Distributed Systems
[Fall 2013]

Lec 3: Example use cases (continued)

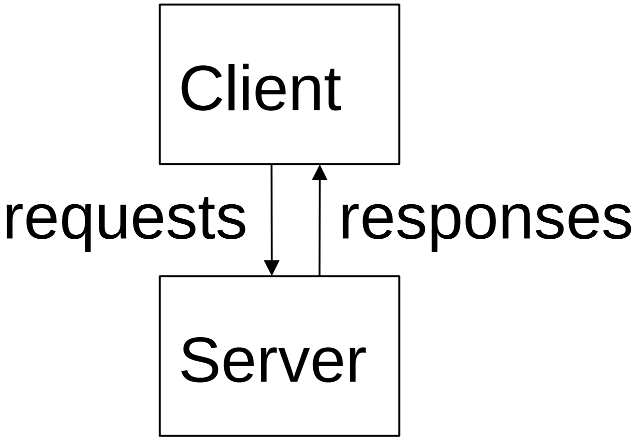
Cloud computing

Example Use Cases

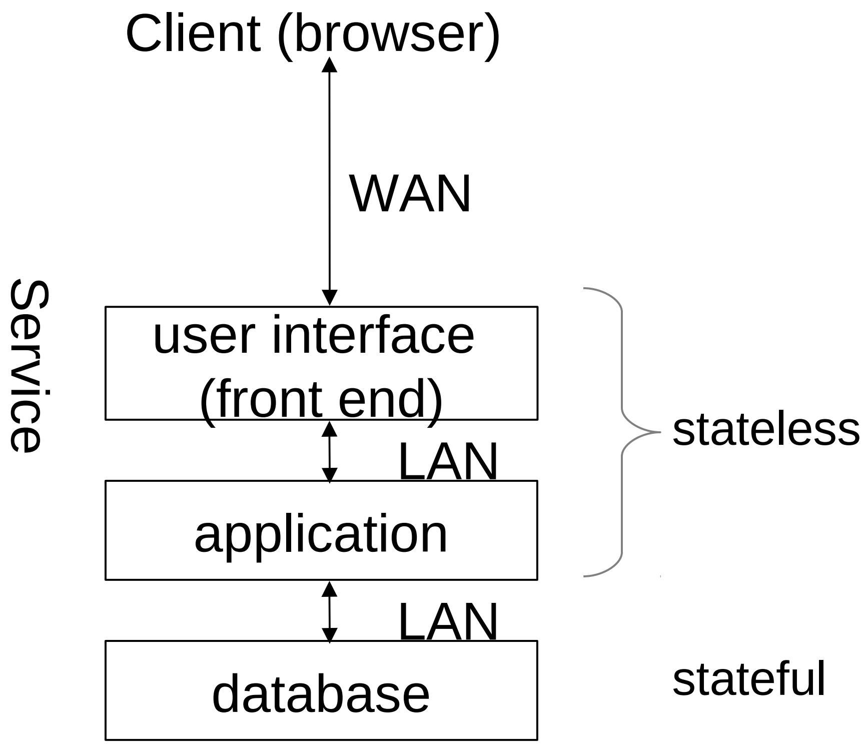
- Web architectures (last time)
  - Simple architectures and real-world architectures
- Cloud computing (today)
  - What it means and how it began

What Are Some Web Architectures?

