Course Overview

15-213/18-243: Introduction to Computer Systems

1st Lecture, 11 January 2010

Instructors:

Bill Nace and Gregory Kesden

The course that gives CMU its "Zip"!

Overview

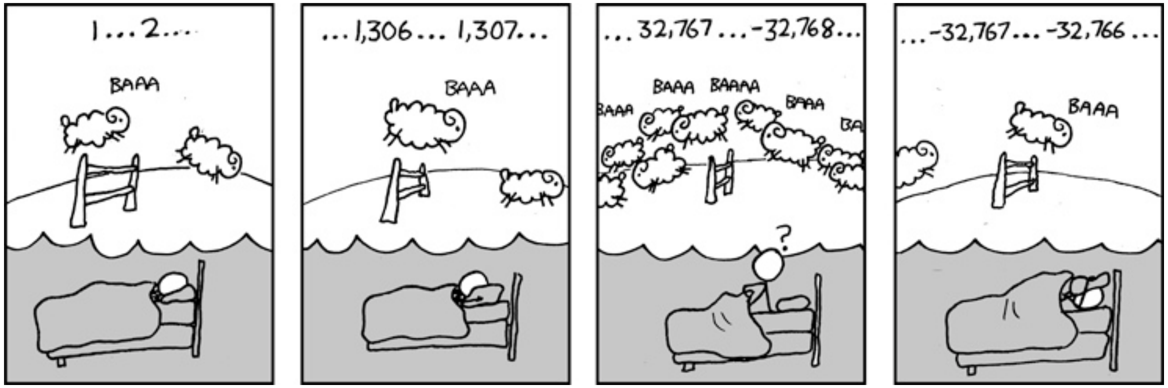
- Course theme
- Five realities
- How the course fits into the CS/ECE curriculum
- Logistics

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 * 40000 → 1600000000
    - 50000 * 50000 → ??
- **Example 2: Is (x + y) + z = x + (y + z)?**
  - Unsigned & Signed Int's: Yes!
  - Float's:
    - (1e20 + -1e20) + 3.14 --> 3.14
    - 1e20 + (-1e20 + 3.14) --> ??

xkcd.com/571

Code Security Example

```
/* 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

```
/* 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

```
/* 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

```
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");
}
```

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**
  - I execute up to fun(11) on my Core 2 Duo Mac

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
```

Explanation:

Saved State	4
d7 ... d4	3
d3 ... d0	2
a[1]	1
a[0]	0

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

Memory System Performance Example

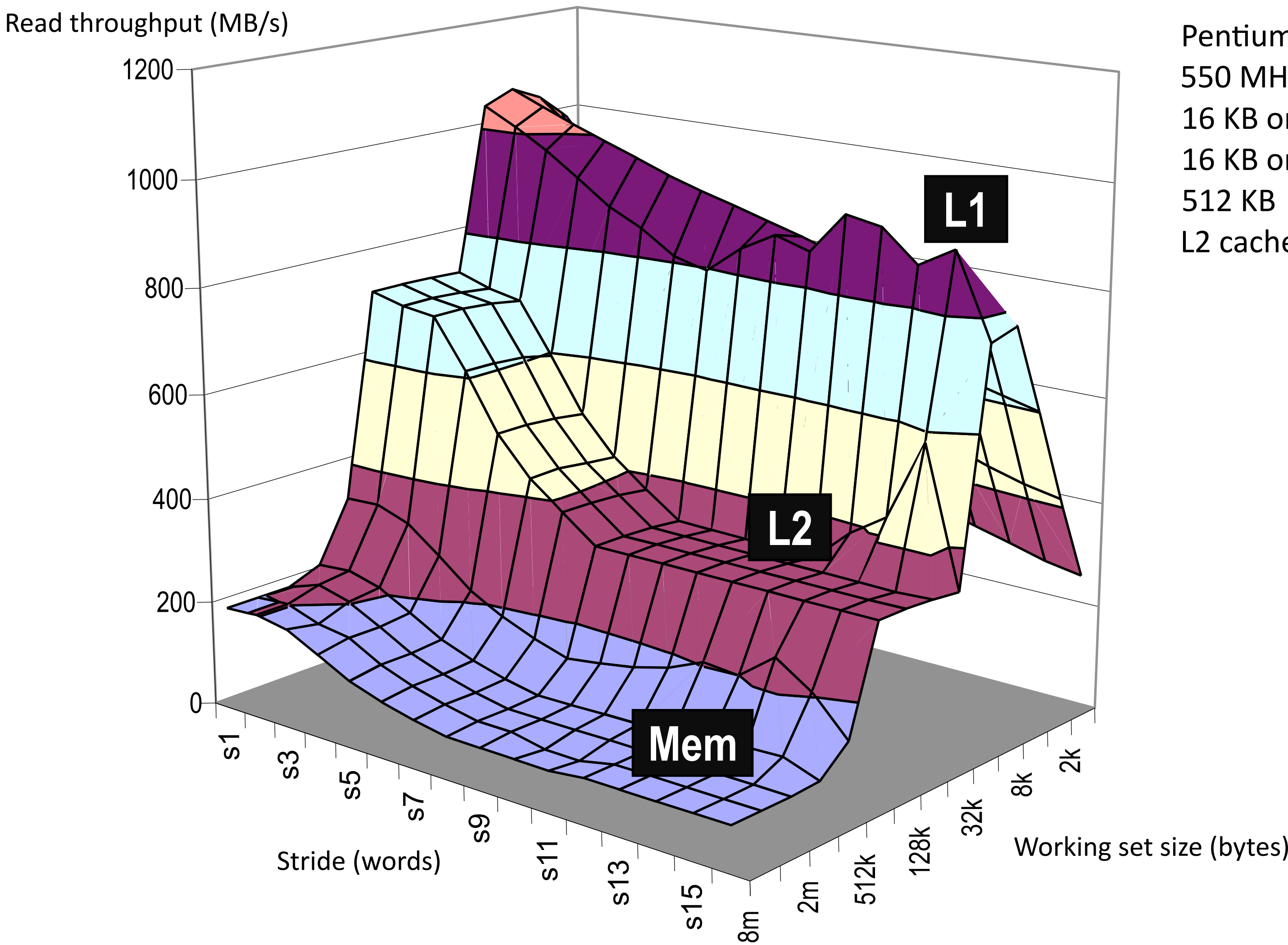
```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
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];
}
```

