## Parallel Algorithms and Programming

# Introduction

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# Organization of the course

## Schedule

- 15 hours of lectures
- 6 hours of tutorials
- 12 hours of labs

## Grading

- 30% graded labs (2 graded labs)
- 70% final exam

## Useful links

- The slides
- The Moodle page

# Teaching staff


- Thomas Ropars (thomas.ropars@univ-grenoble-alpes.fr)
- Martin Schreiber (martin.schreiber@univ-grenoble-alpes.fr)
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- Danilo Carastan-Santos (danilo.carastan-dos-santos@univ-grenoble-alpes.fr)

# Content of the course

- Programming challenges
- Performance
- Parallel architectures
- Shared-memory algorithms and programming
- Message-passing algorithms and programming
- Parallel linear algebra

# Execution Platform

- We might use Google Cloud Platform to run experiments
    - If it is the case, each student will receive $50 of credits
    - Details will be given later during the semester

# Introduction

# Outline of the lecture

- Why we need parallel systems?
- Applications of parallel computing
- Challenges of parallel computing

# References

The content of this lecture is inspired by:

- The lecture notes of F. Desprez
- Introduction to Parallel Computing by B. Barney
- The lecture notes of K. Fatahalian
    - CS149: Parallel Computing @Standford
    - 15418: Parallel Computer Architecture and Programming @CMU
- Parallel Programming – For Multicore and Cluster System. T. Rauber, G. Rünger
- The lecture notes of S. Lantz

# Definition of parallel computing

```
Parallel computing uses multiple processing elements simultaneously to solve
a problem **quickly**.
```

## Goal: Performance

- Solve problems faster
- Solve larger problems
- Get a better answer to a problem

## Parallel vs Concurrent programming:

- Concurrency is about dealing with lots of things at once.
- Parallelism is about doing lots of things at once.

- Concurrent programming refers to multiple flows of executions executing concurrently.
- Concurrent programming does not necessarily imply parallelism

*Note that there are many possible definitions of concurrent programming. Not a very interesting debate here.*

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- Parallelism is about doing lots of things at once.

- Concurrent programming refers to multiple flows of executions executing concurrently.
- Concurrent programming does not necessarily imply parallelism
  - Multiple threads executing on a single processor

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# Why we need parallel computing?

## Until 2000's

- To solve problems that a single processor cannot solve

## Today

- To keep increasing the performance of systems
- **End of Moore's law**

# Moore's law

An observation made by Gordon Moore in 1965 that the number of transistors in processors chips is doubling every 2 years (because of transistor size reduction)

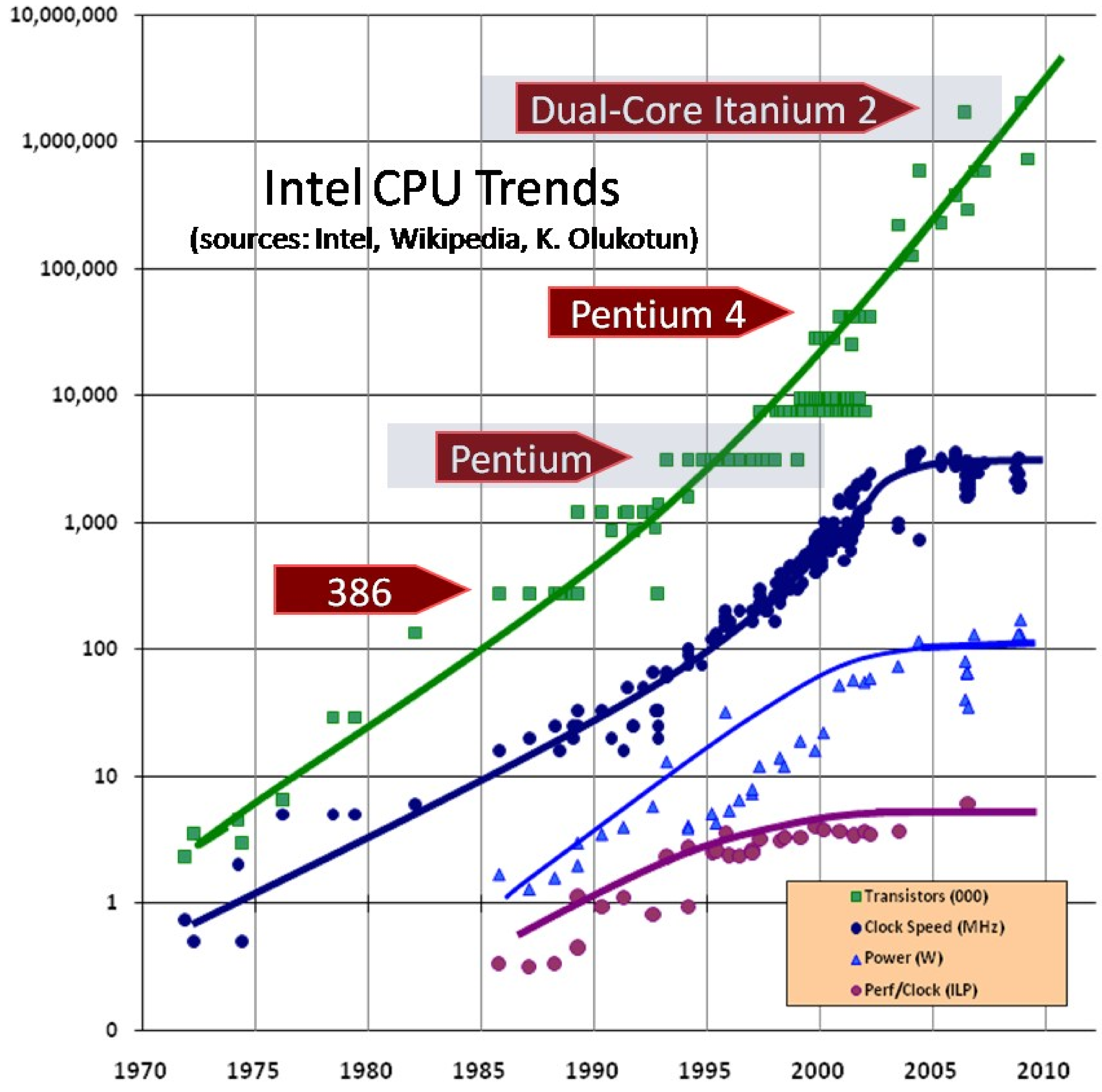
- It was later updated to *doubling every 18 months*

## It was implying that:

- the clock frequency could be increased while keeping the power consumption constant (Dennard scaling).

