# The Hardware/Software Interface CSE351

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# Who is Luis?


**PhD in architecture, multiprocessors, parallelism, compilers.**

# Who are you?

- 85+ students (wow!)
- Who has written programs in assembly before?
- Written a threaded program before?
- What is hardware? Software?
- 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:
```

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

# C vs. Assembler vs. Machine Programs

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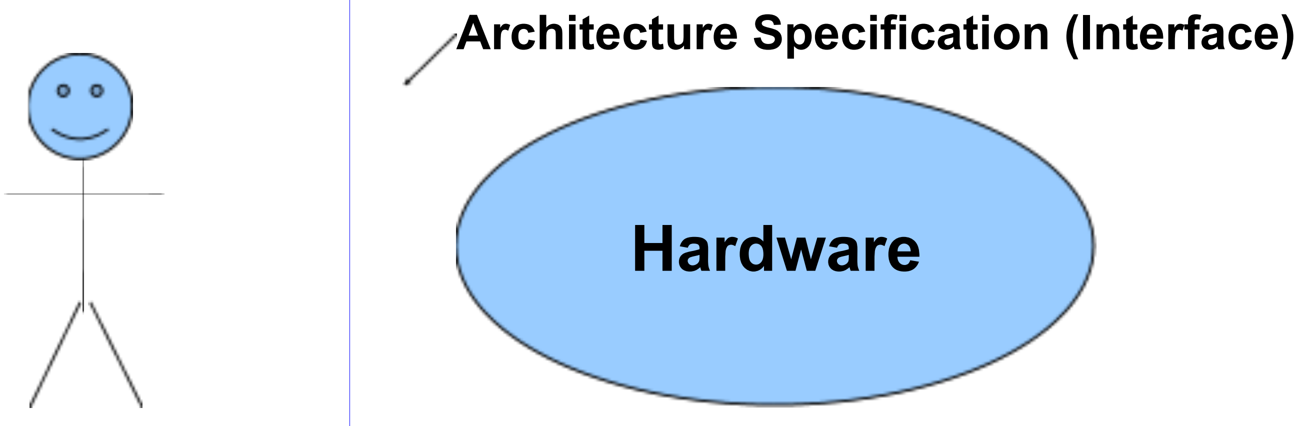
```
1000001101111100001001000001110000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
100011010000010000000010
1000100111000010
110000011111101000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

