Course Overview

15-213 (18-213): Introduction to Computer Systems
1st Lecture, Aug. 28, 2012

Instructors:

Dave O'Hallaron, Greg Ganger, and Greg Kesden

The course that gives CMU its "Zip"!

Overview

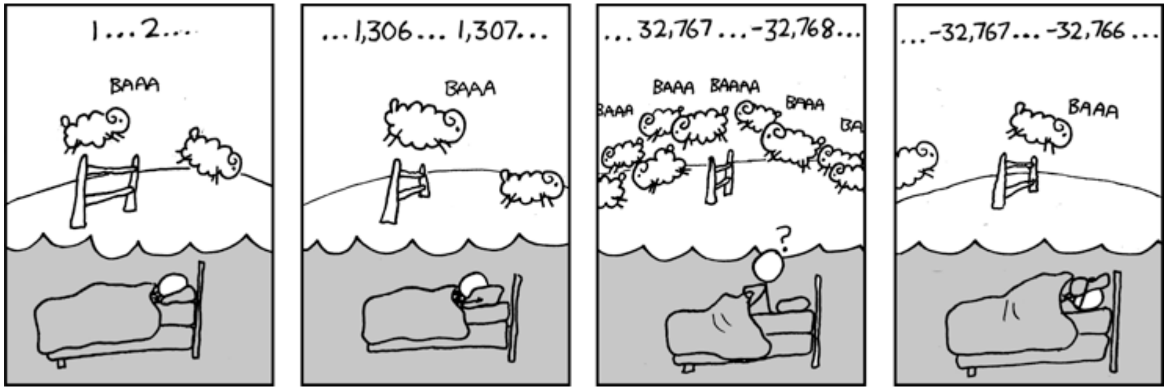
- Course theme
- Five realities
- How the course fits into the CS/ECE curriculum
- Logistics

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 from taking 213**
  - 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, Storage Systems, etc.

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

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!

