CS 470 warm-up activity

- Introduce yourself to nearby classmates
- Work together as a group to answer the following questions:
  - Assume each computer in the room has at least four CPU cores (a reasonable assumption for computers <5 years old). How many cores do we have in this room total?
  - What is the world's largest and fastest supercomputer? Where is it located, and how many cores does it contain?

World's fastest supercomputer (2025)

- **El Capitan** *(at least according to the Top500 list)*
  - **Lawrence Livermore National Laboratory** (California)
  - 11,000+ nodes in 87+ racks taking up 7,500 sq. ft.
  - 43,808 4th Gen EPYC 24C 1.8GHz CPUs
  - 43,808 AMD Instinct MI300A APUs (each w/ 128G memory)
  - Total of **11,039,616 cores**!
  - Slingshot-11 interconnect w/ 12.8 Tbps bandwidth
  - TOSS (based on RHEL)
  - 1.7 Eflops max Linpack performance
  - 29.6 MW power consumption
  - Dedicated January 9, 2025

Sources:

- `top500.org`
- `llnl.gov`
- `nextplatform.com`

CS 470 Spring 2025

Mike Lam, Professor

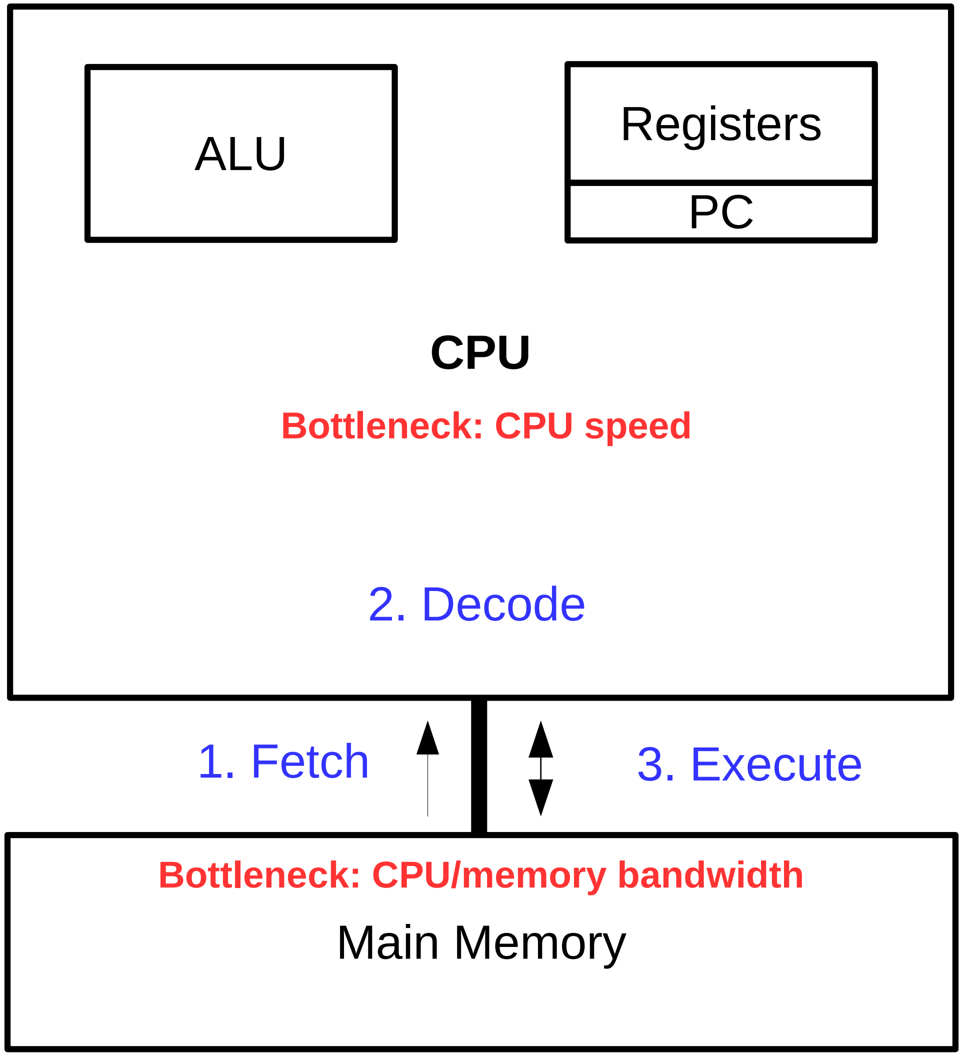
Parallel and Distributed Systems

Advanced System Elective

Motivation

- Why do we have (and why should we study) parallel and distributed systems?
- Let's go back to CS 261 …

von Neumann (CS 261)



