

# COURSE OVERVIEW

## COMPUTER ARCHITECTURE AND ORGANIZATION

**Instructor:**

Professor Emmett Witchel

# Overview

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- Course theme
- Five realities
- Logistics

# Course Theme:

## Abstraction Is Good But Don't Forget Reality

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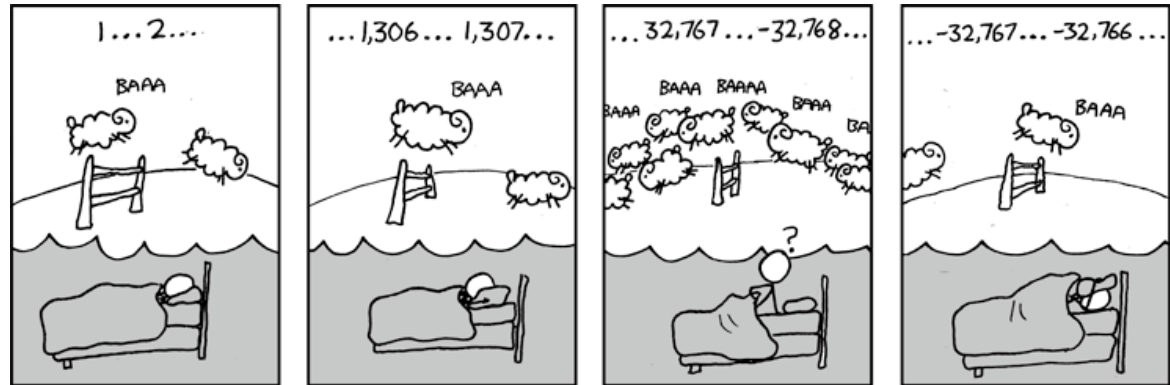
- Most CS and CE courses emphasize abstraction
  - Abstract data types
  - Asymptotic analysis
- These abstractions have limits
  - Especially in the presence of bugs
  - Need to understand details of underlying implementations
- Useful outcomes
  - Become more effective programmers
    - Able to find 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:

- $40000 * 40000 \rightarrow 1600000000$
- $50000 * 50000 \rightarrow ??$

- Example 2: Is  $(x + y) + z = x + (y + z)$ ?

- Unsigned & Signed Ints: Yes!

- Floats:

- $(1e20 + -1e20) + 3.14 \rightarrow 3.14$
- $1e20 + (-1e20 + 3.14) \rightarrow ??$

# 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

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```
/* 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

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- 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

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- 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

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- 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

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- 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

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- 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

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```
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
```

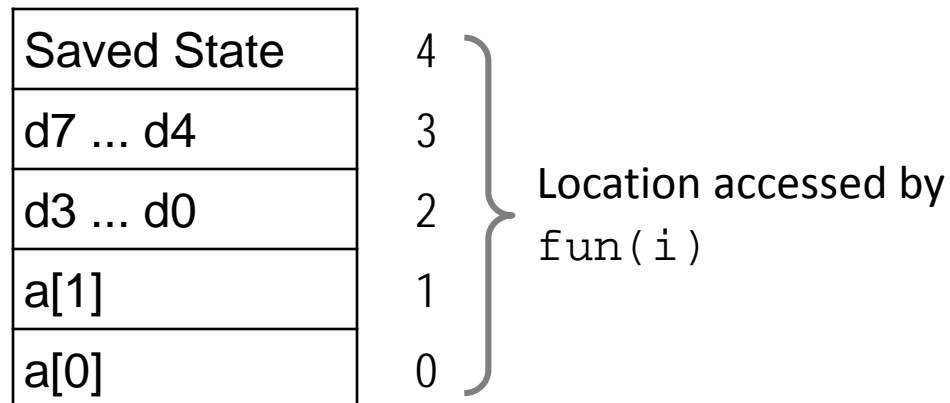
- Result is architecture specific

# 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:



# Memory Referencing Errors

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- 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];
}
```