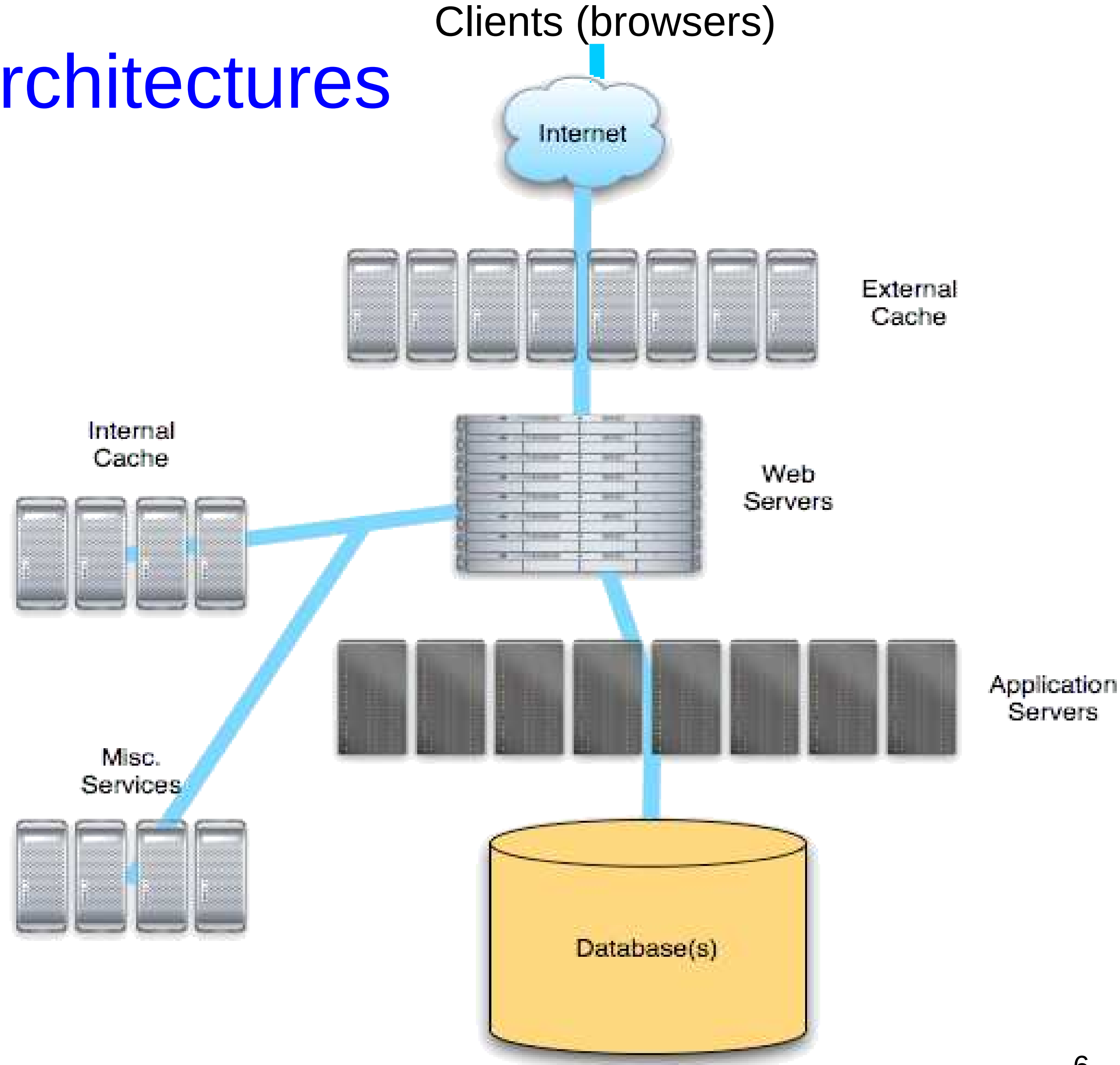
1. The Client-Server Model



2. The Three-Tiered Architecture



3. Real Architectures



http://www.codemass.com/presentations/apachecon2005/ac2005scalablewebarch.ppt

So, What Did We Learn?

- Web architectures are complex
- But there are well-known solutions
- There are lots of tradeoffs and understanding workload is key in choosing the right solution at each layer

- Each layer has distinct hardware requirements and likely distinct bottlenecks

- What does the last observation tell us?

Example Use Cases

- Web architectures (last time)
  - Simple architectures and real-world architectures

- Cloud computing (today)
  - What it means and how it began

What is cloud computing?

- Computing technology in which data and/or computation are outsourced to a massive-scale, multi-user infrastructure that is managed by a third-party.

- Appeared gradually due to two important challenges facing the Web:
  - Scaling
  - Management

- I'll tell you the story of how it appeared, so as to help you understand what it is

Around 1995: The Scaling Challenge

- The Web and e-commerce were gaining traction

- Their challenge: how to scale?
  - 1996 to 1997: eBay grew from 41,000 to 341,000 users!

Pre-1995 Answer: Big, Expensive Computers

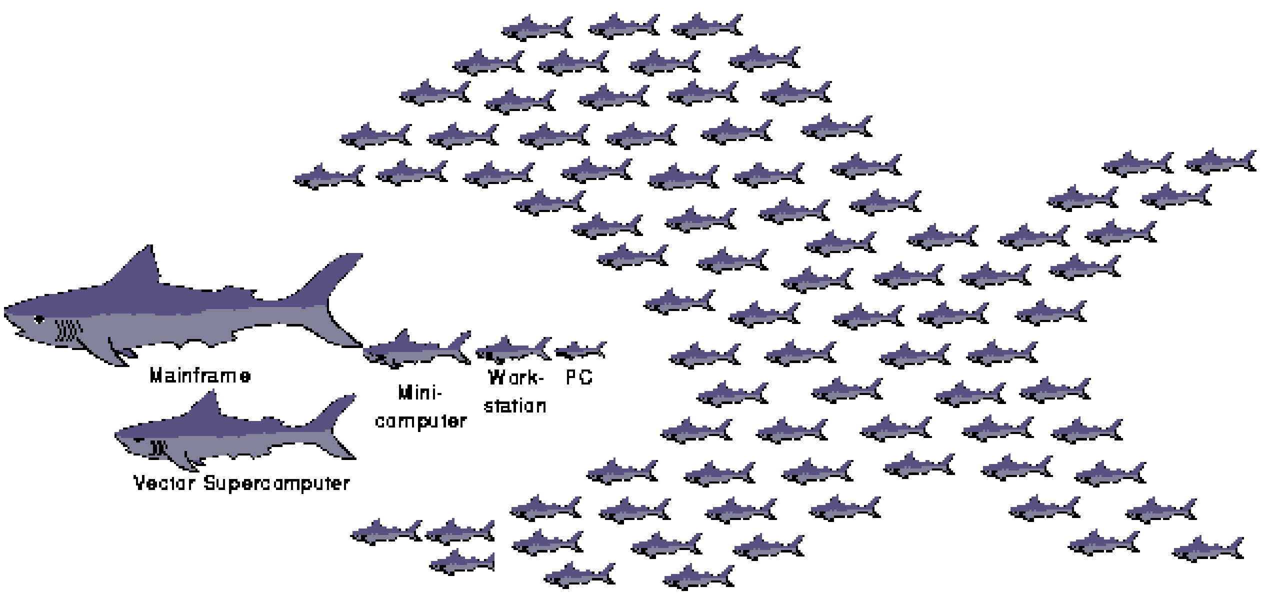
- Example: eBay used Sun E-10000 “supermini”
  - 64 processors @250MHz, 64GB RAM, 20TB disk, ~$1M
- The good:
  - Easy to manage
  - Easy to program
  - Simple failure mode
- The bad:
  - Q: Any ideas?

Pre-1995 Answer: Big, Expensive Computers

- Example: eBay used Sun E-10000 “supermini”
  - 64 processors @250MHz, 64GB RAM, 20TB disk, ~$1M
- The good:
  - Easy to manage
  - Easy to program
  - Simple failure mode
- The bad:
  - Expensive
  - Single point of failure
  - No incremental scalability

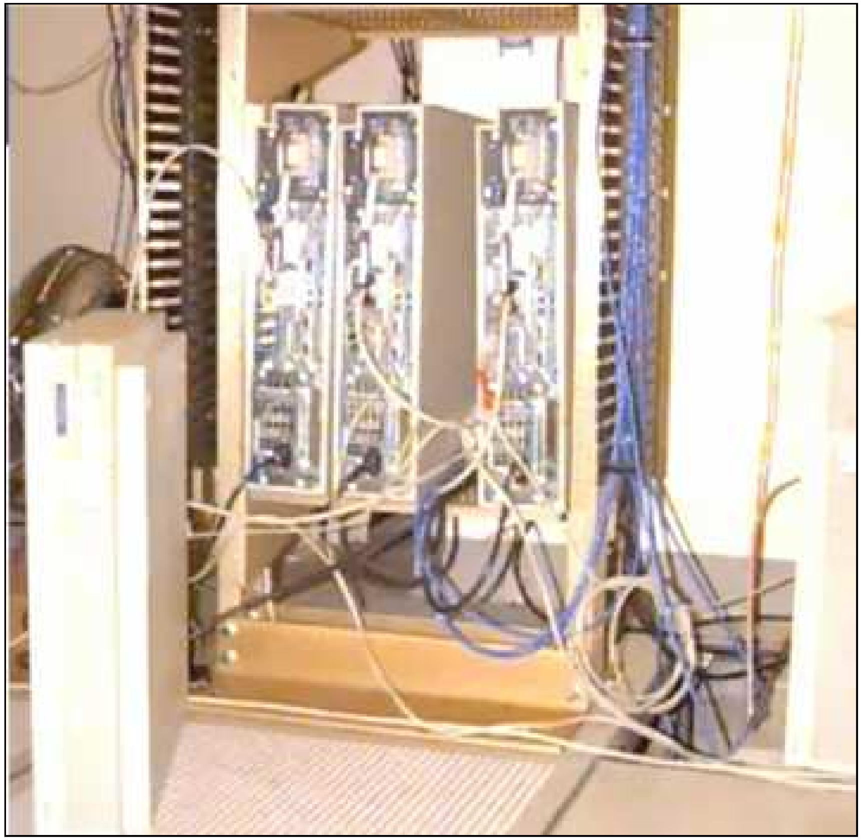
1995: Berkeley Network of Workstations (NOW)

