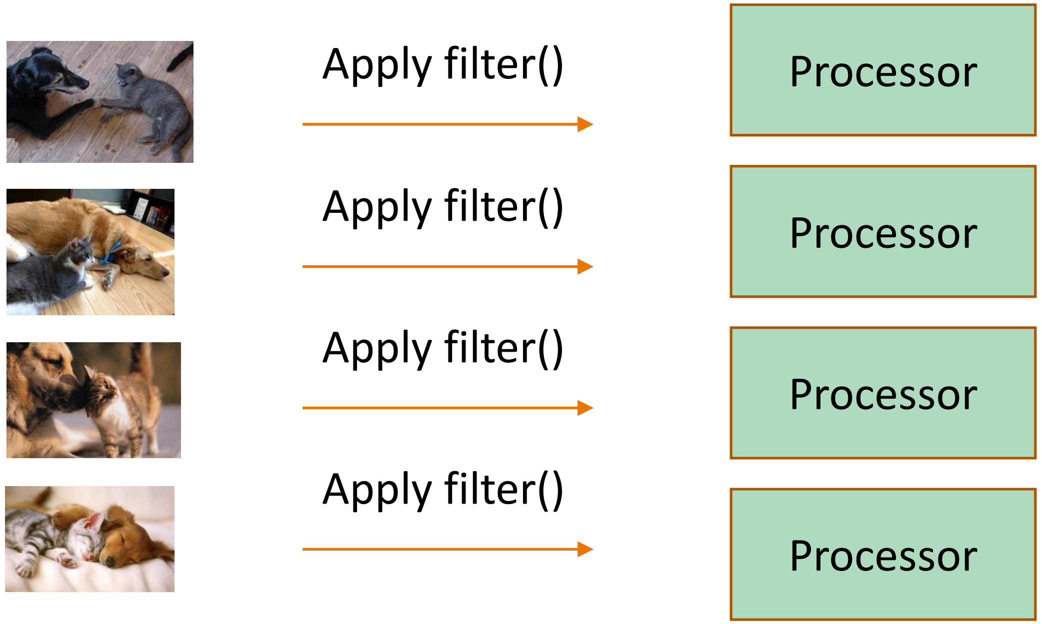

Amdahl’s law is theoretical…

- … and reality is often worse!

- Further issues to tackle
  - Load balancing
  - Process scheduling
  - Communication overhead
  - File Input/Output
  - …

Do we have hope…???

Gustafson's Law

$$Speedup = 1 + p \cdot (N - 1)$$

N = number of processors

p = parallel fraction

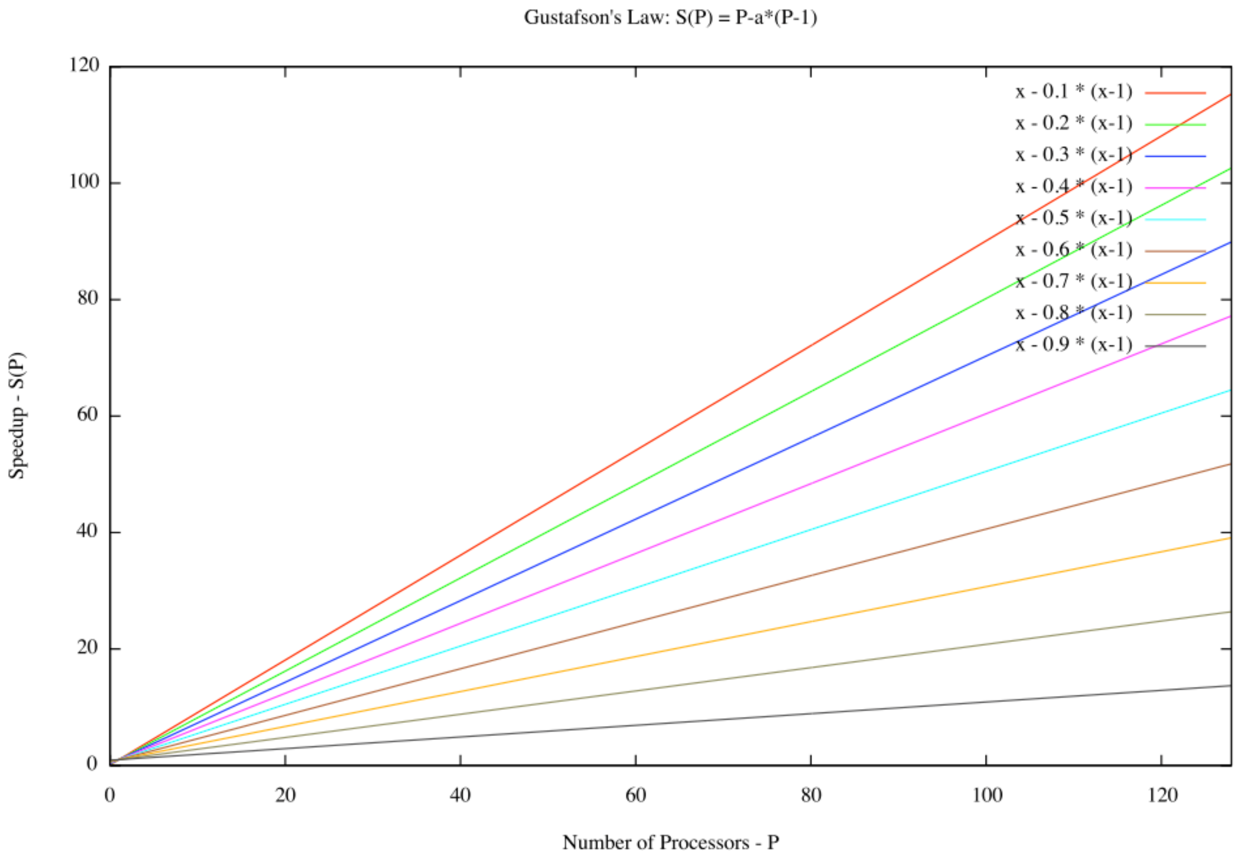

Image source: https://computing.llnl.gov/tutorials/parallel_comp

Gustafson's law describes *weak scaling*

- Weak scaling
  - Variation of solution time with #processors for fixed problem size *per processor*
  - Possibilities to run a bigger problem in the same time

Apply filter()

