Introduction to Computer Systems

15-213/18-243, spring 2009

1st Lecture, Jan. 12th

Instructors:

Gregory Kesden and Markus Püschel

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 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: Int's are not Integers, Float's 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) --> ??

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 */
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    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 program in assembly**
  - Compilers are much better & more patient than you are
- **But: Understanding assembly key to machine-level execution model**
  - Behavior of programs in presence of bugs
    - High-level language model breaks 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
```

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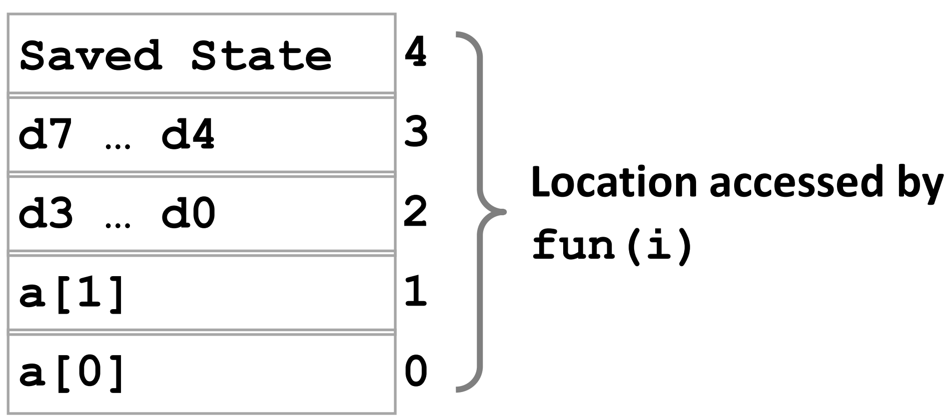
Explanation:



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

Memory System Performance Example

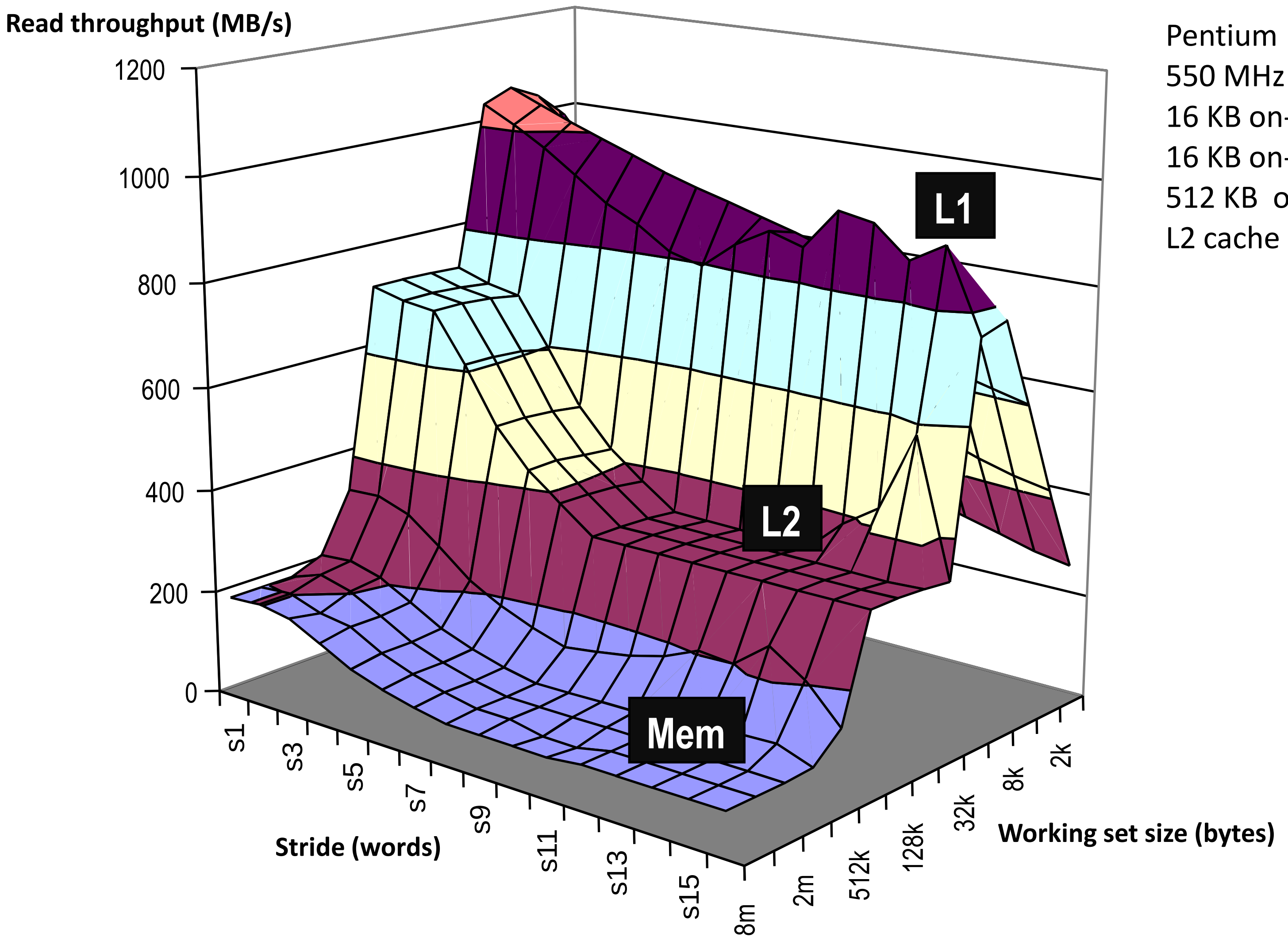
```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
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