- **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

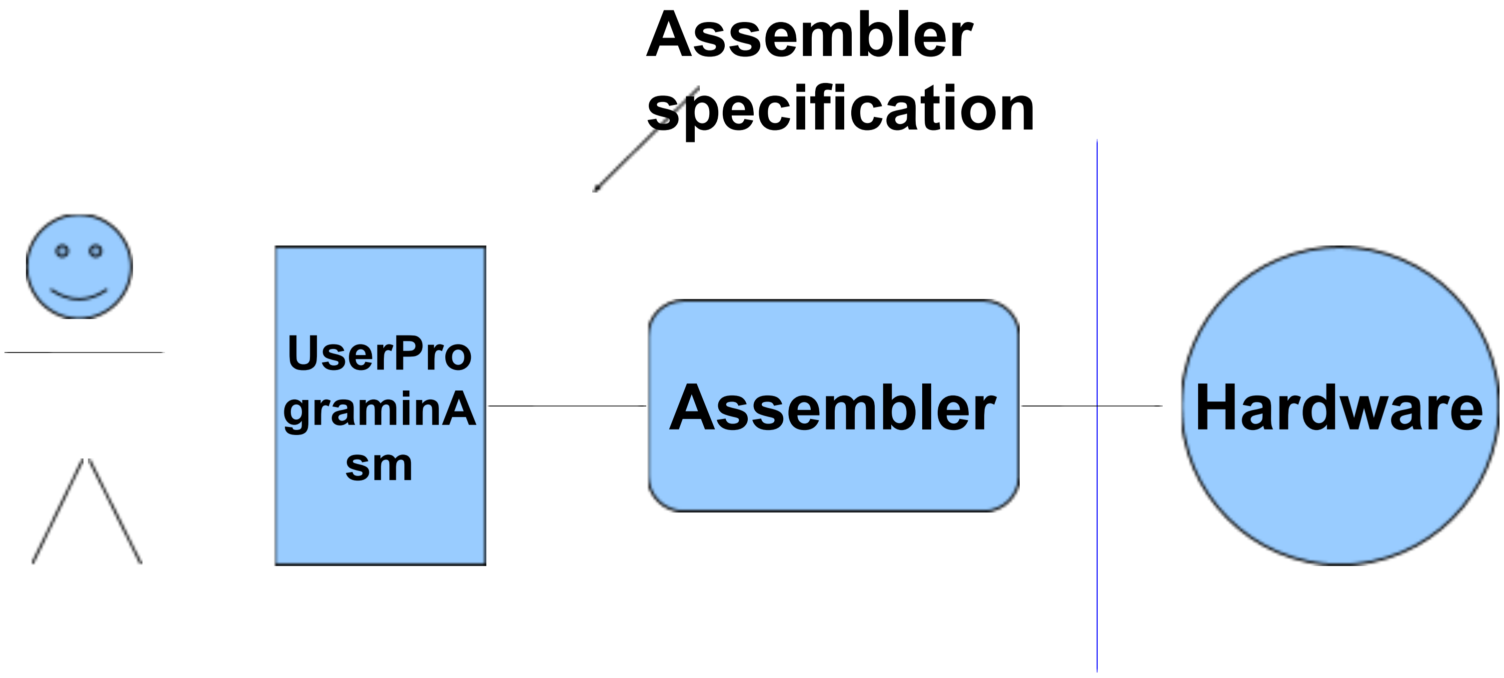
# HW/SW Interface: The Historical Perspective