**To get more performance, you just had to wait for the next generation of processors**

# The end of the free lunch (H. Sutter)



# Lessons learned from previous graph

**Moore's law was having two side effects:**

# Lessons learned from previous graph

## Moore's law was having two side effects:

- Allowing increasing the clock frequency
- More transistors were allowing more complex logic to be implemented
    - Optimizing the execution = doing more work per processor cycle
    - **Instruction Level Parallelism** (ILP)

# Lessons learned from previous graph

## Moore's law was having two side effects:

- Allowing increasing the clock frequency
- More transistors were allowing more complex logic to be implemented
    - Optimizing the execution = doing more work per processor cycle
    - **Instruction Level Parallelism** (ILP)

## In the recent years

- No frequency improvement
- No further improvement in ILP

## Current state

The number of transistors per chip keeps increasing

- Increase in the number of processor cores
- Trend: large number of simpler cores

**To run faster, a program has to be parallel**

# About ILP

- ILP is a measure of the number of instructions per cycle.
- Several techniques to increase the number of instructions per cycle:
    - Pipelining
    - Branch prediction
    - Out-of-order execution
    - Superscalar architecture
    - Vector operations

```
The expected performance improvement is limited by the *parallelism that can be
found* in the sequence of instructions of the program to execute
```

# About ILP

## A simple C code:

```
a = x*x + y*y + z*z
```

# About ILP

## A simple C code:

```
a = x*x + y*y + z*z
```

- 5 operations to be executed (ignoring data movements)

**What is the best performance that can be obtained with ILP?**

# About ILP

## With ILP

| time | operations |
|---|---|
| 1 | `o1=x*x; o2=y*y; o3=z*z` |
| 2 | `o4=o1+o2` |
| 3 | `o5=o4+o3` |

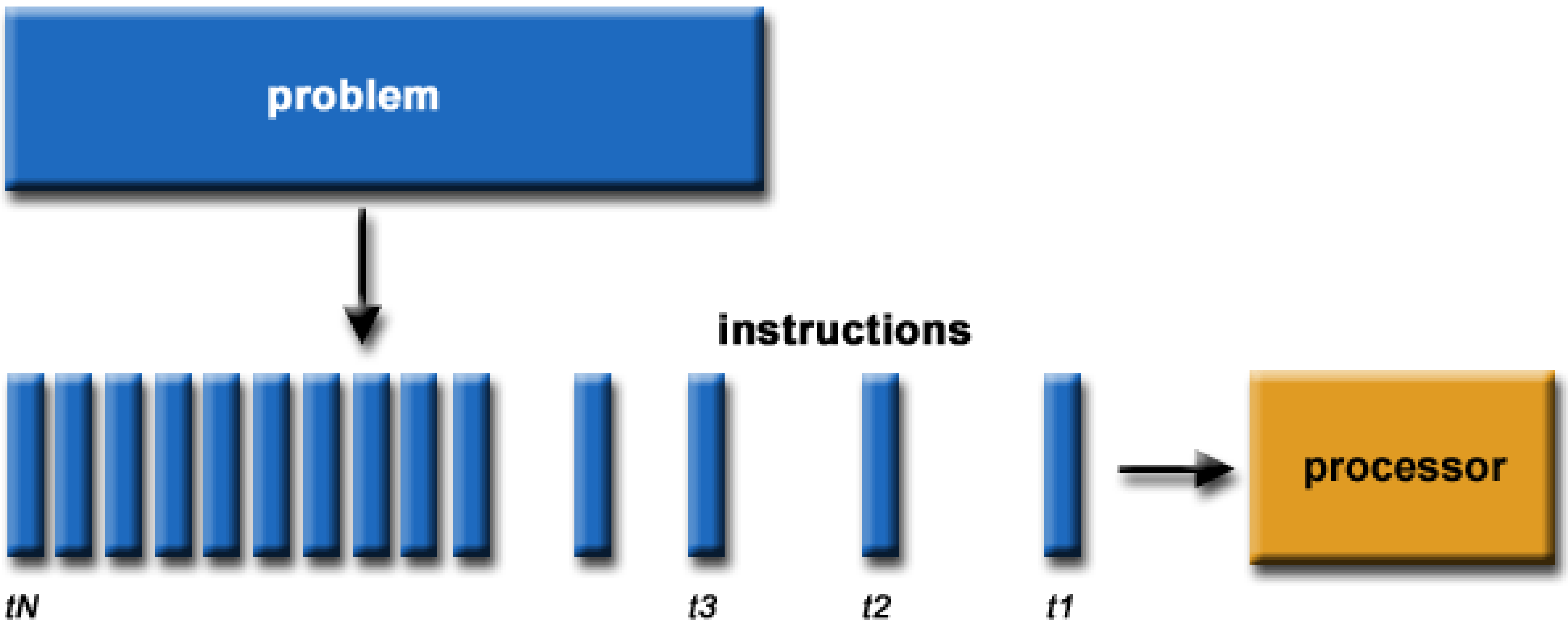
- At most 3 operations can be executed in parallel

