Systems Fundamentals

SWE 622, Spring 2017
Distributed Software Engineering

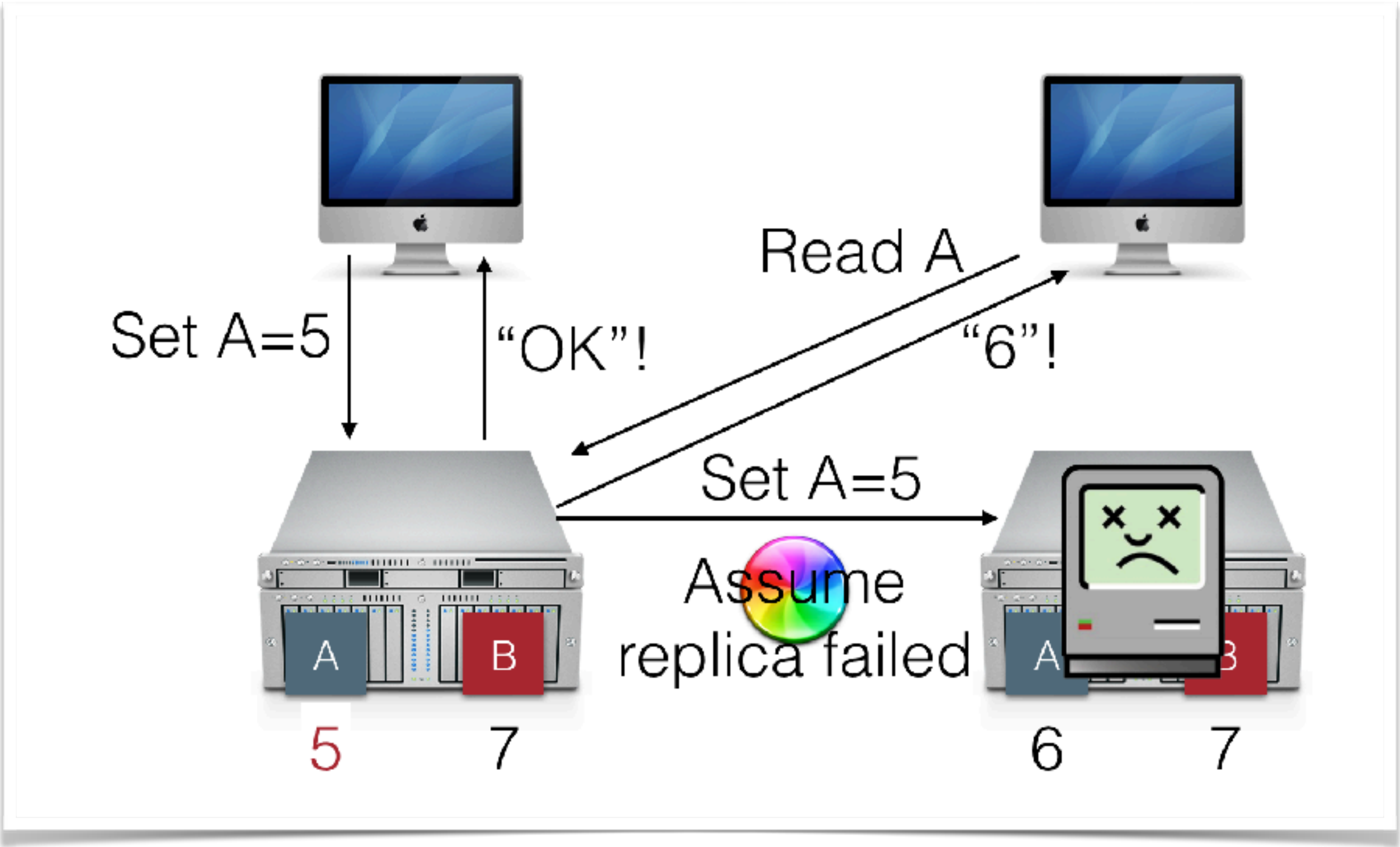
Review

- Why deal with distributed systems?
  - Scalability
  - Performance
  - Latency
  - Availability
  - Fault Tolerance

Review

- More machines, more problems
  - Replication solves everything, and makes everything a lot worse
- CAP Theorem
  - Consistency, Availability, Partition Tolerance