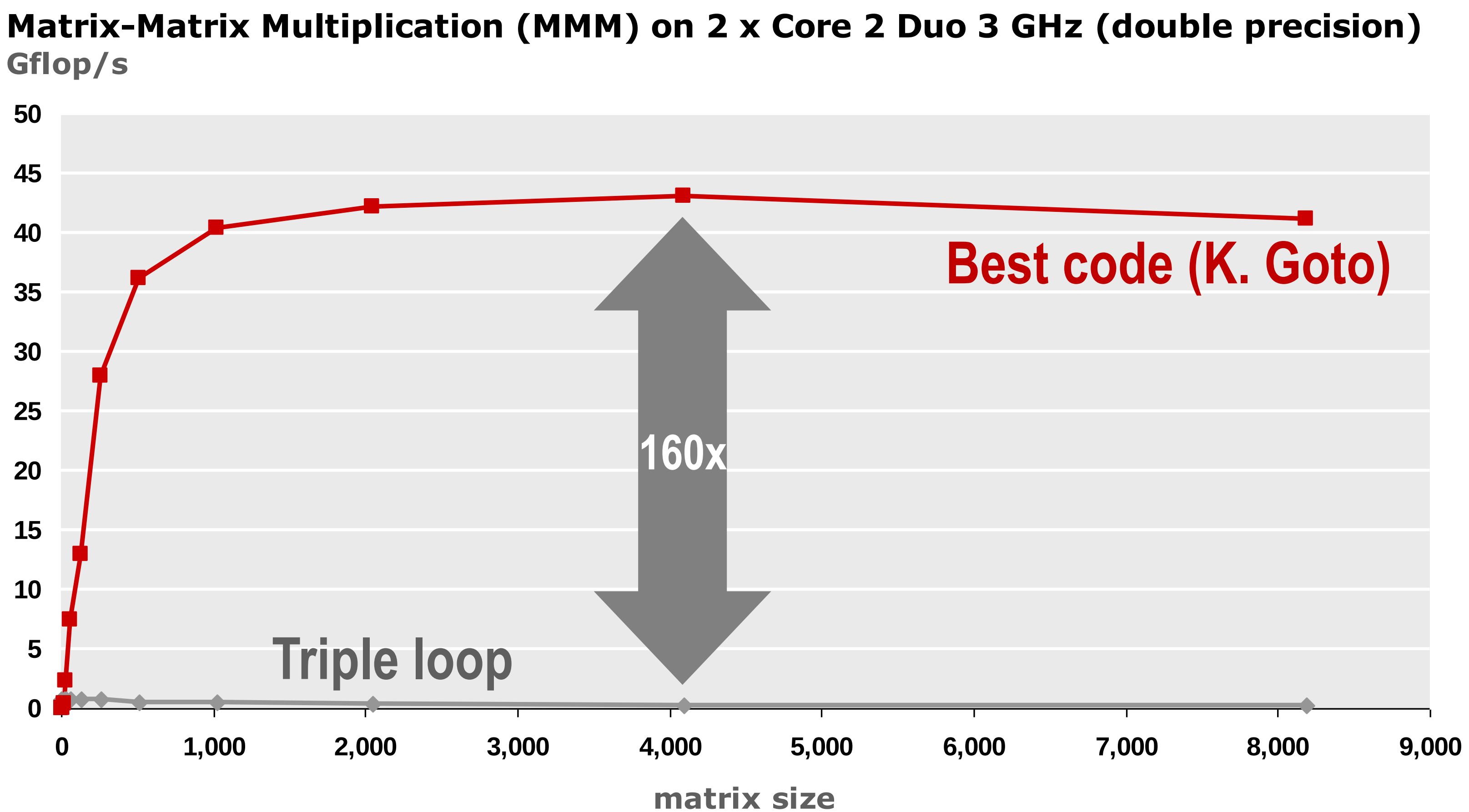


Pentium III Xeon
550 MHz
16 KB on-chip L1 d-cache
16 KB on-chip L1 i-cache
512 KB off-chip unified
L2 cache

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

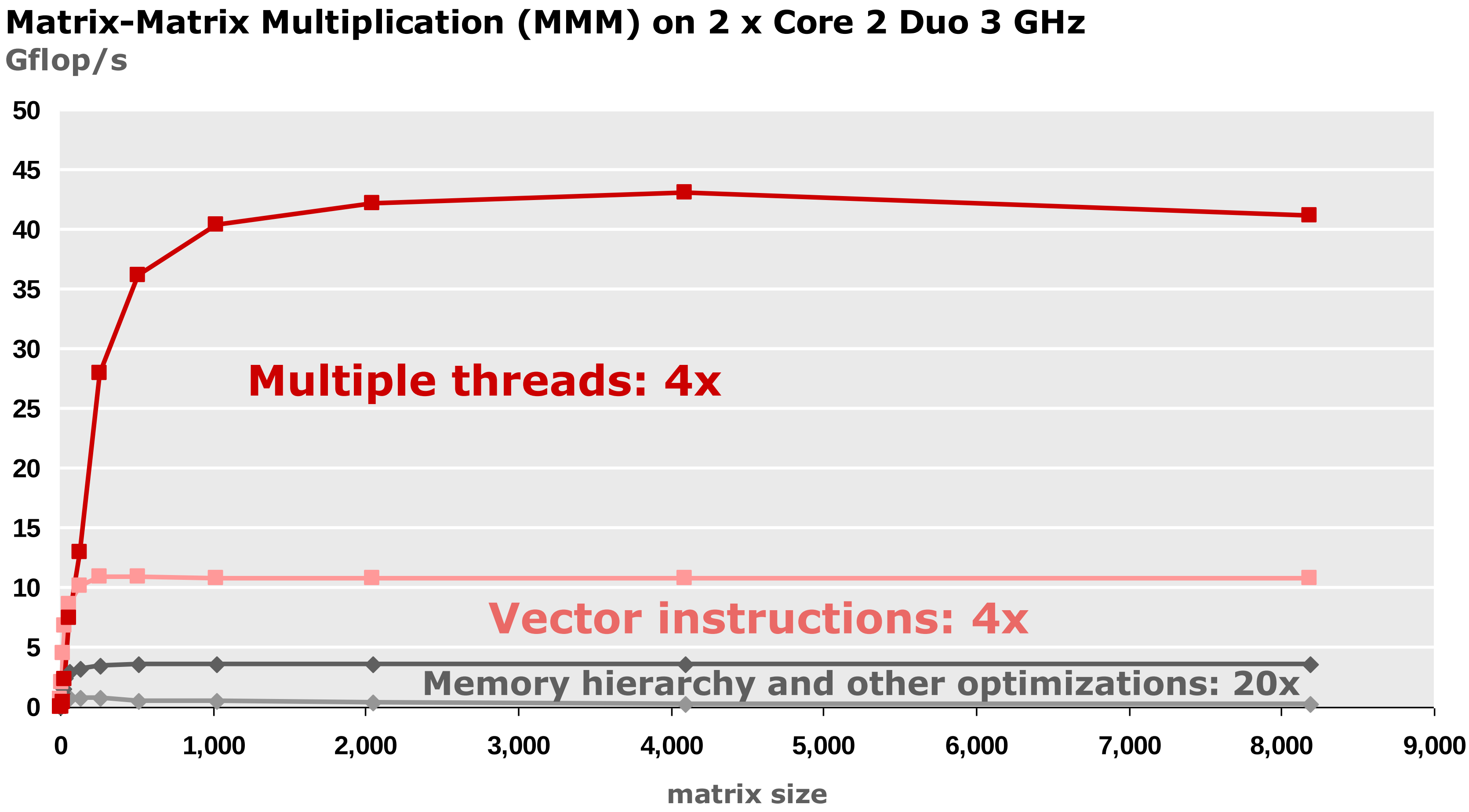
- **Constant factors matter too!**
- **And even exact op count does not predict performance**
  - Easily see 10:1 performance range depending on how code written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- **Must understand system to optimize performance**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