**Most available ILP is exploited by issuing 4 instructions per cycle**

*Exemple from K. Fatahalian*

# What is parallel computing?

## Serial computing

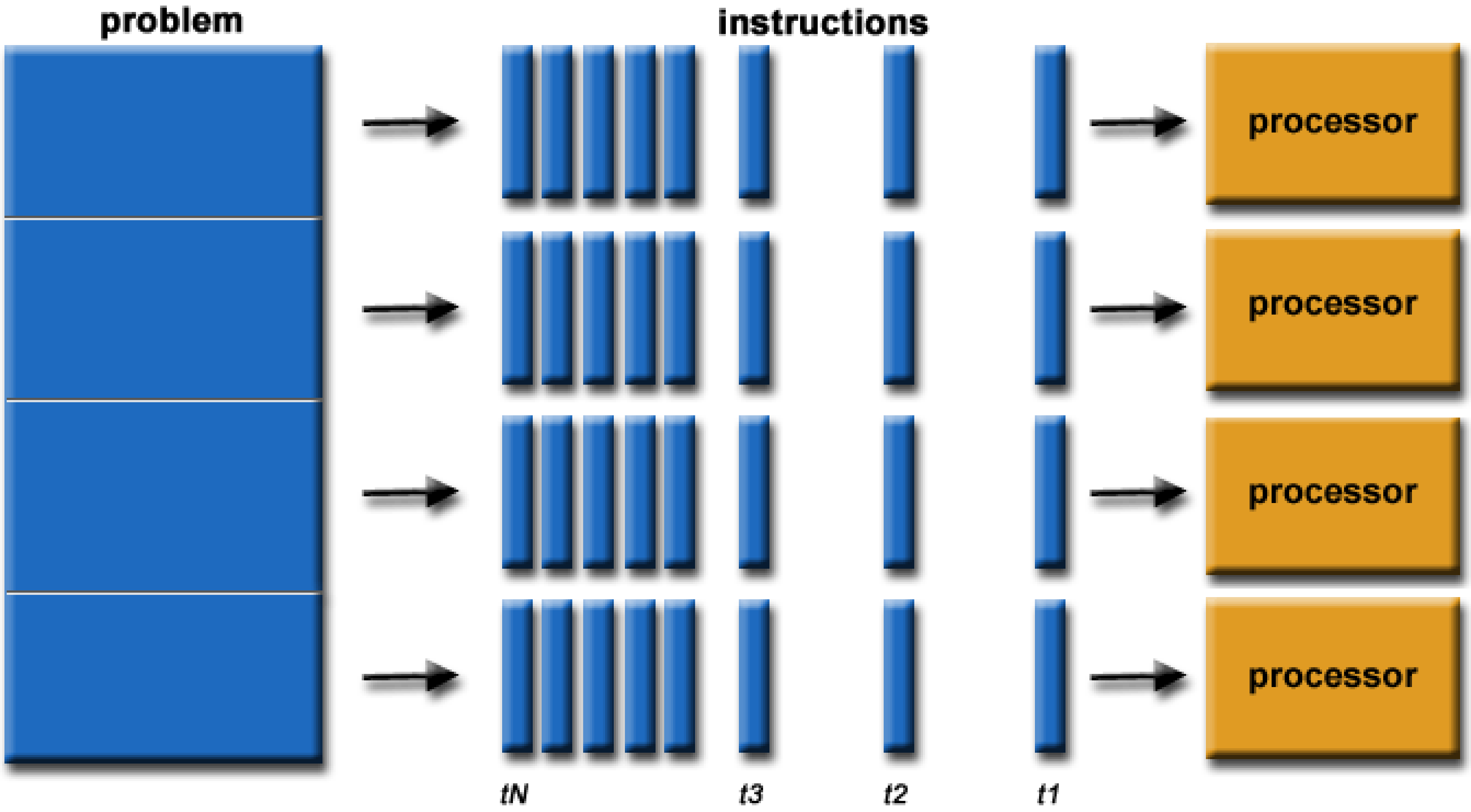



- One instruction is executed at a time (ignoring ILP)

*Illustration by B. Barney*

# What is parallel computing?

## Parallel computing




- A problem is broken into multiple parts
- Instructions from multiple parts are executed in parallel
- An overall control/coordination mechanism should be employed

*Illustration by B. Barney*

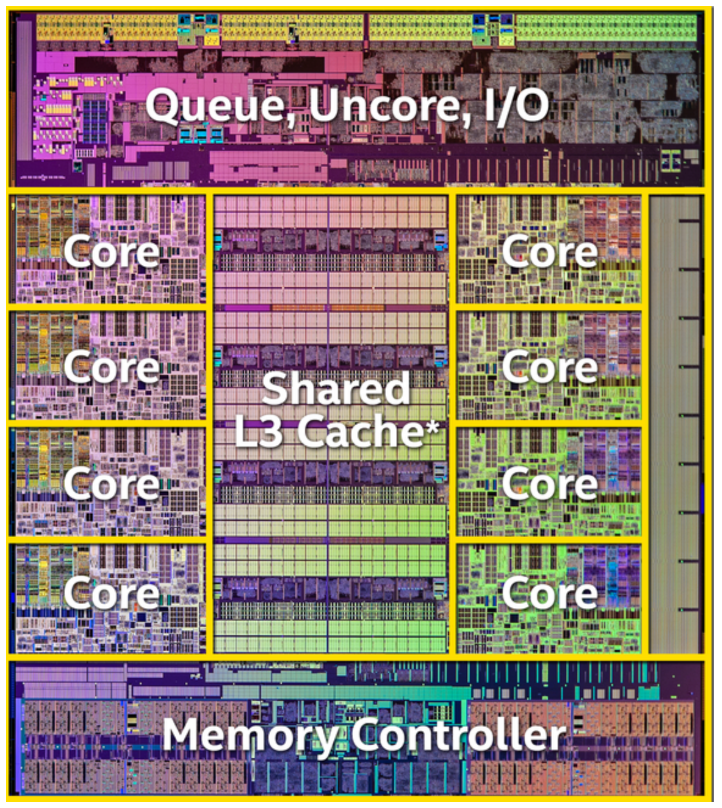
# Parallel systems

## Desktop computer (and mobile devices)

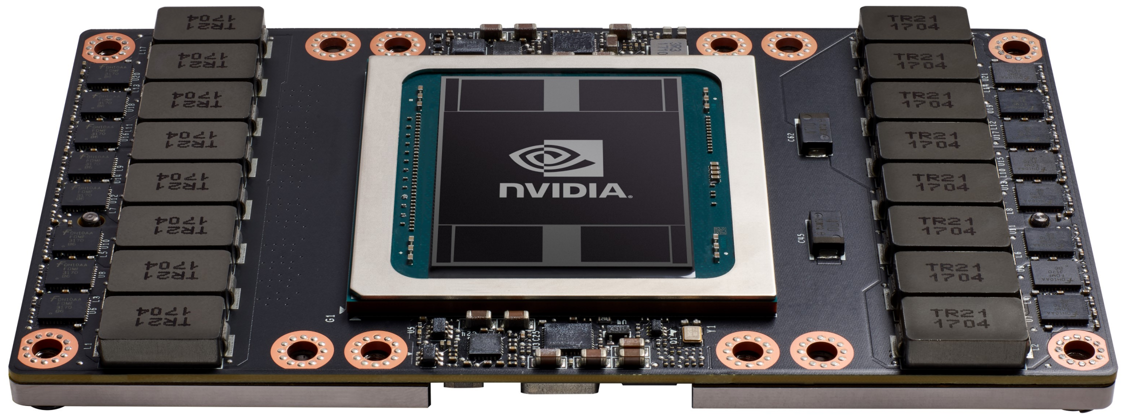
- Multicore processors
- GPUs

## Distributed architectures

- Cluster of commodity nodes
- Cloud computing
- Supercomputers (High Performance Computing)




