Lecture 2: Basic Performance Models For Extreme Scale Systems

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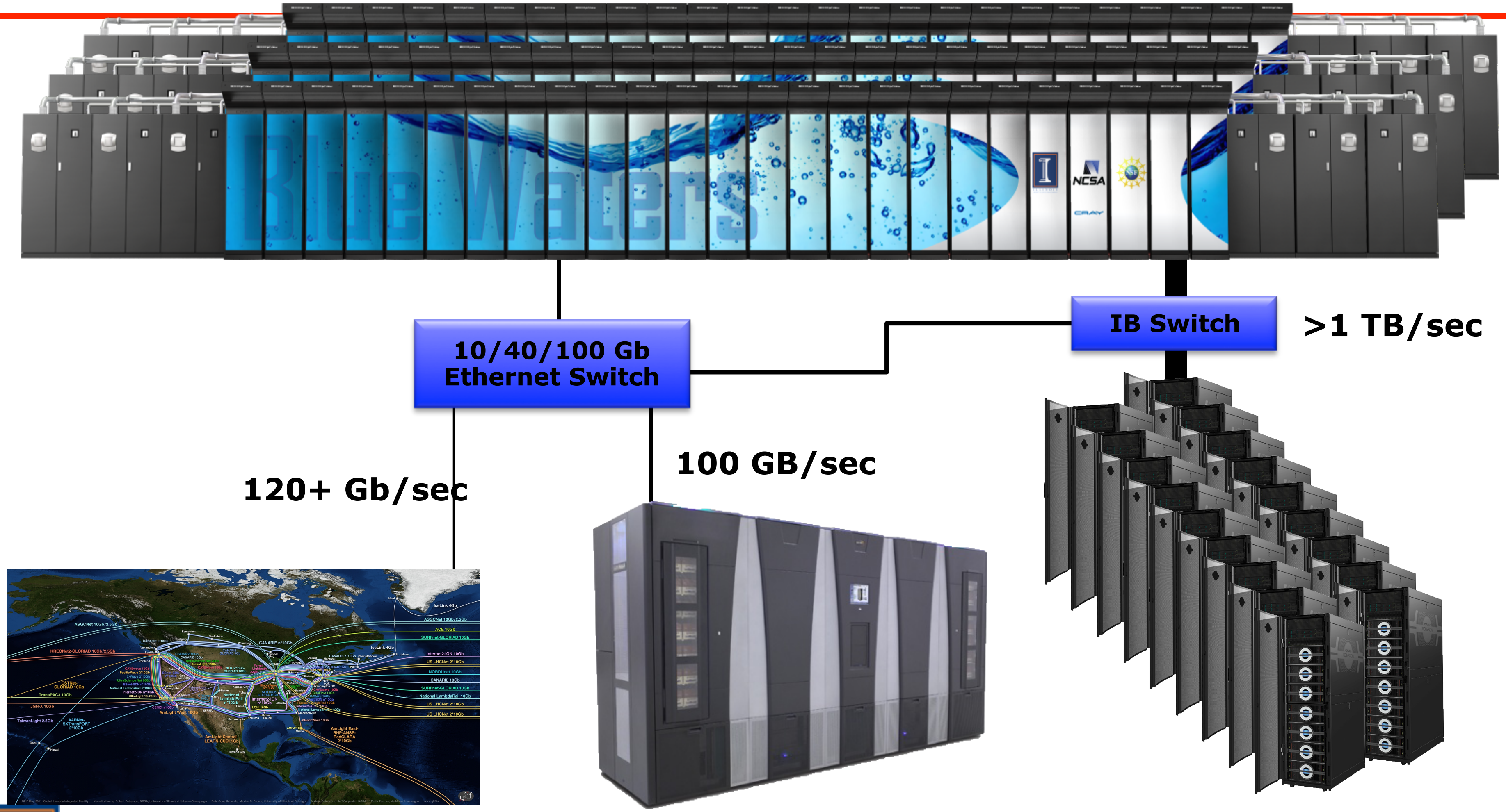
Performance is Key

- Parallelism is (usually) used to get more performance
  - How do you know if you are making good (not even best) use of a parallel system?
- Even measurement-based approaches can be (and all to often are) performed without any real basis of comparison
  - The key questions are
    - Where is most of the time spent?
    - What is the achievable performance, and how do I get there?
  - This latter is often overlooked, leading to erroneous conclusions based on the (immature) state of compiler / runtime / code implementations

Tuning A (Parallel) Code

- Typical Approach
    - Profile code. Determine where most time is being spent
    - Study code. Measure absolute performance, look at performance counters, compare FLOP rates
    - Improve code that takes a long time, reduce time spent in “unproductive” operations
- Why this isn’t the right Approach:
    - How do you know when you are done?
    - How do you know how much performance improvement you can obtain?
- Why is it hard to know?
    - Many problems are too hard to solve without extreme scale computing
    - Its getting harder and harder to provide performance without specialized hardware

