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**

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**
  - Compilers, Operating Systems, Networks, Computer Architecture

Great Reality #1

`Int`'s are not Integers, `Float`'s are not Reals

Examples
- **Is $x^2 \geq 0$?**
  - Float's: Yes!
  - Int's:
    - » `65535 * 65535 --> -131071` **(On most machines)**
    - » `65535L * 65535 --> 4292836225` **(On Alpha)**
- **Is (x + y) + z = x + (y + z)?**
  - Unsigned & Signed Int's: Yes!
  - Float's:
    - » `(1e10 + -1e10) + 3.14 --> 3.14`
    - » `1e10 + (-1e10 + 3.14) --> 0.0`

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 (usually)**
  - 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

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	Sun
-g	5.30498947741318e-315	3.1399998664856	3.14
-O	3.14	3.14	3.14

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

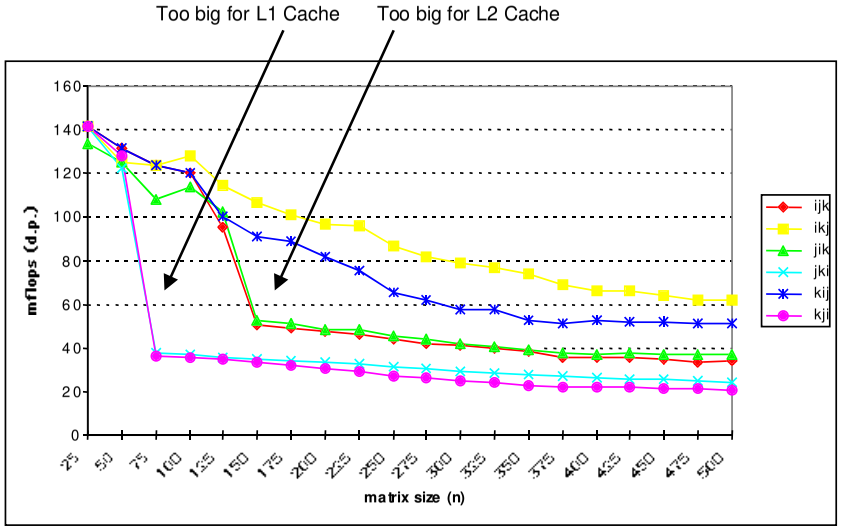
Implementations of Matrix Multiplication

- Multiple ways to nest loops

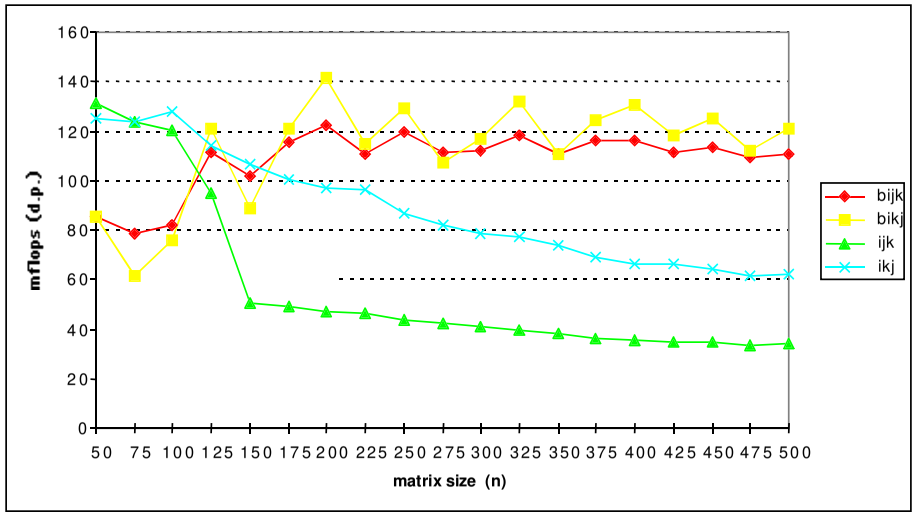
```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

```
/* 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

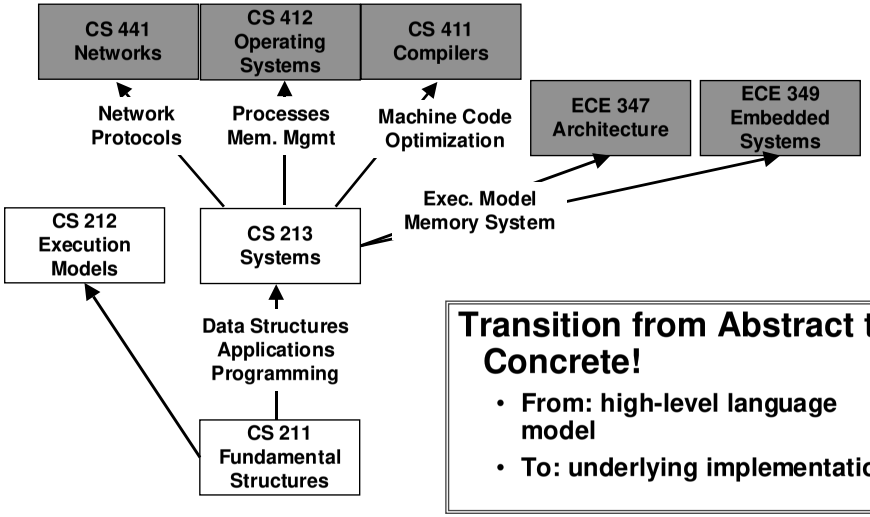
They need to get data in and out

- **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 efficent
  - 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**