CSC 447: Parallel Programming for Multi-Core and Cluster Systems

Why Parallel Programming?

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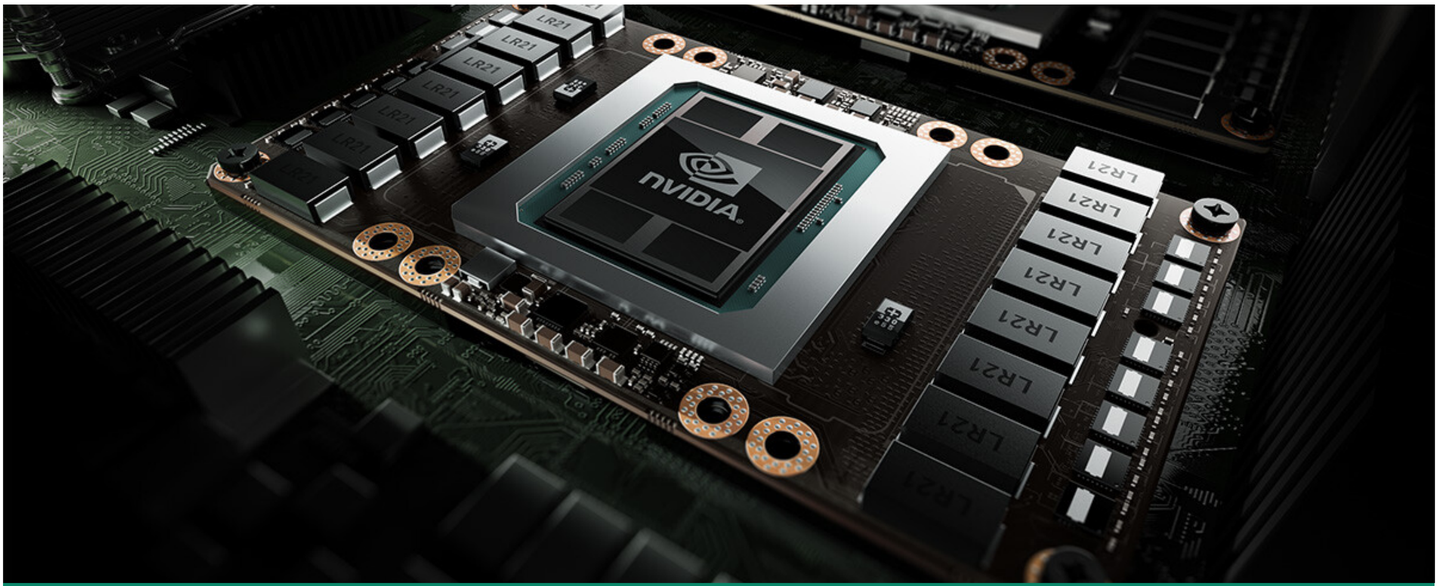
Today's Agenda

- Why Parallel Programming
- Doing parallel Programming



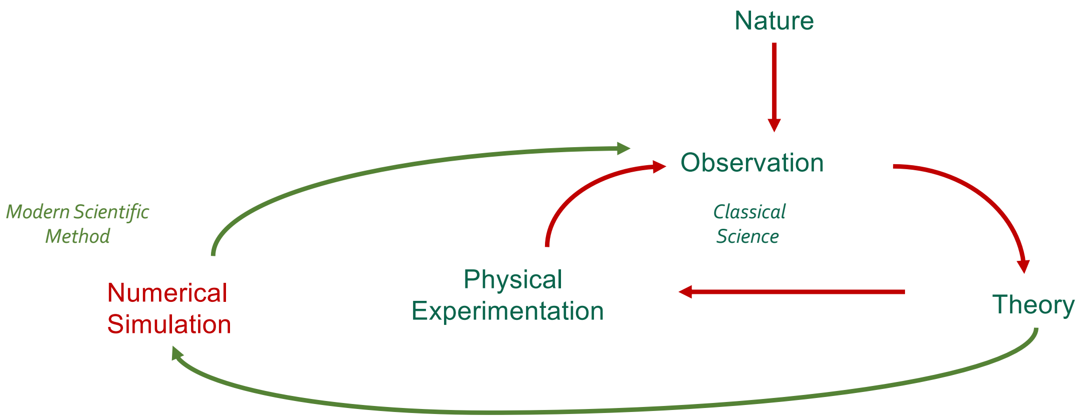
Why Parallel Programming?