Intel Haswell



NVIDIA Tesla v100

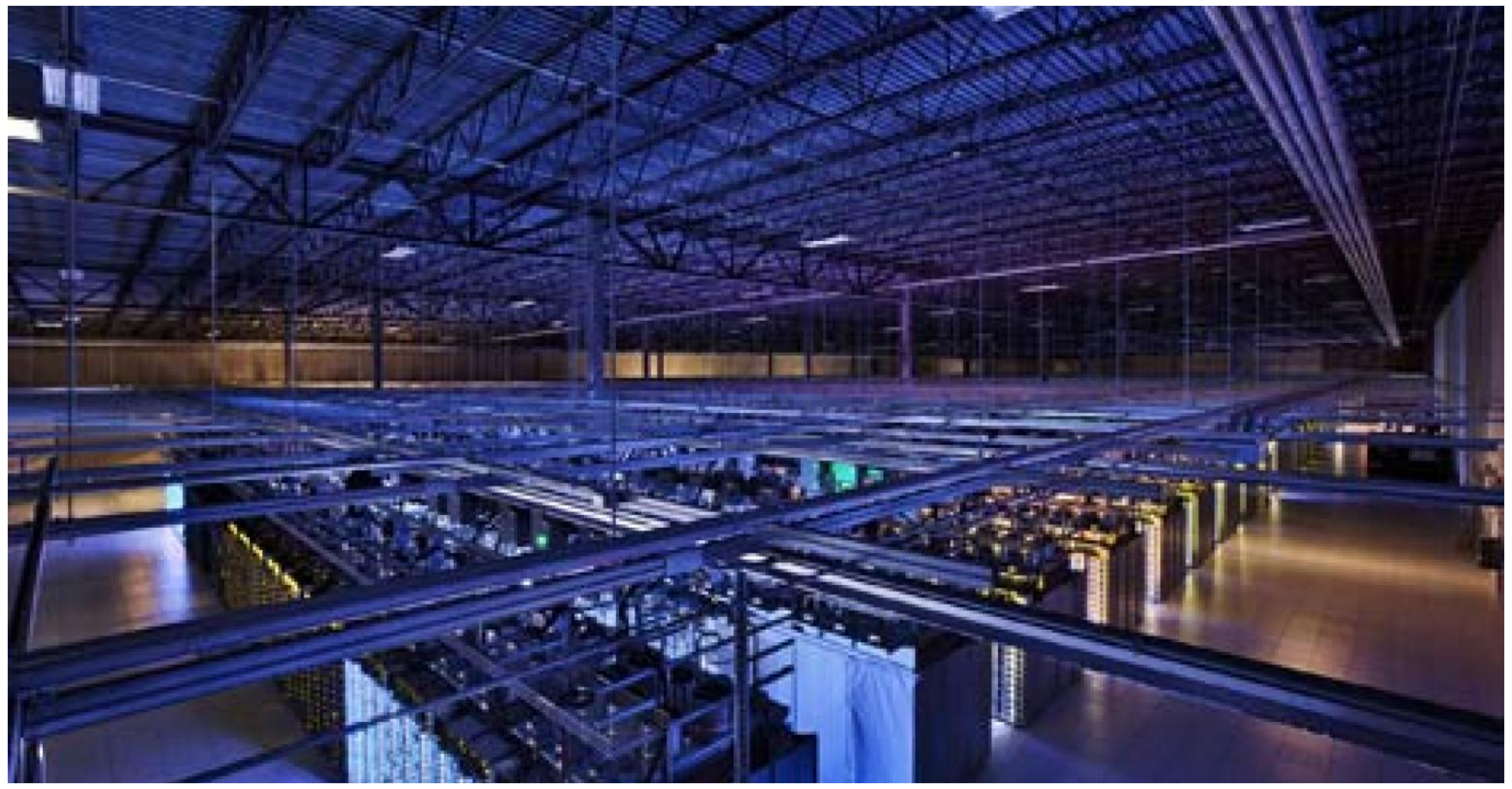
# About distributed architectures

## Definition

```
*Large* set of computing resources that communicate through a network
```

- Allow building very large scale systems at a reasonable price (Scale out)
- Is in general less expensive than scaling up (updating the hardware with more powerful -- and more expensive -- components)


Summit Supercomputer (Oak Ridge National Lab)



