Course Overview

CSCI 2400/ ECE 3217: Computer Architecture

Instructors:

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Slides adapted from Bryant & O'Hallaron's slides

Overview

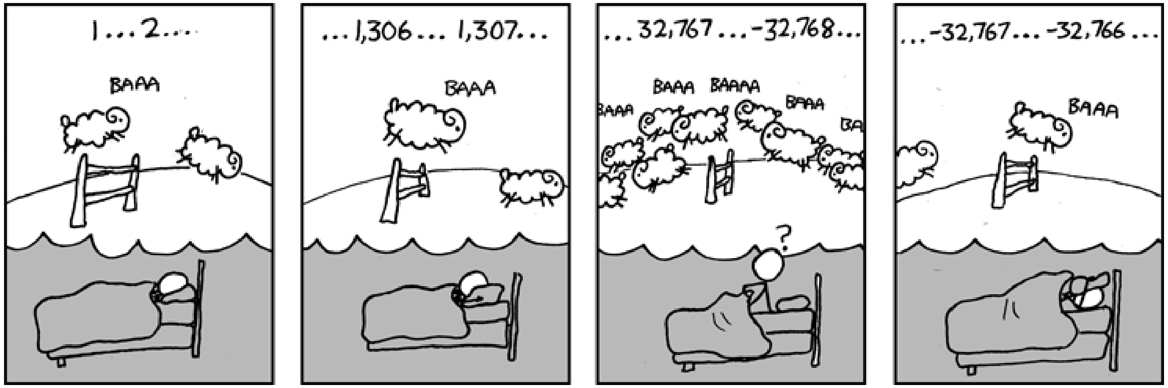
- Course theme
- Five realities
- Logistics

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 $x^2 \geq 0$?**
  - Float's: Yes!



  - Int's:
    - 40000 * 40000 => 1600000000
    - 50000 * 50000 => ??
- **Example 2: Is (x + y) + z = x + (y + z)?**
  - Unsigned & Signed Int's: Yes!
  - Float's:
    - (1e20 + -1e20) + 3.14 --> 3.14
    - 1e20 + (-1e20 + 3.14) --> ??

Source: xkcd.com/571

Consequences of Abstraction: Code Security

```
/* 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);
    . . .
}
```

- **AKA “buffer over-read”**
- **This is essentially what happened with the Heartbleed bug (2014)**