Why Parallel Programming Now?

- All major processor vendors are producing multicore chips
  - All machines have become parallel computers!
- Artificial intelligence and machine learning in addition to the classical applications
  - Autonomous cars
  - Natural Language Processing
  - Medical Applications
  - Drug Development

Why Parallel Computing Now?

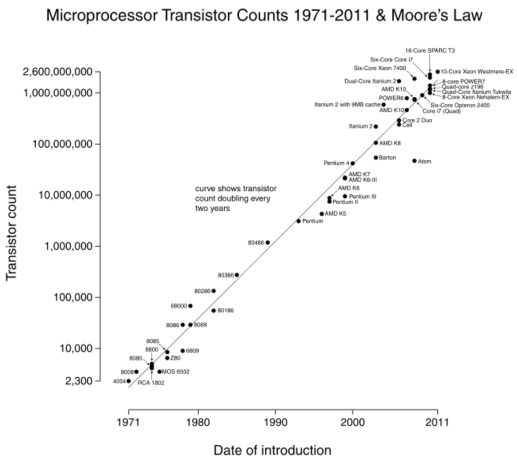
- Researchers have been using parallel computing for decades:
  - Mostly used in computational science and engineering
  - Problems too large to solve on one computer; use 100s or 1000s



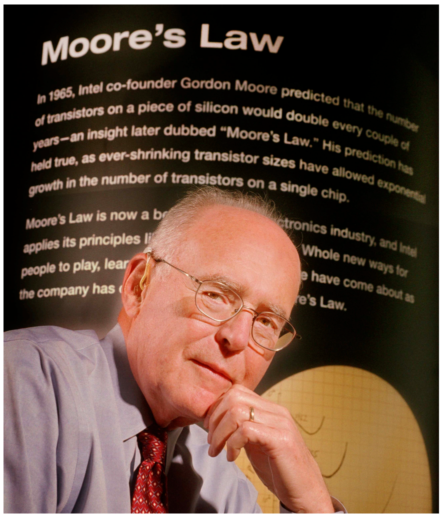
Improving Performance

- There are 3 ways to improve performance:
  - Work Harder
  - Work Smarter
  - Get Help
- Computer Analogy
  - Using faster hardware
  - Optimized algorithms and techniques used to solve computational tasks
  - Multiple computers to solve a particular task

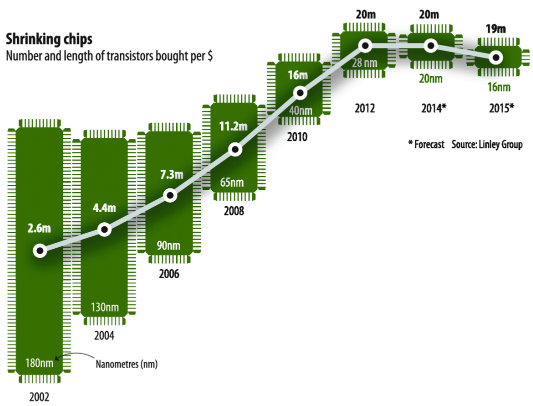
Technology Trends: Microprocessor Capacity

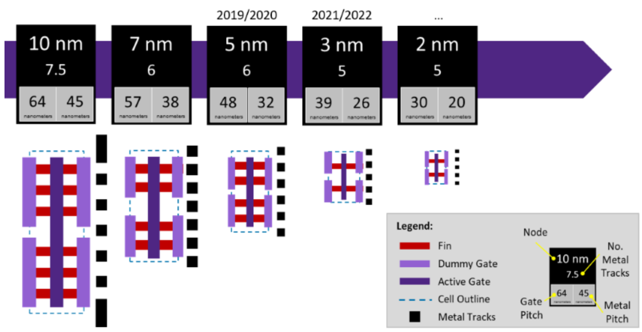


Gordon Moore (co-founder of Intel) predicted in 1965 that the transistor density of semiconductor chips would double roughly every 18 months.



