COURSE OVERVIEW

SYSTEMS I

Instructor:
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Overview

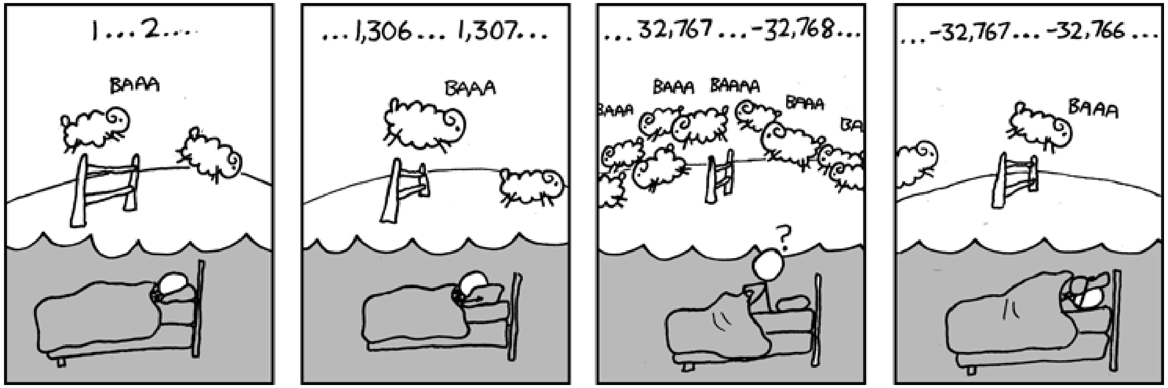
- Course theme
- Five realities
- How the course fits into the CS/ECE curriculum
- Logistics

Course Theme:
Abstraction Is Good But Don’t Forget Reality

- Most CS and CE courses emphasize abstraction
  - Abstract data types
  - Asymptotic analysis
- These abstractions have limits
  - Especially in the presence of bugs
  - Need to understand details of underlying implementations
- Useful outcomes
  - Become more effective programmers
    - Able to find and eliminate bugs efficiently
    - Able to understand and tune for program performance
  - Prepare for later “systems” classes in CS & ECE
    - Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems

Great Reality #1:
Ints are not Integers, Floats are not Reals

- Example 1: Is $x^2 \geq 0$?
  - Floats: Yes!



  - Ints:
    - 40000 * 40000 → 1600000000
    - 50000 * 50000 → ??
- Example 2: Is (x + y) + z = x + (y + z)?
  - Unsigned & Signed Ints: Yes!
  - Floats:
    - (1e20 + -1e20) + 3.14 --> 3.14
    - 1e20 + (-1e20 + 3.14) --> ??

Source: xkcd.com/571

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

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 all “usual” mathematical 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 programs in assembly
  - Compilers are much better & more patient than you are
- But: Understanding assembly is key to machine-level execution model
  - Behavior of programs in presence of bugs
    - High-level language models break down
  - Tuning program performance
    - Understand optimizations done / not done by the compiler
    - 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 (in clock cycles) required by procedure

```
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 Unphysical 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
```