History of parallelism

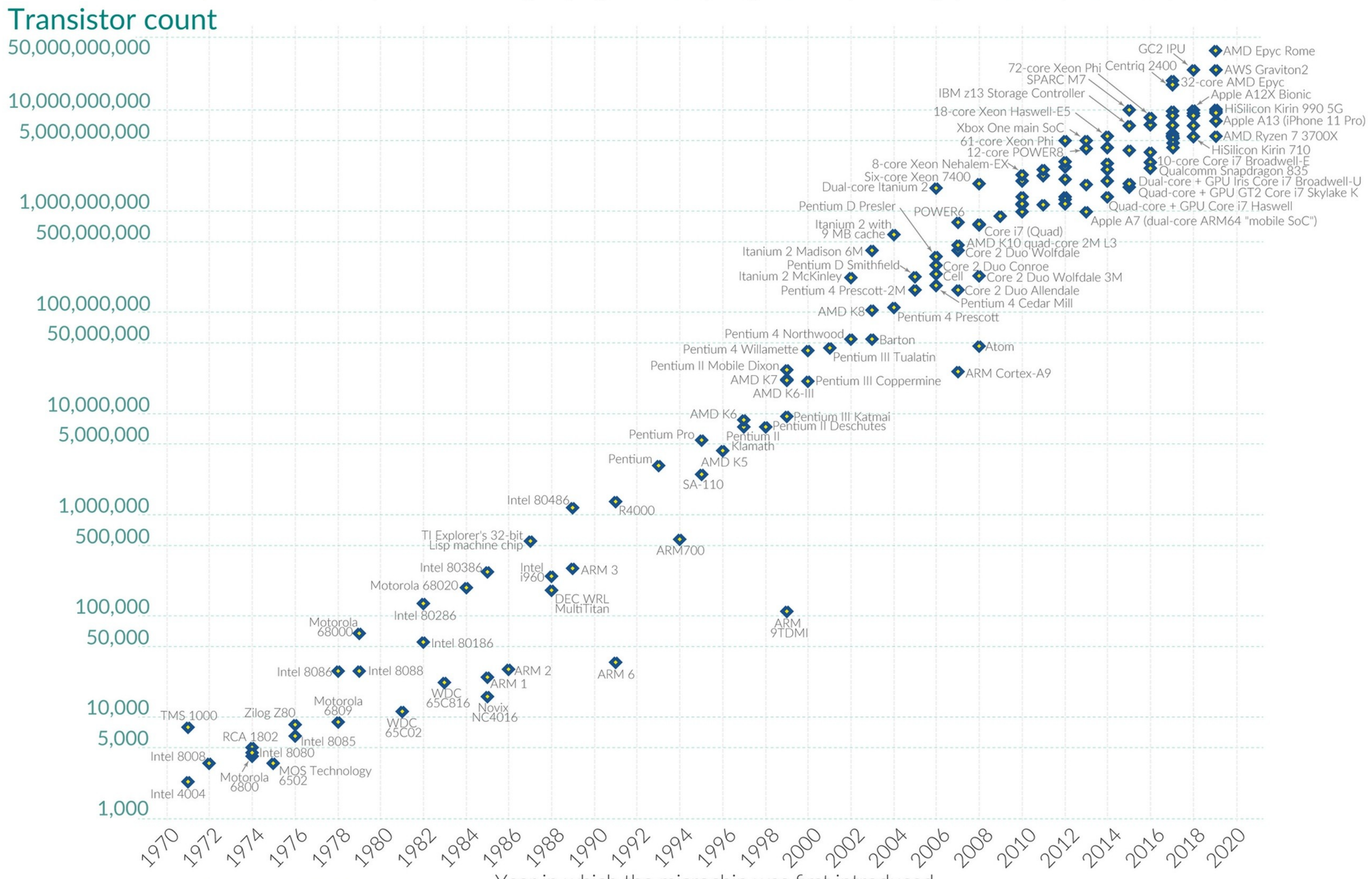
- Uniprogramming / batch (1950s)
  - Traditional von Neumann, no parallelism
- Multiprogramming / time sharing (1960s)
  - Increased utilization, lower response time
- Multiprocessing / shared memory (1970s)
  - Increased throughput, strong scaling
- Distributed computing / distributed memory (1980s)
  - Larger problems, weak scaling
- Hybrid computing / heterogeneous (2000s onward)
  - Energy-efficient strong/weak scaling

