

# SUMMER WORKSHOPS

## FUNDAMENTALS OF DATA SCIENCE



# ICME Fundamentals of Data Science

# Introduction to High-Performance Computing

Eric Darve



# Logistics of workshop

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- Schedule: Thursday and Friday, 1 to 4 PM

- GitHub page:

<https://ericdarve.github.io/icme-hpc-summer-2022/>

- Shared Google notebooks:

[https://drive.google.com/drive/folders/  
1pwvw\\_HvZMtQqZl00n195jDOUt-KPd\\_xy](https://drive.google.com/drive/folders/1pwvw_HvZMtQqZl00n195jDOUt-KPd_xy)

# Content of workshop

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1. **Introduction to High-Performance computing;** history of HPC and current trends
2. **How to program a multicore processor using OpenMP?**  
This is the basis of HPC programming and an easy entry point.
3. GPU processors provide the backbone of HPC platforms for number crunching. We will cover **OpenACC** to write HPC programs for GPU processors.

## Part 1

### Introduction to HPC

### History of HPC computers

# What is high-performance computing?

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- Standard computers perform tasks sequentially, that is, transaction-by-transaction.
- This means that the next transaction, or job, happens only when the computer completes the previous one.
- In contrast, HPC uses many resources such as processors to complete many jobs **simultaneously**.

# Supercomputers

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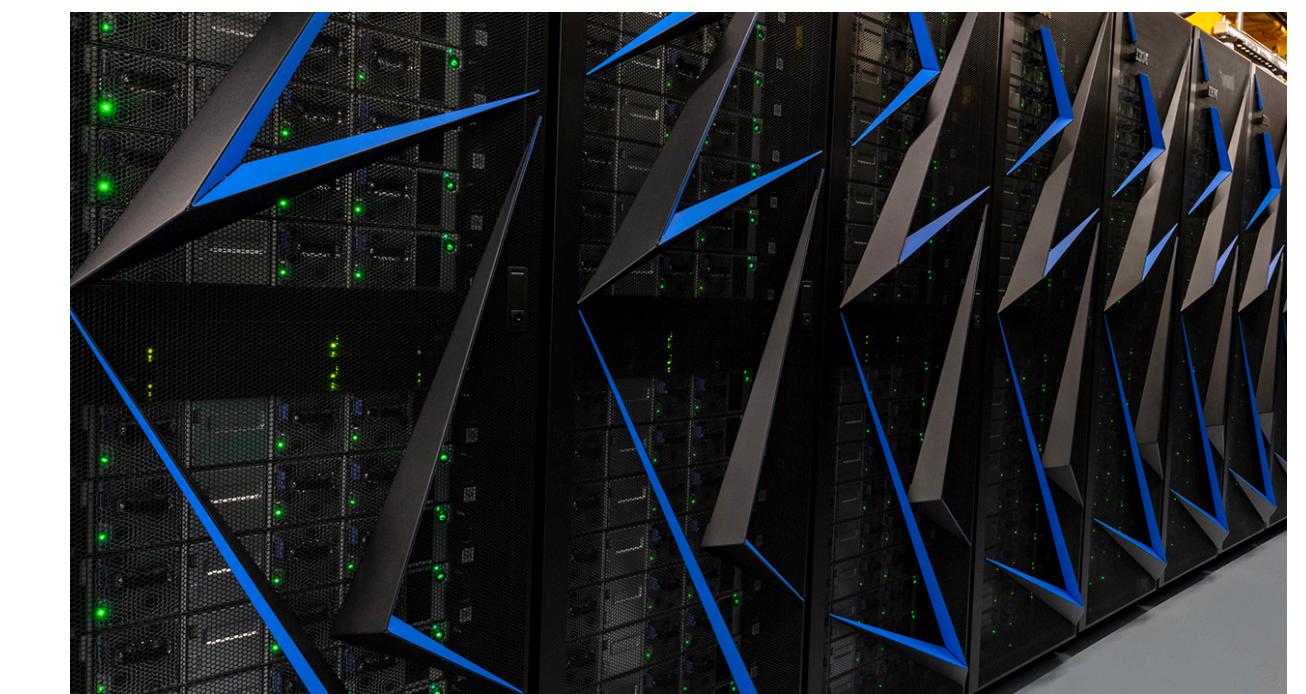
- For the most part, HPC occurs on **supercomputers**.
- These powerful systems help companies solve problems that could otherwise be insurmountable.
- These problems, or tasks, require **processors** that can carry out instructions faster than standard computers.
- This is achieved by running **many processors in parallel** to obtain answers within a practical duration.

# HPC hardware

- HPC jobs require fast **disks** and high-speed **memory**.
- HPC systems include computing and data-intensive servers with powerful **CPUs** that can be **vertically stacked**.
- HPC systems often have powerful **graphics processing units** (GPUs) that can run general-purpose computations.



Stanford XStream compute cluster



NVIDIA HPC system

# HPC system designs

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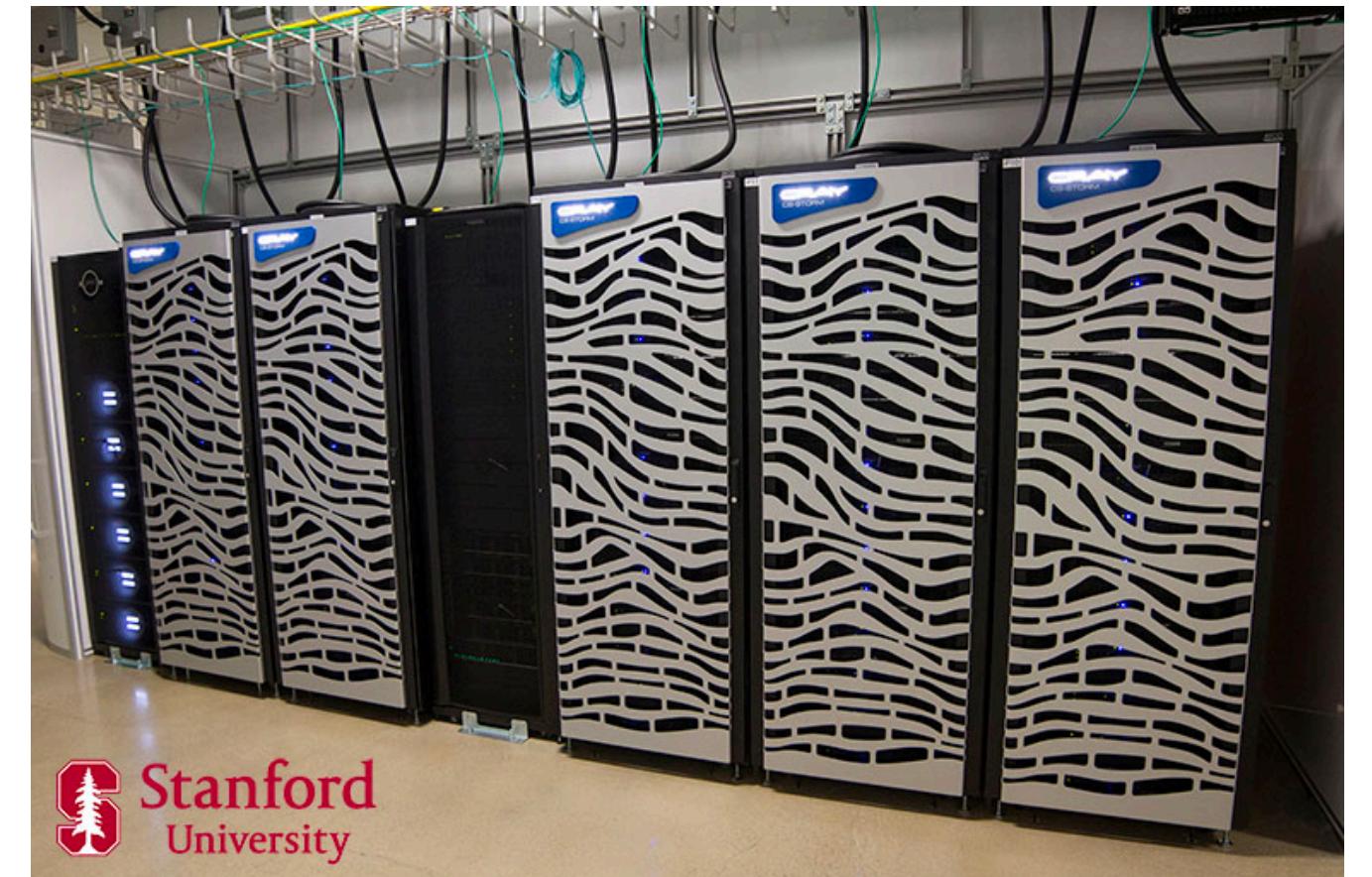
What is parallel computing?

Parallel computing HPC systems involve **hundreds of processors**, each running calculation payloads **simultaneously**.

# HPC system designs

## What is cluster computing?

- Cluster computing is a type of **parallel HPC system** consisting of a collection of computers working together as an integrated resource.
- Clusters can accommodate multiple applications and resources. They are managed by policy-based **scheduling** and can handle a dynamic workload consisting of **large numbers of jobs**.



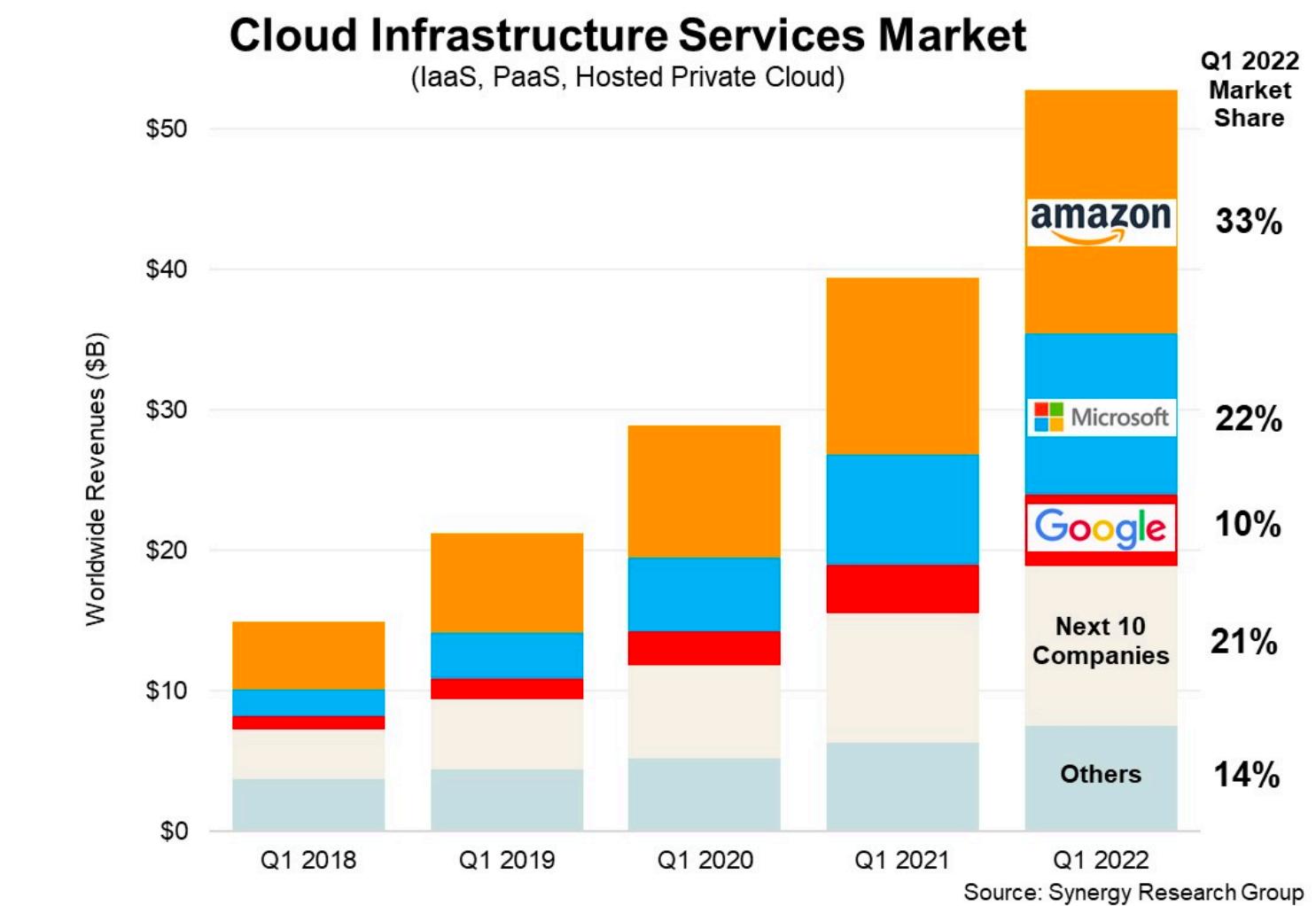
Stanford XStream compute cluster

# HPC system designs

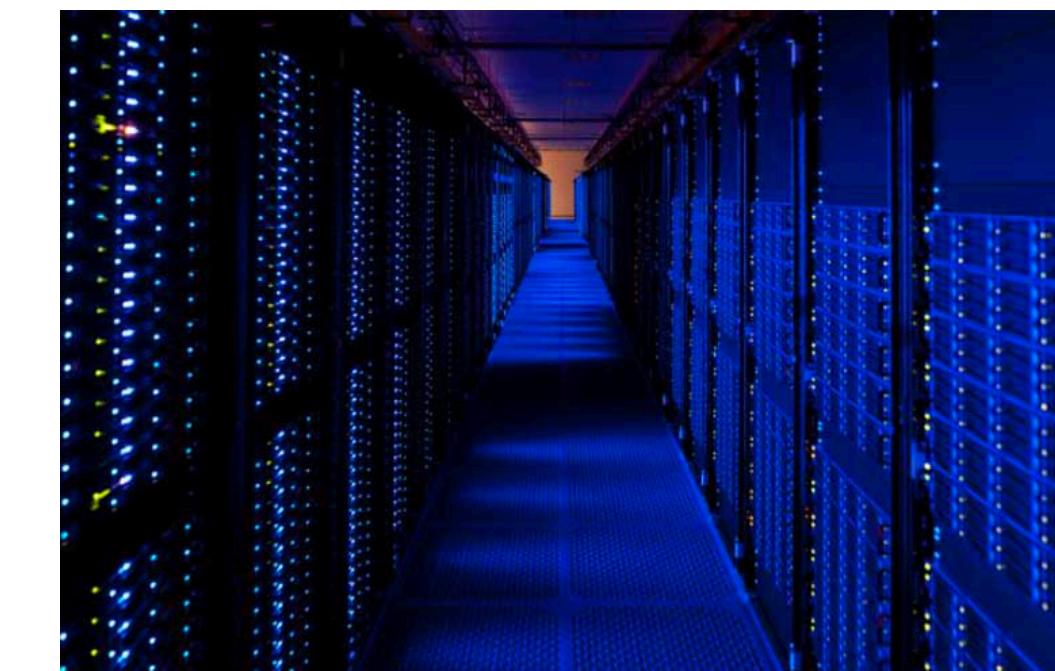
## What are grid and distributed computing?

Grid and distributed computing HPC systems connect the processing power of multiple computers within a network. The network can be a grid at a single location or distributed **across a wide area in different places**, linking network, compute, data, and instrument resources.

Main vendors: **Amazon Web Services (AWS)**, **Microsoft Azure**, and **Google Cloud Platform**



<https://www.srgresearch.com/>



Amazon data center

# Applications of HPC

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Some of the key applications include:

- **Big data:** massive multi-dimensional datasets
- **Data analytics**
- Extreme performance **database**
- **Machine learning**

# Applications!

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## Automotive and aerospace

CFD-aerodynamic modeling

FEA-impact and structural strength analysis

CAD and CAM

## Banking, financial services markets and insurance

Monte Carlo simulations

Risk analysis

Fraud detection

## Electronics design automation (EDA)

Chip design and optimization

Circuit simulation and verification

Manufacturing optimization

## Film, media and gaming

Rendering

Computer-aided graphics

Computer-generated images (CGI)

Transcoding and encoding

Real-time image analysis and processing

## Government and defense

Intelligence agency

Fraud analysis

Climate modeling

Weather forecasting

Energy

Nuclear stewardship

Exploration

## Life sciences

Genomic processing and sequencing

Pharmaceutical design

Molecular modeling and biology simulation

Protein docking

## Oil and gas

Seismic data processing

Reservoir simulation and modeling

Geospatial analytics

Terrain and topology mapping

CFD-aerodynamic modeling

Wind simulation

## Retail

Inventory analysis

Logistics and supply chain optimization

Sentiment analysis

Marketing offers

# A short history of HPC

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The beginnings:

- HPC market: **scientific** discoveries; **Fortran** (Formula Translation)
- **Cray** Research: supercomputers; focus: floating-point operations
- 1960's: specialized and expensive supercomputers; cold war, strategic necessity
- 1980's: number of processors goes up. Multiple processors (sometimes hundreds) are connected through a network.

