Lecture 1:

Why Parallelism?

Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2014
Hi!

Kayvon

Yixin

Eric

Harry

Rick
One common definition

A parallel computer is a collection of processing elements that cooperate to solve problems quickly.

We care about performance *
We care about efficiency

We’re going to use multiple processors to get it

* Note: different motivation from “concurrent programming” using pthreads in 15-213
DEMO 1

(15-418 Spring 2014’s first parallel program)
Speedup

One major motivation of using parallel processing: achieve a speedup

For a given problem:

\[
\text{speedup( using } P \text{ processors )} = \frac{\text{execution time (using 1 processor)}}{\text{execution time (using } P \text{ processors)}}
\]
Class observations from demo 1

- Communication limited the maximum speedup achieved
  - In the demo, communication was communicating partial sums

- Minimizing the cost of communication improved speedup
  - Moved students (“processors”) closer together (or let them shout)
DEMO 2

(scaling up to four processors)
Class observations from demo 2

- Imbalance in work assignment limited speedup
  - Some students ("processors") ran out work to do (went idle), while others were still working on their assigned task

- Improving the distribution of work improved speedup
DEMO 3

(massively parallel execution)
Class observations from demo 3

- The problem I just gave you has a significant amount of communication compared to computation.

- Communication costs can dominate a parallel computation, severely limiting speedup.
Course theme 1: Designing and writing parallel programs ... that scale!

- Parallel thinking
  1. Decomposing work into parallel pieces
  2. Assigning work to processors
  3. Orchestrating communication/synchronization between the processors so that it does not limit speedup

- Abstractions for performing the above tasks
  - Writing code in popular parallel programming languages
Course theme 2:
Parallel computer hardware implementation: how parallel computers work

- Mechanisms used to implement abstractions efficiently
  - Performance characteristics of implementations
  - Design trade-offs: performance vs. convenience vs. cost

- Why do I need to know about HW?
  - Because the characteristics of the machine really matter
    (recall speed of communication issues in class demos)
  - Because you care about efficiency and performance
    (you are writing parallel programs after all)
Course theme 3:
Thinking about efficiency

- FAST ≠ EFFICIENT

- Just because your program runs faster on a parallel computer, it does not mean it is using the hardware efficiently
  - Is 2x speedup on 10 processors a good result?

- Programmer’s perspective: make use of provided machine capabilities

- HW designer’s perspective: choosing the right capabilities to put in system (performance/cost, cost = silicon area?, power?, etc.)
Course logistics
Getting started

- Create an account on the course web site
  - http://15418.courses.cs.cmu.edu

- Sign up for the course on Piazza
  - http://piazza.com/cmu/spring2014/15418/home

- Textbook
  - There is no course textbook, but please see web site for suggested references
Commenting and contributing to lectures

- We have no textbook for this class and so the lecture slides are the primary course reference.

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Question: In 15-213’s web proxy assignment you gained experience writing concurrent programs using pthreads. Think about your motivation for programming with threads in that assignment. How was it different from the motivation to create multi-threaded programs in this class? (e.g., consider Assignment 1, Program 1)

Hint: What is the difference between concurrent execution and parallel execution?
What I am looking for in comments

- Try to explain the slide (as if you were trying to teach your classmate while studying for an exam)
  - “Kayvon said this, but if you think about it this way instead it makes much more sense...”
- Explain what is confusing to you:
  - “What I’m totally confused by here was...”
- Challenge classmates with a question
  - For example, make up a question you think might be on an exam.
- Provide a link to an alternate explanation
  - “This site has a really good description of how multi-threading works...”
- Mention real-world examples
  - For example, describe all the hardware components in the XBox One
- Respectfully respond to another student’s comment or question
  - “@segfault21, are you sure that is correct? I thought that Kayvon said...”
- It is OKAY (and even encouraged) to address the same topic (or repeat someone else’s summary, explanation or idea) in your own words
  - “@funkysenior15s point is that the overhead of communication...”
Assignments

- Four programming assignments
  - First assignment is done individually, the rest may be done in pairs
  - Each uses a different parallel programming environment

Assignment 1: ISPC programming on Intel quad-core CPU
Assignment 2: CUDA programming on NVIDIA GPUs
Assignment 3: OpenMP and MPI programming on a supercomputing cluster
Assignment 4: Create an elastic web server that scales with load
Final project

- 6-week self-selected final project
- May be completed in pairs

Announcing: the THIRD annual 418 parallelism competition!