Moore’s Law

Moore’s Law: The number of transistors on microchips doubles every two years

Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

OurWorldinData.org – Research and data to make progress against the world’s largest problems.

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Semiconductor device fabrication

MOSFET scaling (process nodes)

- 10 µm – 1971
- 6 µm – 1974
- 3 µm – 1977
- 1.5 µm – 1981
- 1 µm – 1984
- 800 nm – 1987
- 600 nm – 1990
- 350 nm – 1993
- 250 nm – 1996
- 180 nm – 1999
- 130 nm – 2001
- 90 nm – 2003
- 65 nm – 2005
- 45 nm – 2007
- 32 nm – 2009
- 22 nm – 2012
- 14 nm – 2014
- 10 nm – 2016
- 7 nm – 2018
- 5 nm – 2020

Future

- 3 nm ~ 2022
- 2 nm ~ 2024

Issue: CPU Physics

- More transistors → higher energy use
- Higher energy use → higher heat
- Higher heat → lower reliability (e.g., signal leakage)
- Manufacturing limitations
- Quantum effects at sub-nanometer resolution
- Related observation: Dennard scaling (i.e., power consumption per area remains constant) failed in 2000s

Will Moore's Law eventually fail?

(some argue it already has)

Alternative to Moore’s Law

- Scale out, not up
  - **More** processors rather than **faster** processors
    - (Remember El Capitan’s 1.8GHz processors?)
  - Requires parallelism at higher levels than instruction-level parallelism (e.g., pipelining)

“Post-Moore’s Law Era”

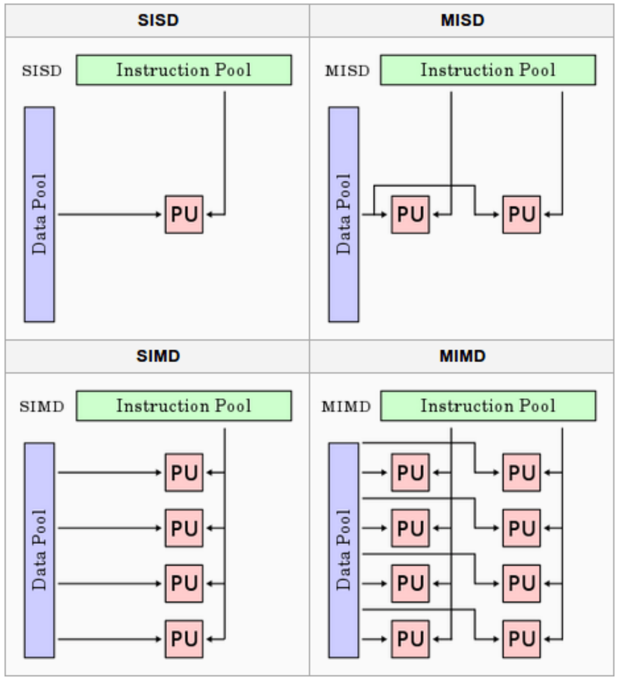
System architectures

- However, there's also a limit to how many cores we can put in a single computer
  - Energy consumption, heat emission, memory saturation
- Solution: more computers! (“nodes”)
  - Communicate via network
  - This is called a distributed system
- There are so many kinds of parallelism
  - We need ways to concisely describe them and discuss their tradeoffs for particular applications