Technology Trends: Microprocessor Capacity





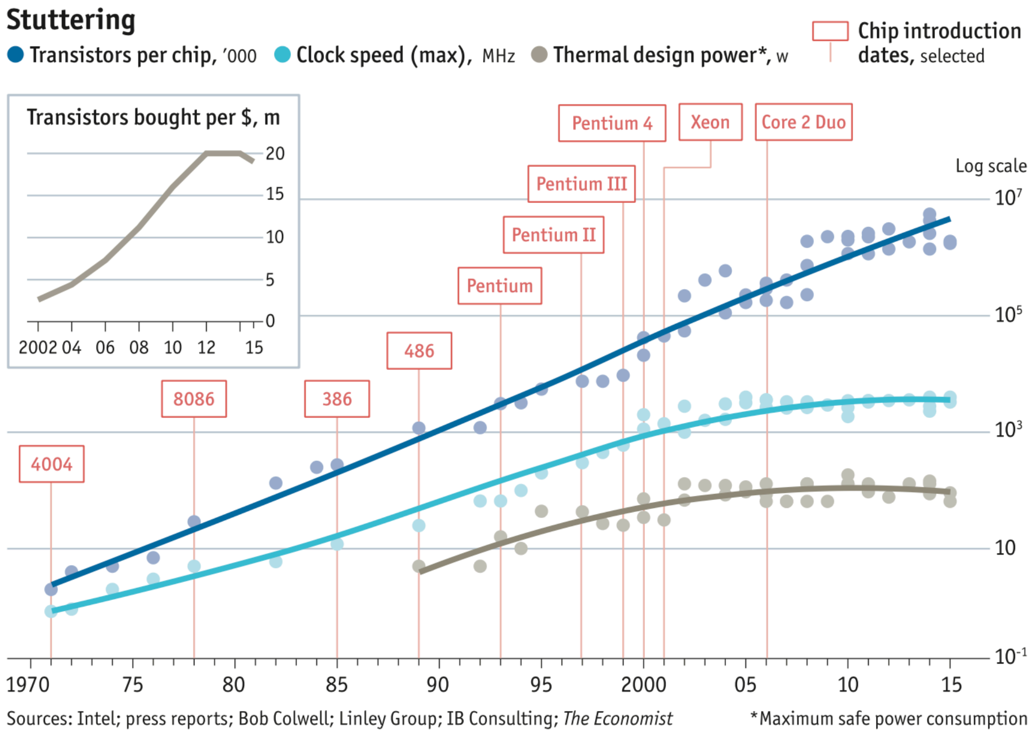
Microprocessors have become smaller, denser, and more powerful.

CPUs 1 Million Times Faster

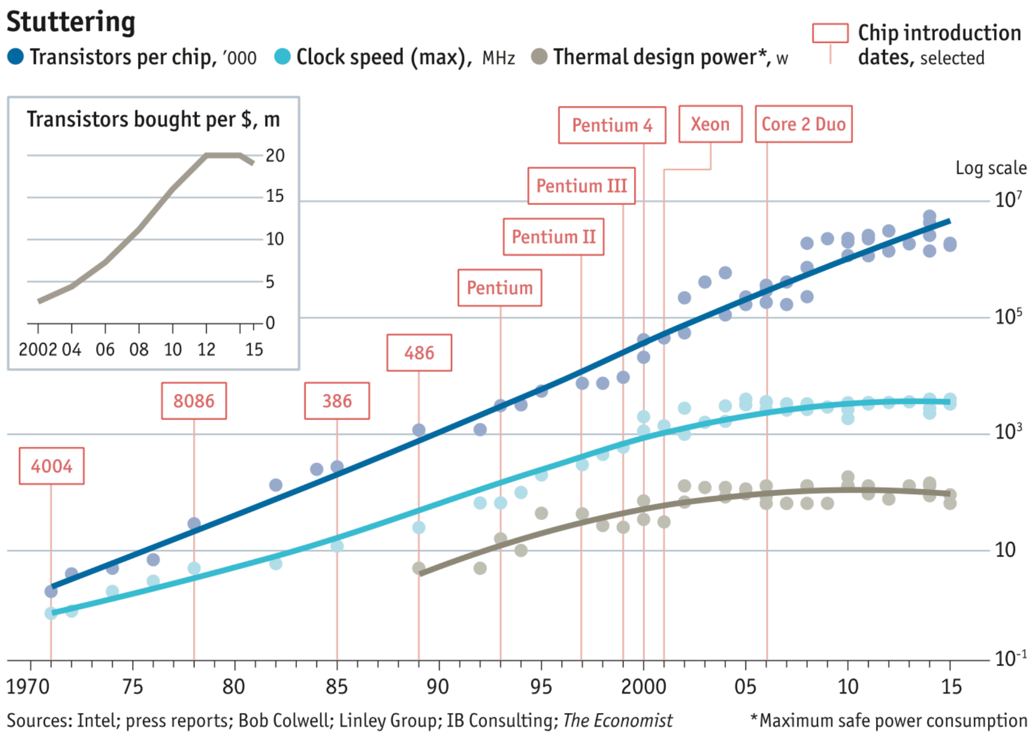
- Faster clock speeds
- Greater system concurrency
  - Multiple functional units
  - Concurrent instruction execution
  - Speculative instruction execution