- Result is architecture specific

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 */
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```
fun(0)  →   3.14
fun(1)  →   3.14
fun(2)  →   3.1399998664856
fun(3)  →   2.00000061035156
fun(4)  →   3.14, then segmentation fault
```

Explanation:

Saved State	4
d7 ... d4	3
d3 ... d0	2
a[1]	1
a[0]	0

Location accessed by `fun(i)`

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, Ruby or ML
  - Understand what possible interactions may occur
  - Use or develop tools to detect referencing errors (e.g. Valgrind)

Memory System Performance Example

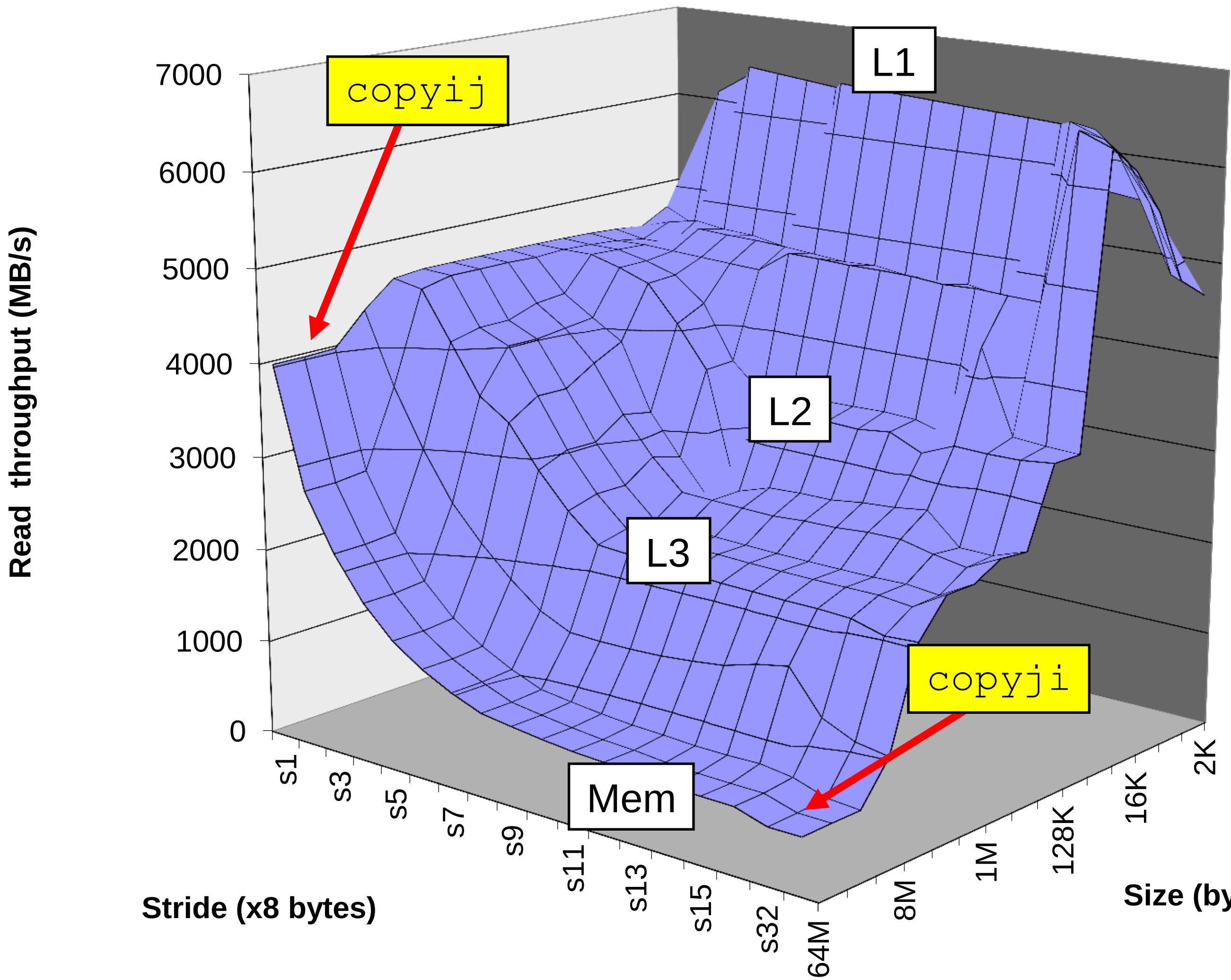
```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
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];
}
```

21 times slower (Pentium 4)

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

The Memory Mountain

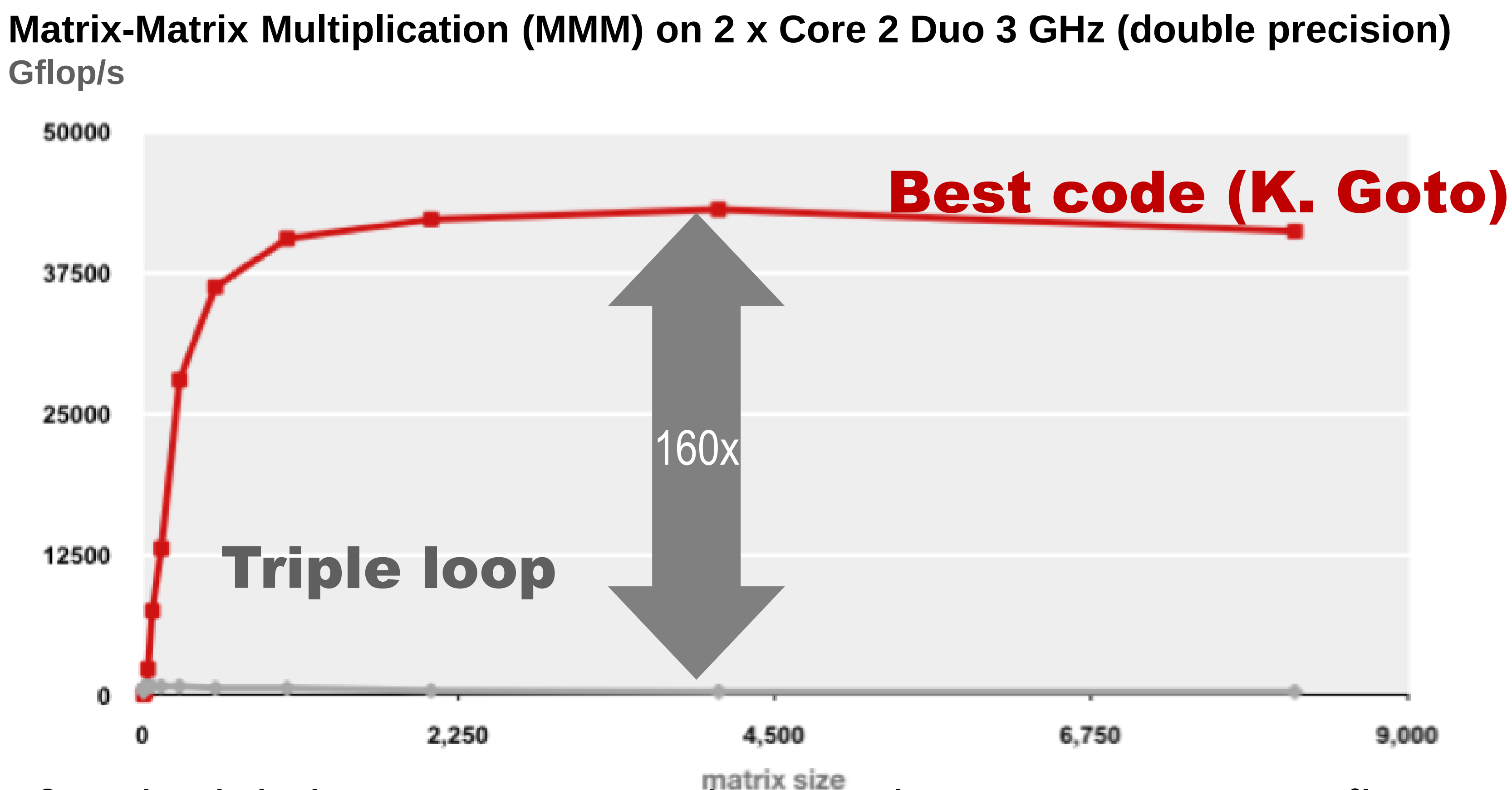


Intel Core i7
2.67 GHz
32 KB L1 d-cache
256 KB L2 cache
8 MB L3 cache

Great Reality #4: There's more to performance than asymptotic complexity

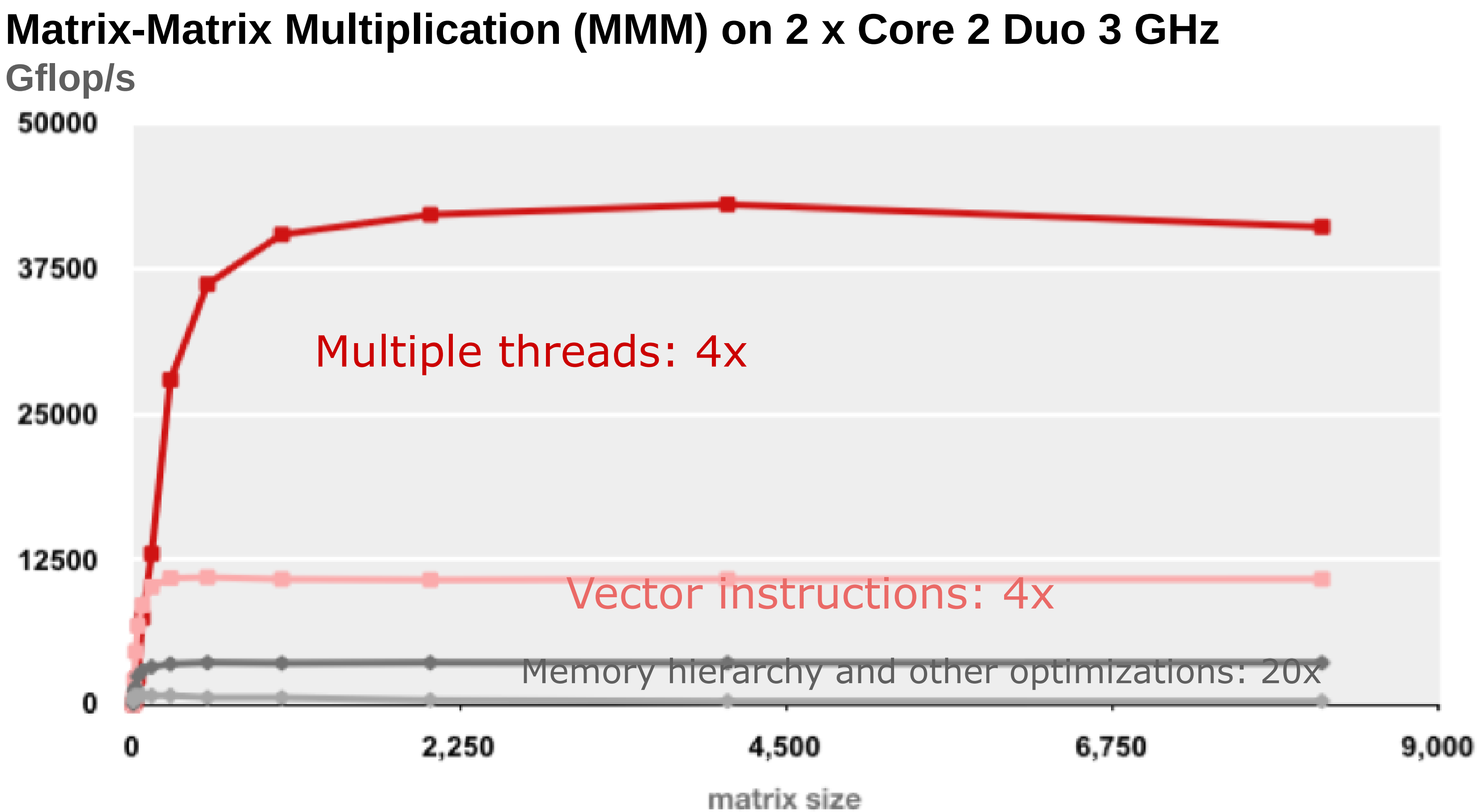
- Constant factors matter too!
- And even exact op count does not predict performance
  - Easily see 10:1 performance range depending on how code written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- Must understand system to optimize performance
  - How programs compiled and executed
  - How to measure program performance and identify bottlenecks
  - How to improve performance without destroying code modularity and generality

Example Matrix Multiplication