21 times slower (Pentium 4)

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

The Memory Mountain

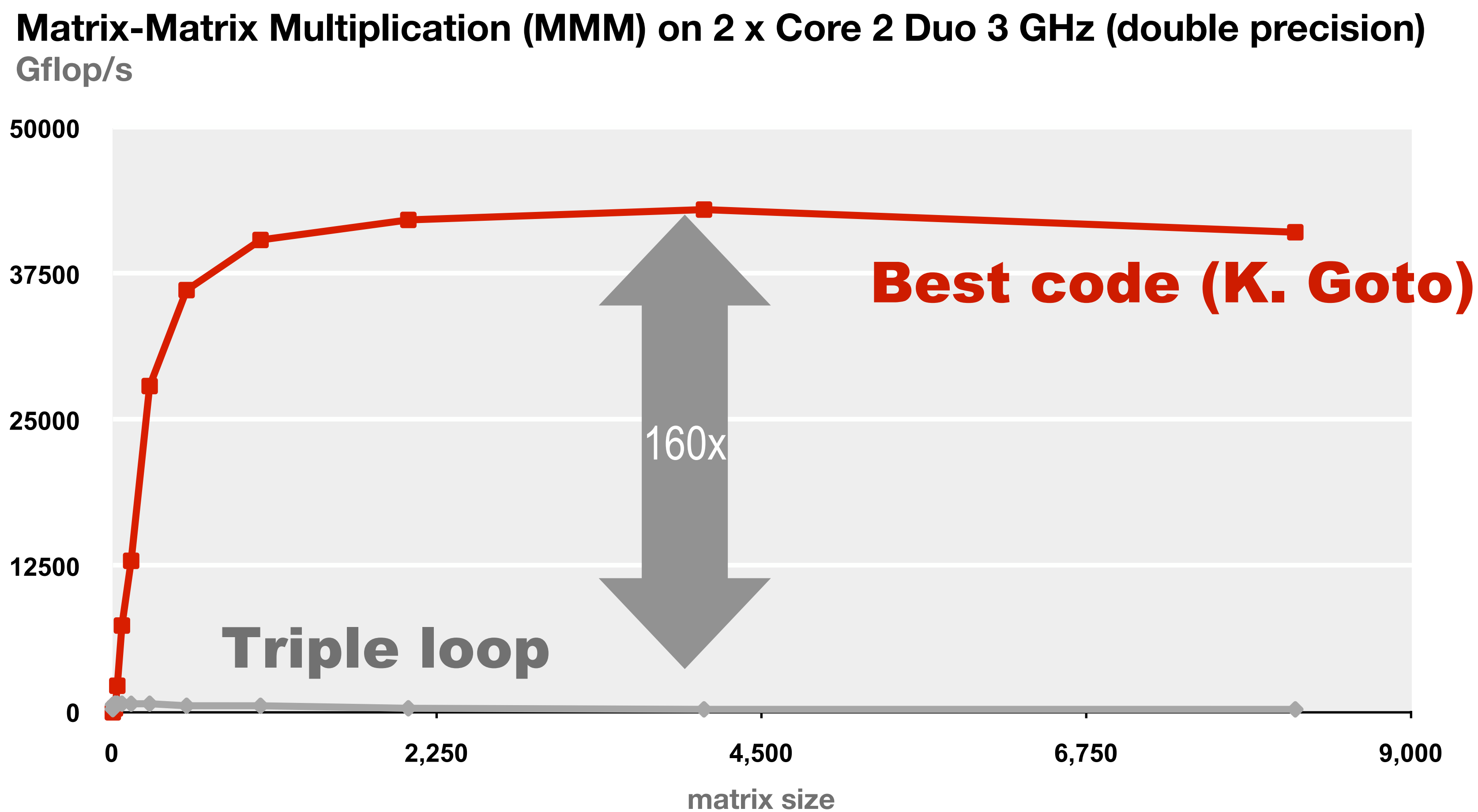


Pentium III Xeon
550 MHz
16 KB on-chip L1 d-cache
16 KB on-chip L1 i-cache
512 KB off-chip unified
L2 cache

Great Reality #4: There's more to performance than asymptotic complexity