Systems 1 Billion Times Faster

- Processors are 1 million times faster
- Combine thousands of processors
- Parallel computer
  - Multiple processors
  - Supports parallel programming
- Parallel computing = Using a parallel computer to execute a program faster



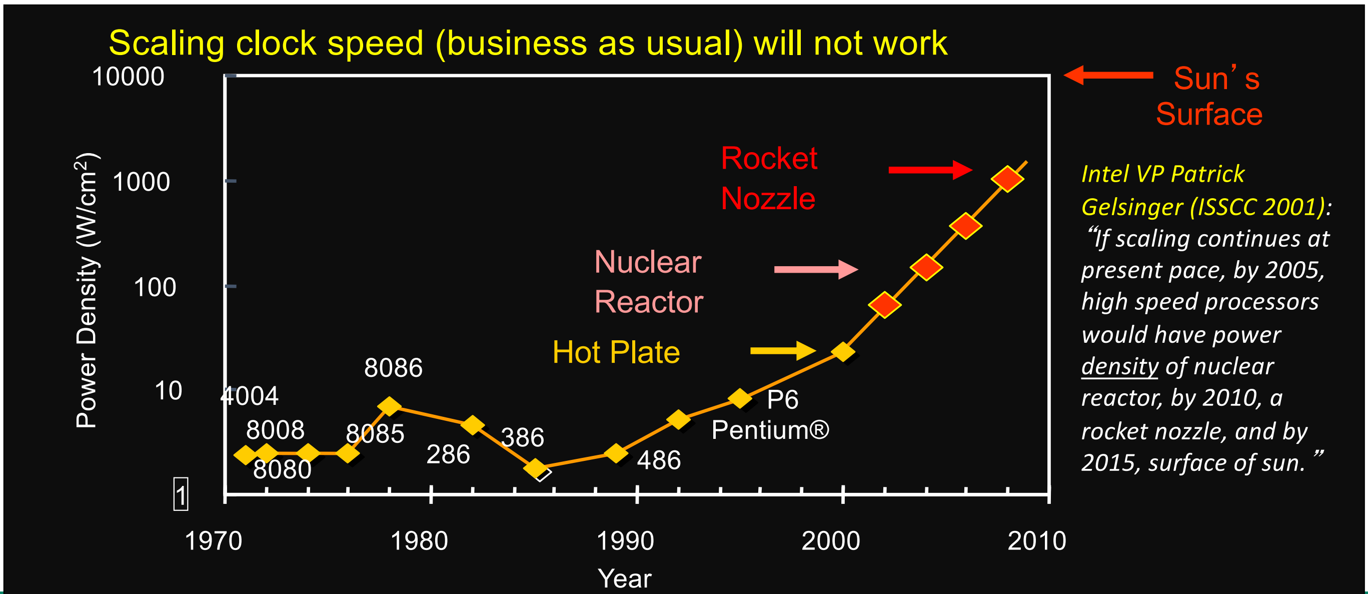
Microprocessor Transistors and Clock Rate



Moore's Law is alive and well!

