Computer Organization
CMSC 311

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Topics:

- Staff, text, and policies
- Lecture topics and assignments
- Lab rationale

Textbooks

Randal E. Bryant and David R. O'Hallaron,

- "Computer Systems: A Programmer's Perspective", Prentice Hall 2003.
- csapp.cs.cmu.edu

Brian Kernighan and Dennis Ritchie,

- "The C Programming Language, Second Edition", Prentice Hall, 1988

Course Components

Lectures

- Higher level concepts

Labs

- The heart of the course
- 1 or 2 weeks
- Provide in-depth understanding of an aspect of systems
- Programming and measurement

Getting Help

Web

- http://www.cs.umd.edu/~waa/UMD/CMSC_311_Fall_2009_Syllabus.html
- http://elms.umd.edu
- Copies of assignments, exams, solutions
- Clarifications to assignments
- Student and News forums for general discussions

Personal help

- My door open means come on in (no appt necessary) but please try and make an appointment first (unless it is office hours)
- TAs: please mail first.
- Office hours posted in syllabus

Policies: Assignments

Work groups

- You must work alone on all labs

Handins

- Assignments due by midnight on specified due date.
- Electronic handins only for labs (details TBD)

Makeup exams and assignments

- OK in extenuating circumstances, but must make PRIOR arrangements with Prof. Arbaugh

Appealing grades

- Within 7 days of due date or exam date.
- Assignments: Talk to the lead person on the assignment
- Exams: Talk to Prof. Arbaugh.

Cheating

What is cheating?

- Sharing code: either by copying, retyping, looking at, or supplying a copy of a file. This includes pulling some thing from Google!

What is NOT cheating?

- Helping others use systems or tools.
- Helping others with high-level design issues.
- Helping others debug their code.

Penalty for cheating:

- Referral to academic counsel for academic dishonesty.

Policies: Grading

Exams (35%)

- Two in class exams (10% each)
- Final (15%)
- All exams are open book/open notes.

Labs (60%)

- 6 labs (10% each)

Class Participation (5%)

- “Pop” quizzes in class
- Participation in forum

Grading Characteristics

- Lab scores tend to be high
  - Serious handicap if you don’t hand a lab in
- Tests typically have a wider range of scores

Policies: Classroom Behavior

- Strive to arrive on time
- Cell phone use (to include texting and ringing) will not be tolerated.
  - You will be asked to leave the classroom
  - I will give a pop quiz to the rest of the class (you'll get a zero)

Facilities

Assignments may use virtual machine technology or LinuxLab (Discussion)

Class Web Page - Elms

- Course web page is utilizing ELMS for online communication
- You'll find:
  - Syllabus
  - Interactive forums
    - News (I post only)
    - Discussion (anyone can post)
  - Assignments
  - Distribution of grades

Class Topics

- Programs and Data
- Reverse Engineering
- Performance
- The Memory Hierarchy
- Linking and Exceptional Flow Control
- Virtual Memory
- Virtualization
- I/O, Networking, and Concurrency

Programs and Data

Topics

- Bits operations, arithmetic, assembly language programs, representation of C control and data structures
- Includes aspects of of architecture and compilers

Assignments

- Lab 1: Manipulating bits
- Lab 2: Defusing a binary bomb

Data Representation

What does 0x41 mean?

Safe Programming and Reverse Engineering

Topics

- Safe Coding techniques
- Disassembly
- Program tracing
- Buffer and Heap Overflows

Assignments

- Lab 2: Defusing a binary bomb
- Lab 3: Buffer Overflows

Performance

Topics

- High level processor models, code optimization (control and data), measuring time on a computer
- Includes aspects of architecture, compilers, and OS

Assignments

- Lab 4: Optimizing Code Performance

The Memory Hierarchy

Topics

- Memory technology, memory hierarchy, caches, disks, locality
- Includes aspects of architecture and OS.

Assignments

- Lab 4: Optimizing Code Performance

Linking and Exceptional Control Flow

Topics

- Object files, static and dynamic linking, libraries, loading
- Hardware exceptions, processes, process control, Unix signals, non-local jumps
- Includes aspects of compilers, OS, and architecture

Assignments

- Lab 5: Writing your own shell with job control

Virtual memory

Topics

- Virtual memory, address translation, dynamic storage allocation
- Includes aspects of architecture and OS

Assignments

- Lab 5: Writing your own malloc package

Virtualizaiton

Topics

- Processor specific virtualization instructions
- IO Chipset additions to support virtualization

I/O, Networking, and Concurrency

Topics

- High level and low-level I/O, network programming, Internet services, Web servers
- concurrency, concurrent server design, threads, I/O multiplexing with select.
- Includes aspects of networking, OS, and architecture.

Assignments

- Lab 6: Writing your own web proxy program

Lab Rationale

Each lab should have a well-defined goal such as solving a puzzle or winning a contest.

