The Hardware/Software Interface

CSE351 Spring 2011
1st Lecture, March 28

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Teaching Assistants:

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Who is Luis?

PhD in architecture, multiprocessors, parallelism, compilers.

Who are you?

- 55+ students (wow!)
- Who has written programs in assembly before?
- Written a threaded program before?

- What is an interface?

- Why do we need a hardware/software interface?

C vs. Assembler vs. Machine Programs

```
if ( x != 0 ) y = (y+z) / x;
```

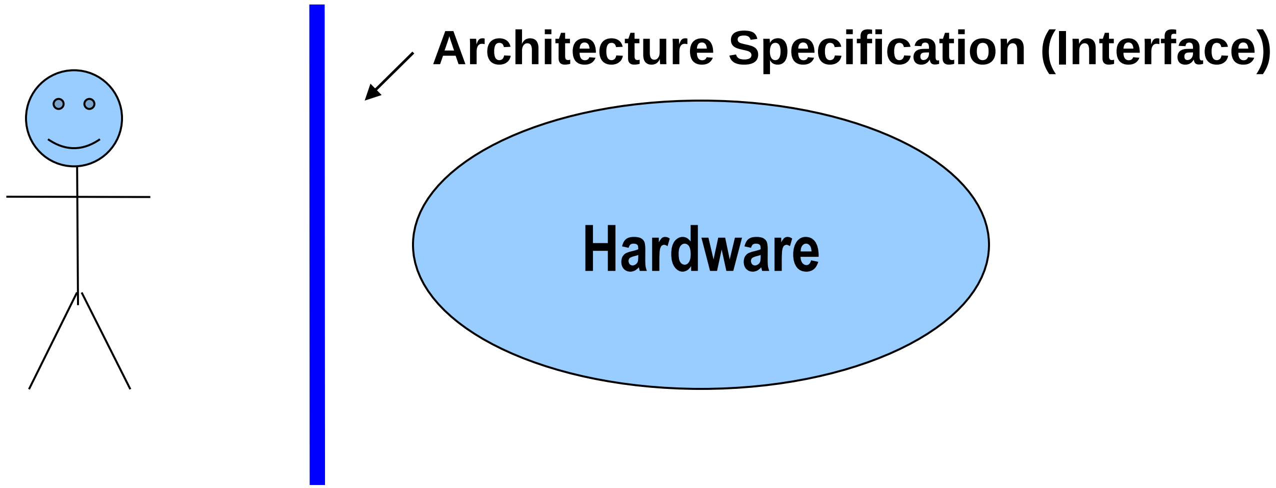
```
        cmpl    $0, -4(%ebp)
        je      .L2
        movl    -12(%ebp), %eax
        movl    -8(%ebp), %edx
        leal    (%edx,%eax), %eax
        movl    %eax, %edx
        sarl    $31, %edx
        idivl   -4(%ebp)
        movl    %eax, -8(%ebp)
.L2:
```

```
10000011011111100001001000001110000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
100011010000010000000010
1000100111000010
110000011111101000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

- **The three program fragments are equivalent**
- **You'd rather write C!**
- **The hardware likes bit strings!**
  - The machine instructions are actually much shorter than the bits required torepresent the characters of the assembler code

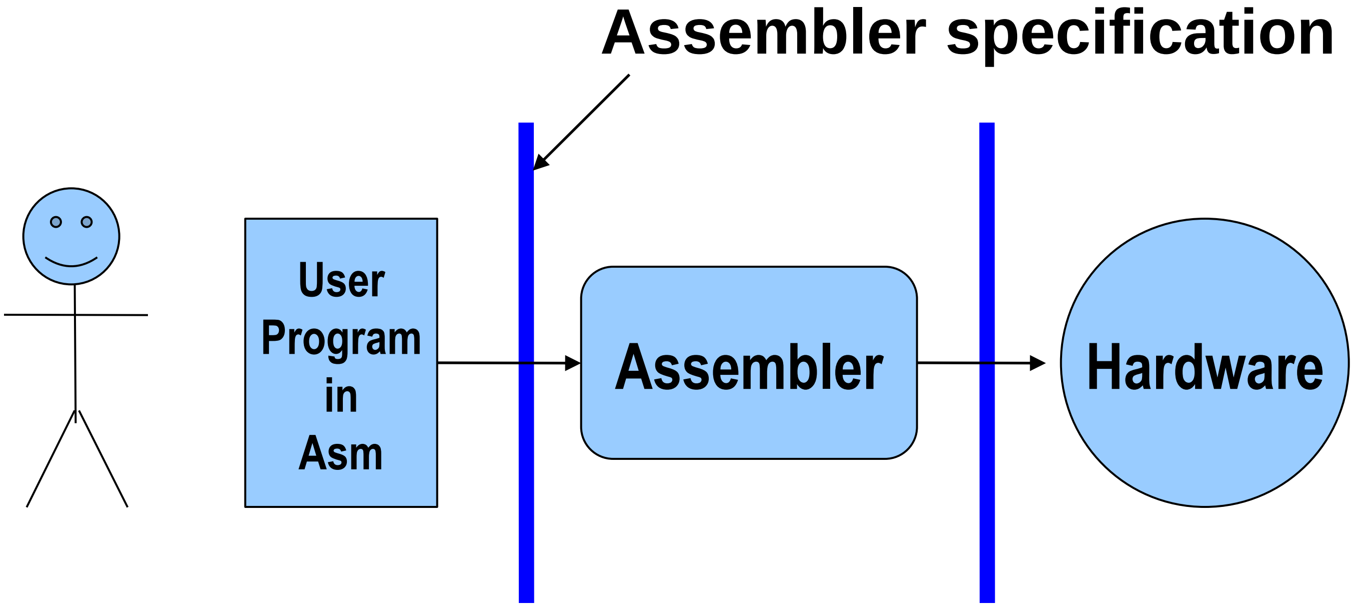
HW/SW Interface: The Historical Perspective

- **Hardware started out quite primitive**
  - Design was expensive ⇒ the instruction set was very simple
    - E.g., a single instruction can add two integers
- **Software was also very primitive**



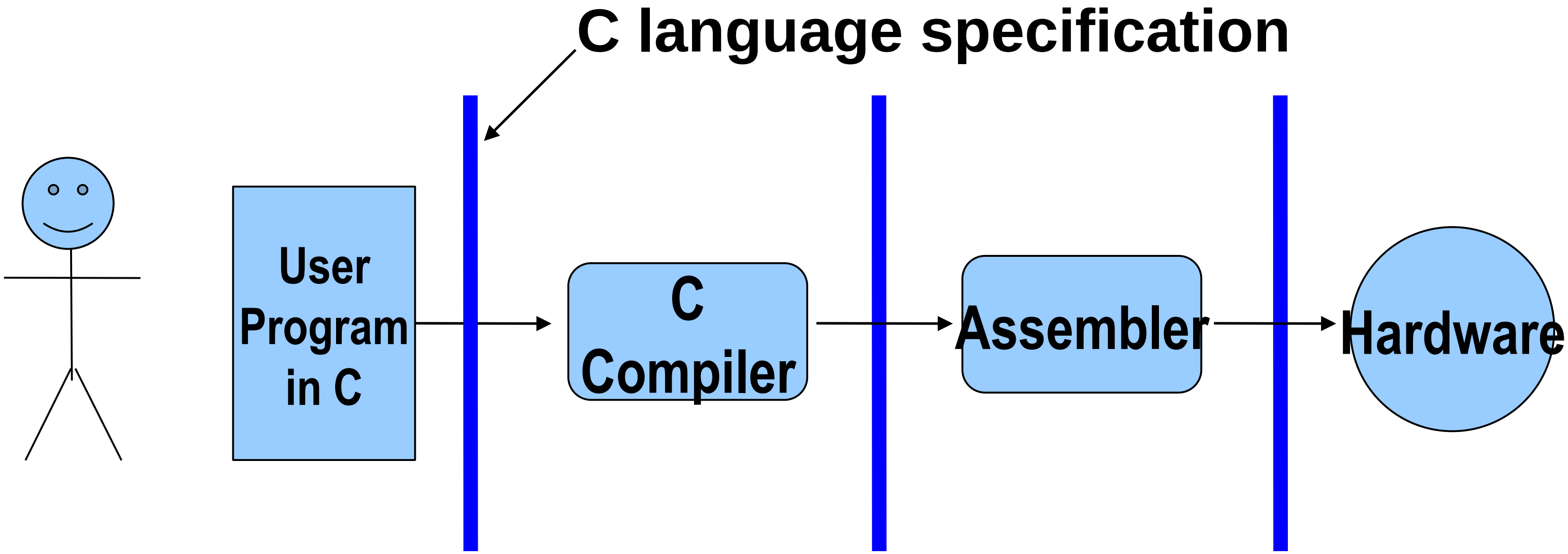
HW/SW Interface: Assemblers

- **Life was made a lot better by assemblers**
  - 1 assembly instruction = 1 machine instruction, but...
  - different syntax: assembly instructions are character strings, not bit strings



HW/SW Interface: Higher Level Languages (HLL's)

- **Higher level of abstraction:**
  - 1 HLL line is compiled into many (many) assembler lines


C language specification

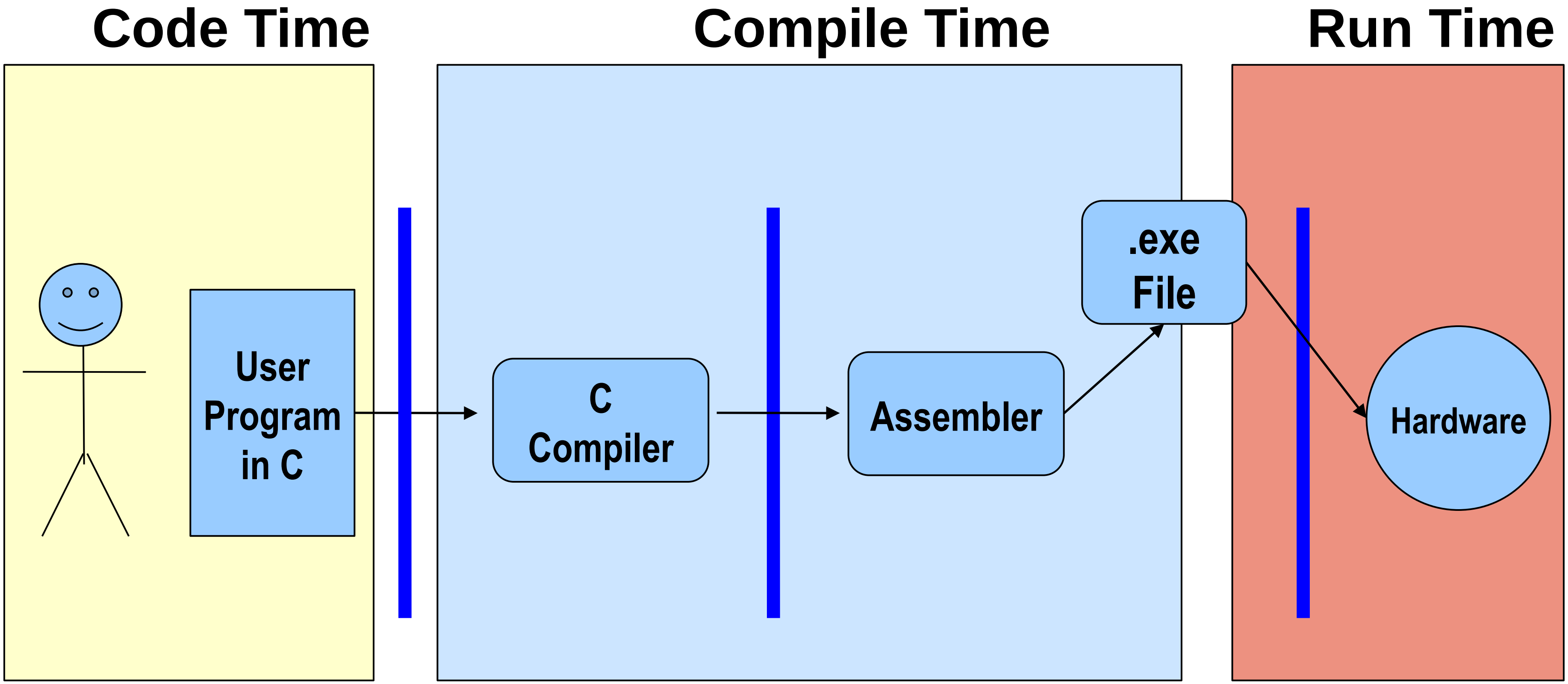
