CS 47

Introduction to Computer Systems

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(adapted from
http://csapp.cs.cmu.edu/public/lectures.html)

Course Theme

- Abstraction is good, but don't forget reality!

Many courses emphasize abstraction

- Abstract data types
- Asymptotic analysis

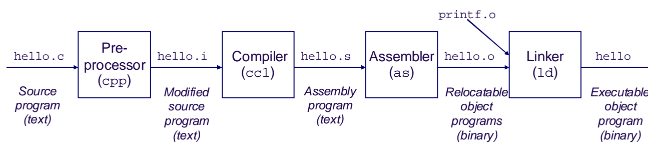
These abstractions have limits

- Especially in the presence of bugs
- Need to understand underlying implementations

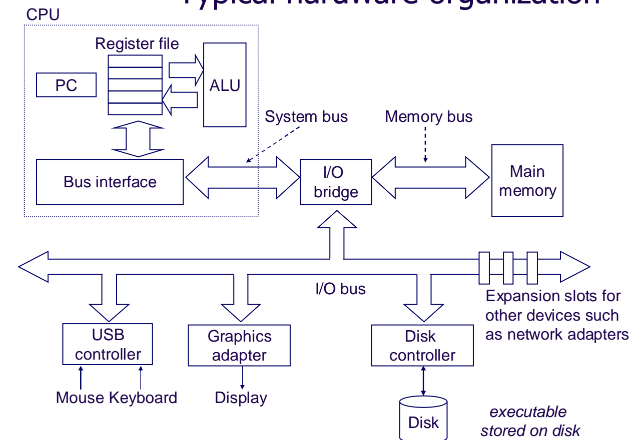
Useful outcomes

- Become more effective programmers
  - Able to find and eliminate bugs efficiently
  - Able to tune program performance
- Prepare for later "systems" classes
  - Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems

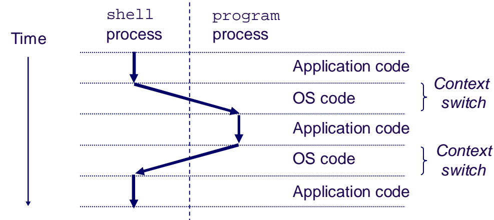
The compilation process in C



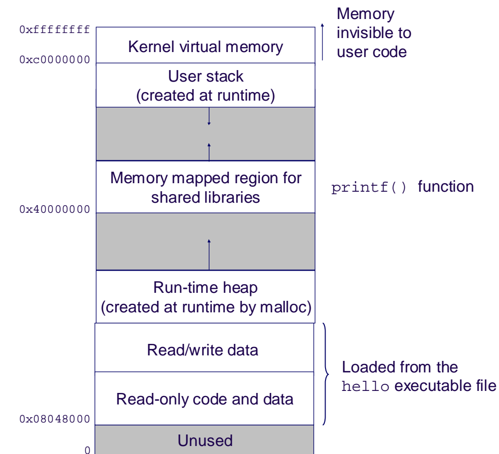
Typical hardware organization



Process context switching



Sample virtual memory address layout for a C "hello" program



Great Reality #1

Int's are not Integers, Float's are not Reals

Examples

- **Is $x^2 \geq 0$?**
  - **Float's: Yes!**
  - **Int's:**
    - » 40000 * 40000 --> 1600000000
    - » 50000 * 50000 --> ??
- **Is (x + y) + z = x + (y + z)?**
  - **Unsigned & Signed Int's: Yes!**
  - **Float's:**
    - » (1e20 + -1e20) + 3.14 --> 3.14
    - » 1e20 + (-1e20 + 3.14) --> ??

Computer Arithmetic

Does not generate random values

- **Arithmetic operations have important mathematical properties**

Cannot assume "usual" properties

- **Due to finiteness of representations**
- **Integer operations satisfy algebraic 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 program in assembly

- Compilers are much better & more patient than you are

Understanding assembly key to machine-level execution model

- Behavior of programs in presence of bugs
  - High-level language model breaks down
- Tuning program performance
  - Understanding sources of program inefficiency
- Implementing system software
  - Compiler has machine code as target
  - Operating systems must manage process state

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 required by procedure
  - In units of clock cycles

```
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");
}
```


Code to Read Counter

```
/* Record the current value of the cycle counter. */
void start_counter()
{
    access_counter(&cyc_hi, &cyc_lo);
}

/* Number of cycles since the last call to start_counter. */
double get_counter()
{
    unsigned ncyc_hi, ncyc_lo;
    unsigned hi, lo, borrow;
    /* Get cycle counter */
    access_counter(&ncyc_hi, &ncyc_lo);
    /* Do double precision subtraction */
    lo = ncyc_lo - cyc_lo;
    borrow = lo > ncyc_lo;
    hi = ncyc_hi - cyc_hi - borrow;
    return (double) hi * (1 << 30) * 4 + lo;
}
```

Measuring Time

Trickier than it Might Look

- Many sources of variation

Example

- Sum integers from 1 to n

n	Cycles	Cycles/n
100	961	9.61
1,000	8,407	8.41
1,000	8,426	8.43
10,000	82,861	8.29
10,000	82,876	8.29
1,000,000	8,419,907	8.42
1,000,000	8,425,181	8.43
1,000,000,000	8,371,230,591	8.37

Great Reality #3

Memory Matters

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

```
#include <stdio.h>

int main()
{
  int d = 1;
  int a[2];
  a[2] = 0; /* Out of bounds reference */
  printf("d = %d\n", d);
  return 0;
}
```

Compiling with gcc on the PC prints 0!

