

15-213

“The Class That Gives CMU Its Zip!”

Introduction to Computer Systems

Randal E. Bryant
August 30, 2006

Topics:

- Theme
- Five great realities of computer systems
- How this fits within CS curriculum

Course Theme

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

Courses to date 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 in CS & ECE
 - Compilers, Operating Systems, Networks, Computer Architecture, Embedded Systems

Great Reality #1

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

Examples

■ Is $x^2 \geq 0$?

- Float's: Yes!

- Int's:

 - » $40000 * 40000 \rightarrow 1600000000$

 - » $50000 * 50000 \rightarrow ??$

■ Is $(x + y) + z = x + (y + z)$?

- Unsigned & Signed Int's: Yes!

- Float's:

 - » $(1e20 + -1e20) + 3.14 \rightarrow 3.14$

 - » $1e20 + (-1e20 + 3.14) \rightarrow ??$

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 “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 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
- 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 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");
}
```

Great Reality #3

Memory Matters: Random Access Memory is an un-physical 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

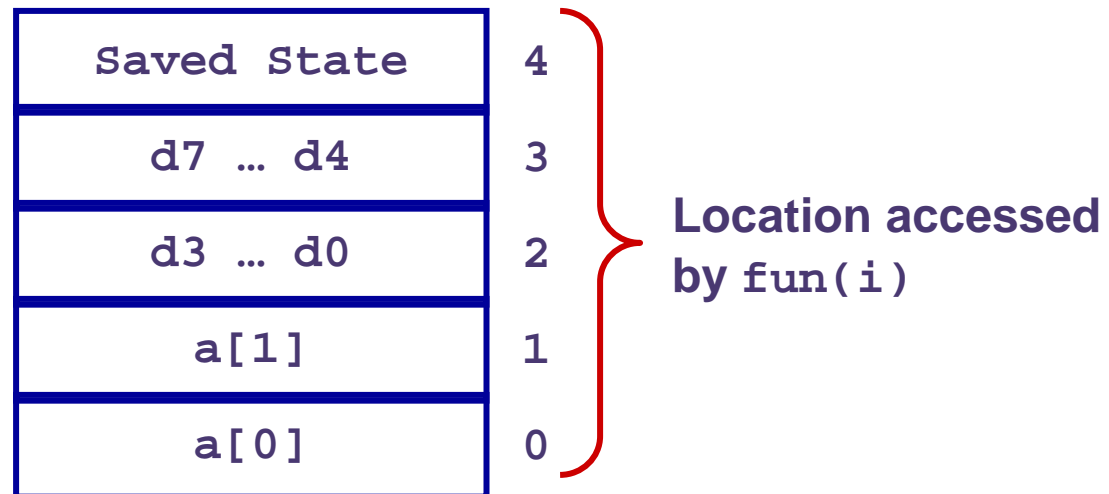
- Cache and virtual memory effects can greatly affect program performance
- Adapting program to characteristics of memory system can lead to major speed improvements

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
```

Referencing Bug Explanation



- C does not implement bounds checking
- Out of range write can affect other parts of program state

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 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];
}
```

59,393,288 clock cycles