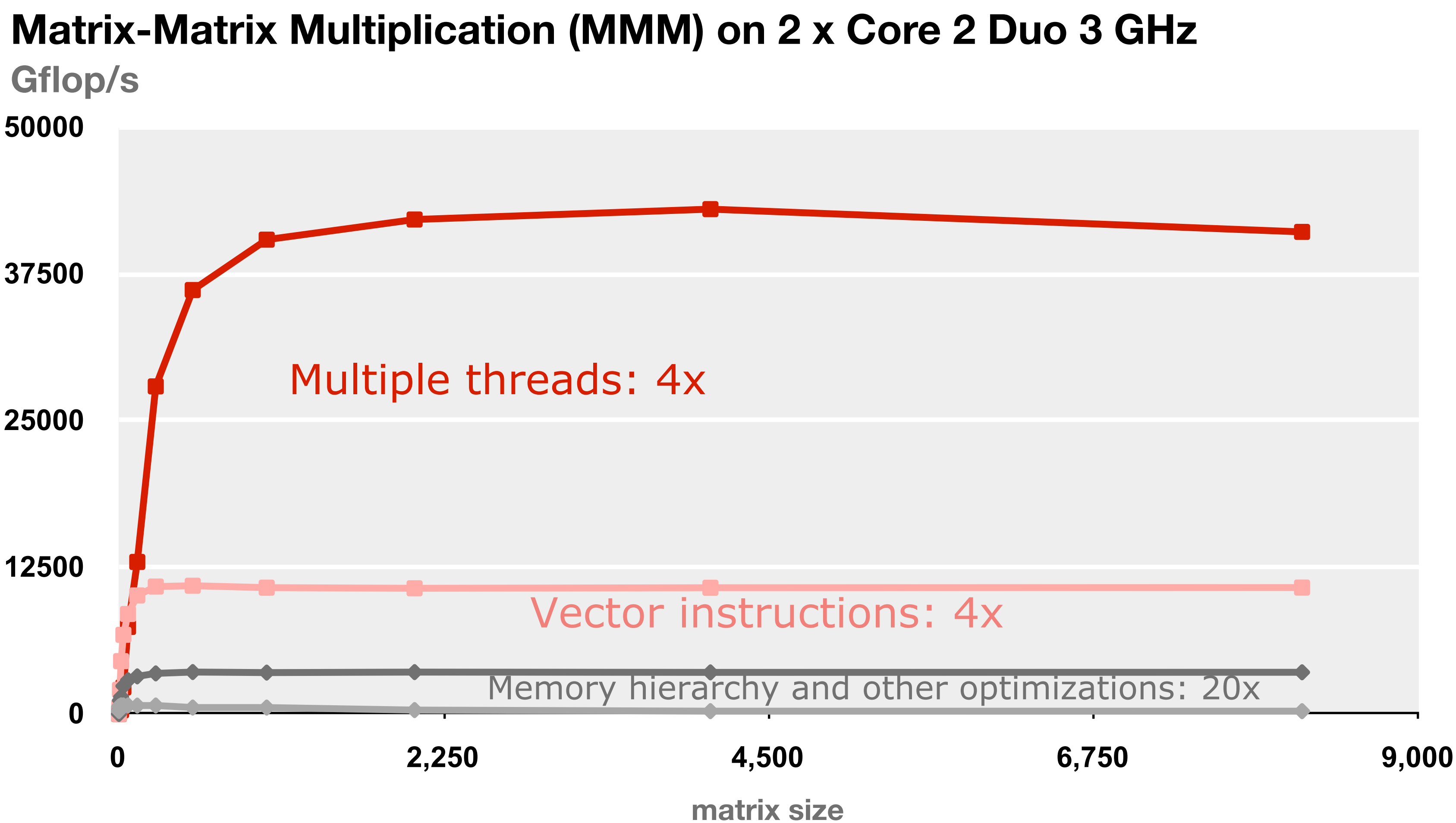
- **Constant factors matter too!**
- **And even exact op count does not predict performance**
  - Easily see 10:1 performance range depending on how code written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- **Must understand system to optimize performance**
  - 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



