The Hardware/Software Interface

CSE351 Winter 2011
1st Lecture, 3 January

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Overview

- **Course Synopsis**
- **Course themes: big and little**
- **Four important realities**
- **How the course fits into the CSE curriculum**
- **Logistics5**

HW0 is out. Due end of day Wednesday.

Course Synopsis: Preliminaries

- **A program is an expression of a computation**
  - It describes what the output should be when given some input
- **Programs are written to some specification**
  - E.g., Java defines how to write statements and what they mean
- **How to write something is called syntax**
  - We usually think of syntax as a relatively minor issue, although it can have substantial impact on the likelihood of making mistakes
- **What it means is called semantics**
  - “if (x != 0) y = (y+z)/x;” vs. “when (x != 0) y = (y+z)/x;”
    - different syntax, same semantics

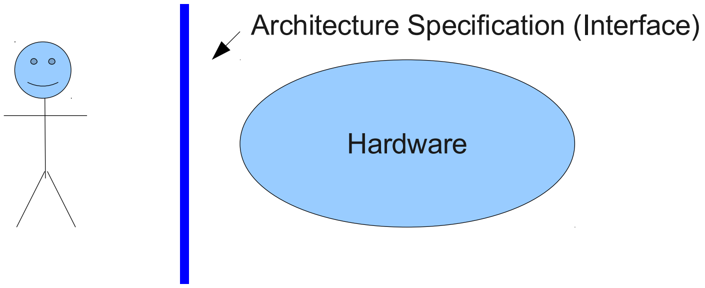
Course Synopsis: Programs and Hardware

- **A hardware architecture defines its programming specification**
  - How to write instructions and what they mean
- **That specification isn't Java!**
  - We'll say why in a moment...
- **So, what happens?**
  - A Java compiler translates the computation as expressed in Java into a computation expressed in the language the hardware defines
  - The translation is correct if the two programs are equivalent
    - For every input, the hardware program produces the same outputs as the Java program would if executed according to the semantics defined by Java

Note: I'm taking some liberties with full truth for the sake of clarity.

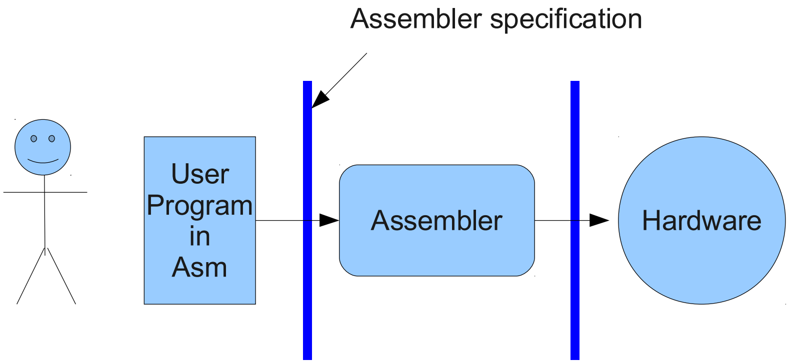
HW/SW Interface: The Historical Perspective

- **Hardware started out quite primitive**
  - Design was expensive ⇒ the instruction set was very simple
    - E.g., a single instruction can add two integers
    - Forget about x = (2*y + 17) / (x*y*z + 3*w)
- **Software was also very primitive**
  - Forget about x = (2*y + 17) / (x*y*z + 3*w)



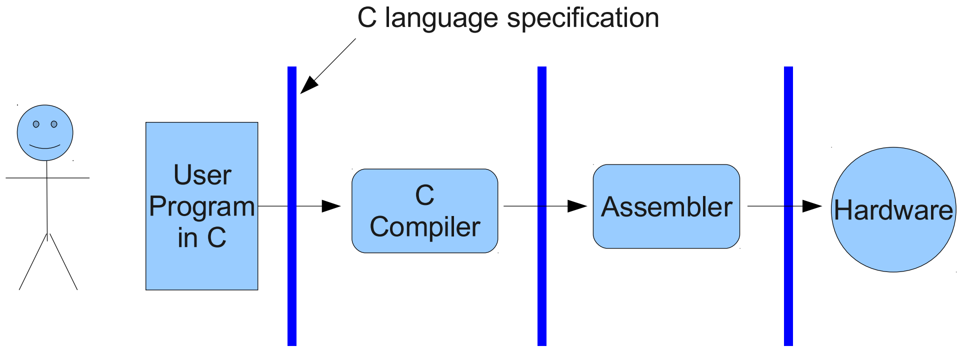
HW/SW Interface: Assemblers

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



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

- **Human was still writing 1 line of assembler for each machine instruction**
- **HLL's (e.g., C) provided a higher level of abstraction:**
  - 1 HLL line is compiled into many (many) assembler lines