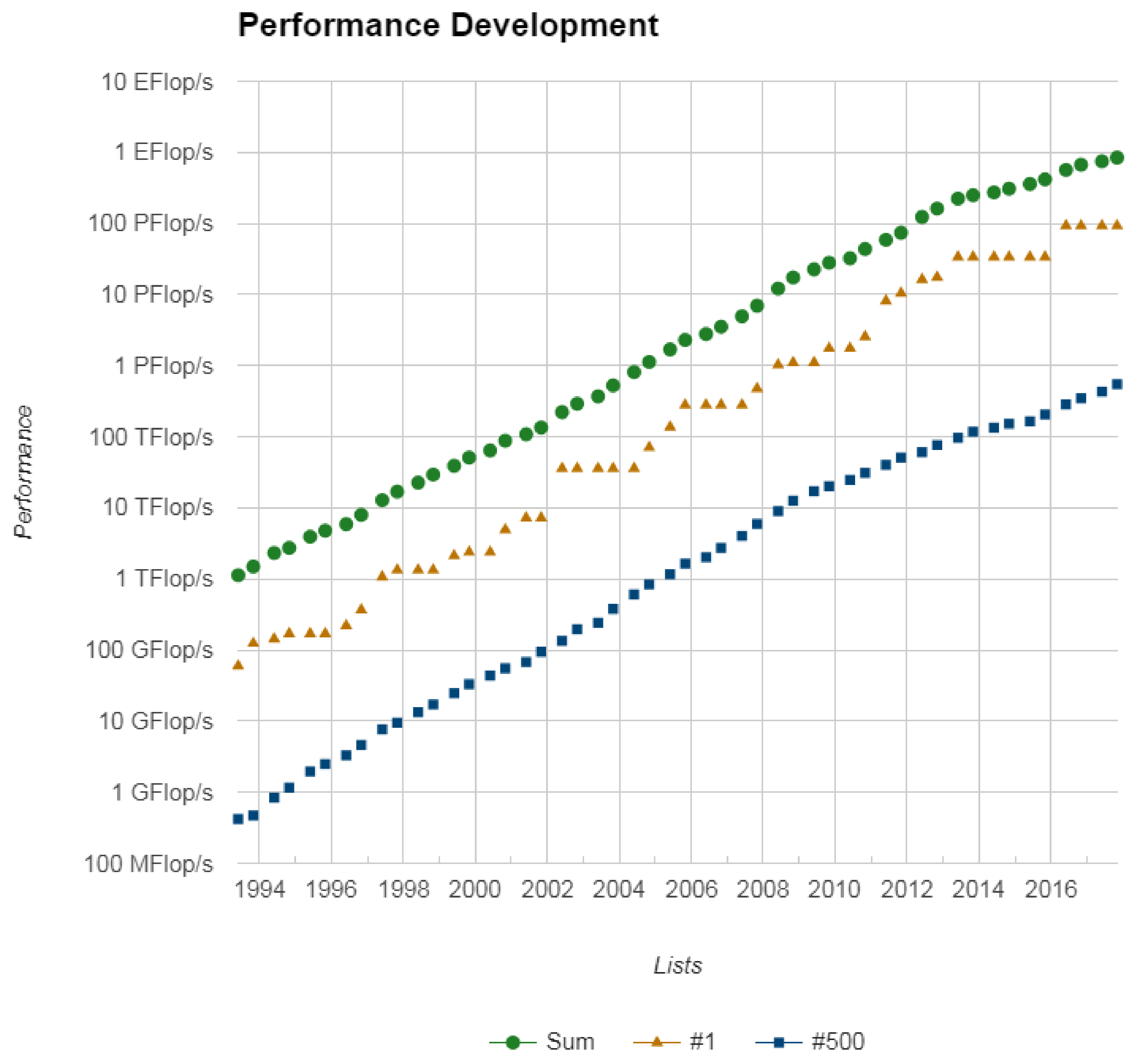
Google data center

# Different levels of parallelism

- **Multicore processors:** 10's of processing cores
- **GPUs:** 1000's of processing cores
- **Supercomputers:** Millions of processing cores (CPU and GPU)
- **Cloud computing infrastructures:** Millions of servers

# Statistics from TOP 500

## Ranking of the 500 hundred most powerful supercomputers (see www.top500.org)



# Applications of parallel computing

# Use of parallel computing

```
With the evolution of processors, going parallel is the only way to
significantly improve the performance of any application
```

## Type of applications requiring large amount of computation

- Numerical simulations
- Data analysis
- Artificial intelligence
- Image processing
- etc.

# Numerical simulations

## Description

- Simulation can be used to study complex systems/phenomenons
- Without simulation:
    - Study on paper
    - Perform real experiments

## Advantages of simulation

- Reduces costs and risks
    - Plane crash
    - Drugs
- Allows simulating phenomena that are hard to study in reality
    - Tsunami
    - Climate evolution