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: Assembly is key to understanding machine-level execution**
  - 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 access is relatively slow
- **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};
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  a[i] = 1073741824; /* Possibly out of bounds */
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```
fun(0)  =>   3.14
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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, Python, etc.
  - 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];
}
```

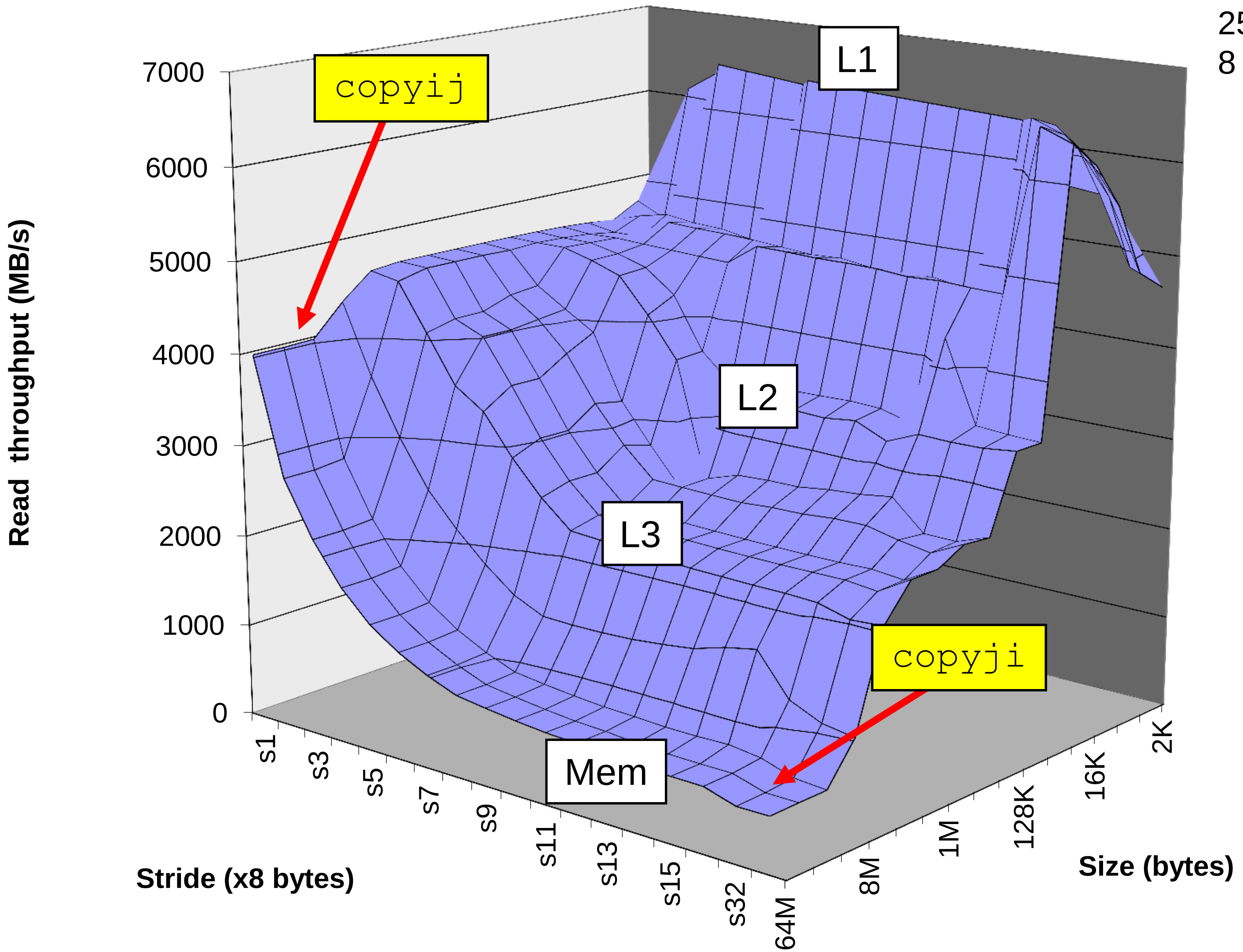
```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

21 times slower (Pentium 4)

- **Hierarchical memory organization**
  - Caches trade off speed and size
- **Performance depends on access patterns**
  - Including how step through multi-dimensional array

