15-213
"The Class That Gives CMU Its Zip!"

Introduction to Computer Systems

Frank Pfenning
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Topics:

- **Theme and objective**
- **Five great realities of computer systems**
- **How this fits within CS curriculum**
- **Course mechanics and overview**

Course Theme

- Abstraction is good, but programs run on real hardware!

Courses to date emphasize abstraction

- Abstract data types
- Asymptotic analysis

These abstractions have limits

- Need to understand underlying implementations
- Performance (time and space)

Useful outcomes

- Become more effective programmers
  - Able to find and eliminate bugs efficiently
  - Able to tune program performance
- Prepare for later “systems” classes in CS & ECE
  - Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems

Great Reality #1

Int's are not Integers, Float's are not Reals

Examples

- **Is $x^2 \geq 0$?**
  - **Float's:** **Yes!**
  - **Int's:**
    - » 40000 * 40000 --> 1600000000
    - » 50000 * 50000 --> ??
- **Is (x + y) + z = x + (y + z)?**
  - **Unsigned & Signed Int's:** **Yes!**
  - **Float's:**
    - » (1e20 + -1e20) + 3.14 --> 3.14
    - » 1e20 + (-1e20 + 3.14) --> ??

Computer Arithmetic

Does not generate random values

- Arithmetic operations have important mathematical properties

Cannot assume “usual” properties

- Due to finiteness of representations
- Integer operations satisfy “ring” properties
  - Commutativity, associativity, distributivity
- Floating point operations satisfy “ordering” properties
  - Monotonicity, values of signs

Observation

- Need to understand which abstractions apply in which contexts
- Important issues for compiler writers and serious application programmers

Great Reality #2

You've got to know assembly

Chances are, you'll never write a program in assembly

- Compilers are much better and more patient than you are

Understanding assembly key to machine-level execution model

- Behavior of programs in presence of bugs
  - High-level language model is inadequate
- Tuning program performance
  - Understanding sources of program inefficiency
- Implementing system software
  - Compiler has machine code as target
  - Operating systems must manage process state

Measuring Time

Trickier than it Might Look

- Many sources of variation

Example

- Sum integers from 1 to n

n	Cycles	Cycles/n
100	961	9.61
1,000	8,407	8.41
1,000	8,426	8.43
10,000	82,861	8.29
10,000	82,876	8.29
1,000,000	8,419,907	8.42
1,000,000	8,425,181	8.43
1,000,000,000	8,371,2305,591	8.37

Great Reality #3

Memory Matters: **Random Access Memory is an un-physical abstraction**

Memory is not unbounded

- It must be allocated and managed
- Many applications are memory dominated

Memory referencing bugs especially pernicious

- Effects are distant in both time and space

Memory performance is not uniform

- Cache and virtual memory effects can greatly affect program performance
- Adapting program to characteristics of memory system can lead to major speed improvements

Memory Referencing Bug Example

```
main ()
{
  long int a[2];
  double d = 3.14;
  a[2] = 1073741824; /* Out of bounds reference */
  printf("d = %.15g\n", d);
  exit(0);
}
```

	Alpha	MIPS	Linux
-g	5.3049847741318e-315	3.1399998664856	3.14
-O	3.14	3.14	3.14

(Linux version gives correct result, but implementing as separate function gives segmentation fault.)

Memory Referencing Errors

C and C++ do not provide any memory protection

- Out of bounds array references
- Invalid pointer values
- Abuses of malloc/free

Can lead to nasty bugs

- Whether or not bug has any effect depends on system and compiler
- Action at a distance
  - Corrupted object logically unrelated to one being accessed
  - Effect of bug may be first observed long after it is generated

How can I deal with this?