User Program in C

C Compiler

Assembler

Hardware

HW/SW Interface: Code / Compile / Run Times



Note: The compiler and assembler are just programs, developed using this same process.

Overview

- Course themes: big and little
- Four important realities
- How the course fits into the CSE curriculum
- Logistics

- (ready? ☺)

The Big Theme

- **THE HARDWARE/SOFTWARE INTERFACE**
- **How does the hardware (0s and 1s, processor executing instructions) relate to the software (Java programs)?**
- **Computing is about abstractions (but don't forget reality)**
- **What are the abstractions that we use?**
- **What do YOU need to know about them?**
  - When do they break down and you have to peek under the hood?
  - What assumptions are being made that may or may not hold in a new context or for a new technology?
  - What bugs can they cause and how do you find them?
- **Become a better programmer and begin to understand the thought processes that go into building computer systems**

Little Theme 1: Representation

- **All digital systems represent everything as 0s and 1s**
- **Everything includes:**
  - Numbers – integers and floating point
  - Characters – the building blocks of strings
  - Instructions – the directives to the CPU that make up a program
  - Pointers – addresses of data objects in memory
- **These encodings are stored in registers, caches, memories, disks, etc.**
- **They all need addresses**
  - A way to find them
  - Find a new place to put a new item
  - Reclaim the place in memory when data no longer needed

Little Theme 2: Translation

- **There is a big gap between how we think about programs and data and the 0s and 1s of computers**
- **Need languages to describe what we mean**
- **Languages need to be translated one step at a time**
  - Word-by-word
  - Phrase structures
  - Grammar
- **We know Java as a programming language**
  - Have to work our way down to the 0s and 1s of computers
  - Try not to lose anything in translation!
