The Hardware/Software Interface

CSE351 Spring 2012
1st Lecture, March 26

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Who is Gaetano?

At UW since ’88

- *PhD at UC Berkeley*
- *MS at Stanford*
- *BS at NYU Poly*

Research trajectory:

- *Integrated circuits →*
- *Computer-aided design →*
- *Reconfigurable hardware →*
- *Embedded systems →*
- *Networked sensors →*
- *Ubiquitous computing →*
- *Mobile devices →*
- *Applications in developing world*

Who are you?

- 80+ students (we will do our best to get to know each of you!)

- What is hardware? Software?
- What is an interface?
- Why do we need a hardware/software interface?

- Who has written a program in assembly language before?
- Written a multi-threaded program before?

C/Java, assembly, and machine code

```
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:
```

```
1000001101111100001001000001110000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
100011010000010000000010
1000100111000010
110000011111101000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

C/Java, assembly, and machine code

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

↓

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

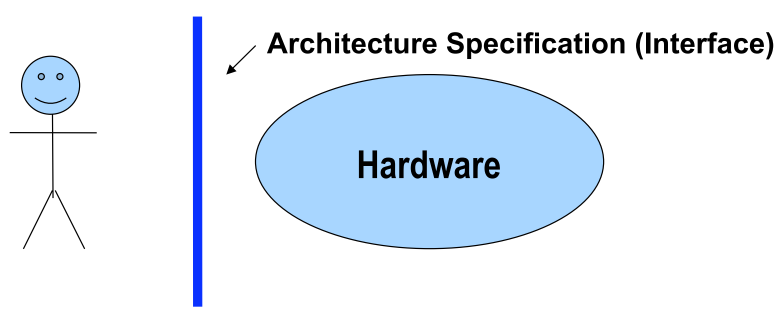
→ ←

```
10000011011111000010010000001110000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
100011010000010000000010
1000100111000010
110000011111101000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

- **The three program fragments are equivalent**
- **You'd rather write C! - a more human-friendly language**
- **The hardware likes bit strings! - everything is voltages**
  - The machine instructions are actually much shorter than if we just used the bits of the characters of the assembly language

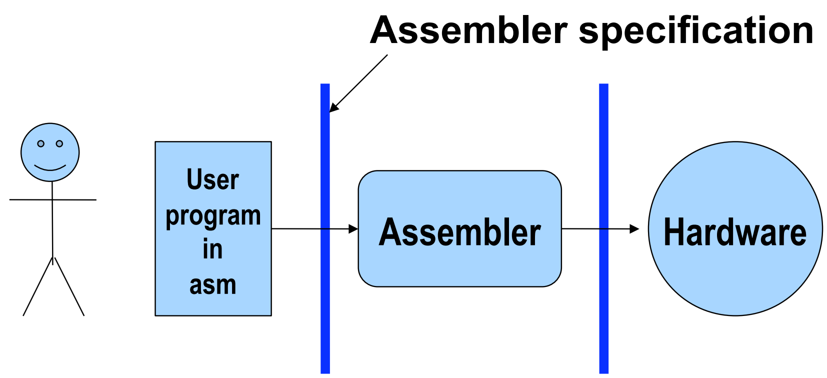
HW/SW Interface: The Historical Perspective

- **Hardware started out quite primitive**
  - Hardware designs were expensive ⇒ instructions had to be very simple – e.g., a single instruction for adding two integers
- **Software was also very primitive**
  - Software primitives reflected the hardware pretty closely



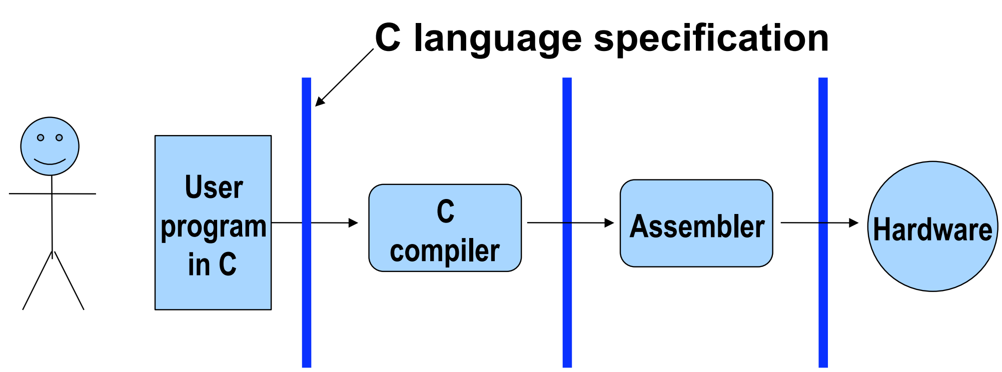
HW/SW Interface: Assemblers

- **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, a lot easier to read/write by humans