CAP Theorem



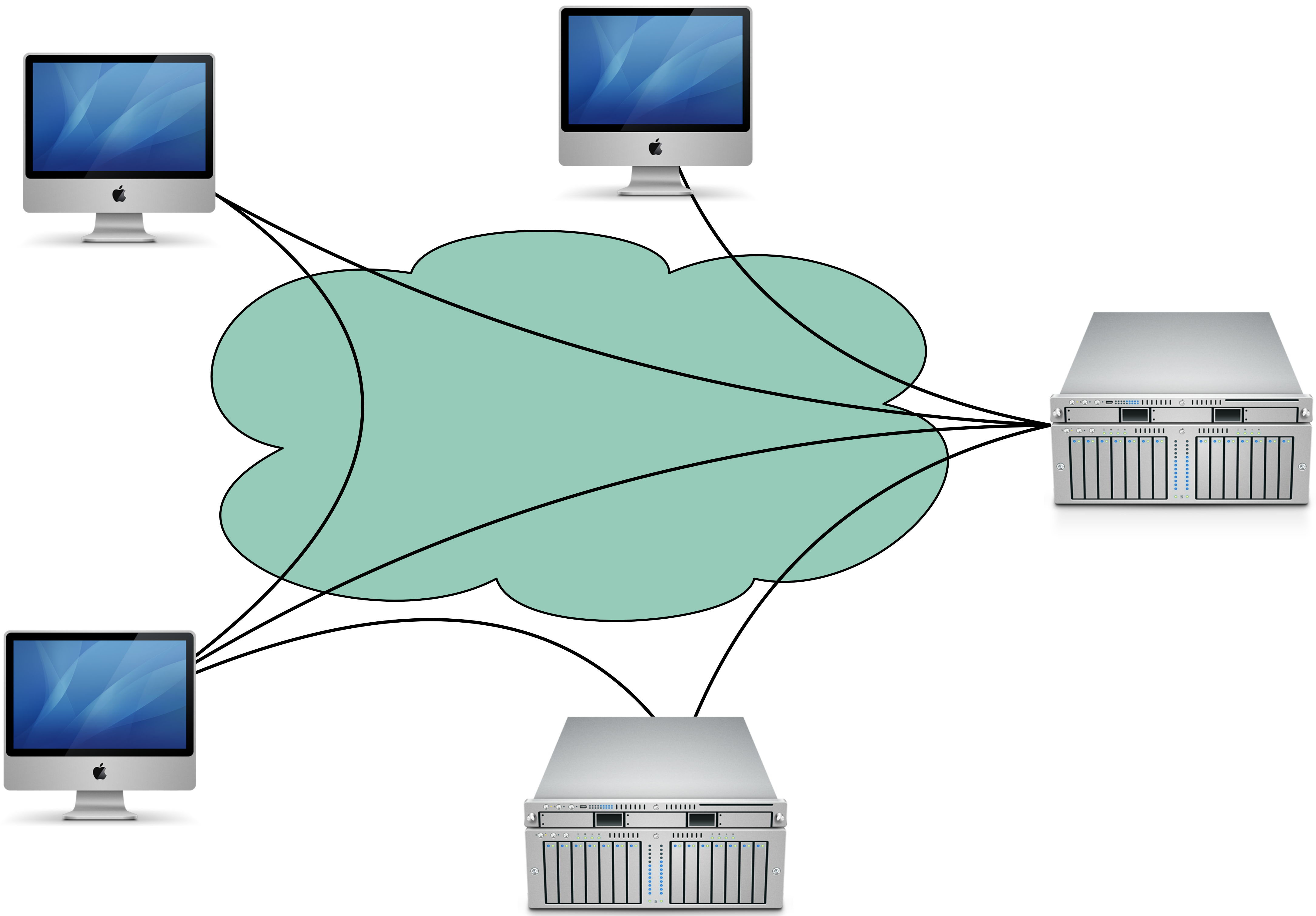
Review: HW1

- Building a cache in front of a filesystem
- In Java
- Tricky part:
  - Consistency (multiple processes can access filesystem at once)

