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

Introduction to Computer Systems

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Topics:
- Theme
- Five great realities of computer systems
- How this fits within CS curriculum
- Staff, text, and policies
- Lecture topics and assignments
- Lab rationale

Course Theme

- Abstraction is good, but don't forget reality!

Courses to date emphasize abstraction
- Abstract data types
- Asymptotic analysis

These abstractions have limits
- Especially in the presence of bugs
- Need to understand underlying implementations

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 --> **-1794967296**
- Is (x + y) + z = x + (y + z)?
  - Unsigned & Signed Int's: Yes!
  - Float's:
    - » (1e20 + -1e20) + 3.14 --> 3.14
    - » 1e20 + (-1e20 + 3.14) --> **0**

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 program in assembly

- Compilers are much better & more patient than you are

Understanding assembly key to machine-level execution model

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

Assembly Code Example

Time Stamp Counter

- Special 64-bit register in Intel-compatible machines
- Incremented every clock cycle
- Read with rdtsc instruction

Application

- Measure time required by procedure
  - In units of clock cycles

```
double t;
start_counter();
P();
t = get_counter();
printf("P required %f clock cycles\n", t);
```


Code to Read Counter

- Write small amount of assembly code using GCC's asm facility
- Inserts assembly code into machine code generated by compiler

```
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

/* Set *hi and *lo to the high and low order bits
   of the cycle counter.
*/
void access_counter(unsigned *hi, unsigned *lo)
{
    asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
        : "=r" (*hi), "=r" (*lo)
        :
        : "%edx", "%eax");
}
```


Code to Read Counter

```
/* Record the current value of the cycle counter. */
void start_counter()
{
    access_counter(&cyc_hi, &cyc_lo);
}

/* Number of cycles since the last call to start_counter. */
double get_counter()
{
    unsigned ncyc_hi, ncyc_lo;
    unsigned hi, lo, borrow;
    /* Get cycle counter */
    access_counter(&ncyc_hi, &ncyc_lo);
    /* Do double precision subtraction */
    lo = ncyc_lo - cyc_lo;
    borrow = lo > ncyc_lo;
    hi = ncyc_hi - cyc_hi - borrow;
    return (double) hi * (1 << 30) * 4 + lo;
}
```

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

Timing System Performance

```
main(int argc, char** argv)
{
  ...
  for (i=0; i<t; i++) {
    start_counter();
    count(n);
    times[i] = get_counter();
  }
  ...
}

int count(int n)
{
  int i;
  int sum = 0;

  for (i=0; i<n; i++) {
    sum += i;
  }
  return sum;
}
```

```
int count(int n)
{
  int i;
  int sum = 0;

  for (i=0; i<n; i++) {
    sum += i;
  }
  return sum;
}

main(int argc, char** argv)
{
  ...
  for (i=0; i<t; i++) {
    start_counter();
    count(n);
    times[i] = get_counter();
  }
  ...
}
```


Timing System Performance

```
main(int argc, char** argv)
{
  ...
}

int count(int n)
{
  ...
}
```

```
int count(int n)
{
  ...
}

main(int argc, char** argv)
{
  ...
}
```

Experiment	n	cycles/n
1	10	1649.2
2	10	17.2
3	1000	24.3
4	1000	6.1

Experiment	n	cycles/n
1	10	1657.6
2	10	26
1a	10	20
2a	10	16.4
3a	1000	1.7
4a	1000	1.6

It's the system, stupid!

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 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 bugs especially pernicious

- Effects are distant in both time and space

Memory Performance Example

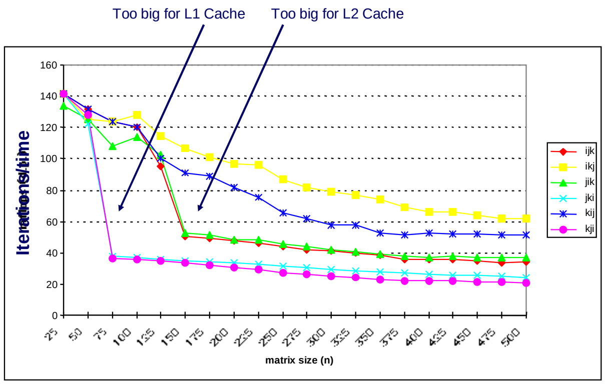
Implementations of Matrix Multiplication