  - We'll encounter Java byte-codes, C language, assembly language, and machine code (for the X86 family of CPU architectures)

Little Theme 3: Control Flow

- **How do computers orchestrate the many things they are doing – seemingly in parallel**
- **What do we have to keep track of when we call a method, and then another, and then another, and so on**
- **How do we know what to do upon "return"**
- **User programs and operating systems**
  - Multiple user programs
  - Operating system has to orchestrate them all
    - Each gets a share of computing cycles
    - They may need to share system resources (memory, I/O, disks)
  - Yielding and taking control of the processor
    - Voluntary or by force?

Course Outcomes

- **Foundation: basics of high-level programming (Java)**
- **Understanding of some of the abstractions that exist between programs and the hardware they run on, why they exist, and how they build upon each other**
- **Knowledge of some of the details of underlying implementations**
- **Become more effective programmers**
  - More efficient at finding and eliminating bugs
  - Understand the many factors that influence program performance
  - Facility with some of the many languages that we use to describe programs and data
- **Prepare for later classes in CSE**

Reality 1: Ints ≠ Integers & Floats ≠ Reals

- **Representations are finite**
- **Example 1: Is $x^2 \geq 0$?**
  - Floats: Yes!
  - Ints:
    - 40000 * 40000 --> 1600000000
    - 50000 * 50000 --> ??
- **Example 2: Is (x + y) + z = x + (y + z)?**
  - Unsigned & Signed Ints: Yes!
  - Floats:
    - (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]; int len = 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 */
    if (KSIZE > maxlen) len = 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]; int len = 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 */
    if (KSIZE > maxlen) len = 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]; int len = 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 */
    if (KSIZE > maxlen) len = maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

