# Lecture 1: Introduction to Heterogeneous Programming

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# Logistics

- **Instructor: Dr. Tsung-Wei Huang (TW)**
  - tsung-wei.huang@utah.edu
  - MEB 2124
- **Time: MoWe / 1:25 PM – 2:45 PM (excluding holidays)**
  - In-person room: WEB L110
  - Zoom: https://utah.zoom.us/j/2468214418
- **Webpage**
  - GitHub: https://github.com/tsung-wei-huang/ece6960-heterogeneous-programming
- **Office hour: by appointment**

# Scoring

- **Total 100 points**
  - Four programming assignments of heterogeneous algorithms
  - A final project plus presentation
- **Academic integrity**
  - You should always finish assignments by yourself!
  - I trust you but don't take it for granted (it's your career not mine…)
  - https://regulations.utah.edu/academics/6-400.php
  - In the past, I usually give everyone "A" as long as you did something
- **Textbook**
  - No need to buy any textbook
  - Slides will be available and are enough

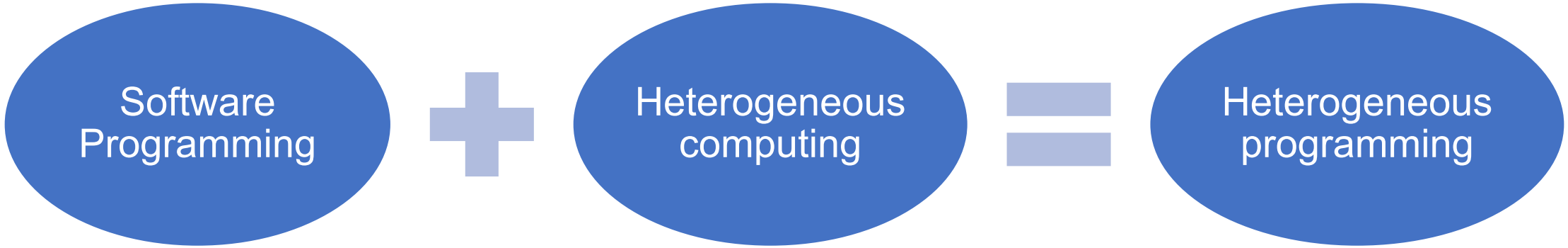
# Class Philosophy

- **Learn to program massively parallel processors to get**
  - High performance
  - Functionality and maintainability
  - Scalability across future generations
  - **With a lot of hands-on programming experience**
- **Technical subjects**
  - Parallel programming basics
  - Principles and patterns of parallel algorithms
  - Programming API, tools and techniques
  - Processor architecture features and constraints
  - Killer apps

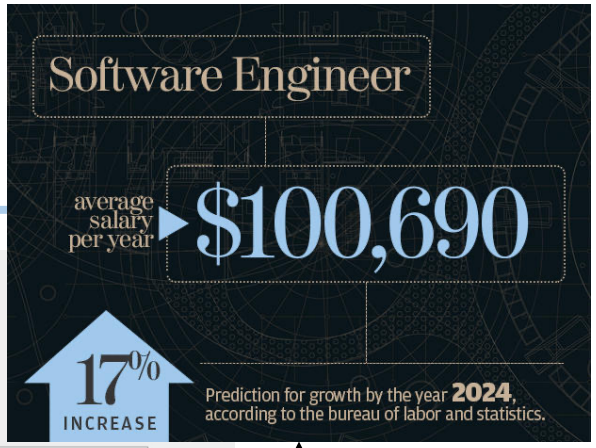
# Programming Machines

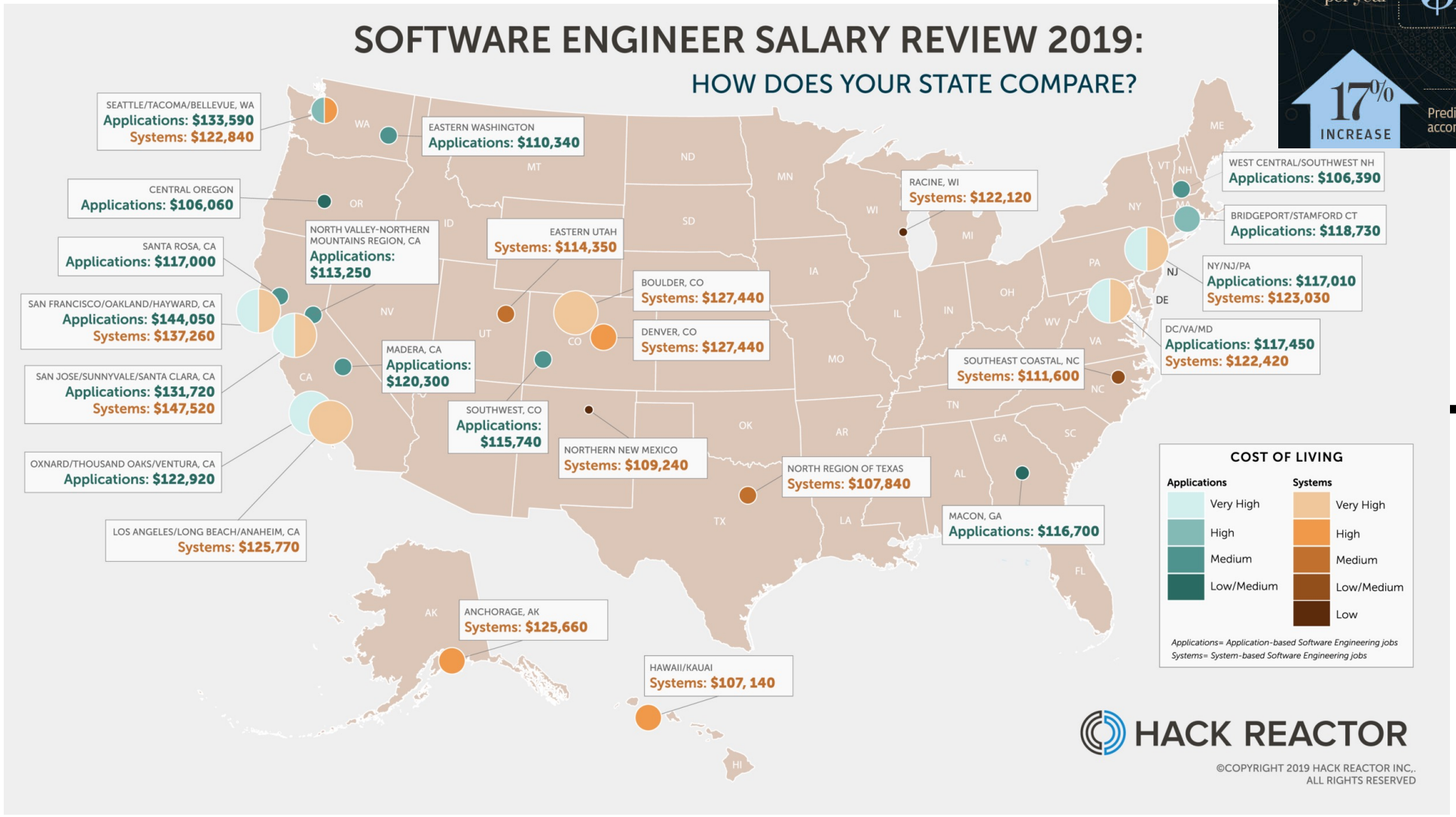
- **Linux programming environment**
  - Utah CADE Linux machine: https://www.cade.utah.edu/
  - Your personal MacBook, Linux desktop, etc.
- **Evaluation environment**
  - Instructor's server: twhuang-server-01.ece.utah.edu
    - 80 CPU threads (hyperthreading)
    - 4 GPUs
  - We will assign everyone an account for programming assignments
- **Programming languages**
  - C and C++
  - Python (a little bit)

