CS 201
Computer Systems Programming

Instructor: A.Prof. Dinh Dien

This lecture is modified from course CS201 of Portland State University

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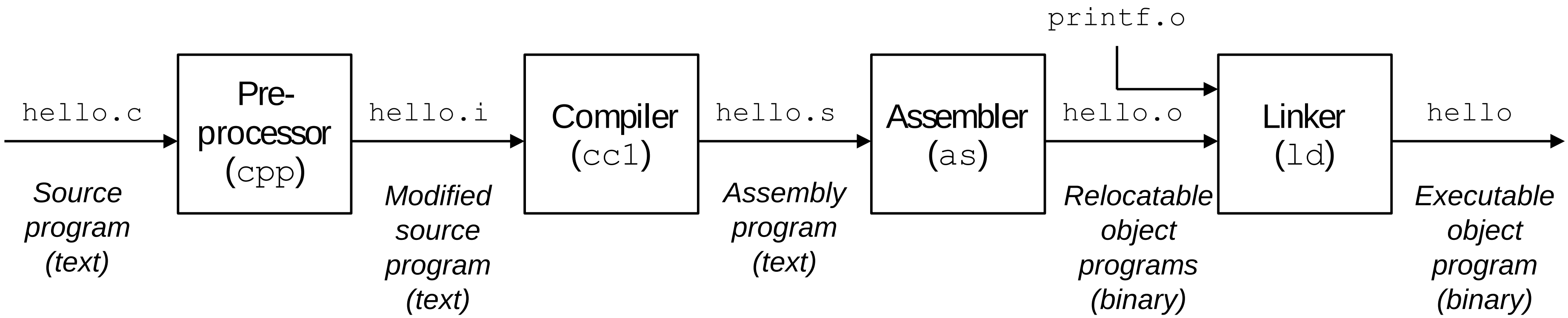
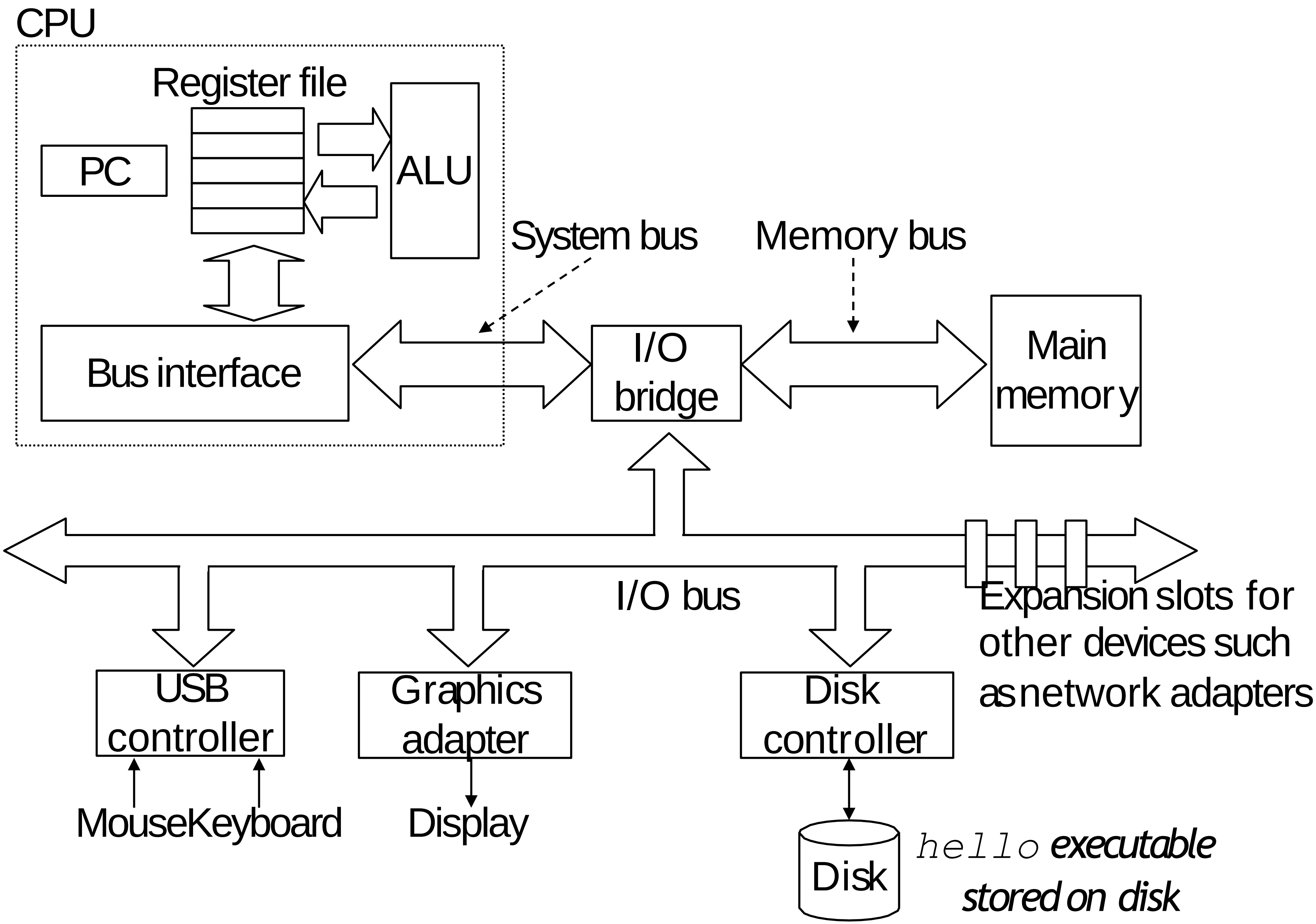
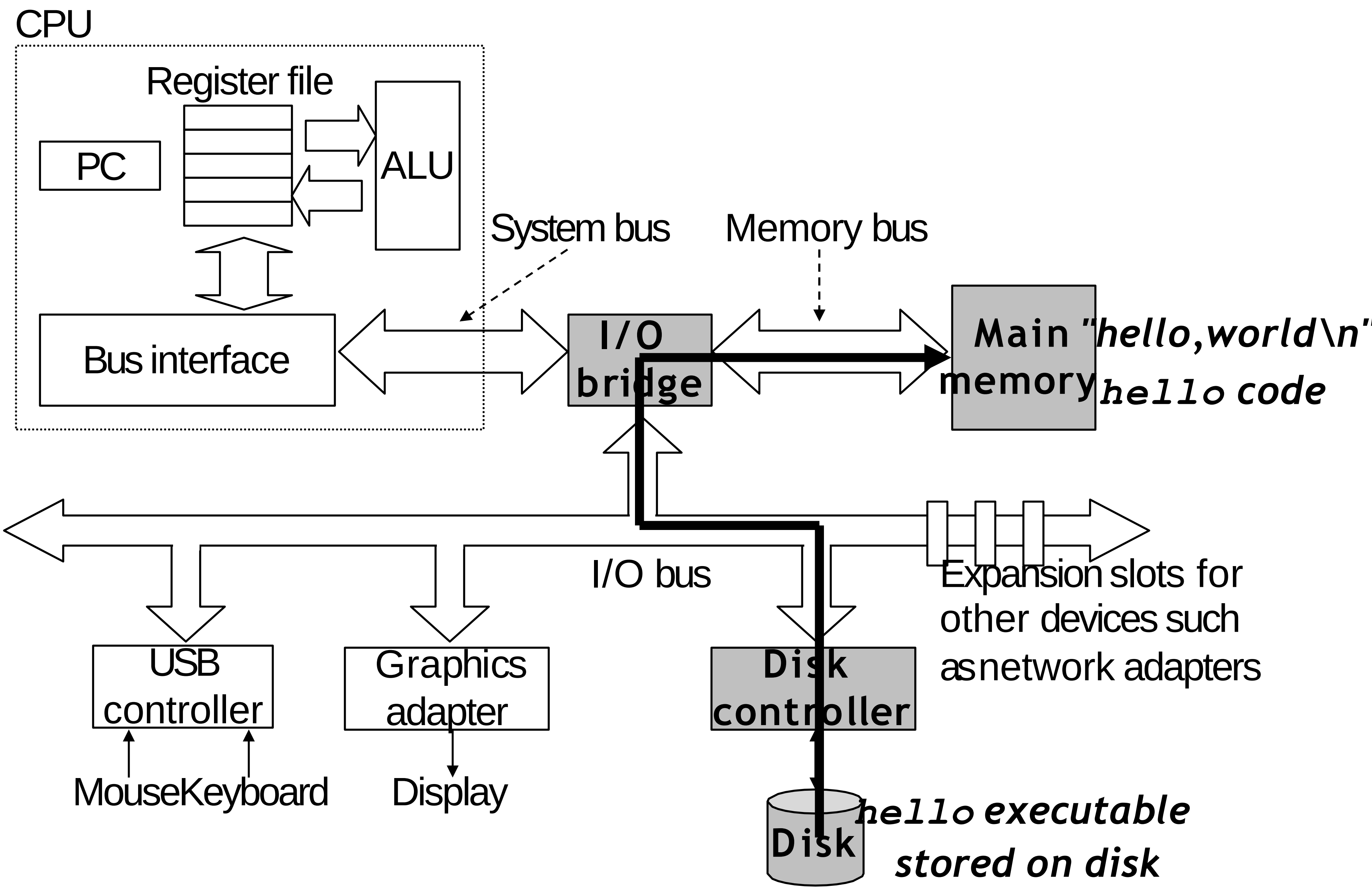
Hello,World

```c
#include <stdio.h>