# Numerical simulations examples

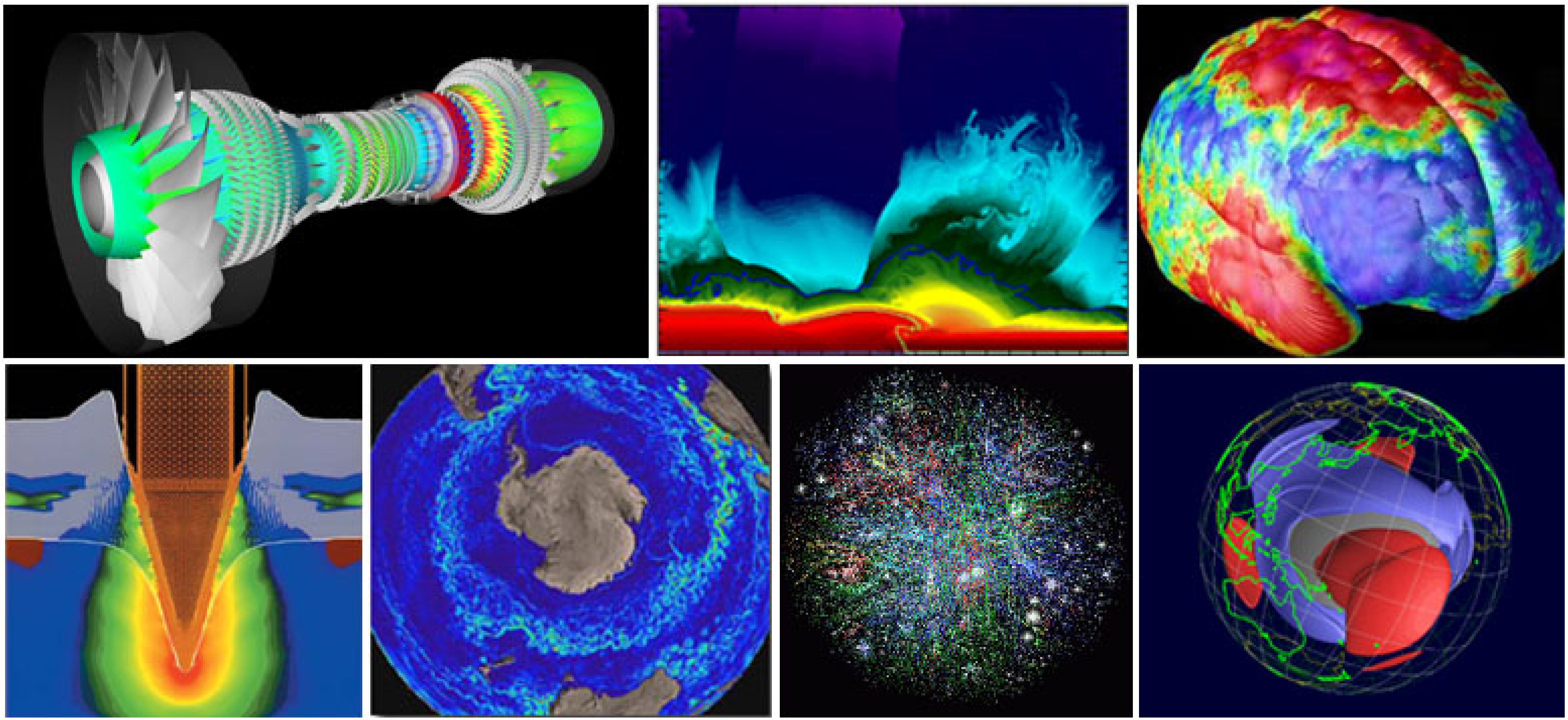


*Illustration by B. Barney*

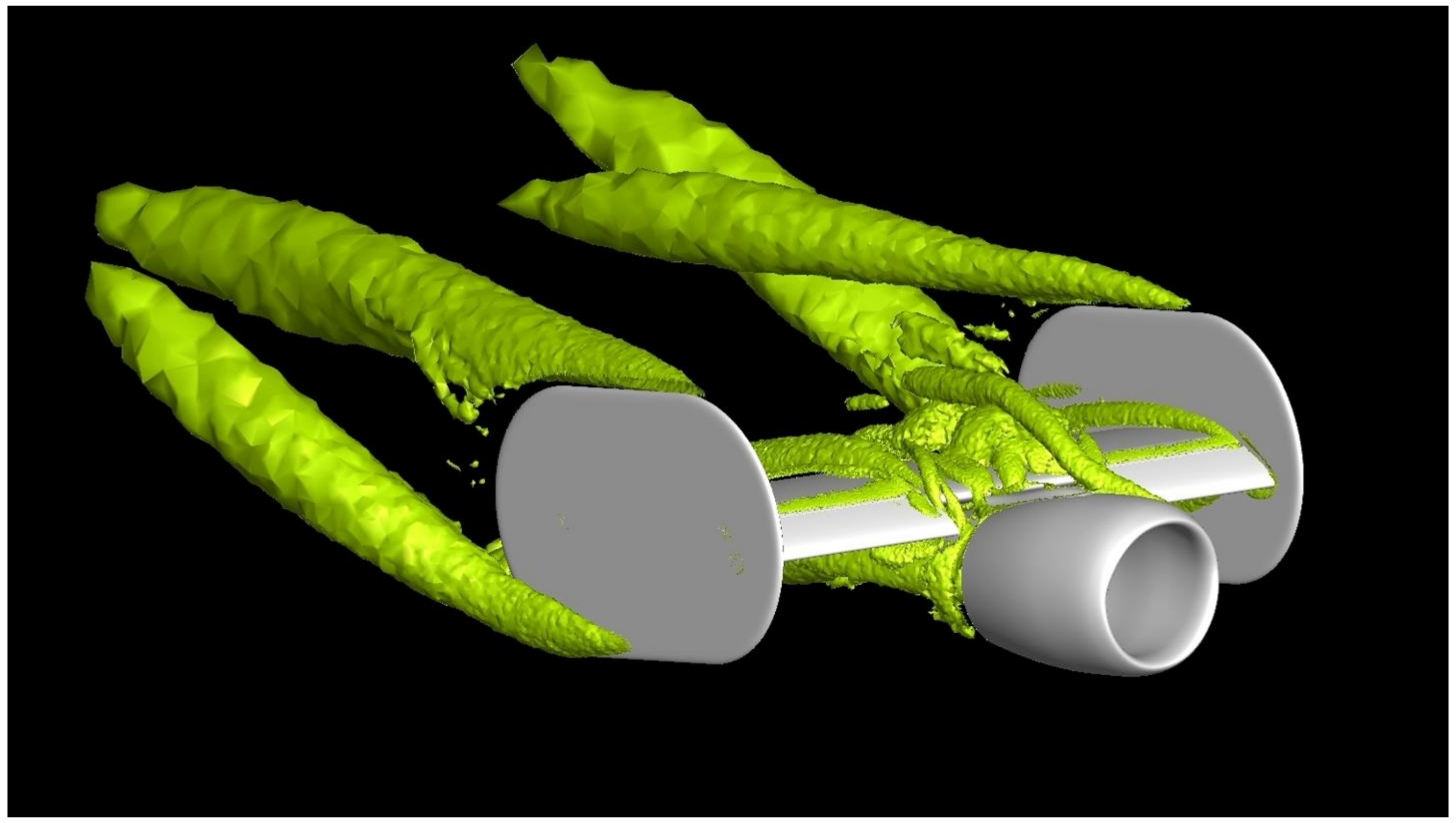
# Domains where numerical simulations is used