# Heterogeneous Programming Concept



# Why Programming…?



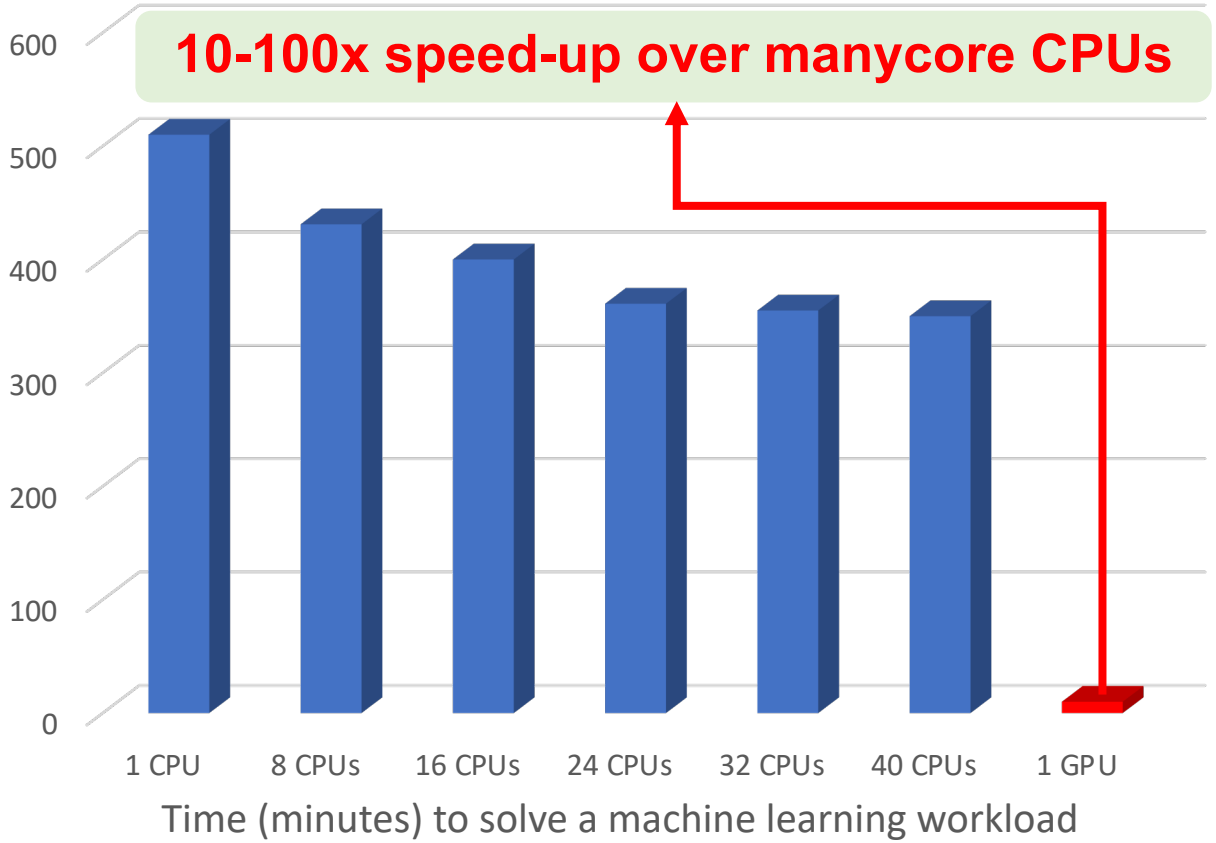
# WHICH PROGRAMMING LANGUAGE TO LEARN FIRST?