System architectures

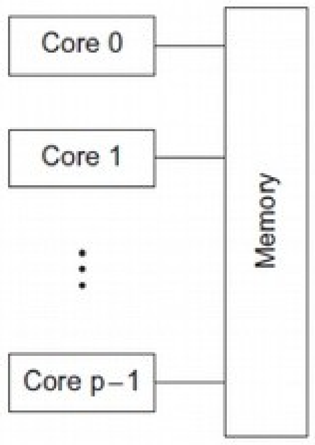
- Flynn's Taxonomy
  - Single Instruction, Single Data (SISD)
    - Traditional von Neumann
    - Increasingly insufficient!
  - Single Instruction, Multiple Data (SIMD)
    - Vector instructions (SSE/AVX) – remember from CS 261?
    - GPUs and other accelerators
  - Multiple Instruction, Multiple Data (MIMD)
    - Single Program, Multiple Data (SPMD)
    - Shared memory and distributed memory
  - Single Instruction, Multiple Threads (SIMT)
    - New term gaining prominence in past few years
    - Alternative way of describing GPUs

Trend: higher number of slower,
more energy-efficient processors

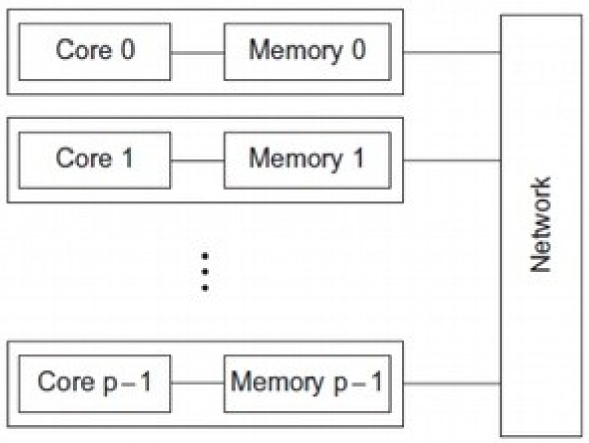


System architectures

- Shared memory
  - Idea: add more **CPUs** or **GPUs**
  - Paradigm: threads
  - Technologies: Pthreads, OpenMP, CUDA
  - Issue: synchronization



- Distributed memory
  - Idea: add more **computers**
  - Paradigm: message passing
  - Technologies: MPI, PGAS
  - Issue: data movement



Usual tradeoff: **simplicity** (shared) vs. **scalability** (distributed)

Shared memory summary

- Shared memory systems can be very efficient
  - Low overhead for thread creation/switching
  - Uniform memory access times (symmetric multiprocessing)
- They also have significant issues
  - Limited scaling (# of cores) due to interconnect costs
  - Requires explicit thread management and synchronization
  - Caching problems can be difficult to diagnose
- Core design tradeoff: synchronization granularity
  - Higher granularity: simpler but slower
  - Lower granularity: more complex but faster
  - Paradigm: synchronization is expensive

Distributed memory summary

- Distributed systems can scale massively
  - Hundreds or thousands of nodes, petabytes of memory
  - Millions of cores, petaflops of computation capacity
- They also have significant issues
  - Non-uniform memory access (NUMA) costs
  - Requires explicit data movement between nodes
  - More difficult debugging and optimization
- Core design tradeoff: data distribution
  - How to partition and arrange the data; is any of it duplicated?
  - Goal: minimize data movement
  - Paradigm: computation is “free” but communication is not

P/D systems are ubiquitous

- “New” problem: writing correct and performant parallel/distributed software
  - Implementing parallelism is often hard
  - Sometimes the **problem** is not naturally parallel
  - Sometimes communication overwhelms computation
  - But the stakes are too high to ignore parallelism!

Core issue: parallelization

- As humans, we usually think sequentially
  - *"Do this, then that"* w/ deterministic execution
- Parallel programming requires a different approach
  - *"Do this and that in any order (or at the same time)"*
  - Introduction of non-determinism
  - Requires sophisticated understanding of dependencies
- Sometimes, the best parallel solution is to discard the serial solution and revisit the problem

Example from IPP

- Compute n values and calculate their sum
- Serial solution:

```
sum = 0;
for (i = 0; i < n; i++) {
    sum += compute_value(i);
}
```

How should we parallelize this?

What problems will we encounter?