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

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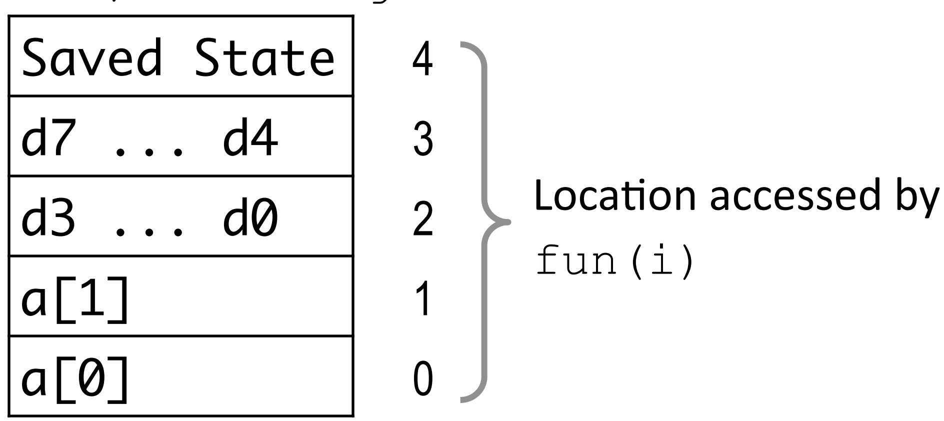
```

Explanation:



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)

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

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)

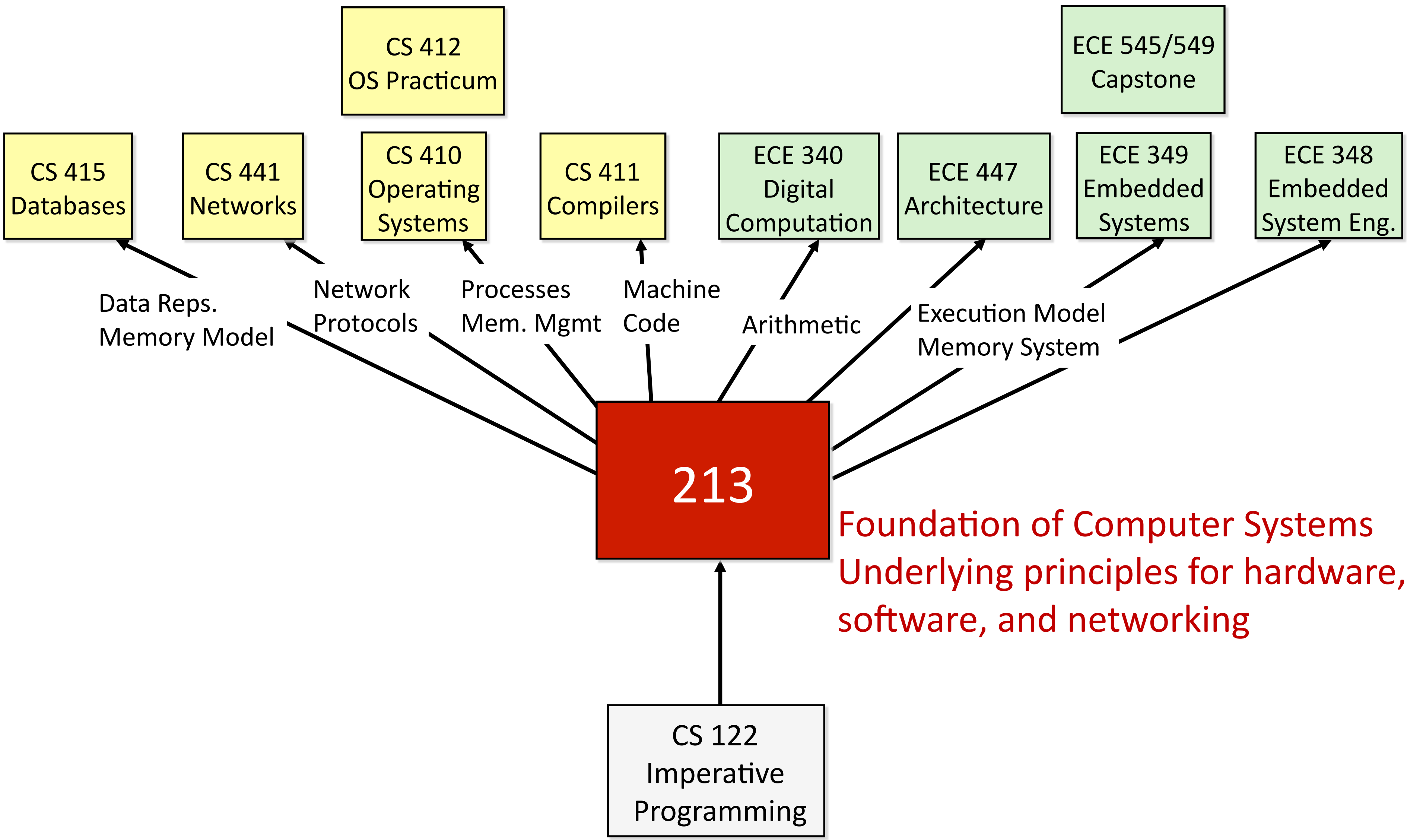
- Hierarchical memory organization
- Performance depends on access patterns
  - Including how step through multi-dimensional array

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 CS/ECE 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 that 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
  - Cover material in this course that you won't see elsewhere
  - Not just a course for dedicated hackers
    - **We bring out the hidden hacker in everyone!**

Teaching staff

Dave O'Halloran

Greg Ganger

Greg Kesden

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
  - 1-2 weeks each
  - Provide in-depth understanding of an aspect of systems
  - Programming and measurement
- Exams (midterm + final)
  - Test your understanding of concepts & mathematical principles

Getting Help

- Class Web page: **http://www.cs.cmu.edu/~213**
  - Complete schedule of lectures, exams, and assignments
  - Copies of lectures, assignments, exams, solutions
  - Clarifications to assignments

- Blackboard
  - We won't be using Blackboard for the course

Getting Help

- Staff mailing list: **15-213-staff@cs.cmu.edu**
  - Use this for all communication with the teaching staff
  - Always CC staff mailing list during email exchanges
  - Send email to individual instructors only to schedule appointments

- Office hours (starting Tue Sept 4):
  - SMTWR, 5:30-7:30pm, WeH 5207

- 1:1 Appointments
  - 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 (except L7)
- Handins
  - Assignments due at 11:59pm on Tues or Thurs evening (except L7, which is due on Sunday)
  - Electronic handins using Autolab (no exceptions!)
- Conflict exams, other irreducible conflicts
  - OK, but must make PRIOR arrangements with Prof. O'Hallaron
  - Notifying us well ahead of time shows maturity and makes us like you more (and thus to work harder to help you out of your problem)
- Appealing grades
  - In writing within 7 days of completion of grading
  - Follow formal procedure described in syllabus

Facilities

- Labs will use the Intel Computer Systems Cluster (aka “the shark machines”)
  - `linux> ssh shark.ics.cs.cmu.edu`

  - 21 servers donated by Intel for 213
    - 10 student machines (for student logins)
    - 1 head node (for Autolab server and instructor logins)
    - 10 grading machines (for autograding)
  - Each server: 8 Nehalem cores, 32 GB DRAM, RHEL 6.1
  - Rack mounted in Gates machine room
  - Login using your Andrew ID and password