The Memory Mountain

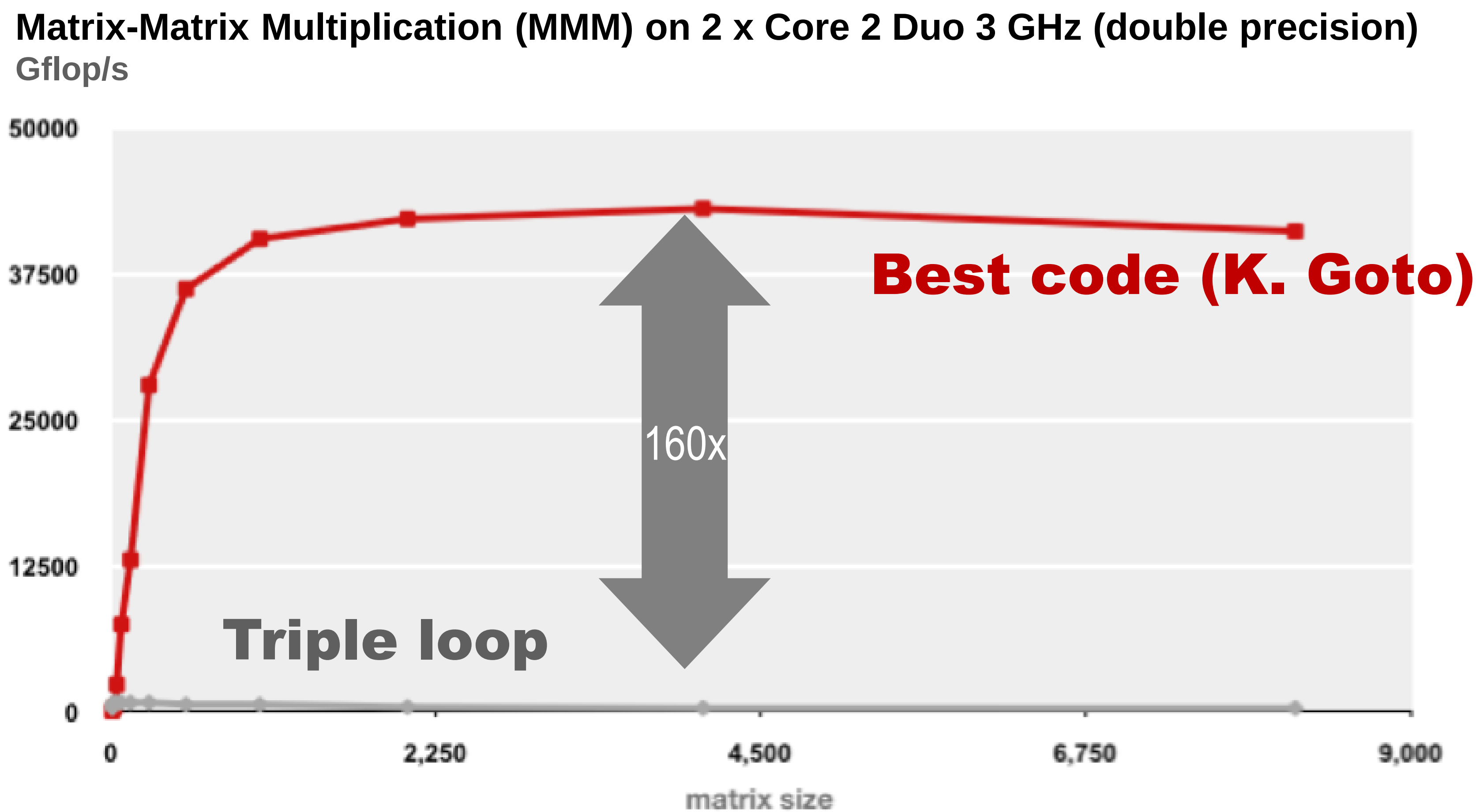
Intel Core i7
2.67 GHz
32 KB L1 d-cache
256 KB L2 cache
8 MB L3 cache