- Program in Java, Lisp, ML, or Cyclone
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors

Memory System Performance Example

```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

59,393,288 clock cycles

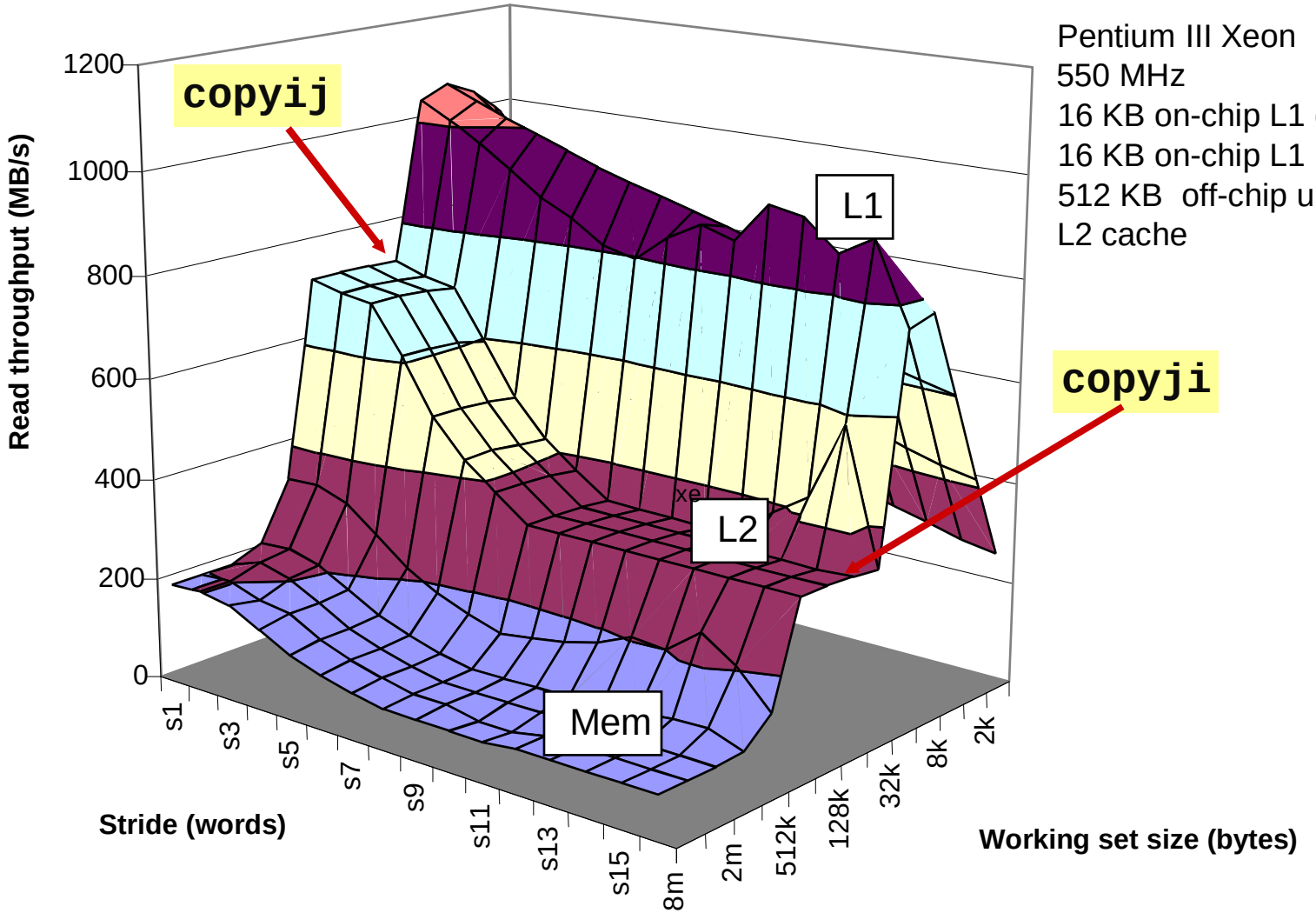
1,277,877,876 clock cycles

21.5 times slower!

(Measured on 2GHz Intel Pentium 4)

- **Hierarchical memory organization**
- **Performance depends on access patterns**
  - **Including how step through multi-dimensional array**

The Memory Mountain



Memory Performance Example

Implementations of Matrix Multiplication

- Multiple ways to nest loops