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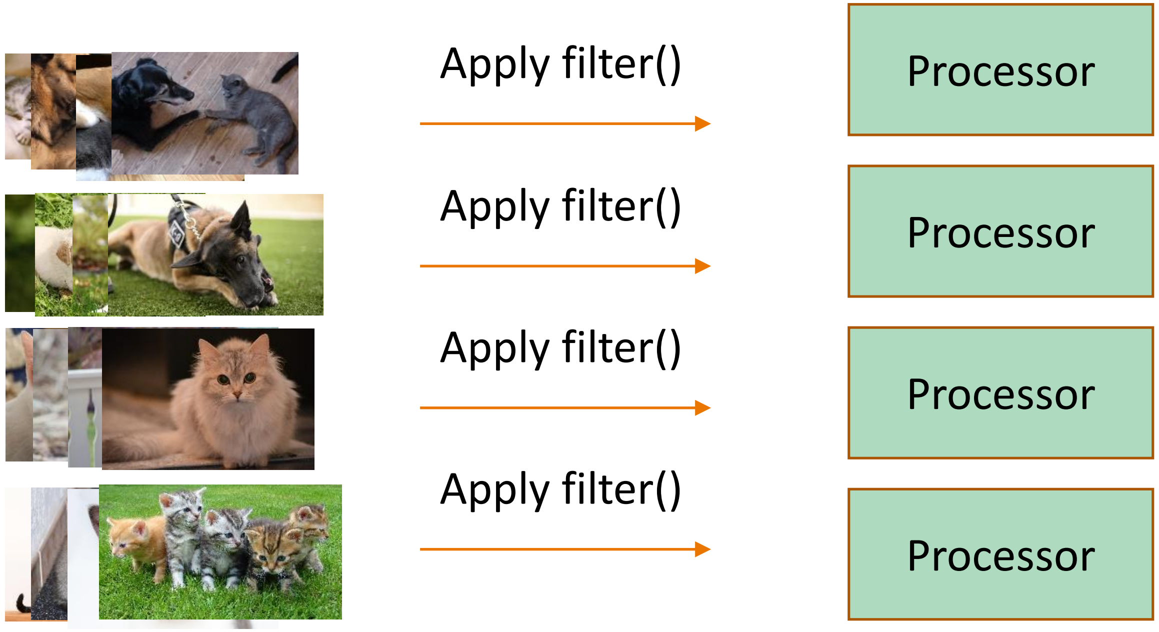
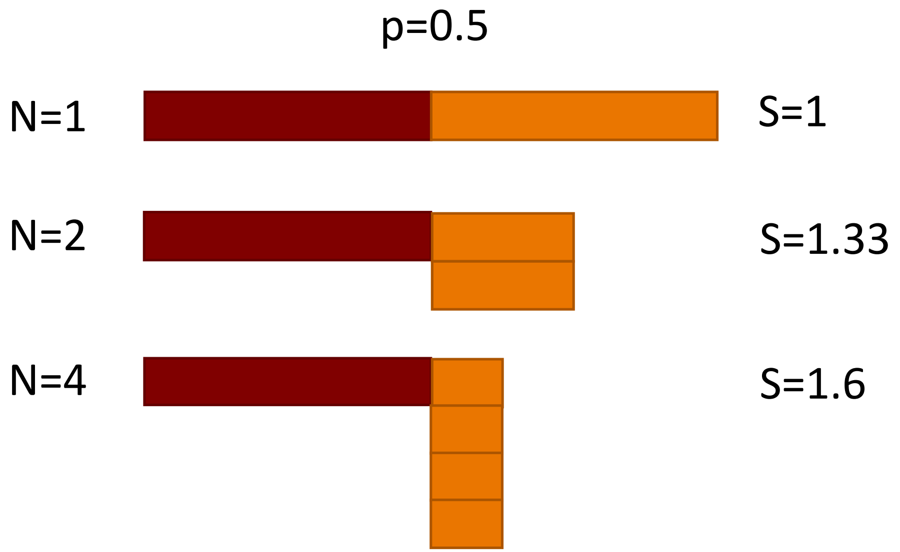


Strong scaling vs. weak scaling

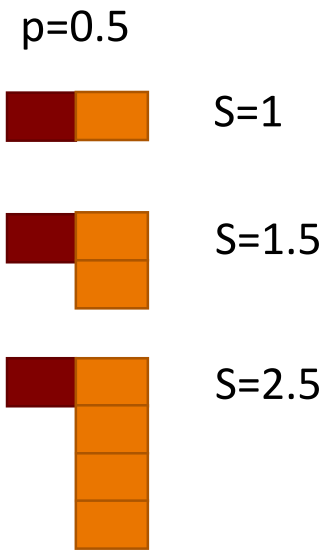
- Strong scaling: fixed work

$$Speedup = \frac{1}{(1-p)+\frac{p}{N}}$$



- Weak scaling: fixed work per processor

$$Speedup = 1 + p \cdot (N-1)$$



Weak scaling is often the most relevant to HPC computations

- Some examples
  - Physics: ”I can only run my fluid simulation a small domain / low resolution on my local PC”
  - Chemistry: “I can simulate a small molecule on my PC, but I want to simulate a big one”
- Common background
  - A big system / molecule increases the *total* work
  - Distributing larger work over multiple processors keeps the work *per processor* constant
  - … this is weak scaling!

So now how can we program in parallel?

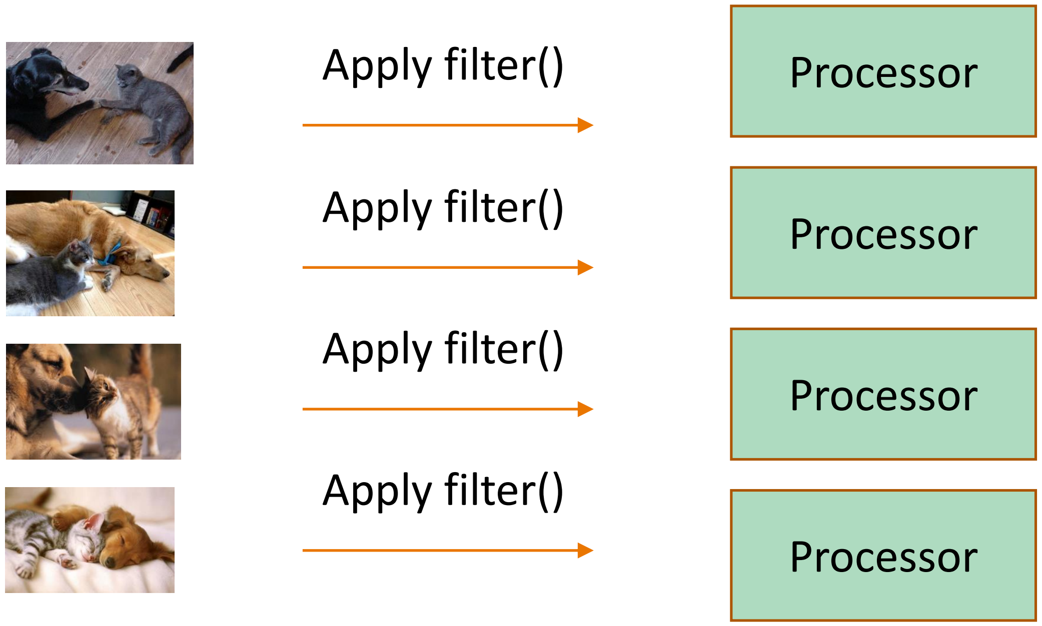
Parallel programming models

- “How do I parallelize my code?”