```
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];
}
```

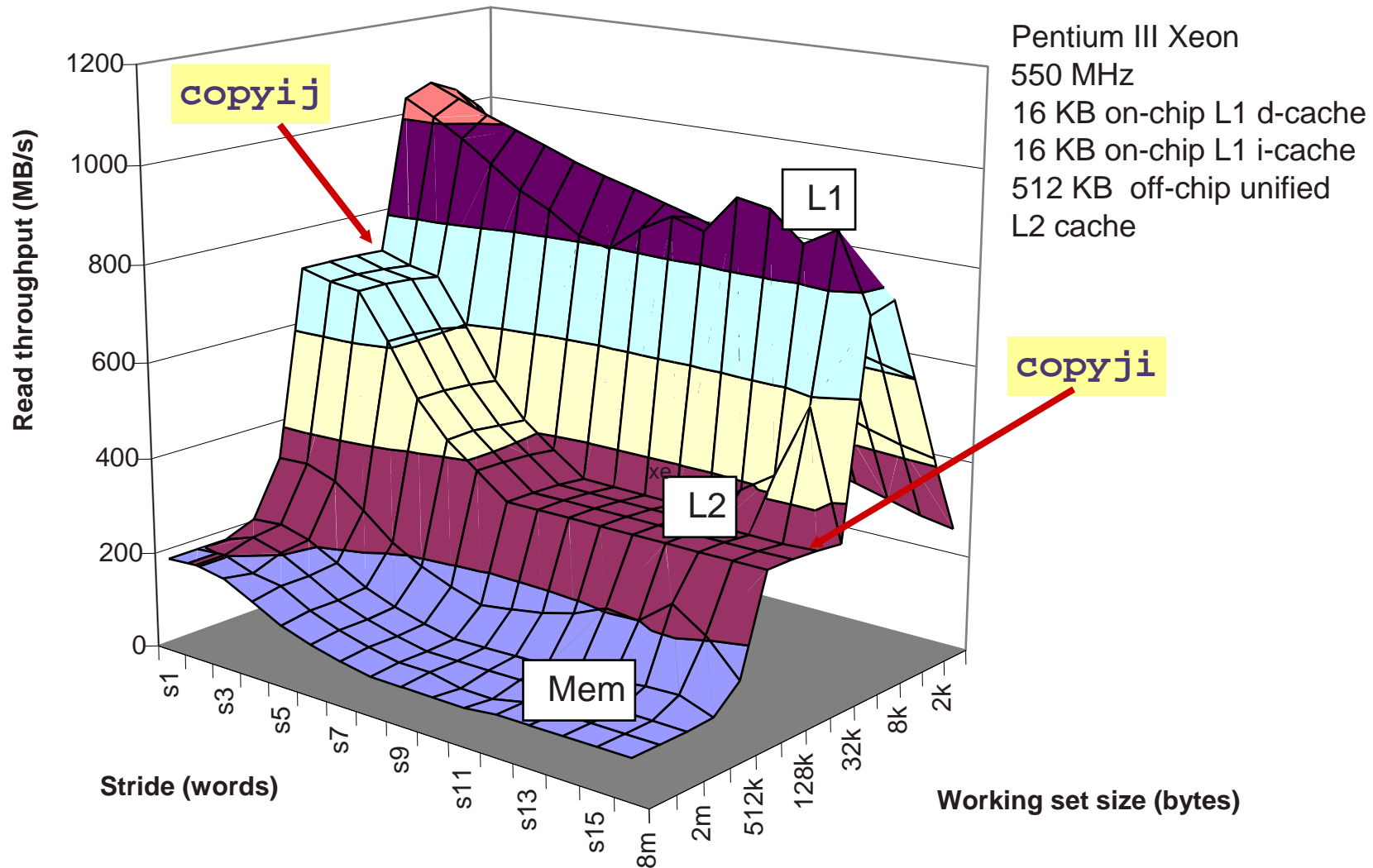
1,277,877,876 clock cycles

21.5 times slower!

(Measured on 2GHz
Intel Pentium 4)

