ECE 454
Computer Systems Programming
Introduction

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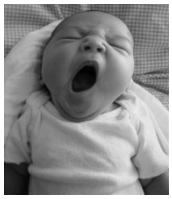
slides courtesy: Greg Steffan

Content of this lecture

- Administration (personnel, policy, agenda, etc.)
  - Boring stuff
    - You can go to sleep now



- Why ECE 454?
  - Fun stuff
    - I will wake you up

Administration

Who am I

- Ding YUAN (call me Ding)
- Research: operating system, software reliability and performance
- Brief BIO:
  - Ph.D. University of Illinois (UIUC), 2012
  - Microsoft Research 2008
  - Technique invented are requested by many large companies
  - Contributed patches to many open-source projects:
    - Linux kernel
    - Hadoop
    - HBase
    - Cassandra
    - Hive
    - …

Personnel

- Instructor:
  - Ding Yuan (*yuan@eecg.toronto.edu*)
  - Office hour: Wednesday after the lecture
  - Office: Sandford Fleming 2002E
  - Homepage: http://www.eecg.toronto.edu/~yuan
- Teaching Assistants:
  - David Lion, Yongle Zhang, Xu Zhao
  - TA available in computer lab GB251 in the first hour of the practice session

Recommended Textbook

- Textbook is not required
  - The relevant contents will be covered in the slides
  - Google & Wikipedia can tell you all
  - I will post some online resources in Piazza
- Randal E. Bryant and David R. O'Hallaron,
  - "Computer Systems: A Programmer's Perspective", 2nd edition, Prentice Hall 2010.

Communications

- Class web site available from instructor's home page
  - http://www.eecg.toronto.edu/~yuan/teaching/ece454/
  - Provides slides, agenda, grading policy, etc.
  - All information regarding to the labs
- Piazza (See course homepage) used for discussion
  - Q/A & discussion with peers, TAs, prof
  - Bonus marks:
    - each instructor endorsed answer on Piazza will get 0.5 bonus marks
    - 1 mark for in-class participation
    - maximum: 2 marks
- UofT Portal is only used for Grades

Policies: Grading

- Exams (65%)
  - Midterm (25%)
  - Final (40%)
  - All exams are close book/close notes.
- Homework (35%)
  - 5 homeworks (varying % each)
  - 10% penalty per day submitted late

Policies: Assignments

- Work groups
  - You can work in groups of two for all labs (or individually)
    - You can change groups for each assignment (if you want)
    - No extensions for group changes mid-assignment
  - Don't put assignment code on public Google or github repositories!
- Handins
  - Electronic hand-ins only
  - Follow the submit procedure (as specified in lab handout)

Policies: Cheating

- Cheating is a serious offence, will be punished harshly
  - 0 grade for assignment, potential for official letter in file.
- What is cheating?
  - Using someone else's solution to finish your assignment to avoid having to understand/learn
  - Sharing code with a non-group-member
  - Copying or retyping
- What is NOT cheating?
  - Helping others use systems or tools.
  - Helping others with high-level design issues.
  - Helping others debug their code.
- We do use cheater-beaters
  - Automatically compares your solutions with others

How NotTo pass ECE454

- Do not come to lecture
  - It's nice out, the slides are online, and material in the book anyway
  - TRUTH: Lecture material is the basis for exams
  - It is much more efficient to learn through discussion
- Copy other people's project
  - It is cheating!
  - How can you answer the questions in midterm or final exams?

How NotTo pass ECE454 (2)

- Do not ask questions in lecture, office hours, or piazza
  - It's scary, I don't want to embarrass myself
  - TRUTH: asking questions is the best way to clarify lecture material at the time it is being presented
    - *"There is no such things as stupid question…"*
- Wait until the last couple of days to start a project
  - The project cannot be done in the last few days

The 'ug' Multicore Machines

Facilities

- Official lab time: Thursdays 12-3 p.m. or 3-6 p.m.
  - Both GB243 and GB 251
  - Optional: you don't have to attend
- Identical workstations:
  - GB243: ug132-ug180
  - SF2102: ug201-ug225
  - GB251: ug226-ug249
  - Develop and measure on any of these
  - Try to measure on an unloaded machine!
- Similar workstations:
  - SF2204: ug51-ug75
  - Can use for development, but don't measure on these!