Blue Waters Computing System



10/40/100 Gb Ethernet Switch

IB Switch

>1 TB/sec

120+ Gb/sec

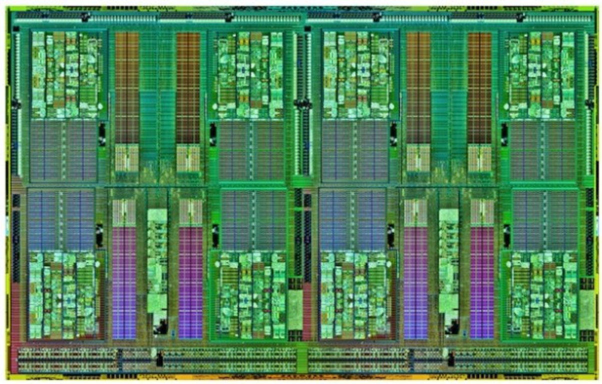
100 GB/sec

WAN

Spectra Logic: 300 PBs

Sonexion: 26 PBs

Heart of Blue Waters: Two Chips



AMD Interlagos

157 GF peak performance

Features:

2.3-2.6 GHz

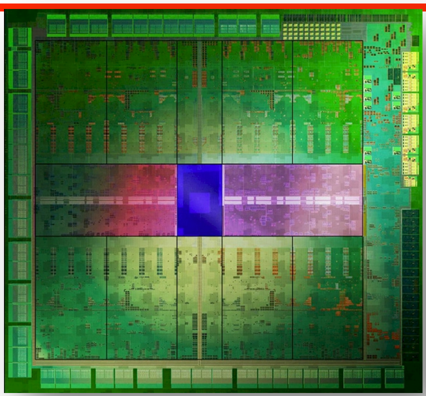
8 core modules, 16 threads

On-chip Caches

- L1 (I:8x64KB; D:16x16KB)
- L2 (8x2MB)

Memory Subsystem

- Four memory channels
- 51.2 GB/s bandwidth



NVIDIA Kepler

1,400 GF peak performance

Features:

15 Streaming multiprocessors (SMX)

- SMX: 192 sp CUDA cores, 64 dp units, 32 special function units
- L1 caches/shared mem (64KB, 48KB)
- L2 cache (1536KB)

Memory subsystem

- Six memory channels
- 180 GB/s bandwidth

What is an Extreme Scale System Today?

- Tianhe 2 (China):
  - 16,000 nodes, each with 2 Intel Ivy Bridge Xeon processors and 3 Xeon Phi coprocessors
  - 3,120,000 cores
  - Interconnect is a “fat tree” of 13 switches, each with 576 ports
- Sequoia (USA):
  - IBM Blue Gene/Q. 98,304 nodes, each with 16 (+1) cores
  - Interconnect is 5 dimensional torus

Likely Directions for Extreme Scale Systems

- 5 Years (2020)
  - Peak performance over 1 ExaFLOPs (10^{18} ops/sec)
  - 100k "nodes"
  - Heterogeneous nodes
- 10 Years (2025)
  - Peak performance over 30 ExaFLOPs
  - Computing distributed throughout node and memory
- 15 Years (2030)
  - Peak performance over 100 ExaFLOPs
  - Radically different systems emerging
    - New digital logic, e.g., nanotubes
    - New computing models, e.g., quantum or molecular

Why Performance Modeling?

- What is the goal?
  - It is *not* precise predictions
  - It *is* insight into whether a code is achieving the performance it could, and if not, how to fix it
- Performance modeling can be used
  - To estimate the baseline performance
  - To estimate the potential benefit of a nontrivial change to the code
  - To identify the critical resource

What do I mean by Performance Modeling?

- Actually two different models
  - ♦ First, an analytic expression based on the application code
  - ♦ Second, an analytic expression based on the application’s *algorithm* and data structures
- Note that a series of measurements from benchmarks are *not* a performance model
- Why this sort of modeling
  - ♦ The obvious: extrapolation to other systems, such as scalability in nodes or different interconnect
  - ♦ Also: comparison of the two models with observed performance can identify
    - Inefficiencies in compilation/runtime
    - Mismatch in developer expectations

Different Philosophies for Performance Models

- Simulation:
  - ♦ Very accurate prediction, little insight beyond specifics of the simulation itself
- Traditional Performance Modeling (PM):
  - ♦ Focuses on accurate predictions
  - ♦ Tool for computer scientists, not application developers
- PM as part of the software engineering process
  - ♦ PM for design, tuning and optimization
  - ♦ PMs are developed with algorithms and used in each step of the development cycle
  - ➢ Performance Engineering