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

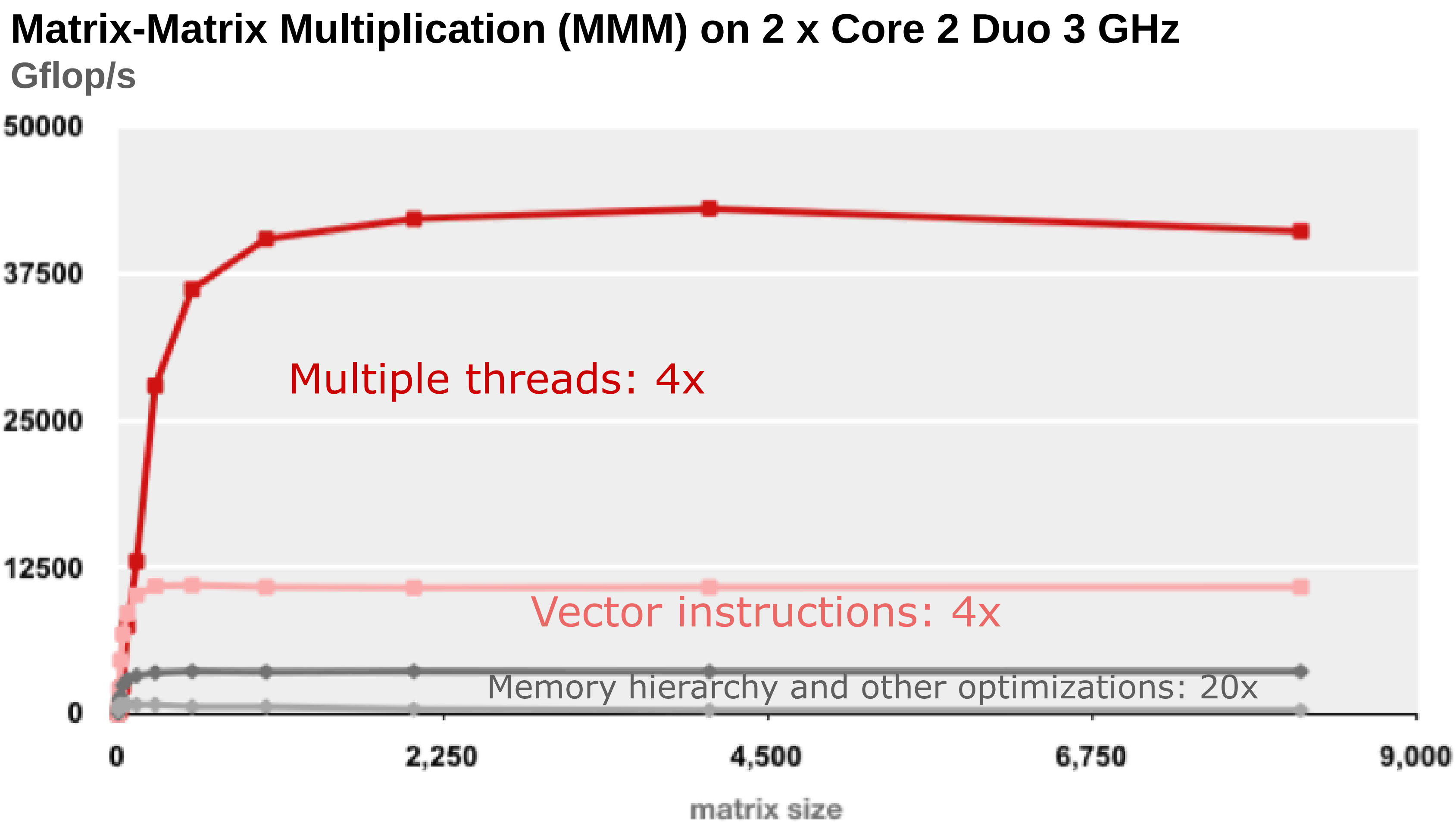
- **Constant factors matter too!**
- **And even exact op count does not predict performance**
  - Easily see 10:1 performance range depending on how code written
  - Must optimize at multiple levels: algorithm, data representations, procedures, and loops
- **Must understand system to optimize performance**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

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
  - Hard drives, SSDs, USB, CD/DVD, keyboards, mice, etc.
  - What's important? Response time, latency, or throughput?
  - Large writes vs. Small (4Kb) writes

- **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 more 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
    - Understand how C/C++ executes in hardware
    - 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
    - Imagine a zoologist that didn’t know biology or chemistry
  - Cover material in this course that you won’t see elsewhere

Course Website

- **Class Website: http://cs.slu.edu/~dferry/courses/csci2400**
  - Detailed class information and policies
  - Full Schedule, including:
    - lecture topics and code examples
    - assignments
    - exam dates
  - All assignments posted on website
  - Most lecture slides posted on website
  - Class website is the official syllabus and takes precedence over anything that is said in slides or in class