# A short history of HPC

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- Vendors turn to **commodity markets** where processors are sold in large quantities.
- Monolithic supercomputer systems splinter as many commodity components can be purchased from competing vendors.
- The **economic barrier of entry** is lowered by at least a factor of ten.

# Beowulf clusters

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- Operating system: **UNIX**.
- 1981, Linus Torvalds released a freely available version of **Linux**.
- Message Passing Interface (MPI) library.



Borg, a 52-node Beowulf cluster used by the McGill University pulsar group to search for pulsations from binary pulsars

# Beowulf clusters

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- The performance of “Beowulf Clusters” (named for the NASA project that developed these systems) comes close to that of supercomputers of the day: commodity-grade computers + free and open source software + MPI.
- **High-performance interconnects** are developed; the market settles on InfiniBand (Mellanox)
- Name “supercomputer” replaced by “**HPC systems.**”

# The multi and many core explosion

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Three issues limit an increase in clock speed:

1. **Memory Speed:** the gap between processor and memory speed continued to grow
2. **Instruction Level Parallelism:** the increasing difficulty of finding enough parallelism in a single instruction stream
3. **Power Wall:** increased processor frequency causes an increase in operating temperature

# The multi and many core explosion

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- The era of **multi-core**: dual-core processors; more cores added to each new generation of processors
- Commodity **Graphics Processing Units** (GPUs) that contain large numbers (hundreds to thousands) of small, efficient cores.

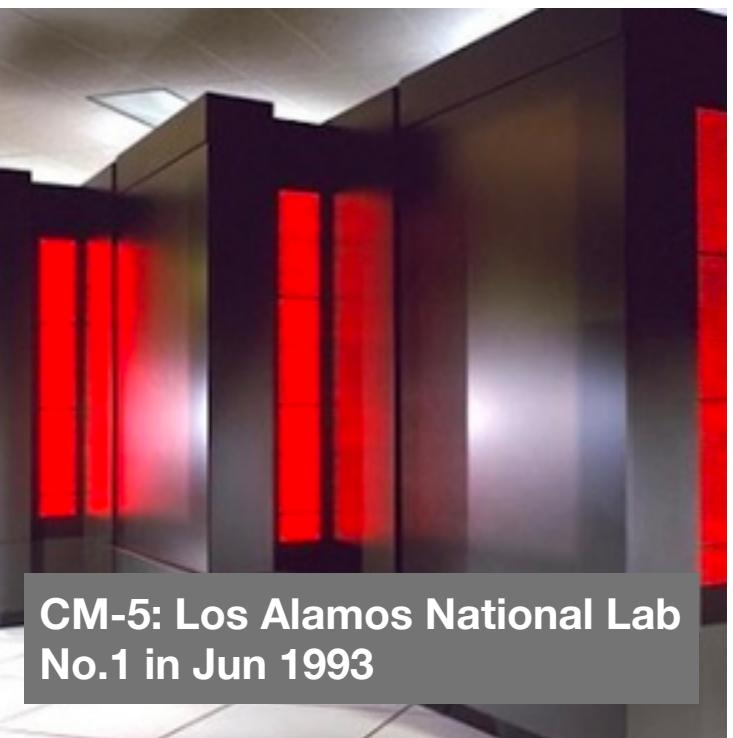
# Exascale computing and co-design

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“On the Role of Co-design in High Performance Computing,” R. F. Barrett et al.

The co-design strategy is based on developing partnerships with **computer vendors and application scientists** and engaging them in a highly **collaborative and iterative design process** well before a given system is available for commercial use. The process is built around identifying leading edge, high-impact scientific applications and providing concrete optimization targets rather than focusing on speeds and feeds (FLOPs and bandwidth) and percent of peak. **Rather than asking “what kind of scientific applications can run on an Exascale system” after it arrives, this application-driven design process instead asks “what kind of system should be built to meet the needs of the most important science problems.”** This leverages deep understanding of specific application requirements and a broad-based computational science portfolio.

# HPC history in pictures



CM-5: Los Alamos National Lab  
No.1 in Jun 1993



ASCI Red: Sandia National  
Laboratory  
No.1 from Jun 1997 until Jun  
2000



BlueGene/L: Lawrence  
Livermore National Laboratory  
No.1 from Nov 2004 until Nov  
2007



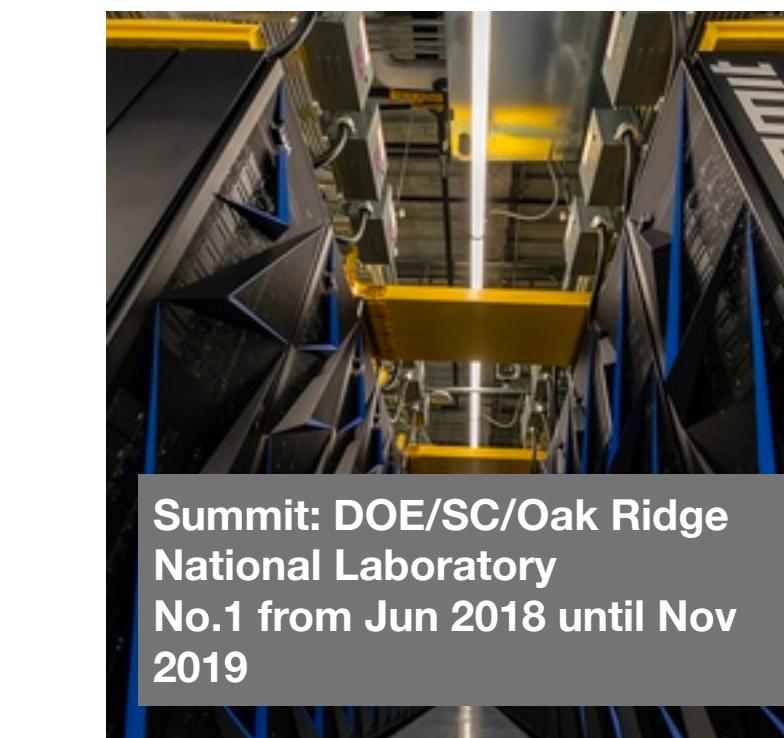
Tianhe-1A: National  
Supercomputing Center in  
Tianjin  
No.1 in Nov 2010



Titan: Oak Ridge National  
Laboratory  
No.1 in Nov 2012



Sunway TaihuLight: National  
Supercomputing Center in  
Wuxi  
No.1 from Jun 2016 until Nov  
2017

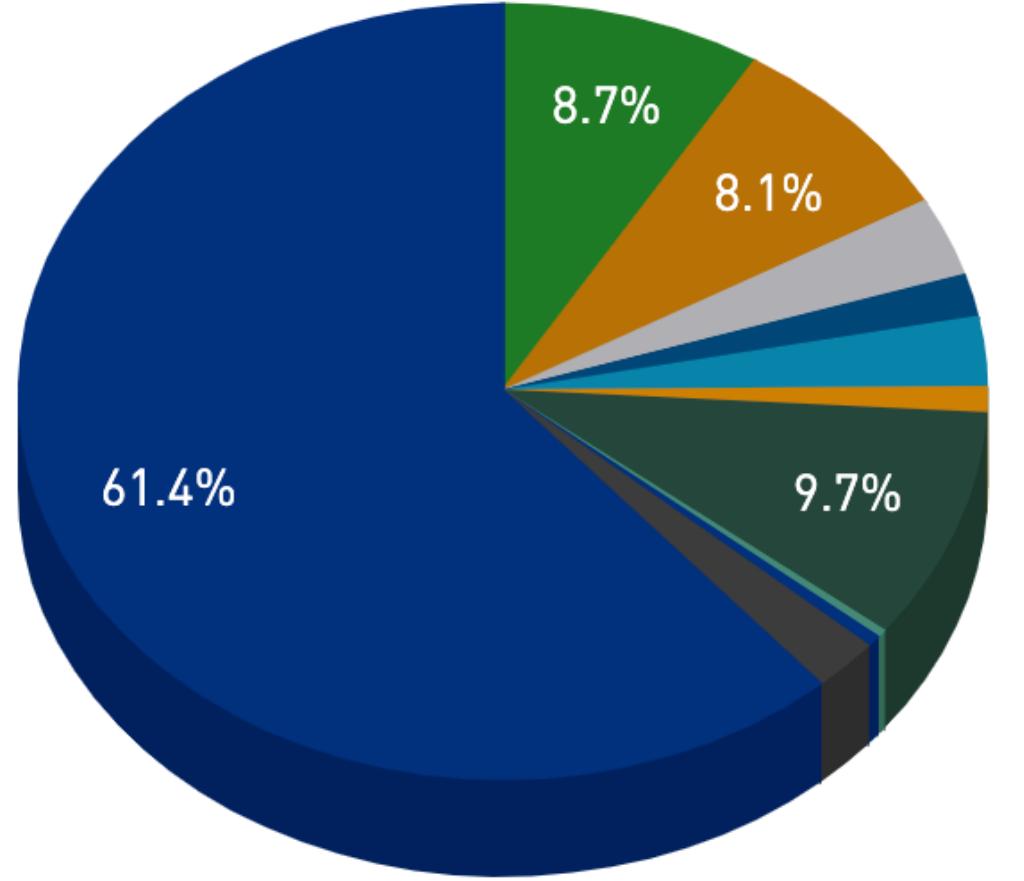


Summit: DOE/SC/Oak Ridge  
National Laboratory  
No.1 from Jun 2018 until Nov  
2019



Supercomputer Fugaku: RIKEN  
Center for Computational  
Science  
No.1 from Jun 2020 until Nov  
2020

## Accelerator/Co-Processor Performance Share

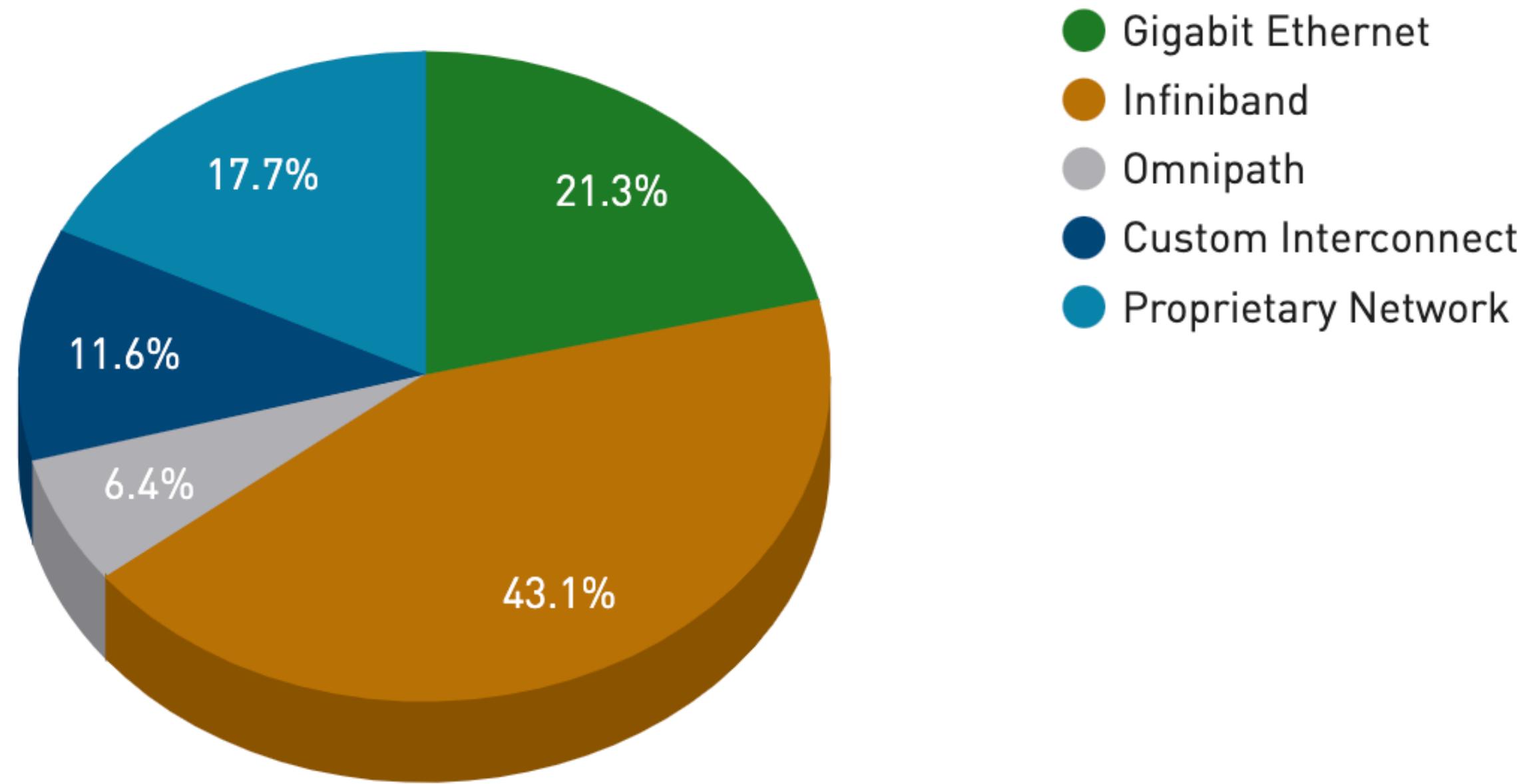


- NVIDIA Tesla V100
- NVIDIA A100
- NVIDIA Tesla V100 SXM2
- NVIDIA Tesla P100
- NVIDIA A100 SXM4 40 GB
- NVIDIA A100 40GB
- NVIDIA Volta GV100
- NVIDIA Tesla K40
- NVIDIA A100 80GB
- Matrix-2000
- Others

LINPACK achieved Theoretical peak

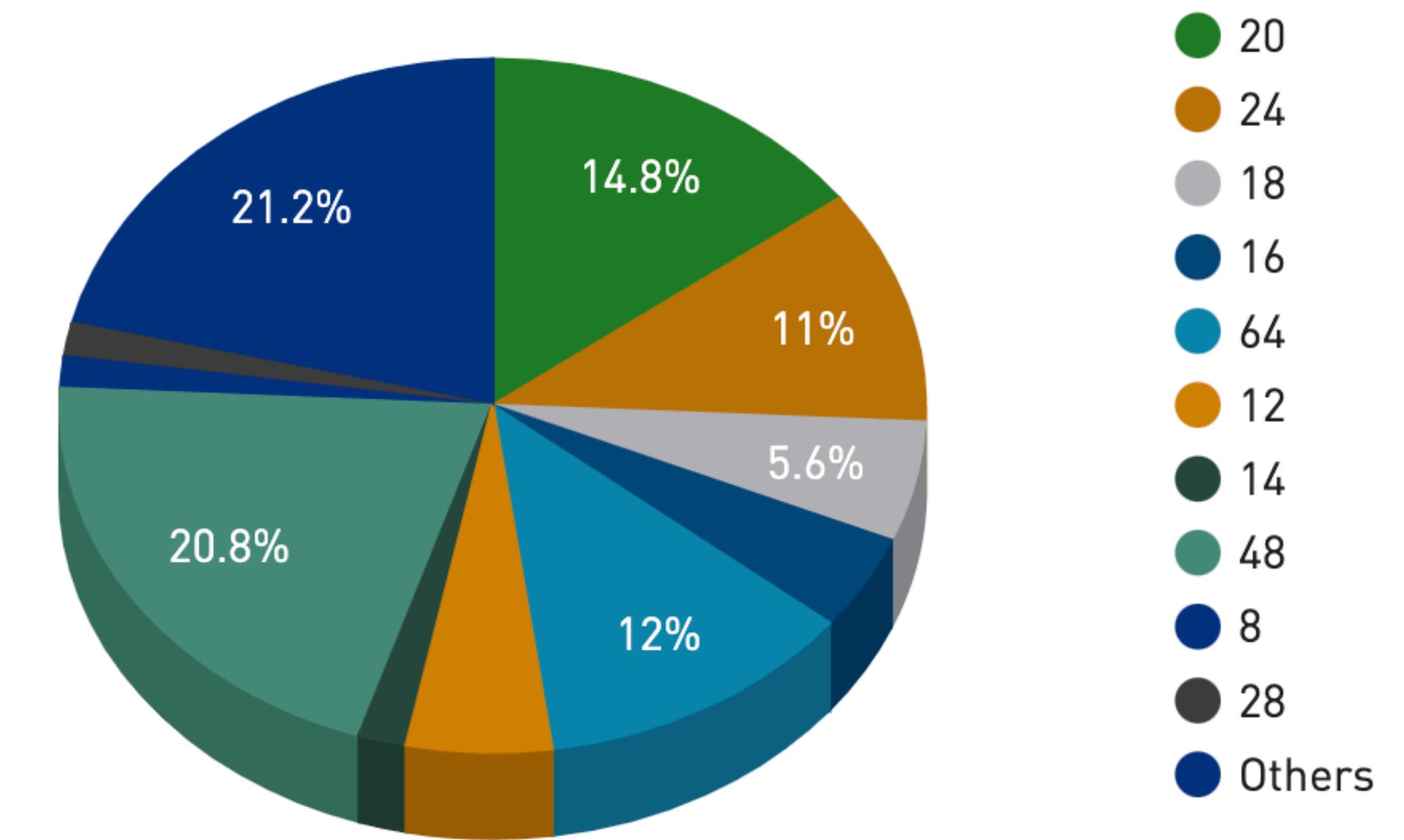
	Accelerator/Co-Processor	Count	System Share (%)	Rmax (GFlops)	Rpeak (GFlops)	Cores
1	NVIDIA Tesla V100	80	16	243,448,930	475,572,809	5,059,976
2	NVIDIA A100	15	3	226,001,000	324,135,290	2,125,952
3	NVIDIA Tesla V100 SXM2	12	2.4	91,975,490	182,486,069	2,059,208
4	NVIDIA Tesla P100	8	1.6	49,751,640	73,680,456	1,005,472
5	NVIDIA A100 SXM4 40 GB	5	1	81,312,000	115,202,938	869,192
6	NVIDIA A100 40GB	4	0.8	30,133,600	47,814,630	315,812
7	NVIDIA Volta GV100	4	0.8	269,439,000	362,564,722	4,408,096
8	NVIDIA Tesla K40	3	0.6	8,824,090	14,612,320	201,328
9	NVIDIA A100 80GB	2	0.4	13,806,000	18,688,410	124,160
10	Matrix-2000	1	0.2	61,444,500	100,678,664	4,981,760
11	NVIDIA 2050	1	0.2	2,566,000	4,701,000	186,368
12	NVIDIA Tesla K40m	1	0.2	2,478,000	4,946,790	64,384
13	NVIDIA Tesla K40/Intel Xeon Phi 7120P	1	0.2	3,126,240	5,610,481	152,692
14	NVIDIA Tesla P100 NVLink	1	0.2	8,125,000	12,127,069	135,828