Example from IPP

- Initial parallel solution:

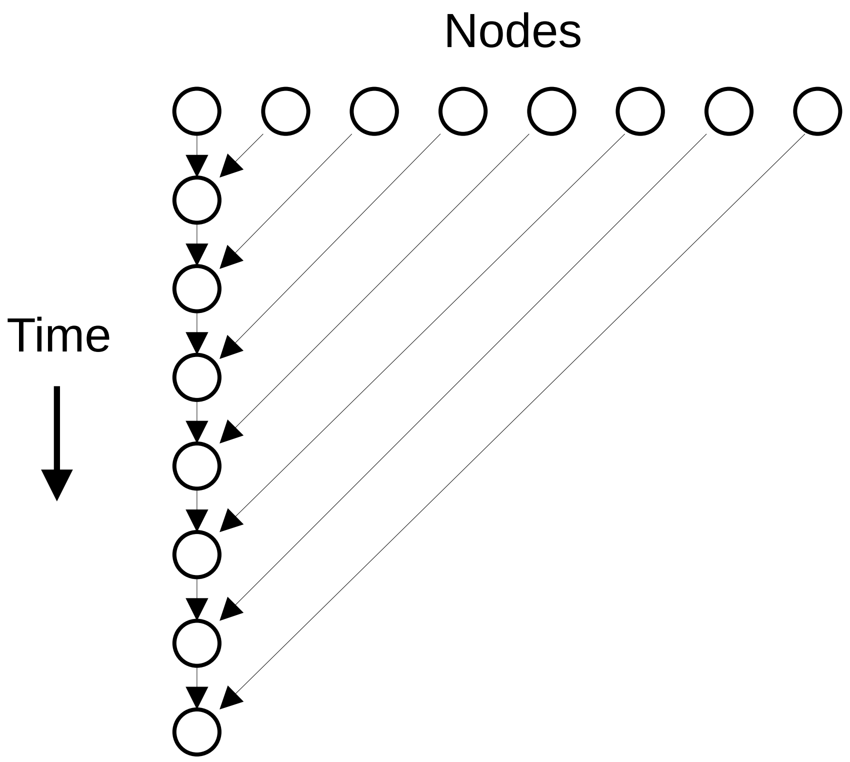
```
sum = 0;
first_i = … ;
last_i = … ;

for (i = first_i; i < last_i; i++) {
    sum += compute_value(i);
}

if (is_main_node()) {
    for (t = 0; t < n_threads; t++) {
        sum += receive(t);
    }
} else {
    send(sum, main_thread);
}
```

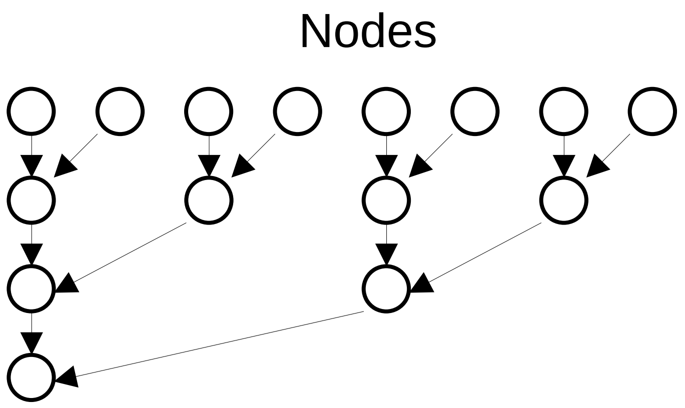
Insight: split up the compute work, then have the main node aggregate the results

Shared-mem alternative: use a mutex!

Example from IPP

- There's a better way to compute the final sum
  - Distribute the work; don't do all the additions serially
  - Fewer computations on the critical path (longest chain of work)





Original version: 7 messages and 7 additions

Clever version: 3 messages and 3 additions

Example from IPP

- Improvement is even greater w/ higher # of nodes
- For 1000 nodes:
  - Original version: 999 messages and 999 additions
  - Clever version: 10 messages and 10 additions

This is an asymptotic improvement!

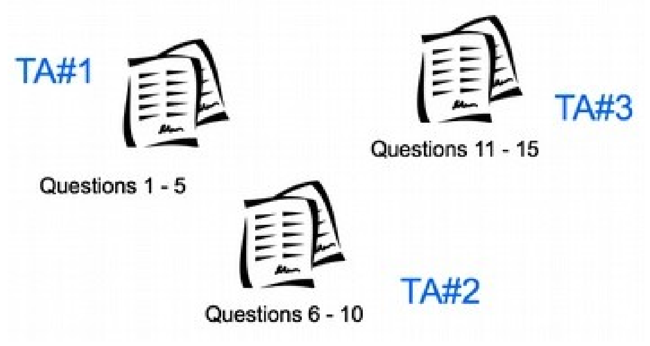
(*why*?)