C vs. Assembler vs. Machine Programs

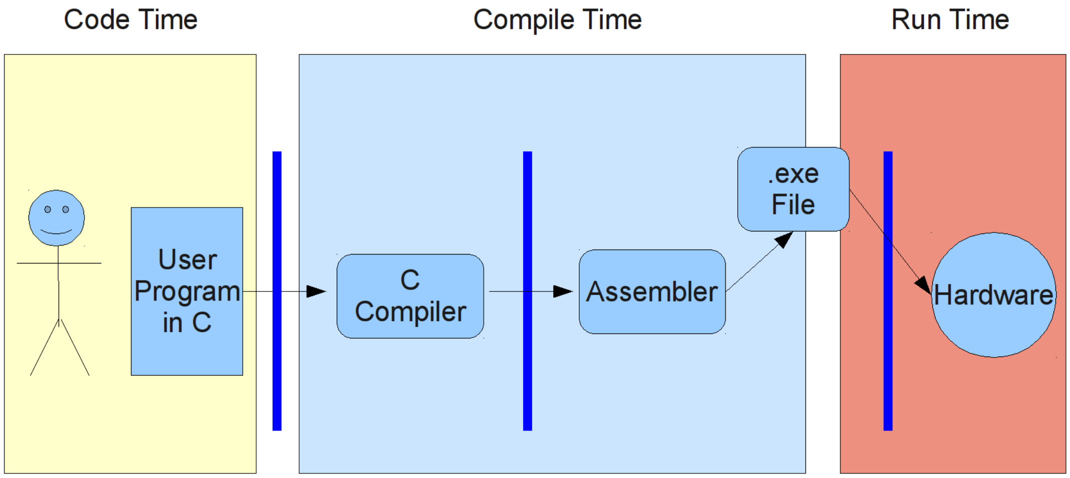
```
if ( x != 0 ) y = (y+z) / x;
```

```
        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:
```

```
10000011011111000010010000001110000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
1000110100000010000000010
1000100111000010
1100000111111010000011111
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: Code / Compile / Run Times

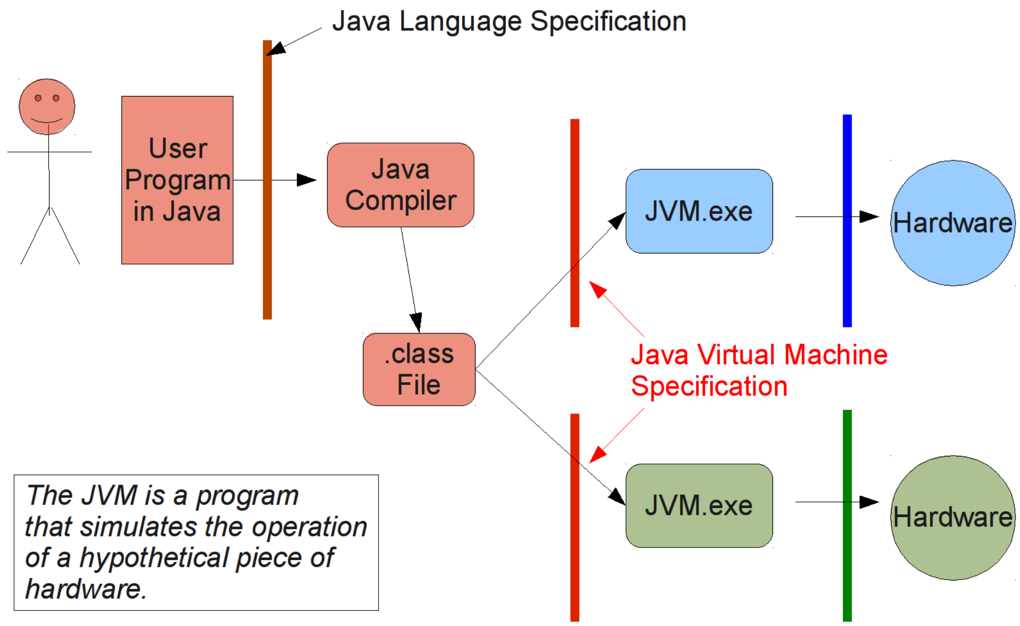


Note: The compiler and assembler are just programs, developed using this same process.

Near-Recent History: Java

- **Hardware is really, really fast and really, really cheap**
- **Programming Is really, really hard, and programmers aren't cheap**
- **So…**
  - Help the programmer by making it harder to make (unnoticed) mistakes
  - One program runs everywhere, not one per system type
- **How?**
  - More precisely defined language semantics
  - More restrictive language semantics
  - The “Java virtual machine”

The Java Virtual Machine (JVM)



The JVM is a program that simulates the operation of a hypothetical piece of hardware.

More Translation: Compiler Optimizations

- **Some compiler optimizations can be viewed as “source to source” translations**