- Idea: Leverage many interconnected small, cheap, general-purpose machines for incremental scalability and reliability
  - Typical PC: 200 MHz CPU, 32MB RAM, 4GB disk



NOW-0

- 1994: NOW had 4 HP-735's



NOW-1

- 1995: NOW had 32 Sun SPARC stations

NOW-2

- 1997: 60 Sun SPARC-2's
- Build Inktomi app

Companies Adopt NOW

- Everybody builds their own clusters and grows them to handle more and more load
  - Examples: eBay, Amazon, Google, all .com bubble companies

- Similar to early days of electricity when everyone built their own generator

Q: What do you think happened next?

Late 1990s: The Manageability Challenge

- Hard to manage and program large clusters
  - How to write scalable distributed programs?
  - How to debug large-scale programs?
  - How to make services reliable?
  - How to architect the network infrastructure?
  - How to provision a cluster to handle peak load?
  - How to administer a huge number of computers?
  - …
- Each company had to build own complex software
  - Like each of us building an OS from scratch!

Early 2000s: Scalable Cluster Primitives

- Very few technically strong companies create powerful scalable and reliable primitives for cluster management and programming
- Examples:
  - Google's Map/Reduce
  - The Google File System (GFS)
  - Google's Bigtable
  - Amazon's Dynamo
  - Distributed debugging and tracing tools
  - Datacenter temperature regulators
  - Scalable distributed communication mechanisms
  - …

Mid 2000s: Three Valuable Commodities

- Giant-scale clusters with enormous excess capacity
  - Everybody provisioned for peak

Q: How big was a typical Google datacenter around 2005?

a. 1,000 machines

b. 5,000 machines

c. 10,000 machines

d. 50,000 machines

e. 100,000 machines

Mid 2000s: Three Valuable Commodities

- Giant-scale clusters with enormous excess capacity
  - Everybody provisioned for peak
- Expertise for managing and operating clusters at low cost
  - "Economies of scale"
- Complex software to help program/manage clusters
  - Even full applications (e.g., Gmail, Google Calendar, etc.)

Q: What do you think happened next?

2006: Cloud computing

- AWS sells resources, expertise, and access to cloud primitives in a pay-for-what-you-use model
  - Resources: CPU, network bandwidth, persistent storage
  - Cloud primitives: Amazon S3, EC2, SQS, Map/Reduce, ...
- Google launches Google Apps for Your Domain
  - Customizable Gmail, Google Docs, Google Calendar under a custom domain (e.g., **`gmail.cs.columbia.edu`**)
- Google then launches the App Engine
  - Web hosting infrastructure (such infrastructures existed before, but didn't come with many primitives)
- Microsoft launches Azure in 2009

Advantages of cloud computing

- Low barrier of market entry for startups
- Cheaper, low-management email, calendars, CRM solutions
- New mobile applications
- Faster batch processing via parallelization across many machines

What do Clouds have to do w/ distributed systems?

- Clouds are powered by (and sell) distributed, scalable systems, which can be used as building blocks for easy bootstrap of new applications and services
  - Often times, you hear about clouds as being great because you don't have to purchase machines upfront
  - I think their major advantage lies in fact in the scalable services they provide

- This is unlike prior Web hosting infrastructures that predated "clouds" by many years
  - Those offered (and some still do) bare-metal and no add-on value-added services

Next time

- Communication: remote procedure calls
- Homework 1 is due tomorrow

- Homework 2 will be out on Thursday
  - Start with the writing piece and then do the coding
  - It's long, so start coding soon
  - Next time TA will go over the YFS series

Distributed Systems
[Fall 2012]

Lec 3 (Part 2): OS Background

Processes, Threads, and Local Coordination

OS Background

- Topics:
  - Processes
  - Threads
  - Local coordination
    - Inter-process communication (or how processes coordinate)
    - Thread synchronization (or how threads coordinate)

- Is this an OS course?!
  - No, but concepts are essential for distributed systems
  - They often have 1:1 relationships with distributed coordination concepts

Outline

- Processes
- Inter-process communication (IPC)
- Threads
- Thread synchronization

- Slide acknowledgements:
  - Junfeng Yang (www.cs.columbia.edu/~junfeng/12sp-w4118/lectures/l04-proc.pdf)
  - Dave Andersen (www.cs.cmu.edu/~dga/15-440/F10/lectures/04-work.pdf)
  - Jinyang Li (www.news.cs.nyu.edu/~jinyang/fa09/notes/ds-lec2.pdf)

What Is a Process?