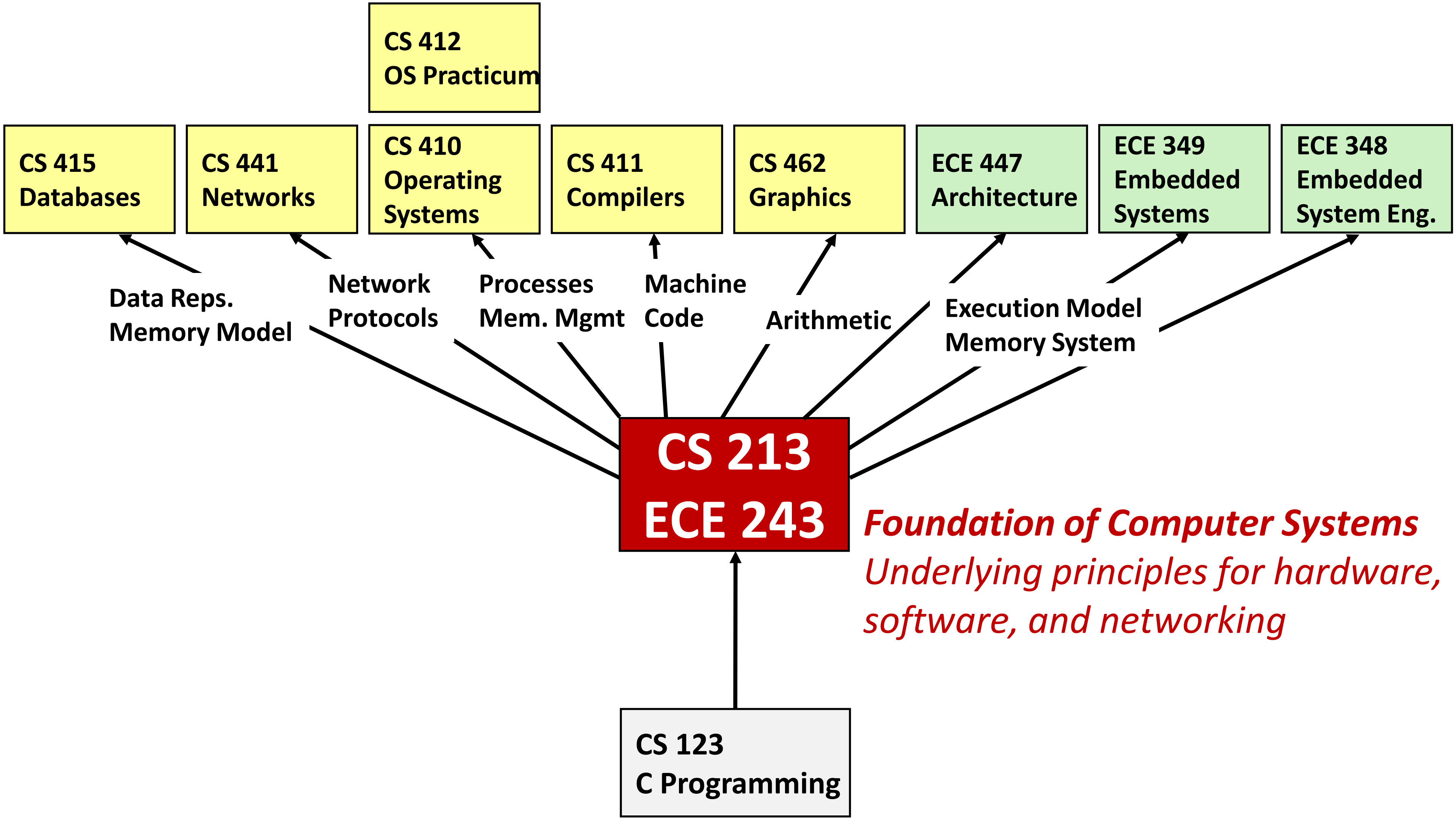


- Reason for 20x: Blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice
- *Effect: less register spills, less L1/L2 cache misses, less TLB misses*

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. Markus Püschel
- **TA's**
  - Ben Blum
  - Dan Burrows
  - Alex Gartrell
  - Christina Johns
  - Celestine Lau
  - Ian Lenz
  - Nathan Mickulicz
  - Hunter Pitelka
  - Brett Simmers
  - Hormoz Zarnani
- **Course Admin**
  - Cindy Chemsak (NSH 4303)

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

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 (7)**
  - The heart of the course
  - 2 or 3 weeks
  - 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 or Andrew)

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, Pueschel: see course website**
- **TAs:**
  - Sundays – Thursdays, 5:30pm – 9:30pm
  - West Wing cluster

Policies: Assignments (Labs) And Exams

- **Work groups**
  - You must work alone on all but final lab
- **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/Pueschel
- **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/Pueschel

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 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, …
  - Work with your academic advisor to formulate plan for getting back on track
- **Advice**
  - Once you start running late, it's really hard to catch up

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.
  - 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.
- **Detection of cheating:**
  - We do check and our tools for doing this are much better than you think!

Other Rules

- **Laptops: permitted**
- **Electronic communications: *forbidden***
  - Violation: course failure
- **Presence in lectures, recitations: voluntary**

Policies: Grading

- **Exams: weighted ¼, ¼, ½ (final)**
- **Labs: weighted according to effort (determined near the end)**

- **The worse of lab score and exam score is weighted 60%, the better 40%:**
  - Lab score: $0 \le L \le 100$,
    Exam score: $0 \le E \le 100$
    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.
- **Assignments**
  - Partially tested in Perflab (later)

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

Performance

- **Topics**
  - Coptimization (control and data), measuring time on a computer
  - Includes aspects of architecture, compilers, and OS

- **Assignments:**
  - L7 (Perflab): Optimize the runtime of a routine

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**

- **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!