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

The Memory Mountain



Memory Performance Example

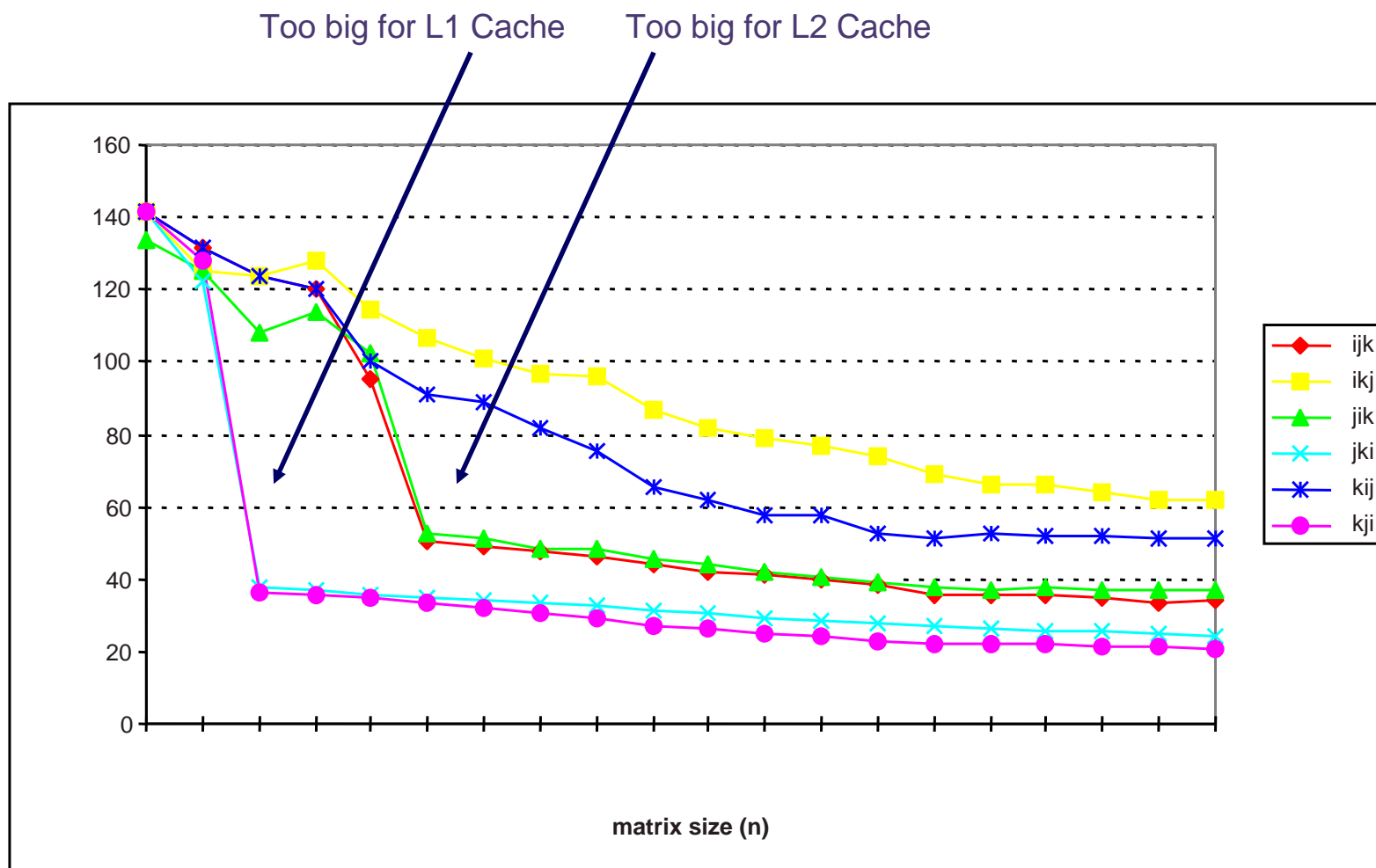
Implementations of Matrix Multiplication

- Multiple ways to nest loops