- Standard desktop computer, vendor compiler, using optimization flags
- Both implementations have exactly the same operations count ($2n^3$)
- What is going on?

MMM Plot: Analysis



- Reason for 20x: Blocking or tiling, loop unrolling, array scalarization, instruction scheduling, search to find best choice
- ***Effect: fewer register spills, L1/L2 cache misses, and TLB misses***

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

Textbooks

- Randal E. Bryant and David R. O'Hallaron,
  - "Computer Systems: A Programmer's Perspective, Second Edition" (CS:APP2e), Prentice Hall, 2011
  - 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 (7)
  - The heart of the course
  - 1-3 weeks each
  - Provide in-depth understanding of an aspect of systems
  - Programming and measurement
- Exams (3)
  - Test your understanding of concepts & mathematical principles

Course Learning

- Lectures
  - Good for overview, resolving questions, flagging topics for further review
- Reading
  - Good for specifics, good preparation for lecture
- Homeworks
  - Cement your understanding, give each other questions
- Exams will require you to understand the material. Such understanding likely requires attending lecture and reading.

Getting Help

- Class Web Page
  - Complete schedule of lectures, exams, and assignments
  - Copies of lectures, assignments, exams, solutions
  - Clarifications to assignments

- Message Board
  - We will use piazza

- 1:1 Appointments
  - Office hours on web page
  - You can schedule 1:1 appointments with any of the teaching staff

Policies: Assignments (Labs) And Exams

- Work groups