```
#define MSIZE 528

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

Reality #2: You've Got to Know Assembly

- **Chances are, you'll never write a program in assembly code**
  - Compilers are much better and more patient than you are
- **But: Understanding assembly is the key to the 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
    - 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

```
/* 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) /* output    */
        :                          /* input     */
        : "%edx", "%eax");         /* clobbered */
}
```

Reality #3: Memory Matters

- **Memory is not unbounded**
  - It must be allocated and managed
  - Many applications are memory-dominated
- **Memory referencing bugs are 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
```

Memory Referencing Bug Example

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double fun(int i)
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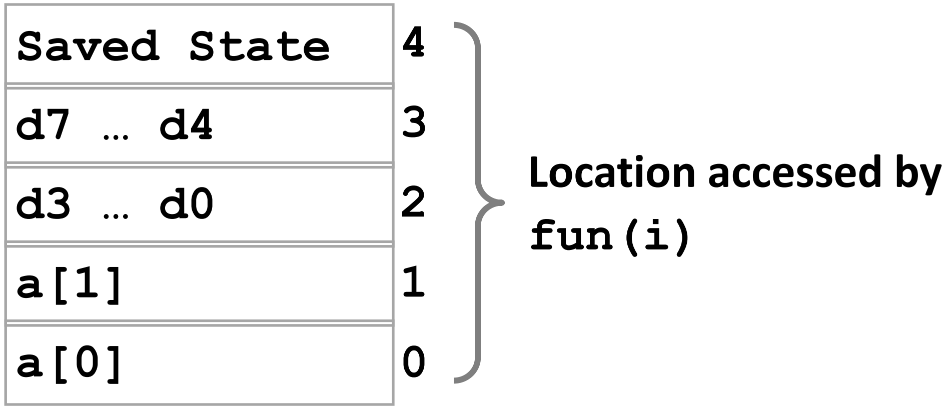
fun(4)  ->     3.14, then segmentation fault
```

Explanation:



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

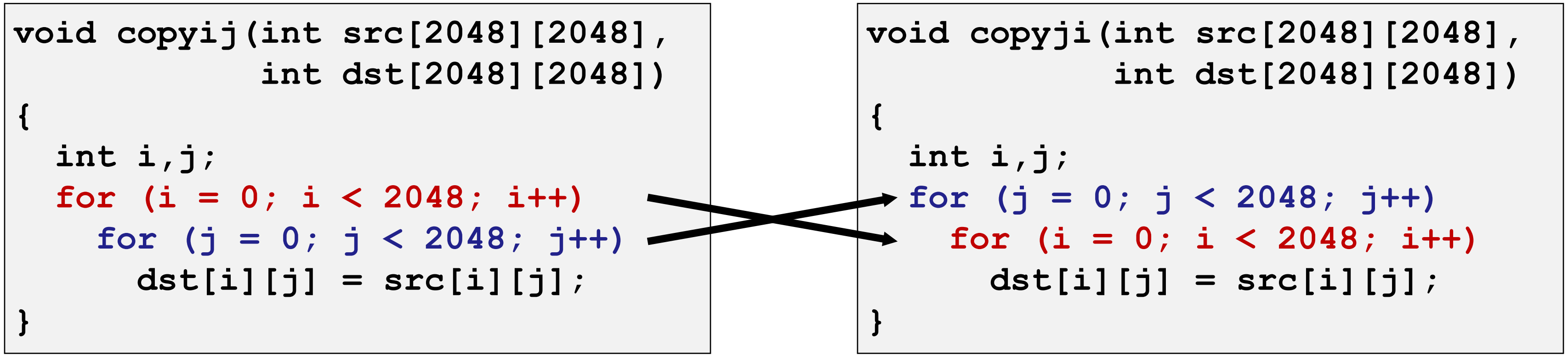
Location accessed by `fun(i)`

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 (or C#, or ML, or …)
  - Understand what possible interactions may occur
  - Use or develop tools to detect referencing errors