```
for (i=0; i<10; i++) {
    a[i] = i;
}
```

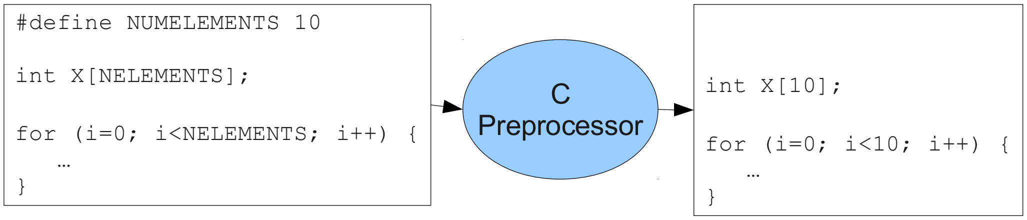
1 scalar assignment +
11 integer compares +
11 integer increments +
10 array element assignments

```
a[0] = 0;
a[1] = 1;
a[2] = 2;
a[3] = 3;
a[4] = 4;
a[5] = 5;
a[6] = 6;
a[7] = 7;
a[8] = 8;
a[9] = 9;
i = 10;
```

1 scalar assignment +
10 array element assignments

And more translation: The C Preprocessor

- **C programs can include "preprocessor directives," which are executed <u>at compile time</u>**
- **The directives can alter the program that is actually compiled by the C compiler**



```
#define NUMELEMENTS 10

int X[NELEMENTS];

for (i=0; i<NELEMENTS; i++) {
    …
}
```

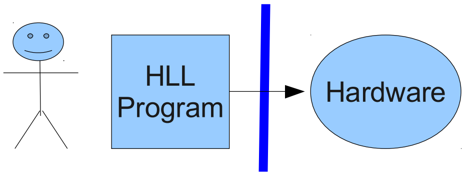
```
int X[10];