- **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**



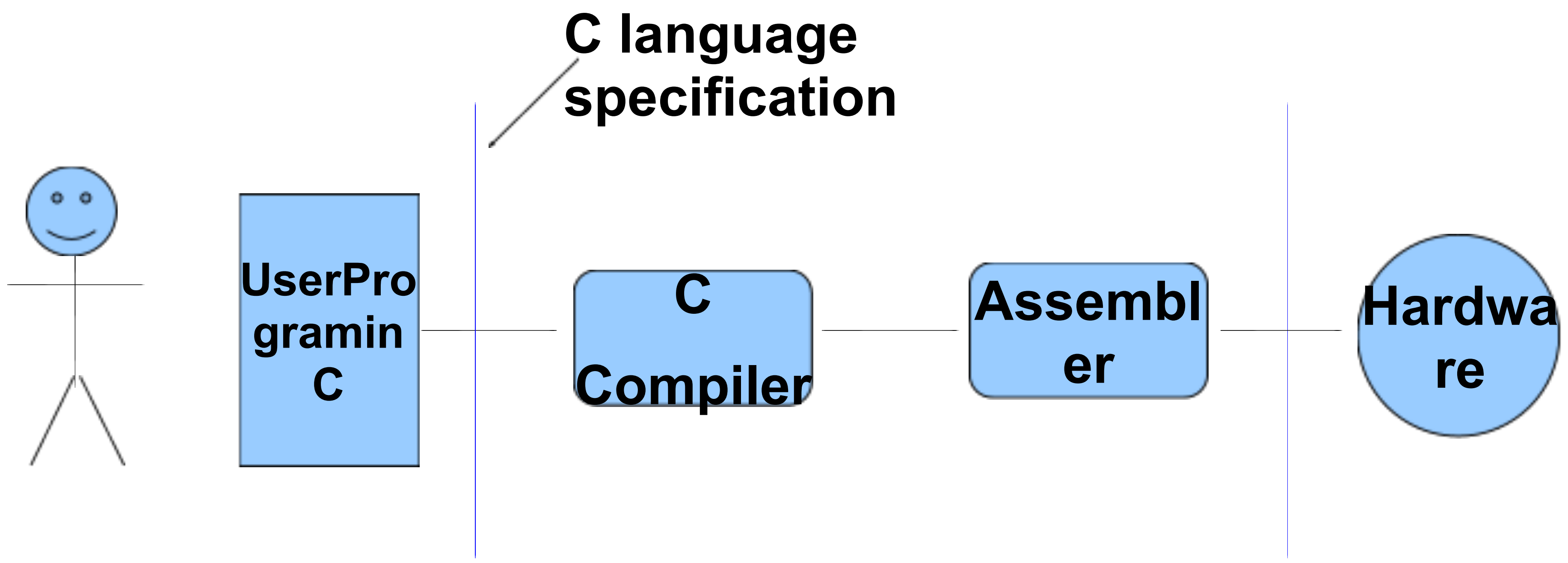
# HW/SW Interface: Assemblers

- **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

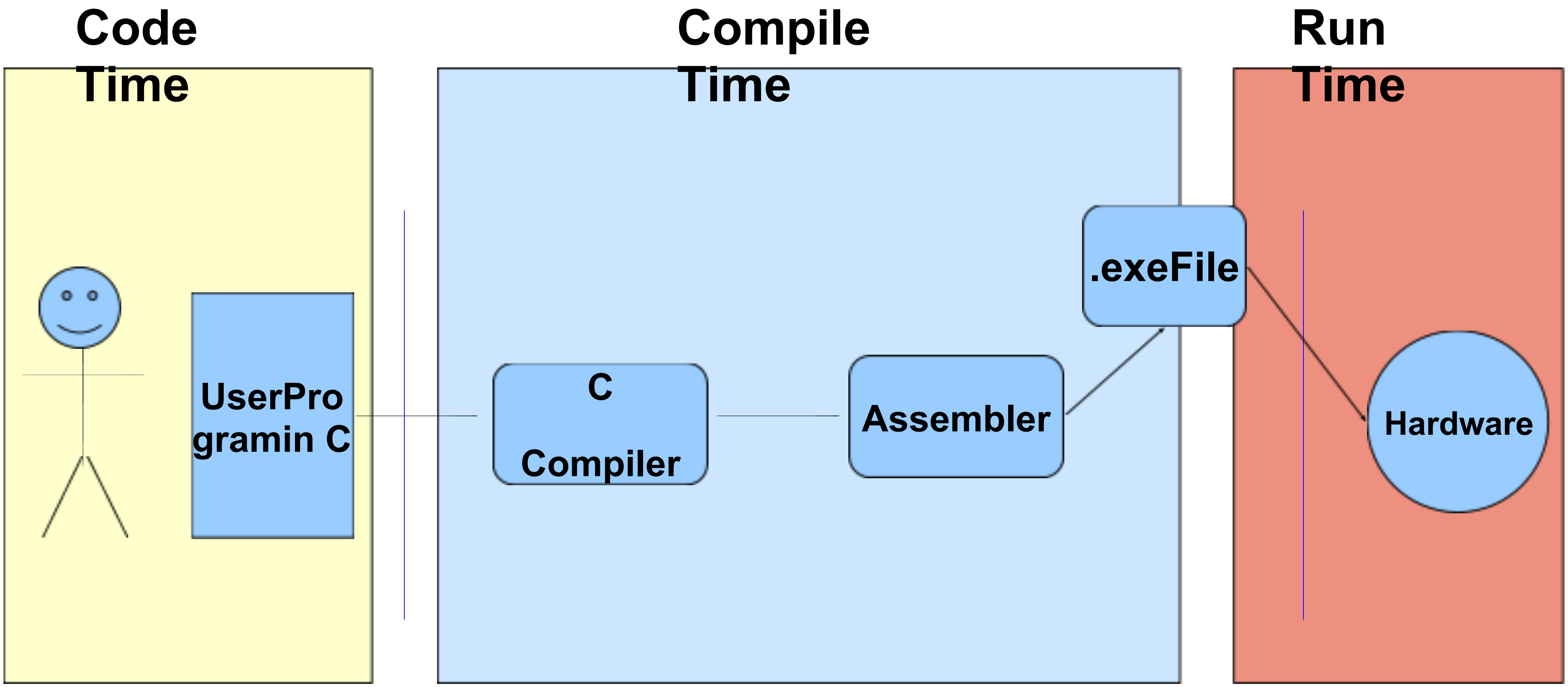


# HW/SW Interface: Higher Level Languages (HLL's)

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



# 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
- HW0 released! Have fun!
- (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 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 x2 ≥ 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

