Course Overview

15-213: Introduction to Computer Systems
1\textsuperscript{st} Lecture, Aug. 24, 2010

\textbf{Instructors:}
Randy Bryant and Dave O’Hallaron

\textit{The course that gives CMU its “Zip”!}
Overview

- Course theme
- Five realities
- How the course fits into the CS/ECE curriculum
- Logistics
Course Theme: Abstraction Is Good But Don’t Forget Reality

- Most CS and CE courses emphasize abstraction
  - Abstract data types
  - Asymptotic analysis

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

- Useful outcomes
  - Become more effective programmers
    - Able to find and eliminate bugs efficiently
    - Able to understand and tune for program performance
  - Prepare for later “systems” classes in CS & ECE
    - Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems
Great Reality #1:
Ints are not Integers, Floats are not Reals

■ Example 1: Is \( x^2 \geq 0? \)
  - Float’s: Yes!
  - Int’s:
    - \( 40000 \times 40000 \rightarrow 1600000000 \)
    - \( 50000 \times 50000 \rightarrow ?? \)

■ Example 2: Is \( (x + y) + z = x + (y + z)? \)
  - Unsigned & Signed Int’s: Yes!
  - Float’s:
    - \( (1e20 + -1e20) + 3.14 \rightarrow 3.14 \)
    - \( 1e20 + (-1e20 + 3.14) \rightarrow ?? \)

Source: xkcd.com/571
Code Security Example

```c
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

- Similar to code found in FreeBSD’s implementation of getpeername
- There are legions of smart people trying to find vulnerabilities in programs
Typical Usage

```c
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}

#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, MSIZE);
    printf("%s\n", mybuf);
}
```
Malicious Usage

```c
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}

#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, -MSIZE);
    . . .
}
```
Computer Arithmetic

- Does not generate random values
  - Arithmetic operations have important mathematical properties

- Cannot assume all "usual" mathematical 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 programs in assembly
  - Compilers are much better & more patient than you are
- But: Understanding assembly is key to machine-level execution model
  - Behavior of programs in presence of bugs
    - High-level language models break down
  - Tuning program performance
    - Understand optimizations done / not done by the compiler
    - Understanding sources of program inefficiency
  - Implementing system software
    - Compiler has machine code as target
    - Operating systems must manage process state
  - Creating / fighting malware
    - x86 assembly is the language of choice!
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 (in clock cycles) required by procedure

```c
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

```c
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");
}
```
Great Reality #3: Memory Matters
Random Access Memory Is an Unphysical 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

double fun(int i)
{
    volatile double d[1] = {3.14};
    volatile long int a[2];
    a[i] = 1073741824; /* Possibly out of bounds */
    return d[0];
}

fun(0) ➞  3.14
fun(1) ➞  3.14
fun(2) ➞  3.1399998664856
fun(3) ➞  2.00000061035156
fun(4) ➞  3.14, then segmentation fault

- Result is architecture specific
Memory Referencing Bug Example

double fun(int i)
{
    volatile double d[1] = {3.14};
    volatile long int a[2];
    a[i] = 1073741824; /* Possibly out of bounds */
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fun(0) ➞ 3.14
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fun(3) ➞ 2.00000061035156
fun(4) ➞ 3.14, then segmentation fault

Explanation:

<table>
<thead>
<tr>
<th>Saved State</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>d7 ... d4</td>
<td>3</td>
</tr>
<tr>
<td>d3 ... d0</td>
<td>2</td>
</tr>
<tr>
<td>a[1]</td>
<td>1</td>
</tr>
<tr>
<td>a[0]</td>
<td>0</td>
</tr>
</tbody>
</table>

Location accessed by fun(i)
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, Ruby or ML
  - Understand what possible interactions may occur
  - Use or develop tools to detect referencing errors (e.g. Valgrind)
Memory System Performance Example

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

```c
void copyji(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 copyij(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];
}
```

21 times slower (Pentium 4)
The Memory Mountain

Copy

Intel Core i7
2.67 GHz
32 KB L1 d-cache
256 KB L2 cache
8 MB L3 cache
Great Reality #4: There’s more to performance than asymptotic complexity

- Constant factors matter too!
- And even exact op count does not predict performance
  - 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
Example Matrix Multiplication

Matrix-Matrix Multiplication (MMM) on 2 x Core 2 Duo 3 GHz (double precision) Gflop/s

- Standard desktop computer, vendor compiler, using optimization flags
- Both implementations have exactly the same operations count \((2n^3)\)
- What is going on?

Best code (K. Goto)
Matrix-Matrix Multiplication (MMM) on 2 x Core 2 Duo 3 GHz

Gflop/s

Reason for 20x: Blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice

Effect: fewer register spills, L1/L2 cache misses, and TLB misses
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 CS/ECE Curriculum

CS 213
ECE 243

Foundation of Computer Systems
Underlying principles for hardware, software, and networking

CS 123
C Programming

CS 415
Databases

CS 441
Networks

CS 410
Operating Systems

CS 411
Compilers

ECE 340
Digital Computation

ECE 447
Architecture

ECE 349
Embedded Systems

ECE 545/549
Capstone

Data Reps.
Memory Model

Network Protocols

Processes Mem. Mgmt

Machine Code

Arithmetic

Execution Model Memory System
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

Randy Bryant

Dave O’Hallaron
Textbooks

- Randal E. Bryant and David R. O’Hallaron,
  - [http://csapp.cs.cmu.edu](http://csapp.cs.cmu.edu)
  - This book really matters for the course!
    - How to solve labs
    - Practice problems typical of exam problems