```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

```
/* jik */
for (j=0; j<n; j++) {
  for (i=0; i<n; i++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

Great Reality #4

There's more to performance than asymptotic complexity

Constant factors matter too!

- Easily see 10:1 performance range depending on how code written
- Must optimize at multiple levels: algorithm, data representations, procedures, and loops

Must understand system to optimize performance

- How programs compiled and executed
- How to measure program performance and identify bottlenecks
- How to improve performance without destroying code modularity and generality

Great Reality #5

Computers do more than execute programs

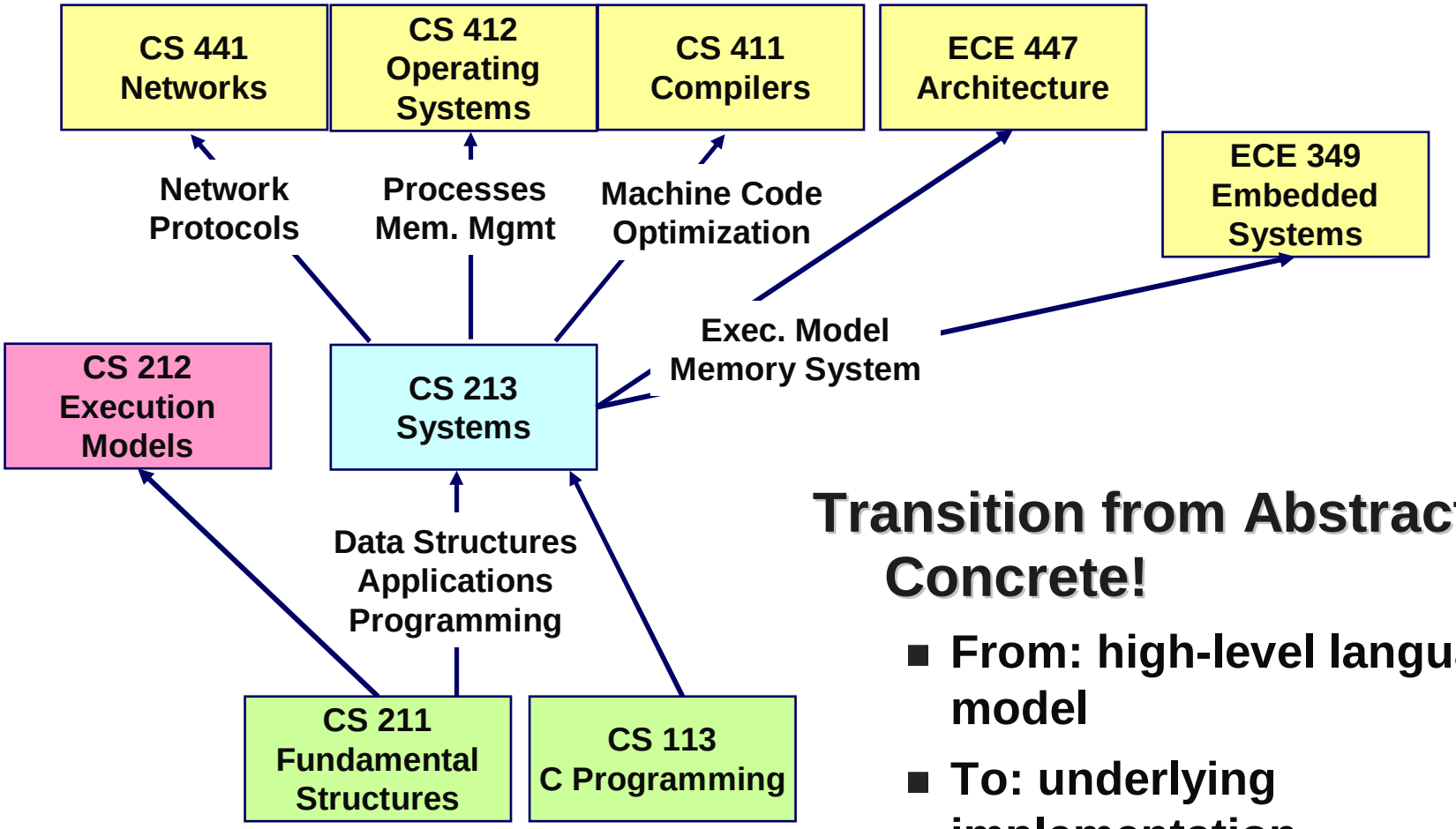
They need to get data in and out

- I/O system critical to program reliability and performance

They communicate with each other over networks

- Many system-level issues arise in presence of network
  - Concurrent operations by autonomous processes
  - Coping with unreliable media
  - Cross platform compatibility
  - Complex performance issues

Role within Curriculum



Transition from Abstract to Concrete!

- From: high-level language model
- To: underlying implementation

Course Perspective

Most Systems Courses are Builder-Centric

- Computer Architecture
  - Design pipelined processor in Verilog
- Operating Systems
  - Implement large portions of operating system
- Compilers
  - Write compiler for simple language
- Networking
  - Implement and simulate network protocols

Course Perspective (Cont.)

Our Course is Programmer-Centric

- **Purpose is to show how by knowing more about the underlying system, one can be more effective as a programmer**
- **Enable you to**
  - **Write programs that are more reliable and efficient**
  - **Incorporate features that require hooks into OS**
    - » E.g., concurrency, signal handlers
- **Not just a course for dedicated hackers**
  - **We bring out the hidden hacker in everyone**
- **Cover material in this course that you won't see elsewhere**

Teaching staff

- **Instructor**
  - **Frank Pfenning (WeH 8117)**
- **TA's (with Mon recitations in OSC 203)**
  - **Yongjun Jeon (10:30)**
  - **Naju Mancheril (11:30)**
  - **Colin Rothwell (12:30)**
  - **Kevin Bowers (1:30)**
  - **Matus Telegarsky (2:30)**
  - **Jernej Barbic (3:30)**
- **Course Admin**
  - **Jenn Landefeld (WeH 8120)**

Come talk to us anytime!
(or phone or send email)

Must go to section that you registered for

Textbooks

Randal E. Bryant and David R. O'Hallaron,

- **"Computer Systems: A Programmer's Perspective", Prentice Hall 2003.**
- **csapp.cs.cmu.edu**

Brian Kernighan and Dennis Ritchie,

- **"The C Programming Language, Second Edition", Prentice Hall, 1988**

Need both, especially for exams and quizzes

Course Components

Lectures

- Higher level concepts and context
- Sometimes differ from book (IA32-EM64T)
- No slides

Recitations

- Applied concepts, important tools and skills for labs, clarification of lectures, review for exams

Labs

