15-213
"The Class That Gives CMU Its Zip!"

Introduction to Computer Systems

Randal E. Bryant
August 28, 2001

Topics:

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

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 * 40000  --> 1600000000`**
    - » **`50000 * 50000  --> ??`**
- **Is (x + y) + z = x + (y + z)?**
  - Unsigned & Signed Int's: Yes!
  - Float's:
    - » **`(1e20 + -1e20) + 3.14 --> 3.14`**
    - » **`1e20 + (-1e20 + 3.14) --> ??`**

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 & patient at this 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

```
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**

```
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");
}
```


Code to Read Counter

```
/* 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

n	Cycles	Cycles/n
100	961	9.61
1,000	8,407	8.41
1,000	8,426	8.43
10,000	82,861	8.29
10,000	82,876	8.29
1,000,000	8,419,907	8.42
1,000,000	8,425,181	8.43
1,000,000,000	8,371,2305,591	8.37

Great Reality #3

Memory Matters

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

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

	Alpha	MIPS	Linux
-g	5.30498947741318e-315	3.1399998664856	3.14
-O	3.14	3.14	3.14

(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
  - E.g., Purify

Memory Performance Example

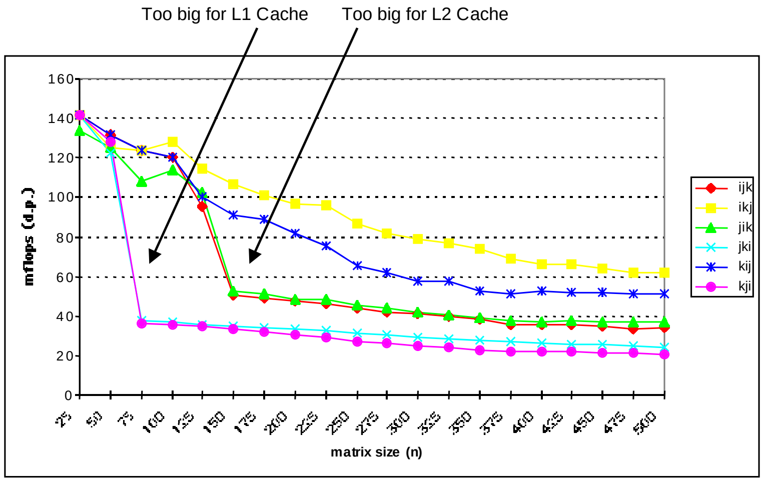
Implementations of Matrix Multiplication

- Multiple ways to nest loops

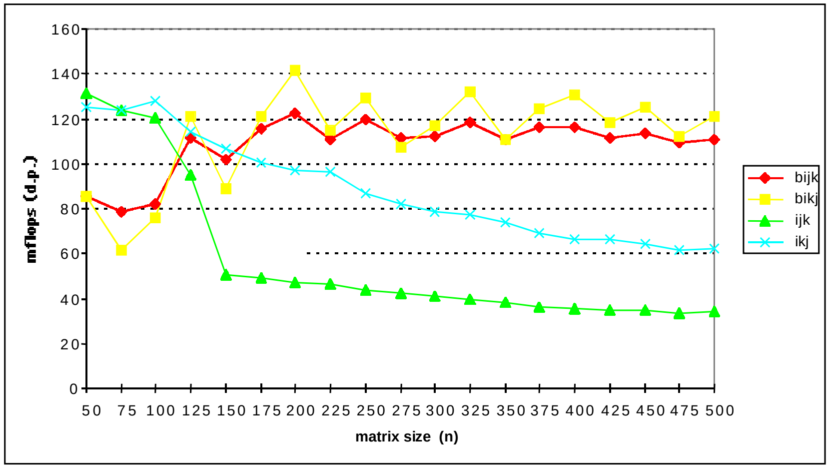
```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

```
/* 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)



Blocked matmult perf (Alpha 21164)



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

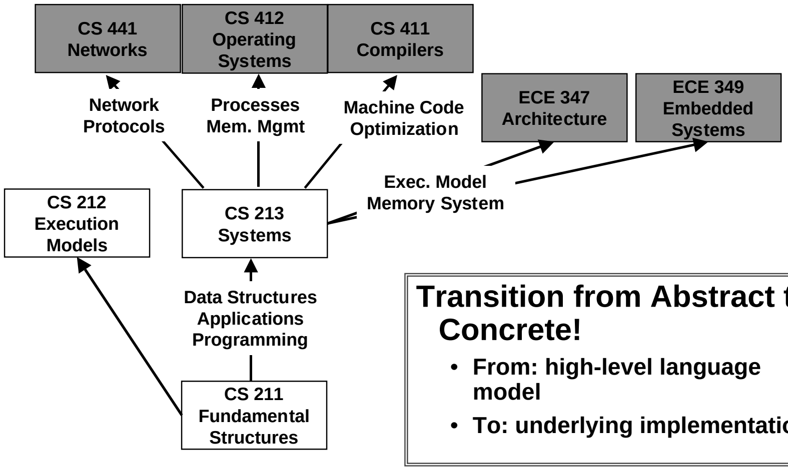
They need to get data in and out

- **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**