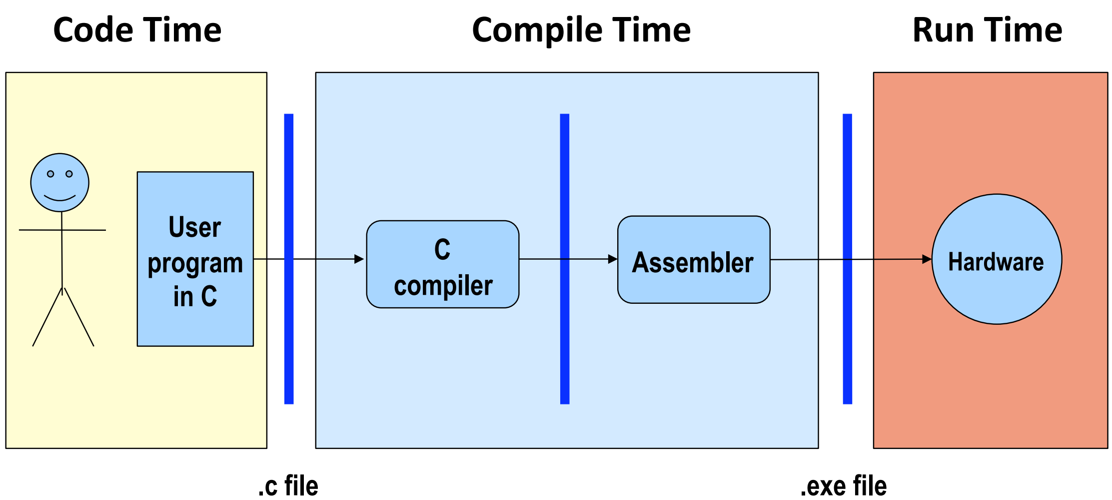


HW/SW Interface: Higher-Level Languages

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



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

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 we can'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 bugs can they cause and how do you find them?
- **Become a better programmer and begin to understand the important concepts that have evolved in building ever more complex computer systems**

Little Theme 1: Representation

- **All digital systems represent everything as 0s and 1s**
  - The 0 and 1 are really two different voltage ranges in the electronics
- **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 stored away in memory
- **These encodings are stored throughout a computer system**
  - 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 some of the many factors that influence program performance
  - Facility with a couple more 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

- Why? Because we want you to suffer?☺

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
  - Use special thingees (timers, I/O co-processors, etc.) inside processor!

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 (two 32-bit values) 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

- Ehm, what is memory?

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(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 (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)

Reality #4: Performance isn't counting ops

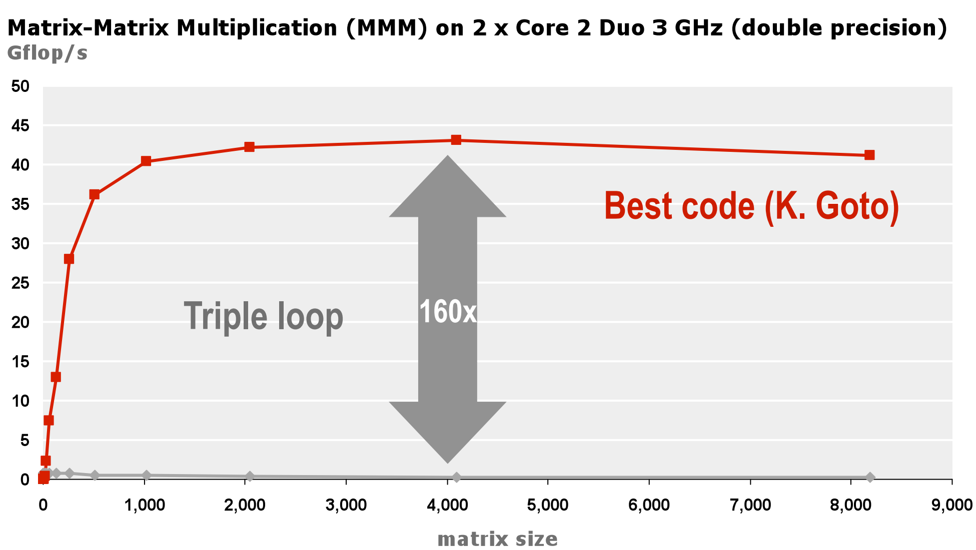
- Can you tell how fast a program is just by looking at the code?