- Getting help with the cluster machines:
  - Please direct questions to staff mailing list

Timeliness

- Grace days
  - **7 grace days** for the course (5 for L1-L6, 2 for L7)
  - Limit of **2 grace days** per lab used **automatically**
  - Covers scheduling crunch, out-of-town trips, illnesses, minor setbacks
  - Save them until late in the term!
- Lateness penalties
  - Once grace day(s) used up, get penalized **15% 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
- 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: permitted
- Electronic communications: forbidden
  - No email, instant messaging, cell phone calls, etc
- Presence in lectures, recitations: voluntary, recommended
- No recordings of ANY KIND

Policies: Grading

- Exams (50%): midterm (20%), final (30%)
- Labs (50%): weighted according to effort
- Final grades based on a combination of straight scale and curving.

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 (bomblab): Defusing a binary bomb
  - L3 (buflab): Hacking a buffer bomb

The Memory Hierarchy

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

- Assignments
  - L4 (cachelab): Building a cache simulator and optimizing for locality.
    - Learn how to exploit locality in your programs.

Exceptional Control Flow

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

- Assignments
  - L5 (tshlab): Writing your own Unix shell.
    - A first introduction to concurrency

Virtual Memory

- Topics
  - Virtual memory, address translation, dynamic storage allocation
  - Includes aspects of architecture and OS
- Assignments
  - L6 (malloclab): Writing your own malloc package
    - Get a real feel for systems-level programming

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
  - L7 (proxylab): Writing your own Web proxy
    - Learn network programming and more about concurrency and synchronization.

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
  - Post intermediate results (anonymized) on Web page for glory!

autolab.cs.cmu.edu

- Labs are provided by the CMU Autolab system
  - Developed by CMU faculty and students
  - Key ideas: Autograding and Scoreboards
    - Autograding: Using VMs on-demand to evaluate untrusted code.
    - Scoreboards: Real-time, rank-ordered, and anonymous summary.
  - Used by 1,400 students each semester, since Fall, 2010
- With Autolab you can use your Web browser to:
  - Download the lab materials
  - Handin your code for autograding by the Autolab server
  - View the class scoreboard
  - View the complete history of your code handins, autograded result, instructor's evaluations, and gradebook.
- Students enrolled on Friday, Aug 24 have accounts
  - If you add in, contact 15-213-staff@cs.cmu.edu for an account

Welcome and Enjoy!

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);
    . . .
}
```