Memory System Performance Example

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

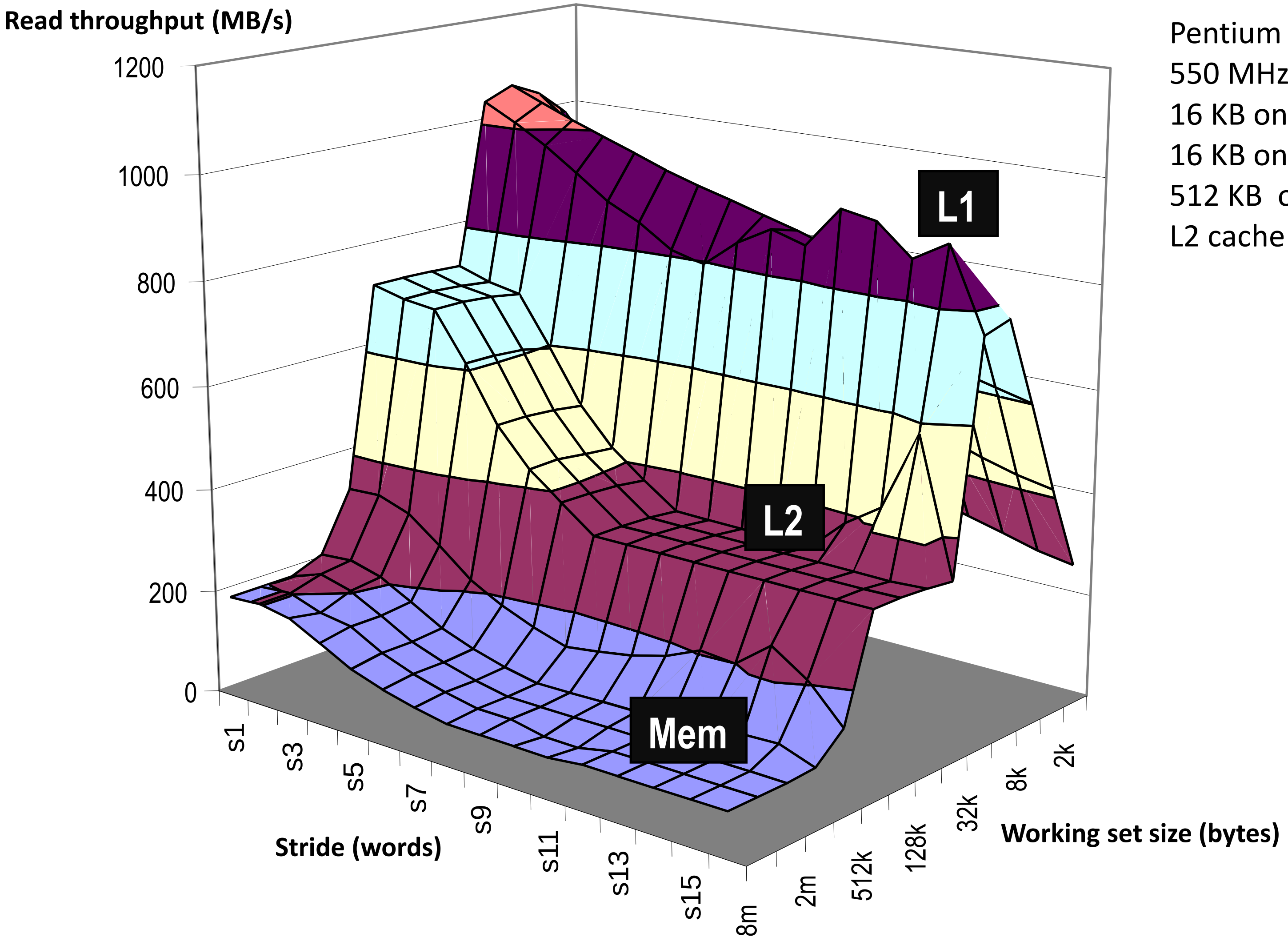


```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
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)

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

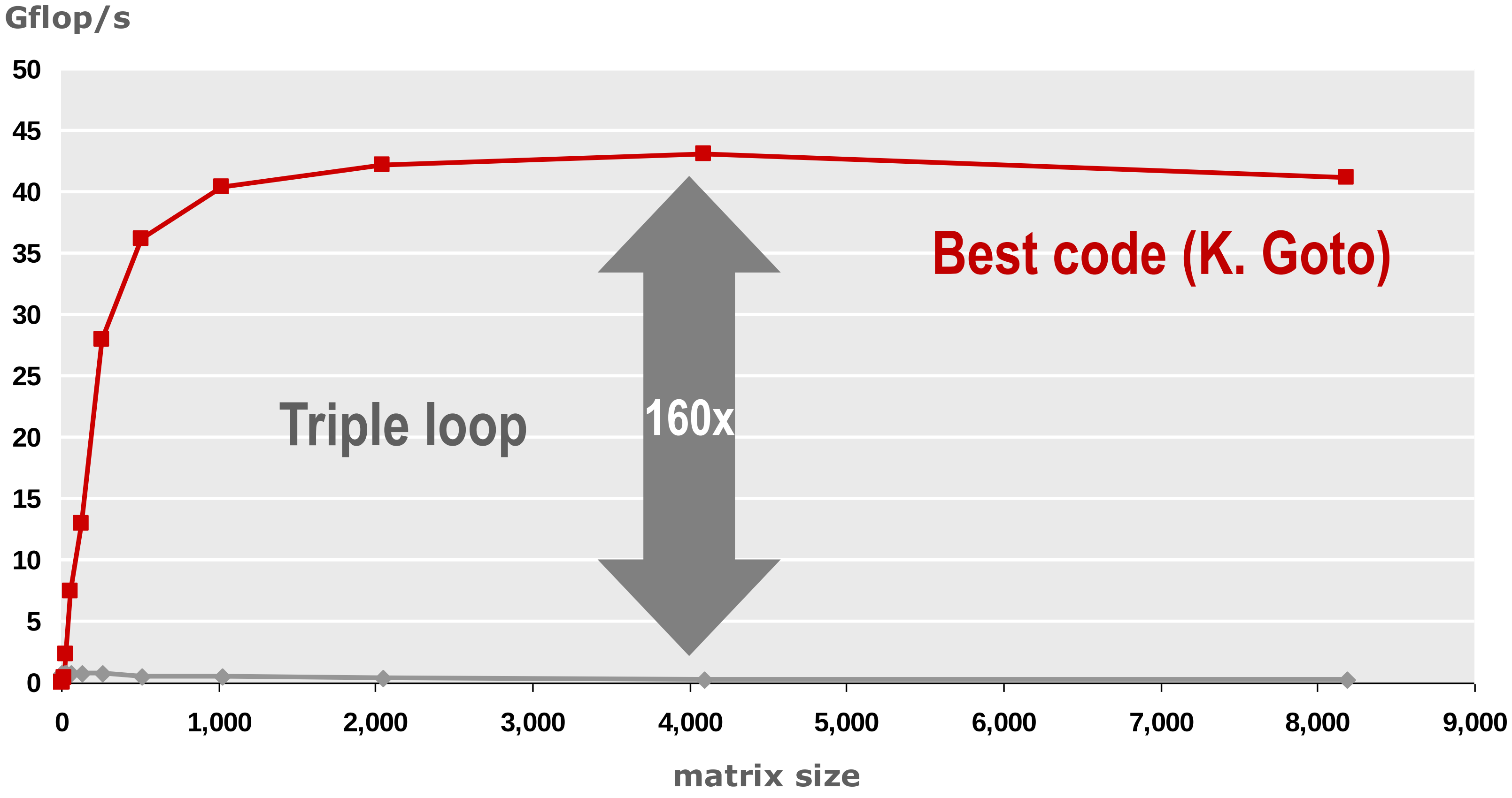
Reality #4: Performance isn't counting ops

- **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 memory system is organized
  - How to measure program performance and identify bottlenecks
  - How to improve performance without destroying code modularity and generality

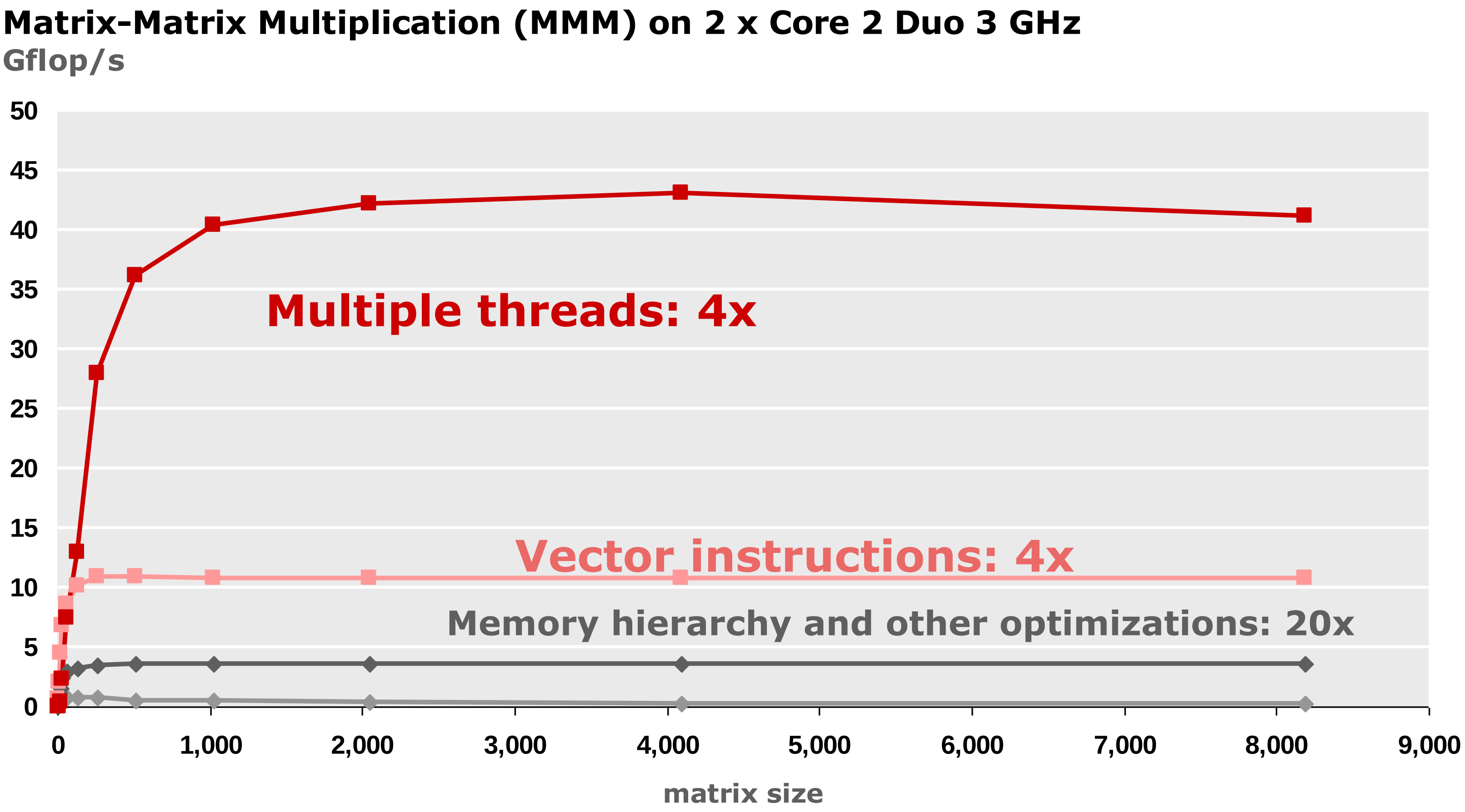
Example Matrix Multiplication

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

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



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*

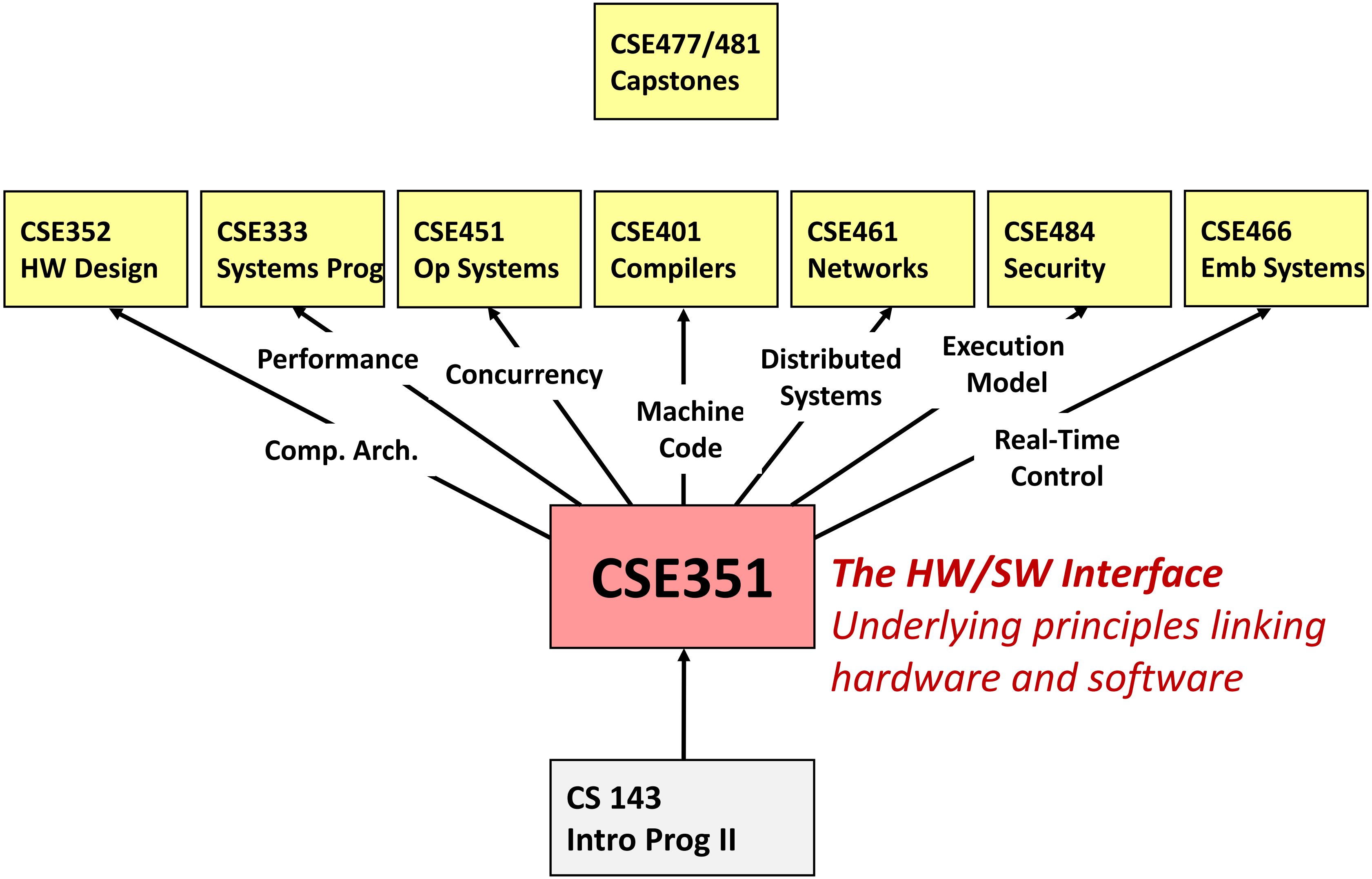
CSE351's role in new CSE Curriculum

- **Pre-requisites**
  - 142 and 143: Intro Programming I and II

- **One of 6 core courses**
  - 311: Foundations I
  - 312: Foundations II
  - 331: SW Design and Implementation
  - 332: Data Abstractions
  - 351: HW/SW Interface
  - 352: HW Design and Implementation

- **351 sets the context for many follow-on courses**