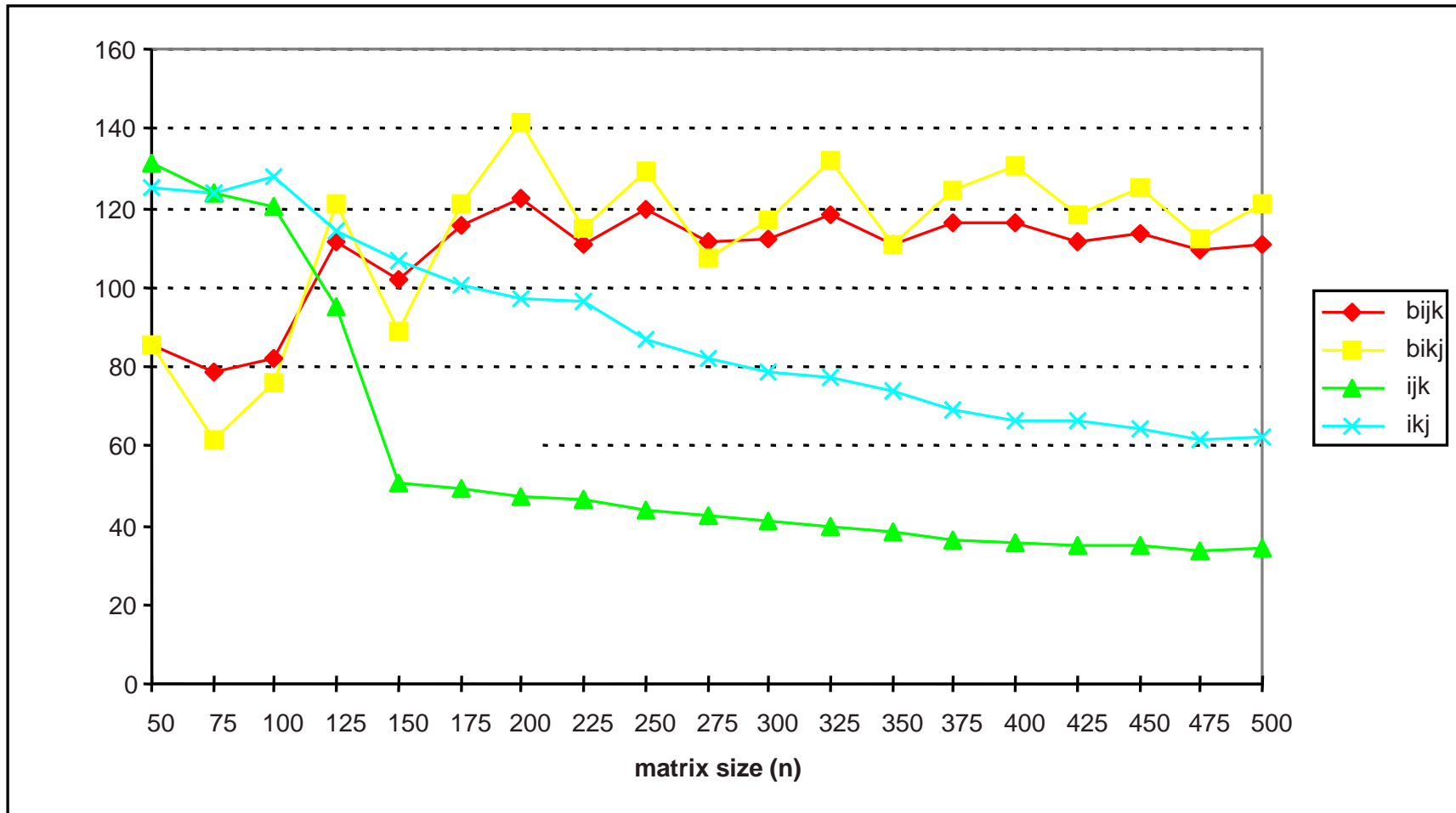
```
/* ijk */
for (i=0; i<n; i++) {
    for (j=0; j<n; j++) {
        sum = 0.0;
        for (k=0; k<n; k++)
            sum += a[i][k] * b[k][j];
        c[i][j] = sum;
    }
}
```