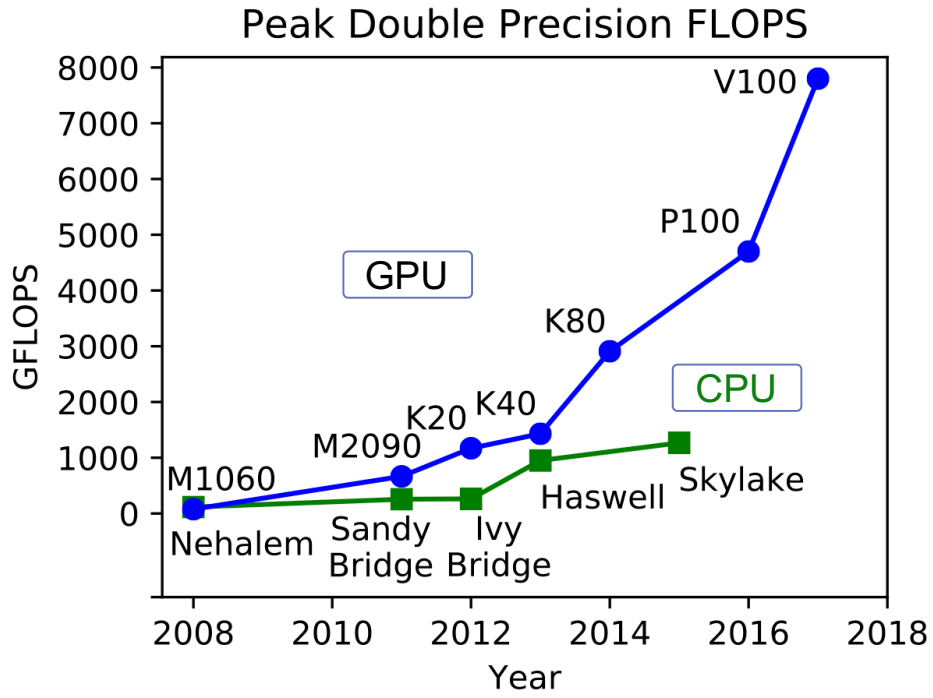
# My 10-year Programming Perspective

- **In general, your logic thinking matters the most**
  - How to formulate a problem computationally?
  - How to solve a computational problem efficiently?
  - How to improve the solution quality programmatically?
- **However, as a CE/CS student, I highly recommend C++**
  - C/C++ let you know how performance works
    - Software design patterns
    - Computer hardware and memory hierarchies
  - Python let you know how productivity works
  - Java let you know how portability works

# Why Heterogeneous Computing (HC)?

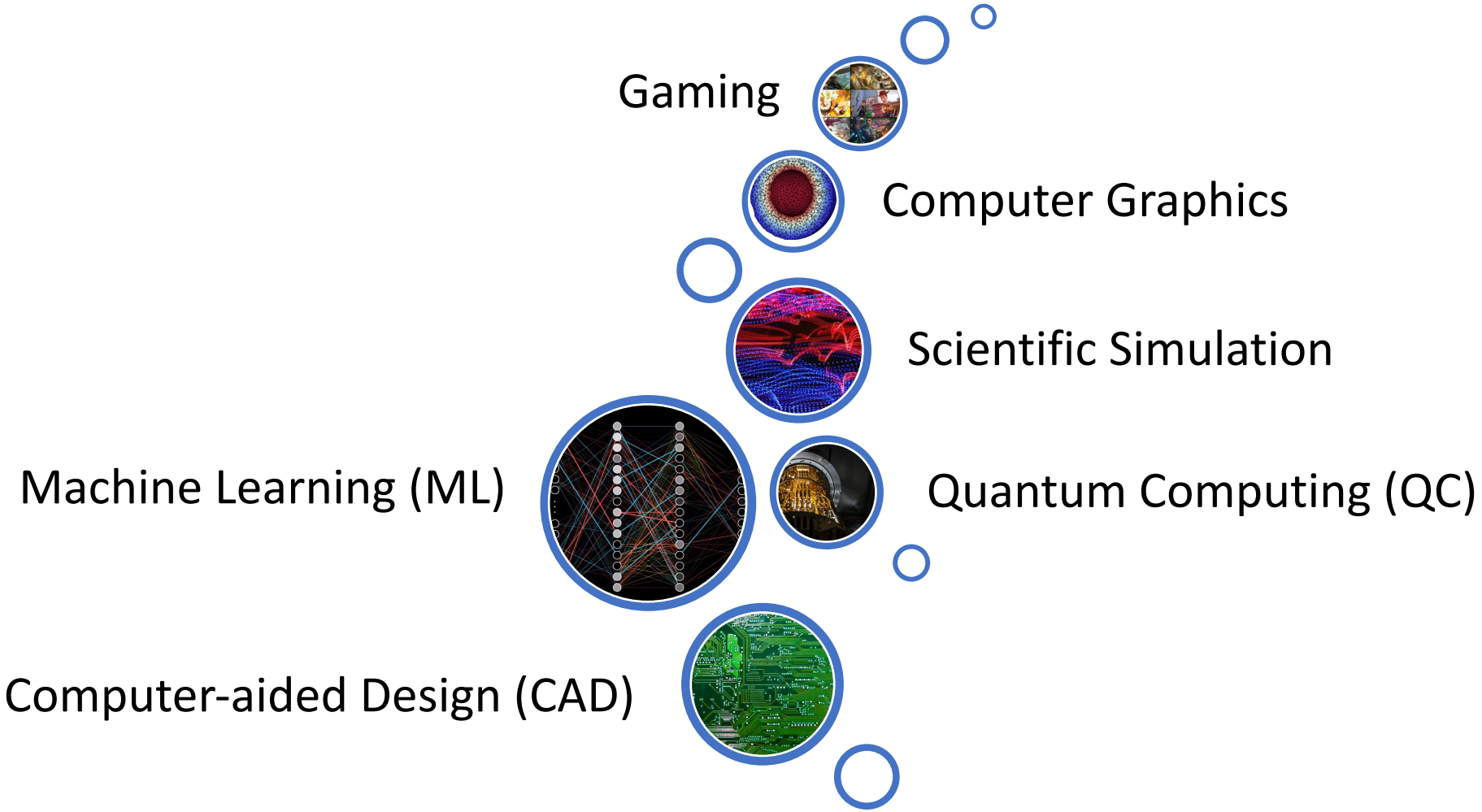
- **Advances performance to a new level previously out of reach**




Over **60x** speedup in neural network training since 2013

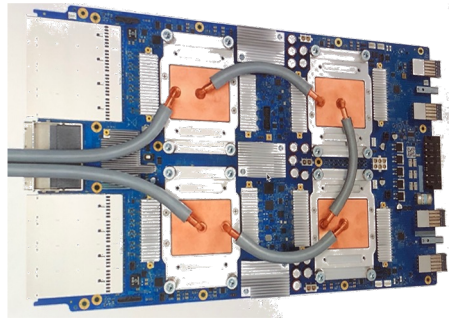
# HC Enabled Vast Success in Computing



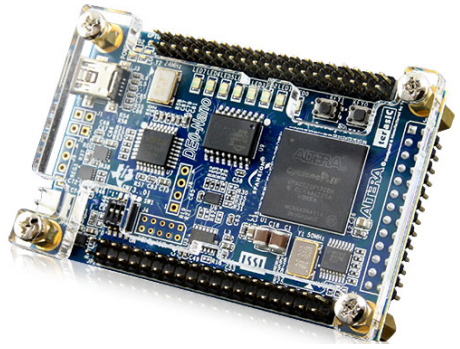
# Increasing Heterogeneity in Computers …


Central Processing Unit (CPU)

Graphics Processing Unit (GPU)



Tensor Processing Unit (TPU)



FPGA


Neuromorphic Devices

Quantum Accelerator

The future of computing is heterogeneous – *DARPA ERI, DOE ASCR, NSF PPoSS, SRC Jump 2.0, etc*.