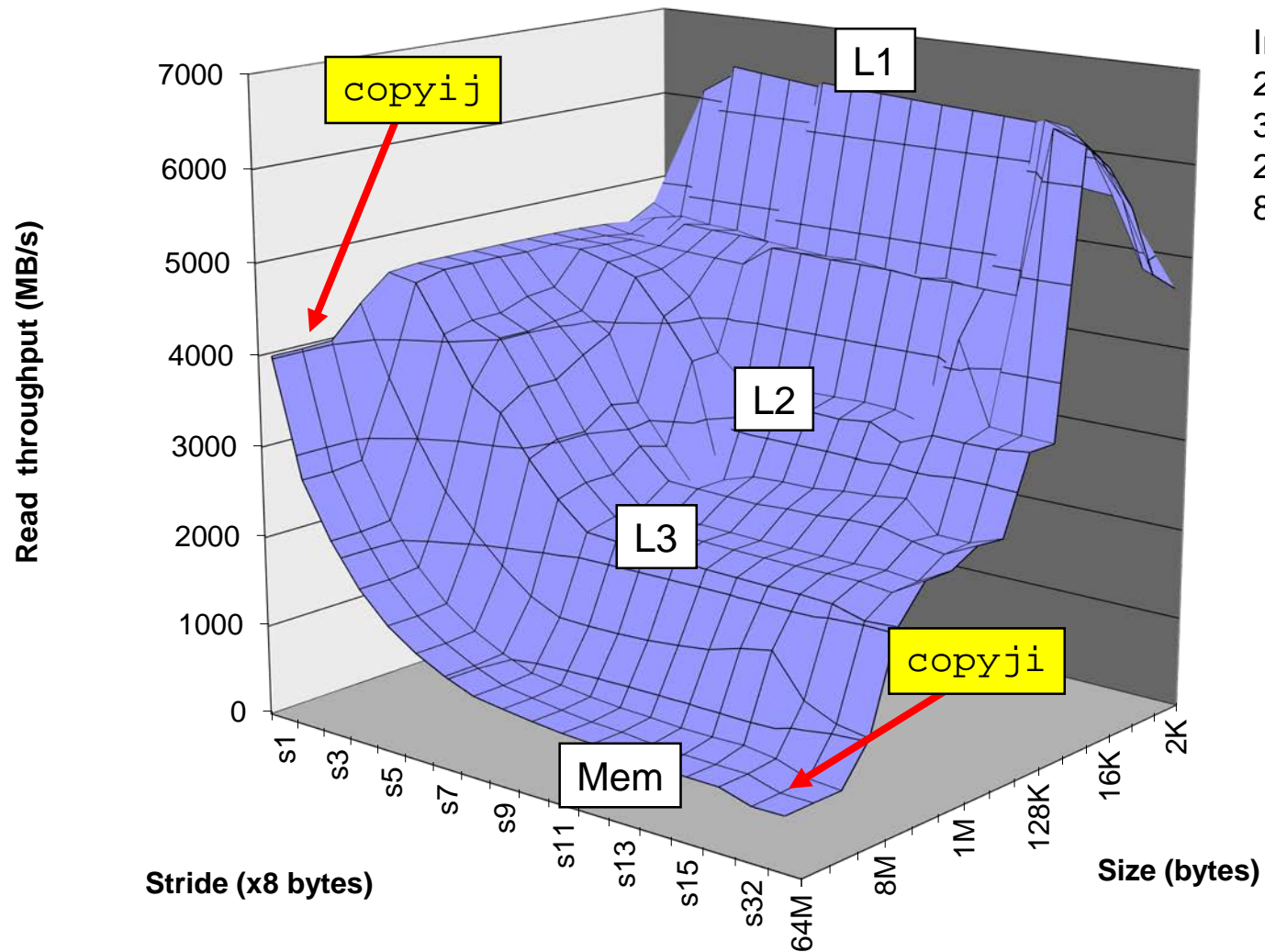


21 times slower

- Hierarchical memory organization (Pentium 4)
- 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