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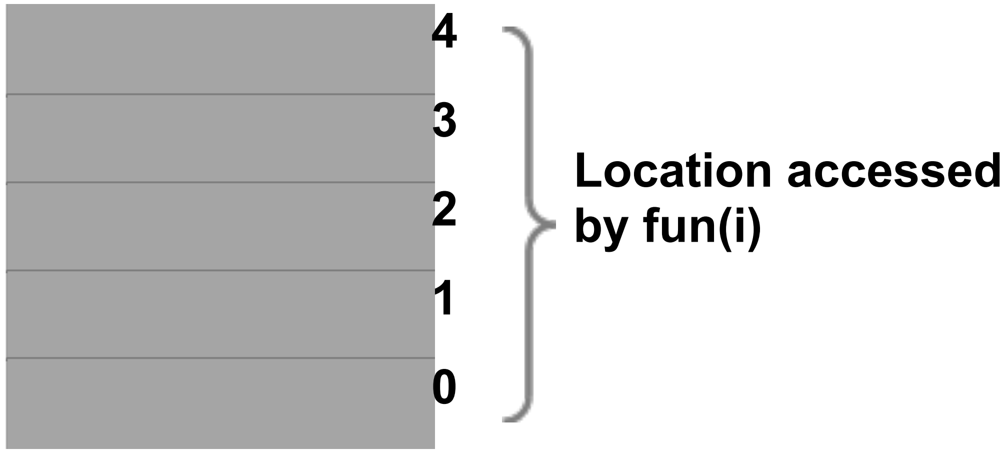
---