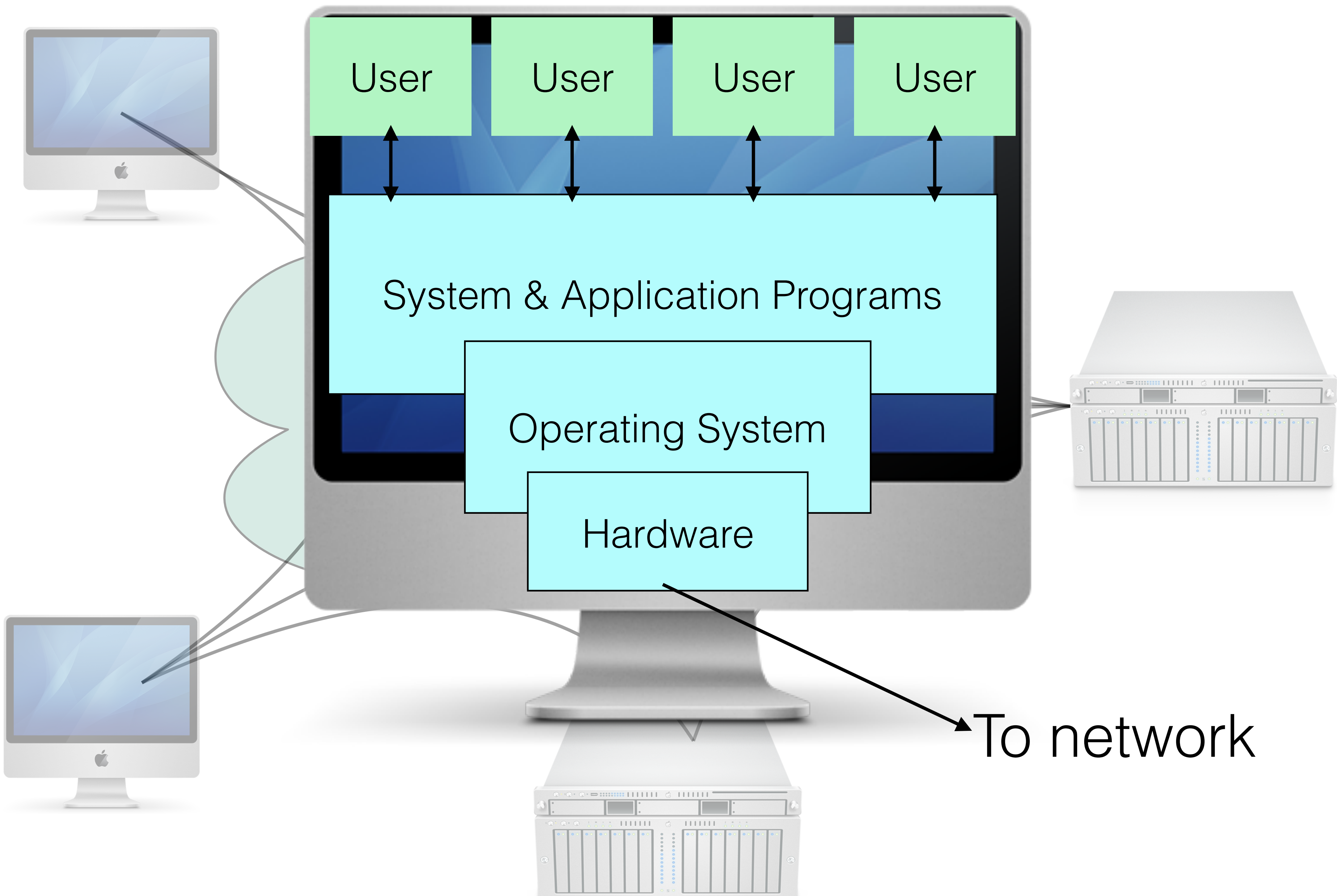
Today

- Systems fundamentals and abstractions
- Synchronization + Critical Section Problem
- A ton of Java
- Some tips to get you through HW1
- Resources:
  - http://winterbe.com/posts/2015/04/07/java8-concurrency-tutorial-thread-executor-examples/
  - http://docs.oracle.com/javase/7/docs/api/java/util/concurrent/locks/Lock.html
  - http://stackoverflow.com/questions/2536692/a-simple-scenario-using-wait-and-notify-in-java
  - https://developers.google.com/protocol-buffers/

Today



Today


User
User
User
User
System & Application Programs
Operating System
Hardware
To network