Discussion

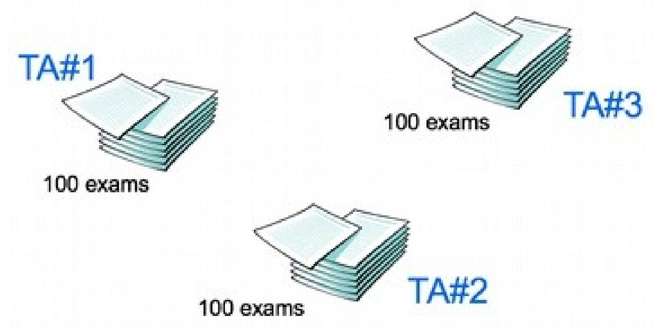
- Assume we have three grading TAs to grade a 15-question exam for roughly 300 students. How do we finish the grading as quickly as possible?
  - Are there multiple valid approaches?

Kinds of parallelism

- **Task** parallelism / decomposition
  - Partition **tasks** among processes
  - Pass data between processes
  - Work can be highly optimized



- **Data** parallelism / decomposition
  - Partition **data** among processes
  - Each process performs all tasks
  - Lower latency for individual outputs



Potential tradeoff: **throughput** (task) and **latency** (latency)

Our goals this semester

- Learn some parallel & distributed programming technologies
  - Pthreads, OpenMP, CUDA, MPI
- Study parallel & distributed system architectures
  - Shared memory, distributed cluster, hybrid, cloud
- Study general parallel computing approaches
  - Parallel algorithms, message passing, task/data decomposition
- Analyze application performance
  - Speedup, weak/strong scaling, locality, communication overhead
- Explore parallel & distributed issues
  - Networks, synchronization & consistency, fault tolerance, security

Parallel & distributed systems

- Hardware architectures
- Performance analysis and profiling
- Networks and naming
- Software patterns & frameworks

  (w/ standard projects P1-P3)

First half of CS 470

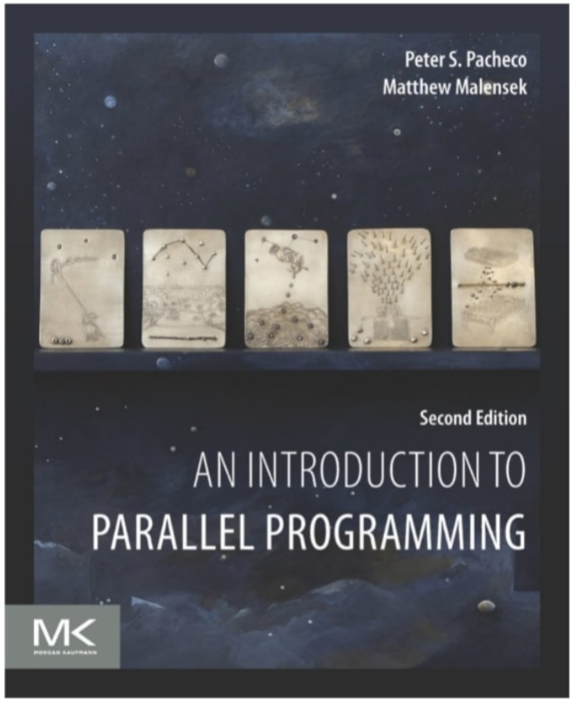
- Fault tolerance
- Synchronization and consistency
- Security
- Cloud computing
- Applications: Web & File Systems

  (w/ final project)

Second half of CS 470

Course textbook

- **An Introduction to Parallel Programming, 2nd Edition**
  - Peter S. Pacheco and Matthew Malensek
  - New-ish edition!
- Sources:
  - Amazon ($53)
  - Elsevier ScienceDirect (**free!**)
    - (electronic, link on syllabus)