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

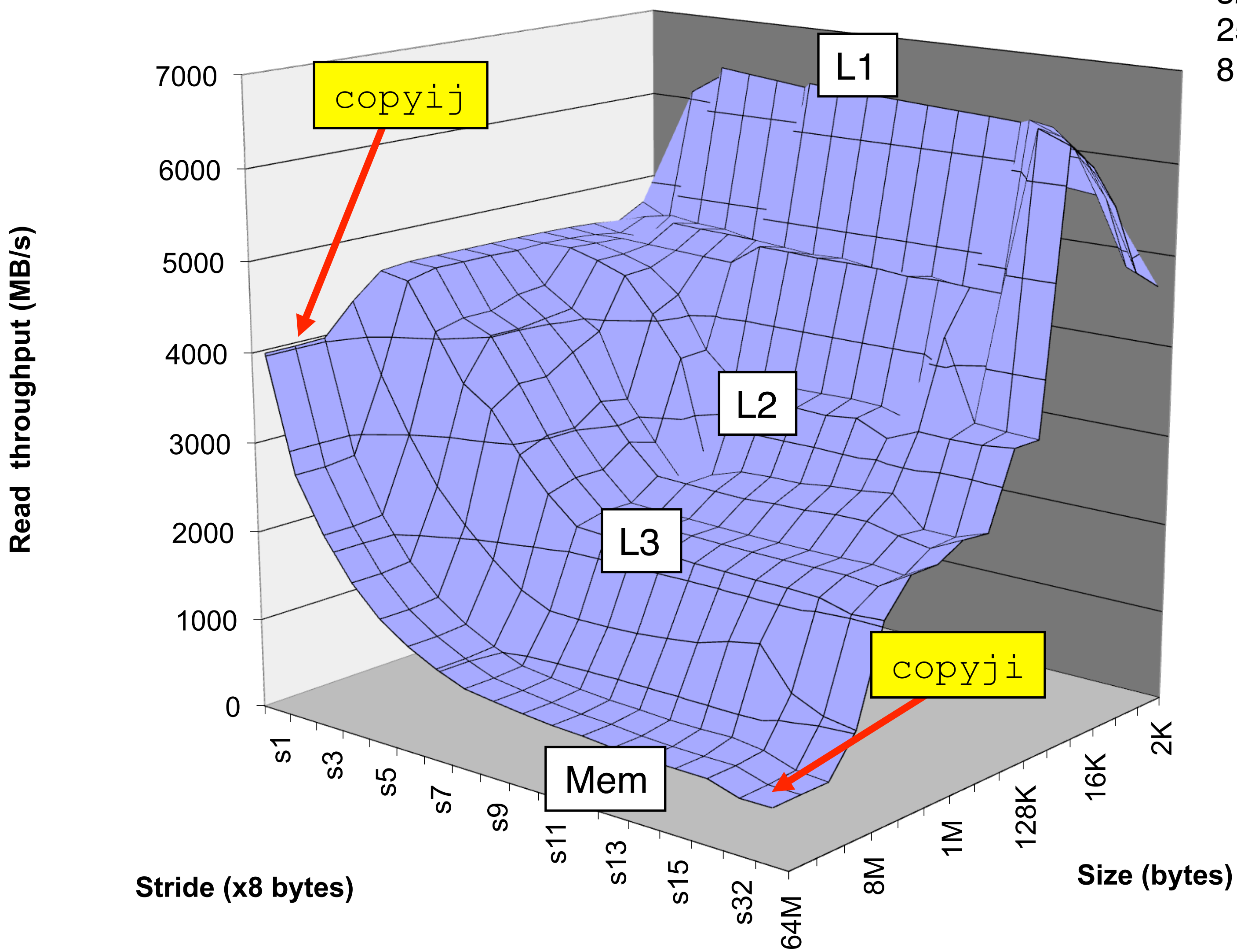
- Write small amount of assembly code using GCC's asm facility
- Inserts assembly code into machine code generated by compiler

```
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