- Two well-known programming models
  - Data parallelism
  - Task parallelism

Parallel programming models: data parallelism

- Each processor performs the same task on different data



Parallel programming models: data parallelism

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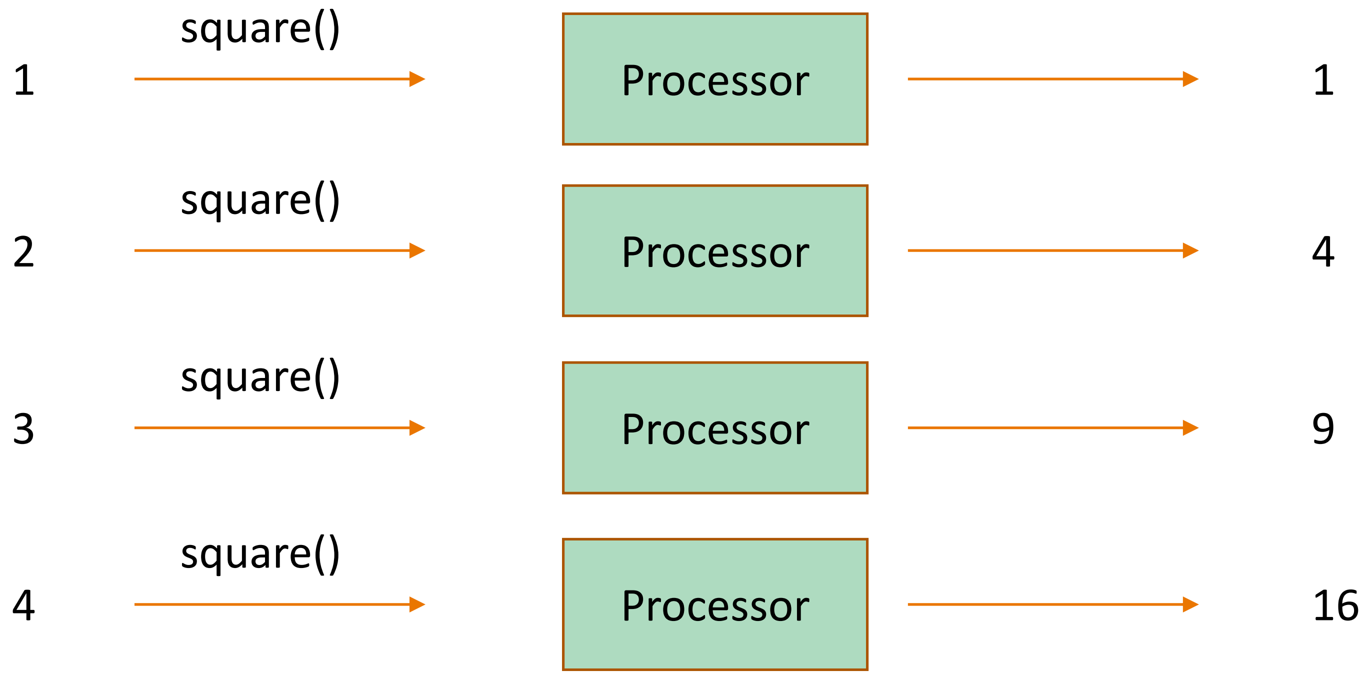
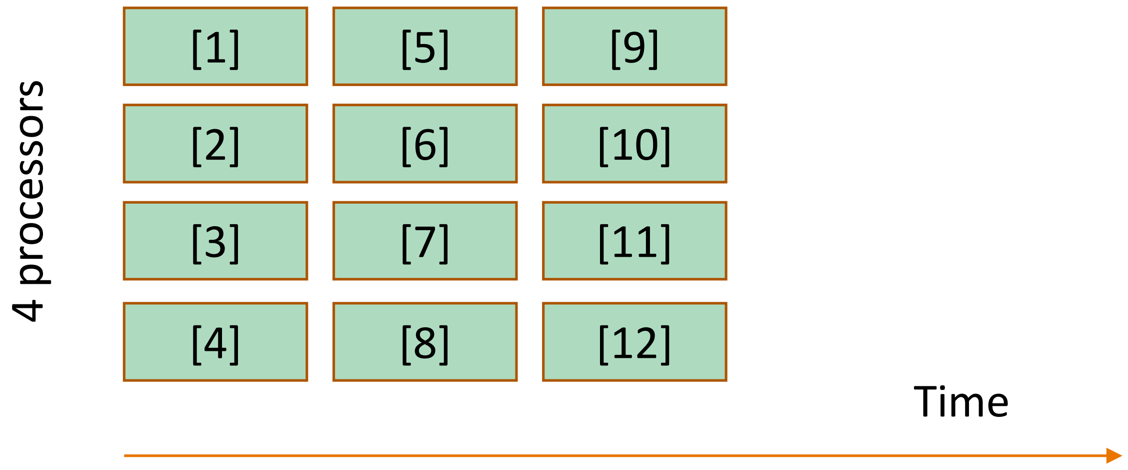


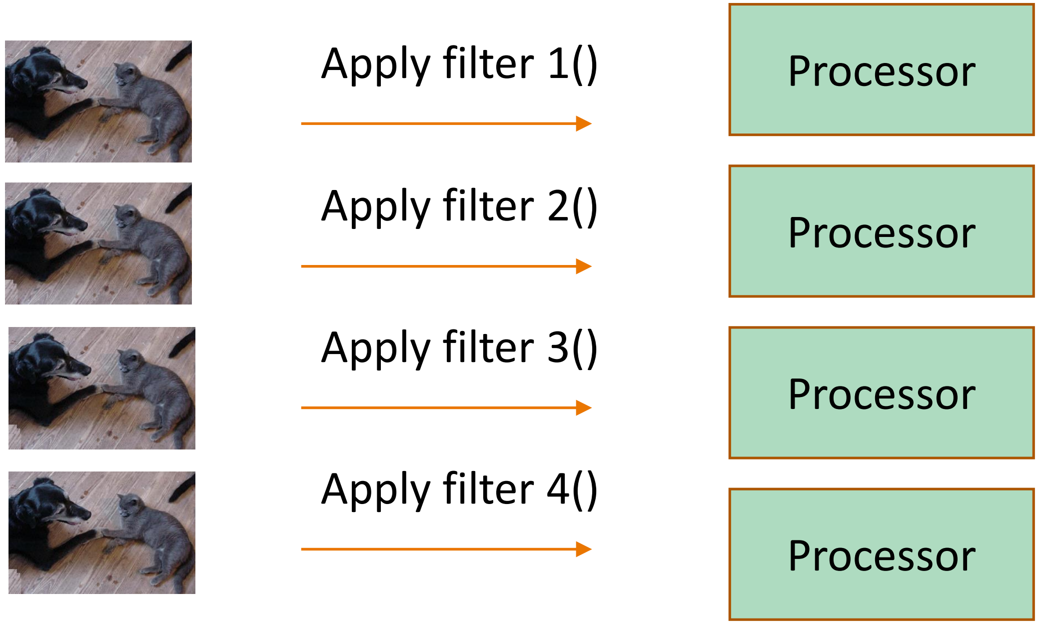
Parallel programming models: data parallelism

- Amount of parallelization depends on input data size
- Load balancing may be relatively easy
  - Same task on each data element
  - Approximately same time per element