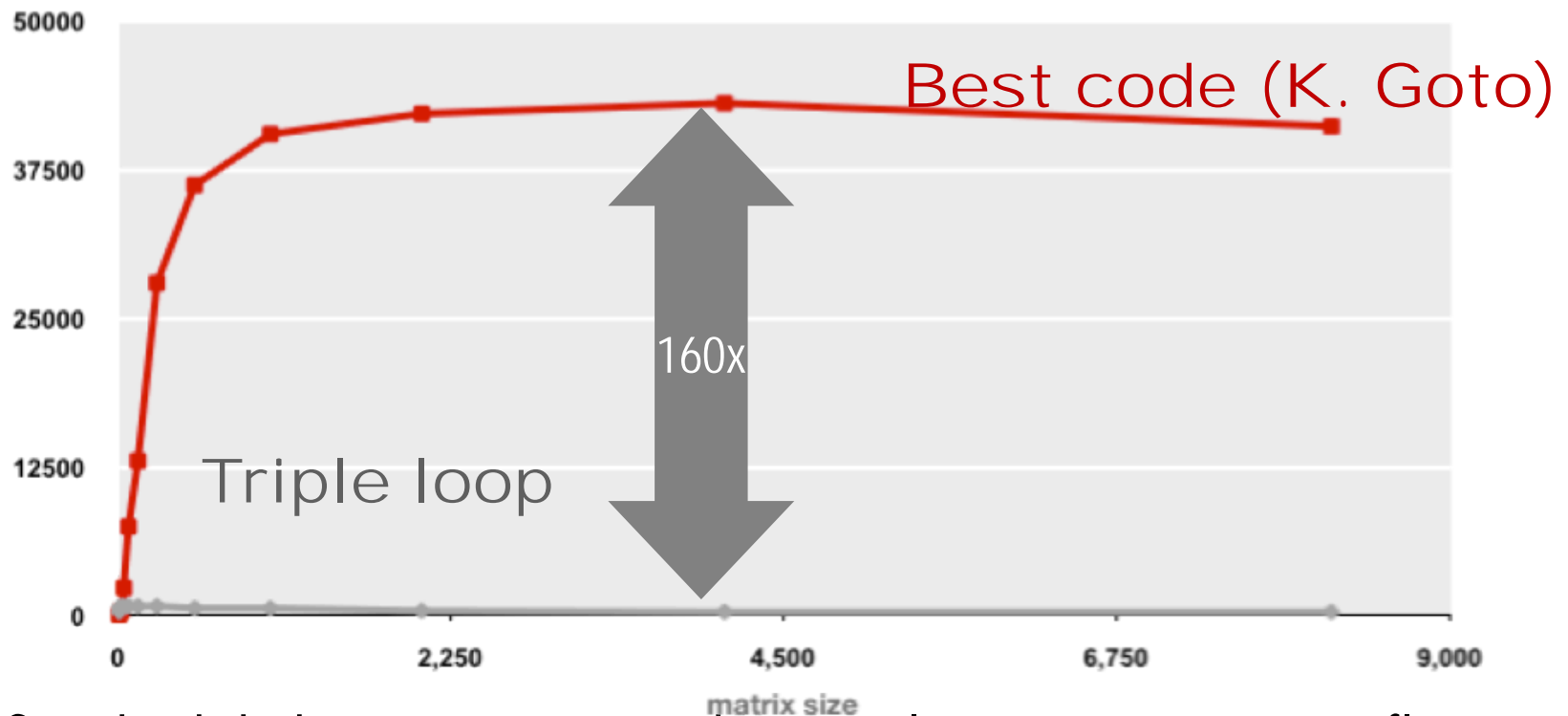
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- Constant factors matter too!
- And even exact op count does not predict performance
  - Easily see 10:1 performance range depending on how code written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- 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

Matrix-Matrix Multiplication (MMM) on 2 x Core 2 Duo 3 GHz (double precision)