On the other hand, compiling with optimizations (-O) prints 1!

Memory Referencing Errors

C and C++ do not provide any memory protection

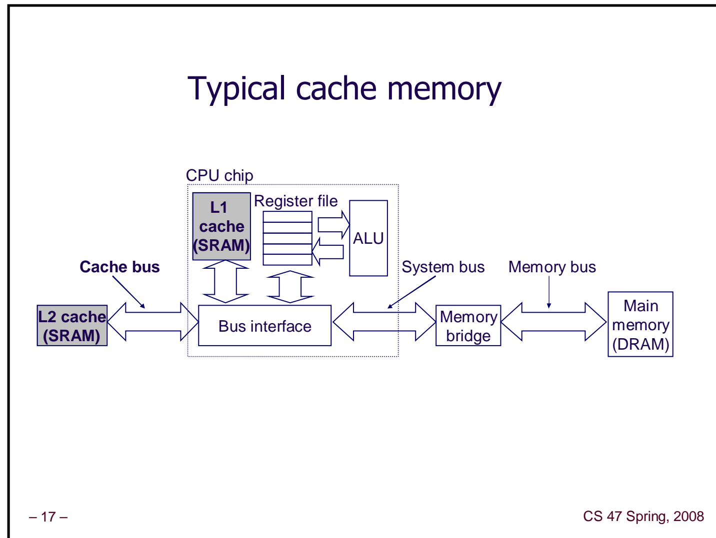
- Out of bounds array references
- Invalid pointer values
- Abuses of malloc/free

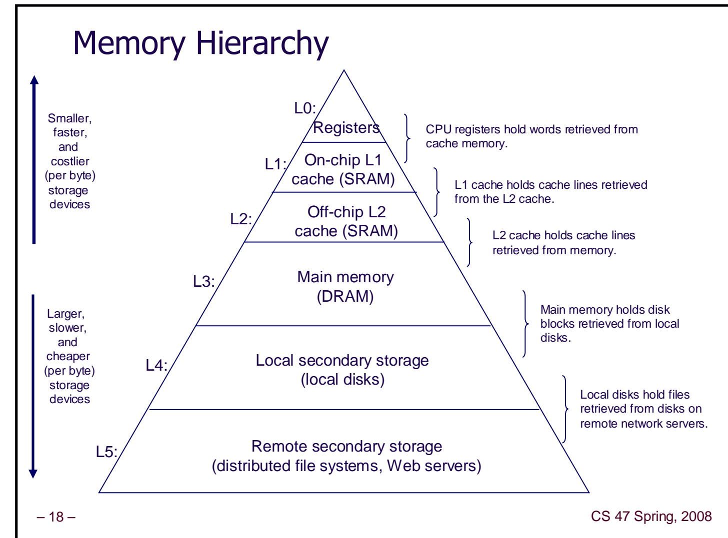
Can lead to nasty bugs

- 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, Lisp, or ML
- Understand what possible interactions may occur
- Use or develop tools to detect referencing errors





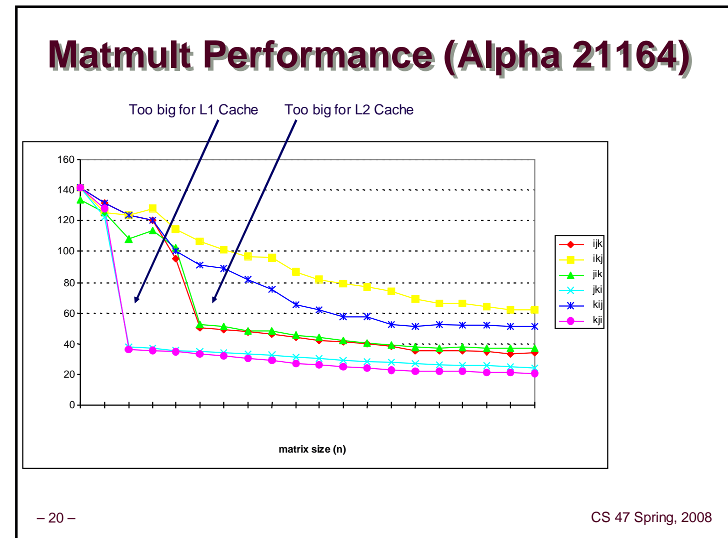
Memory Performance Example

Implementations of Matrix Multiplication

- **Multiple ways to nest loops**

```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

```
/* jik */
for (j=0; j<n; j++) {
  for (i=0; i<n; i++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum
  }
}
```

Great Reality #4

There's more to performance than asymptotic complexity

Constant factors matter too!

- **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**