```
/* 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;
    }
}
```

Matmult Performance (Alpha 21164)



Blocked matmult perf (Alpha 21164)



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

Great Reality #5

Computers do more than execute programs

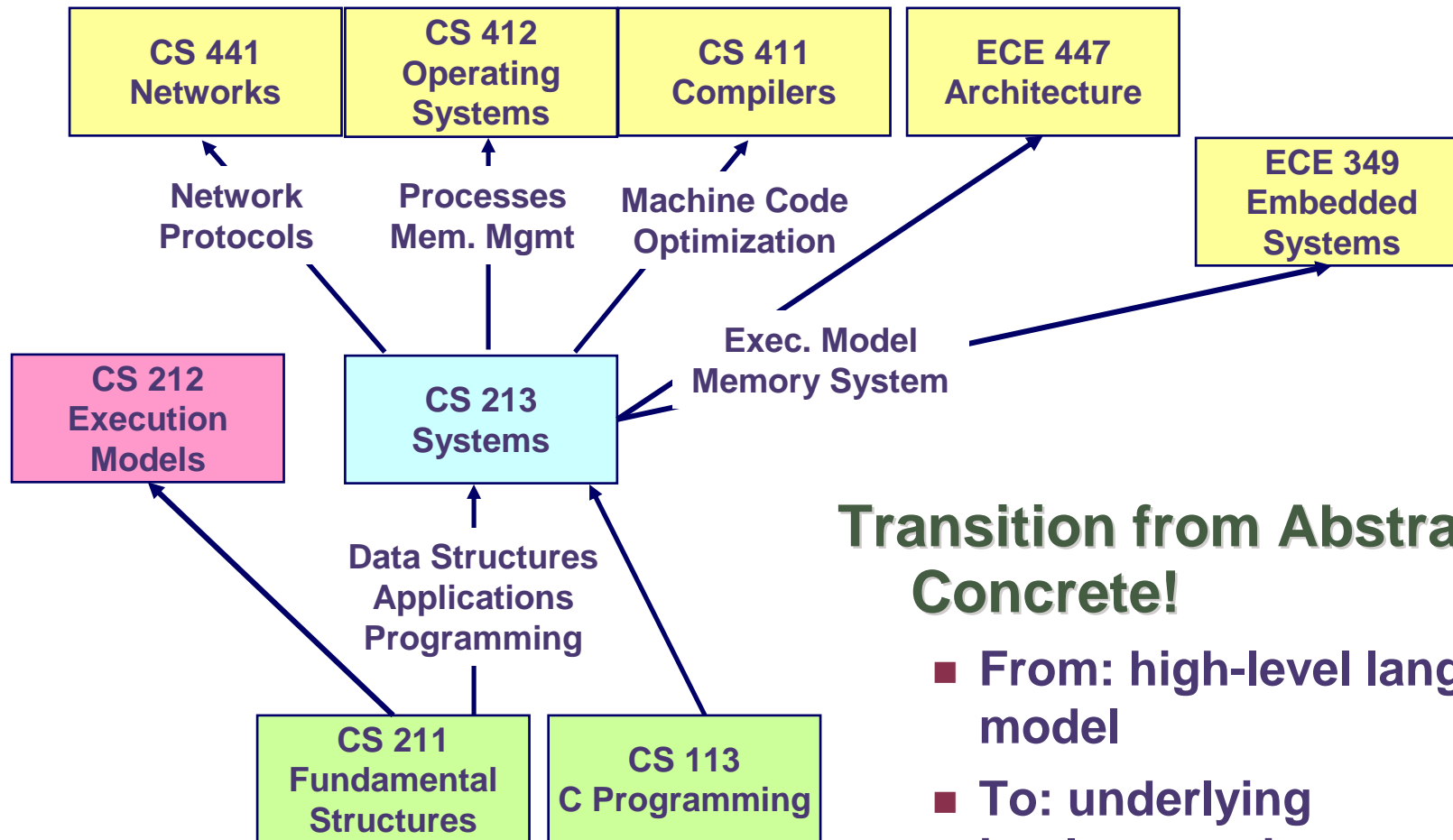
They need to get data in and out

- 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 Curriculum



Transition from Abstract to Concrete!

- From: high-level language model
- To: underlying implementation

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 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