15-213
“The Class That Gives CMU Its Zip!”

Introduction to Computer Systems

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Topics:

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

15-213 was developed and fine-tuned by Randal E. Bryant and David O’Halleran. They wrote *The Book!*
Course Theme

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

Courses to date 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
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");
}
```
/* Record the current value of the cycle counter. */
void start_counter()
{
    access_counter(&cyc_hi, &cyc_lo);
}

/* Number of cycles since the last call to start_counter. */
double get_counter()
{
    unsigned ncyc_hi, ncyc_lo;
    unsigned hi, lo, borrow;
    /* Get cycle counter */
    access_counter(&ncyc_hi, &ncyc_lo);
    /* Do double precision subtraction */
    lo = ncyc_lo - cyc_lo;
    borrow = lo > ncyc_lo;
    hi = ncyc_hi - cyc_hi - borrow;
    return (double) hi * (1 << 30) * 4 + lo;
}
## Measuring Time

### Trickier than it Might Look

- Many sources of variation

### Example

- Sum integers from 1 to n

<table>
<thead>
<tr>
<th>n</th>
<th>Cycles</th>
<th>Cycles/n</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>961</td>
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<tr>
<td>1,000,000,000</td>
<td>8,371,2305,591</td>
<td>8.37</td>
</tr>
</tbody>
</table>
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

```c
main ()
{
    long int a[2];
    double d = 3.14;
    a[2] = 1073741824; /* Out of bounds reference */
    printf("d = %.15g\n", d);
    exit(0);
}
```

<table>
<thead>
<tr>
<th>Alpha</th>
<th>MIPS</th>
<th>Linux</th>
</tr>
</thead>
<tbody>
<tr>
<td>-g</td>
<td>5.30498947741318e-315</td>
<td>3.1399998664856</td>
</tr>
<tr>
<td>-O</td>
<td>3.14</td>
<td>3.14</td>
</tr>
</tbody>
</table>

(Linux version gives correct result, but implementing as separate function gives segmentation fault.)
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, Lisp, or ML
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors
Implementations of Matrix Multiplication

- Multiple ways to nest loops

```c
/* ijk */
for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum;
    }
}

/* jik */
for (j=0; j<n; j++) {
    for (i=0; i<n; i++) {
        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum;
    }
}
```
Matmult Performance (Alpha 21164)

Too big for L1 Cache
Too big for L2 Cache

matrix size (n)
Blocked matmuilt perf (Alpha 21164)
Real Memory Performance

Pointer-Chase Results

From Tom Womack’s memory latency benchmark
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
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

Transition from Abstract to Concrete!
- From: high-level language model
- To: underlying implementation
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