## Interconnect Family Performance Share

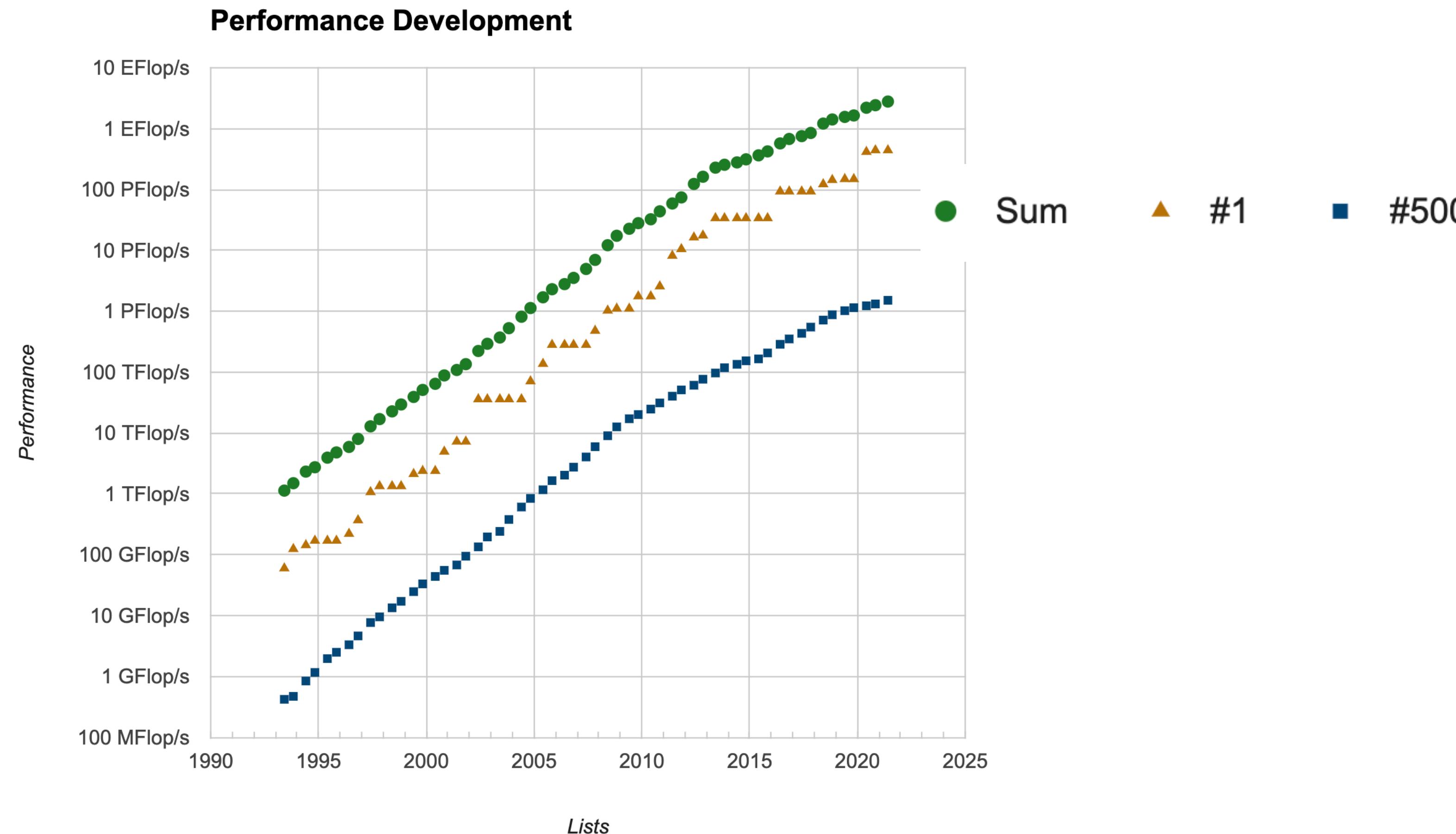


	Interconnect Family	Count	System Share (%)	Rmax (GFlops)	Rpeak (GFlops)	Cores
Mellanox	1 Gigabit Ethernet	247	49.4	592,043,220	1,210,167,243	19,827,104
	2 Infiniband	168	33.6	1,200,636,818	1,832,049,310	22,511,764
Intel	3 Omnipath	42	8.4	178,516,898	281,314,234	4,361,016
	4 Custom Interconnect	37	7.4	322,955,564	483,020,993	21,616,076
	5 Proprietary Network	6	1.2	491,906,300	597,474,433	8,609,792

### Cores per Socket Performance Share



# Performance development



**But before diving in further...  
Let's get to know each other**

# Instructor

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- Eric Darve, ME, ICME, [darve@stanford.edu](mailto:darve@stanford.edu)
- Numerical linear algebra, machine learning for mechanics and engineering, parallel computing

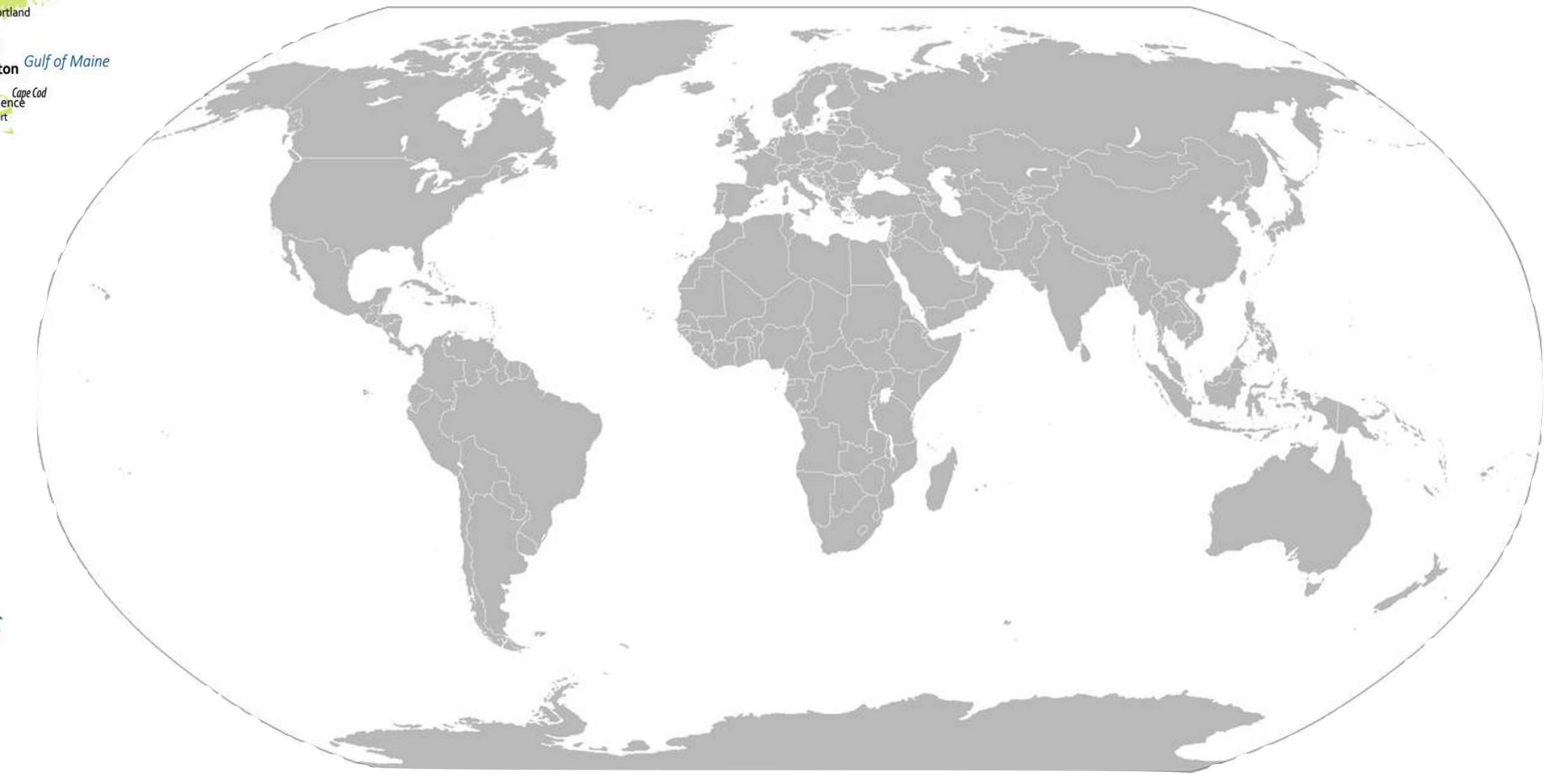
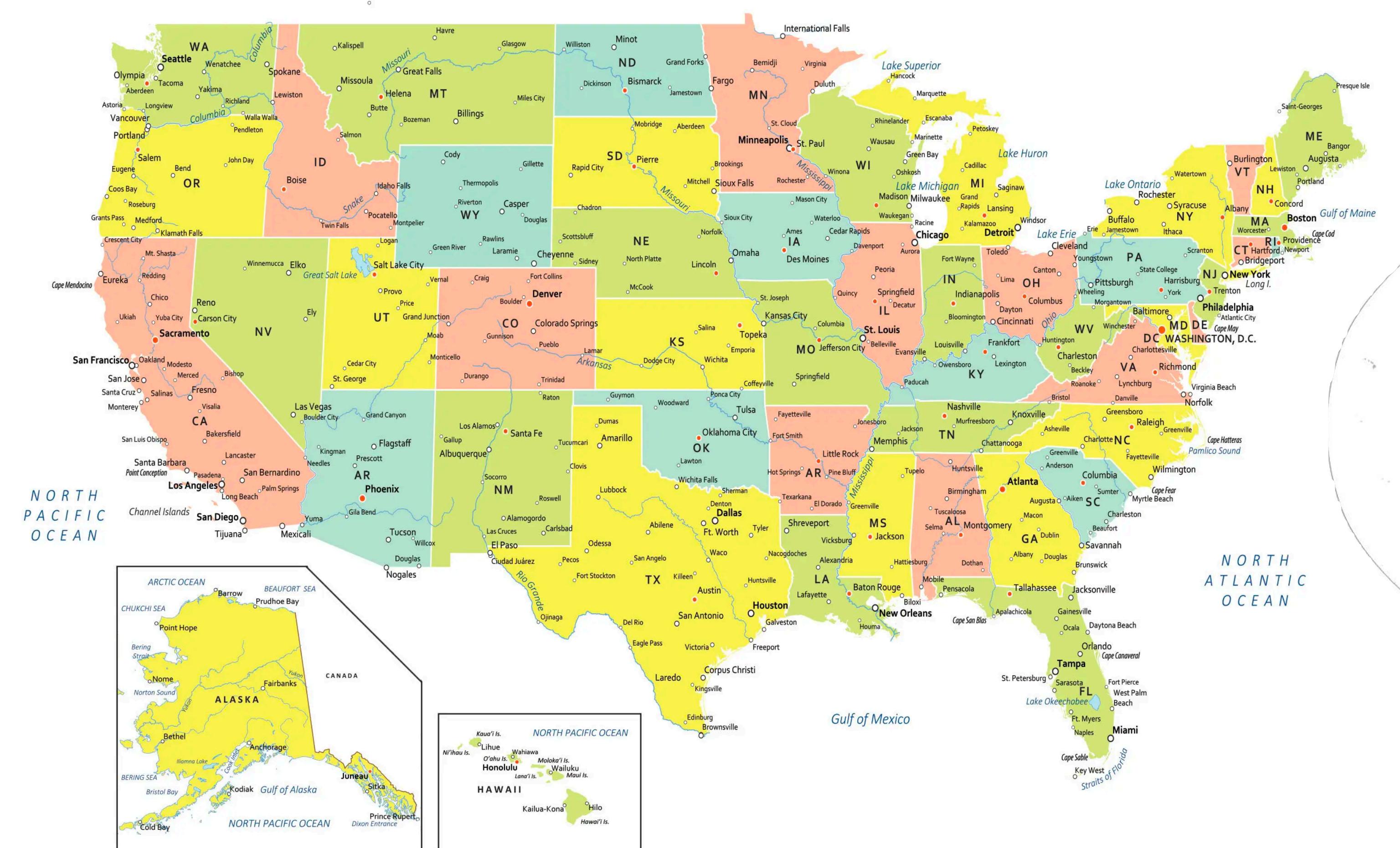


# Teaching Assistant

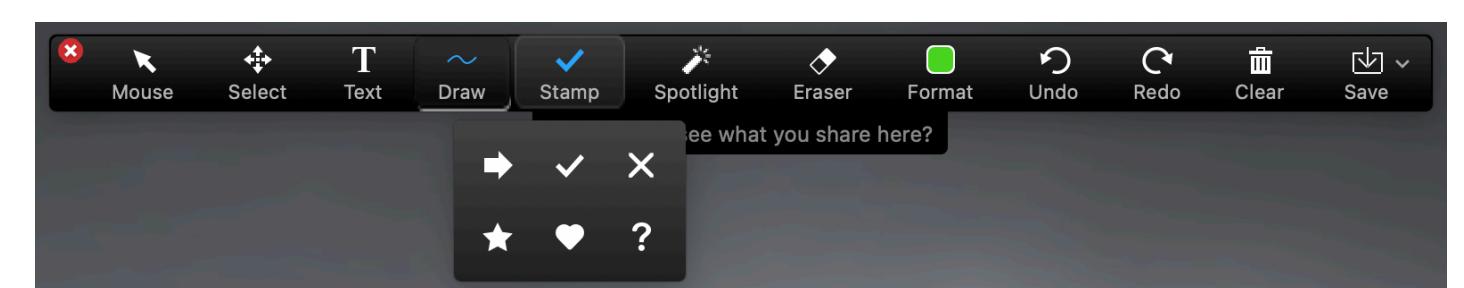
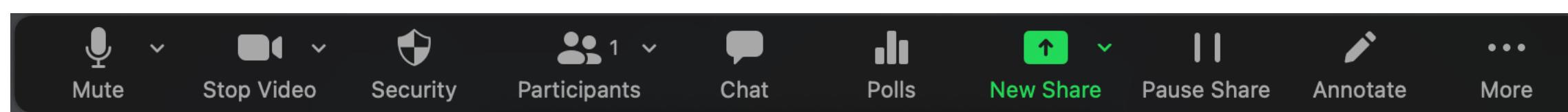
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- Chenzhuo Zhu
- I am a graduating Ph.D student at Stanford EE, advised by Prof. Bill Dally. I am interested in computer architecture and memory system design for data center applications.
- I grew up in Beijing, China. I received my B.S degree from Tsinghua University before coming to Stanford.
- I have worked as a teaching assistant for CME courses on scientific and parallel programming.
- I am also a snowboarder and a private pilot.