for (i=0; i<10; i++) {
    …
}
```

Now this text is compiled

One More Thing...

- **Attempts have been made to build hardware that directly executes HLL's**
    - That is, the hardware architecture defines instruction syntax and semantics very similar to HLL's



- **It hasn't worked**
    - The hardware was slow
- **Generally applicable moral:** ***Simpler is faster.***
- ***Hardware architectures today look a lot like architectures from decades ago.***

Translation Summary

- **Pros:**
  - Translation overhead is suffered once (at compile time), not for each execution of the program
  - Raises level of abstraction for the programmer (C vs. assembler)
- **Cons:**
  - Raising level of abstraction can come at the cost of some inefficiency
    - On the other hand, the compiler is better at some sorts of optimizations than humans
  - The program that's actually running isn't the one you wrote
    - That can make debugging somewhat tricky...

Big Theme #1: The HW/SW Interface

- **THE HARDWARE VIEW**
  - **What is the programming model supported by the hardware?**
  - **How does that influence programs you might write?**
    - **How does it influence programming languages?**
  - **How do the requirements of programs and systems software (e.g., compilers, operating systems) influence what the hardware supports?**
- **Understanding the HW/SW interface might make you a more effective programmer**
  - **It will certainly make you a more versatile and comfortable one**

Big Theme #2: The HW/SW Interface

- THE SOFTWARE VIEW
  - A “system” is an orchestration of hw & sw
  - The sw needs hw to run, but the hw needs the sw as well
    - Compilers/translators
    - Resource allocators
    - Protection mechanisms
    - I/O systems
    - ...
- We'll look at some of the functionality that “systems software” provides

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Little Theme 1: Representation

- At the hardware level, everything is 0s and 1s
  - numbers, characters, strings, instructions, objects, classes, ...

- We'll look at the base representations
  - The ones the hardware “understands”
    - numbers, characters, hardware instructions
  - We'll also look up a few layers of abstraction to the ones created by software
    - procedure class, objects

- An important implication:
  - We'll better understand what a type is in a programming language

Little Theme 2: Translation

- Translation is everywhere...
- But, we'll look particularly at the path C programs to execution, and from Java programs to execution
  - We'll encounter Java byte-codes, C language, assembly language, and machine code (for the X86 family of CPU architectures)

Little Theme 3: Correctness + Performance

- Up to now you've mostly struggled just with getting an implementation that works
  - Optimizing performance was ignored, or...
  - Performance was assumed to be purely an (asymptotic) algorithmic issue
- In this course we'll consider the effect of implementation (rather than algorithm) on performance
  - For example:
    - Choice of language
    - How the language is used
- And, we'll explain why!

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 ≠ the Integers & Floats ≠ Reals

- **Representations are finite**
- **Example 1: Is $x^2 \geq 0$?**
  - Floats: Yes!
  - Ints:
  - 40,000 * 40,000 --> 1,600,000,000
  - 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) --> ??

Reality #2: 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 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 (valgrind)

Memory System Performance Example

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

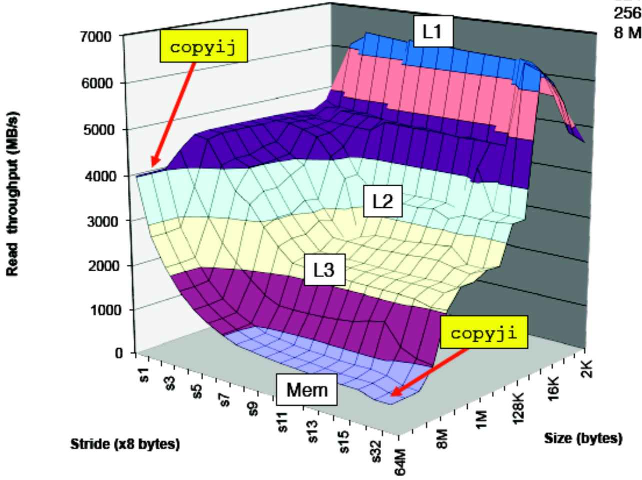
```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
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

Intel Core i7
2.67 GHz
32 KB L1 d-cache
256 KB L2 cache
8 MB L3 cache



Reality #3: 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

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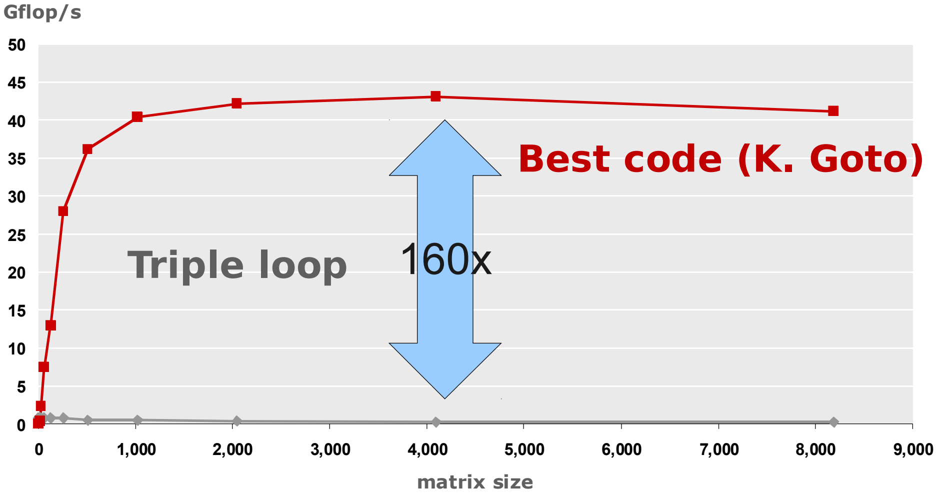
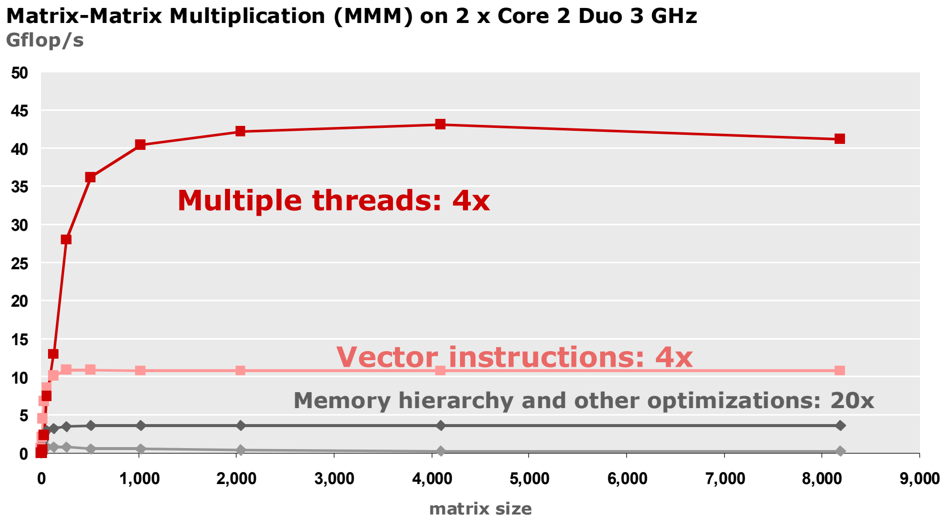
Example Matrix Multiplication