Example

- Lets look at a simple example
- Matrix-matrix multiply
  - ♦ Classic example, often used in discussion of compiler optimizations
  - ♦ Core of the “HPLinpack” benchmark
  - ♦ Simple to express: In Fortran,

```
do i=1, n
   do j=1,n
       c(i,j) = 0
       do k=1,n
            c(i,j) = c(i,j) + a(i,k) * b(k,j)
```

Performance Estimate

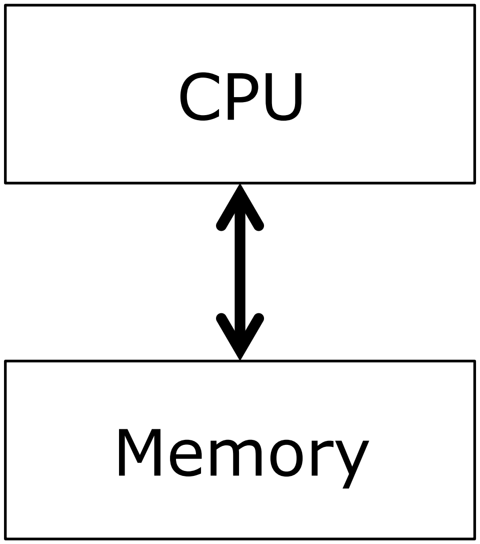
- How fast should this run?
  - ♦ Standard complexity analysis in numerical analysis counts floating point operations
  - ♦ Our matrix-matrix multiply algorithm has $2n^3$ floating point operations
    - 3 nested loops, each with n iterations
    - 1 multiply, 1 add in each inner iteration
  - ♦ For n=100, $2x10^6$ operations, or about 1 msec on a 2GHz processor :)
  - ♦ For n=1000, $2x10^9$ operations, or about 1 sec

The Reality

- N=100
  - 1818 MF (1.1ms)
- N=1000
  - 335 MF (6s)
- What this tells us:
  - Obvious expression of algorithms are not transformed into leading performance.

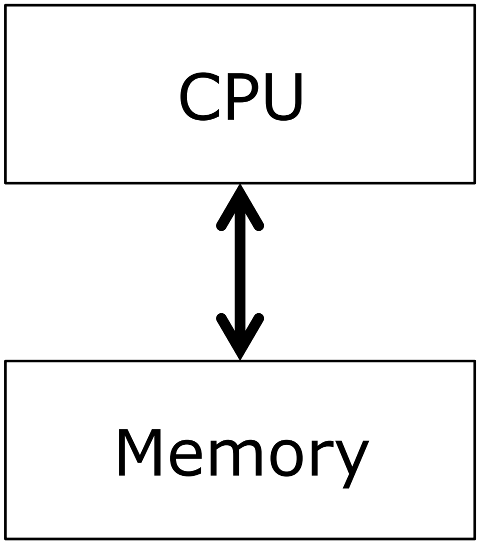
Thinking about Performance

- The performance model assumes the computer looks like the figure on the right
    - Memory is infinitely large
    - Memory is infinitely fast



Thinking about Performance

- We will incrementally improve our performance models by adding features to our model of the computer hardware
  - That model of the computer hardware is a major part of what is often called an *execution model*
- In the first enhancement, lets make memory not infinitely fast



CPU

Memory

A Simple Performance Model

- Use the following:
  - Number of operations (e.g., floating point multiply)
  - Number of loads from memory
  - Number of stores to memory
- We are ignoring for now the many features of an architecture that are used to optimize performance
  - We will cover many of them during the class

A Simple Example

- Consider this code:

```
Do i=1,n
    y(i) = a*x(i) + y(i)
enddo
```

- 2n operations (floating add, floating multiply)
- 2n Loads (x(i) and y(i) for i=1 to n)
- N Stores (y(i))

Performance Model

- Assume that
  c = time for operation
  r = time to read an element
  w = time to write an element
- Then a very crude estimate of the time for this operation is
  T = n(2c + 2r + w)
- Call this a *model* because it is too crude to be an estimate

Some Comments on This Model

- Many analysis of algorithms set r and w to zero
- We will spend much of our time considering different ways to model *communication* time
  - ♦ Load and Store to memory
  - ♦ Sharing of data between threads
  - ♦ Communication between nodes in a parallel computer
  - ♦ Load and Store to a file system

Discussion Topics for Matrix-Matrix Multiply

- Why do you think the algorithm runs slowly at large sizes?
- Why do you think the compiler doesn’t do a better job?
- What about other algorithms such as Strassen’s algorithm?
  - How would that algorithm change this analysis?