The Hardware/Software Interface
CSE 351 Winter 2016

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Teaching Assistants:
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Welcome!

10 weeks to see the key abstractions “under the hood” to describe “what really happens” when a program runs

- How is it that “everything is 1s and 0s”?
- Where does all the data get stored and how do you find it?
- How can more than one program run at once?
- What happens to a Java or C program before the hardware processor can execute it?
- Why is recursion not even slightly magical?
- And much, much, much more...

An introduction that will:

- Profoundly change/augment your view of computers and programs
- Connect your source code down to the hardware
Concise To-Do List

- Review syllabus, course goals, collaboration policy, etc.: http://courses.cs.washington.edu/courses/cse351/16wi/
- Email-list settings, if necessary
- Beginning-of-course survey, “due” Wednesday 5PM
- Lab 0, due Monday, January 11 at 5pm
  - Make sure you get our virtual machine set up and are able to do work
  - Basic exercises to *start* getting familiar with C
  - Credit/no-credit
  - Get this done as quickly as possible
- Section Thursday
  - Please install the virtual machine BEFORE coming to section
  - BRING your computer with you to section
  - Includes activities to help you get started with Lab 0
Who: Course Staff

- Dan Grossman: Faculty since 2003, veteran of 341, 332, 331, 373, but first time in 351
  - Know and love the content, new to the course
  - Not planning “changes” but will be “fresh eyes”

- TAs: 7 (!), all have taken the course, 3 TA veterans (2 multi-)

- Office hours will be figured out ASAP

- Get to know us!
  - We are here to help you succeed
  - And to make the course better
  - And to enjoy showing you a new world
Acknowledgments

Many thanks to the many people whose course content we are liberally reusing with at most minor changes

- CMU: Randy Bryant, David O’Halloran, Gregory Kesden, Markus Püschel
- Harvard: Matt Welsh (now at Google-Seattle)
- UW: Gaetano Borriello, Luis Ceze, Peter Hornyack, Hal Perkins, Ben Wood, John Zahorjan, Katelin Bailey, Ruth Anderson
- Not listed: dozens of TAs
Who are you?

- ~90 registered
  - My intention: Make it feel like 40; learn all your names

- CSE majors, EE majors, some want-to-be majors
  - Most of you will find almost everything in the course “brand new”

- Please get to know each other
Staying In Touch

- **Course web page**
  - 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 cse351a_wi16@u.washington.edu**
  - Low traffic – mostly announcements; your @uw.edu is subscribed

- **Office hours, appointments, drop-ins**
  - We will spread our office hours throughout the week

- **Staff e-mail (Dan + TAs): cse351-staff@cse.uw.edu**
  - For things that are not appropriate for the discussion board

- **Anonymous feedback**
  - Comments about anything related to the course where you would feel better not attaching your name: goes directly to Dan
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 textbook to solidify understanding

- **Programming labs/assignments (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 Monday February 8, in class
  - Final time set by the university: Wednesday March 16, 2:30-4:20PM ☹️
Textbooks

- **Computer Systems: A Programmer’s Perspective, 3rd Edition**
  - Randal E. Bryant and David R. O’Hallaron
  - Prentice-Hall, 2015
  - [http://csapp.cs.cmu.edu](http://csapp.cs.cmu.edu)
  - 3rd edition includes complete rewrite of Chapter 3
    - All code examples in x86-64
    - [http://csapp.cs.cmu.edu/3e/changes3e.html](http://csapp.cs.cmu.edu/3e/changes3e.html)
  - 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) [instructor preference]
  - The C Programming Language (Kernighan and Ritchie)
Videos / Online course

- Gaetano Borriello and Luis Ceze made videos in 2013 covering the course content [for an online version of the course]
  - And self-check quiz questions

- These are a great resource – encourage you to watch them
  - Generally optional unless class is cancelled or something
  - Occasionally may “require before class” so you don’t get lost in an example

- But the course is now “all 64-bit” so some parts of the course no longer have [relevant] videos available
  - New videos not yet made – may get some progress on that
Policies: Grading

- **Exams (45%): 15% midterm, 30% final**
  - Many old exams on course website (but now 64-bit and new instructor)

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

- **Lab assignments (35%): 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.cse.uw.edu/education/courses/cse351/16wi/policies.html](http://www.cse.uw.edu/education/courses/cse351/16wi/policies.html)
  - [http://www.cse.uw.edu/students/policies/misconduct](http://www.cse.uw.edu/students/policies/misconduct)
  - Do not cheat!!! It’s an affront to the course staff, your fellow students, and yourself. CSE courses are special and valuable – keep it that way!
Other details

- Consider taking CSE 390A Unix Tools, 1 credit, useful skills
  - Available to all CSE majors and everyone registered in CSE351

- Office hours will be held this week, check web page for times

- Remember Lab 0 asap and bring laptop to section
Anything I forgot about course mechanics before we discuss, you know, hardware and software?
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

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

High Level Language
(e.g. C, Java)