- Brian Kernighan and Dennis Ritchie,
Course Components

- Lectures
  - Higher level concepts

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

- Labs (7)
  - The heart of the course
  - 1-2 weeks each
  - Provide in-depth understanding of an aspect of systems
  - Programming and measurement

- Exams (2 + final)
  - Test your understanding of concepts & mathematical principles
Getting Help

- Class Web Page: http://www.cs.cmu.edu/~213
  - Complete schedule of lectures, exams, and assignments
  - Copies of lectures, assignments, exams, solutions
  - Clarifications to assignments

- Message Board
  - We won’t be using Blackboard for the course
Getting Help

- **Staff mailing list:** 15-213-staff@cs.cmu.edu
  - Use this for all communication with the teaching staff
  - Always CC staff mailing list during email exchanges
  - Send email to individual instructors only to schedule appointments

- **Office hours:**
  - MTWR, 5:30-7:30pm, WeH 5207

- **1:1 Appointments**
  - You can schedule 1:1 appointments with any of the teaching staff
Policies: Assignments (Labs) And Exams

- **Work groups**
  - You must work alone on all assignments

- **Handins**
  - Assignments due at 11:59pm on Tues or Thurs evening
  - Electronic handins using Autolab (no exceptions!)

- **Conflict exams, other irreducible conflicts**
  - OK, but must make PRIOR arrangements with Prof. O’Hallaron
  - Notifying us well ahead of time shows maturity and makes us like you more (and thus to work harder to help you out of your problem)

- **Appealing grades**
  - Within 7 days of completion of grading
    - Following procedure described in syllabus
  - Labs: Email to the staff mailing list
  - Exams: Talk to Prof. O’Hallaron
Facilities

- Labs will use the Intel Computer Systems Cluster (aka “the shark machines”)
  - 21 servers donated by Intel for ICS
    - 10 student machines (for student logins)
    - 1 head node (for Autolab server and instructor logins)
    - 10 grading machines (for autograding)
  - Each server: 8 Nehalem cores, 32 GB DRAM
  - Running Andrew Red Hat Enterprise Linux
  - Rack mounted in Gates machine room
  - Your accounts are ready or nearing readiness
  - Login using your Andrew ID and password

- Getting help with the cluster machines:
  - Please direct questions to staff mailing list
Timeliness

■ Grace days
  ▪ **3 grace days** for the course
  ▪ Limit of **1 grace day** per lab used automatically
  ▪ Covers scheduling crunch, out-of-town trips, illnesses, minor setbacks
  ▪ Save them until late in the term!

■ Lateness penalties
  ▪ Once grace day(s) used up, get penalized **20% per day**
  ▪ No handins later than **3 days after due date**

■ Catastrophic events
  ▪ Major illness, death in family, ...
  ▪ Formulate a plan (with your academic advisor) to get back on track

■ Advice
  ▪ Once you start running late, it’s really hard to catch up
Cheating

- What is cheating?
  - Sharing code: by copying, retyping, looking at, or supplying a file
  - Coaching: helping your friend to write a lab, line by line
  - Copying code from previous course or from elsewhere on WWW
    - Only allowed to use code we supply, or from CS:APP website
- What is NOT cheating?
  - Explaining how to use systems or tools
  - Helping others with high-level design issues
- Penalty for cheating:
  - Removal from course with failing grade
  - Permanent mark on your record
- Detection of cheating:
  - We do check
  - Our tools for doing this are much better than most cheaters think!
Other Rules of the Lecture Hall

- Laptops: permitted

- Electronic communications: **forbidden**
  - No email, instant messaging, cell phone calls, etc

- Presence in lectures, recitations: voluntary, recommended
Policies: Grading

- Exams (50%): weighted 12.5%, 12.5%, 25% (final)

- Labs (50%): weighted according to effort

- Guaranteed:
  - > 90%: A
  - > 80%: B
  - > 70%: C
Programs and Data

- **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
The Memory Hierarchy

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

Assignments
  - Learn how to exploit locality in your programs.
Performance

Topics

- Co-optimization (control and data), measuring time on a computer
- Includes aspects of architecture, compilers, and OS
Exceptional Control Flow

- **Topics**
  - Hardware exceptions, processes, process control, Unix signals, nonlocal jumps
  - Includes aspects of compilers, OS, and architecture

- **Assignments**
  - L5 (proclab): Writing puzzles using processes and signals.
    - A first introduction to concurrency
Virtual Memory

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

- Assignments
  - L6 (mallocclab): Writing your own malloc package
    - Get a real feel for systems programming
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 (proxylab): Writing your own Web proxy
  - Learn network programming and more about concurrency and synchronization.
Lab Rationale

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

- Doing the lab should result in new skills and concepts

- We try to use competition in a fun and healthy way
  - Set a reasonable threshold for full credit
  - Post intermediate results (anonymized) on Web page for glory!
Autolab Web Service

Labs are provided by the Autolab system

- Autograding system developed by Hunter Pitelka and Dave O’Hallaron
- Using transient VMs on-demand to autograde untrusted code.
- Beta testing version 2.0 in Fall 2010
- Precursor to worldwide autograding system

With Autolab you can use your Web browser to:

- Review lab notes, clarifications
- Download the lab materials
- Stream autoresults to a Web scoreboard as you work
- 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 scoreboard
Welcome and Enjoy!