  - You must work alone on all assignments
- Handins
  - Assignments due at 11:59pm on Thurs evening
  - Electronic handins using turnin (no exceptions!)
- Conflicts for exams, other irreducible conflicts
  - OK, but must make PRIOR arrangements at start of semester
  - Notifying us well ahead of time shows maturity and makes things easier for us (and thus we work harder to help you with *your* problem)
- Testing accommodation
  - Please submit requests within 1 week of course start
- Appealing grades
  - Within 7 days of completion of grading, in writing

Facilities

- See course information for lab location
- Need a cs account (mandatory!)
  - Request one here
  - https://apps.cs.utexas.edu/udb/newaccount/
- cs.utexas.edu machines
  - http://apps.cs.utexas.edu/unixlabstatus/
- Public labs
  - http://www.cs.utexas.edu/facilities/public-labs

Timeliness

- Grace days
  - **4 slip days for the course**
  - Covers scheduling crunch, out-of-town trips, illnesses, minor setbacks
  - Save them until late in the term!
- Lateness penalties
  - Once slip day(s) used up, get penalized **20% per day**
  - No handins later than **3 days after due date**
- Catastrophic events
  - Major illness, death in family,
  - Formulate a plan (with your academic advisor) to get back on track
- Advice
  - Once you start running late, it's really hard to catch up

Cheating

- What is cheating?
  - Sharing code: by copying, retyping, looking at, or supplying 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
  - Please identify your collaborators explicitly on HW and labs
- Penalty for cheating:
