The Hardware/Software Interface
CSE351 Autumn 2010
1st Lecture, 29 September

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Overview

- Course themes: big and little
- Four important realities
- How the course fits into the CSE curriculum
- Logistics
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 assumptions are being made that may or may not hold in a new context or for a new technology?
  - 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 \( x^2 \geq 0? \)
  - 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:
    - \((1e20 + -1e20) + 3.14 \rightarrow 3.14\)
    - \(1e20 + (-1e20 + 3.14) \rightarrow ??\)
Code Security Example

/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[FSIZE]; 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 (FSIZE > 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[FSIZE]; 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 (FSIZE > maxlen) len = maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}

#define MSIZE 528

void getstuff() {
    char mybuf[FSIZE];
    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

```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 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 */
         : "%edx", "%eax" /* input */
         : /* 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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fun(2)  ->  3.1399998664856
fun(3)  ->  2.00000061035156
fun(4)  ->  3.14, then segmentation fault

Explanation:

<table>
<thead>
<tr>
<th>Saved State</th>
<th>Location accessed by fun(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d7 ... d4</td>
<td>4</td>
</tr>
<tr>
<td>d3 ... d0</td>
<td>3</td>
</tr>
<tr>
<td>a[1]</td>
<td>2</td>
</tr>
<tr>
<td>a[0]</td>
<td>1</td>
</tr>
</tbody>
</table>

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

```c
void copyji(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];
}
```

```c
void copyij(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

Pentium III Xeon
550 MHz
16 KB on-chip L1 d-cache
16 KB on-chip L1 i-cache
512 KB off-chip unified L2 cache
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 (2n³)

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

Gflop/s

<table>
<thead>
<tr>
<th>matrix size</th>
<th>Triple loop</th>
<th>Best code (K. Goto)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>160x</td>
</tr>
<tr>
<td>1,000</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>2,000</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>3,000</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>4,000</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>5,000</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>6,000</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>7,000</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>8,000</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>9,000</td>
<td>90</td>
<td>120</td>
</tr>
</tbody>
</table>
Matrix-Matrix Multiplication (MMM) on 2 x Core 2 Duo 3 GHz

Gflop/s

- Memory hierarchy and other optimizations: 20x
- Vector instructions: 4x
- Multiple threads: 4x

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*

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**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

CSE351

CSE352
HW Design

CSE333
Systems Prog

CSE451
Op Systems

CSE401
Compilers

CSE461
Networks

CSE484
Security

CSE466
Emb Systems

The HW/SW Interface
Underlying principles linking hardware and software

CS 143
Intro Prog II

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](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)
  - Test your understanding of concepts and principles

Resources

- Course Web Page
  - [http://www.cse.washington.edu/351](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 course where 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