int main()
{
    printf("hello, world\n");
}
```




CPU
Register file
PC
ALU
System bus
Memory bus
Bus interface
I/O bridge
Main memory
I/O bus
Expansion slots for other devices such as network adapters
USB controller
Graphics adapter
Disk controller
Mouse
Keyboard
Display
Disk
hello executable stored on disk



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"hello,world\n"
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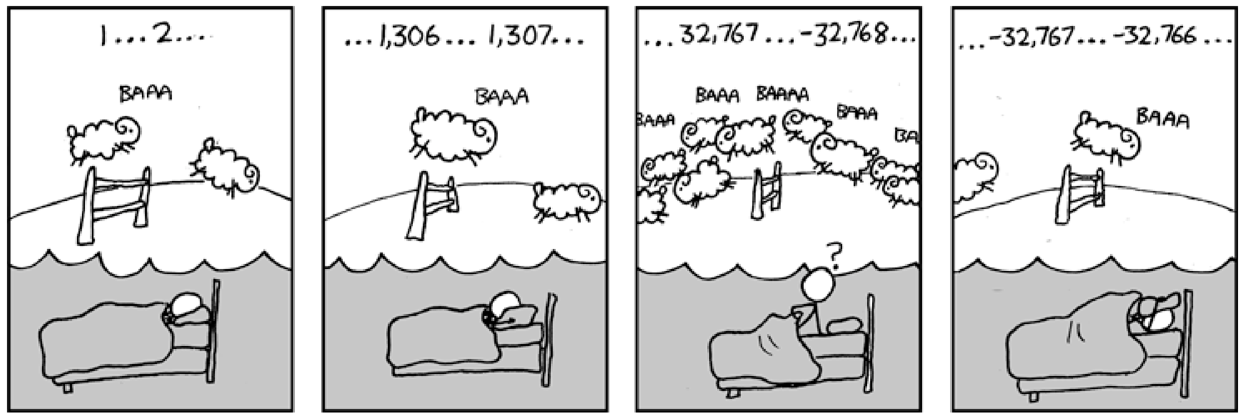
Course Theme:
Abstraction Is Good But Don’t Forget Reality

- **Most CS and CE courses emphasize abstraction**
  - Abstract data types
  - Processes, Files
- **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, Architecture