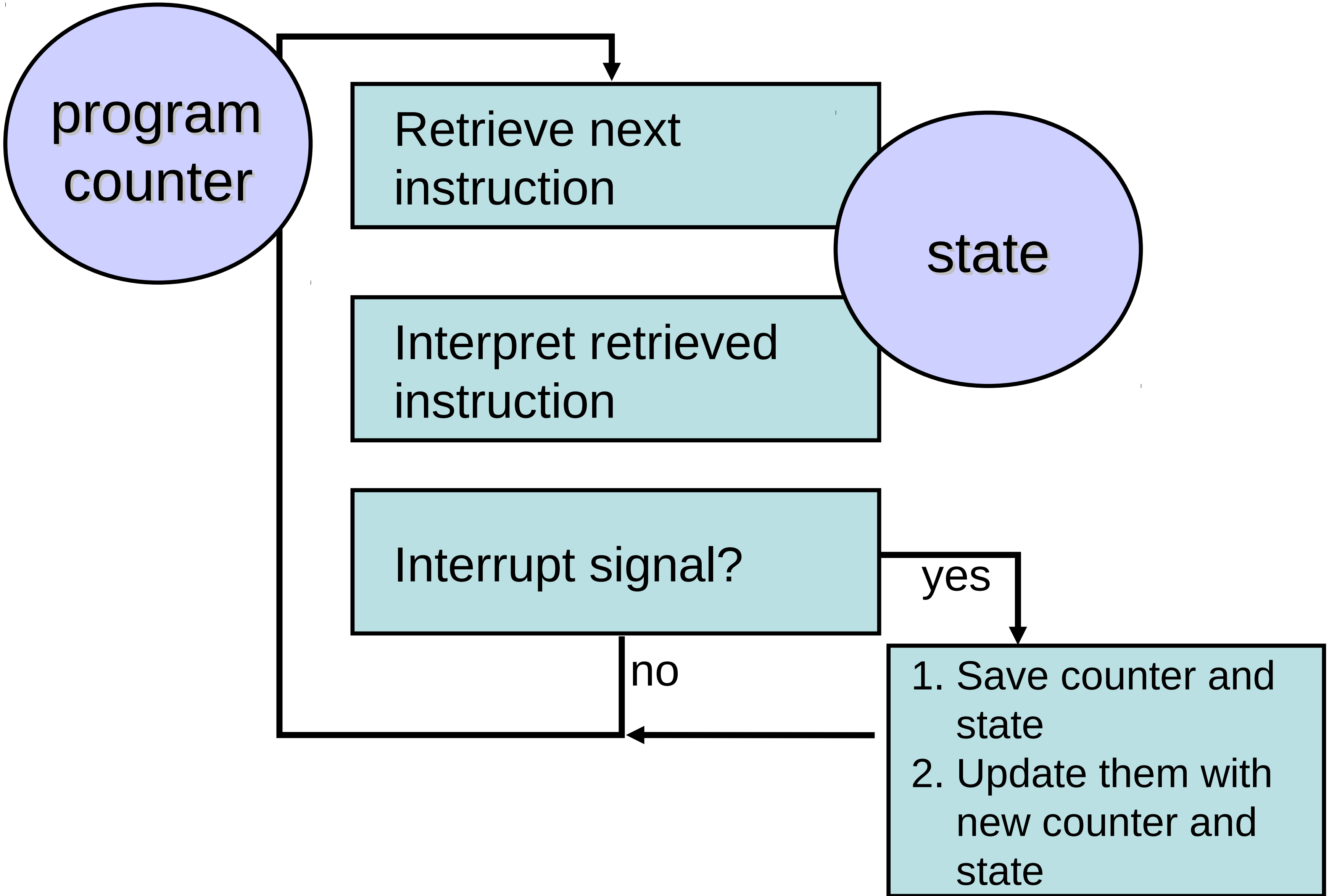
- Process: an execution stream (or program) in the context of a particular process state
  - "Program in execution," "virtual CPU"
- Execution stream: a stream of instructions
- Process state: determines effect of running code
  - Registers: general purpose, instruction pointer (program counter), floating point, …
  - Memory: everything a process can address, code, data, stack, heap, …
  - I/O status: file descriptor table, …

Program vs. Process

- Program != process
  - Program: static code + static data
  - Process: dynamic instantiation of code + data + more

- Program ⇔ process: no 1:1 mapping
  - Process > program: more than code and data
  - Program > process: one program runs many processes
  - Process > program: many processes of same program

The CPU



program counter
Retrieve next instruction
state
Interpret retrieved instruction
Interrupt signal?
yes
no
1. Save counter and state
2. Update them with new counter and state

Why Use Processes?

- Express concurrency
  - Systems have many concurrent jobs going on
  - E.g. Apache can spawn multiple processes to process requests in parallel on multiple CPUs and parallelize I/O…
  - OS manages concurrency

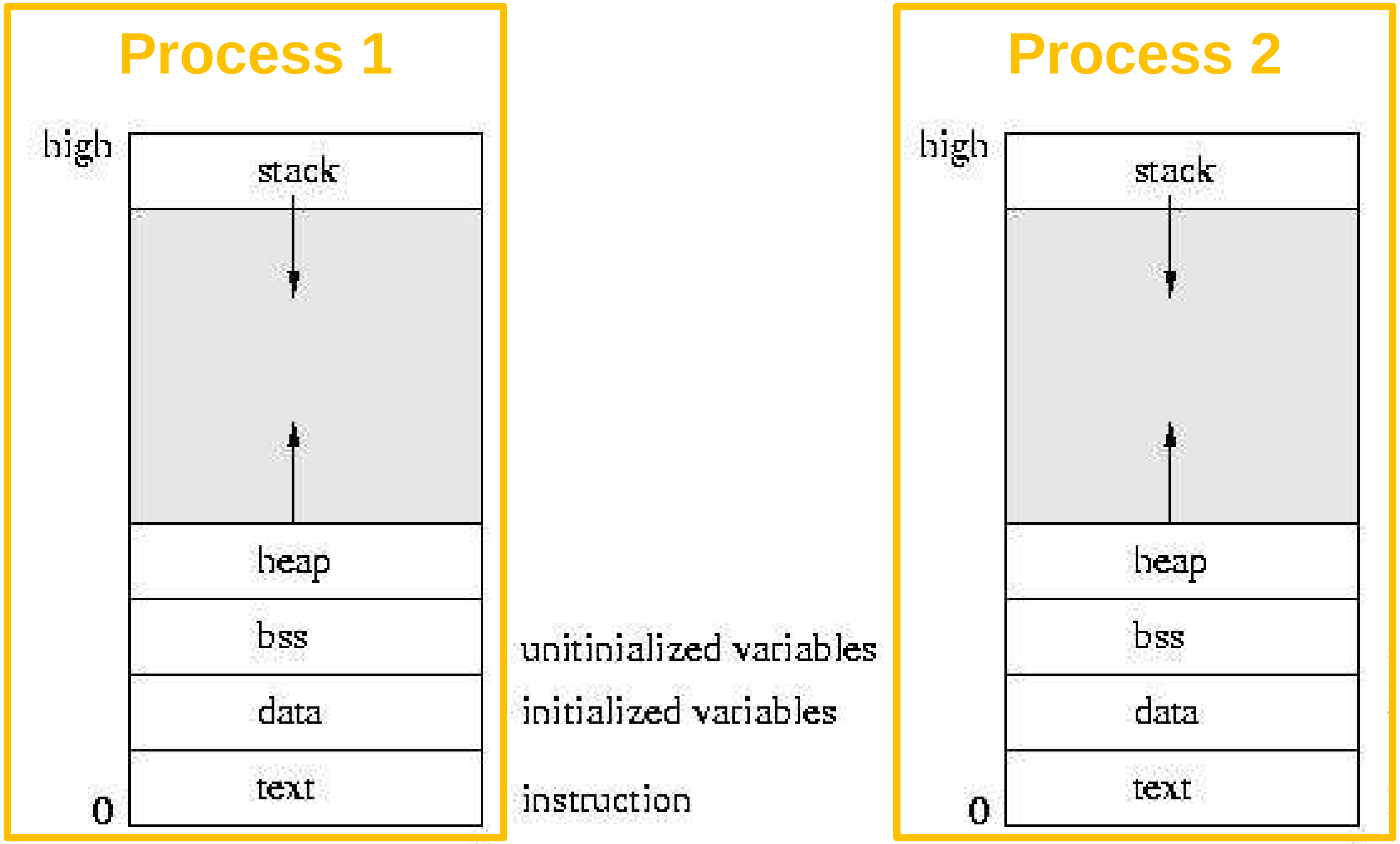
- General principle of divide and conquer
  - Decompose a large problem into smaller ones easier to think of well contained smaller problems