Why bother with parallel programming? Just wait a year or two…

Limit #1: Power density



Parallelism Saves Power

- Exploit explicit parallelism for reducing power

  Power = (C * V^2 * F)/4   Performance = (Cores * F)*1

  C= Capacitance, V = Voltage , F = Frequency

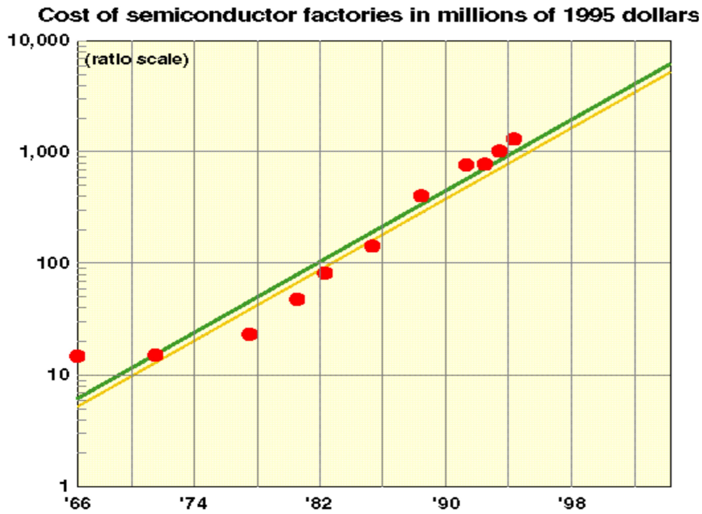
- Using additional cores
  - Increase density (= more transistors = more capacitance)
  - Can increase cores (2x) and performance (2x)
  - Or increase cores (2x), but decrease frequency (1/2): same performance at ¼ the power
- Additional benefits
  - Small/simple cores → more predictable performance

Limit #2: Hidden Parallelism Tapped Out

- Superscalar designs provided many forms of parallelism not visible to programmer
  - Multiple instruction issue
  - Dynamic scheduling: hardware discovers parallelism between instructions
  - Speculative execution: look past predicted branches
  - Non-blocking caches: multiple outstanding memory ops
- Unfortunately, these sources have been used up

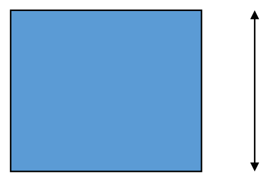
Limit #3: Manufacturing costs and yield problems limit use of density

- Moore's (Rock's) 2nd law: fabrication costs go up
- Yield (% usable chips) drops
- Parallelism can help
  - Smaller, simpler processors are easier to design and validate
  - Can use partially working chips:
  - E.g., Cell processor (PS3) is sold with 7 out of 8 "on" to improve yield



Limit #4: Speed of Light (Fundamental)

- Consider the 1 Tflop/s sequential machine:
  - Data must travel some distance, r, to get from memory to CPU.
  - To get 1 data element per cycle, this means 1012 times per second at the speed of light, c = 3x108 m/s.
    - Thus r < c/1012 = 0.3 mm.
- Now put 1 Tbyte of storage in a 0.3 mm x 0.3 mm area:
  - Each bit occupies about 1 square Angstrom, or the size of a small atom.
- No choice but parallelism



So what is the problem?

Writing (fast) parallel programs is hard!

Parallel Programming Workflow

- Identify compute intensive parts of an application
- Adopt scalable algorithms
- Optimize data arrangements to maximize locality
- Performance Tuning
- Pay attention to code portability and maintainability

Principles of Parallel Computing

- Finding enough parallelism (Amdahl's Law)
- Granularity
- Locality
- Load balance
- Coordination and synchronization
- Performance modeling

→ *All of these make parallel programming even harder than sequential programming.*