☞try your UG-machine accesss ASAP!

Before we start

- Any questions?

Why ECE 454?

Why Take this Course?

- Become a superstar programmer
  - Most engineering jobs involve programming
  - Superstar programmers are increasingly in demand
  - *A superstar programmer is worth 1000x normal* – Bill Gates

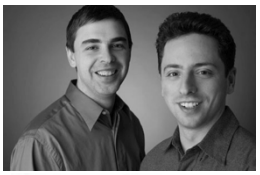
Google Offers Staff Engineer $3.5 Million To Turn Down Facebook Offer

MICHAEL ARRINGTON

Why Take this Course?

- Better understanding of software/hardware interaction
  - Important whether you are a software or hardware type
  - Considering a programming job or grad school
- Jobs and Entrepreneurial Opportunities
  - Computing is at the heart of most interesting ventures

Start a Company in your 20's!



What Good Programmers Care About

1) Readability
2) Debugability
3) Reliability
4) Maintainability

} Productivity (choice of language, practice)

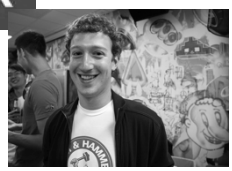
5) Scalability
6) Efficiency

} Performance (systems understanding)

☞ECE 454

Let's be more concrete

- Suppose you're building facebook
  - The "homepage" feature



```
void display_homepage (user) {
  friendlist = get_friendlist (user);
  foreach (friend in friendlist) {
    update = get_update_status (friend);
    display (update);
  }
}
```

☞How can I double the speed?

☞*Easy: TAKE ECE 454!!!*

Pre 2005

- To improve the performance, just buy a new computer

Recent Intel Processors

Year Processor Chip Frequency # Transistors

199

199

199

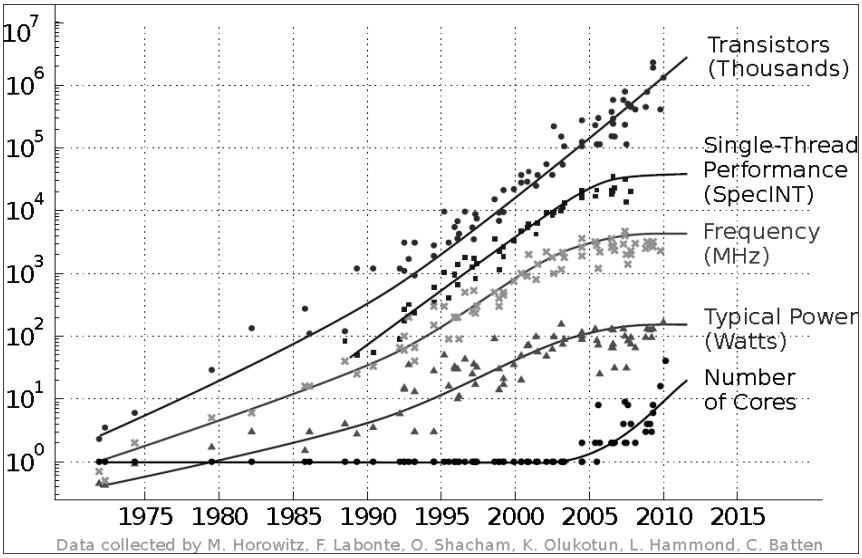
200

"Moore's Law"