# Old Paradigm

**We were able to understand, design, and manufacture what we can measure**

- Physical instruments allowed us to see farther, capture more, communicate better, understand natural processes, control artificial processes…

# New Paradigm

**We are able to understand, design, and create what we can compute**

- Computational models are allowing us to see even farther, going back and forth in time, learn better, test hypothesis that cannot be verified any other way, create safe artificial processes…

# Example: Old Paradigm

# New Paradigm

# Examples of Paradigm Shift

- Semiconductor Lithography → Computational correction
- Electron Microscopy → Computational Microscopy
- Film Photography → Deep-learning driven imaging
- X-Rays → CT & MRI Scans with reconstruction
- Land-line phones → Zoom video conferencing
- Cars → Self-driving electric taxis
- Print and Broadcast Ads → AI-assisted Digital Ad Placement

- **So, why is this happening now?**

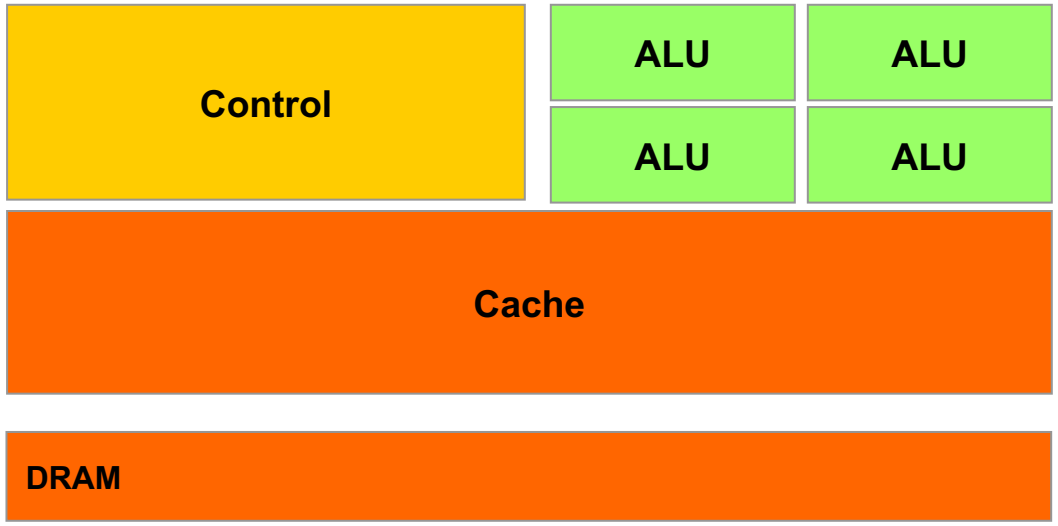
# Today's Computer Architecture

- Multiple cores with more moderate clock frequencies
- Heavy use of threading, vector execution
- Systems-on-a-chip with latency-oriented cores, throughput-oriented cores, and specialized cores
- 3D packaging for more memory bandwidth

- **It's all because of performance need!**

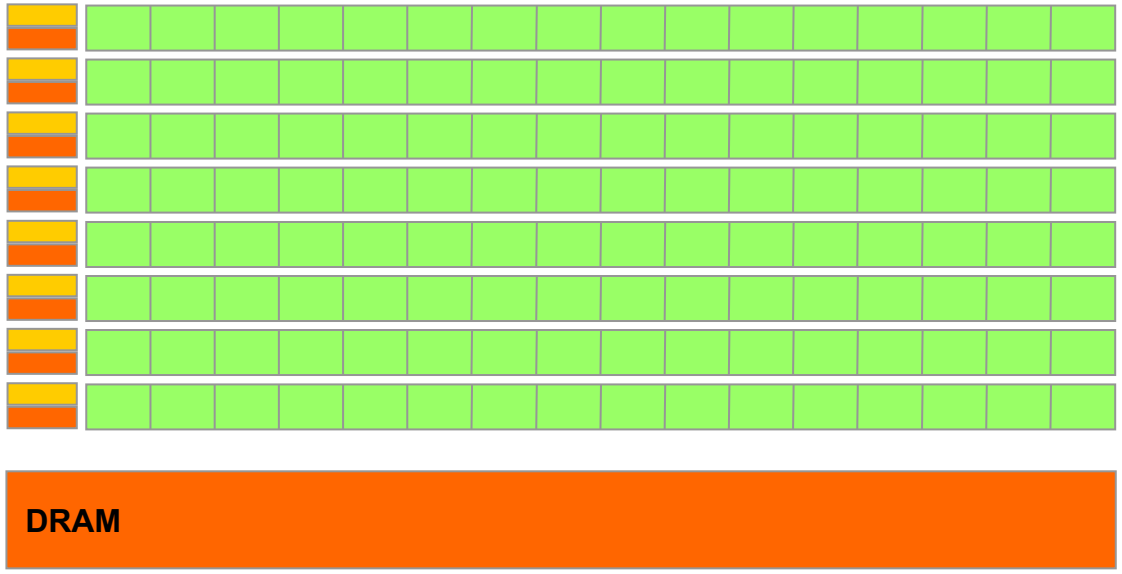
# CPU: Latency Oriented Design

- **High clock frequency**
- **Large caches**
  - Convert long latency memory accesses to short latency cache accesses
- **Sophisticated control**
  - Branch prediction for reduced branch latency
  - Data forwarding for reduced data latency
- **Powerful ALU**
  - Reduced operation latency