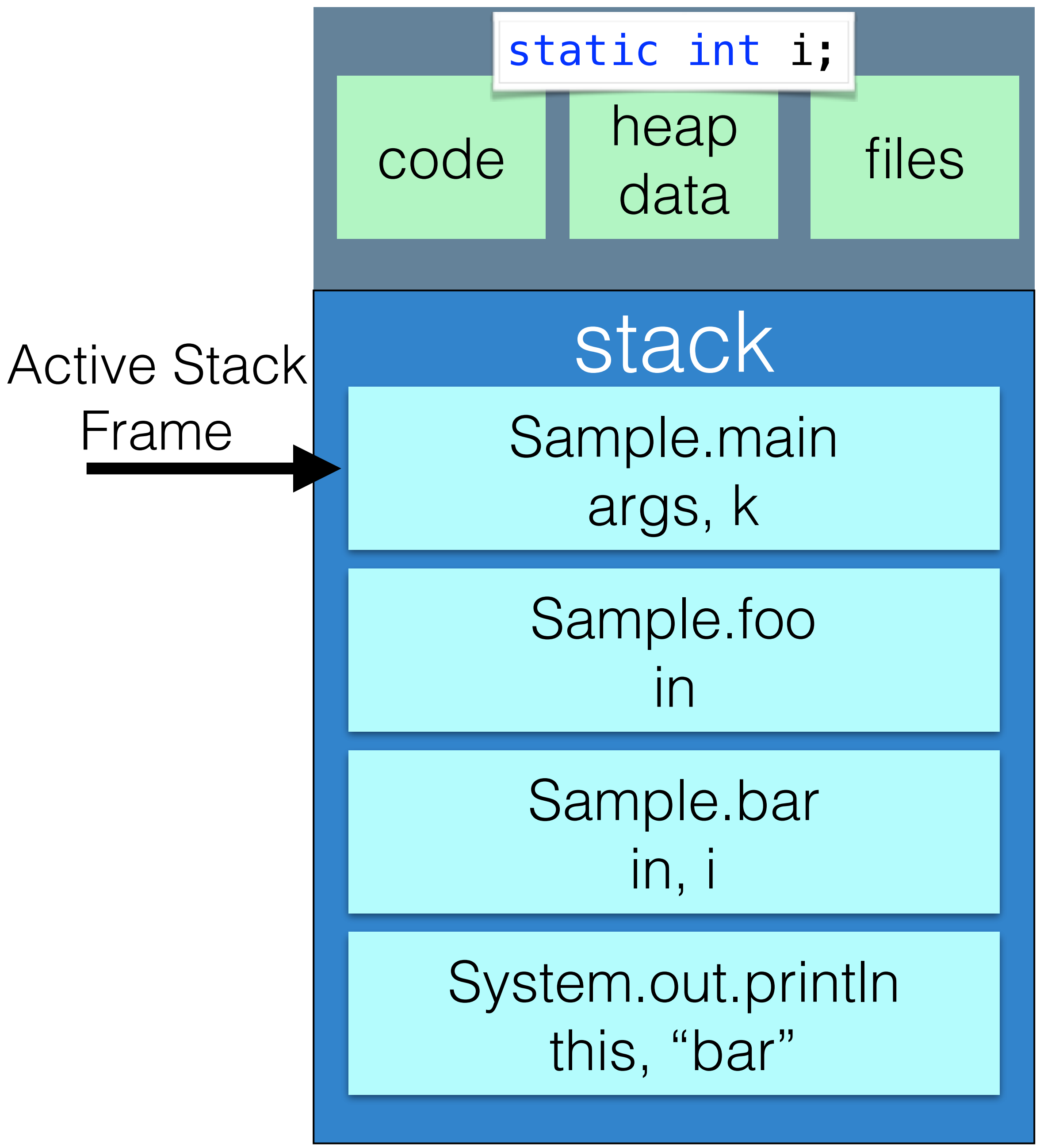
The role of the Operating System

- Mediates access to hardware from many simultaneous processes
- Manages resources
  - CPU, network, memory, storage, etc
- Receives requests from processes to access resources, provides responses

Processes

- What's a process?
    - Some program that is executing; execution is always sequential
- Represented as:
    - Code
    - Program counter (position in code)
    - Stack
    - Heap
- A program is what we store on disk: can run a program more than once simultaneously: multiple processes
- By default, hard to communicate

Processes




```java
public class Sample
{
    static int i;
    public static void main(String[] args)
    {
        int k = 10;
        foo(k);
    }
    public static void foo(int in)
    {
        bar(in);
    }
    public static void bar(int in)
    {
        i = in;
        System.out.println("bar");
    }
}
```

Java: Heap vs Stack

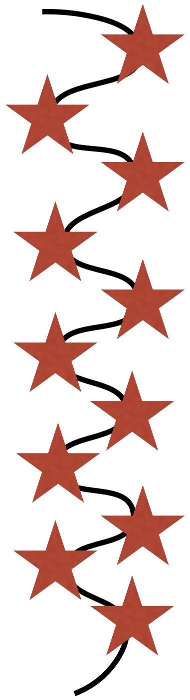
- Stack contains local variables and method arguments
- Heap contains everything else
- Stack might contain pointers to the heap

```java
public class Sample
{
    static int i;
    static String str = "myString";
    public static void main(String[] args)
    {
        int k = 10;
        String stackPointer = str;
        foo(k);
    }
    public static void foo(int in)
    {
        bar(in);
    }
    public static void bar(int in)
    {
        i = in;
        System.out.println("bar");
    }
}
```

Threads

Program execution: a series of sequential method calls (★s)

App Starts



App Ends

Threads

Program execution: a series of sequential method calls (★s)

App Starts

App Ends

Multiple threads can run at once -> allows for asynchronous code

What do we use threads for?

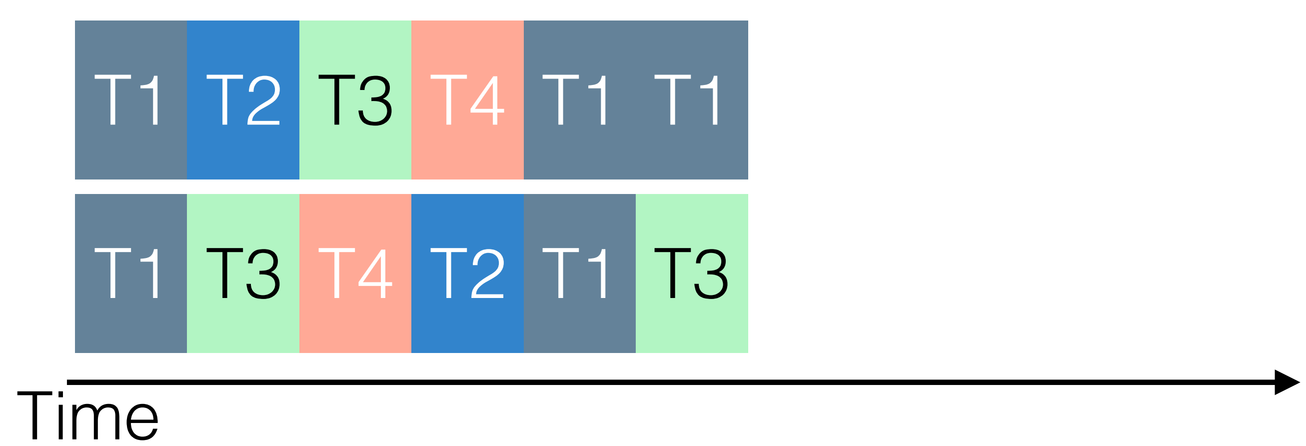
- Run multiple tasks seemingly at once
  - Update UI
  - Fetch data
  - Respond to network requests
- Process creation: heavyweight, thread creation: lightweight
- Improve responsiveness, scalability
- Concurrency + Parallelism