  - Removal from course with failing grade
  - Permanent mark on your record
- Detection of cheating:
  - We do check
  - Our tools for doing this are much better than most cheaters think!

Other Rules of the Lecture Hall

- Laptops: not permitted (danger, youtube)
  - See me for exceptions
- Electronic communications: *forbidden*
  - No email, instant messaging, cell phone calls, etc
- No audio or video recording
- Presence in lectures, recitations: mandatory

Policies: Grading (approximate)

- Exams (50-60%)
- Labs (30-40%)
- Homeworks (5%)
- Class particpation (5%)
- Graded on a curve

Programs and Data

- 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 (archlab): Y86 (assembly) Programming
  - L3 (bomblab): Defusing a binary bomb

Architecture: Datapath & Pipelining

- Topics
  - How does a processor fetch, decode & execute code?
  - Pipelined processors, latency, and throughput
- Assignments
  - L4 (archlab): Extending a basic processor implementation
  - L5 (archlab): Modifying a pipelined processor

The Memory Hierarchy

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

- Assignments
  - L6 (memlab): Mapping the performance of the memory hierarchy

Performance Analysis

- Topics
  - Co-optimization (control and data), measuring time on a computer
  - Includes aspects of architecture, compilers, and OS
- Assignments
  - L7(perflab): Manually optimizing an algorithm

Lab Rationale

- Each lab has a well-defined goal such as solving a puzzle or winning a contest
- Doing the 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

Welcome
and Enjoy!