Mark your current location using zoom “Annotate → Stamp”



# What this class is about

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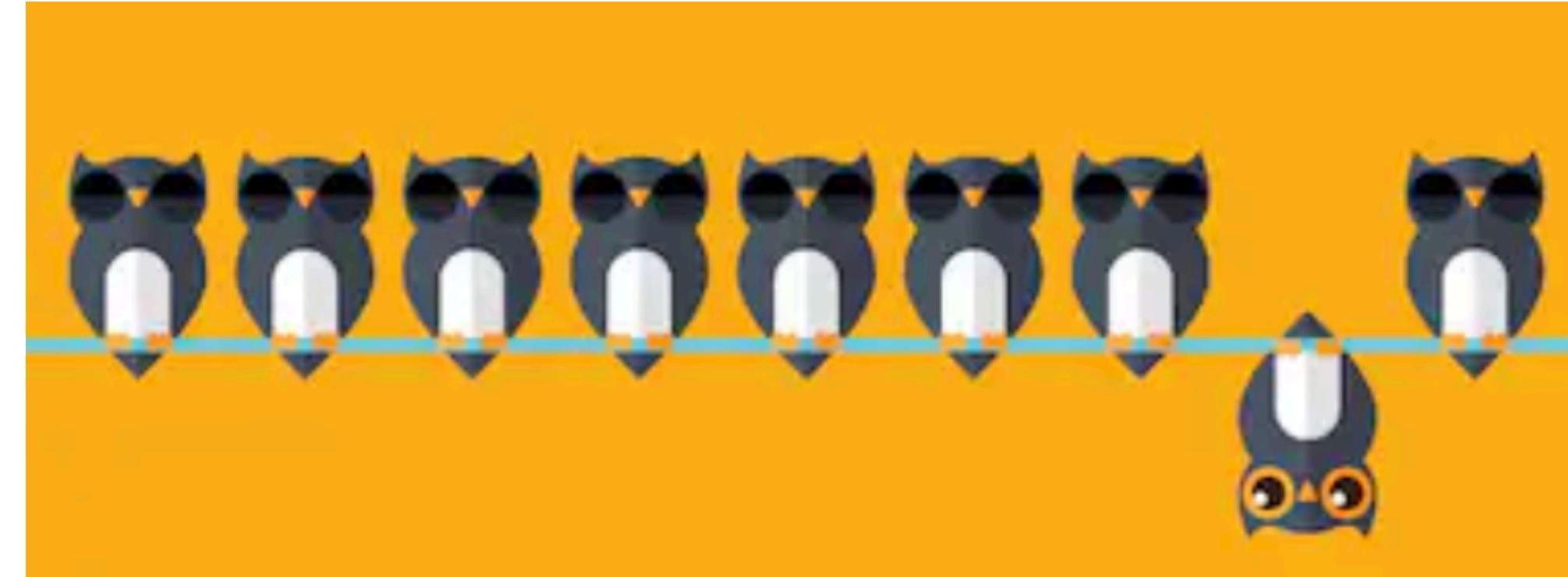
We will get an overview of parallel programming using two very accessible but powerful techniques:

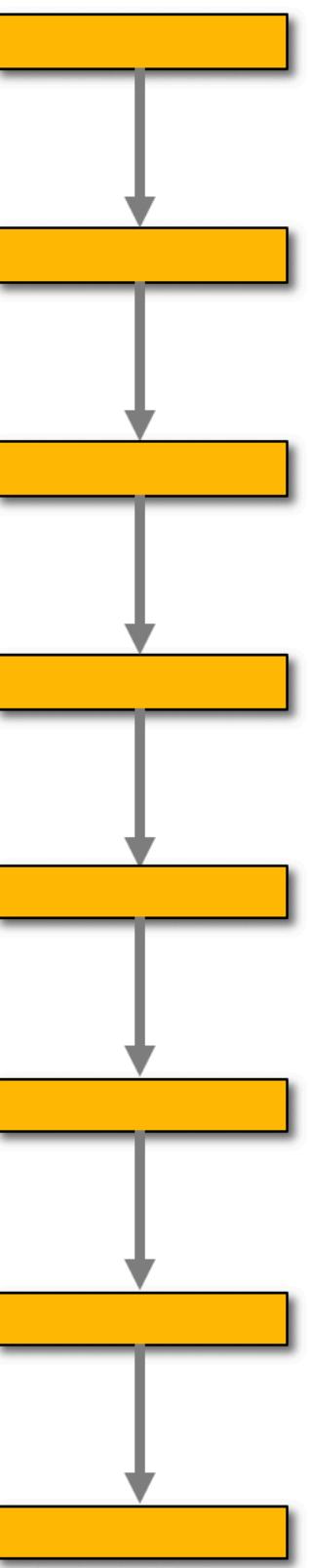
1. **Shared memory** multicore processors using OpenMP.
2. **GPU** computing (NVIDIA + AMD) using OpenACC.

# Thinking parallel

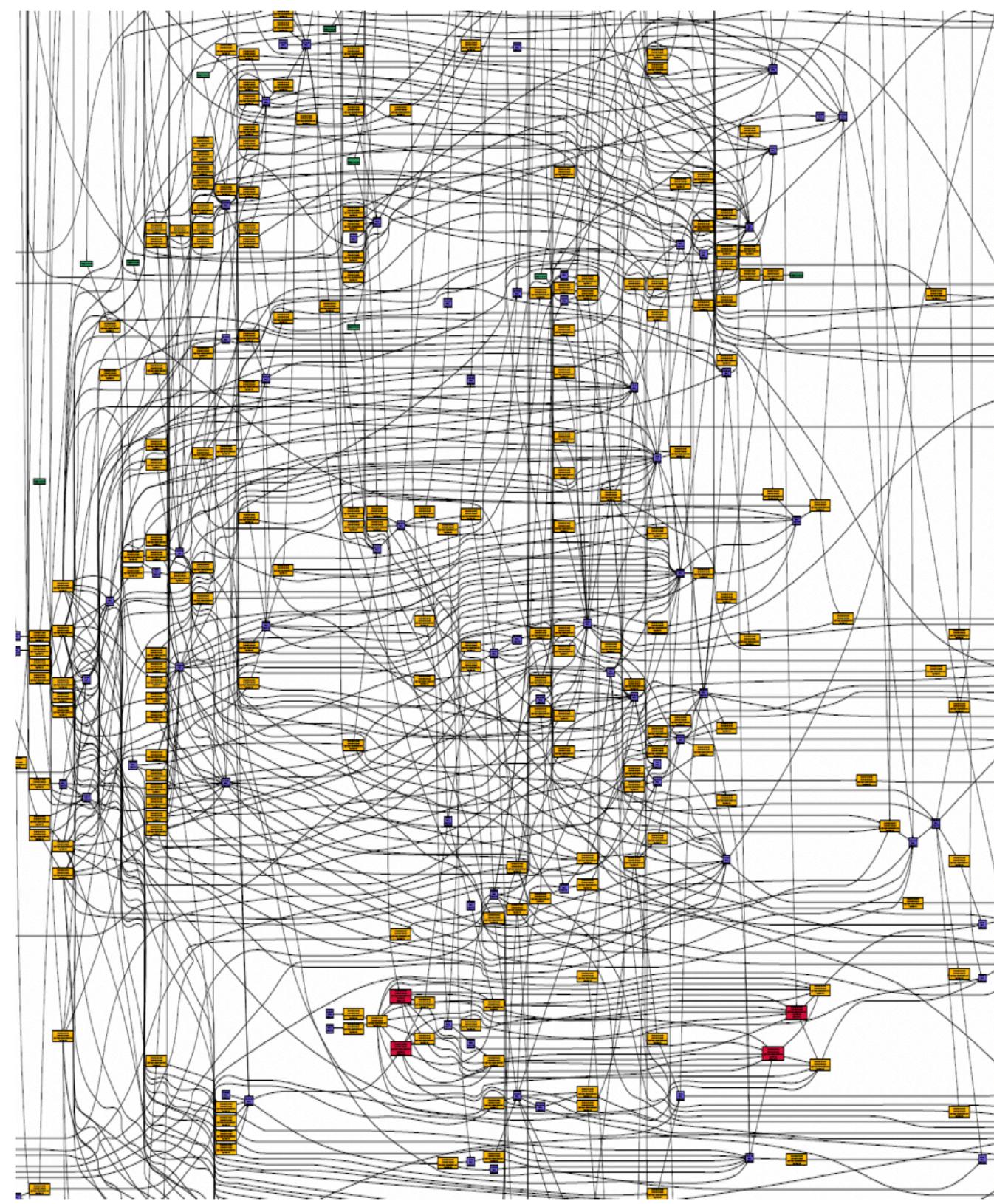
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Parallel programs often look very different from sequential programs.





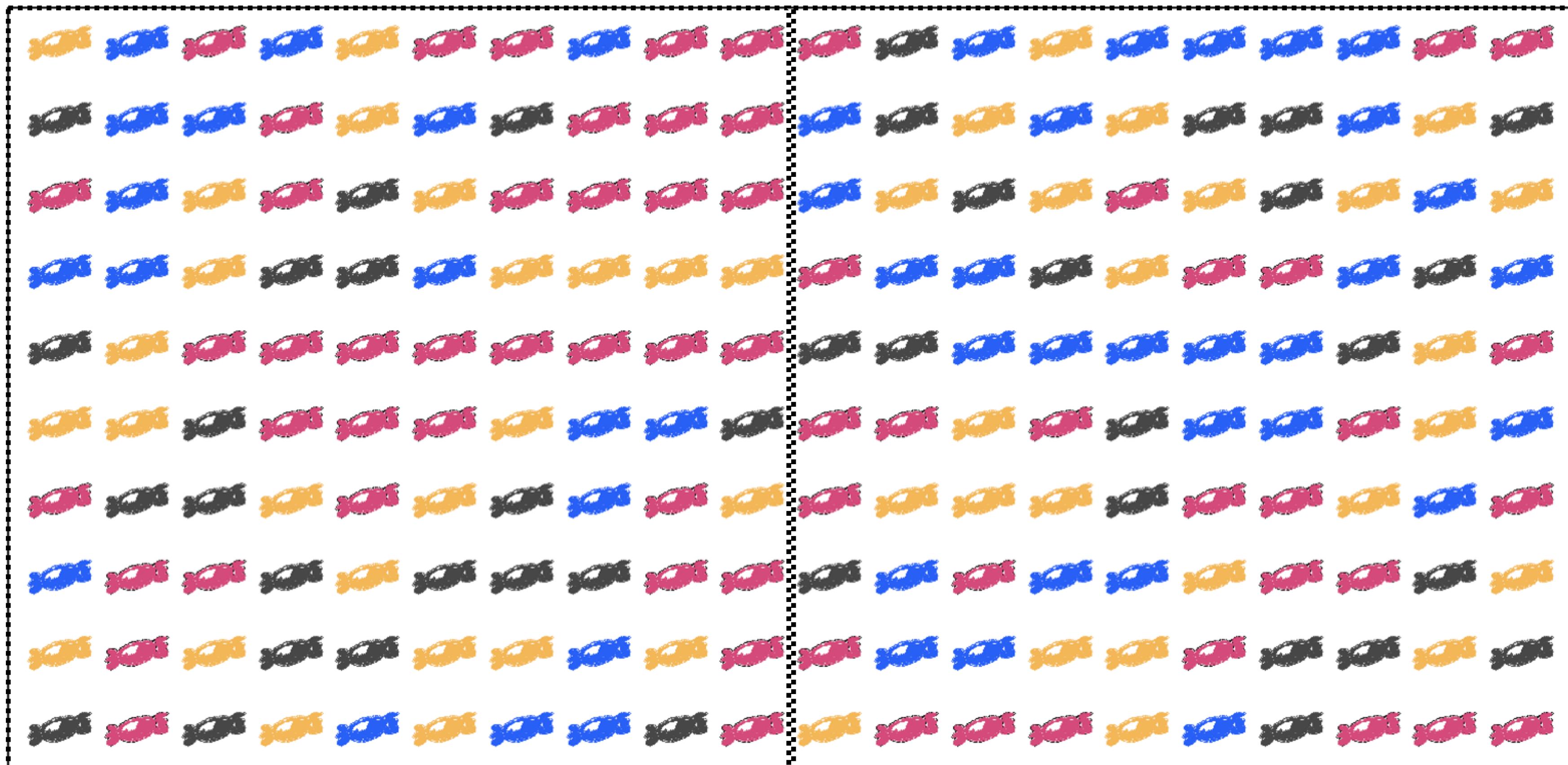
Sequential thinking



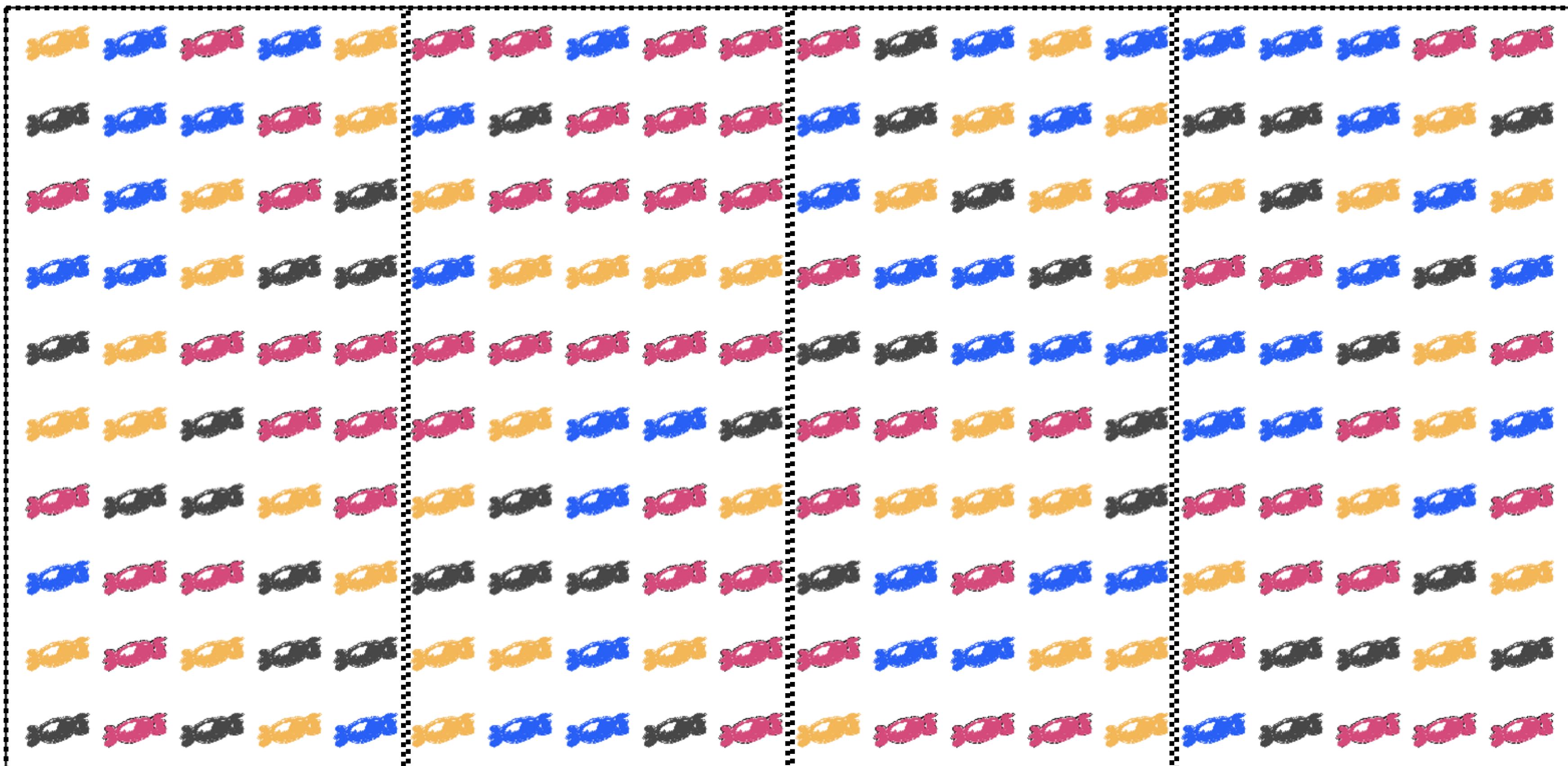
Parallel thinking

How would you count the number of candies of each color?