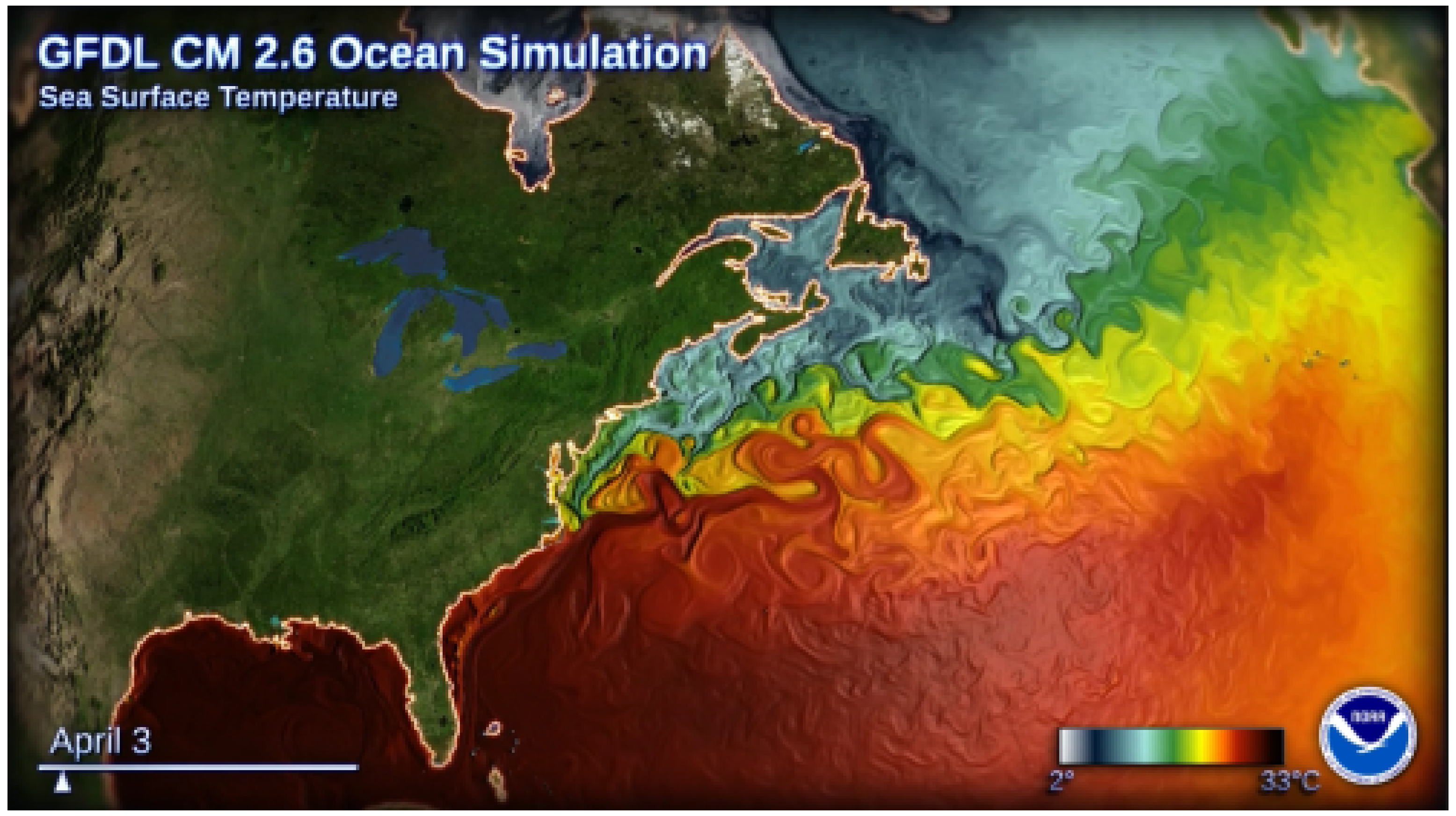
## Science

- Climate prediction
- Molecular science
- Seismology
- Bio-science

## Engineering

- Engine design
- Airplane design
- Structural modeling



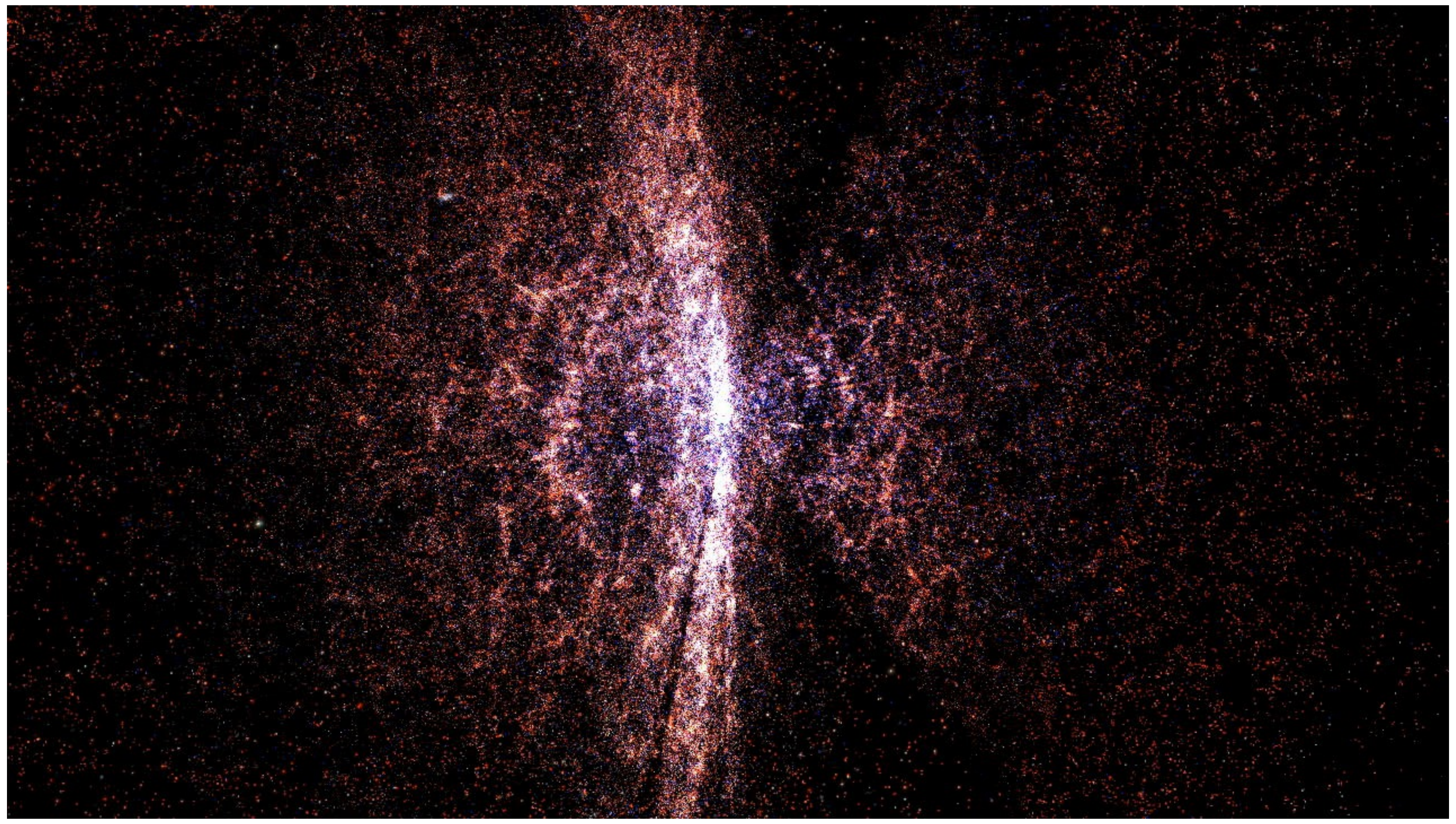


# Data analysis (Big Data)

```
Parallel systems can also be used to process huge amounts of data.
```

## Domains of application

- DNA analysis
- Data generated by large equipments
  - Telescopes
  - Large Hadron Collider (CERN)
- Data from the Web
  - Analysis of data from social networks
  - Search engines



