The Hardware/Software Interface
CSE351 Summer 2013

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Course Staff

Ben
instructor

Jacob
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Riley
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Who are you?

- 22ish students
- Majors, non-majors
- Fans of computer science, no doubt!

Who has written a program:
- in Java?
- in C?
- in Assembly language?
- with multiple threads?
Quick Announcements

- Website: cs.uw.edu/351
- Section location to be updated soon...
- Lab 0 released, due Friday 5pm.
  - Simple exercises to get familiar with C.
  - Credit/no-credit.
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:
```

```
1000001101111100001001000011100000000000
0111010000011000
10001011010001000100010010000010100
1000101101000110010010100100010100
10001101000001000000000010
1000100111000010
1000100111000010
1000100111000010
10001101000001000000000010
1000100111000010
110000011111101000011111
11110111011111000010010000011100
1000100101000100001001000011000
```

C/Java, assembly, and machine code

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

- 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:

```c
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
100011010000010000000010
1000100111000010
110000011111101000011111
```

Computer system:

OS:

Memory, data, & addressing
Integers & floats
Machine code & C
x86 assembly
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?

- 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”?
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:
    - $40000 \times 40000 \rightarrow 1600000000$
    - $50000 \times 50000 \rightarrow ??$
- Example 2: Is $(x + y) + z = x + (y + z)$?
  - Unsigned & Signed Ints: Yes!
  - Floats:
    - $(1e20 + -1e20) + 3.14 \rightarrow 3.14$
    - $1e20 + (-1e20 + 3.14) \rightarrow ??$
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

```c
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

```c
/* 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:

<table>
<thead>
<tr>
<th>Saved State</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>d7 ... d4</td>
<td>3</td>
</tr>
<tr>
<td>d3 ... d0</td>
<td>2</td>
</tr>
<tr>
<td>a[1]</td>
<td>1</td>
</tr>
<tr>
<td>a[0]</td>
<td>0</td>
</tr>
</tbody>
</table>

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 Haskell, or Ruby, or Racket, 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

```c
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 the 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 the CSE Curriculum

The HW/SW Interface: underlying principles linking hardware and software
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](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 (25)
  - Introduce the concepts; supplemented by textbook

- Sections (8+)
  - 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 Wednesday, July 24, in class.
  - Final is definitely Friday, August 23, in class (last day).

- Summer quarter is only 9 weeks long!
Resources

- **Course web page**
  - [cs.uw.edu/351](http://cs.uw.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 – check your @uw.edu**
  - Low traffic – mostly announcements; you are already subscribed

- **Office hours, appointments, drop-ins**
  - Poll: will be posted this week

- **Staff e-mail: cse351-staff@cs.washington.edu**
  - 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 (35%): 15% midterm, 20% final
- Written assignments (20%): weighted according to effort
  - We’ll try to make these about the same
- Lab assignments (45%): 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/students/policies/misconduct](http://www.cs.washington.edu/students/policies/misconduct)
Other details

- Consider taking CSE 390A, 1 credit, useful skills
- Poll: office hours + reschedule section 2 (week of July 4)
  - (OH) Monday late morning / afternoon
  - (OH, S2) Tuesday late morning / afternoon
  - (OH, S2) Wednesday late morning / afternoon
  - (OH) Thursday late morning / afternoon
  - (OH, S2) Friday late morning / afternoon
- Lab 0 due Friday 5pm.
  - On the website
  - Non-majors accounts
  - CSE home VM
  - Thursday section on C and tools.
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, Hal Perkins, John Zahorjan, Peter Hornyack, Luis Ceze