- Multiple ways to nest loops

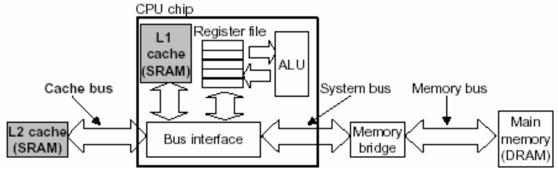
```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

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

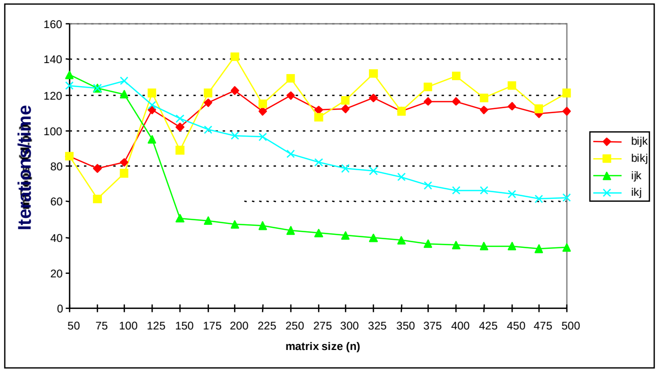

Matmult Performance (Alpha 21164)



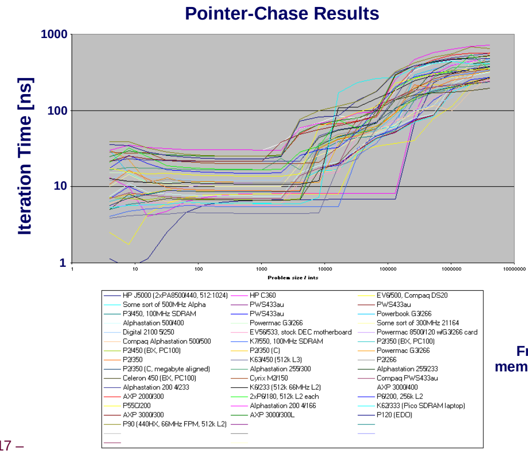
Memory System



Blocked matmult perf (Alpha 21164)



Real Memory Performance



From Tom Womack's memory latency benchmark

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	5.30498947741318e-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, or ML
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors

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

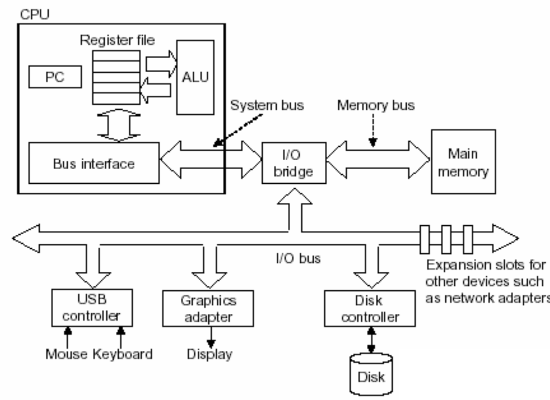
They need to get data in and out

- I/O system critical to program reliability and performance

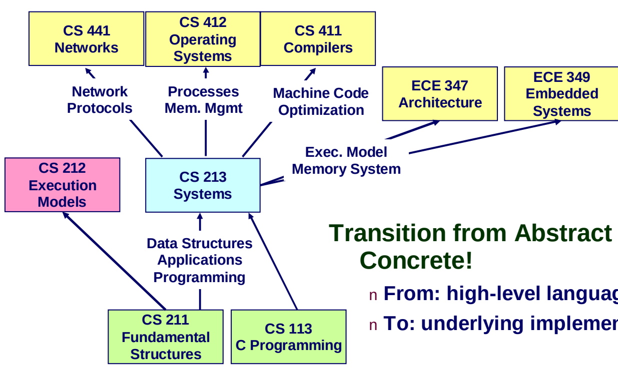
They communicate with each other over networks

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

Hardware Organization (Naïve)



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 knowing more about the underlying system, leads one to be a more effective 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

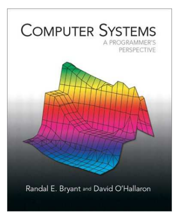
- Instructors
  - Prof. Seth Goldstein (Wed 1--2pm, WeH 7122)
  - Prof. Andreas Nowatzyk (Tue 3--4pm, NSH 4117)
- TA's
  - Ningning Hu (A, Tue 5--6pm, WeH 8205)
  - Carolyn Au (B, Wed 3--4pm, WeH 3108)
  - David Charlton (C, Fri 11:30--12:30pm, Weh 3108)
  - David Fields (D, Wed 12:30am--1:30pm, Weh 3108)
  - Mike Nollen (E, Thu 3--4pm, Weh 3108)
- Course Admin
  - Norene Mears (WeH 7114)

These are the nominal office hours. Come talk to us anytime!
(Or phone or send email)

Textbooks

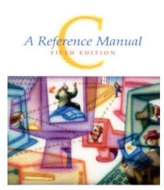
Randal E. Bryant and David R. O'Hallaron,

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



Samuel P. Harbison III and Guy L. Steele Jr.,

- "C A Reference Manual 5th Edition", Prentice Hall, 2002
- http://careferencemanual.com/



Course Components

Lectures

- Higher level concepts

Recitations

- Applied concepts, important tools and skills for labs, clarification of lectures, exam coverage

Labs

- The heart of the course
- 1, 2, or 3 weeks
- Provide in-depth understanding of an aspect of systems
- Programming and measurement

Getting Help

Web

- www.cs.cmu.edu/~213
- Copies of lectures, assignments, exams, solutions
- Clarifications to assignments

Newsgroup

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

Personal help

- Professors: door open means come on in (no appt necessary)
- TAs: please mail or zephyr first.

Policies: Assignments

Work groups

- Labs: You must work alone on all labs

Handins

- Assignments due at 11:59pm on specified due date
- Typically 11:59pm Wednesday evening
- Electronic handins only
- Allowed a total of up to 5 late days for the semester

Makeup exams and assignments

- OK, but must make PRIOR arrangements with either Prof. Goldstein or Nowatzyk

Appealing grades

- Within 7 days of due date or exam date
- Assignments: Talk to the lead person on the assignment
- Exams: Talk to either Prof. Goldstein or Nowatzyk

Cheating