- **SLU Blackboard**
  - Blackboard is not used for this course

Textbook

- **Randal E. Bryant and David R. O'Hallaron,**
  - "Computer Systems: A Programmer's Perspective", Third Edition *(CS:APP3e)*, Prentice Hall, 2016
  - Textbook's website: http://csapp.cs.cmu.edu
  - Recommend getting a hardcopy, since exams are often open book & notes
    - Laptops, tablets, etc. not allowed during exams

- **C reference textbook**
  - "C Programming"
  - a free online reference text for C programming, that may prove beneficial for those who haven't used C (or C++) before

Grading

- **Exams (50%)**
  - mid-semester exams: 15% each
  - final 20%
- **Assignments (45%): approximately 7-9 assignments**
- **Class Participation (5%)**
  - for participation in hands-on work during class
- **Curving policy on website**
- **Late Policy:**
  - 10% penalty for up to 24 hours late
  - 20% penalty for up to 48 hours late
  - Penalty waived or accepted after 48 hours only at instructor’s discretion

Attendance and Class Guidelines

- **Attendance is at students' discretion, but highly recommended**

- **Questions and Participation highly encouraged**
  - If you have a question or need clarification, it's very likely that other students will likewise benefit from your question

- **Laptops / computers may be used during class**
  - But NOT during exams

Policy for Collaborating on Assignments

- **Collaboration allowed, even encouraged, PROVIDED that:**
  - you only discuss the problem, not the solution
  - students may help guide each other in the process of solving the problem, BUT each student MUST turn in their own answer
  - students MUST indicate who they collaborated with on their cover sheet

Cheating

- **What is cheating?**
  - *Sharing code or answers:* copying, retyping, looking at, or supplying a file
  - *Detailed coaching:* helping your friend to write code or an answer, line by line
  - *Copying code* from previous course or from elsewhere on WWW
    - only allowed to use code supplied in class or on course website
    - must cite such code
- **What is NOT cheating?**
  - Explaining how to use systems or tools
  - Helping others understand design issues or the process for solving a problem
- **Penalty for cheating:**
  - Ranges, based on severity, from zero on assignment to being sent before Academic Honesty Committee
  - Records saved for all incidents of cheating
- **Detection of cheating:**
  - Instructor is (unfortunately) extremely experienced at detecting cheating

Topic: Programs and Data

- **Topics**
  - Assembly (and machine) language vs. High-level languagues (HLLs)
  - Instruction set architecture
    - CPU (core)
    - register file
    - processing units (ALU, FPU, etc.)
  - Types of instructions
    - arithmetic
    - logical
    - shifts and bit manipulation
    - memory
    - compares
    - branches and jumps
    - procedure calls & returns
  - Representation of variables, arrays and data structures

Topic: Computer Architecture

- **Topics**
  - Fundamentals of Logic Design (gates & circuits)
  - Processor Organization
  - CPU (core) Organization
  - Fetch-Decode-Execute Cycle and Datapath Flow
  - Sequential (single-cycle) Datapath
  - Pipelined Datapath
    - purpose / benefit
    - data and control dependencies
    - hazards
    - bypassing / forwarding
    - branch prediction

Topic: Memory and the Memory Hierarchy

- **Topics**
  - Data representation
  - Memory technology (disk vs. RAM vs. ROM vs. cache)
  - Loads & Stores (reads & writes)
  - Physical vs. Virtual memory
    - page tables, address translation, and TLB
    - how memory organized within a process
      - global vs. heap vs. stack memory
  - Cache memory
    - purpose / benefit
    - locality
    - how it works

Topic: Performance and Optimization

- **Topics**
  - How simple modifications in assembly / machine code can dramatically affect execution time
  - Co-optimization (control and data)
  - Measuring time on a computer
  - Related to architecture, compilers, and OS

Welcome

and Enjoy!