Concurrency vs Parallelism

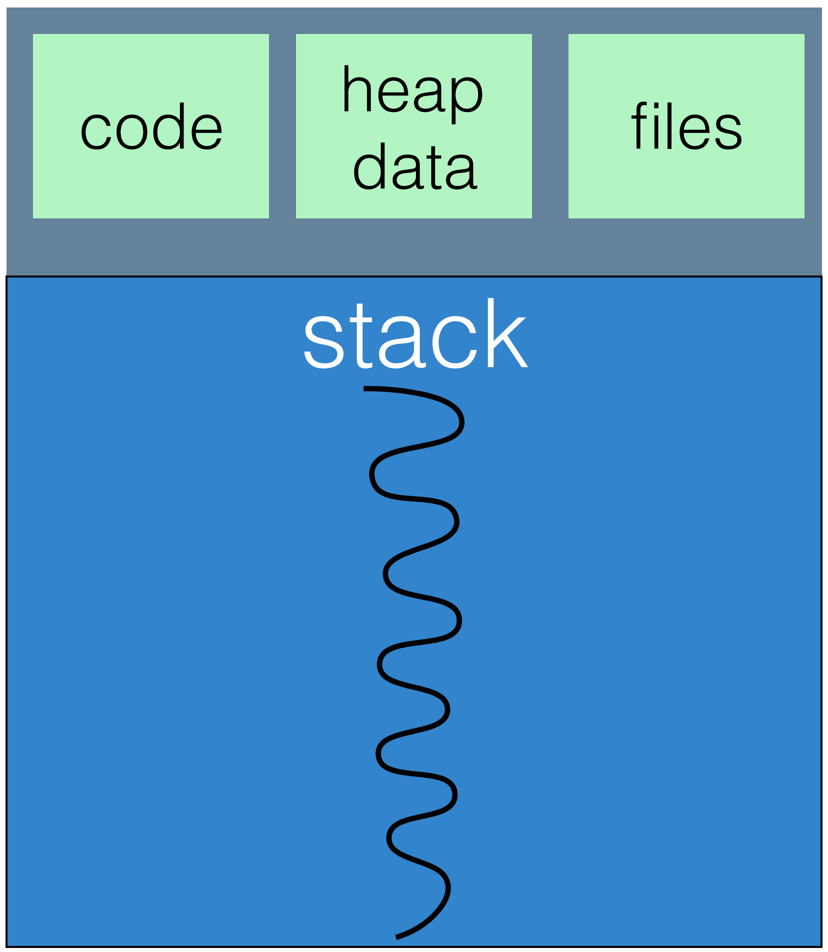
4 different threads: T1 T2 T3 T4

Concurrency:
(1 processor)

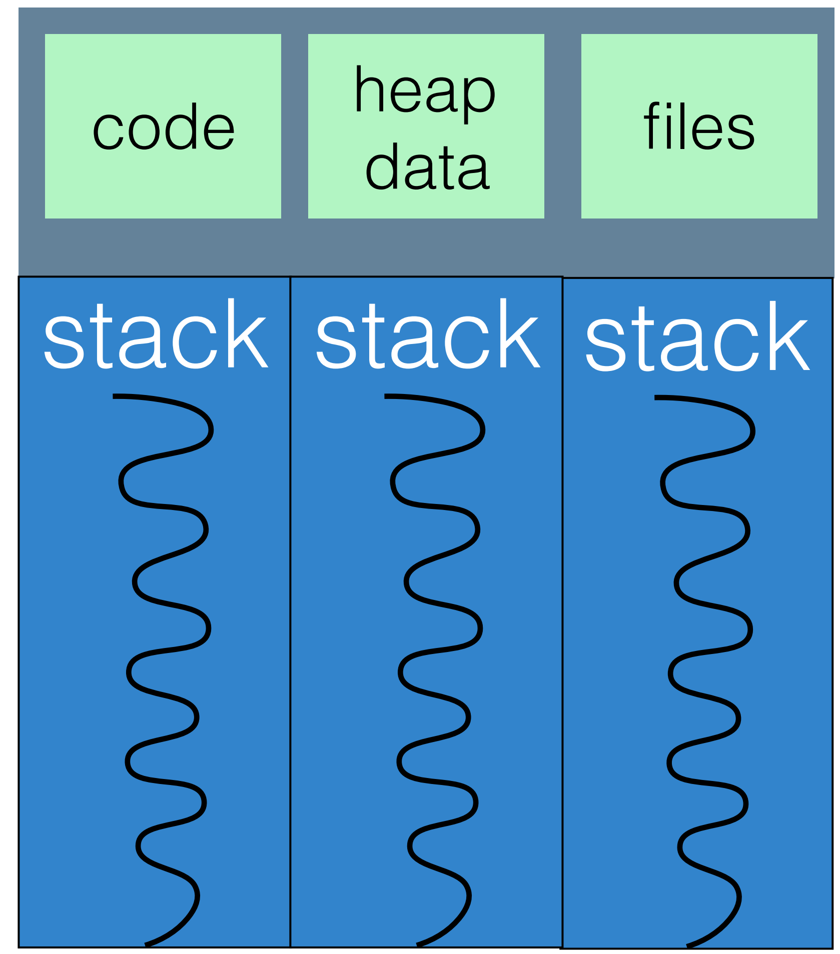
Parallelism:
(2 processors)



