Computer Systems:  
A Programmer’s Perspective  

aka:  CS:APP  

- Five realities  
- How CSAPP fits into the CS curriculum  

These slides courtesy of Randal E. Bryant and David R. O'Hallaron, Carnegie Mellon University. http://csapp.cs.cmu.edu
CSAPP Theme:
Abstraction Is Good But Don’t Forget Reality

- Most CS 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:
  - $40000 \times 40000 \rightarrow 1600000000$
  - $50000 \times 50000 \rightarrow ??$

Example 2: Is $(x + y) + z = x + (y + z)$?
- Unsigned & Signed Int’s: Yes!
- Float’s:
  - $(1e20 + -1e20) + 3.14 \rightarrow 3.14$
  - $1e20 + (-1e20 + 3.14) \rightarrow ??$

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

```c
/* 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

```c
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

```c
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
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:

<table>
<thead>
<tr>
<th>Saved State</th>
<th>Location accessed by fun(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d7 ... d4</td>
<td>4</td>
</tr>
<tr>
<td>d3 ... d0</td>
<td>3</td>
</tr>
<tr>
<td>a[1]</td>
<td>2</td>
</tr>
<tr>
<td>a[0]</td>
<td>1</td>
</tr>
<tr>
<td>a[0]</td>
<td>0</td>
</tr>
</tbody>
</table>
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

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

```c
void copyji(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];
}
```

```c
void copyij(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)
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

160x

Best code (K. Goto)

Triple loop

- Standard desktop computer, vendor compiler, using optimization flags
- Both implementations have exactly the same operations count (2n³)
- What is going on?
**MMM Plot: Analysis**

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

- Gflop/s

- **Multiple threads:** 4x
- **Vector instructions:** 4x
- **Memory hierarchy and other optimizations:** 20x

- 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

- 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
Topics will be 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,**
  
  
  - 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,**
  