Gflop/s

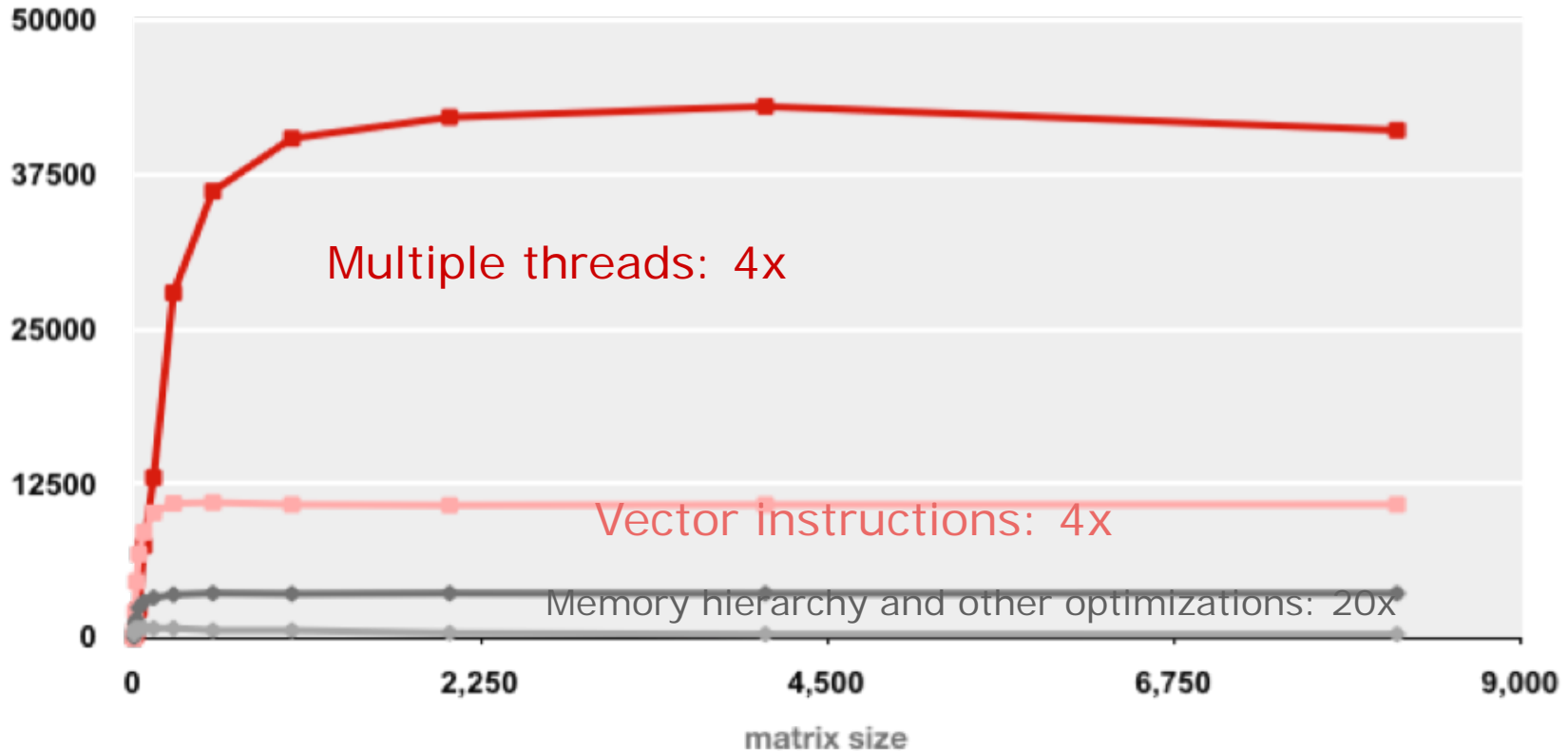


- Standard desktop computer, vendor compiler, using optimization flags
- Both implementations have **exactly** the same operations count ( $2n^3$ )
- **What is going on?**

# MMM Plot: Analysis

## Matrix-Matrix Multiplication (MMM) on 2 x Core 2 Duo 3 GHz

Gflop/s



- 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

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- 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.)

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- 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

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- 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

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- 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

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- 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

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- 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

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- 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

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- 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

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- 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

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- 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

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- 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)

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



# Programs and Data

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- **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

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- 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

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- 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

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- 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

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- 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!*