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

MMM Plot: Analysis



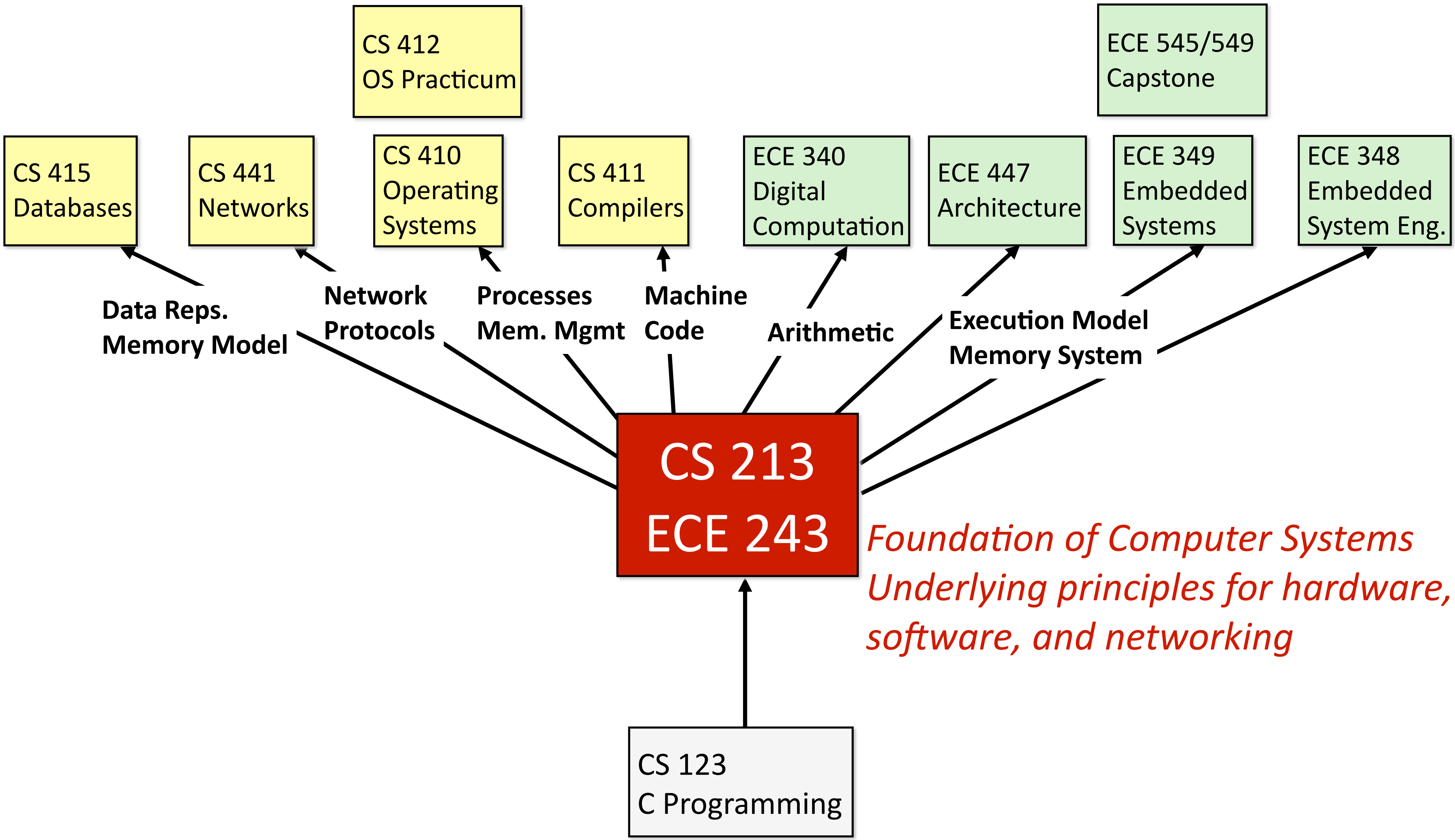
- Reason for 20x: Blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice
- ***Effect: less register spills, less L1/L2 cache misses, less TLB misses***