Reality #4: Performance isn't counting ops

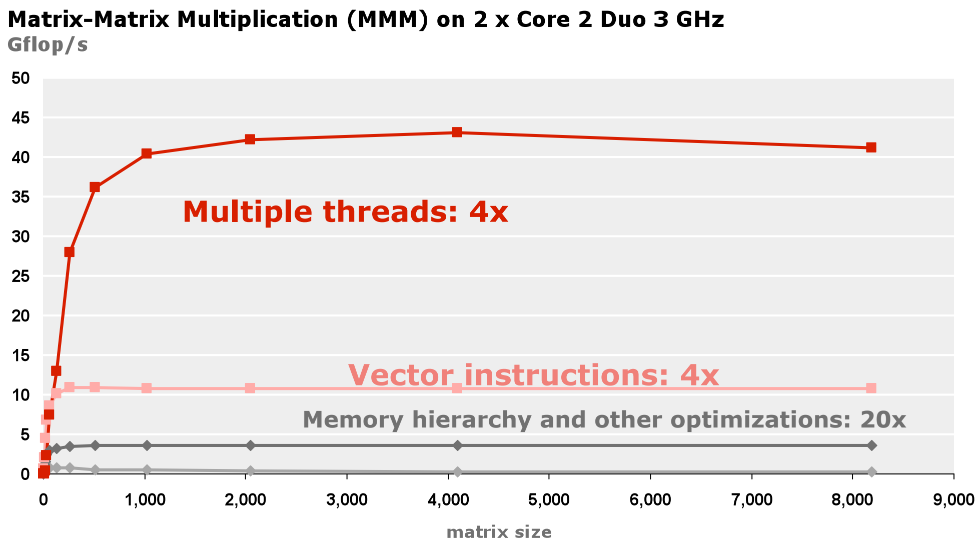
- **Exact op count does not predict performance**
  - Easily see 10:1 performance range depending on how code is written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- **Must understand system to optimize performance**
  - How programs are compiled and 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 ($2n^3$)



MMM Plot: Analysis

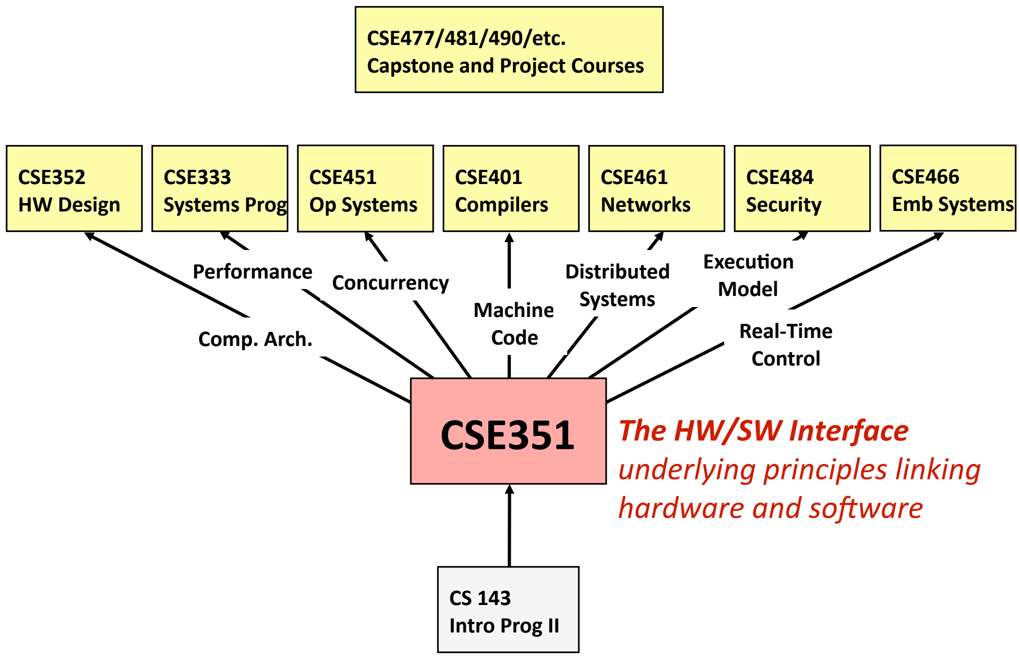


- Reason for 20x: blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice
- *Effect: less register spills, less L1/L2 cache misses, less TLB misses*

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



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

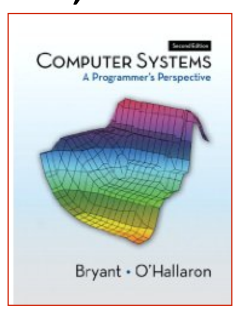
Course Perspective (cont'd)

- **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

University of Washington

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 – any will do**
  - C: A Reference Manual (Harbison and Steele)
  - The C Programming Language (Kernighan and Ritchie)

Course Components

- **Lectures (28)**
  - 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)**
  - Mostly problems from text to solidify understanding
- **Labs (5)**
  - 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 E-mail**
  - Things that are not appropriate for discussion board or better offline
- **Anonymous Feedback**
  - Any comments about anything related to the course where you would feel better not attaching your name

Policies: Grading

- **Exams (40%): weighted 15/40 (midterm) and 25/40 (final)**

- **Written assignments (20%): weighted according to effort**
  - We'll try to make these about the same

- **Labs assignments (40%): weighted according to effort**
  - These will likely increase in weight as the quarter progresses

Welcome to CSE351!

- **Let's have fun**
- **Let's learn – together**
- **Let's communicate**
- **Let's make this a useful class for all of us**

- **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**
  - CMU: Randy Bryant, David O'Halloran, Gregory Kesden, Markus Püschel
  - Harvard: Matt Welsh (now at Google-Seattle)
  - UW: Luis Ceze, Hal Perkins, John Zahorjan
  - I also taught the Inaugural edition of CSE 351 in Spring 2010