- Processes are isolated from each other
  - Sequential with well defined interactions

Address Spaces

- Address Space (AS): all memory a process can address
  - Really large memory to use
  - Linear array of bytes: [0, N), N roughly 2^{32} / 2^{64}
- Process ⇔ address space: 1 : 1 mapping
  - Address space = protection domain
- OS isolates address spaces
  - One process can't access another's address space
  - Same pointer address in different processes point to different memory

Address Space Illustration



Practical Stuff: Using Processes

- Creating a new *process*: fork()
  - Makes an almost exact copy of calling process (PID changes, etc.)
  - New process has its own memory (although some of it is shared – copy-on-write)
  - How to tell difference between the two processes? Return value is 0 in child, child PID in parent.
- Executing a different *program*: exec()
  - Replaces the process' image with a new one running the new program

Example: Fork/Exec

```
#include <iostream>
#include <sys/wait.h>
#include <unistd.h>

using namespace std;

int main() {
  pid_t pid;
  int status, died;
  switch (pid = fork()) {
    case -1: cout << "can't fork\n";
                 exit(-1);
    case 0 : execl("/usr/bin/date","date",0);  // this is the code the child runs
    default:  died= wait(&status);  // this is the code the parent runs
  }
}
```

Source: students.cs.byu.edu

Outline

- Processes
- Inter-process communication (IPC)
- Threads
- Thread synchronization

Interprocess Communication

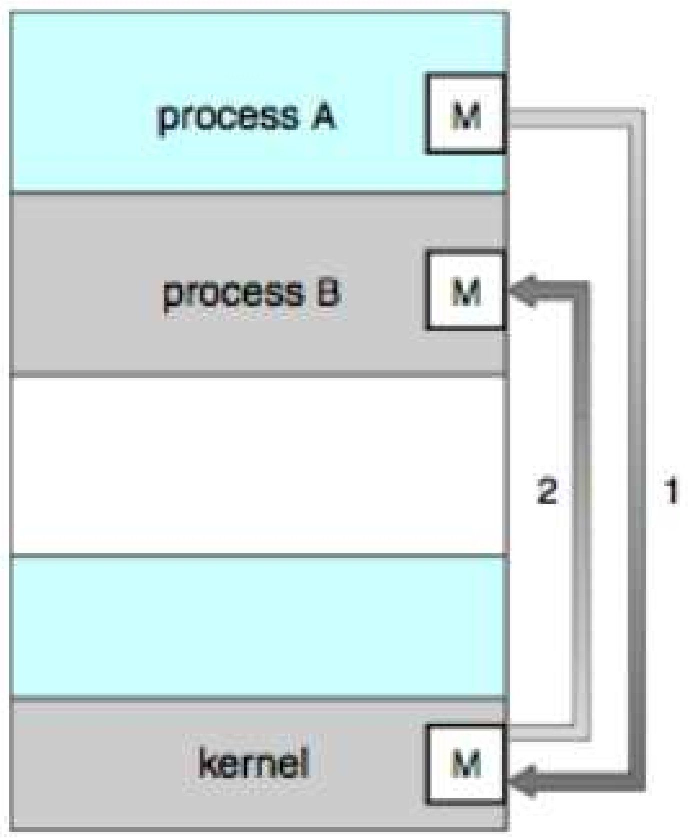
- Often, multiple processes are part of the same "program"
- Hence, they need to coordinate

- Example: Apache and its worker processes, each serving a request
  - Apache must send requests to each worker

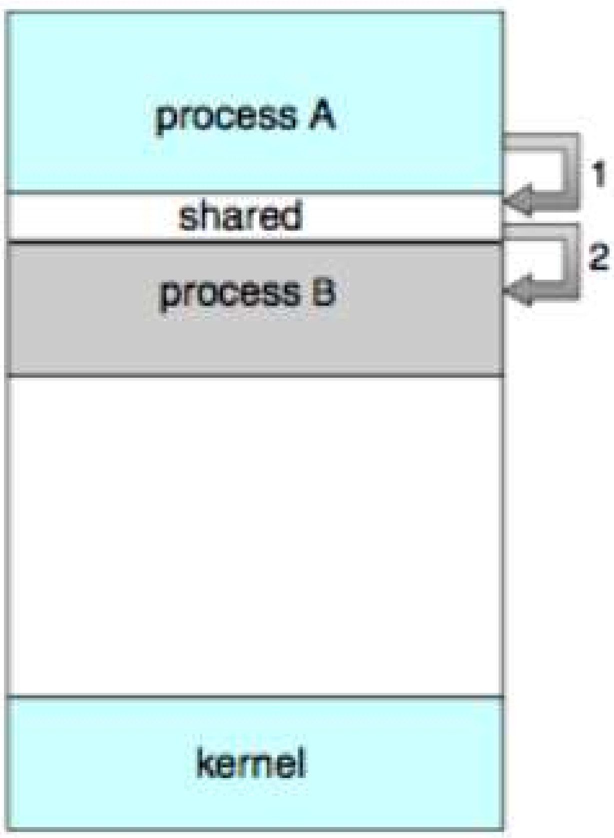
- This is very similar to how processes (or tasks) in distributed systems must coordinate