Parallel programming models: task parallelism

- Each processor performs a different task on the same data



Parallel programming models: task parallelism

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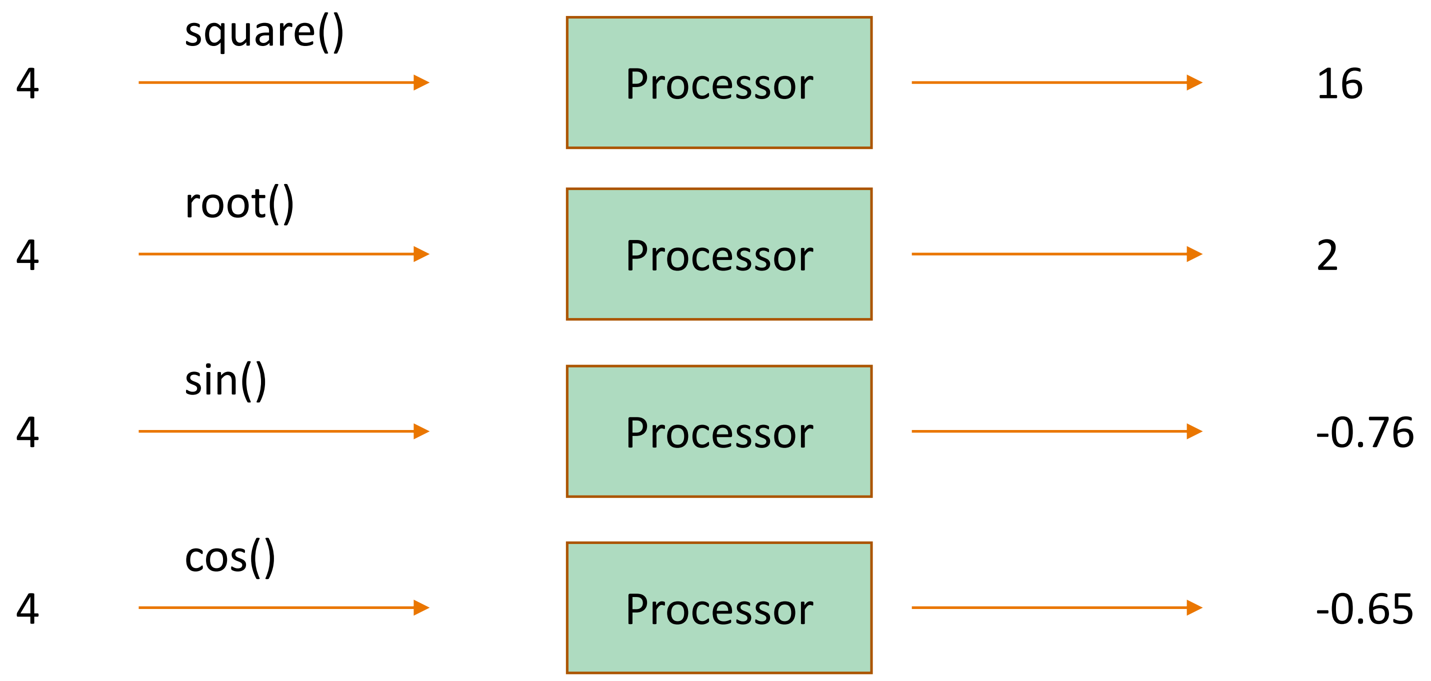
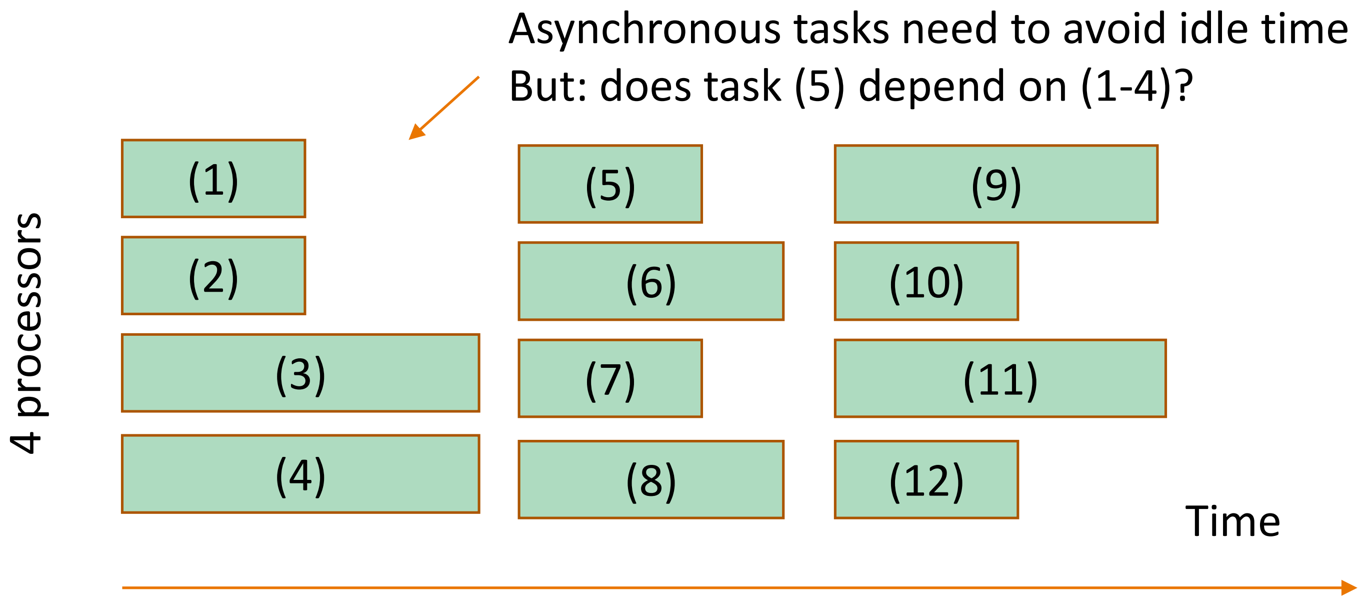


Parallel programming models: task parallelism

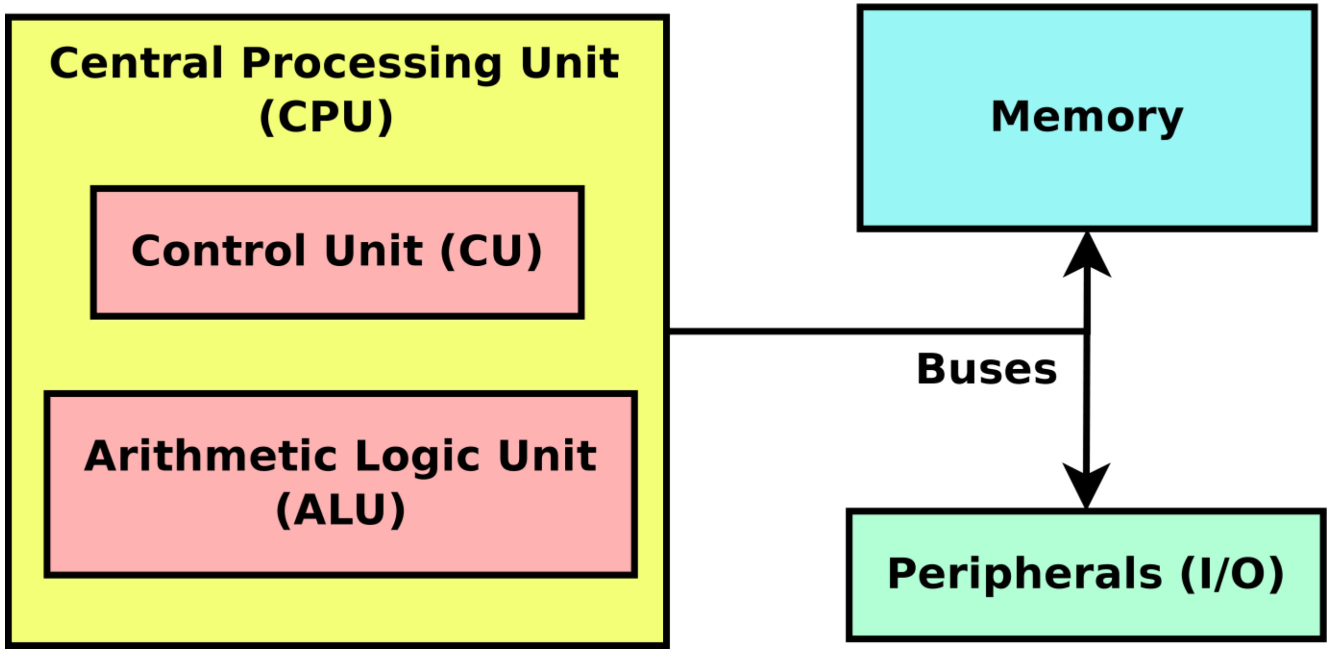
- Amount of parallelization depends on the number of tasks
- Load balancing can be very difficult
  - Heterogeneous tasks may be executed over the same data
  - Each task may take a very different amount of time



Theory is essential to understand concepts…

but parallel programming also requires understanding of the systems!

A computer is...