Course notes

- The course slides are the course notes, and they are quite comprehensive
  - Especially during the second half
  - Not all topics will be covered explicitly in class
  - **Most** topics will not be covered extensively in lectures
  - We'll focus on the most useful / difficult topics during class
  - You are responsible for reviewing the slides for all material not fully covered in class
  - Ask clarification questions during next class period

Course format

- Public files and calendar on website (bookmark it!)
- Private files and grades on Canvas

- Canvas quizzes (usually 1-2 per week)
  - Two attempts; goal is to prompt re-reading if needed
- In-class labs (usually ~1 per week) w/ Canvas submission
  - Groups of two or three (submit one copy with everyone's names)
- Standard projects (every 2-3 weeks in 1st half) w/ Canvas submission
  - Groups of up to two
- Final project (entire semester, starting now!)
  - Groups of up to four (**three HIGHLY recommended**)
- In-class exams (two midterms & final)

Course grades

Quizzes and Labs	20%
Projects	30%
Exams	50%

- Quizzes and labs are **formative**
  - Designed to help you learn
- Exams are **summative**
  - Designed to assess what you have learned
- Projects are **both**
  - Designed to give you experience writing parallel and distributed programs
  - Intended as both a learning experience but also to measure progress

Assumed skills

- All material in CS 261 and CS 361
  - (we will review Pthreads a bit)
- Some other things you should be able to do:
  - Login to a remote Linux server via SSH in a terminal
  - Copy files and folders on the command line (cp)
  - Edit files from the command line (e.g., nano or vim)
  - Download files using the command line (e.g., curl or wget)
  - Implement a singly-linked list
  - Use GDB to find segfault sources
  - Use GDB or logs to trace execution
  - Use Valgrind to locate memory problems

Standard projects

- Practice using parallel and distributed technologies
  - Pthreads, OpenMP, and MPI
- Practice good software engineering and code analysis
- Code can be written individually or in teams of two
  - Benefits vs. costs of working in a team
  - AI-assist technologies are **allowed** – statement required re: use
- Analysis results must be included in comments at top
  - Requirements will vary by assignment

Final project

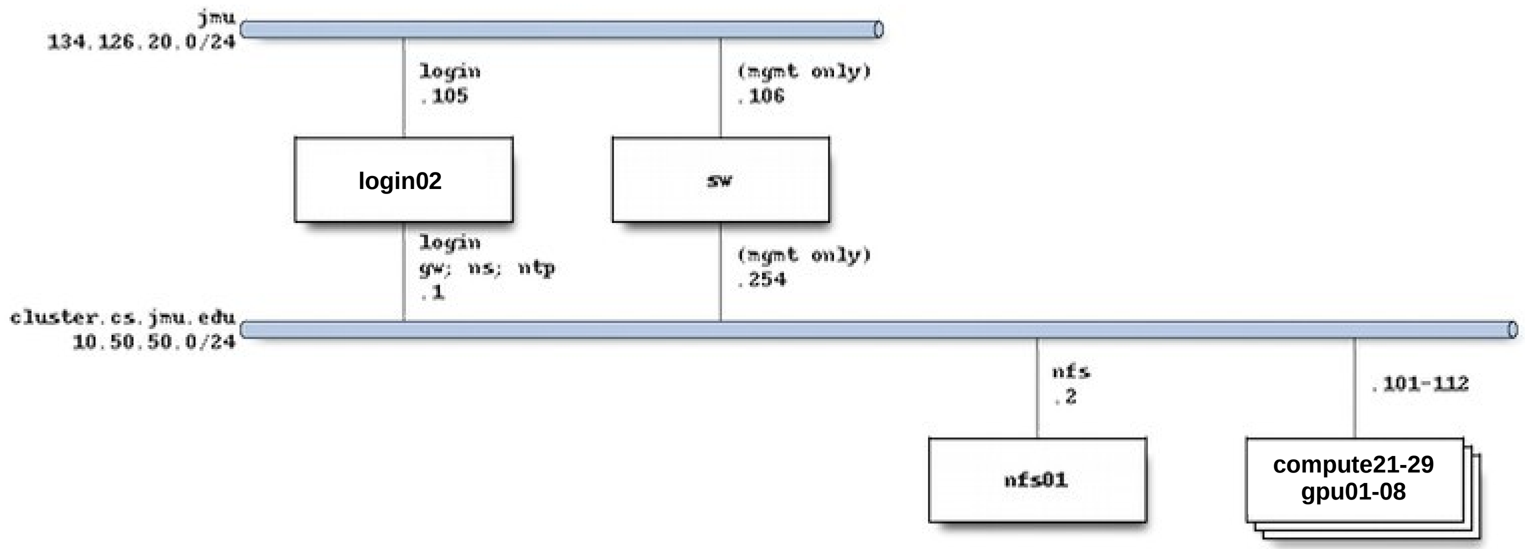
- Semester-long project
  - Teams of 2-4 people (**three HIGHLY recommended**)
  - Personalized topic; somewhat open-ended
  - Find an existing parallel/distributed software system
  - Three parts:
    - 1) Analysis, 2) insights, and 3) contributions
  - Multiple submissions:
    - Ideas, groups, design, draft, poster/showcase, final
  - Graded on progress, quality, and application of course concepts
  - Goal: **significant, open-ended** “capstone” experience
  - More details on final project overview website

