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

Introduction to Computer Systems

Randal E. Bryant
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Topics:

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

`class01.ppt`

Course Theme

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

Most CS courses 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) --> ??

Code Security Example

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

- Similar to code found in FreeBSD's implementation of getpeername.
- There are legions of smart people trying to find vulnerabilities in programs
  - Think of it as a very stringent testing environment

Typical Usage

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

```
#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, MSIZE);
    printf("%s\n", mybuf);
}
```


Malicious Usage

```
/* Kernel memory region holding user-accessible data */
#define KSIZE 1024
char kbuf[KSIZE];

/* Copy at most maxlen bytes from kernel region to user buffer */
int copy_from_kernel(void *user_dest, int maxlen) {
    /* Byte count len is minimum of buffer size and maxlen */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

```
#define MSIZE 528

void getstuff() {
    char mybuf[MSIZE];
    copy_from_kernel(mybuf, -MSIZE);
    . . .
}
```


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
- Creating / fighting malware
  - x86 assembly is the language of choice!

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");
}
```


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

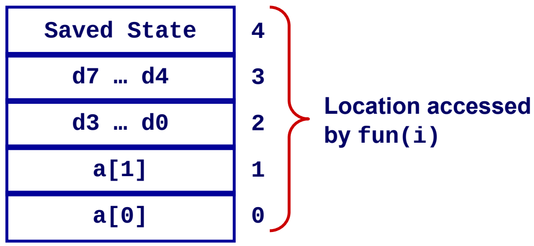
- Cache and virtual memory effects can greatly affect program performance
- Adapting program to characteristics of memory system can lead to major speed improvements

Memory Referencing Bug Example

```
double fun(int i)
{
  volatile double d[1] = {3.14};
  volatile long int a[2];
  a[i] = 1073741824; /* Possibly out of bounds */
  return d[0];
}
```

```
fun(0)  ->   3.14
fun(1)  ->   3.14
fun(2)  ->   3.1399998664856
fun(3)  ->   2.00000061035156
fun(4)  ->   3.14, then segmentation fault
```

Referencing Bug Explanation



- C does not implement bounds checking
- Out of range write can affect other parts of program state

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 or ML
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors

Memory System Performance Example

```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

59,393,288 clock cycles

```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

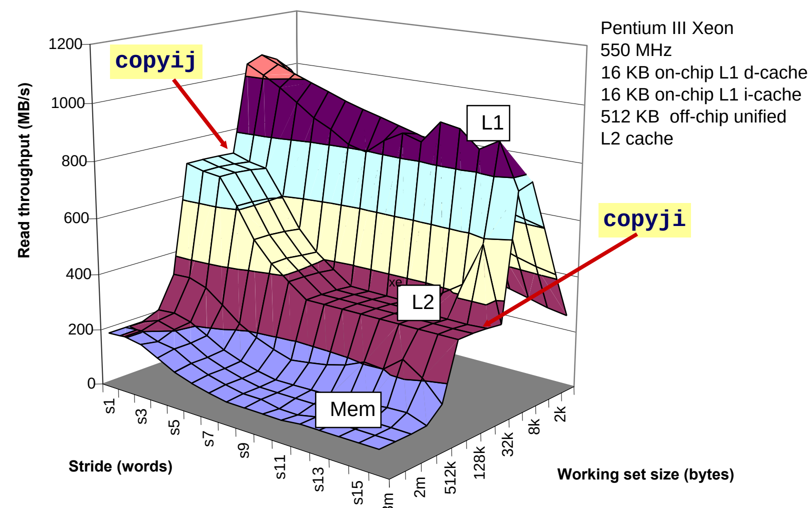
1,277,877,876 clock cycles

21.5 times slower!