A memory is…

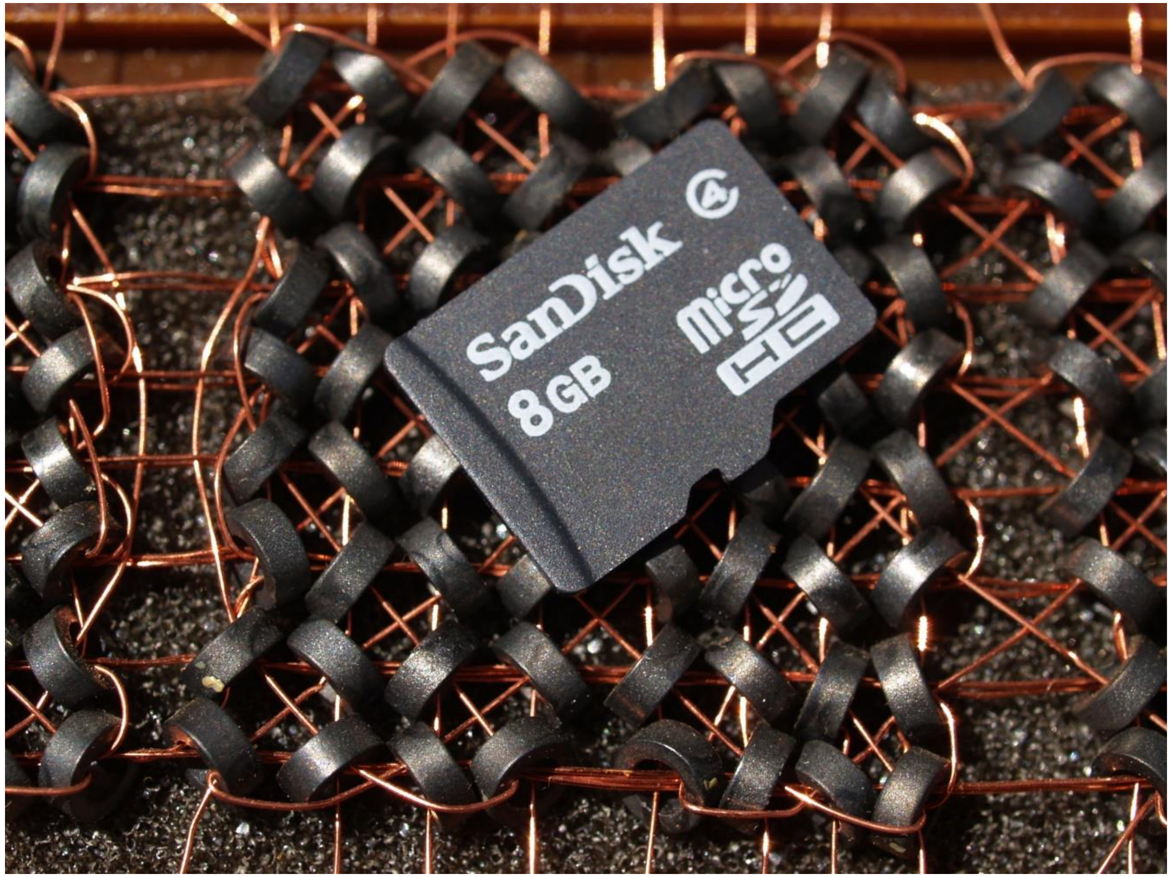
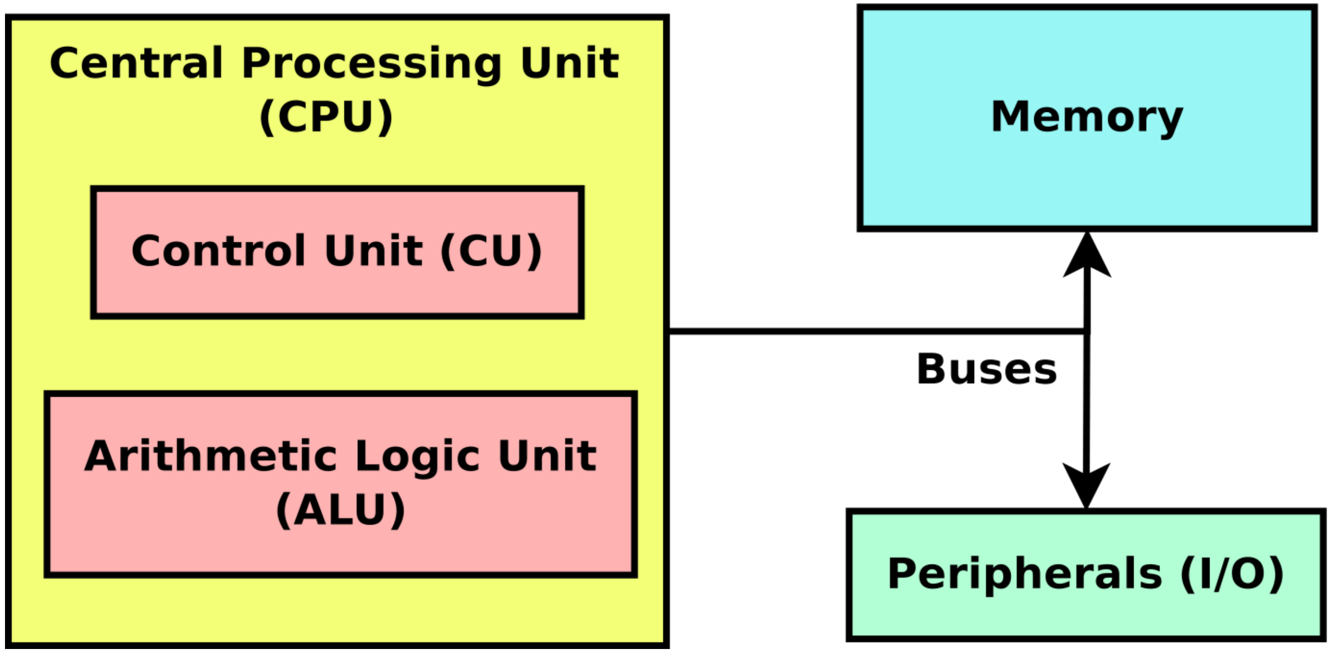


Image source: https://upload.wikimedia.org/wikipedia/commons/c/c0/8 bytes vs. 8Gbytes.jpg

A computer is...



A CPU is…

Example of the MIPS architecture: control unit lines in orange, data lines in black

