Introduction to Computer Systems

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Topics:
- Theme
- Five great realities of computer systems
- How this fits within CS curriculum

"The Class That Gives CMU Its Zip!"
Course Theme

- Abstraction is good, but don’t forget reality!

Most CS courses emphasize abstraction

- Abstract data types
- Asymptotic analysis

These abstractions have limits

- Especially in the presence of bugs
- Need to understand underlying implementations

Useful outcomes

- Become more effective programmers
  - Able to find and eliminate bugs efficiently
  - Able to tune program performance
- Prepare for later “systems” classes in CS & ECE
  - Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems
Great Reality #1

Int’s are not Integers, Float’s are not Reals

Examples

■ Is \( x^2 \geq 0? \)
  - Float’s: Yes!
  - Int’s:
    » \( 40000 \times 40000 \rightarrow 1600000000 \)
    » \( 50000 \times 50000 \rightarrow ?? \)

■ Is \( (x + y) + z = x + (y + z)? \)
  - Unsigned & Signed Int’s: Yes!
  - Float’s:
    » \( (1e20 + -1e20) + 3.14 \rightarrow 3.14 \)
    » \( 1e20 + (-1e20 + 3.14) \rightarrow ?? \)
Computer Arithmetic

Does not generate random values
- Arithmetic operations have important mathematical properties

Cannot assume “usual” properties
- Due to finiteness of representations
- Integer operations satisfy “ring” properties
  - Commutativity, associativity, distributivity
- Floating point operations satisfy “ordering” properties
  - Monotonicity, values of signs

Observation
- Need to understand which abstractions apply in which contexts
- Important issues for compiler writers and serious application programmers
Great Reality #2

You’ve got to know assembly

Chances are, you’ll never write program in assembly
- Compilers are much better & more patient than you are

Understanding assembly key to machine-level execution model
- Behavior of programs in presence of bugs
  - High-level language model breaks down
- Tuning program performance
  - Understanding sources of program inefficiency
- Implementing system software
  - Compiler has machine code as target
  - 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 required by procedure
  - In units of clock cycles

```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
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

/* 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)
         : "%edx", "%eax");
}
```
Great Reality #3

**Memory Matters:** Random Access Memory is an un-physical abstraction

**Memory is not unbounded**
- It must be allocated and managed
- Many applications are memory dominated

**Memory referencing bugs 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
**Referencing Bug Explanation**

- C does not implement bounds checking
- Out of range write can affect other parts of program state

<table>
<thead>
<tr>
<th>Saved State</th>
<th>Location accessed by <code>fun(i)</code></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>
<tr>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

```r
1 2 3 4
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 ML
- 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 step 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];
}
```

59,393,288 clock cycles

1,277,877,876 clock cycles

21.5 times slower!

(Measured on 2GHz Intel 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
Great Reality #4

There’s more to performance than asymptotic complexity

Constant factors matter too!
- 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 to measure program performance and identify bottlenecks
- How to improve performance without destroying code modularity and generality
Code Performance Example

- Multiply all elements of array
- Performance on class machines: ~7.0 clock cycles per element
  - Latency of floating-point multiplier
Loop Unrollings

- Do two loop elements per iteration
  - Reduces overhead

- Cycles per element:
  - u2: 7.0
  - u2r: 3.6
u2: Serial Computation

Computation (length=12)

\[
((((((1 * d[0]) * d[1]) * d[2]) * d[3]) * d[4]) * d[5]) * d[6]) * d[7]) * d[8]) * d[9]) * d[10]) * d[11])
\]

Performance

- N elements, D cycles/operation
- N*D cycles

result = (result * d[i]) * d[i+1];
u2r: Reassociated Computation

Performance

- N elements, D cycles/operation
- \((N/2+1)\times D\) cycles

result = result * (d[i] * d[i+1]);
Great Reality #5

Computers do more than execute programs

They need to get data in and out

- I/O system critical to program reliability and performance

They communicate with each other over networks

- Many system-level issues arise in presence of network
  - Concurrent operations by autonomous processes
  - Coping with unreliable media
  - Cross platform compatibility
  - Complex performance issues
Role within Curriculum

Foundation of Computer Systems

- Underlying principles for hardware, software, and networking
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.)

Our Course is Programmer-Centric

- Purpose is to show how by knowing more about the underlying system, one can be more effective as a programmer
- Enable you to
  - Write programs that are more reliable and efficient
  - Incorporate features that require hooks into OS
    » E.g., concurrency, signal handlers
- Not just a course for dedicated hackers
  - We bring out the hidden hacker in everyone
- Cover material in this course that you won’t see elsewhere