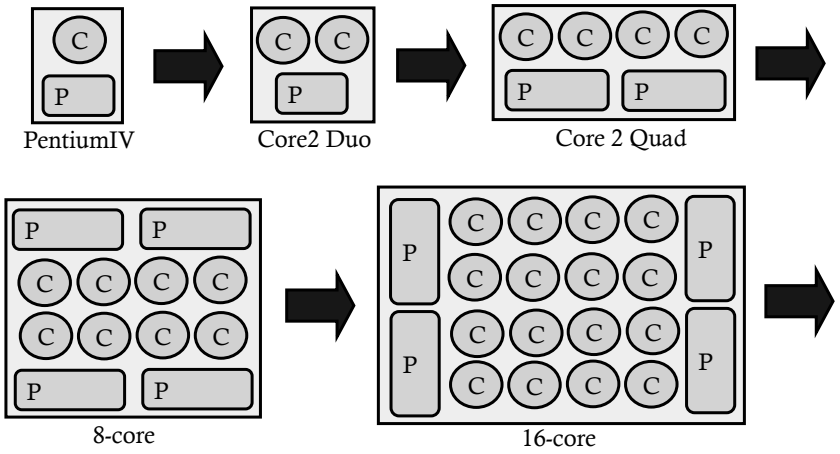
The number of transistors per chip seems to be doubling every 18 months!

Gordon Moore, 1965

Increases in Transistors vs. Clock Freq.



A Multicore Present and Future

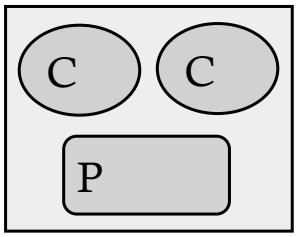


☞ 2x cores every 1-2yrs: 1000 cores by 2020!?

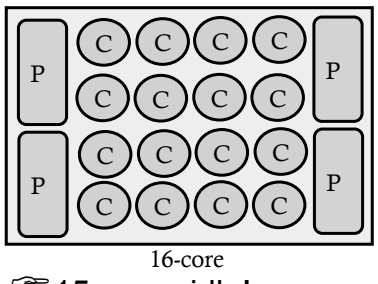
Only One Sequential Program to Run?

Time

```
void display_homepage (user) {
  friendlist = get_friendlist (user);
  foreach (friend in friendlist) {
    update = get_update_status (friend);
    display (update);
  }
}
```



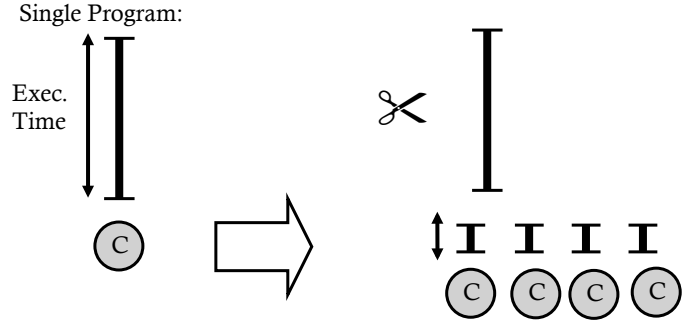
☞ one core idle



☞ 15 cores idle!

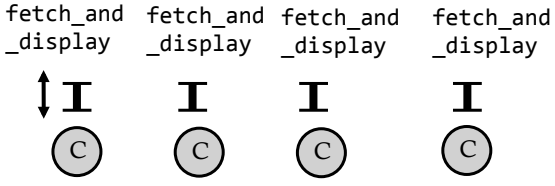
Improving Execution Time

Single Program:



☞need parallel threads to reduce execution time

```
void display_homepage (user) {
  friendlist = get_friendlist (user);
  foreach (friend in friendlist) {
    pthread_create(fetch_and_display, friend);
  }
}

void fetch_and_display (friend) {
   update = get_update_status (friend);
   display (update);
}
```



Punch line: We Must Parallelize All Software!

☞ *You will learn it in ECE 454*

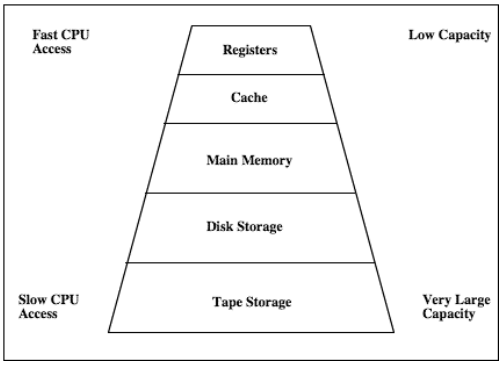
But…

- So far we only discussed CPU
- But is it true that faster CPU -> faster program?
  - *The same program may run slower on a faster CPU. Why?*

```
void display_homepage (user) {
  friendlist = get_friendlist (user);
  foreach (friend in friendlist) {
    update = get_update_status (friend);
    display (update);
  }
}
```

Storage hierarchy

- Your program needs to access data. That takes time!