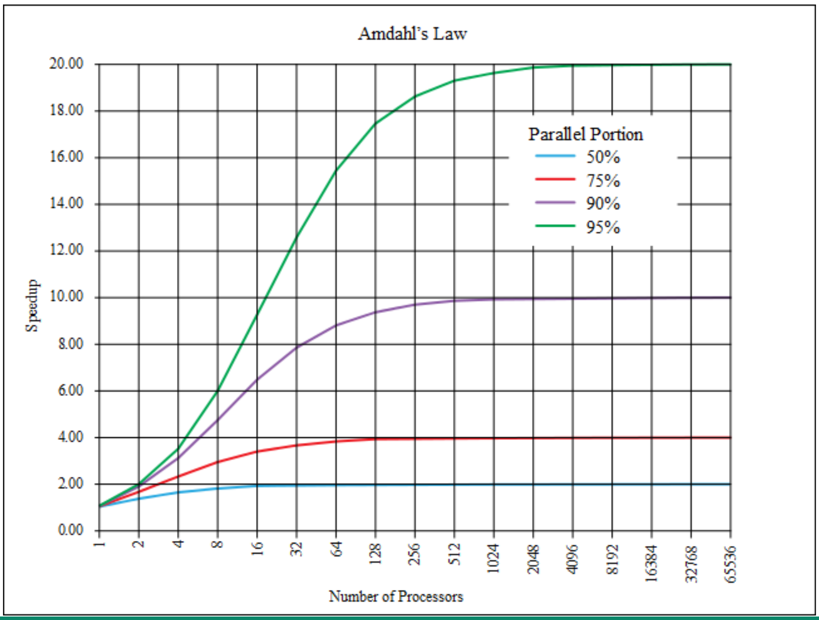
Finding Enough Parallelism

- Suppose only part of an application seems parallel
- Amdahl's law
  - let s be the fraction of work done sequentially, so (1-s) is fraction parallelizable
  - P = number of processors

```
Speedup(P) = Time(1)/Time(P)
          <= 1/(s + (1-s)/P)
          <= 1/s
```

- Even if the parallel part speeds up perfectly performance is limited by the sequential part

Finding Enough Parallelism (Amdahl's Law)



Granularity

- Parallelism is not free. Overhead includes:
  - Cost of starting a thread or process
  - Cost of communicating shared data
  - Cost of synchronizing
  - Extra (redundant) computation
- Each of these can be in the range of milliseconds (=millions of flops) on some systems

Tradeoff: Algorithm needs sufficiently large units of work to run fast in parallel (I.e. large granularity), but not so large that there is not enough parallel work

Load Balance/Imbalance

- Load imbalance is the time that some processors in the system are idle due to
  - insufficient parallelism (during that phase)
  - unequal size tasks
- Examples of the latter
  - adapting to "interesting parts of a domain"
  - tree-structured computations
  - fundamentally unstructured problems
- Algorithm needs to balance load