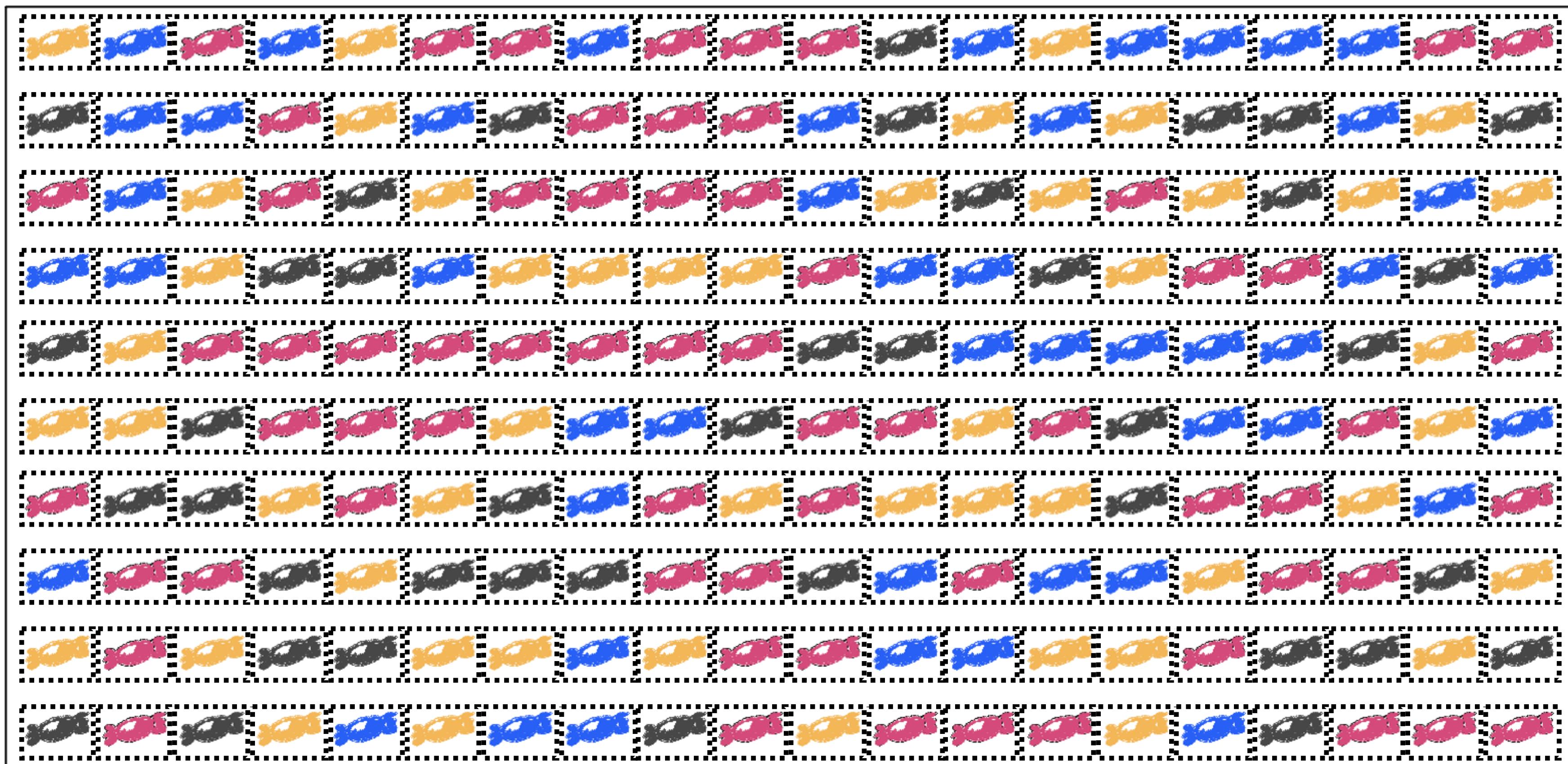




Using 2 cores



Using 4 cores



Using 200 cores

The initial step of counting candies goes fast.

But after that, the following steps of reduction become problematic.

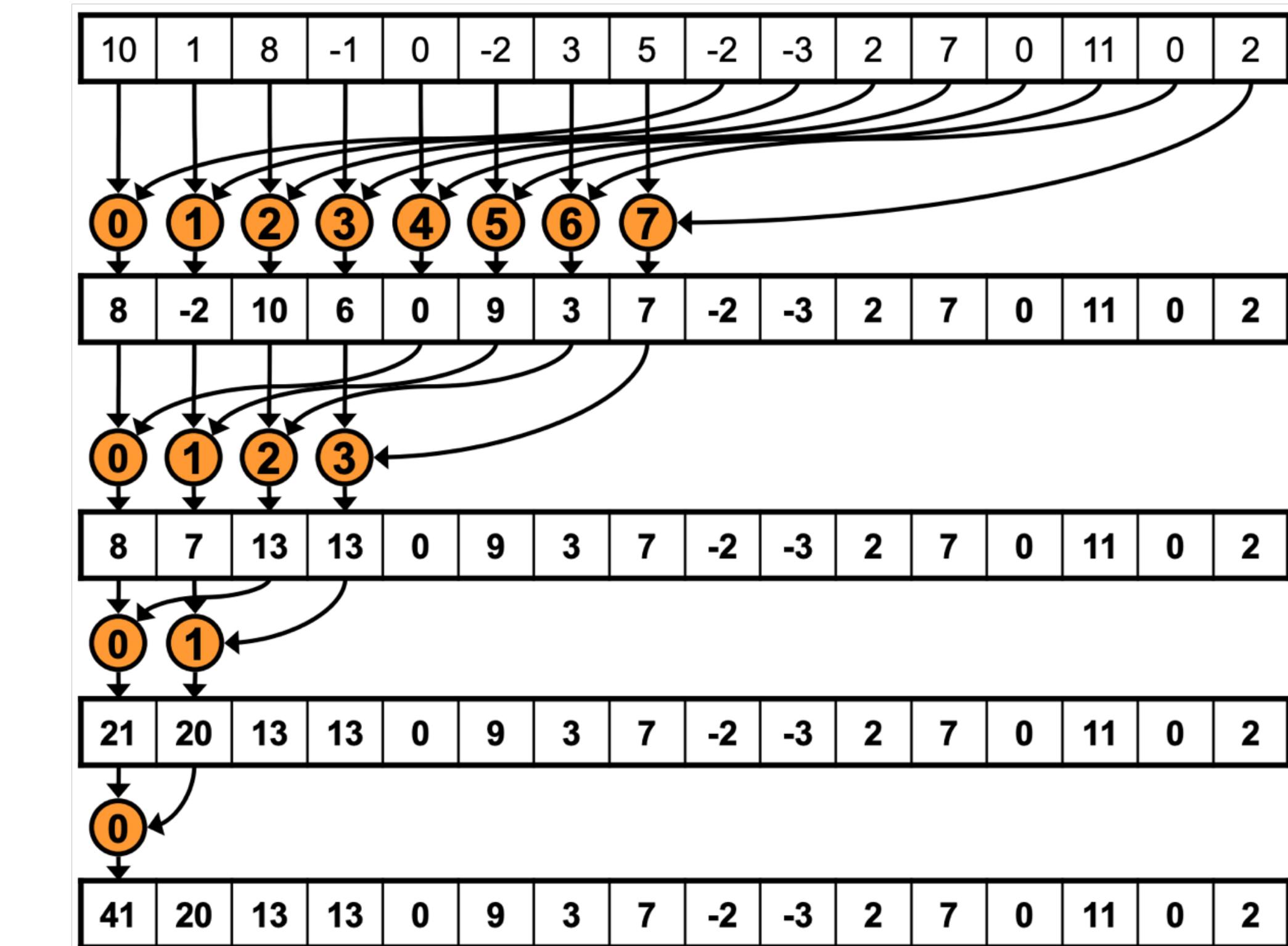
Can we use a single core to calculate the final sum for each candy?

- This is inefficient

How can we compute the final reduction efficiently and in parallel?



# Efficient algorithm requires a tree reduction



Counting candies in parallel is more complicated than we initially thought.

## Part 2

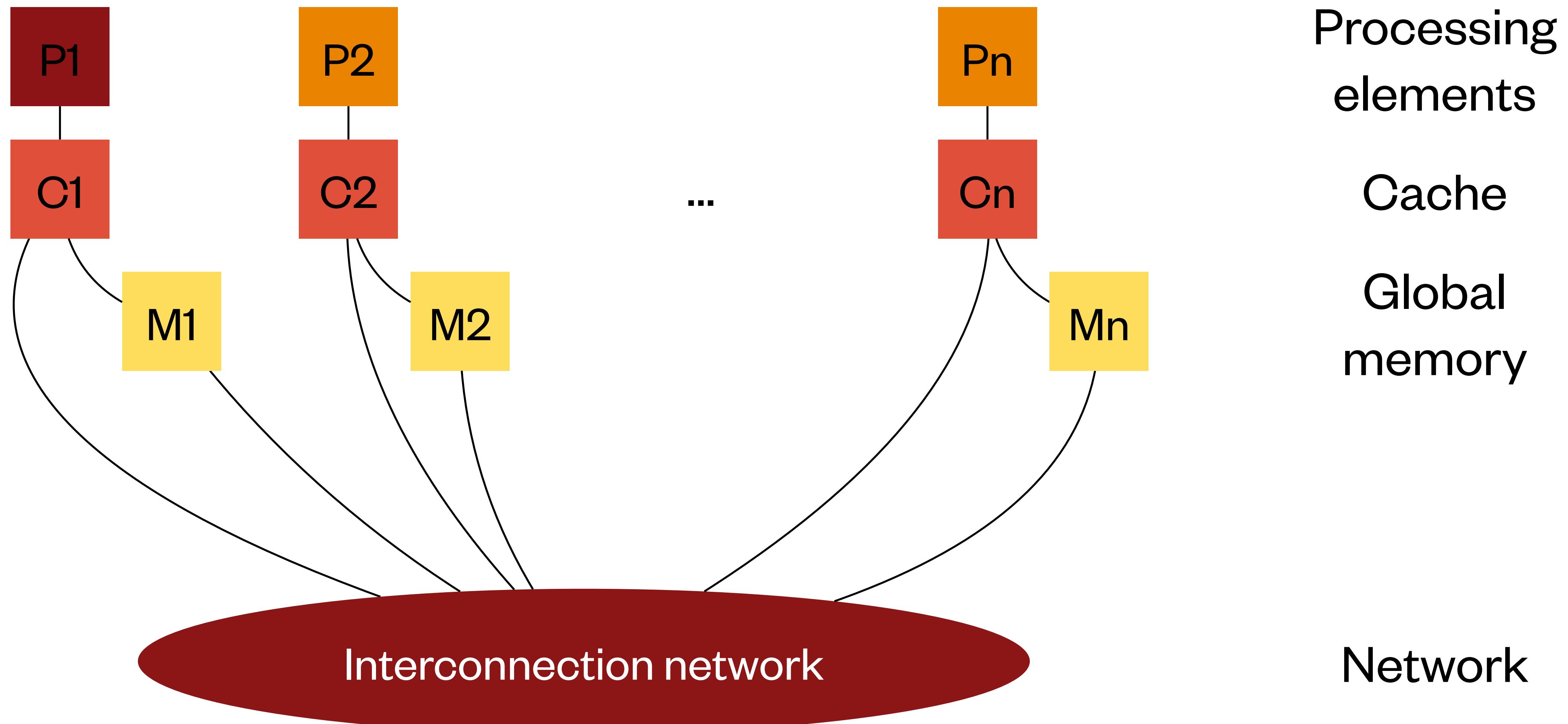
Programming multicore processors using OpenMP

Let's talk about shared memory computing.

This is the simplest method.

It applies to your laptop, desktop computer, or even your phone.

# Shared memory processor architecture



# Shared memory processor architecture

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## Schematic

- Several processors or **cores**
- A shared physical **memory** (global memory)
- An interconnection **network** to connect the processors with the memory

# Multicore performance

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- **Memory** is key to developing high-performance multicore applications
- More cores do not necessarily mean faster execution.
- **Memory traffic and time to access memory are often more critical than flops.**
- Memory is hierarchical and complex.



# Our teaching platform

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- Google Colab
- Allows running **CPU and GPU sample codes in the cloud** with no setup required!
- Demo: colab\_demo.ipynb

# OpenMP and OpenACC

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In this workshop, we will focus on two solutions:

- **OpenMP** to program multicore processors
- **OpenACC** to program GPUs

# OpenMP makes scientific multithreaded programming very easy!

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- OpenMP simplifies multicore programming significantly.
- In many cases, adding one line of code is sufficient to make it run in parallel.
- OpenMP is the standard approach in scientific computing for multicore processors.

# Goals of OpenMP

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## Standardization:

- Provide a **standard** among a variety of shared memory architectures/ platforms.
- Jointly defined and endorsed by a group of major computer hardware and software vendors.

## Simple but powerful:

- Establish a simple and limited set of **directives** for programming shared memory machines.
- Significant parallelism can be implemented by using just 3 or 4 directives.
- *This goal is becoming less true with each new release, unfortunately.*

# Goals of OpenMP

---

## **Ease of use:**

- Provide the capability to parallelize a serial program **incrementally**.
- Provide the ability to implement both coarse-grained and fine-grained parallelism.

## **Portability:**

- The API is specified for **C/C++ and Fortran**.
- Public forum for API and membership
- **Most major platforms** have been implemented, including Unix/Linux and Windows.

# Reference material

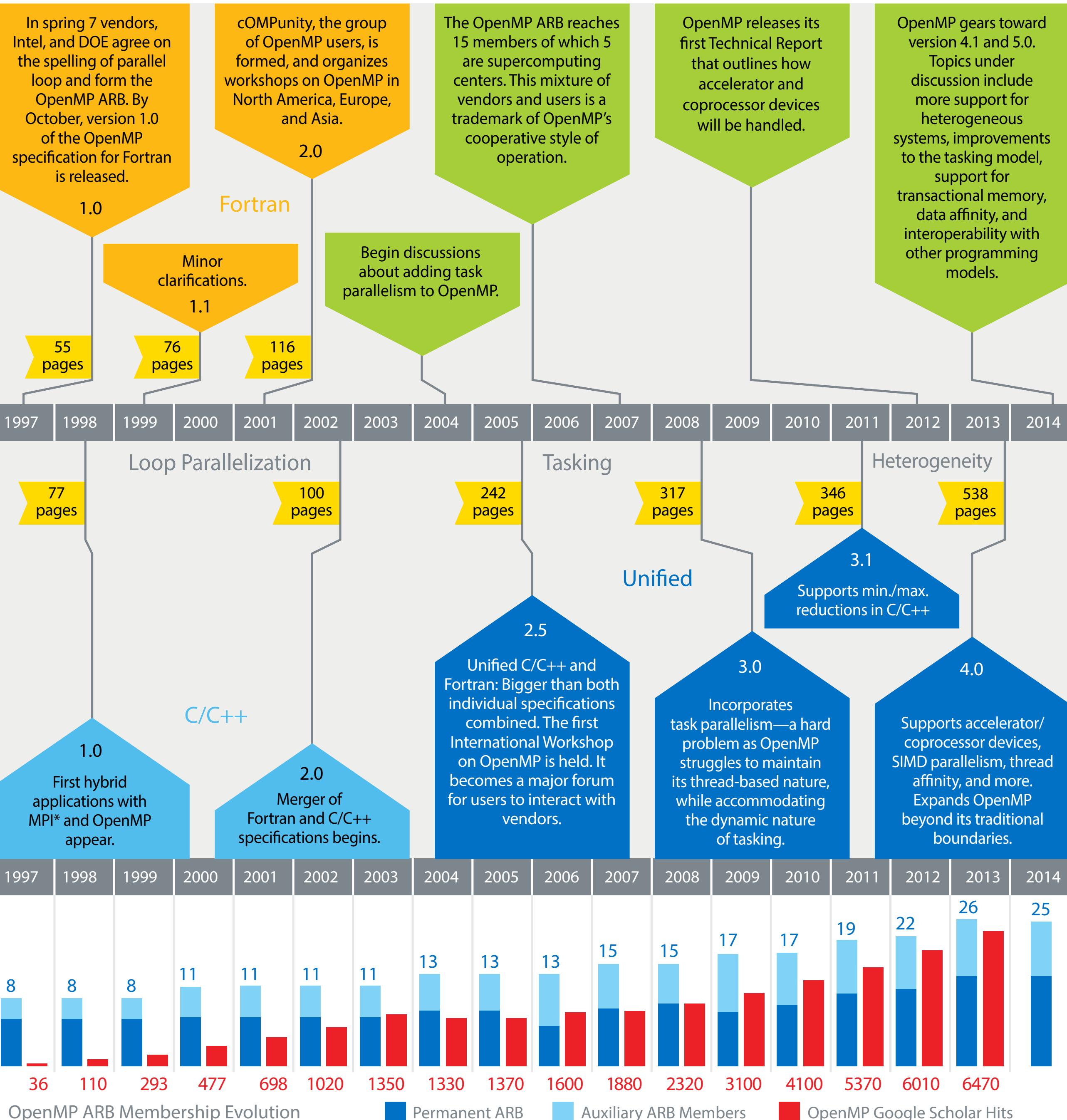
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- OpenMP website <https://openmp.org>
- Wikipedia <https://en.wikipedia.org/wiki/OpenMP>
- LLNL tutorial <https://hpc-tutorials.llnl.gov/openmp>
- Intel [https://www.intel.com/content/dam/www/public/apac/xa/en/pdfs/ssg/Programming\\_with\\_OpenMP-Linux.pdf](https://www.intel.com/content/dam/www/public/apac/xa/en/pdfs/ssg/Programming_with_OpenMP-Linux.pdf)

# History of OpenMP

[https://www.openmp.org/  
uncategorized/openmp-timeline/](https://www.openmp.org/uncategorized/openmp-timeline/)

1996 Vendors provide similar but different solutions for loop [parallelism](#), causing portability and maintenance problems.  
 Kuck and Associates, Inc. (KAI) | SGI | Cray | IBM | High Performance Fortran (HPF) | Parallel Computing Forum (PCF)



# Hello World example

---

Let's take a simple piece of code to get started:

```
for (int i = 0; i < n; ++i) {  
    x[i] = i;  
    y[i] = std::sqrt(float(i));  
}
```

Demo: omp\_hello\_world.ipynb

# How can we parallelize this code?

---

- Assume you have **multiple cores** that can do computation **in parallel**.
- The for loop can be split across the cores, and each core can compute a small chunk of the iterations.

```
for (int i = 0; i < n; ++i) {  
    x[i] = i;  
    y[i] = std::sqrt(float(i));  
}
```

# How can we parallelize this code?

```
i = 0                                     i = n-1
```

core 0

core 1

core 2

core 3

```
for (int i = 0; i < n; ++i) {  
    x[i] = i;  
    y[i] = std::sqrt(float(i));  
}
```

We can distribute the computation across the different cores using OpenMP.