(Measured on 2GHz Intel Pentium 4)

- Hierarchical memory organization
- Performance depends on access patterns
  - Including how step through multi-dimensional array

The Memory Mountain



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

Code Performance Example

```
/* Compute product of array elements */
double product(double d[], int n)
{
    double result = 1;
    int i;
    for (i = 0; i < n; i++)
      result = result * d[i];
    return result;
}
```

- Multiply all elements of array
- Performance on class machines: ~7.0 clock cycles per element
  - Latency of floating-point multiplier

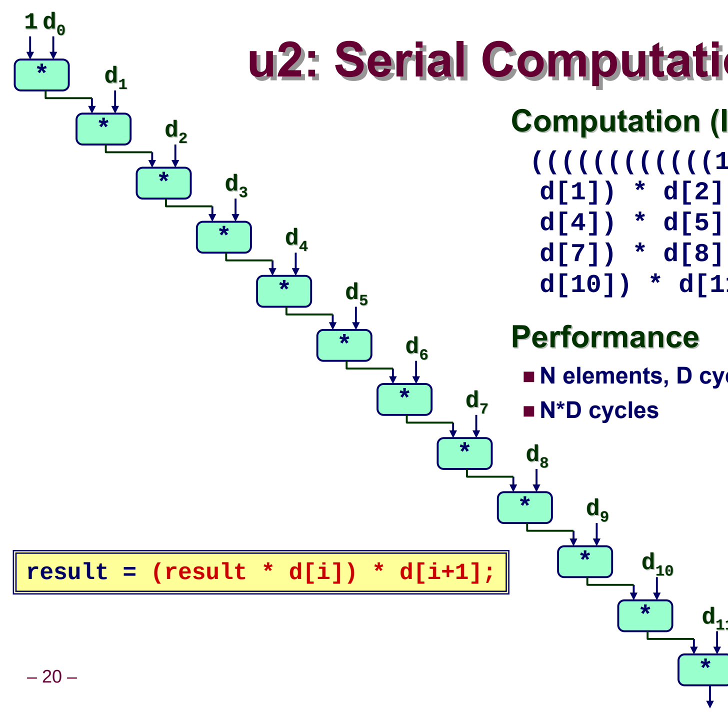
Loop Unrollings

```
/* Unroll by 2.  Assume n is even */
double product_u2(double d[], int n)
{
  double result = 1;
  int i;
  for (i = 0; i < n; i+=2)
    result = (result * d[i]) * d[i+1];
  return result;
}
```

```
/* Unroll by 2.  Assume n is even */
double product_u2r(double d[], int n)
{
  double result = 1;
  int i;
  for (i = 0; i < n; i+=2)
    result = result * (d[i] * d[i+1]);
  return result;
}
```

- Do two loop elements per iteration
  - Reduces overhead
- Cycles per element:
  - u2: 7.0
  - u2r: 3.6

u2: Serial Computation



Computation (length=12)

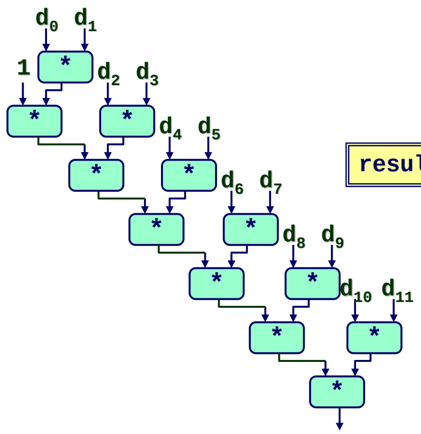
```
((((((((((((1 * d[0]) *
 d[1]) * d[2]) * d[3]) *
 d[4]) * d[5]) * d[6]) *
 d[7]) * d[8]) * d[9]) *
 d[10]) * d[11])
```

Performance

- N elements, D cycles/operation
- N*D cycles

```
result = (result * d[i]) * d[i+1];
```