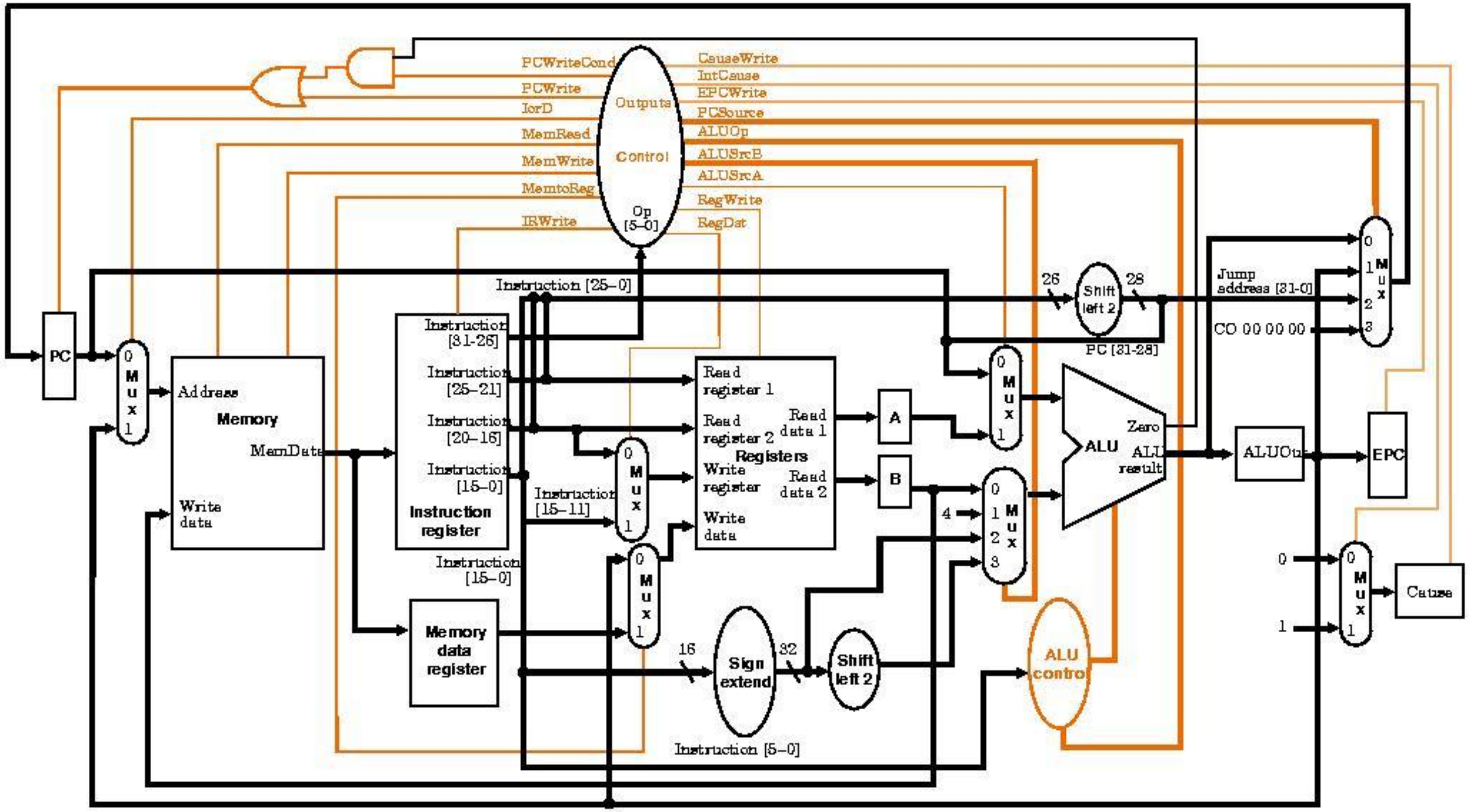


Image source: http://people.cs.pitt.edu/˜don/coe1502/current/Unit4a/Unit4a.html (last visited: 2018)

A program becomes a process…

SOURCE CODE

```c
void main() {
  int id = 0;
  printf("hello world from %d !\n",id);
}
```

ASSEMBLY CODE

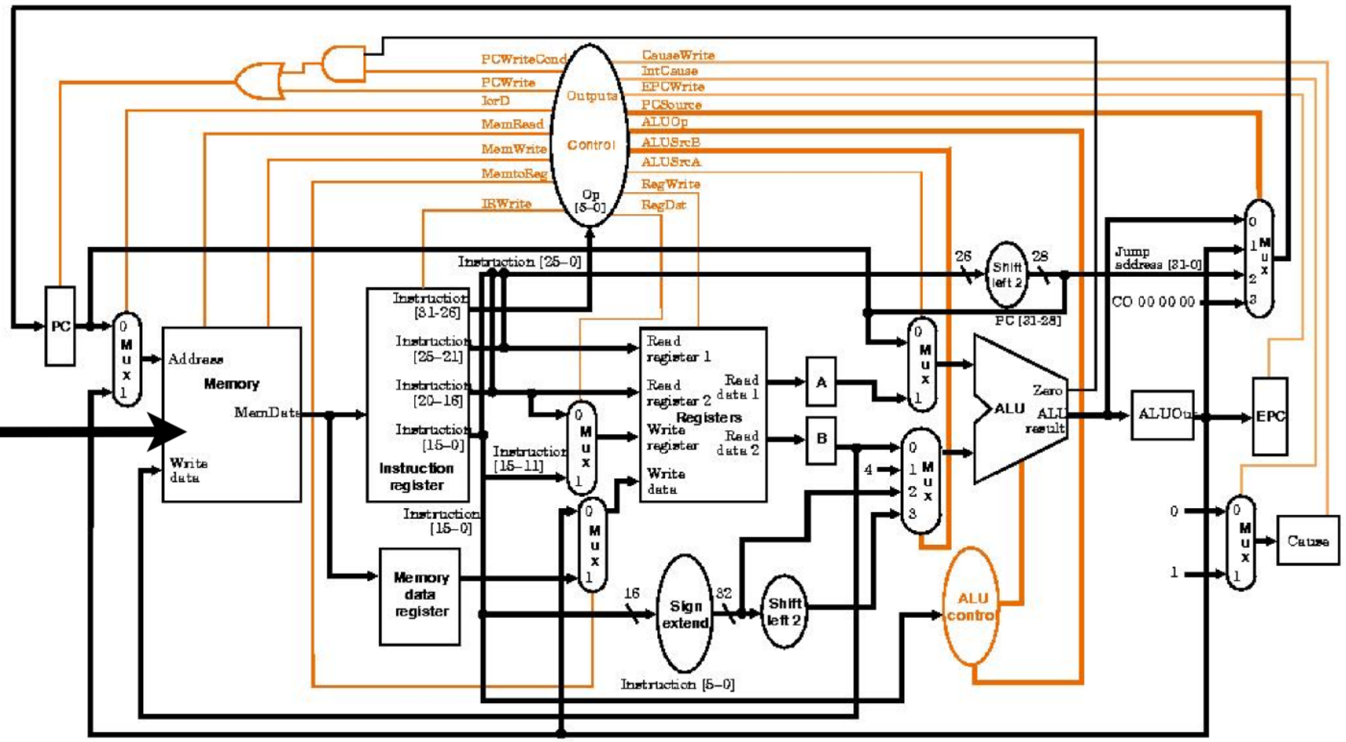
```asm
.data
str: .asciiz "hello world from "
...

.text
main:
    li $v0, 4
    la $a0, str
    ...
    syscall
    ...
```

```
00111100000000100000000000000100
00110100010000100000000000000100
00111100000001000001011100010101
00110100100001000010000000110010
...
```