- Held during the final exam slot
- Non-CMU judges... (previous years: from Intel, NVIDIA)
- Expect non-trivial prizes... (e.g., high-end GPUs, solid state disks) and fame, glory, and respect from your peers.
Grades

39%  Programming assignments (4)
28%  Exams (2)
28%  Final project
5%   Participation (lecture comments)

Each student (or group) gets up to five late days on programming assignments (see web site for details)
Why parallelism?
Why parallel processing?

- **The answer 10-15 years ago**
  - To realize performance improvements that exceeded what CPU performance improvements could provide
  - Because if you just waited until next year, your application would run faster on a new CPU

- **Implication: working to parallelize your code was often not worth the time**
  - Software developer does nothing: CPU performance doubles ~ every 18 months. Woot!

![Relative CPU Performance vs Year Graph](image_credit: Olukutun and Hammond, ACM Queue 2005)
Until 10 years ago: two significant reasons for processor performance improvement

1. Increasing clock frequency

2. Exploiting instruction level parallelism (superscalar execution)
Instruction level parallelism (ILP)

- Processors did in fact leverage parallel execution to make programs run faster, it was just invisible to the programmer

- Instruction level parallelism (ILP)
  - Idea: Instructions are meant to be executed in program order. BUT independent instructions can be executed simultaneously by a processor without changing program correctness
  - Superscalar execution: processor detects independent instructions in an instruction sequence and executes them in parallel
ILP example

\[ a = (x^2 + y^2 + z^2) \]
Diminishing returns of superscalar execution

Most available ILP exploited by processor capable of issuing four instructions per clock

Source: Culler & Singh (data from Johnson 1991)
ILP tapped out + end of frequency scaling

Intel CPU Trends
(sources: Intel, Wikipedia, K. Olukotun)

- Dual-Core Itanium 2
- Pentium 4
- Pentium
- 386

Processor clock rate stops increasing
No further benefit from ILP

Image credit: Herb Sutter
The “power wall”

Per transistor:
dynamic power $\propto$ capacitive load $\times$ voltage$^2$ $\times$ frequency

High power = high heat

Power is a critical design constraint in modern processors

<table>
<thead>
<tr>
<th></th>
<th>TDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel Core i7 (in this laptop):</td>
<td>45W</td>
</tr>
<tr>
<td>Intel Core i7 2700K (fast desktop CPU):</td>
<td>95W</td>
</tr>
<tr>
<td>NVIDIA GTX 780 GPU</td>
<td>250W</td>
</tr>
<tr>
<td>Mobile phone processor</td>
<td>$\frac{1}{2}$ - 2W</td>
</tr>
<tr>
<td>World’s fastest supercomputer</td>
<td>megawatts</td>
</tr>
<tr>
<td>Standard microwave oven</td>
<td>700W</td>
</tr>
</tbody>
</table>

Source: Intel, NVIDIA, Wikipedia, Top500.org
Core voltage increases with frequency

Pentium M CPU

Core Voltage [V]

Power [W]

Image credit: Intel
Single-core performance scaling

The rate of single-instruction stream performance scaling has decreased (essentially to 0)

1. Frequency scaling limited by power
2. ILP scaling tapped out

Architects are now building faster processors by adding processing cores

Software must be written to be parallel to see performance gains. No more free lunch for software developers!
Why parallelism?

- The answer 10 years ago
  - To realize performance improvements that exceeded what CPU performance improvements could provide
    (specifically, in the early 2000’s, what clock frequency scaling could provide)
  - Because if you just waited until next year, your code would run faster on the next generation CPU

- The answer today:
  - Because it is the only way to achieve significantly higher application performance for the foreseeable future *

* We’ll revisit this comment later in the heterogeneous processing lecture
Intel Haswell (2013)

- Quad-core CPU + multi-core GPU integrated on one chip
NVIDIA Kepler GTX 780 GPU (2013)

- Twelve major processing blocks
  (but much, much more parallelism to use... details next class)
Mobile parallel processing

- Power constraints heavily influence design of mobile systems

Apple A7: (in iPhone 5s and modern iPad)
Dual-core CPU + GPU + image processor
and more on one chip

NVIDIA Tegra 4:
Quad core CPU + GPU + image processor...
Supercomputing

- Today: clusters of CPUs + GPUs
- Pittsburgh Supercomputing Center: Blacklight
  - 512 eight-core Intel Xeon processors (4,096 total cores)
Summary

- Single-thread of control performance scaling has ended
  - To run faster, you will need to use multiple processing elements
  - Which means you need to know how to write parallel code

- Writing parallel programs can be challenging
  - Problem partitioning, communication, synchronization
  - Knowledge of machine characteristics is important

- I suspect you will find that modern computers have tremendously more processing power than you might realize, if you just use it!

- Welcome to 15-418!