# The Hardware/Software Interface
CSE351 Winter 2013

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**Teaching Assistants:**
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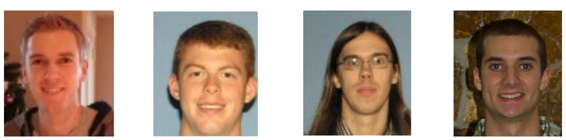
# Who is your instructor?

- **History:**
  - **Undergrad at University of Pennsylvania**
  - **Software engineer at Cisco**
  - **Grad student at UW**
- **My research:**
  - **Operating systems**
  - **Computer architecture**
  - **Security / privacy**
- **First-time instructor**
  - **I am not a doctor, nor a professor**





# Who are your TAs?



**Elliott (AC)** | **Matt (AB)** | **Dustin** | **Mark (AA)**





# Notice

- **This lecture is being recorded!**
  - The microphone and projector are captured and will be combined into a screencast
  - Recordings are only accessible to students enrolled in the class after logging in with UW ID
    - Audio recordings can be downloaded
  - If any of this concerns you, see these links and come speak to me:
    - http://www.css.washington.edu/pdf/ScreencastInfo.pdf
    - http://www.css.washington.edu/wiki/Frequently_Asked_Questions_about_On-Demand_Audio_Service
- **Information about how to view the recordings will be posted to website**

# Who are you?

- **85 students**
  - We'll do our best to get to know each of you!
- **Who has written a program in:**
  - Java?
  - C?
  - Assembly language?





# The Hardware/Software Interface

- **What is hardware? Software?**
- **What is an interface?**
- **Why do we need a hardware/software interface?**
- **Why do we need to understand both sides of this interface?**





# 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

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1000001101111100001001000001110000000000
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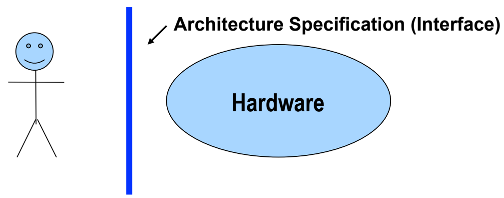
100011010000010000000010
1000100111000010
110000011111101000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

- **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 the number of bits we would need to represent the characters in 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 basic**
  - Software primitives reflected the hardware pretty closely

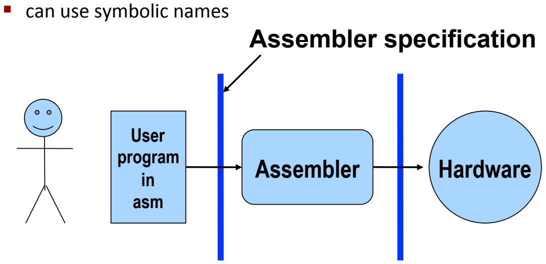







# HW/SW Interface: Assemblers

- **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
  - can use symbolic names

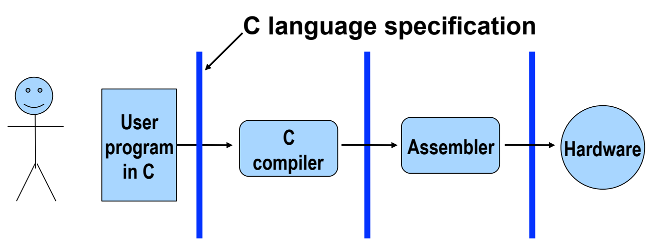







# HW/SW Interface: Higher-Level Languages

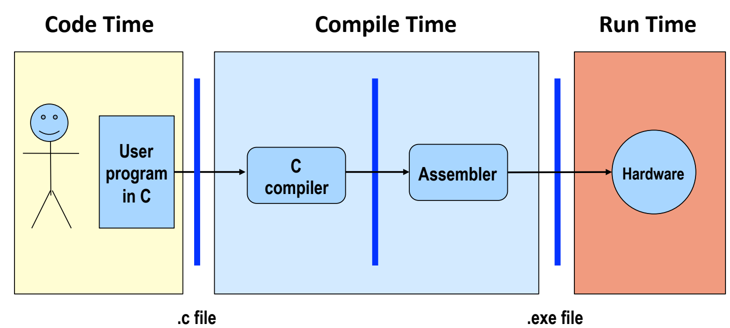
- **Higher level of abstraction:**
  - 1 line of a high-level language is compiled into many (sometimes very many) lines of assembly language