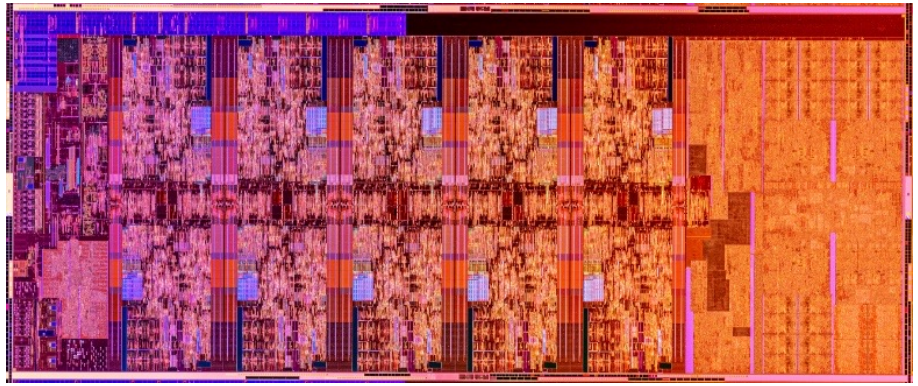
# GPU: Throughput Oriented Design

- **Moderate clock frequency**
- **Small caches**
  - To boost memory throughput
- **Simple control**
  - No branch prediction
  - No data forwarding
- **Energy efficient ALUs**
  - Many, long latency but heavily pipelined for high throughput
- Require massive number of threads to tolerate latencies

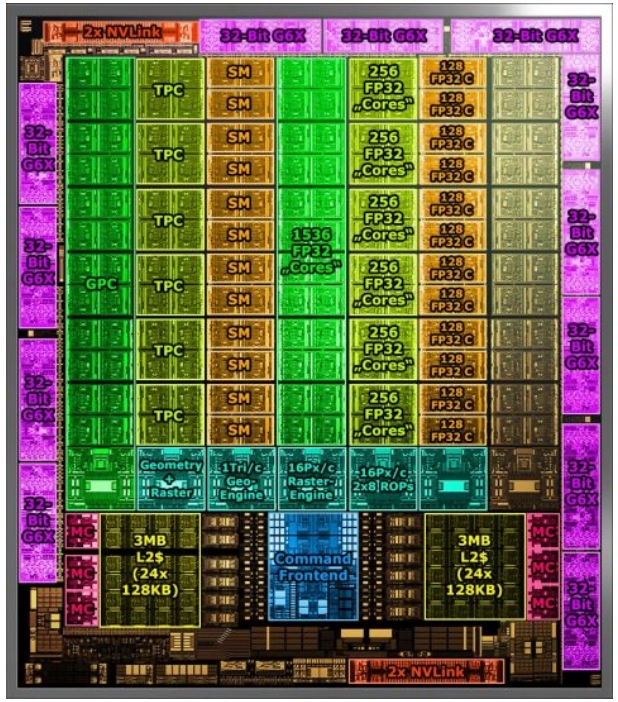


# CPU vs GPU

- 10th Gen Intel Core
  - 10 cores in silicon
  - 14 nm process

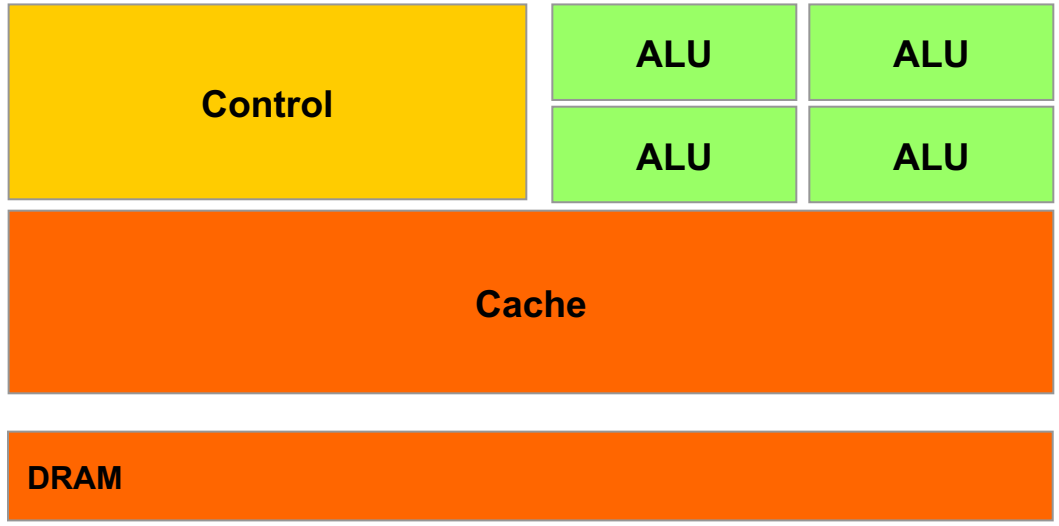


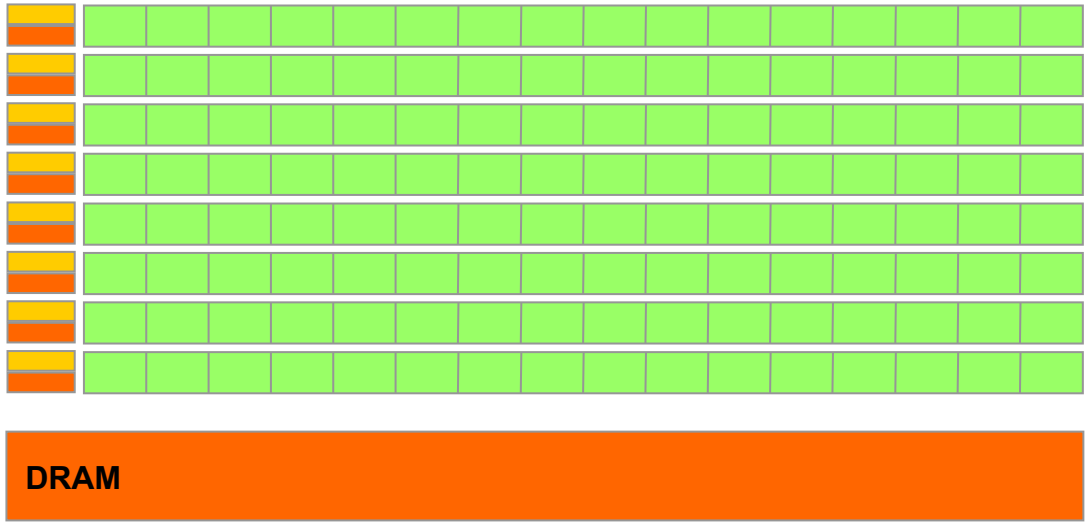
- NVIDIA A100
  - 3456 CUDA cores
  - 7 nm process