Threads: Memory View



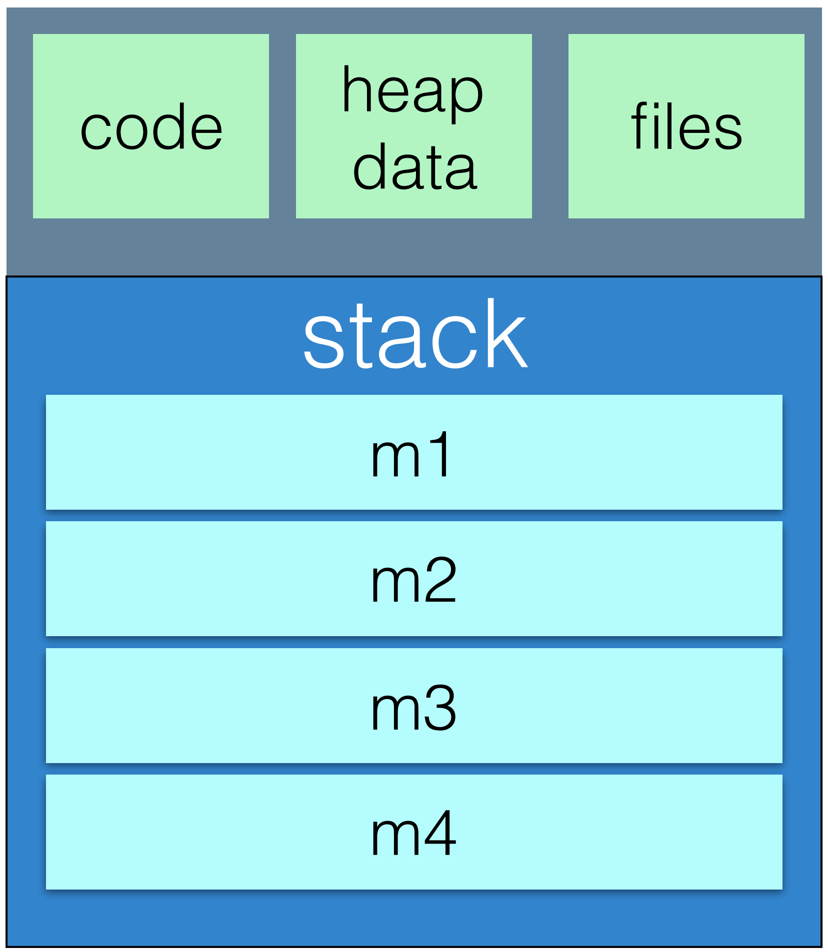
Single-Threaded Process



Multi-Threaded Process

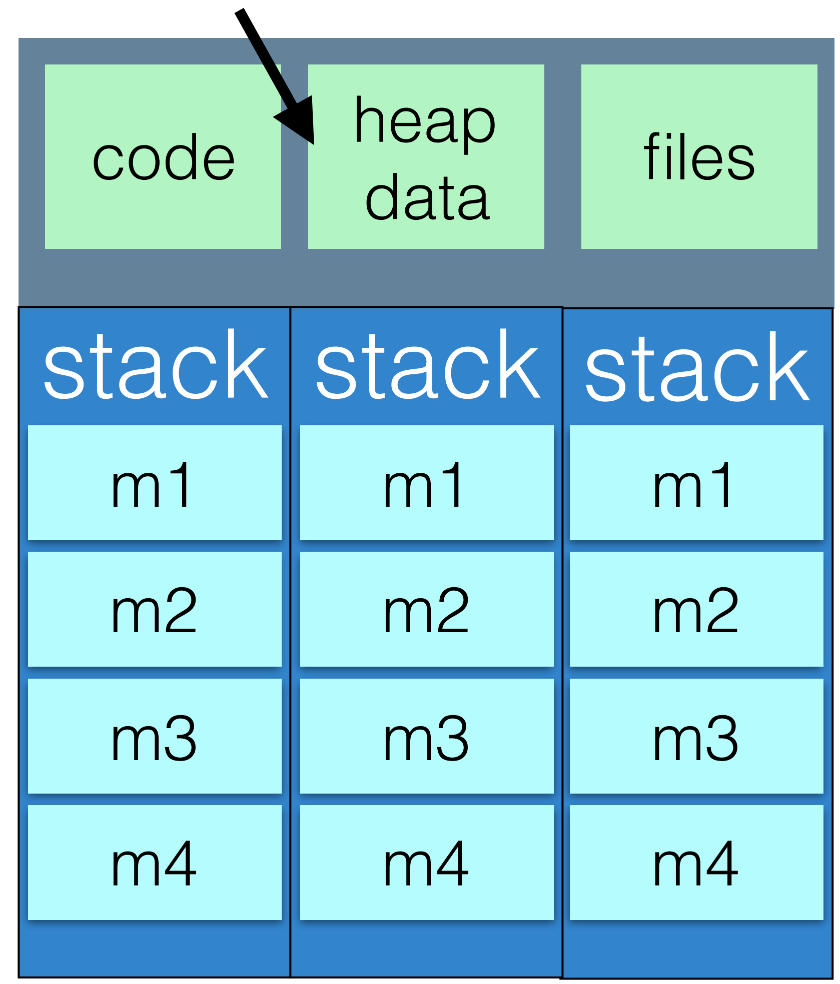
Each thread has its own stack

Threads: Memory View



Single-Threaded Process

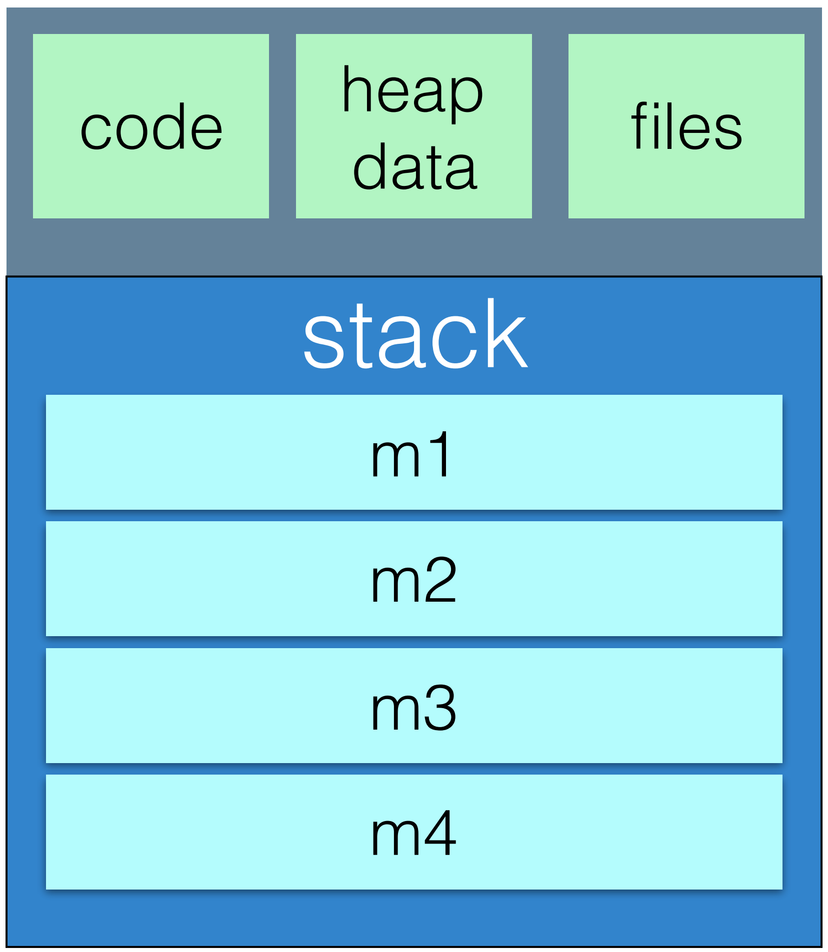
Heap data: still shared between threads



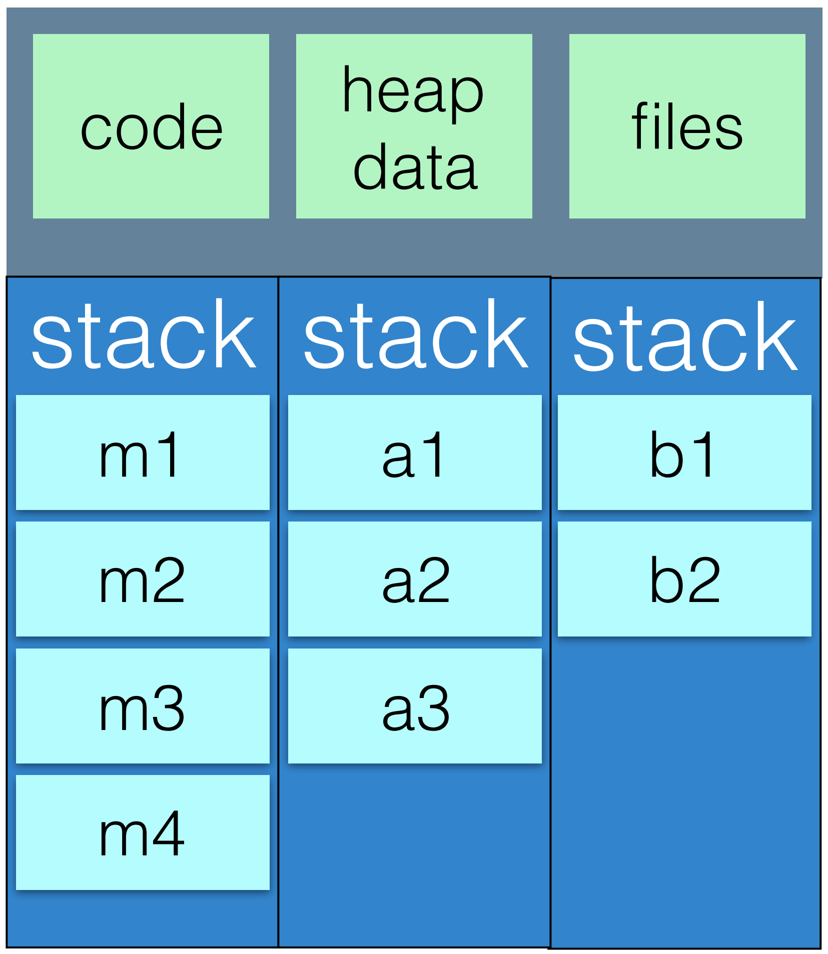
Multi-Threaded Process

Each thread might be executing the same code, but with different local variables (and hence doing different stuff)

Threads: Memory View



Single-Threaded Process



Multi-Threaded Process

Each thread might be executing totally different code, too

How to split up the work

- **Data parallelism** - distribute subsets of same data across multiple cores, perform same operation on each
- **Task parallelism** - distribute multiple threads, each thread performs a different operation
- In either case, there is some need to coordinate and share data between threads

Threads in Java

- In Java, make a new thread by instantiating the class java.lang.Thread
- Pass it an object that implements *Runnable*
- When you call thread.start(), the run() method of your runnable is called, from a new thread
- join() waits for a thread to finish

```
Thread t = new Thread(new Runnable() {
 @Override
   public void run() {
    //This code will now run in a new thread
   }
});
t.start();
```

Threads in Java

```
public static void main(String[] args) throws InterruptedException {
  Thread t = new Thread(new Runnable() {
      @Override
      public void run() {
        //This code will now run in a new thread
        System.out.println("Hello from the thread!");
      }
    });
    t.start();
    System.out.println("Hello from main!”);
    t.join();
}
```

What is the output of this code?