IPC Models

Message passing



Shared memory



Message Passing vs. Shared Memory

- Message passing
  - Why good? All sharing is explicit – less chance for error
  - Why bad? Overhead
    - Data copying, across protection domains (context switches)

- Shared memory
  - Why good? Performance
    - Set up shared memory once, then access w/o crossing protection domains
  - Why bad? Things change behind your back – error prone

IPC Example: UNIX Signals

- Signals
  - A very short message: just a small integer
  - A fixed set of available signals. Examples:
    - 9: kill
    - 11: segmentation fault

- Installing a handler for a signal: **signal()**
  - sighandler_t **signal**(int signum, sighandler_t handler);

- Send a signal to a process: **kill()**
  - **kill**(pid_t pid, int signum)

IPC Example: UNIX Pipe

- int **pipe**(int fds[2])
  - Creates a one way communication channel
  - fds[2] holds the returned two file descriptors
  - Bytes written to fds[1] will be read from fds[0]

```
int pipefd[2];
pipe(pipefd);  // error handling ignored
switch(pid = fork()) {
  case -1: perror("fork"); exit(1);
  case 0:  close(pipefd[0]);
           // write to fd 1
           break;
  default:  close(pipefd[1]);
           // read from fd 0
   break;
}
```

IPC Example: UNIX Shared Memory

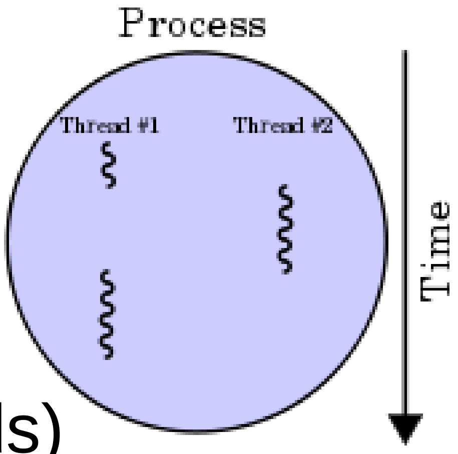
- int **shmget**(key_t key, size_t size, int shmflg)
  - Create a shared memory segment; returns ID of segment
  - key: unique key of a shared memory segment, or IPC_PRIVATE
- int **shmat**(int shmid, const void *addr, int flg)
  - Attach shared memory segment to address space of calling process
  - shmid: id returned by **shmget**()
- int **shmdt**(const void *shmaddr);
  - Detach from shared memory
- Problem: synchronization! (similar concept as in threads)

Today

- Processes
- Inter-process communication (IPC)
- Threads
- Thread synchronization

Threads

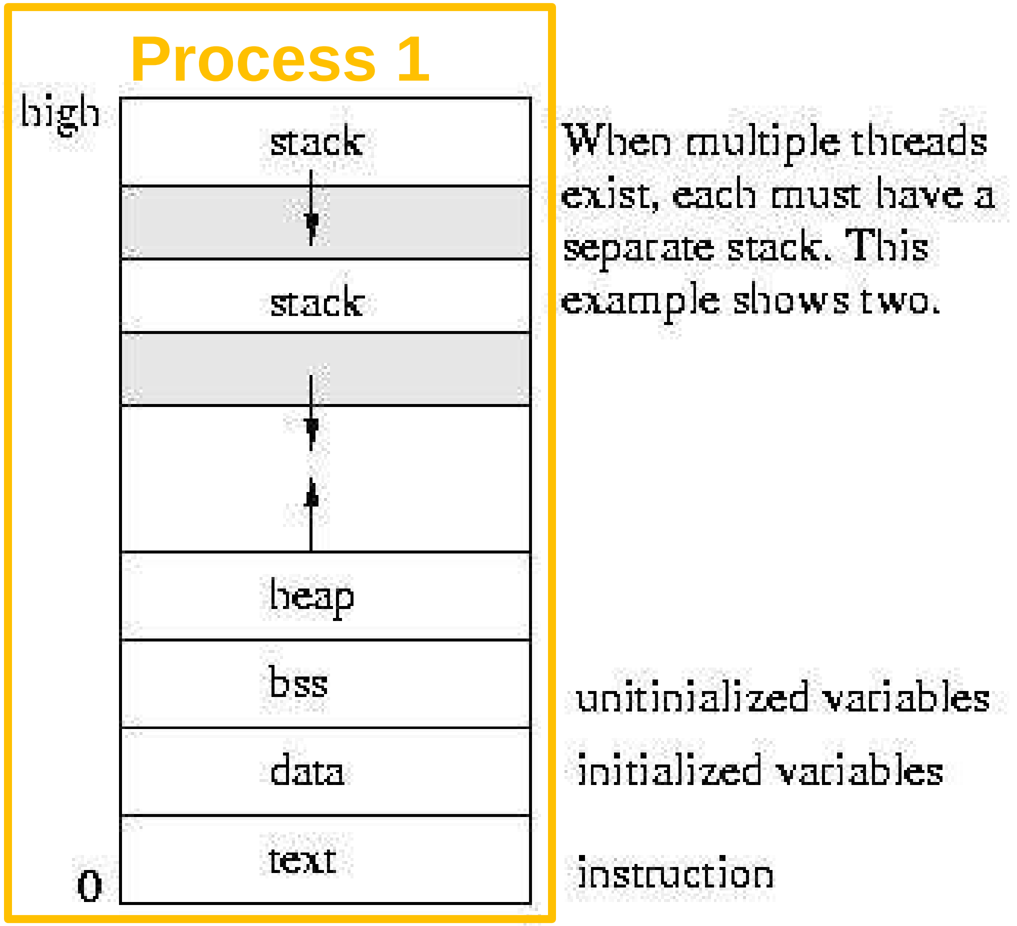
- Threads: separate streams of executions that share an address space
  - Allow one process to have multiple points of execution, can use multiple CPUs



- Per-thread state (not shared across threads)
  - Program counter (EIP on x86)
  - Other registers
  - Stack