# Today's Heterogeneous Programming

- CPUs for sequential parts where latency hurts
  - CPUs can be 10+X faster than GPUs for sequential code
- GPUs for parallel parts where throughput wins
  - GPUs can be 10+X faster than CPUs for parallel code



# Heterogeneous Computing Applications

| | | | |
|---|---|---|---|
| Financial Analysis | Scientific Simulation | Engineering Simulation | Data Analytics |
| Digital Audio Processing | Digital Video Processing | Computer Vision | Machine Learning |
| Biomedical Informatics | Statistical Modeling | Ray Tracing Rendering | Interactive Physics |
| Medical Imaging | Design Automation | Numerical Methods | … |

# Heterogeneous Programming Workflow

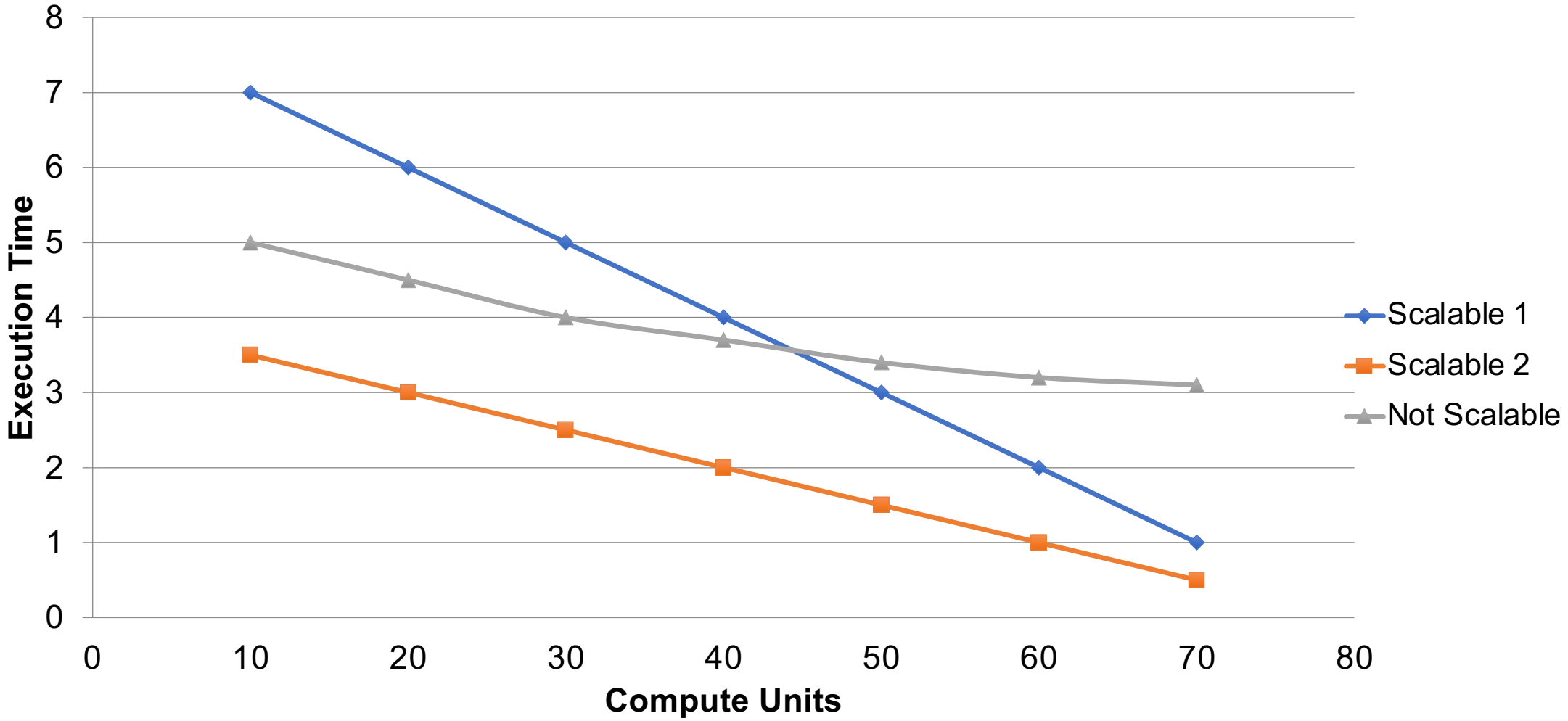
- Identify compute intensive parts of an application
- Adopt/create scalable algorithms
- Optimize data arrangements to maximize locality
- Performance tuning
- Pay attention to code **portability**, **scalability**, and **maintainability**