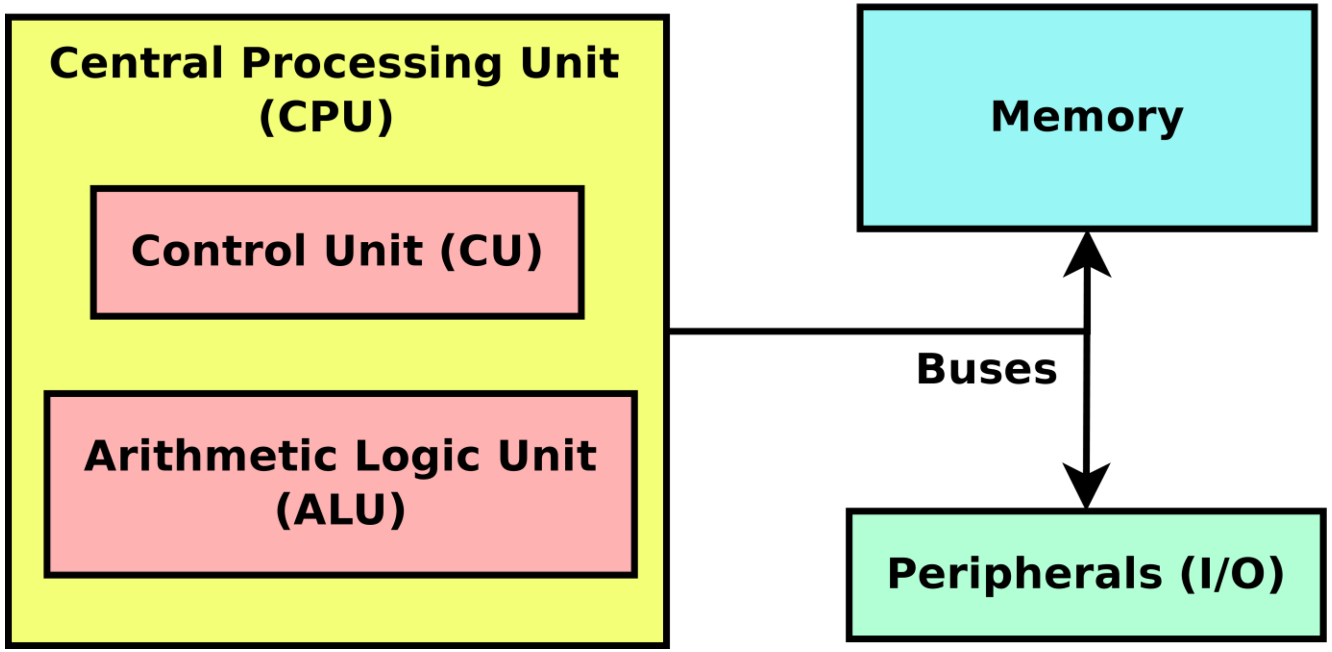
MACHINE CODE

A program becomes a process…

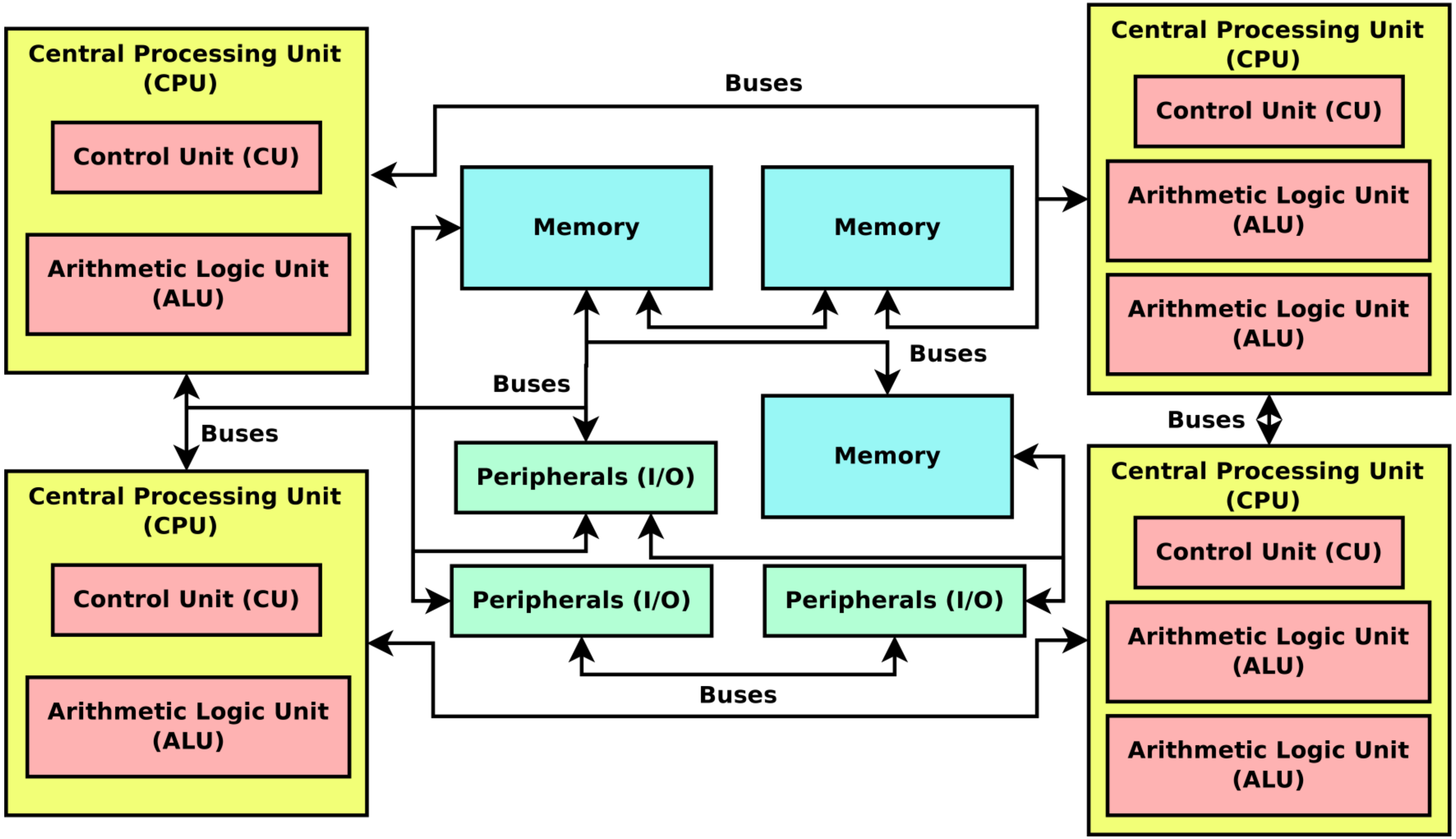
```
00111100000000010000000000000100
00110100010000100000000000000100
00111100000000100000101110001010 1
00110100100001000010000000110010
...
```



Different types of computer architectures



Different types of computers architectures (!!1!!!!!11!!eleven!!)



Different types of computer architectures

- Shared memory: all processors access the same memory (e.g. typical laptop)
  - Early model: uniform memory access for every processor (UMA)

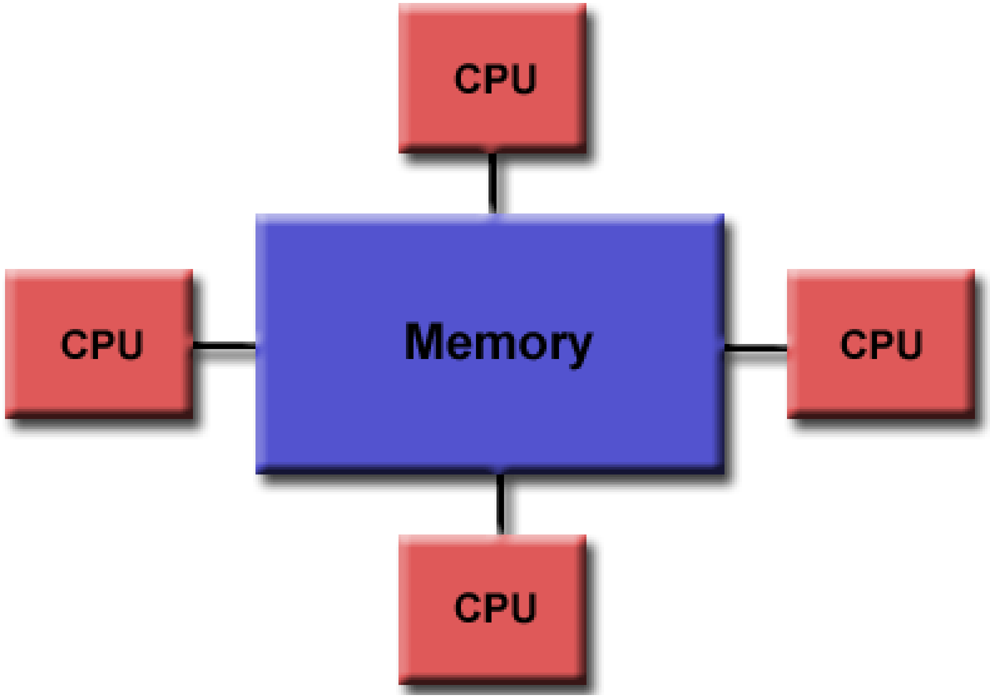


Image source: computing.llnl.gov

Different types of computer architectures

- Shared memory: all processors access the same memory (e.g. typical server)
  - General model: non-uniform memory access for every processor with protocol for cache coherency (ccNUMA)