- Conceptually similar to processes, but different
  - Often called "lightweight processes"

Threads in Memory



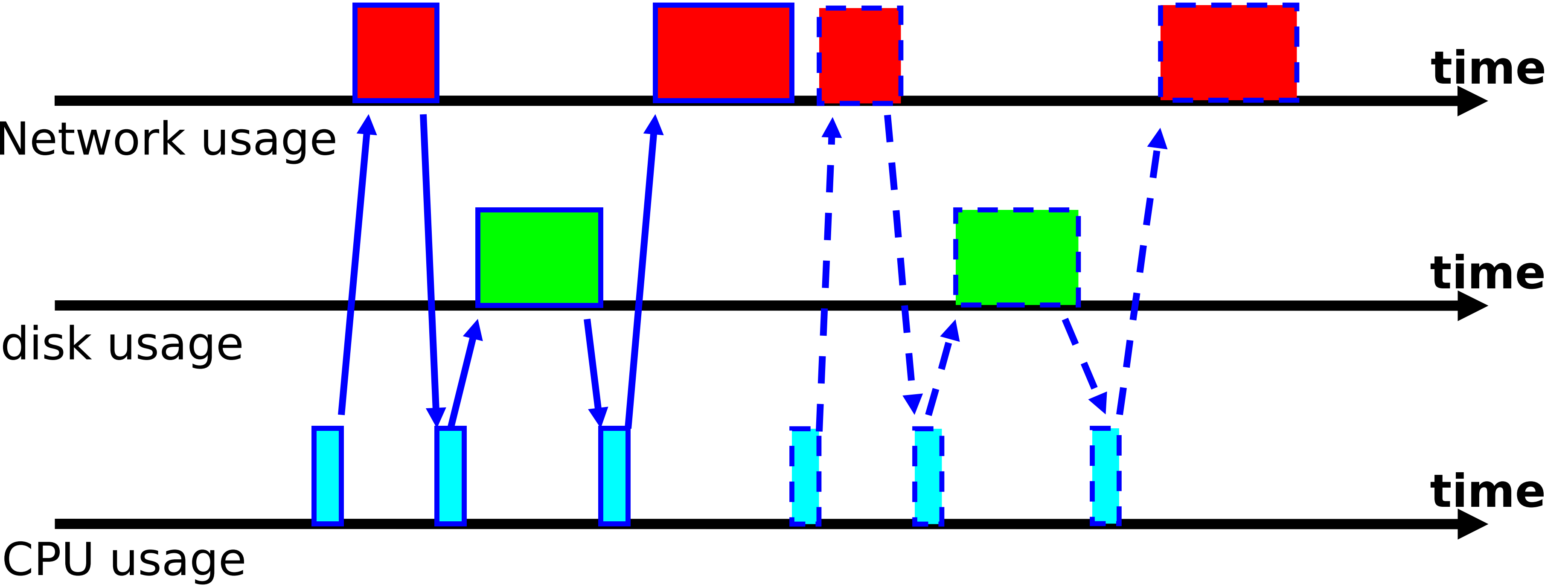
Thread vs. Process

- Why threads?
  - Thread allows running code concurrently within a single process
  - Switching among threads is lightweight
  - Sharing data among threads requires no IPC
- Why processes?
  - Fault isolation: One buggy process cannot crash others

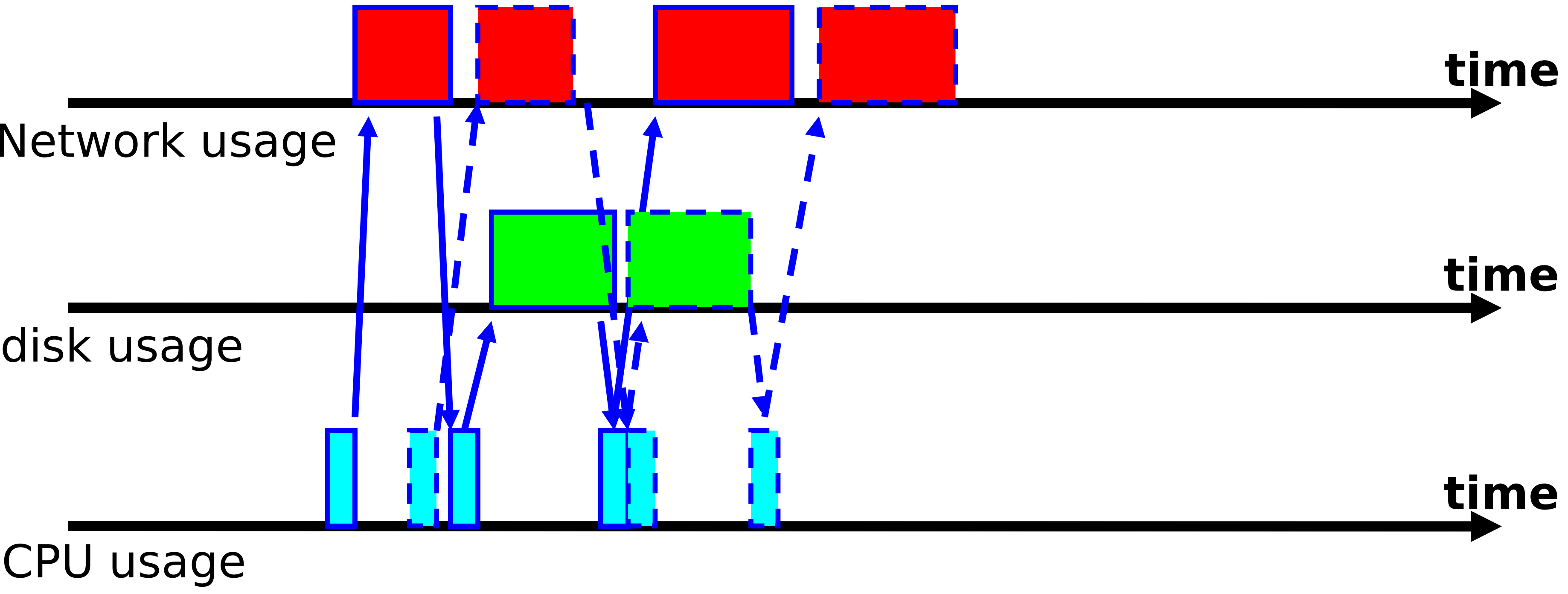
Why Multi-threaded Programming?