- The heart of the course (600 pts out of 1000 for course)
- 1.5 or 2 weeks
- Provide in-depth understanding of an aspect of systems
- Programming and measurement

Quizzes and Exams

Quizzes

- 30 minutes on-line (Blackboard); not before or after exams
- Out Monday, due Tuesday night
- 8 quizzes in total, 15 points each (drop lowest) = 100(+5) pts
- Help you keep up, practice skills for exams

Exams

- 2 exams, 75 points each = 150 pts
- In lecture, open book, open notes, closed computer
- Prior exams available as study aid

Final

- Cumulative, emphasizes last part of course, 150 pts
- Three hour, open book, open notes, closed computer

Getting Help

Web

- http://www.cs.cmu.edu/~fp/courses/15213-s06/
- Copies of lectures, exams, solutions, handouts
- Course schedule
- Blackboard for grades and quizzes

Newsgroup

- cmu.cs.class.cs213
- Clarifications to assignments, general discussion

Personal help

- Frank Pfenning: WeH 8117
  - Use office hour (Wed 2:30-3:30) or stop by
- TAs
  - Email, office hour, phone, stop by (see web page)
  - One lead instructor for each lab

Policies: Assignments

Work groups

- You must work alone on all labs

Handins

- Assignments due at 11:59pm on specified due date
- Typically 11:59pm Tuesday or Thursday evening
- Electronic handins only (no exceptions!)
- 5 grace days to use throughout the term
- At most 2 late days for each lab!

Grading

- Autograding plus code review
  - Code must compile and run
  - Code must be readable and intelligible
- Grade only official handins

Cheating

What is cheating?

- Sharing code: either by copying, retyping, looking at, or supplying a copy of a file
- Coaching: helping your friend to write a lab, line by line
- Printing out or helping each other on quizzes

What is NOT cheating?

- Helping others use systems, compilers, or tools

Penalty for cheating:

- Removal from course with failing grade
- Official letter to dean's office at first offense

Detection of cheating:

- Will use MOSS cheating checker which speaks C!

Policies: Grading

Quizzes (10%)

- 8 quizzes at 15 points each, drop lowest

Exams (30%)

- Two in class exams (75 points each)
- Final (150 points)
- All exams are open book / open notes

Labs (60%)

- 7 labs (60-100 points each)

Grading Characteristics

- Lab scores tend to be high
  - Serious handicap if you don't hand a lab in
- Exams typically have a wider range of scores

Facilities

Assignments will use the Intel Computer Systems Cluster (aka “the fish machines”)

- 12 (+3) Nocona Xeon servers donated by Intel for CS 213
- Dual 3.2 Ghz 64-bit (EM64T) Nocona Xeon processors
- 2 GB, 400MHz DDR2 SDRAM memory
- Running Fedora Core 3 (Linux kernel 2.6.11), 64 bit version
- Rack mounted in the 3rd floor Wean Hall machine room
- Your accounts will be ready by the end of the week
- First lab out next Tuesday

Getting help with the cluster machines:

- See course Web page for info

Account Initialization

For using the Fish machines:

- Read description on the course web-page carefully

For using autolab:

- Give yourself a nickname