*Credits: NASA/University of Chicago and Adler Planetarium and Astronomy Museum*

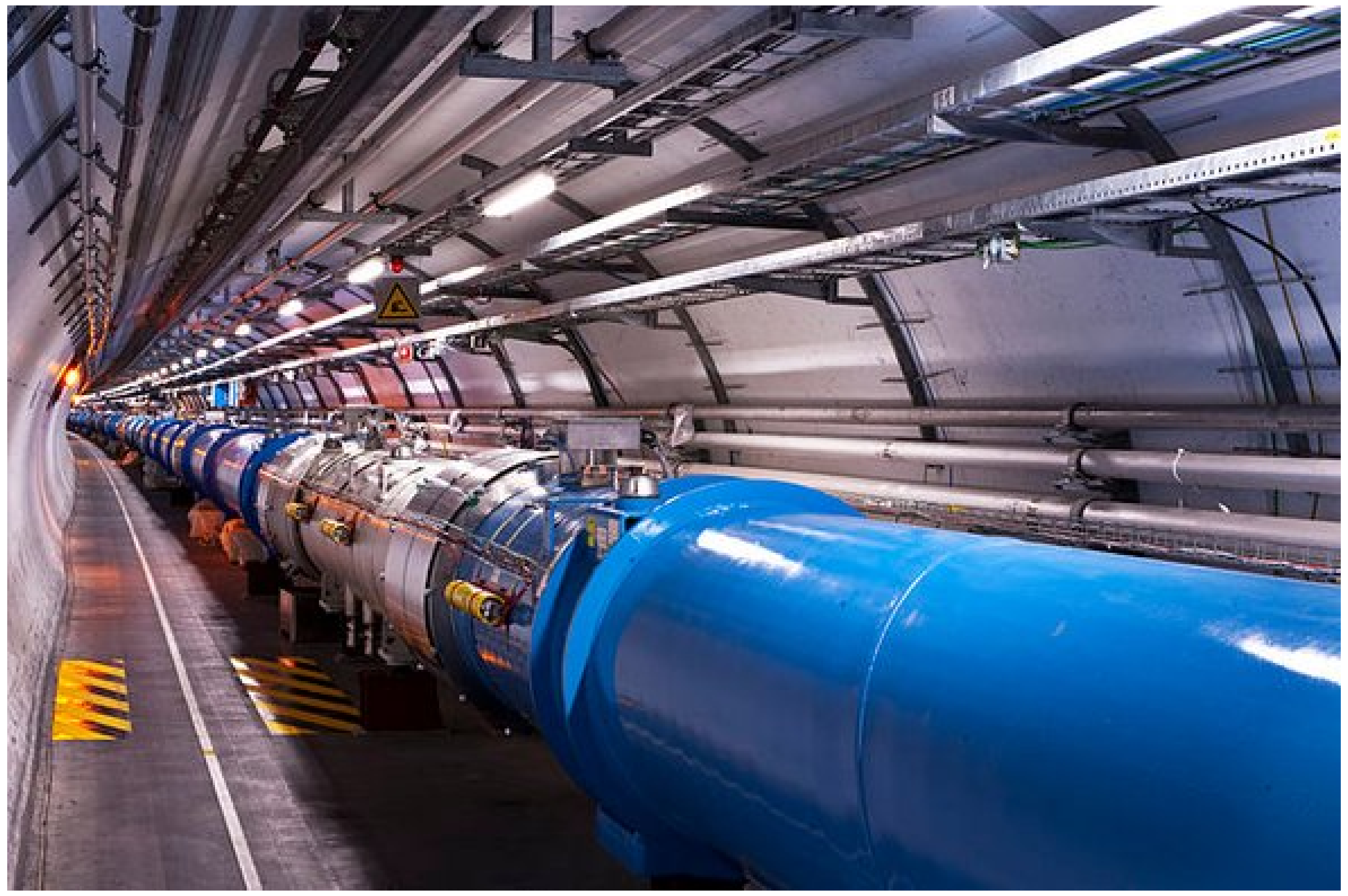
# Some numbers

## Big Data

- Every 2 days, we create as much information as we did since 2013
- 30M messages posted on Facebook every minute
- 570 new web sites every minute

## Large Hadron Collider

- The most powerful instrument ever built to investigate elementary particles
- 40 PB of raw data per second during an experiment
- 10 PB of useful data per year



*Credit: https://www.slideshare.net/BernardMarr/big-data-25-facts | Maximilien Brice (CERN)/Wikimedia Commons*

# Entertainment industry

## Computer-generated imagery

- Advanced graphics
    - Animation movies
- Virtual reality

- Exemple: 2001, Pixar, Monster Inc.: 250 servers with 14 processors (3500 processors)

# Artificial intelligence

## Machine learning

```
Build a mathematical model out of training data
```

- Classification
- Clustering
- Regression

## Applications

- Recommendation systems
- Anomaly detection
- Speech recognition
- etc.

## The case of deep learning

- Execution on clusters of GPUs (from 10's to 1000's of nodes)
- Training a neural network = Operations on large matrices

# Conclusion

# Take-away points

## Single-thread performance increases very slowly

- *End* of Moore's law
- To improve performance, the programs have to be parallel

## A need for parallel computing

- Several application domains require much more computing power than what a single processor core can provide
- Parallel systems can fullfill this need
    - They can feature huge numbers of computing resources