u2r: Reassociated Computation




```
result = result * (d[i] * d[i+1]);
```

Performance
- N elements, D cycles/operation
- (N/2+1)*D cycles

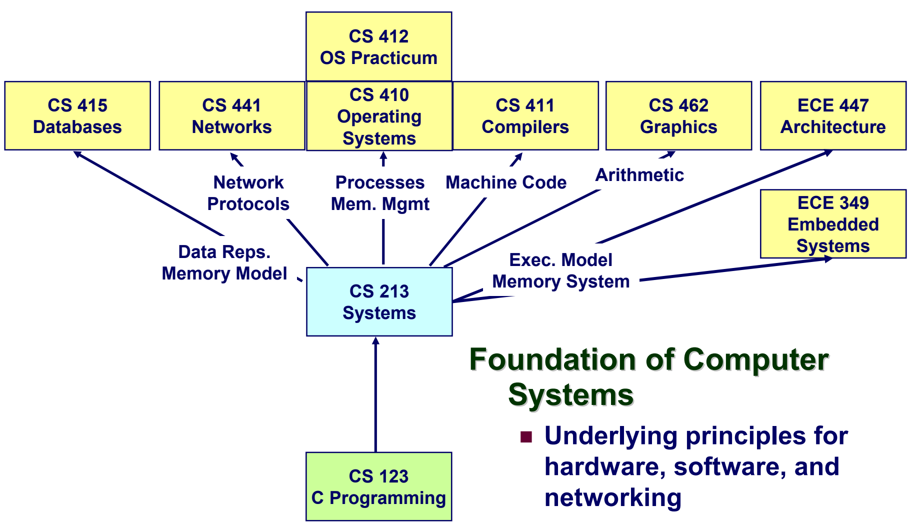
Great Reality #5

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



Foundation of Computer Systems
- Underlying principles for hardware, software, and networking

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

Teaching staff


Instructors

- Prof. Randal E. Bryant
- Prof. Greg Ganger

We're glad to talk with you, but please send email or phone first.

- TA's
  - Taiyang Chen
  - Tessa Eng
  - Elie Krevat
  - Bryant Lee
  - Christopher Lu
  - Swapnil Patil
  - Vijay Prakash
  - Jiri Simsa
- Course Admin
  - Cindy Chemsak (NSH 4303)

Textbooks

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

- "Computer Systems: A Programmer's Perspective", Prentice Hall 2003.
- http://csapp.cs.cmu.edu
- This book really matters for the course!
  - How to solve labs
  - Practice problems typical of exam problems

Brian Kernighan and Dennis Ritchie,

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

Course Components

Lectures

- Higher level concepts

Recitations

- Applied concepts, important tools and skills for labs, clarification of lectures, exam coverage

Labs

- The heart of the course
- 2 or 3 weeks
- Provide in-depth understanding of an aspect of systems
- Programming and measurement

Exams

- Test your understanding of concepts & mathematical principles
  - Critical component of grade

Getting Help

Class Web Page

- http://www.cs.cmu.edu/~213
- Copies of lectures, assignments, exams, solutions
- Clarifications to assignments

Message Board

- http://autolab.cs.cmu.edu
- Clarifications to assignments, general discussion
- The only board your instructors will be monitoring (No blackboard or Andrew)

Getting Help

Staff mailing list

- 15-213-staff@cs.cmu.etc
- "The autolab server is down!"
- "Who should I talk to about ..."
- "This code {...}, which I don't want to post to the bboard, causes my computer to melt into slag."

Teaching assistants

- I don't get "associativity"...
- Office hours, e-mail, by appointment
  - Please send mail to 15-213-staff, *not a randomly-selected TA*

Professors

- Office hour or appt.
- "Should I drop the class?" "A TA said ... but ..."

Policies: Assignments

Work groups

- You must work alone on all but final lab

Handins

- Assignments due at 11:59pm on Tues or Thurs evening
- Electronic handins using Autolab (no exceptions!).

Conflict exams, other irreducible conflicts

- OK, but must make PRIOR arrangements with Prof. Ganger.

Appealing grades

- Within 7 days of completion of grading.
  - Following procedure described in syllabus
- Labs: Talk to the lead person on the assignment
- Exams: Talk to Prof. Ganger.

Timeliness

Grace Days

- 4 for the course
- Covers scheduling crunch, out-of-town trips, illnesses, minor setbacks
- Save them until late in the term!

Lateness Penalties

- Once grace days used up, get penalized 15%/day
- Typically shut off all handins 2—3 days after due date

Catastrophic Events

- Major illness, death in family, …
- Work with your academic advisor to formulate plan for getting back on track

Advice

- Once you start running late, it's really hard to catch up

Cheating

What is cheating?

- Sharing code: either by copying, retyping, looking at, or supplying a copy of a file.
- Coaching: helping your friend to write a lab, line by line.
- Copying code from previous course or from elsewhere on WWW
  - Only allowed to use code we supply, or from CS:APP website

What is NOT cheating?