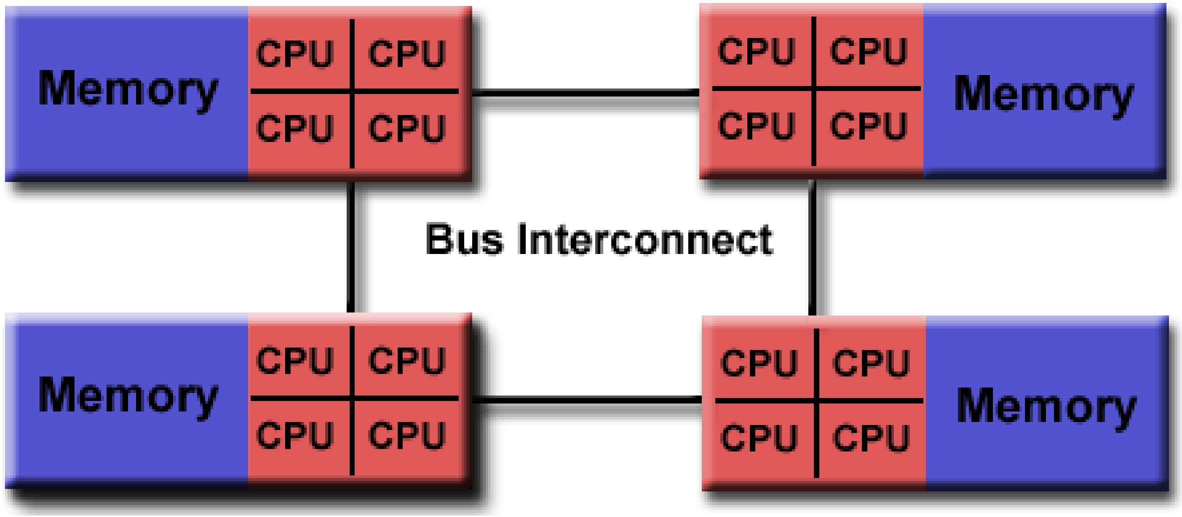
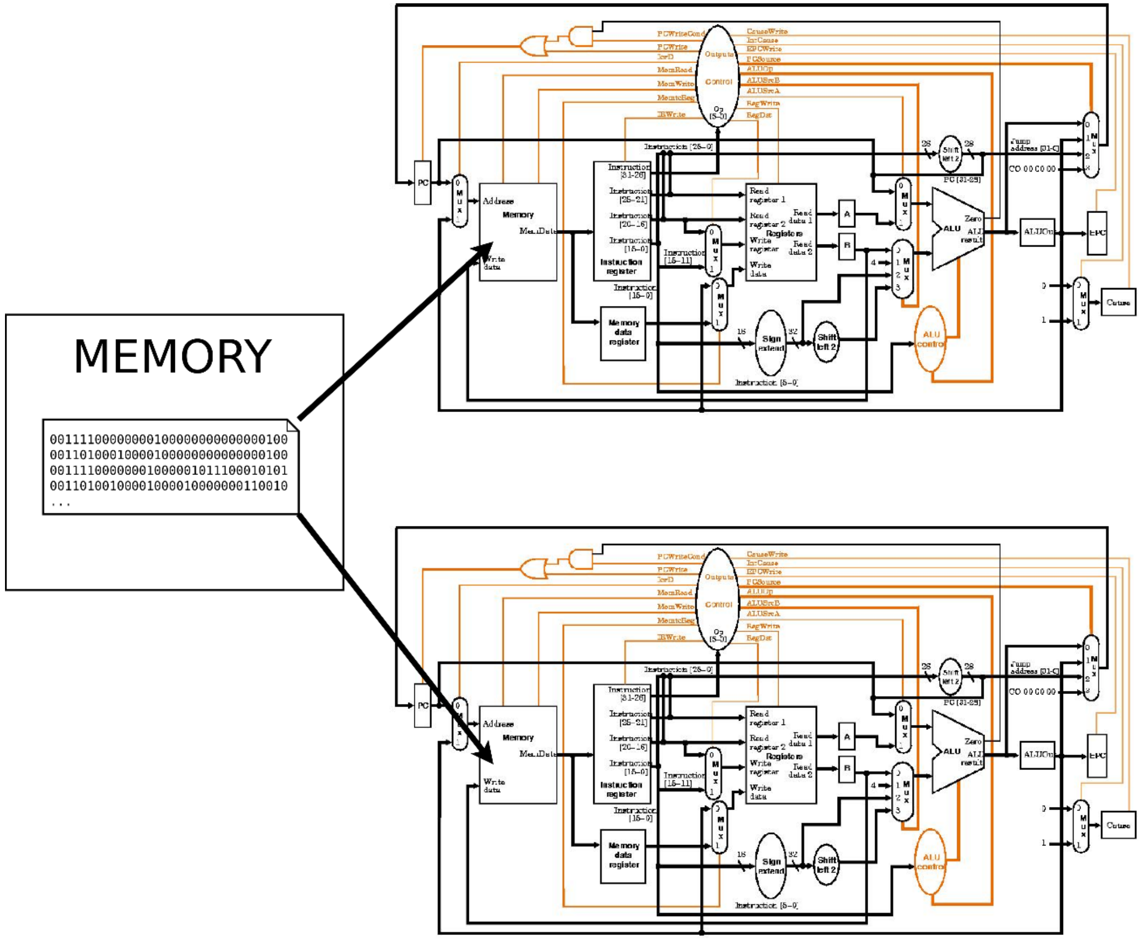


Image source: computing.llnl.gov

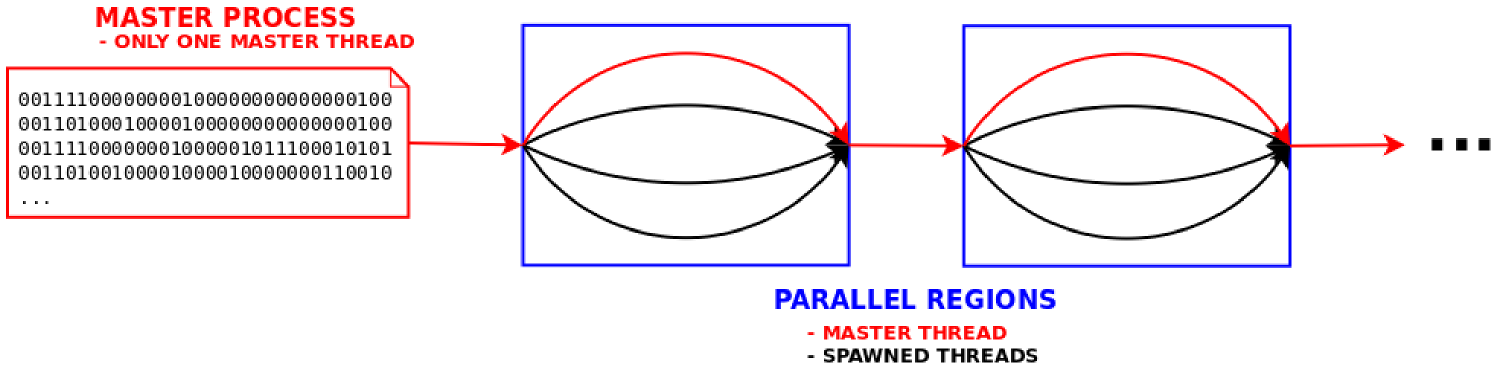
Different types of computer architectures

- Shared memory: all processors access the same memory
  - The programmer is seeing a single unified memory
  - Different sequences of execution (threads) run on the same process
  - Different memory modules may be used, but only one logical memory space is addressed
  - Communication between processors is done implicitly



Many threads in a process: OpenMP

- A process creates lightweight instances of itself (threads) that are coordinated for simultaneous execution
  - A thread shares the program code and data section with all other threads inside the same process
  - The parallel computing approach is called fork-join
    - A sequential program begins with one process (that is, only one thread)
    - A parallel region is defined by creating (spawning) threads from the process and destroying the original thread remains



… and this is where we are going to start!

(Break until 10:45)

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