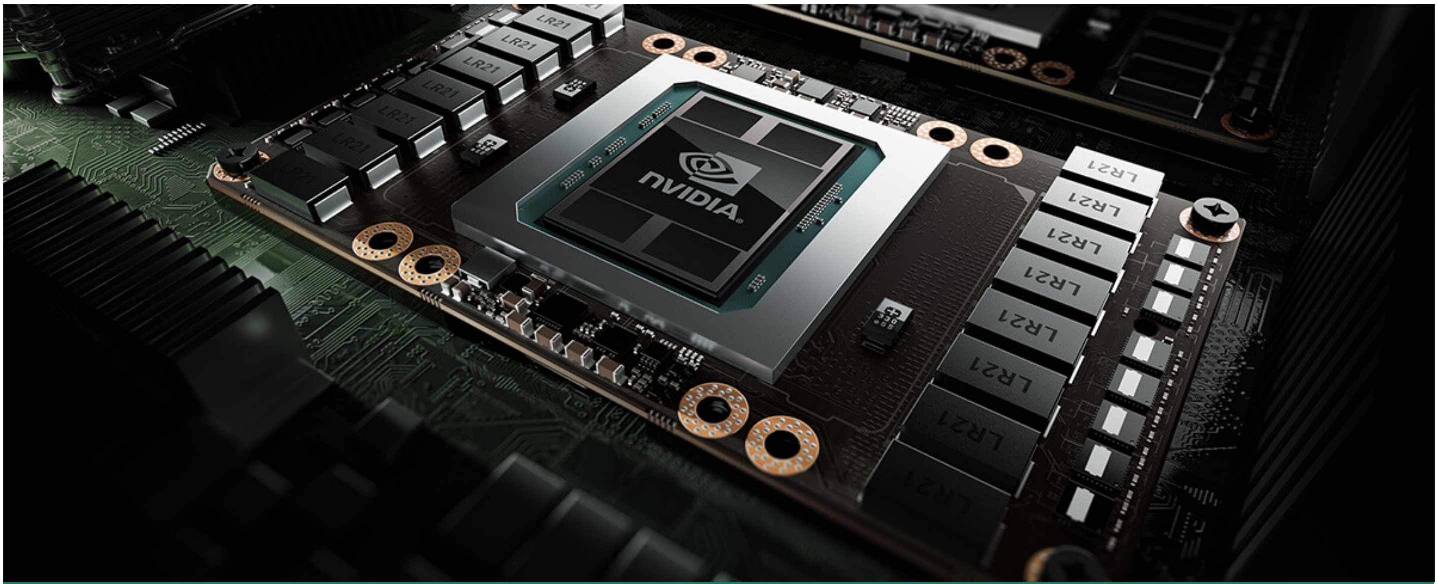
Load Balance

Synchronization

- Need to manage the sequence of work and the tasks performing
- Often requires "serialization" of segments of the program
- Various types of synchronization maybe involved
  - Locks/Semaphores
  - Barrier
  - Synchronous Communication Operations

Performance Modeling

- Analyzing and tuning parallel program performance is more challenging than for serial programs.
- There is a need for parallel program performance analysis and tuning.



So how do we do parallel computing?

Strategy 1: Extend Compilers

- Focus on making sequential programs parallel
- Parallelizing compiler
  - Detect parallelism in sequential program
  - Produce parallel executable program
- Advantages
  - Can leverage millions of lines of existing serial programs
  - Saves time and labor
  - Requires no retraining of programmers
  - Sequential programming easier than parallel programming
- Disadvantages
  - Parallelism may be irretrievably lost when programs written in sequential languages
  - Performance of parallelizing compilers on broad range of applications still up in air

Strategy 2: Extend Language

- Add functions to a sequential language
  - Create and terminate processes
  - Synchronize processes
  - Allow processes to communicate
- Advantages
  - Easiest, quickest, and least expensive
  - Allows existing compiler technology to be leveraged
  - New libraries can be ready soon after new parallel computers are available
- Disadvantages
  - Lack of compiler support to catch errors
  - Easy to write programs that are difficult to debug

Strategy 3: Add a Parallel Programming Layer

- Lower layer
  - Core of computation
  - Process manipulates its portion of data to produce its portion of result
- Upper layer
  - Creation and synchronization of processes
  - Partitioning of data among processes
- A few research prototypes have been built based on these principles

Strategy 4: Create a Parallel Language

- Develop a parallel language "from scratch" or add parallel constructs to an existing language
  - Fortran 90
  - High Performance Fortran
  - C*
- Advantages
  - Allows programmer to communicate parallelism to compiler
  - Improves probability that executable will achieve high performance
- Disadvantages
  - Requires development of new compilers
  - New languages may not become standards
  - Programmer resistance

Conclusion: Three Options

- Good: "Accelerate" Legacy Codes
  - Recompile/Run
  - => good work for domain scientists (minimal CS required)
- Better: Rewrite / Create new codes
  - Opportunity for clever algorithmic thinking
  - => good work for computer scientists (minimal domain knowledge required)
- Best: Rethink Numerical Methods & Algorithms
  - Potential for biggest performance advantage
  - => Interdisciplinary: requires CS and domain insight
  - => Exciting time to be a computational scientist

Think, Understand… then, Program

- Think about the problem you are trying to solve
- Understand the structure of the problem
- Apply mathematical techniques to find solution
- Map the problem to an algorithmic approach
- Plan the structure of computation
  - Be aware of in/dependence, interactions, bottlenecks
- Plan the organization of data
  - Be explicitly aware of locality, and minimize global data
- Finally, write some code! (this is the easy part ☺)