# OpenMP code

---

Let's parallelize the first loop that calculates  $x[i]$  and  $y[i]$ .

```
const int num_threads = 4;
omp_set_num_threads(num_threads);
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    x[i] = i;
    y[i] = std::sqrt(float(i));
    core[i] = omp_get_thread_num();
}
for (int i = 0; i < n; ++i)
    printf("Iteration %d was computed by thread %d\n", i, core[i]);
```

# Output

---

Iteration 0 was computed by thread 0  
Iteration 1 was computed by thread 0  
Iteration 2 was computed by thread 1  
Iteration 3 was computed by thread 1  
Iteration 4 was computed by thread 2  
Iteration 5 was computed by thread 2  
Iteration 6 was computed by thread 3  
Iteration 7 was computed by thread 3

# Unit testing

---

Writing HPC code for scientific applications is not easy.

Thinking in parallel is much more complicated than thinking sequentially and is error-prone.

An important strategy to find errors is to use **unit testing**:

- Write a small piece of code in a function
- Immediately **test that the function works as expected**

# GoogleTest

---

An excellent library for **unit testing** is **GoogleTest**.

It provides a simple infrastructure to write and manage tests.

Let's learn how it works and how to use it.

# Example of test

---

Function to initialize a vector:

```
void init_i() {  
    for (int i = 0; i < n; ++i) x[i] = i;  
}
```

Demo: googletest.ipynb

# How to write a unit test

---

- Use the macro TEST
- Use testing macros like ASSERT\_EQ.
- Many additional macros and functions available in the library.

```
TEST(demoTest, init) {  
    init_i();  
    for (int i = 0; i < n; ++i) ASSERT_EQ(x[i], float(i));  
}
```

# Beware of roundoff errors

---

- Calculations on a computer **are not exact.**
- **Each operation generates a small roundoff error.**
- The approximate number of accurate digits depends on the precision of the floating point format.

Single precision	Double precision
~ 7.2	~ 15.9

# “Exact” test

---

This test does not suffer from roundoff errors.

```
void init_1() {
    for (int i = 0; i < n; ++i) x[i] = 1;
}
void sum_x() {
    sum = 0;
    for (int i = 0; i < n; ++i) sum += x[i];
}
TEST(demoTest, sum) {
    init_1();
    sum_x();
    ASSERT_EQ(sum, float(n));
}
```

# With larger numbers, roundoff errors start appearing

```
void init_i() {
    for (int i = 0; i < n; ++i) x[i] = i;
}
void sum_x() {
    sum = 0;
    for (int i = 0; i < n; ++i) sum += x[i];
}
TEST(demoTest, sum_i) {
    init_i();
    sum_x();
    const float expd = float(n * (n - 1) / 2.);
    ASSERT_NEAR(sum, expd, n * expd * mach_eps); ←
    printf("Roundoff errors are equal to: %9.6f; tolerance threshold: %9.6f.\n",
        abs((sum - expd) / expd), n * mach_eps);
}
```

Roundoff errors are equal to: 0.000042; tolerance threshold:  
0.001192.

# Is my calculation accurate?

---

Determining whether a calculation is “correct” can be difficult.

Is the difference due to a coding error, or is it a roundoff error?

# Unit testing and debugging

---

- Unit testing is one of the many methods you need to learn to be able to write correct code for complex applications.
- Additional documentation at:  
<https://google.github.io/googletest/>

```
TEST(ompTest, omp_loop) {
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    x[i] = i;
    y[i] = i * i;
}
for (int i = 0; i < n; ++i) {
    ASSERT_EQ(x[i], i);
    ASSERT_EQ(y[i], i * i);
}
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    z[i] = x[i] + y[i];
}
for (int i = 0; i < n; ++i) {
    ASSERT_EQ(z[i], (float)(i + i * i));
}
}
```

# Let's test our OpenMP Hello World!

```
Running main() from googletest-main/googletest/src/gtest_main.cc
[=====] Running 4 tests from 1 test suite.
[=====] Global test environment set-up.
[=====] 4 tests from ompTest
[ RUN   ] ompTest.omp_loop
[ OK   ] ompTest.omp_loop (0 ms)
[ RUN   ] ompTest.omp_reduction
[ OK   ] ompTest.omp_reduction (0 ms)
[ RUN   ] ompTest.omp_schedule
[ OK   ] ompTest.omp_schedule (0 ms)
[ RUN   ] ompTest.omp_collapse
[ OK   ] ompTest.omp_collapse (0 ms)
[=====] 4 tests from ompTest (1 ms total)

[=====] Global test environment tear-down
[=====] 4 tests from 1 test suite ran. (1 ms total)
[ PASSED ] 4 tests.
```

Demo: `omp_lab.ipynb`

# More on OpenMP

---

- OpenMP is a vast topic with a lot of additional functionalities.
- We will only review some of the main features.
- An important one is the **reduction** operator.

# Reduction

---

Consider the following code:

```
float sum = 0;
for (int i = 0; i < n; ++i) {
    sum += x[i];
}
```

# Race condition

---

```
sum += x[i];
```

If multiple cores attempt to update the variable sum at the same time, the result becomes undetermined.

This will lead to an erroneous result. **This is a bug!**

# OpenMP reduction

---

We need to tell the compiler that sum should be computed differently.

Adding numbers is called a reduction operation.

We have to use the OpenMP **reduction** clause to get the correct code.

# Reduction clause

---

```
float sum = 0;  
#pragma omp parallel for reduction(+ : sum)  
for (int i = 0; i < n; ++i) {  
    sum += x[i];  
}
```

- The final result will now be correct.
- Other reduction operators: - , \* , max , min
- + logical and boolean operators

# How should we schedule loops?

---

- **Loop scheduling is critical for performance.**
- OpenMP has extensive functionalities to improve performance of for loop executions.
- This can be achieved by specifying different loop scheduling policies.

# Example of static policy

---

```
#pragma omp parallel for schedule(static, 32)
for (int i = 0; i < n; ++i) {
    z[i] = x[i] + y[i];
}
```

**What does this do?**

# schedule(static, 1)

---

```
#pragma omp parallel for schedule(static, 1)
```

<b>thread 0</b>	0	4	8
<b>thread 1</b>	1	5	9
<b>thread 2</b>	2	6	10
<b>thread 3</b>	3	7	11

# schedule(static, 2)

```
#pragma omp parallel for schedule(static, 2)
```

<b>thread 0</b>	0	1	8
<b>thread 1</b>	2	3	9
<b>thread 2</b>	4	5	10
<b>thread 3</b>	6	7	11

# Example

---

```
#pragma omp parallel for
for (int i = 0; i < n; ++i) {
    x[i] = i;
    y[i] = i * i;
}
#pragma omp parallel for schedule(static, 32)
for (int i = 0; i < n; ++i) z[i] = x[i] + y[i];

for (int i = 0; i < n; ++i) ASSERT_EQ(z[i], (float)(i+i*i));
```

# schedule(dynamic, 1)

```
#pragma omp parallel for schedule(dynamic, 1)
```



# Example

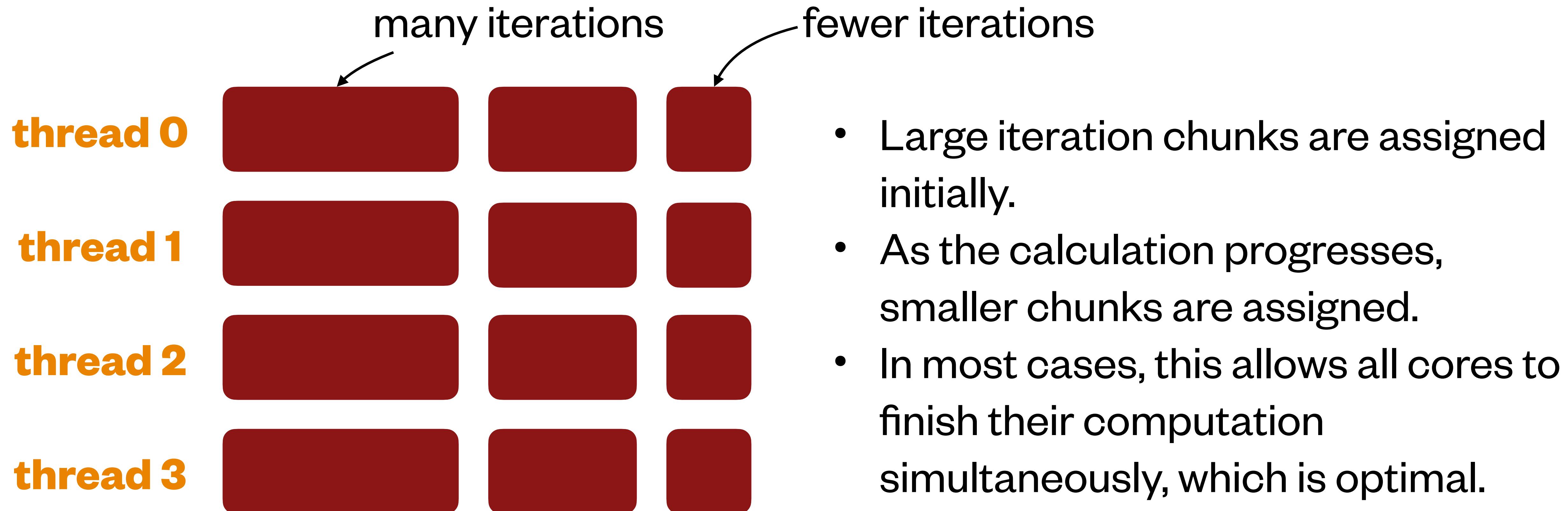
---

```
#pragma omp parallel for schedule(dynamic, 32)
for (int i = 0; i < n; ++i) z[i] = x[i] + y[i];

for (int i = 0; i < n; ++i) ASSERT_EQ(z[i], (float)(i+i*i));
```

# schedule(guided)

```
#pragma omp parallel for schedule(guided)
```



# Nested loops

- What happens if the **number of iterations is small?**
- Few iterations are assigned to each core.
- This may lead to a significant **load imbalance**, i.e., one of the cores finishes much later than the others.



# Balancing the workload

---

- In general, it is better to parallelize loops **with many iterations.**
- This makes it easier for the scheduler to assign work to the cores so that they **all finish around the same time.**
- If your loop does not have enough iteration, you have the option of “merging” it with the following nested loop.
- This is called **loop collapse** in OpenMP.

# Example of loop collapse

---

```
#pragma omp parallel for collapse(2)
for (int i = 0; i < n0; ++i) {
    for (int j = 0; j < n0; ++j) {
        x[i * n0 + j] = i * n0 + j;
        y[i * n0 + j] = i - j;
    }
}
for (int i = 0; i < n; ++i) ASSERT_EQ(x[i], float(i));
for (int i = 0; i < n0; ++i)
    for (int j = 0; j < n0; ++j) ASSERT_EQ(y[i * n0 + j], float(i - j));
```

# Example of loop collapse

---

```
#pragma omp parallel for collapse(2)
for (int i = 0; i < n0; ++i)
    for (int j = 0; j < n0; ++j) z[i * n0 + j] = x[i * n0 + j] + y[i * n0 + j];

for (int i = 0; i < n0; ++i)
    for (int j = 0; j < n0; ++j) ASSERT_EQ(z[i * n0 + j], float(i * (n0 + 1)));
```

# Many other OpenMP concepts

---

- atomic
- critical
- single
- task
- barrier, taskwait
- ...
- Reference guides

## Part 3

# Programming GPU processors using OpenACC

# GPUs!



# GPU for scientific computing

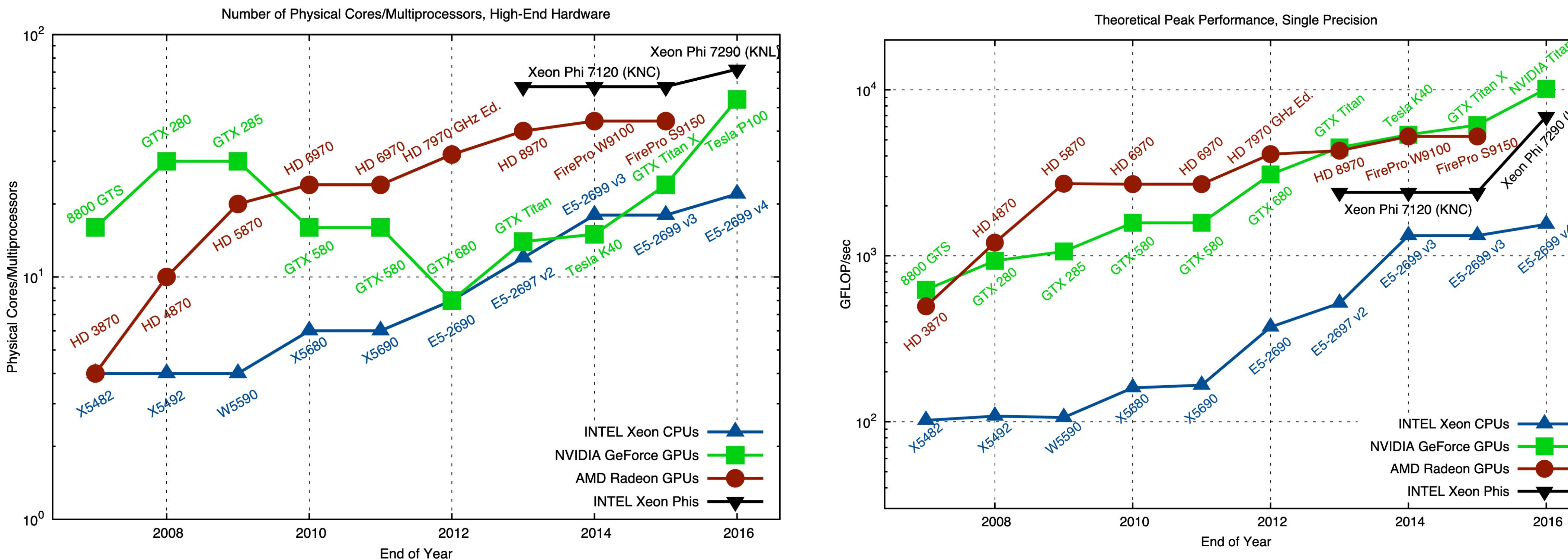
---

GPUs from NVIDIA and AMD boast significant single and double precision **performance due to a huge number of cores.**

These are specialized processors that can deliver high-performance but only on certain types of calculations:

- **Massive** amount of parallel operations
- Must be mainly **data parallel**
- Requires offloading large chunks of computations to the GPU to amortize the cost of **transferring** data to/from the GPU.

# Performance trends



# History

---

- GPUs initially focused on 3D graphics = computing the color of each pixel on the screen based on a 3D scene model.
- Featured example: ray tracing global illumination (RTXGI)



# GPGPU

---

General purpose GPU computing:

- Extension to general scientific computations.
- Solving equations on a grid is similar to rendering: perform the same regular calculations on a large dataset.