CSE351's place in new CSE Curriculum



CSE477/481
Capstones

CSE352
HW Design

CSE333
Systems Prog

CSE451
Op Systems

CSE401
Compilers

CSE461
Networks

CSE484
Security

CSE466
Emb Systems

Performance

Concurrency

Distributed Systems

Execution Model

Comp. Arch.

Machine Code

Real-Time Control

CSE351

The HW/SW Interface

Underlying principles linking hardware and software

CS 143
Intro Prog II

Course Perspective

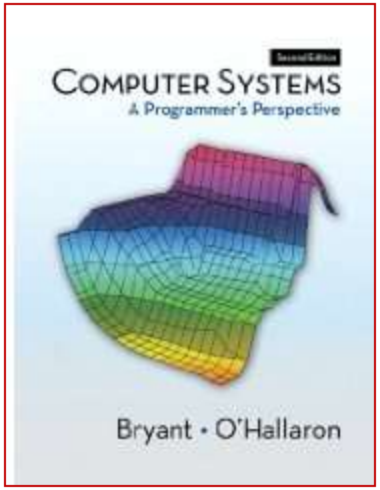
- **Most systems courses are Builder-Centric**
  - Computer Architecture
    - Design pipelined processor in Verilog
  - Operating Systems
    - Implement large portions of operating system
  - Compilers
    - Write compiler for simple language
  - Networking
    - Implement and simulate network protocols

Course Perspective (Cont.)

- **This course is Programmer-Centric**
  - Purpose is to show how software really works
  - By understanding the underlying system, one can be more effective as a programmer
    - Better debugging
    - Better basis for evaluating performance
    - How multiple activities work in concert (e.g., OS and user programs)
  - Not just a course for dedicated hackers
    - What every CSE major needs to know
