CSCE 230J
Computer Organization

Introduction to Computer Systems

Dr. Steve Goddard
goddard@cse.unl.edu

http://cse.unl.edu/~goddard/Courses/CSCE230J

Giving credit where credit is due

- **Most of slides for this lecture are based on slides created by Drs. Bryant and O'Hallaron, Carnegie Mellon University.**
- **Some examples and slides are based on lecture notes created by Dr. Shard Seth, UNL.**
- **I have modified them and added new slides.**

Topics

- **Why do we care about this stuff?**
- **Course theme**
- **Five great realities of computer systems**
- **Computer system overview**

Why Do We Care…

Rapidly changing field:

- **vacuum tube -> transistor -> IC -> VLSI**
- **doubling every 1.5 years:**
  memory capacity
  processor speed *(Due to advances in technology and organization)*

Things you'll be learning:

- **how computers work, a basic foundation**
- **how to analyze their performance (or how not to!)**
- **issues affecting modern processors (caches, pipelines)**

Why learn this stuff?

- **you want to call yourself a "computer scientist"**
- **you want to build software people use (need performance)**
- **you need to make a purchasing decision or offer "expert" advice**

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 & CE**
  - **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 a program in assembly

- Compilers are much better & more patient than you are

Understanding assembly is key to understanding the 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 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

```
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**

Memory Performance Example

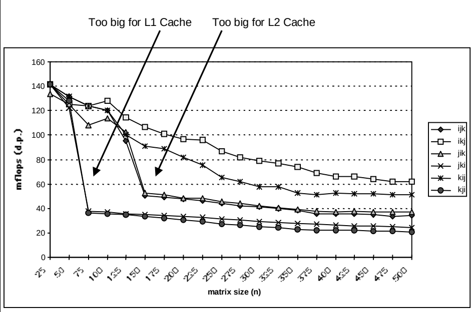
Implementations of Matrix Multiplication

- **Multiple ways to nest loops**

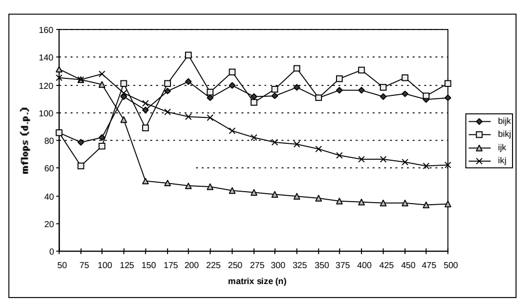
```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

```
/* 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 is 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**

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**

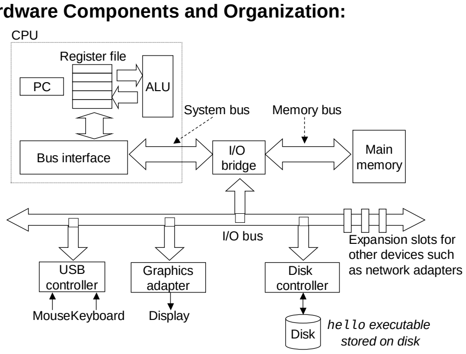
Course Perspective (Cont.)

This Course is Programmer-Centric

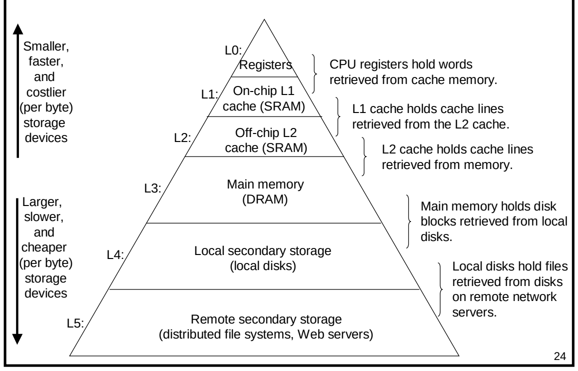
- **Purpose is to show how by knowing more about the underlying system, one can be more effective as a programmer**
- **Enable you to**
  - **Write programs that are more reliable and efficient**
  - **Incorporate features that require hooks into OS**
    - » E.g., concurrency, signal handlers
- **Not 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**

What is a computer?

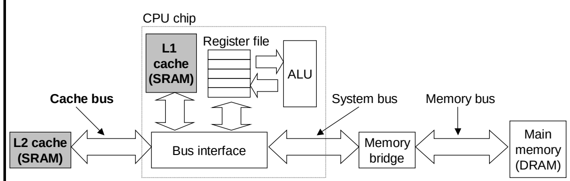
Hardware Components and Organization:



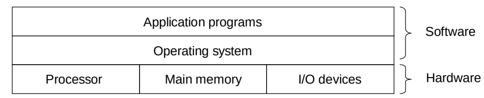
Memory Hierarchy

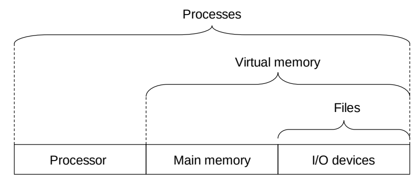


Cache Memories



OS Abstracts HW





Summary

The Computer system is more than just hardware!

We have to understand both the hardware and the system interfaces to properly understand and use a computer.

The rest of this semester will be spent studying these concepts in much more detail.