# HW/SW Interface: Code / Compile / Run Times




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

# Outline for today

- Course themes: big and little
- Roadmap of course topics
- Three important realities
- How the course fits into the CSE curriculum
- Logistics





# The Big Theme: Interfaces and Abstractions

- 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?
- How does the hardware (0s and 1s, processor executing instructions) relate to the software (C/Java programs)?
  - Become a better programmer and begin to understand the important concepts that have evolved in building ever more complex computer systems





# Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

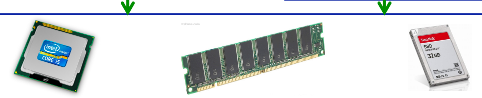
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS: Windows 8, Mac

Computer system:



Memory & data
Integers & floats
Machine code & C
x86 assembly programming
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C





# 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 wires
- "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**
  - Words, phrases and grammars
- **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) --> ??

# Reality #2: Assembly still matters

- **Why? Because we want you to suffer?**





# Reality #2: Assembly still matters

- **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
  - Fighting malicious software
  - Using special units (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

- So, 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
```





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```

**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)**





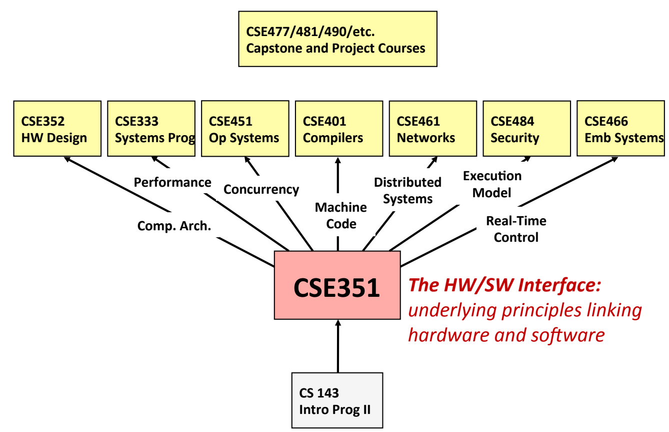
# CSE351's role in CSE Curriculum

- **Pre-requisites**
  - 142 and 143: Intro Programming I and II
  - Also recommended: 390A: System and Software Tools
- **One of 6 core courses**
  - 311: Foundations of Computing I
  - 312: Foundations of Computing II
  - 331: SW Design and Implementation
  - 332: Data Abstractions
  - 351: HW/SW Interface
  - 352: HW Design and Implementation
- **351 provides the context for many follow-on courses**





# CSE351's place in CSE Curriculum



# Course Perspective

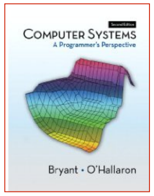
- **This course will make you a better programmer**
  - Purpose is to show how software really works
  - By understanding the underlying system, one can be more effective as a programmer
    - Better debugging
    - Better basis for evaluating performance
    - How multiple activities work in concert (e.g., OS and user programs)
  - Not just a course for dedicated hackers
    - What every CSE major needs to know
    - Job interviewers love to ask questions from 351!
  - 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 – any will do**
  - The C Programming Language (Kernighan and Ritchie)
  - C: A Reference Manual (Harbison and Steele)





# Course Components

- **Lectures (27)**
  - Introduce the concepts; supplemented by textbook
- **Sections (10)**
  - Applied concepts, important tools and skills for labs, clarification of lectures, exam review and preparation
- **Written homework assignments (4)**
  - Mostly problems from text to solidify understanding
- **Labs (5, plus "lab 0")**
  - Provide in-depth understanding (via practice) of an aspect of system
- **Exams (midterm + final)**
  - Test your understanding of concepts and principles
  - Midterm currently scheduled for Friday, February 15





# Resources

- **Course web page**
  - http://www.cse.washington.edu/351
  - Schedule, policies, labs, homeworks, and everything else
- **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
- **Office hours**
  - Will be posted this week
- **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%): 15% midterm, 25% final**
- **Written assignments (20%): weighted according to effort**
  - We'll try to make these about the same
- **Lab assignments (40%): weighted according to effort**
  - These will likely increase in weight as the quarter progresses
- **Late days:**
  - 3 late days to use as you wish throughout the quarter – see website
- **Collaboration:**
  - http://www.cs.washington.edu/education/courses/cse351/13wi/policies.html
  - http://www.cs.washington.edu/students/policies/misconduct





# 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: Gaetano Borriello, Luis Ceze, Hal Perkins, John Zahorjan