  - Provide a context in which to place the other CSE courses you'll take

Textbooks

- **Computer Systems: A Programmer’s Perspective, 2nd Edition**
  - Randal E. Bryant and David R. O’Hallaron
  - Prentice-Hall, 2010
  - http://csapp.cs.cmu.edu
  - This book really matters for the course!
    - How to solve labs
    - Practice problems typical of exam problems



- **A good C book.**
  - C: A Reference Manual (Harbison and Steele)
  - The C Programming Language (Kernighan and Ritchie)

Course Components

- **Lectures (~30)**
  - Higher-level concepts – I'll assume you've done the reading in the text
- **Sections (~10)**
  - Applied concepts, important tools and skills for labs, clarification of lectures, exam review and preparation
- **Written assignments (4)**
  - Problems from text to solidify understanding
- **Labs (4)**
  - Provide in-depth understanding (via practice) of an aspect of systems
- **Exams (midterm + final)**
  - Test your understanding of concepts and principles

Resources

- **Course Web Page**
  - http://www.cse.washington.edu/351
  - Copies of lectures, assignments, exams
- **Course Discussion Board**
  - Keep in touch outside of class – help each other
  - Staff will monitor and contribute
- **Course Mailing List**
  - Low traffic – mostly announcements; you are already subscribed
- **Staff email**
  - Things that are not appropriate for discussion board or better offline
- **Anonymous Feedback (will be linked from homepage)**
  - Any comments about anything related to the course where you would feel better not attaching your name

Policies: Grading

- **Exams: weighted 1/3 (midterm), 2/3 (final)**
- **Written assignments: weighted according to effort**
  - We'll try to make these about the same
- **Labs assignments: weighted according to effort**
  - These will likely increase in weight as the quarter progresses

- **Grading:**
  - 25% written assignments
  - 35% lab assignments
  - 40% exams

Welcome to CSE351!

- **Let’s have fun**
- **Let’s learn – together**
- **Let’s communicate**
- **Let’s set the bar for a useful and interesting class**

- **Many thanks to the many instructors who have shared their lecture notes – I will be borrowing liberally through the qtr – they deserve all the credit, the errors are all mine**
  - UW: Gaetano Borriello (Inaugural edition of CSE 351, Spring 2010)
  - CMU: Randy Bryant, David O’Halloran, Gregory Kesden, Markus Püschel
  - Harvard: Matt Welsh
  - UW: Tom Anderson, Luis Ceze, John Zahorjan