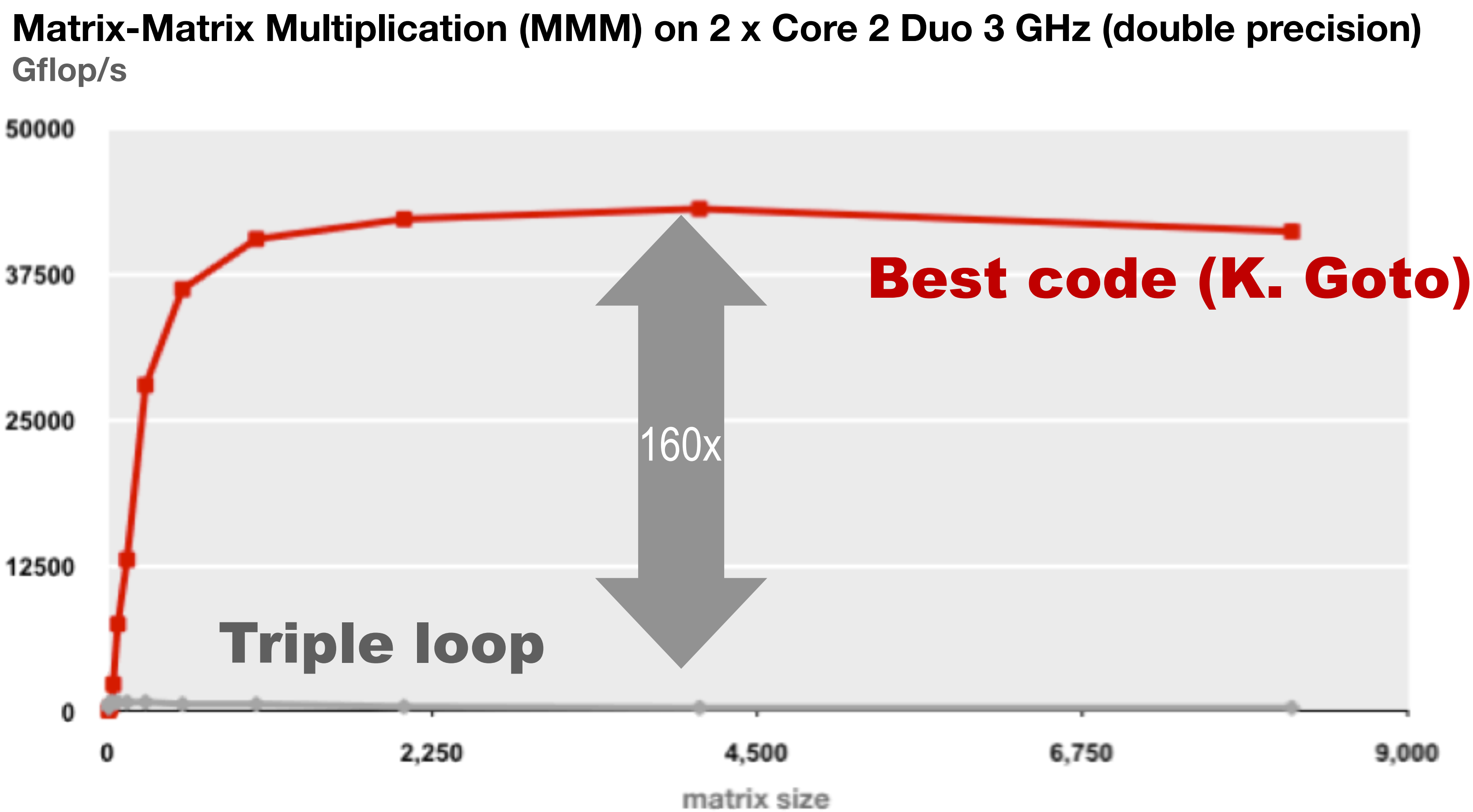
/* Set *hi and *lo to the high and low order bits
   of the cycle counter.
*/
void access_counter(unsigned *hi, unsigned *lo)
{
    asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
        : "=r" (*hi), "=r" (*lo)
        :
        : "%edx", "%eax");
}
```