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

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)  ➙3.1399998664856
fun(2)  ➙3.14
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
  */  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
```

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];
}
```

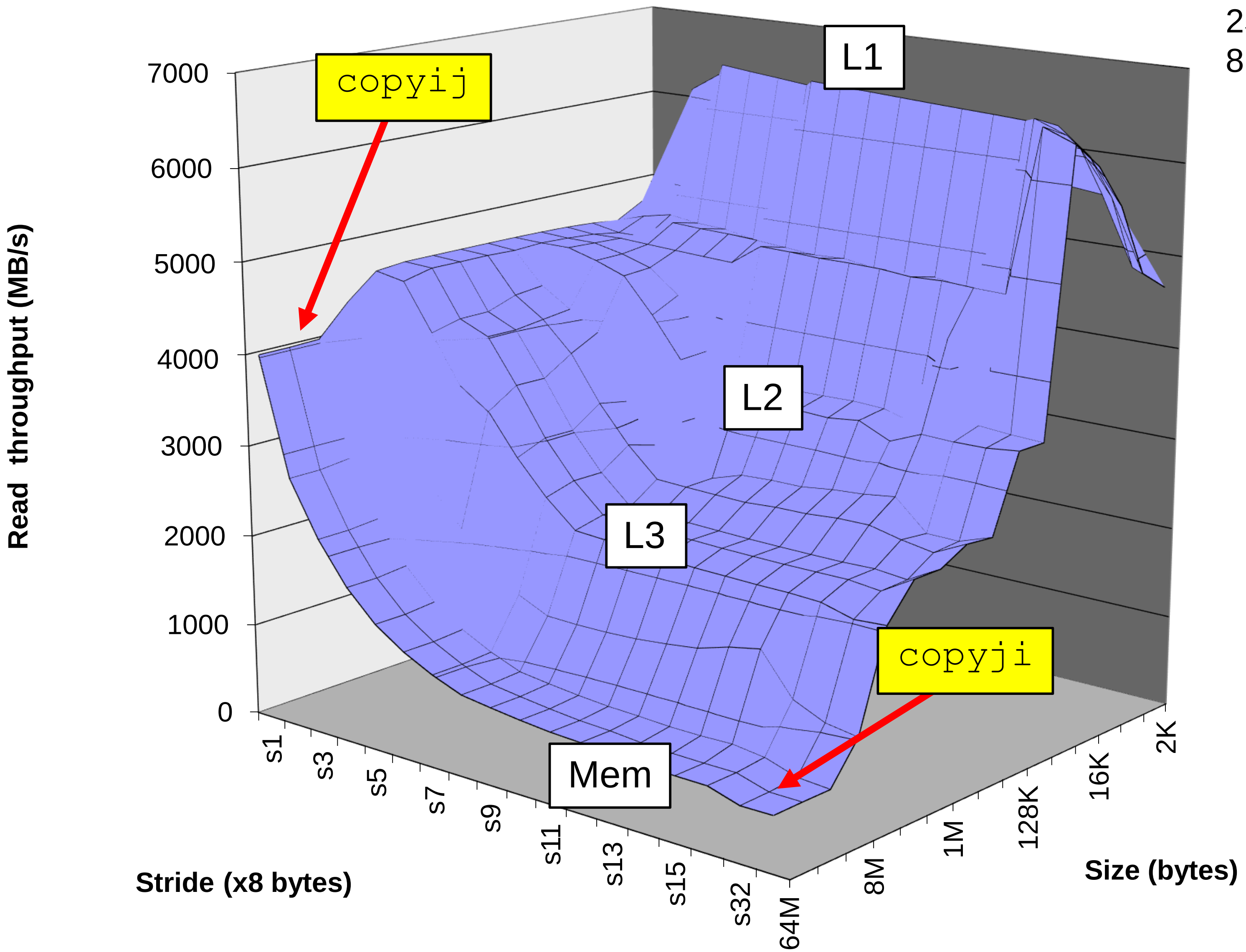
```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

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

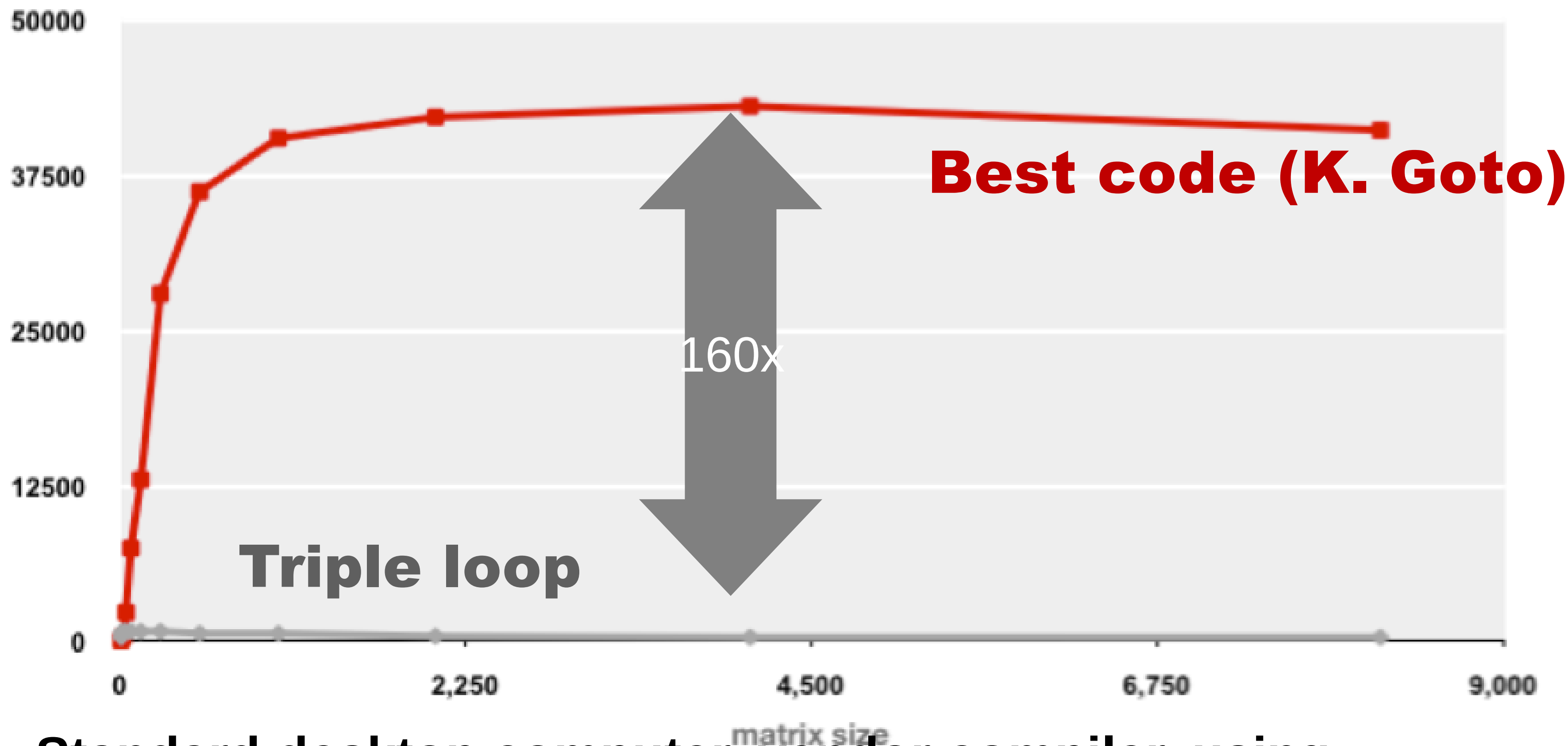


Great Reality #4: There's more to performance than asymptotic complexity

- **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

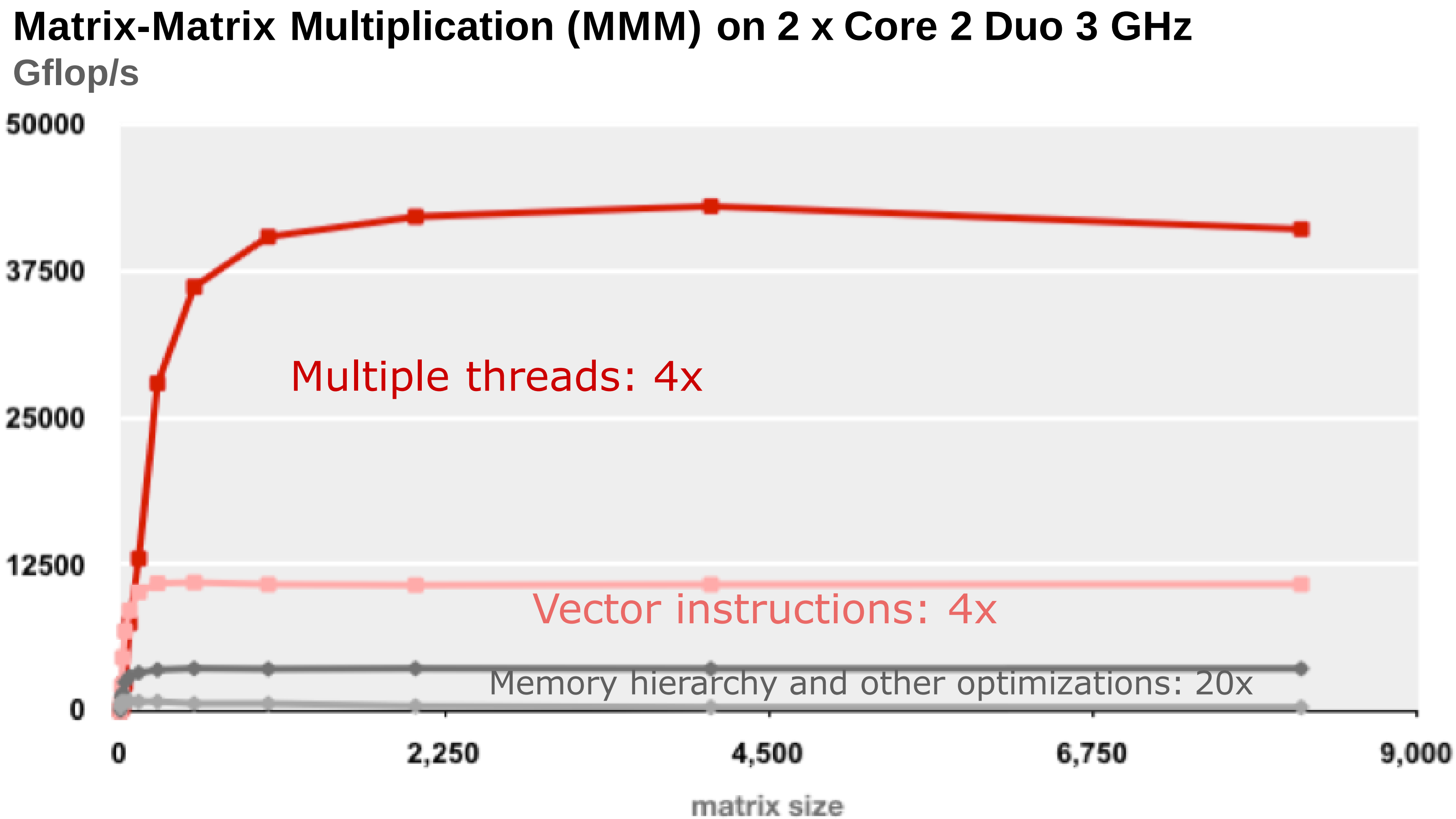
Example Matrix Multiplication

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



- 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
  - Data movement is currently seen as our biggest obstacle to pushing the high end of computing even higher

- **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

Great Reality #6: Security Matters!!!