Numbers everyone should know

- L1 cache reference 0.5 ns* (L1 cache size: < 10 KB)
- Branch mispredict 5 ns
- L2 cache reference 7 ns (L2 cache size: hundreds KB)
- Mutex lock/unlock 100 ns
- Main memory reference 100 ns (mem size: GBs)
- Send 2K bytes over 1 Gbps network 20,000 ns
- Read 1 MB sequentially from memory 250,000 ns
- Round trip within same datacenter 500,000 ns
- Flash drive read 40,000 ns
- Disk seek 10,000,000 ns (10 milliseconds)
- Read 1 MB sequentially from network 10,000,000 ns
- Read 1 MB sequentially from disk 30,000,000 ns
- Send packet Cal.->Netherlands->Cal. 150,000,000 ns

Data from Jeff Dean

**1 ns = 1/1,000,000,000 second*
For a 2.7 GHz CPU (my laptop), 1 cycle = 0.37 ns

Performance optimization is about finding the *bottleneck*

- If you can avoid unnecessary disk I/O
  - ---> your program could be 100,000 times faster
    - Have you heard of Facebook's memcached?
- If you allocate your memory in a smart way
  - ---> your data can fit entirely in cache
    - and your program could be another 100 times faster
    - You will learn this in lab assignments

Back to the Facebook example

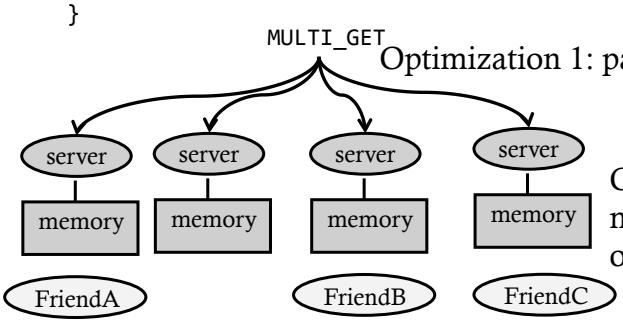
```
void display_homepage (user) {
  friendlist = get_friendlist (user);
  foreach (friend in friendlist) {
    pthread_create(fetch_and_display, friend);
  }
}

void fetch_and_display (friend) {
   update = get_update_status (friend);
   display (update);
}
```

☞Challenge: the data rows are too BIG!

100 Petabytes = 200,000 x my laptop

Back to the Facebook example

```
void display_homepage (user) {
  friendlist = get_friendlist (user);
  updates = MULTI_GET ("updates", friendlist);
  display (updates);
}
```



Optimization 1: parallelization

Opt. 2: Store in memory instead of hard disk

Course Content

Course Breakdown

- Module 1: Code Measurement and Optimization
- Module 2: Memory Management and Optimization
- Module 3A: Multi-core parallelization
- Module 3B: Multi-machine parallelization

1) Code Measurement and Optimization

- Topics
  - Finding the ***bottleneck***!
  - code optimization principles
  - measuring time on a computer and profiling
  - Understanding and using an optimizing compiler
- Assignments
  - HW1: Compiler optimization and program profiling
    - basic performance profiling, finding the bottleneck.

2) Memory Management and Opt.