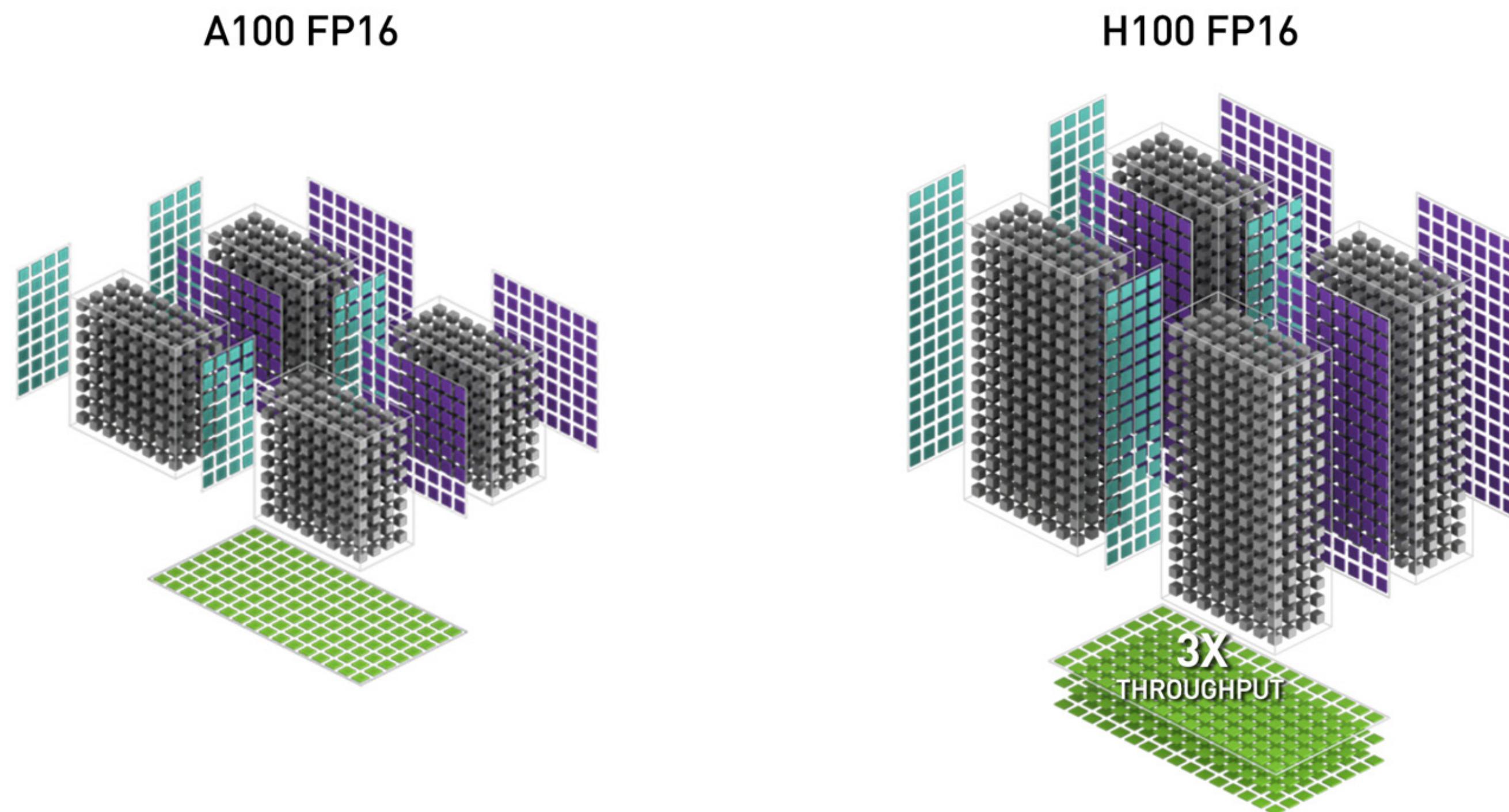
# Deep learning

---

Recent advances in GPU computing target deep learning.

1. Linear algebra: matrix-matrix multiplications.
2. Mixed precision arithmetic: represents floating point numbers using different numbers of binary bits.

# Tensor Cores



**H100 FP16 Tensor Core has 3x throughput compared to A100 FP16 Tensor Core**

# GPUs are great for

---

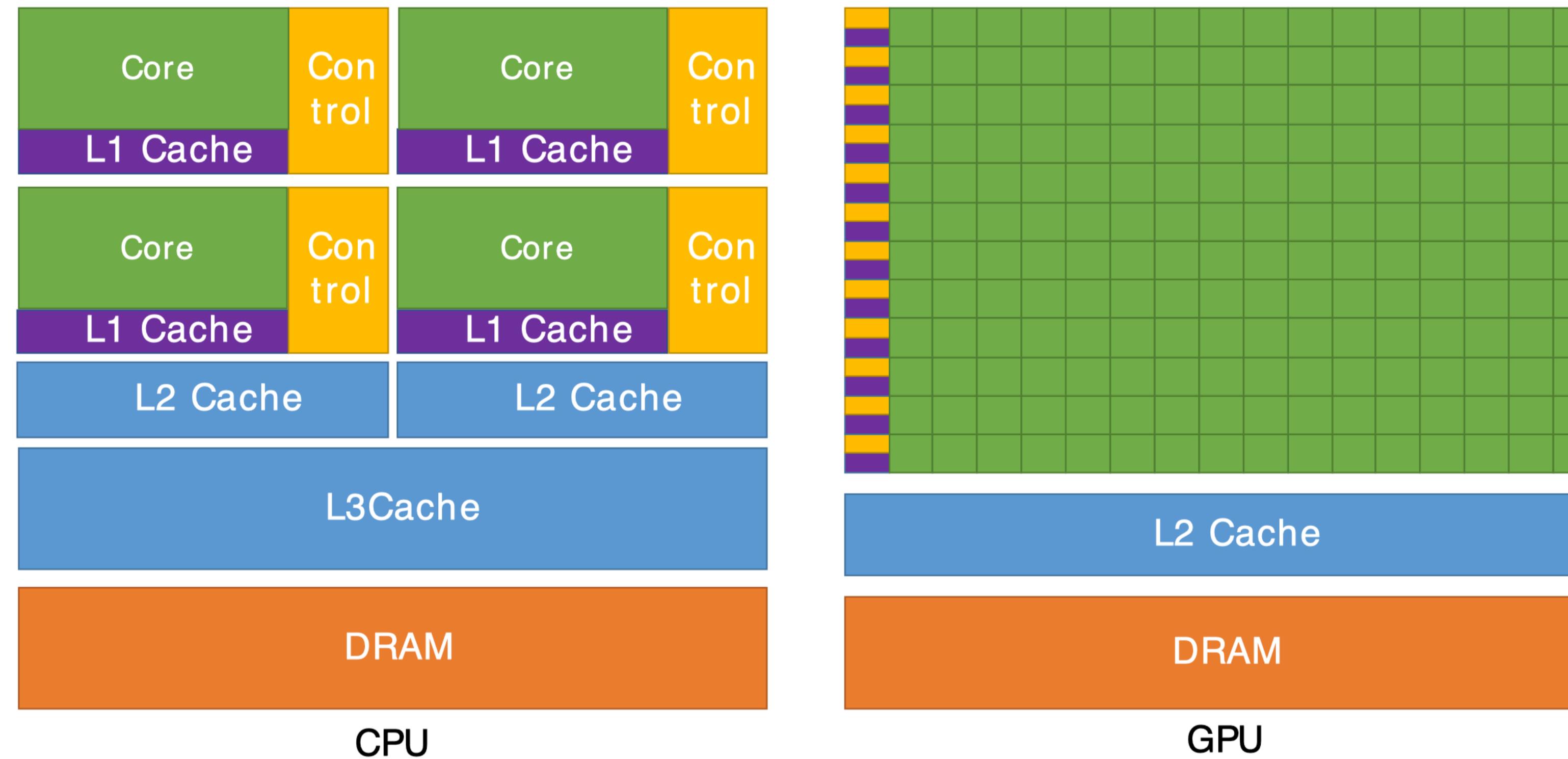
- **Dense linear algebra** with a massive amount of flops
- **Partial differential equation solvers:** finite-difference and regular grid calculations
- **Deep neural networks.**

## Less suitable for:

- **Irregular** calculations with branching and uneven workloads
- Long series of **sequential** operations

**What does a GPU processor look  
like?**

# Schematic organization



The GPU devotes more transistors to data processing.

# GH100 (Hopper) with 144 Streaming Multiprocessors (SM)



NVLink allows GPU processors to communicate without using the CPU

# GH100 Streaming Multiprocessor (SM)

- *Special Functions Units (SFUs):* execute transcendental instructions such as sin, cosine, reciprocal, and square root.
- *Dispatch Unit:* instruction dispatch



# **How to program GPUs**

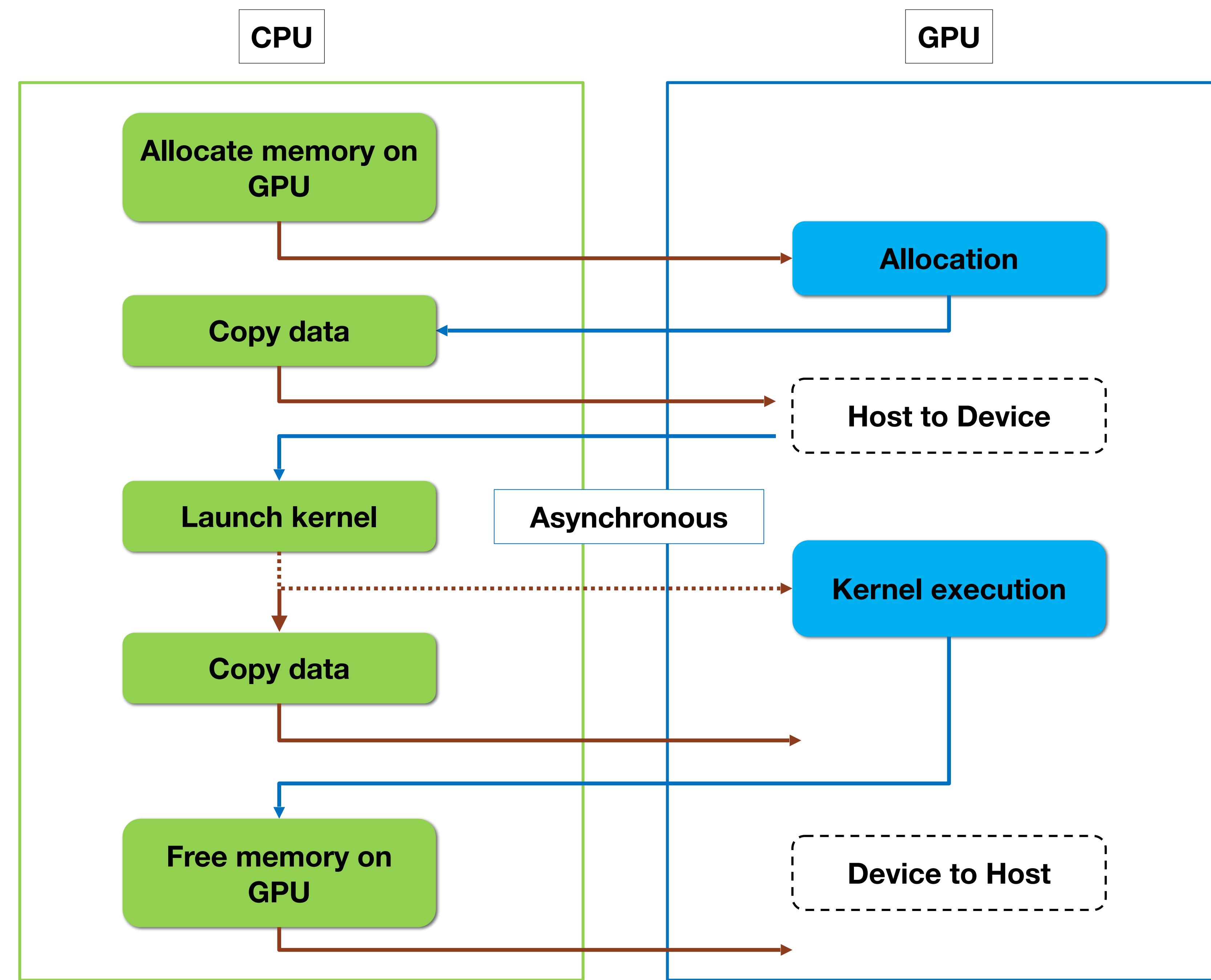
## **Introduction**

# GPU processors are co-processors

---

- GPUs are different from conventional processors.
- They only work as co-processors.
- This means you need a host processor (e.g., Intel Core/Xeon).

- Your program runs on the host and uses an application programming interface (API) to move data back and forth to the GPU and run programs on the GPU.
- You cannot log on to the GPU directly or run an OS on the GPU.



# OpenACC

---

- OpenMP can be used to program GPUs, but this is a recent, less robust addition to the language.
- Support is currently somewhat limited.
- We will cover instead **OpenACC**, which was designed from the beginning to program GPUs.
- OpenACC = OpenMP for **accelerator** processor.

# Other programming solutions

---

## **Vendor agnostic:**

- OpenCL
- Numba

## **Vendor specific:**

- CUDA
- HIP

# OpenCL

---

- OpenCL: Open Computing Language
- Framework for writing programs that execute across heterogeneous platforms, e.g., GPUs, digital signal processors (DSPs)
- OpenCL provides a standard interface for parallel computing using task- and data-based parallelism.
- OpenCL is an open standard maintained by the non-profit technology consortium Khronos Group.

# Python

---

Python has extensions that allow generating GPU code.

Example: **Numba**



# Numba

---

Many uses.

Just-in-time compilation of Python code for performance:

```
from numba import jit
import random

@jit(nopython=True)
def monte_carlo_pi(nsamples):
    acc = 0
    for i in range(nsamples):
        x = random.random()
        y = random.random()
        if (x ** 2 + y ** 2) < 1.0:
            acc += 1
    return 4.0 * acc / nsamples
```

# Numba multi-threaded programming

---

Example of **parallel** for loop in Numba:

```
@jit(nopython=True, parallel=True)
def simulator(out):
    # iterate loop in parallel
    for i in prange(out.shape[0]):
        out[i] = run_sim()
```

# Numba for NVIDIA GPUs (CUDA)

---

```
from numba import cuda, float32

@cuda.jit
def matmul(A, B, C):
    i, j = cuda.grid(2)
    if i < C.shape[0] and j < C.shape[1]:
        tmp = 0.
        for k in range(A.shape[1]):
            tmp += A[i, k] * B[k, j]
        C[i, j] = tmp
```

# Numba for AMD ROC GPUs

---

```
from numba import roc, float32

@roc.jit
def matmul(A, B, C):
    i = roc.get_global_id(0)
    j = roc.get_global_id(1)
    if i < C.shape[0] and j < C.shape[1]:
        tmp = 0.
        for k in range(A.shape[1]):
            tmp += A[i, k] * B[k, j]
        C[i, j] = tmp
```

# **Vendor specific solutions**

# NVIDIA CUDA

---

- Currently, the standard for writing GPU code.
- It only targets **NVIDIA GPU**.
- **Very mature and robust.**
- But **complex** to use and requires significant code changes
- Initial release: June 23, 2007 (14 years ago)

# AMD GPUs

---

- AMD has a proprietary language for programming its GPUs called **HIP**.
- HIP can generate code for AMD and NVIDIA GPUs.
- HIP is close to CUDA.
- HIP is designed to allow developers to convert CUDA code easily.
- Part of the open-source **ROCM** stack.

**Let's get started with OpenACC**

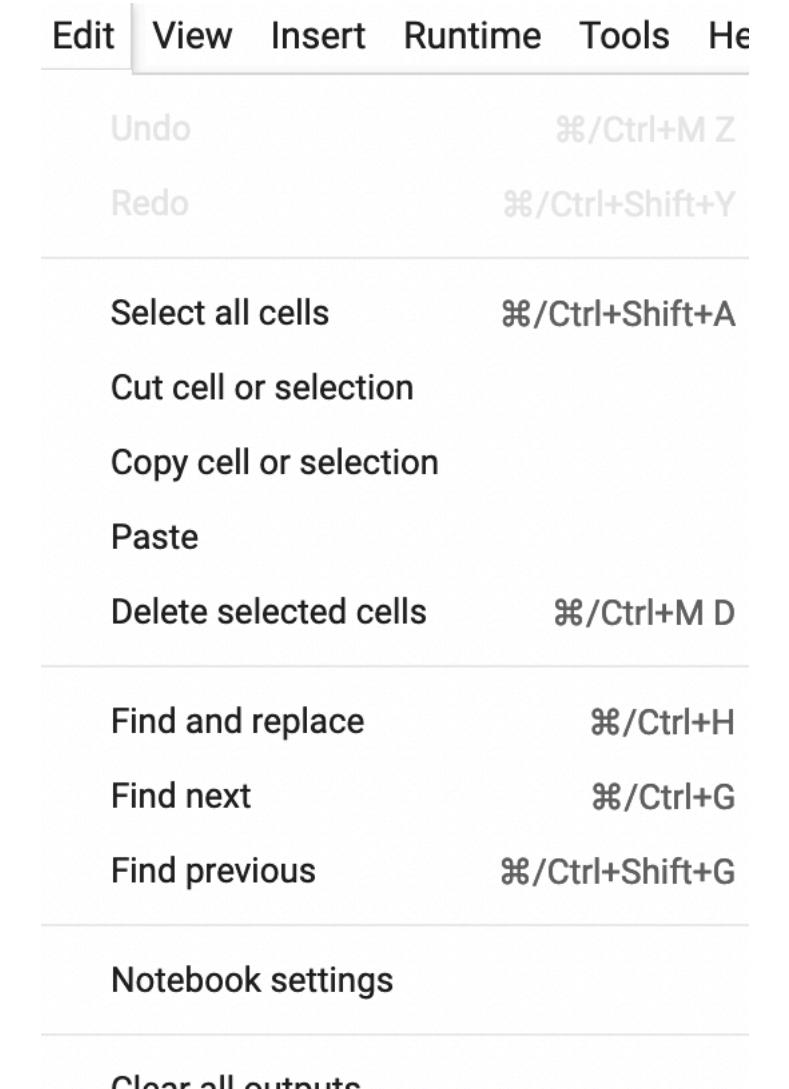
# GPU access

First, you will need a GPU!