- Provide your preferred e-mail address

Course Sections and Labs

Programs and Data (approx 8 lectures)

Memory and Performance (4)

Linking and Exceptional Control Flow (3)

Virtual Memory and Garbage Collection (5)

I/O, Networking, and Concurrency (6)

Programs and Data (8)

Topics

- Bits operations, arithmetic, assembly language programs, representation of C control and data structures
- Includes aspects of architecture and compilers

Assignments

- L1 (datalab): Manipulating bits
- L2 (bomblab): Defusing a binary bomb
- L3 (buflab): Hacking a buffer bomb

Memory and Performance (4)

Topics

- High level processor models, code optimization (control and data), measuring time on a computer
- Memory technology, memory hierarchy, caches, disks, locality
- Includes aspects of architecture, compilers, and OS

Assignments

- L4 (perflab): Optimizing code performance

Linking and Exceptional Control Flow (3)

Topics

- Object files, static and dynamic linking, libraries, loading
- Hardware exceptions, processes, process control, Unix signals, nonlocal jumps
- Includes aspects of compilers, OS, and architecture

Assignments

- L5 (tshlab): Writing your own shell with job control

Virtual Memory and Garbage Collection(5)

Topics

- Virtual memory, address translation, dynamic storage allocation
- Garbage collection for high-level languages
- Debugging and program analysis
- Includes aspects of architecture and OS

Assignments

- L6 (malloclab): Writing your own malloc package

I/O, Networking, and Concurrency (6)

Topics

- High level and low-level I/O, network programming, Internet services, Web servers
- Concurrency, concurrent server design, threads
- Includes aspects of networking, OS, and architecture.

Assignments

- L7 (proxylab): Writing your own Web proxy

Lab Rationale

Each lab should have a well-defined goal such as solving a puzzle or winning a contest

Doing a lab should result in new skills and concepts

- Data Lab: number representations, logic, bit manipulation
- Bomb Lab: assembly, using debugger, understanding stack
- Buffer Lab: awareness of security issues
- Perf Lab: profiling, measurement, performance debugging
- Shell Lab: understanding Unix process control and signals
- Malloc Lab: understanding pointers and nasty memory bugs
- Proxy Lab: network programming, server design

We try to use competition in a fun and healthy way.

- Set a reasonable threshhold for full credit.
- Post intermediate results (anonymized) for glory!

Autolab Web Service

Labs are provided by the Autolab system

- Developed in summer 2003 and 2005 by Dave O'Hallaron
- Apache Web server + Perl CGI programs

With Autolab you can use your Web browser to:

- Review lab notes, clarifications
- Download the lab materials
- Stream autoresults to a class status Web page as you work
- Hand in your code for autograding by the Autolab server
- View the complete history of your code handins, autoresult submissions, autograding reports, and instructor evaluations
- View the class status page

Good Luck and Have Fun!