What is cheating?

- Sharing code: either by copying, retyping, looking at, or supplying a copy of a file.
- Using solutions or tools other than those from the course book, lectures, or staff.

What is NOT cheating?

- Helping others use systems or tools.
- Helping others with high-level design issues.
- Helping others debug their code.

Usual penalty for cheating:

- Removal from course with failing grade.
- Note in student's permanent record

Policies: Grading

Exams (40%)

- Two in class exams (10% each)
- Final (20%)
- All exams are open book/open notes.

Labs (60%)

- 7 labs (8-12% each)

Grading Characteristics

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

Facilities

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

- 25 Pentium III Xeon servers donated by Intel for CS 213
- 550 MHz with 256 MB memory.
- Rack mounted in the 3rd floor Wean machine room.
- We'll be setting up your accounts this week.

Getting help with the cluster machines:

- See course Web page for info
- Please direct questions to your TAs

Programs and Data

Topics

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

Assignments

L1 Available THUR! (Due 1/25 11:59pm)

- L1: Manipulating bits
- L2: Defusing a binary bomb
- L3: Hacking a buffer bomb

Performance

Topics

- High level processor models, code optimization (control and data), measuring time on a computer
- Includes aspects of architecture, compilers, and OS

Assignments

- L4: Optimizing Code Performance

The Memory Hierarchy

Topics

- Memory technology, memory hierarchy, caches, disks, locality
- Includes aspects of architecture and OS.

Assignments

- L4: Optimizing Code Performance

Linking and Exceptional Control Flow

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: Writing your own shell with job control

Virtual memory

Topics

- Virtual memory, address translation, dynamic storage allocation
- Includes aspects of architecture and OS

Assignments

- L6: Writing your own malloc package

I/O, Networking, and Concurrency

Topics

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

Assignments

- L7: Writing your own Web proxy

Lab Rationale

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

- Defusing a binary bomb.
- Winning a performance contest.

Doing a lab should result in new skills and concepts

- Data Lab: computer arithmetic, digital logic.
- Bomb Labs: assembly language, using a debugger, understanding the stack
- 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 threshhold for full credit.
- Post intermediate results (anonymized) on Web page for glory!

Autolab Web Service

Labs are provided by the Autolab system

- Developed in summer 2003 by Dave O'Hallaron
- Apache Web server + Perl CGI programs
- Beta tested in Fall 2003, so of course, bug free now

With Autolab you can use your Web browser to:

- Review lab notes
- Download the lab materials
- Stream autoresults to a class status Web page as you work.
- Upload (handin) 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

Acknowledgement

15-213 was developed and fine-tuned by Randal E. Bryant and David O'Hallaron. They wrote *The Book*!

Have a Great Semester!