- Defusing a binary bomb.
- Winning a performance contest.

Doing a lab should result in new skills and concepts

- Data Lab: computer arithmetic, digital logic.
- Bomb/buf Labs: assembly language, using a debugger, understanding the stack
- Perf Lab: profiling, measurement, performance debugging.
- Shell Lab: understanding Unix process control and signals
- Malloc Lab: understanding pointers and nasty memory bugs.
- Proxy Lab: Understanding how to write network programs

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 & 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

```
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;
}
```

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 a memory system can lead to major speed improvements

Memory Referencing Bug Example

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

	Alpha	MIPS	Linux
-g	5.3049894774131 8e-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, Python, or ML
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors

Memory Performance Example

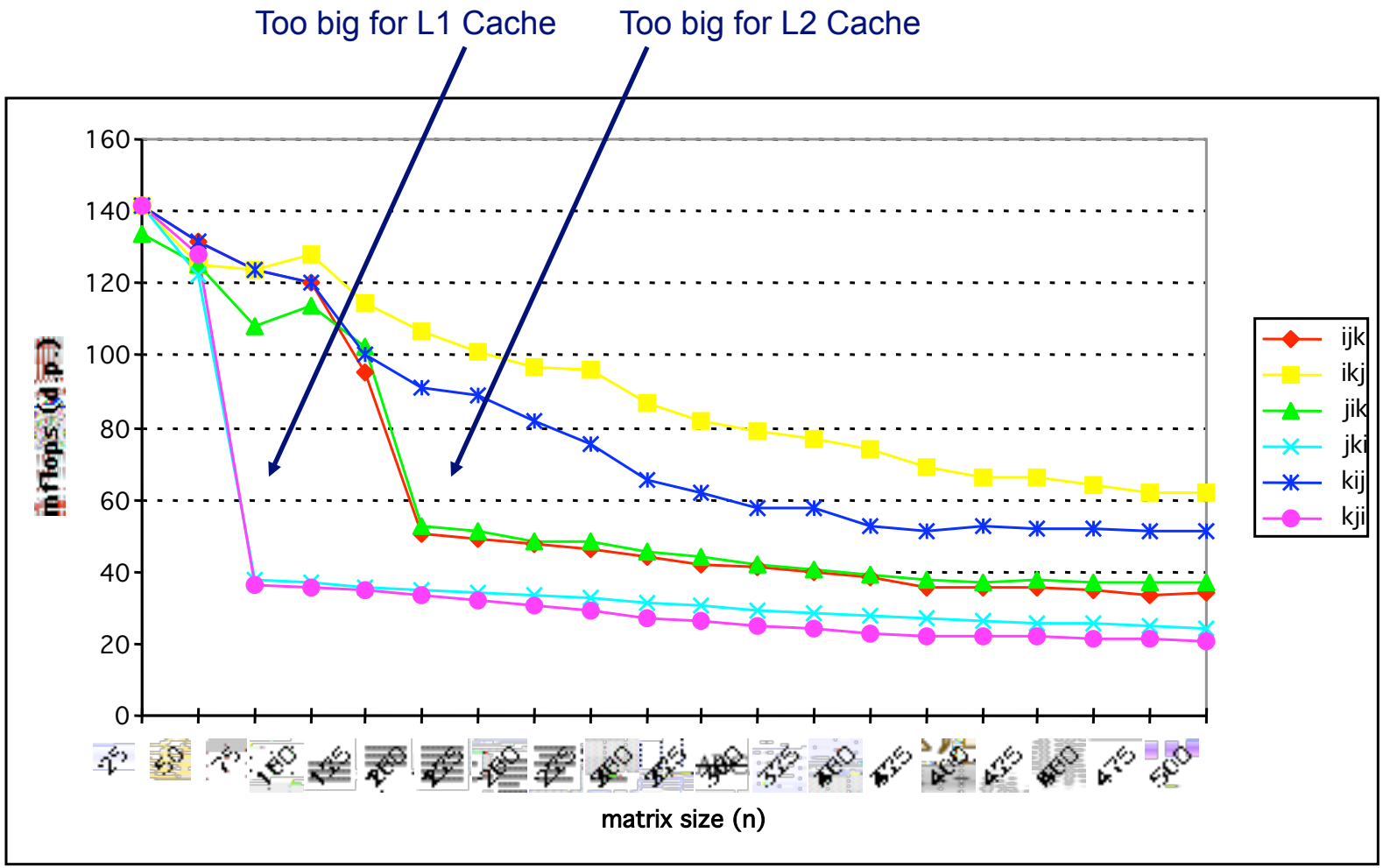
Implementations of Matrix Multiplication

- 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)



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

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
- Security

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
- Cover material in this course that you won't see elsewhere, but is needed to be successful and save time in future system classes