Final Project Guidelines

- Most importantly: **DON’T STRESS!**
- Find a topic you are interested in that is related to our course topics
- Find two or three like-minded students in the class to work with
- Start early and schedule regular work sessions to make steady progress
- Avoid naturally-parallel problems; try to find something non-trivial
- Unless approved, the software must run on our cluster or lab machines
- Unless approved, the majority of the code must be written in C or C++
- Prefer large software systems (e.g., thousands of lines of code or more)
- Prefer distributed software systems (e.g., MPI-based or networked)

Our distributed cluster

- **Compute nodes**:
  - 9x Dell PowerEdge R6525 w/ 2x AMD EPYC 7252 (8C, 3.1 Ghz, HT) 64 GB
  - 8x Dell PowerEdge R6525 w/ 2x AMD EPYC 7252 (8C, 3.1 Ghz, HT) 64 GB and NVIDIA A2 GPU
- **Login node**: Dell PowerEdge R6525 w/ 2x AMD EPYC 7252 (8C, 3.1 Ghz, HT) 64 GB
- **File server**: Dell PowerEdge R730 w/ Xeon E5-2640v3 (8C, 2.6Ghz, HT) 32 GB
  - **Storage**: 8x 1.2TB 10K SAS HDD w/ RAID
- **Interconnect**: Dell N3024 Switch 24x1GbE, 2x10GbE SFP+ (212Gbps duplex)



Cluster access

- Detailed instructions online: `w3.cs.jmu.edu/lam2mo/cs470/cluster.html`
- Connect to login node via SSH
  - Hostname: `login02.cluster.cs.jmu.edu`
  - User/password: *(your e-ID and password)*
- Recommended conveniences
  - Set up public/private key access from `stu`
  - Set up `.ssh/config` entries
    - w/ `stu` as jump host if you want off-campus access

Cluster access

Hostname: `login02.cluster.cs.jmu.edu`

- Things to play with:
  - "`squeue`" or "`watch squeue`" to see jobs
  - "`srun <command>`" to run an interactive job
    - Use "`-n <p>`" to launch *p* processes
    - Use "`-N <n>`" to request *n* nodes (defaults to *p*/16)
    - The given "`<command>`" will run in every process
    - Use "`--gres=gpu`" to request one of the GPU nodes
  - "`srun -n <p> <command>`" to run an interactive MPI job
    - Will launch *p* MPI processes

```
srun hostname
srun -n 4 hostname
srun -n 16 hostname
srun -N 4 hostname
srun sleep 5
srun -N 2 sleep 5
```

```
module load mpi
srun -n 1 /shared/cs470/mpi-hello/hello
srun -n 2 /shared/cs470/mpi-hello/hello
srun -n 4 /shared/cs470/mpi-hello/hello
srun -n 8 /shared/cs470/mpi-hello/hello
srun -n 16 /shared/cs470/mpi-hello/hello
(etc.)
```

What's the max *n*?

TODO items for this weekend

- Take course welcome survey if you haven’t already
- Review Pthreads slides
- Make sure you can SSH into `login02.cluster.cs.jmu.edu`
  - Must be on JMU network (e.g., proxy jump through `stu`)
  - Email me **BEFORE** the next class if you encounter issues
- Final project overview and idea quiz due next Friday
  - Start talking with others about topics!