The Memory Mountain

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

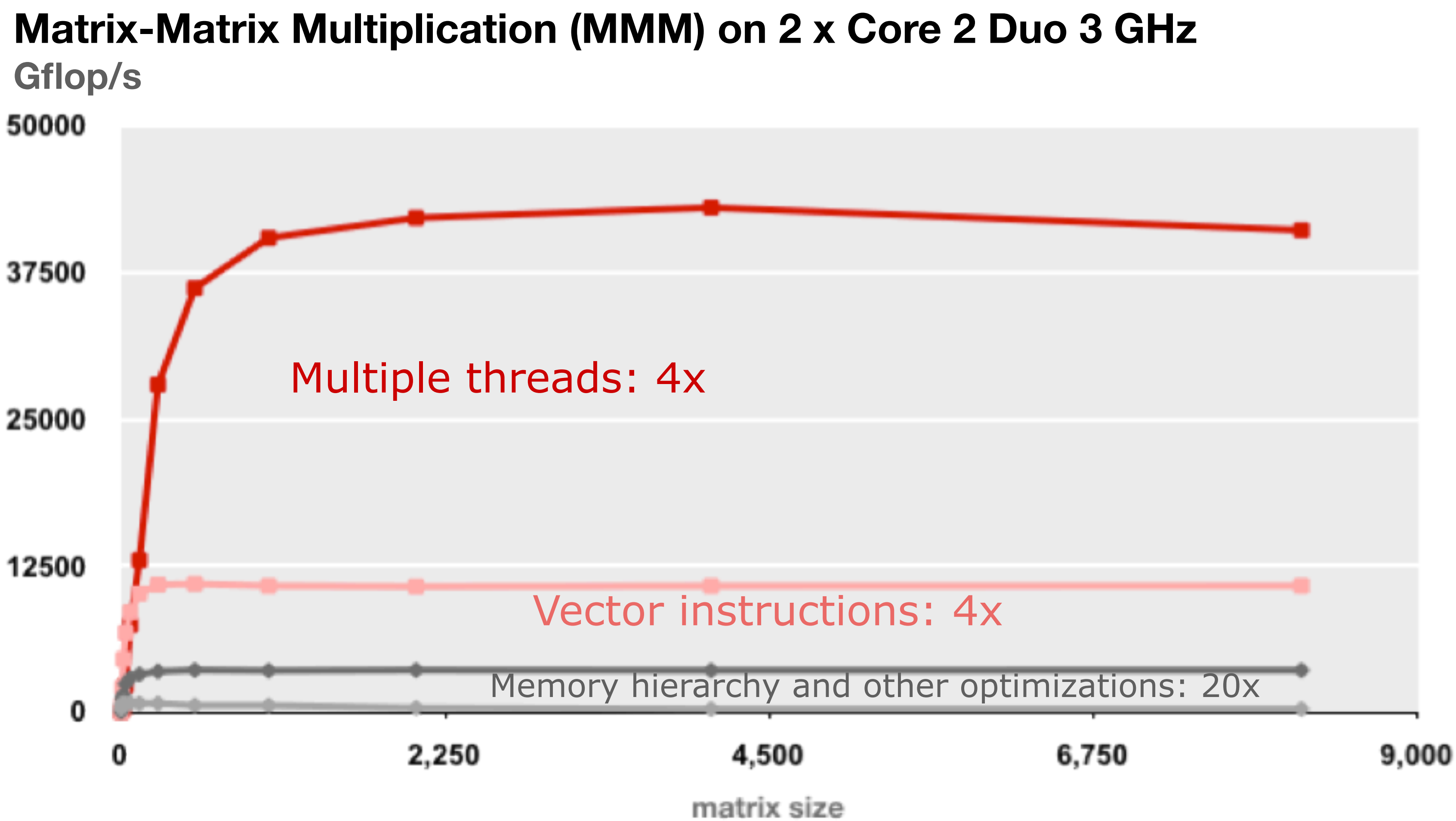


Example Matrix Multiplication



- 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