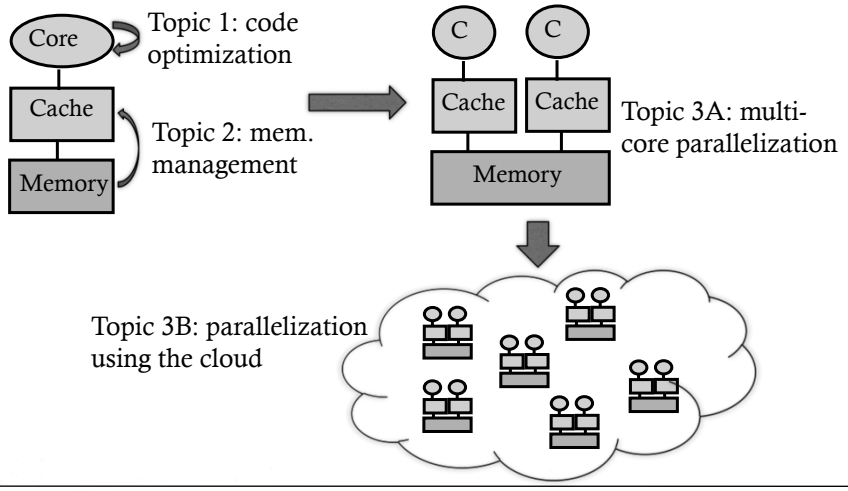
- Topics
  - Memory hierarchy
  - Caches and Locality
  - Virtual Memory

  Note: all involve aspects of software, hardware, and OS
- Assignments
  - HW2: Optimizing Memory Performance
    - profiling, measurement, locality enhancements for cache performance
  - HW3: Writing your own memory allocator package
    - understanding dynamic memory allocation (malloc)

3) Parallelization

- Topics
  - A: Parallel/multicore architectures (high-level understanding)
    - Threads and threaded programming
    - Synchronization and performance
  - B: Parallel on multiple machines
    - Big data & cloud computing
- Assignments
  - HW4: Threads and Synchronization Methods
    - Understanding synchronization and performance
  - HW5: Parallelizing a program
    - Parallelizing and optimizing a program for multicore performance

A big picture



Homework Schedule

- HW1: 2 weeks 5%
- HW2: 2 weeks 7%
- HW3: 4 weeks 9%
- HW4: 1.5 weeks 7%
- HW5: 2 weeks 7%
- 35% total

The bigger picture

- **Optimization is not the ONLY goal!**

1) Readability
2) Debugability
3) Reliability
4) Maintainability

} **More important than performance!!!!**

5) Scalability
6) Efficiency

Premature optimization is the root of all evil!

– Donald Knuth

Example 1

- Premature optimization causing bugs
  - cp /proc/cpuinfo .
    - Created an empty file!!! (Demo)

```
bool copy_reg (.. ) {
  if (src.st_size != 0) {
        /* Copy the file content */
  }
  else {
       /* skip the copy if the file size = 0 */
  }
}
```

⟸ Premature optimization!!!

Example 2

- Optimization might reduce readability

```
int count (unsigned x) {
  int sum = x;
  while (x != 0) {
    x = x >> 1;
    sum = sum – x;
  }
  return sum;
}
```

```
int count (unsigned x) {
  int sum, i;
  sum = x;
  for (i = 1; i < 31; i++) {
    x = rotatel(x, 1);
    sum = sum + x;
  }
  return -sum;
}
```

They're both to count the number of '1' bits in 'x'.
How could someone else is to maintain this code?

```
/*
 * When I wrote this, only God and
 * I understood what I was doing.
 * Now, only God knows
 */
```

But how do I know if my optimization is "*premature*"?

- Hard to answer…
- *"Make it work; Make it right; Make it Fast*" --- Butler Lampson
  - *Purpose of my program?*
    -- e.g., will it have a long lifetime or it's a one-time thing (e.g., hackathon or ACM programming contest)
  - *Am I optimizing for the bottleneck?*
    -- e.g., if the program is doing a lot of I/O, there is no point to optimize for "count the number of bits in an integer"
  - *Am I optimizing for the common case or special case?*
    -- e.g., the "cp" bug was optimizing for a special case…
  - *What's the price I pay? e.g., reduced readability, increase program size, etc.*

- **Again, "Premature optimization is the root of all evils"**
  - If you are only going to remember one thing from ECE 454, *this is it!*
- *And let the fun begin!*