# Simple Parallelism

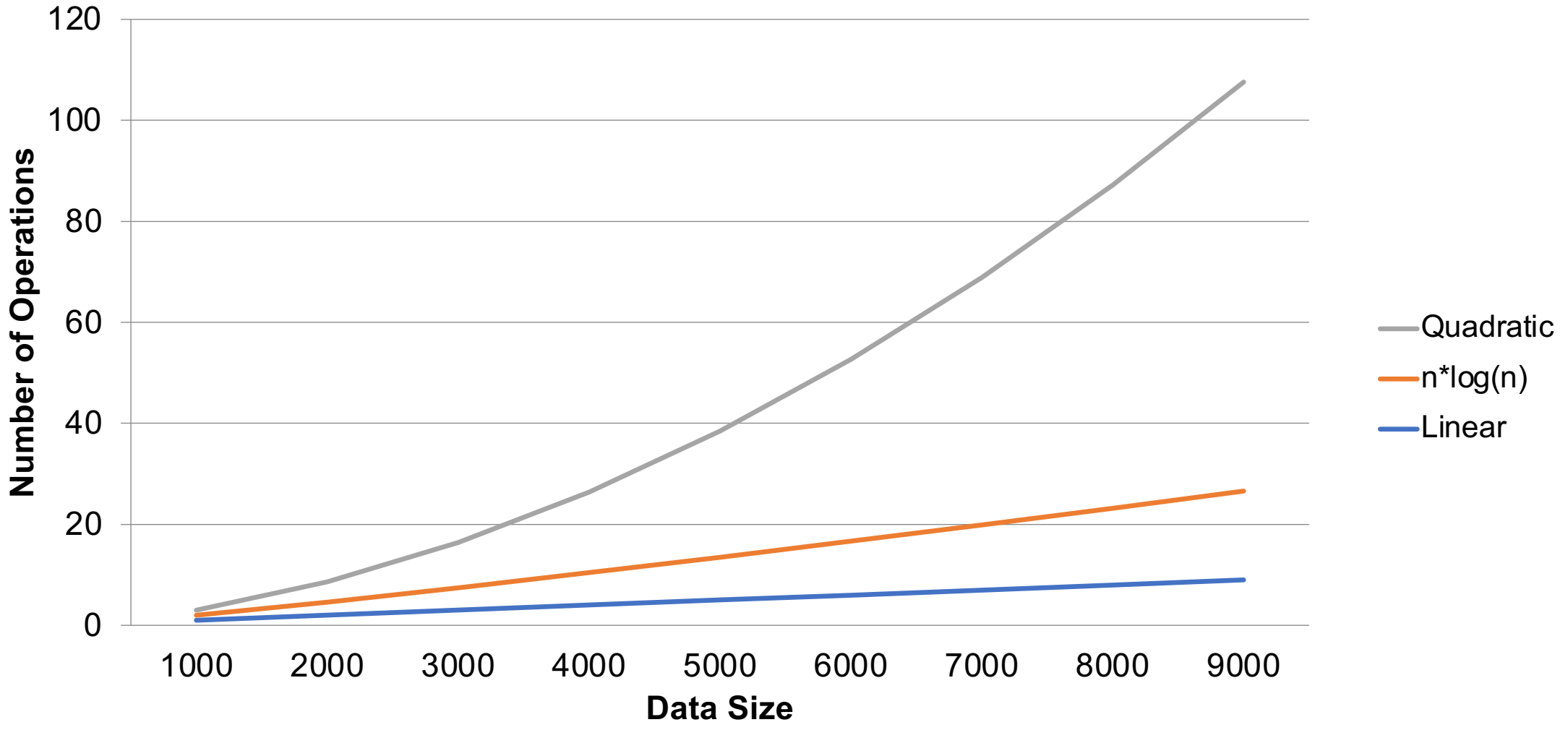
```
for (i = 0, i < n, i++) {
    C[i] = A[i] + B[i];
}
```

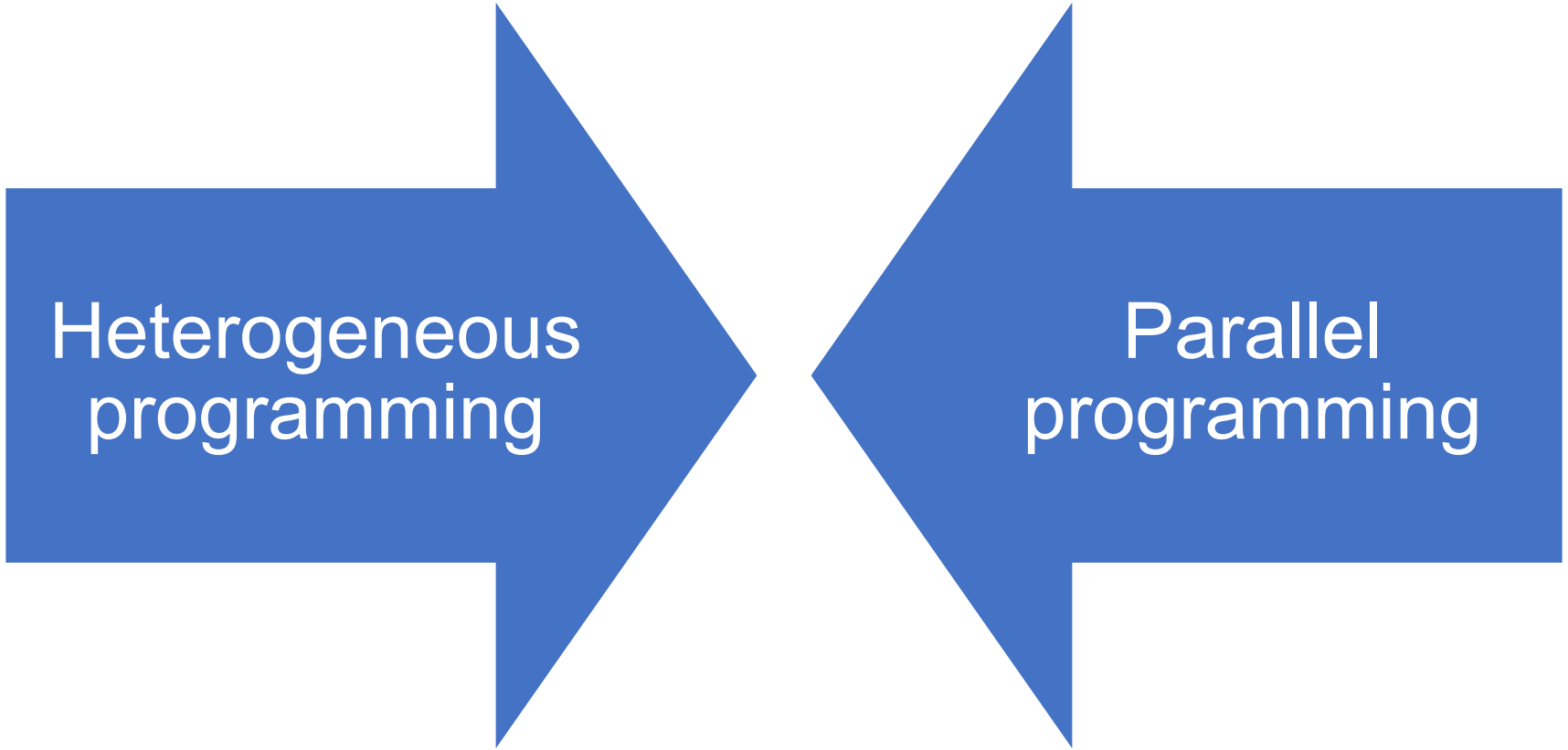
- Loop iterations are independent of each other (caveat: what about `i`?)
- We want to express this loop in a form where the parallelism can be converted into independent operations.
- This semester we will learn how to parallelize it …