- If you do not understand this level of programming, you are at risk to introduce security holes in code you write

Required Course Textbook

- **Randal E. Bryant and David R. O'Hallaron,**
  - "Computer Systems: A Programmer's Perspective, Third Edition" (CS:APP3e), Prentice Hall, 2015
  - Additional student materials at: http://csapp.cs.cmu.edu
  - NOTE: BRAND NEW BOOK
  - Key change from 2nd edition: focus on 64-bit architecture
    - "what's 64-bit architecture?" - stay tuned!

- **C Programming notes available online for free: https://www.eskimo.com/~scs/cclass/cclass.html**

Getting Help

- **Class Web Page: http://web.cecs.pdx.edu/~karavan/cs201**
- **We will transition to D2L**
- **TA Office Hours: TBD**
- **Instructor office hour: TBD**
- **Appointments are always possible modulo my schedule:**
  - Email me and list some different days/times you can meet
  - If you cannot make it – please email and let me know if at all possible
- **"Open Door" Policy**
  - I am in my office and the door is open == Welcome !
  - I am in my office and the door is [latched] shut == Oops! Not Now.
    - I am in a meeting or on a deadline and request no interruptions other than life and death emergencies

Facilities

- **Labs and homeworks will use the Computer Science Linux Lab**
  - Remote login: ssh myloginname@linuxlab.cs.pdx.edu
  - CS tutors sit outside of the lab during posted hours
  - Small library of relevant books maintained by tutors
- **Homeworks**
  - Homeworks will be tested and graded on the Linux Lab machines
  - We do not have the resources to accommodate your individual personal machine setups – please test your work on the lab machines before submitting

Timeliness

- **Grace days**
  - **2 “free passes” (48 hours each) for the homeworks**
  - Covers scheduling crunch, out-of-town trips, illnesses, minor setbacks
  - Murphy Says: Save them until late in the term!
- **Lateness penalties**
  - Once free passes(s) used up, receive a score of 0
  - TURN IN WHATEVER YOU HAVE !
- **Free Lunch**
  - Your homework score is computed using the BEST 7 of 8 homeworks
- **Advice**
  - Once you start running late, it’s really hard to catch up
  - 8 Weeks goes by VERYVERY quickly

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
  - Looking at anyone else's exam or showing anyone yours, in the exam room
  - Posting in any form or forum the homework or exam answers
- **What is NOT cheating?**
  - Explaining how to use systems or tools or getting that explained
  - Helping others with high-level design issues or getting that help
  - Getting help from the tutors or Course Expert
- **Murphy Says:**
  - Tends to happen when you're tired, behind, and worried – so stay on track
  - 2 min rule: after an explanation, 2mins before hands are back on keyboard
  - "Why are we spending all this time talking about cheating? "
    - Because it happens EVERY YEAR and if it happens to you, you will FAIL

Other Rules of the CS 201 Classroom

- **Laptops: permitted**

- **Electronic communications:** *forbidden*
  - No email, instant messaging, cell phone calls, etc
  - You will be asked to leave
  - Why? This is *a Learning Environment*
  - *OK- looking things up as we go, electronic textbook, etc.*
  - *OK – asking questions in the class*

- ***Note: Some students have been granted specific permission to record the lectures. Without permission it's a no-no.***

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HW #1 Part 1

- **The Full Homework will be available on Thursday (April 4)**
- **But it's a good idea to get started**

1. **Readings:**

   B&O [textbook] chapter 1

   Steve Summit's C Programming Notes Chapter 1:

   https://www.eskimo.com/~scs/cclass/notes/top.html

1) **Hands on:**
   - Online Tutorial (SKIP 105.7): http://pages.cs.wisc.edu/~remzi/OSTEP/lab-tutorial.pdf
     - Focus on your initial goals: to be able to write, compile, run C Programs on the PSU Linux Lab machines
   - *The Key*: Learn a command line editor: vim or emacs

Welcome
and Enjoy!