Go to: [Notebook settings](#)

Then select GPU under Hardware accelerator

Demo: openacc\_lab.ipynb



## Notebook settings

### Hardware accelerator

GPU

To get the most out of Colab, avoid using a GPU unless you need one. [Learn more](#)

Background execution

Want your notebook to keep running even after you close your browser? [Upgrade to Colab Pro+](#)

Omit code cell output when saving this notebook

Cancel

Save

# Hardware

---

You should be able to test which GPU you have access to:

```
[2]  1 !nvidia-smi --query-gpu=gpu_name,gpu_bus_id,vbios_version --format=csv  
  
name, pci.bus_id, vbios_version  
Tesla T4, 00000000:00:04.0, 90.04.A7.00.01
```

Demo: openacc\_lab.ipynb

# Installation

---

You will need to install the NVIDIA HPC SDK, which contains the OpenACC compiler and can generate code for NVIDIA GPUs.

Run the cells at the beginning of the notebook to install:

1. `install_hpc.sh` installs the NVIDIA HPC SDK
2. `install_gtest.sh` installs Google Test

The installation takes a few minutes.

# Our first GPU parallel loop

Very similar to OpenMP (at least in appearance)

```
const int n = 32000000;
float* x = new float[n];
```

**Offloads to GPU**

```
#pragma acc parallel loop
for (int i = 0; i < n; ++i) x[i] = i;
```

```
for (int i = 0; i < n; ++i) ASSERT_EQ(x[i], float(i));
```

Demo: openacc\_lab.ipynb

# Let's see what the compiler says

---

```
acc_lab.cpp:  
accTest_loop_Test::TestBody():  
    7, Generating NVIDIA GPU code  
        10, #pragma acc loop gang, vector(128) /* blockIdx.x threadIdx.x */  
    7, Generating implicit copyout(x[:3200000]) [if not already present]
```

What are these messages saying?

Let's focus on gang/vector first.

# Gang, worker, vector

---

This is less important for us.

These variables are used because they reflect the way the hardware is organized.

**Thread:** smallest execution unit in the program.

# Gang, worker, vector

---

**Vector:** a group of threads that can coordinate and execute “together.”

*Worker: a group of vectors that can coordinate and execute “together;” this is a less important concept.*

**Gang:** a group of workers/vectors.

# Gang, worker, vector

---

For optimization purposes, the sizes of a vector, worker, or gang can be specified.

**This is a more advanced optimization.**

```
#pragma acc parallel loop num_gangs(40) num_workers(32) vector_length(32)
for (int i = 0; i < n; ++i) x[i] = i;
```

```
accTest_vector_loop_Test::TestBody():
    37, Generating NVIDIA GPU code
        40, #pragma acc loop gang(40), worker(32), vector(32) /* blockIdx.x threadIdx.y threadIdx.x */
    37, Generating implicit copyout(x[:3200000]) [if not already present]
```

# CPU and GPU memories

---

- The memory of the CPU and the GPU are physically **separate**.
- So data need to be transferred between the two memories before a calculation can be run on the GPU.
- In this case, the compiler detected that  $x$  was initialized on the GPU.
- It automatically generated instructions to copy the result from the GPU to the CPU memory.

# Data transfer clauses

```
#pragma acc parallel loop copyout(x[:n])
for (int i = 0; i < n; ++i) x[i] = i;
```

Clause	Description
copy	create space, initialize by copying to the device, copy back to host at the end, release device memory
copyin	same but without copy back to host
copyout	same but without initial copy to the device
create	create space at the beginning, release at the end
present	no action taken

# Array shaping

---

```
#pragma acc parallel loop copyout(x[:n])
```

```
x[:n]
```

- `copy(array[starting_index:length])`
- The first number is the **start index** of the array.
- The second number is **how much data** is to be transferred.

Demo: openacc\_lab.ipynb

# Data locality

---

- (x,y) initialization
- Vector z computation

```
for (int i = 0; i < n; ++i) {  
    x[i] = i;  
    y[i] = i * i;  
}  
for (int i = 0; i < n; ++i) {  
    ASSERT_EQ(x[i], float(i));  
    ASSERT_EQ(y[i], float(i * i));  
}  
for (int i = 0; i < n; ++i) z[i] = x[i] + y[i];  
for (int i = 0; i < n; ++i) ASSERT_EQ(z[i], float(i * (i + 1)));
```

Demo: openacc\_lab.ipynb

# Data transfer

---

By default, the code would:

- Copy  $(x,y)$  to the device.
- Copy them back to the host for testing.
- Copy  $(x,y)$  again to the device.
- Copy  $z$  to the host.

**The copies of  $(x,y)$  can be optimized.**

# acc enter data

---

```
#pragma acc enter data create(x[:n], y[:n])
#pragma acc parallel loop
  for (int i = 0; i < n; ++i) {
    x[i] = i;
    y[i] = i * i;
}
```

enter data create

- creates the data on the GPU and leaves it there until instructed to delete the data.

# acc update self

---

```
#pragma acc update self(x[:n], y[:n])
for (int i = 0; i < n; ++i) {
    ASSERT_EQ(x[i], float(i));
    ASSERT_EQ(y[i], float(i * i));
}
```

- Because we used `enter data create`, the data is not automatically copied back to the host.
- We need to add `update self` to copy the data from device to host.
- Also `#pragma acc update device()`

# acc exit data

---

```
#pragma acc exit data delete(x[:n], y[:n])
```

This deletes the data on the GPU and frees resources.

Each enter must be matched with an exit.

# Full code

---

```
#pragma acc enter data create(x[:n], y[:n])
#pragma acc parallel loop
for (int i = 0; i < n; ++i) {
    x[i] = i;
    y[i] = i * i;
}

#pragma acc update self(x[:n], y[:n])
for (int i = 0; i < n; ++i) {
    ASSERT_EQ(x[i], float(i));
    ASSERT_EQ(y[i], float(i * i));
}

#pragma acc parallel loop copyout(z[:n])
for (int i = 0; i < n; ++i) z[i] = x[i] + y[i];

#pragma acc exit data delete (x[:n], y[:n])

for (int i = 0; i < n; ++i) ASSERT_EQ(z[i], float(i * (i + 1)));
```

# Reduction

---

As in OpenMP, we need to use a special construct when we have a reduction.

```
sum += x[i];
```

Otherwise, the different cores will attempt to access and modify sum at the same time, **which is a bug.**

# Reduction example

---

```
float sum = 0;
#pragma acc data create(x[:n])
{
#pragma acc parallel loop
    for (int i = 0; i < n; ++i) x[i] = 1;
#pragma acc parallel loop reduction(+: sum)
    for (int i = 0; i < n; ++i) sum += x[i];
}
for (int i = 0; i < n; ++i) ASSERT_EQ(sum, float(n));
```

Note the data create to avoid unnecessary copies.

# collapse

---

- GPU are massively parallel processors.
- They can contain thousands of cores.
- Example: GeForce RTX 3090 Ti: **10,752 cores.**
- So we need to generate as much concurrency (parallelism) in our code.
- **Loop fusion** is critical for performance when the number of iterations is not large enough.

# for loop with collapse

---

```
#pragma acc parallel loop collapse(2)
  for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
      z[i * n + j] = x[i * n + j] + y[i * n + j];
    }
  }
```

- i and j loops will be merged and executed in parallel.
- Without collapse, only the i loop is parallelized while the j loop is executed sequentially.
- **collapse allows generating  $n*n$  parallel threads instead of just n.**
- This can potentially improve **performance** significantly.

# Complete example with collapse

```
#pragma acc enter data create(x[:n * n], y[:n * n])
#pragma acc parallel loop collapse(2)
for (int i = 0; i < n; ++i)
    for (int j = 0; j < n; ++j) {
        x[i * n + j] = i * n + j;
        y[i * n + j] = i - j;
    }

#pragma acc update self(x[:n * n], y[:n * n])
for (int i = 0; i < n * n; ++i) ASSERT_EQ(x[i], float(i));
for (int i = 0; i < n; ++i)
    for (int j = 0; j < n; ++j) ASSERT_EQ(y[i * n + j], float(i - j));

#pragma acc parallel loop collapse(2) copyout(z[:n * n])
for (int i = 0; i < n; ++i)
    for (int j = 0; j < n; ++j) z[i * n + j] = x[i * n + j] + y[i * n + j];

#pragma acc exit data delete(x[:n * n], y[:n * n])
for (int i = 0; i < n; ++i)
    for (int j = 0; j < n; ++j) ASSERT_EQ(z[i * n + j], float(i * (n + 1)));
```

# n body problem

---

Let's look at a more complex real-life application.

We want to model the gravitational interactions between n bodies with mass.

This is similar to modeling the motions of the planets around the sun in the solar system.

# Gravitational force

---

We start from  $F_i = m_i a_i$ .

The acceleration is given by the gravitational force:

$$F_i = m_i \sum_{j \neq i} m_j \frac{r_j - r_i}{\|r_j - r_i\|_2^3}$$

# Equations of motion

---

$$F_i = m_i \sum_{j \neq i} m_j \frac{r_j - r_i}{\|r_j - r_i\|_2^3}$$

Equations of motion:

$$\frac{d^2 r_i}{dt^2} = \sum_{j \neq i} m_j \frac{r_j - r_i}{\|r_j - r_i\|_2^3}$$

# Time integrator

---

- We numerically solve these equations using the **velocity Verlet** time integrator.
- It's not very accurate, but it is very stable over many time steps.
- This is a two-step method.

# Velocity Verlet

---

- **Step 1:** advance the velocity

$$\nu_i^{n+1} = \nu_i^n + \Delta t \sum_{j \neq i} m_j \frac{r_j - r_i}{\|r_j - r_i\|_2^3} \Big|_n$$

- **Step 2:** advance the position

$$r_i^{n+1} = r_i^n + \Delta t \nu_i^{n+1}$$

- **Repeat**

# Force computation

---

```
for (int i = 0; i < n; i++) {
    real fx, fy, fz; fx = fy = fz = 0;
    for (int j = 0; j < n; j++) {
        real3 ff = forceComputation(pos[i].x, pos[i].y, pos[i].z,
                                      pos[j].x, pos[j].y, pos[j].z, pos[j].w);
        fx += ff.x;
        fy += ff.y;
        fz += ff.z;
    }
    force[i].x = fx;
    force[i].y = fy;
    force[i].z = fz;
}
```

# Time step

---

```
for (int i = 0; i < n; i++) {  
    // acceleration = force / mass;  
    // new velocity = old velocity + acceleration * deltaTime  
    vel[i].x += force[i].x * dt;  
    vel[i].y += force[i].y * dt;  
    vel[i].z += force[i].z * dt;  
  
    // new position = old position + velocity * deltaTime  
    pos[i].x += vel[i].x * dt;  
    pos[i].y += vel[i].y * dt;  
    pos[i].z += vel[i].z * dt;  
}
```

# Time integration

---

```
for (int i = 0; i < iterations; i++) {  
    seqIntegrate(pos, vel, force, dt, n);  
}
```

# Parallel time stepping loop

---

```
#pragma acc data copy(pos[:n], vel[:n]) copyout(force[:n])
for (int i = 0; i < iterations; i++) {
    integrate(pos, vel, force, dt, n);
}
```

- Optimize the movement of data by **reducing memory copies between host and device.**
- Only done before the iterations start and after they are complete.

# Nested parallel loops with reduction

---

```
#pragma acc parallel loop
for (int i = 0; i < n; i++) {
    real fx, fy, fz;
    fx = fy = fz = 0;
#pragma acc loop reduction(+ : fx, fy, fz)
    for (int j = 0; j < n; j++) {
        real3 ff = forceComputation(pos[i].x, pos[i].y, pos[i].z, pos[j].x,
                                      pos[j].y, pos[j].z, pos[j].w);
        fx += ff.x;
        fy += ff.y;
        fz += ff.z;
    }
    force[i].x = fx;
    force[i].y = fy;
    force[i].z = fz;
}
```

# Parallel time step

---

```
#pragma acc parallel loop
for (int i = 0; i < n; i++) {
    vel[i].x += force[i].x * dt;
    vel[i].y += force[i].y * dt;
    vel[i].z += force[i].z * dt;
    pos[i].x += vel[i].x * dt;
    pos[i].y += vel[i].y * dt;
    pos[i].z += vel[i].z * dt;
}
```

# Performance results

```
1 !name=nbody; nvcc -I. -acc=host -O -o $name $name.cpp && ./$name 4096 20
2 !name=nbody; nvcc -I. -acc=multicore -O -o $name $name.cpp && ./$name 4096 20
3 !name=nbody; nvcc -I. -acc=gpu -O -o $name $name.cpp && ./$name 4096 20
4 !name=nbody; nvcc -I. -mp=multicore -O -o $name $name.cpp && ./$name 4096 20
5 !name=nbody; g++ -std=c++17 -I. -O -o $name $name.cpp && ./$name 4096 20
```

```
n = 4096 bodies for 20 iterations
OpenACC:      2185.000000 ms: 3.071344 GFLOP/s
Sequential:   2206.000000 ms: 3.042106 GFLOP/s
n = 4096 bodies for 20 iterations
OpenACC:      1959.000000 ms: 3.425669 GFLOP/s
Sequential:   2197.000000 ms: 3.054568 GFLOP/s
n = 4096 bodies for 20 iterations
OpenACC:      380.000000 ms: 17.660228 GFLOP/s
Sequential:   2155.000000 ms: 3.114100 GFLOP/s
n = 4096 bodies for 20 iterations
OpenMP:        2197.000000 ms: 3.054568 GFLOP/s
Sequential:   2169.000000 ms: 3.094000 GFLOP/s
n = 4096 bodies for 20 iterations
C++:          4257.000000 ms: 1.576436 GFLOP/s
Sequential:   4257.000000 ms: 1.576436 GFLOP/s
```

We only use a **single CPU thread** on Google compute.

```
1 !name=test_nbody; nvc++ -I. -acc=gpu -o $name $name.cpp gtest_main.a && ./$name
```

```
test_nbody.cpp:  
Running main() from googletest-main/googletest/src/gtest_main.cc  
[=====] Running 5 tests from 1 test suite.  
[-----] Global test environment set-up.  
[-----] 5 tests from nbodyTest  
[ RUN ] nbodyTest.iterations_small_0  
8 tests PASSED. Maximum error = 0.  
6 tests PASSED. Maximum error = 0.  
6 tests PASSED. Maximum error = 0.  
[ OK ] nbodyTest.iterations_small_0 (259 ms)  
[ RUN ] nbodyTest.iterations_small_1  
128 tests PASSED. Maximum error = 1.13687e-13.  
96 tests PASSED. Maximum error = 9.31323e-10.  
96 tests PASSED. Maximum error = 7.45058e-09.  
[ OK ] nbodyTest.iterations_small_1 (0 ms)  
[ RUN ] nbodyTest.iterations_medium_0  
4096 tests PASSED. Maximum error = 2.27374e-13.  
3072 tests PASSED. Maximum error = 1.49012e-08.  
3072 tests PASSED. Maximum error = 1.49012e-07.  
[ OK ] nbodyTest.iterations_medium_0 (14 ms)  
[ RUN ] nbodyTest.iterations_medium_1  
4096 tests PASSED. Maximum error = 4.76837e-07.  
3072 tests PASSED. Maximum error = 3.8147e-06.  
3072 tests PASSED. Maximum error = 1.22935e-07.  
[ OK ] nbodyTest.iterations_medium_1 (32 ms)  
[ RUN ] nbodyTest.iterations_large  
16384 tests PASSED. Maximum error = 5.96046e-07.  
12288 tests PASSED. Maximum error = 3.8147e-06.  
12288 tests PASSED. Maximum error = 4.02331e-07.  
[ OK ] nbodyTest.iterations_large (457 ms)  
[-----] 5 tests from nbodyTest (764 ms total)  
  
[-----] Global test environment tear-down  
[=====] 5 tests from 1 test suite ran. (764 ms total)  
[ PASSED ] 5 tests.
```

# Accuracy

## Roundoff errors between CPU and GPU in single precision

*We hope you enjoyed this workshop!*