- Explaining how to use systems or tools.
- Helping others with high-level design issues.

Penalty for cheating:

- Removal from course with failing grade.

Detection of cheating:

- We do check and our tools for doing this are much better than you think!

Policies: Grading

Exam Score E (out of 100):

- Two in class exams (25% each)
- Final (50%)
- All exams are open book / open notes.

Labs Score L (out of 100):

6 labs (10-25% each)

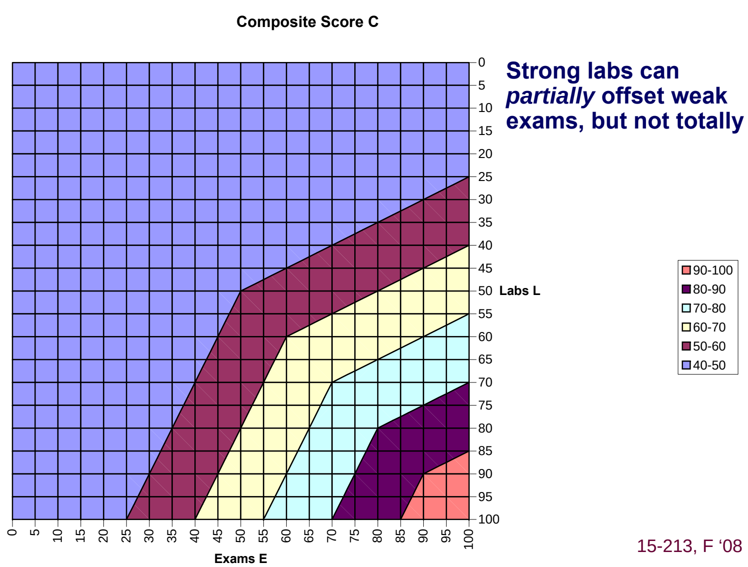
Composite Score:

S = (L + E + min(L,E))/3

if L < E: (2L + E)/3

if E < L: (L + 2E)/3

Achieving Composite Score Levels



Strong labs can *partially* offset weak exams, but not totally

Facilities

Labs will use the Intel Computer Systems Cluster (aka "the fish machines")

- 15 Pentium Xeon servers donated by Intel for CS 213
- Dual 3.2 Ghz 64-bit (EM64T) Nocona Xeon processors
- 2 GB, 400 MHz DDR2 SDRAM memory
- Rack mounted in the 3rd floor Wean Hall machine room.
- Your accounts are ready nearing readiness.

Getting help with the cluster machines:

- See course Web page for login directions
- Please direct questions to your TA's first

Programs and Data (7)

Topics

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

Assignments

- L1 (datalab): Manipulating bits
- L2 (bomblab): Defusing a binary bomb
- L3 (buflab): Hacking a buffer bomb

The Memory Hierarchy (3)

Topics

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

Assignments

Exceptional Control Flow (3)

Topics

- Hardware exceptions, processes, process control, Unix signals, nonlocal jumps
- Includes aspects of compilers, OS, and architecture

Assignments

- L4 (tshlab): Writing your own shell with job control

Virtual Memory (4)

Topics

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

Assignments

- L5 (malloclab): Writing your own malloc package
  - Get a real feel for systems programming

Networking, and Concurrency (6)

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

- L6 (proxylab): Writing your own Web proxy

Performance (2)

Topics

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

Assignments

Lab Rationale

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

Doing a lab should result in new skills and concepts

We try to use competition in a fun and healthy way.

- Set a reasonable threshold for full credit.
- Post intermediate results (anonymized) on Web page for glory!

Autolab Web Service

Labs are provided by the Autolab system

- Autograding handin system developed in 2003 by Dave O'Hallaron
- Apache Web server + Perl CGI programs
- Beta tested Fall 2003, very stable by now

With Autolab you can use your Web browser to:

- Review lab notes, clarifications
- Download the lab materials
- Stream autoresults to a *class status Web page* as you work.
- Handin your code for autograding by the Autolab server.
- View the complete history of your code handins, autoresult submissions, autograding reports, and instructor evaluations.
- View the class status page

Good Luck!