- 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


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

- 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 the “new CSE Curriculum”

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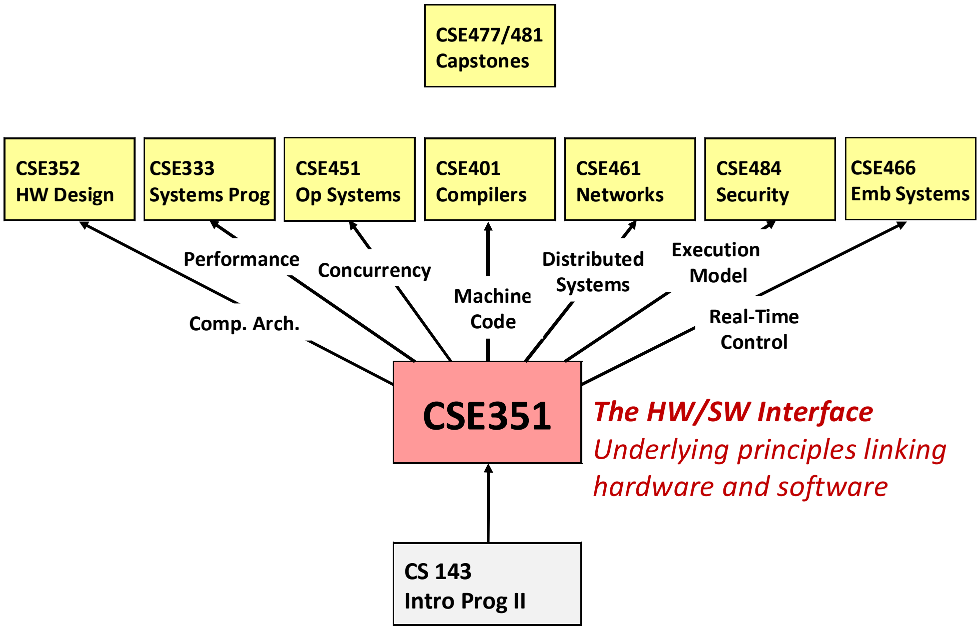
- **Pre-requisites**
  - 142 and 143: Intro Programming I and II

- **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

Comp. Arch.

Performance

Concurrency

Machine
Code

Distributed
Systems

Execution
Model

Real-Time
Control

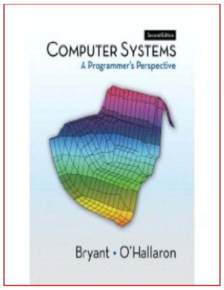
CSE351

The HW/SW Interface
Underlying principles linking hardware and software

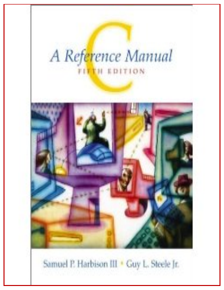
CS 143
Intro Prog II

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



- **C: A Reference Manual, 5th Edition**
  - Samuel P. Harbison III and Guy L. Steele, Jr.
  - Prentice-Hall, 2002
  - Solid C programming language reference
  - Useful book to have on your shelf



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)**
  - Motivation to stay on top of things
  - Demonstrate your understanding of concepts and principles

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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 (linked from homepage)**
  - Any comments about anything related to the course where you would feel better not attaching your name
  - By default, all anonymous feedback is posted (so you can view it)

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
- **Late Policy**
  - Two discretionary late days
  - 10%/day after that
- **Grading:**
  - 55%assignments
  - 45% 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