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



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

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

- **Instructors**
  - Prof. Gregory Kesden
  - Prof. Bill Nace
- **TA's**
  - Dan Burrows
  - Timothy Douglas
  - Joel Feinstein
  - Jason Franklin
  - Alex Gartrell
  - Ted Martin
  - Machong (Mike) Mu
  - Hunter Pitelka
  - Josh Primero
  - Tom Tuttle
- **Course Admin**
  - Cindy Chemsak (NSH 4303)

We're glad to talk with you, but please send email or phone first

```
if (you_love('C')){
   honk( );
   }
```

Textbooks

- **Randal E. Bryant and David R. O'Hallaron,**
  - "Computer Systems: A Programmer's Perspective", Prentice Hall 2003
  - 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,**
  - "The C Programming Language, Second Edition", Prentice Hall, 1988

Course Components

- **Lectures**
  - Higher level concepts
- **Recitations**
  - Applied concepts, important tools and skills for labs, clarification of lectures, exam coverage
- **Labs (6)**
  - The heart of the course
  - 2 or 3 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
  - Copies of lectures, assignments, exams, solutions
  - Clarifications to assignments

- **Message Board**
  - http://autolab.cs.cmu.edu
  - Clarifications to assignments, general discussion
  - The only board your instructors will be monitoring (No Blackboard)

Getting Help

- **Staff mailing list**
  - 15-213-staff@cs.cmu.edu
  - "The autolab server is down!"
  - "Who should I talk to about ..."
  - "This code {...}, which I don't want to post to the bboard, causes my computer to melt into slag."
- **Teaching assistants**
  - I don't get "associativity"...
  - Office hours, e-mail, by appointment
    - Please send mail to 15-213-staff, *not a randomly-selected TA*
- **Professors**
  - Office hours or appointment
  - "Should I drop the class?" "A TA said ... but ..."

Getting Help: Office Hours

- **Kesden: see course website**
- **Nace: Wednesdays, 2:00pm - 4:30pm**

- **TAs:**
  - Sundays – Thursdays, 6:00pm – 9:00pm
  - Wean Hall 5207 cluster

Policies: Assignments (Labs) And Exams

- **Work groups**
  - You must work alone unless told otherwise in writing
- **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. Kesden / Nace
  - 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. Kesden / Nace

Facilities

- **Labs will use the Intel Computer Systems Cluster (aka “the fish machines”)**
  - 15 Pentium Xeon servers donated by Intel for CS 213
  - Dual 3.2 Ghz 64-bit (EM64T) Nocona Xeon processors
  - 2 GB, 400 MHz DDR2 SDRAM memory
  - Rack mounted in the 3rd floor Wean Hall machine room
  - Your accounts are ready or nearing readiness
- **Getting help with the cluster machines:**
  - See course Web page for login directions
  - Please direct questions to your TA’s first

Timeliness

- **Grace days**
  - **4 for the course**
  - Covers scheduling crunch, out-of-town trips, illnesses, minor setbacks
  - Save them until late in the term!
- **Lateness penalties**
  - Once grace days used up, get penalized 15% / day
  - Typically shut off all handins 2—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: weighted ¼, ¼, ½ (final)**
- **Labs: weighted according to effort (determined near the end)**

- **The lower of lab score and exam score is weighted 60%, the higher 40%:**
  - Lab score: $0 \leq L \leq 100$,
    Exam score: $0 \leq E \leq 100$
    Total score: 0.6 min(L, E) + 0.4 max(L,E)

- **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

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**
  - L4 (tshlab): Writing your own shell with job control

Virtual Memory

- **Topics**
  - Virtual memory, address translation, dynamic storage allocation
  - Includes aspects of architecture and OS
- **Assignments**
  - L5 (malloclab): 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**
  - L6 (proxylab): Writing your own Web proxy

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 handin system developed in 2003 by Dave O'Hallaron
  - Apache Web server + Perl CGI programs
  - Beta tested Fall 2003, very stable by now
- **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
  - 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

Have Fun!