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

Assembly Language

```
1000001101111100001001000001110000000000
0111010000011000
10001011010001000010010000011100
10001001010001000010010000011000
100011010000010000000010
1000100111000010
11000001111101000011111000010010000011100
100010010100001000010010000011100
100010010100001000010010000011100
100010010100001000010010000011100
```

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

Compiler

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:

Assembler

Machine Code

1000001101111100001001000001110000000000
0111010000011000
100101101000100001001000010100
100010110001100010010000011000
110000111111010000111111
1110111101111100001001000000011100
100100100010001000001000011000

High Level Language (e.g. C, Java)

Assembly Language

Machine Code
C/Java, assembly, and machine code

- 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

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

```c
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
100010110100010001000001001000000010
1000101101000101000011000000000000
1000010000010010000000000000
1000100111000010
1100000111110100000000000000
11101101111100001001000001110000000000
100010010100000000000000000000000000
```

```
1100000111110100000000000000
1111011011111000010010000000000000
100010010100000000010001000000000000
```

```
1100000111110100000000000000
1111011011111000010010000000000000
100010010100000000000000000000000000
```

```
1100000111110100000000000000
1111011011111000010010000000000000
100010010100000000000000000000000000
```
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
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
Higher level of abstraction:

- 1 line of a high-level language is compiled into many (sometimes very many) lines of assembly language
Note: The compiler and assembler are just programs, developed using this same process.
The Big Theme: Abstractions and Interfaces

- 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
HTTP://XKCD.COM/676/

AN x64 PROCESSOR IS SCREAMING ALONG AT BILLIONS OF CYCLES PER SECOND TO RUN THE XNU KERNEL, WHICH IS FRANTICALLY WORKING THROUGH ALL THE POSIX-SPECIFIED ABSTRACTION TO CREATE THE DARWIN SYSTEM UNDERLYING OS X, WHICH IN TURN IS STRAINING ITSELF TO RUN FIREFOX AND ITS GECKO RENDERER, WHICH CREATES A FLASH OBJECT WHICH RENDERS DOZENS OF VIDEO FRAMES EVERY SECOND

BECAUSE I WANTED TO SEE A CAT JUMP INTO A BOX AND FALL OVER.

I AM A GOD.
### Roadmap

**C:**
```c
#include "car.h"
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

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

**Assembly language:**
```assembly
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

**Machine code:**
```
0111010000011000
1000110100000100
1000100111000010
1100000011111010
1000001111110100
```

**Computer system:**
- OS: Windows 8, Mac
- Processor: Intel Core i5
- Memory: RAM
- Storage: SSD

**Memory & data:**
- Integers & floats
- Machine code & C

**x86 assembly:**
- Procedures & stacks

**Arrays & structs:**
- Memory & caches

**Processes:**
- Virtual memory

**Memory allocation:**
- Java vs. C

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**Winter 2016**
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
  - Or magnetic positions on a disc, or hole depths on a dvd, or...

- “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
- 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)
    - Not in that order, but will all connect by the last lecture!!!
Little Theme 3: Control Flow

- How do computers orchestrate the many things they are doing?

- In one program:
  - How do we implement if/else, loops, switches?
  - What do we have to keep track of when we call a procedure, and then another, and then another, and so on?
  - How do we know what to do upon “return”?

- Across 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”?
Writing Assembly Code??? In 2016???

- 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!
Course Outcomes

- 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
  - Less important later, but cannot “get it” without “doing it” and “doing it” requires details

- Become more effective programmers
  - Understand some of the many factors that influence program performance
  - More efficient at finding and eliminating bugs
  - Facility with a couple more of the many languages that we use to describe programs and data

- Prepare for later classes in CSE
CSE351’s role in the CSE Curriculum

- **Pre-requisites**
  - 142 and 143: Intro Programming I and II
  - Also recommended: 390A: System and Software Tools

- **Complementary to:**
  - CSE311->CSE369->EE371 / EE271->EE371: hardware design “below us”
    - “arranging wires to do addition and stuff”
  - EE/CSE474 embedded systems: CSE351 invaluable but not a pre-req [EE]
  - CSE331/332/341: high-level software design and structures

- **Essential pre-req for:**
  - CSE401: compilers – write a program to do CSE351 translations
  - CSE333: building well-structured systems in C/C++
  - Courses after CSE333: OS, networks, distributed systems, graphics, ...
Course Perspective

- CSE351 will make you a better programmer
  - Purpose is to show how software really works
  - Understanding the underlying system makes you more effective
    - Better debugging
    - Better basis for evaluating performance
    - How multiple activities work in concert (e.g., OS and user programs)
  - Not just a course for hardware enthusiasts!
    - What every CSE major needs to know (plus many more details)
    - Job interviewers love to ask questions from 351!
  - Like other 300-level courses, “stuff everybody learns and uses and forgets not knowing”

- CSE351 presents a world-view that will empower you
  - The intellectual tools and software tools to understand the trillions+ of 1s and 0s that are “flying around” when your program runs