- Exploit multiple CPUs (multi-core) with little overhead
- Exploit I/O concurrency
  - Do some processing while waiting for disk, network, user
- Reduce latency of networked services
  - Servers serve multiple requests in parallel
  - Clients issue multiple requests in parallel
- Example:
  - In addition to multi-process support, Apache has multi-thread support, which is much more common.

Single-threaded servers do not fully utilize I/O and CPU



Multi-threaded servers achieve I/O concurrency



Practical Stuff: The `pthread` Library

- int **pthread_create**(pthread_t ***thread**, const pthread_attr_t ***attr**,
  void *(***start_routine**)(void*), void ***arg**);
  - Create a new thread to run **start_routine** on **arg**
  - **thread** holds the new thread's id
  - Can be customized via **attr**

- int **pthread_join**(pthread_t **thread**, void ****value_ptr**);
  - Wait for thread termination, and retrieve return value in **value_ptr**

- void **pthread_exit**(void ***value_ptr**);
  - Terminates the calling thread, and returns **value_ptr** to threads waiting in **pthread_join**

Pthread Creation Example

```
void* thread_fn(void *arg) {
  int id = (int)arg;
  printf("thread %d runs\n", id);
  return NULL;
}

int main() {
  pthread_t t1, t2;
  pthread_create(&t1, NULL, thread_fn, (void*)1);
  pthread_create(&t2, NULL, thread_fn, (void*)2);
  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
  return 0;
}
```

```
$ gcc –o threads threads.c –Wall –lpthread
$ ./threads
thread 1 runs
thread 2 runs
```

Thread Pools

- Problem:
  - Creating a thread for each request: costly
    - And, the created thread exits after serving a request
  - More user requests → more threads, server overload
- Solution: thread pool
  - Pre-create a number of threads waiting for work
  - Wake up thread to serve user request – faster than thread creation
  - When request done, don't exit – go back to pool and wait
  - Limits the max number of threads
- Your YFS server will have thread pools
- Apache supports thread (and process) pools

Today

- Processes
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- Threads
- Thread synchronization

The Problem

- Memory is shared across all threads
- Hence threads must coordinate so as to update shared memory correctly

Banking Example

```
int balance = 1000;
int main() {
    pthread_t t1, t2;
    pthread_create(&t1, NULL, withdraw, (void*)800);
    pthread_create(&t2, NULL, withdraw, (void*)800);
    pthread_join(t1, NULL);
    pthread_join(t2, NULL);
    printf(“All done: balance is $%d\n”, balance);
    return 0;
}

void* withdraw(void *arg) {
    int amount = (int)arg;
    if (balance >= amount) {
        balance -= amount;
        printf(“ATM gives user $%d\n”, amount);
    }
}
```

Imagine that these threads are created in response to requests from ATM machines

What are possible results?

Results of Banking Example

$ gcc –Wall –lpthread –o bank bank.c

$ ./bank
ATM gives user $800 Result 1
All done: balance is $200

$ ./bank
ATM gives user $800
ATM gives user $800 Result 2
All done: balance is $-600

How are each of these achieved?

$ ./bank
ATM gives user $800
ATM gives user $800 Result 3
All done: balance is $200

Schedule 1 (for Result 1)

Thread 1	Thread 2
if (balance >= amount)	
register = balance - amount;	
balance = register	
	if (balance >= amount)
	register = balance - amount;
	balance = register

time

Schedule 2 (for Result 2)

Thread 1	Thread 2
if (balance >= amount)	
	if (balance >= amount)
register = balance - amount;	
balance = register	
	register = balance - amount;
	balance = register

time

Schedule 3 (for Result 3)

Thread 1	Thread 2
if (balance >= amount)	
	if (balance >= amount)
register = balance - amount;	
	register = balance - amount;
balance = register	
	balance = register

time

Race Conditions

- Definition: a timing dependent error involving shared state
- Can be very bad
  - "Non-deterministic:" don't know what the output will be, and it is likely to be different across runs
  - Hard to detect: too many possible schedules
  - Hard to debug: debugging changes timing so hides bugs ("heisenbug")

Synchronization Mechanisms

- Multiple mechanisms, each solving a different problem
  - Locks
  - Condition variables
  - Semaphores
  - Monitors
  - Barriers

We'll cover here briefly (Locks, Condition variables)

Read in OS textbook or lectures: http://www.cs.columbia.edu/~junfeng/12sp-w4118/lectures/l09-lock.pdf, http://www.cs.columbia.edu/~junfeng/12sp-w4118/lectures/l10-semaphore-monitor.pdf) (Semaphores, Monitors, Barriers)

- Synchronization – both local and distributed – is used pervasively in distributed systems
  - Will use synchronization mechanisms in most labs
  - Will build distributed locking for Lab 1
  - MapReduce uses barriers to synchronize threads
  - …

Locks

- Locks allow only one thread to pass through a “critical section” at any time
  - **lock**(**l**): acquire lock exclusively; wait if not available
  - **unlock**(**l**): release exclusive access to lock

```
pthread_mutex_t   l = PTHREAD_MUTEX_INITIALIZER;
 void* withdraw(void *arg) {
     int amount = (int)arg;
     pthread_mutex_lock(l);
     if (balance >= amount) {
         balance -= amount;
         printf(“ATM gives user $%d\n”, amount);
     }
     pthread_mutex_unlock(l);
 }
```

What’s the problem now?

Common Pitfalls

- Wrong lock granularity
  - Too small granularity leads to races
  - Too large granularity leads to bad performance
- Deadlocks
  - Better bugs than race
- Starvation
- Discussion of each is subject of another course…

Processes, Threads, and Coordination in Distributed Systems

- All these topics are extremely relevant for distributed systems
  - Every server is multi-threaded
  - Servers need to coordinate, and they do so using similar methods as IPC, shared memory, locking, barriers, etc.

- In distributed systems, a process is often times called a "task" (unit of processing)
- A program is often times called a "job"

Next Time

- Inter-machine communication
  - Remote procedure calls
  - Semantics and complexities of RPCs

Appendix

Cool Process Internals: Copy-on-Write (CoW)

- CoW is a useful, general technique that shows up all over in systems
  - Mark parents' memory read-only
  - Have child *share* parents memory instead of copying
  - If either one writes -- hey, it was read only! (CPU will raise an exception)
    - *Now* give the child its own copy of the page of memory someone was writing