# Parallelism Scalability



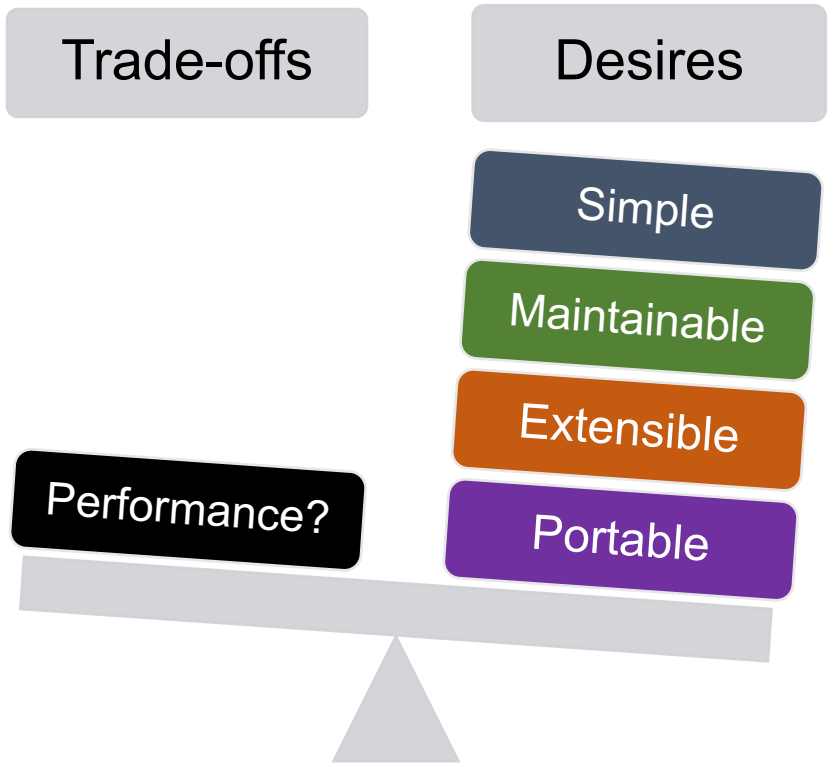
# Algorithm Complexity




Heterogeneous programming
Parallel programming

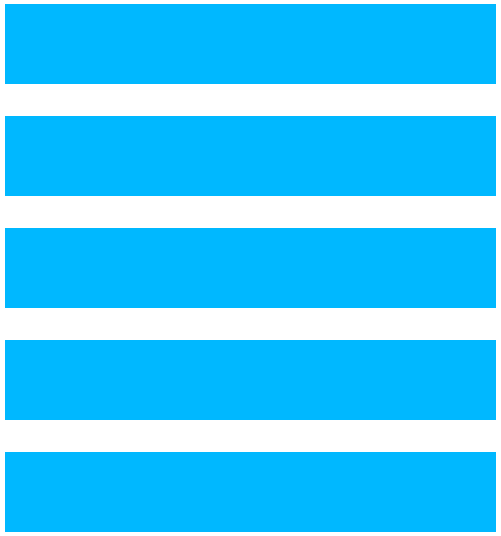
# Parallel Programming is a “Big” Challenge

- **You need to deal with A LOT OF technical details**
  - Parallelism abstraction (software + hardware)
  - Concurrency control
  - Task and data race avoidance
  - Dependency constraints
  - Scheduling efficiencies (load balancing)
  - Performance portability
  - …
- **And, don’t forget about trade-offs**
  - Desires vs Performance



# Load Balance

- The total amount of time to complete a parallel job is limited by the thread that takes the longest to finish



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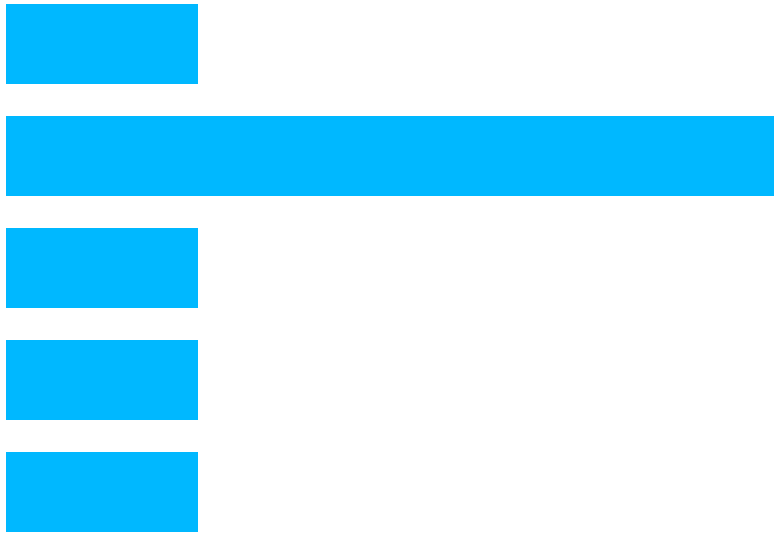

bad!

# Global Memory Bandwidth

- Ideal

- Reality

# Data Conflicts Cause Serialization

- Massively parallel execution cannot afford serialization


- Contentions in accessing critical data causes serialization

# Memory Optimization

```
std::string* ptr = nullptr;
int data = 0;

void producer()
{
    std::string* p  = new std::string("Hello");
    data = 42;
    ptr = p;
}

void consumer()
{
    std::string* p2;
    while (!(p2 = ptr));
    assert(*p2 == "Hello");
    assert(data == 42);
}

int main()
{
    producer();
    consumer();
}
```

```
std::string* ptr = nullptr;
int data = 0;

void producer()
{
    std::string* p  = new std::string("Hello");
    data = 42;
    ptr = p;
}

void consumer()
{
    std::string* p2;
    while (!(p2 = ptr));
    assert(*p2 == "Hello");
    assert(data == 42);
}

int main()
{
    std::thread t1(producer);
    std::thread t2(consumer);
    t1.join();
    t2.join();
}
```

# Summary

- **We have discussed class logistics**
- **We have discussed heterogeneous programming**
- **We have discussed application shift**
- **We have discussed modern computer architectures**
- **We have discussed scalability**
- **We have discussed three key challenges**
  - Memory bandwidth
  - Data conflicts
  - Memory optimization