## 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 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++)
[redacted] (i = 0; i < 2048; i++)
[redacted][i][j] = src[i][j];
}
```

**21 times slower (Pentium 4)**

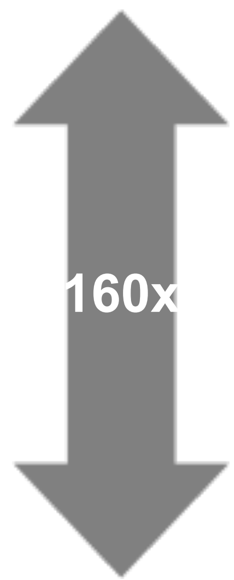
# Reality #4: Performance isn't counting ops

- **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 ($2n^3$)

**Best code (K. Goto)**




**Triple loop**

# MMM Plot: Analysis

**Multiple threads: 4x**

**Vector instructions: 4x**

**Memory hierarchy and other optimizations: 20x**

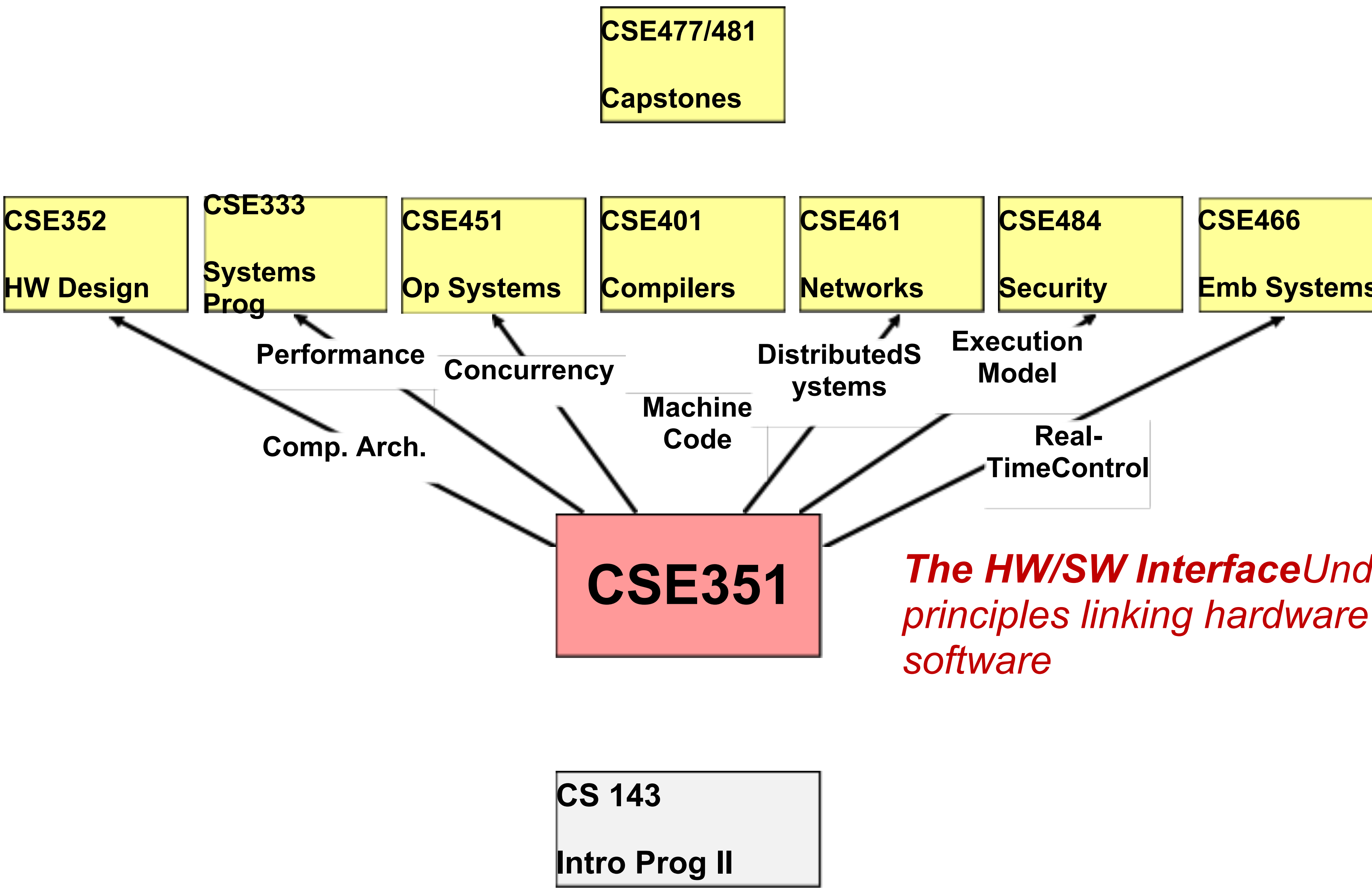
- Reason for 20x: blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice

- *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




***The HW/SW Interface****Underlying principles linking hardware and software*

# Course Perspective

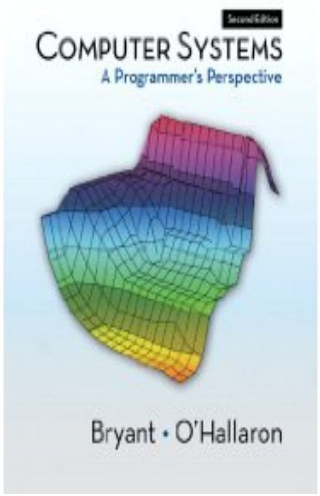
- **Most systems courses are Builder-Centric**
  - Computer Architecture
    - Design pipelined processor in Verilog
  - Operating Systems
    - Implement large portions of operating system
  - Compilers
    - Write compiler for simple language
  - Networking
    - Implement and simulate network protocols

# 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 coursewhere 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