#1 Hello from the thread!
Hello from main!

This is a race condition

#2 Hello from main!
Hello from the thread!

Race Conditions

```
static int i = 0;
public static void increment()
{
    i = i + 1;
}
```

Thread 1	Thread 2
increment()	increment()
read i = 0	
write i = 1	read i = 0
	write i =1

Critical Section Problem

- Each thread/process has some *critical section* of code that:
  - Changes shared variables, files etc
  - When one thread/process is in a critical section, no other may be in the same critical section
- Critical section problem: design a protocol to solve this
- Each process/thread asks for permission to enter critical section, does its work, then exits the section

Critical Section in increment()

```
static int i = 0;
public static void increment()
{
    enterSection();
    i = i + 1;
    exitSection();
}
```

Only one thread can read/write i at once

But how to implement enterSection() and exitSection()?

Solution to Critical-Section Problem

- Need to guarantee **mutual exclusion**
  - If one thread/process is executing its critical section, no other can execute in their critical sections
- Need to guarantee **progress:**
  - If no process is executing in its critical section, and some other would like to, then some process must be allowed to continue
- Need to guarantee **bounded waiting:**
  - If some process wants to enter its critical section, it must eventually be granted access

Peterson's Solution

- Simple algorithm that solves critical section problem
- Requires two variables: `int turn`, `boolean flag[]`
- `turn` indicates which process can enter the critical section
- `flag` is an array indicating which process is ready to enter its critical section, `flag[i] = true` means P_i is ready to enter its critical section

Peterson's Solution

Algorithm for P_i

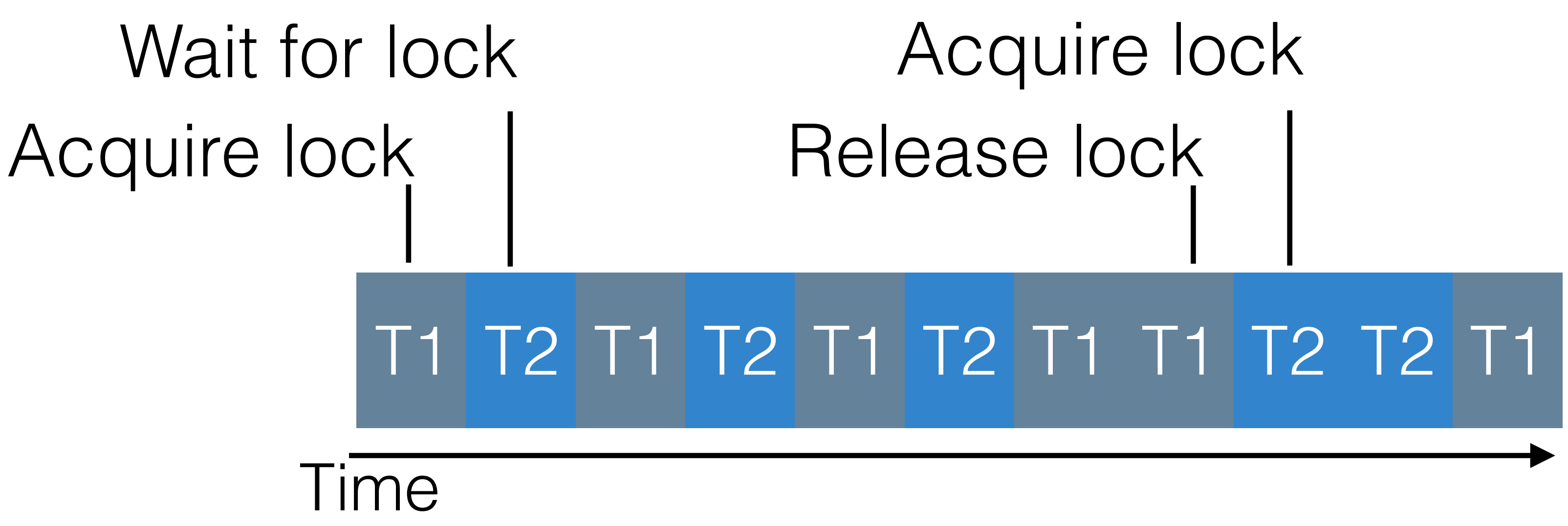
```
while(true) {
    flag[i] = true;
    turn = j;
    while(flag[j] && turn == j); //wait if j is in its critical section
    //critical section
    flag[i] = false; //signal we are done
    //do anything else that is not in critical section
}
```

"Busy waiting"

Problem: Inefficient - this thread keeps checking flag[], preventing other things from running on your CPU

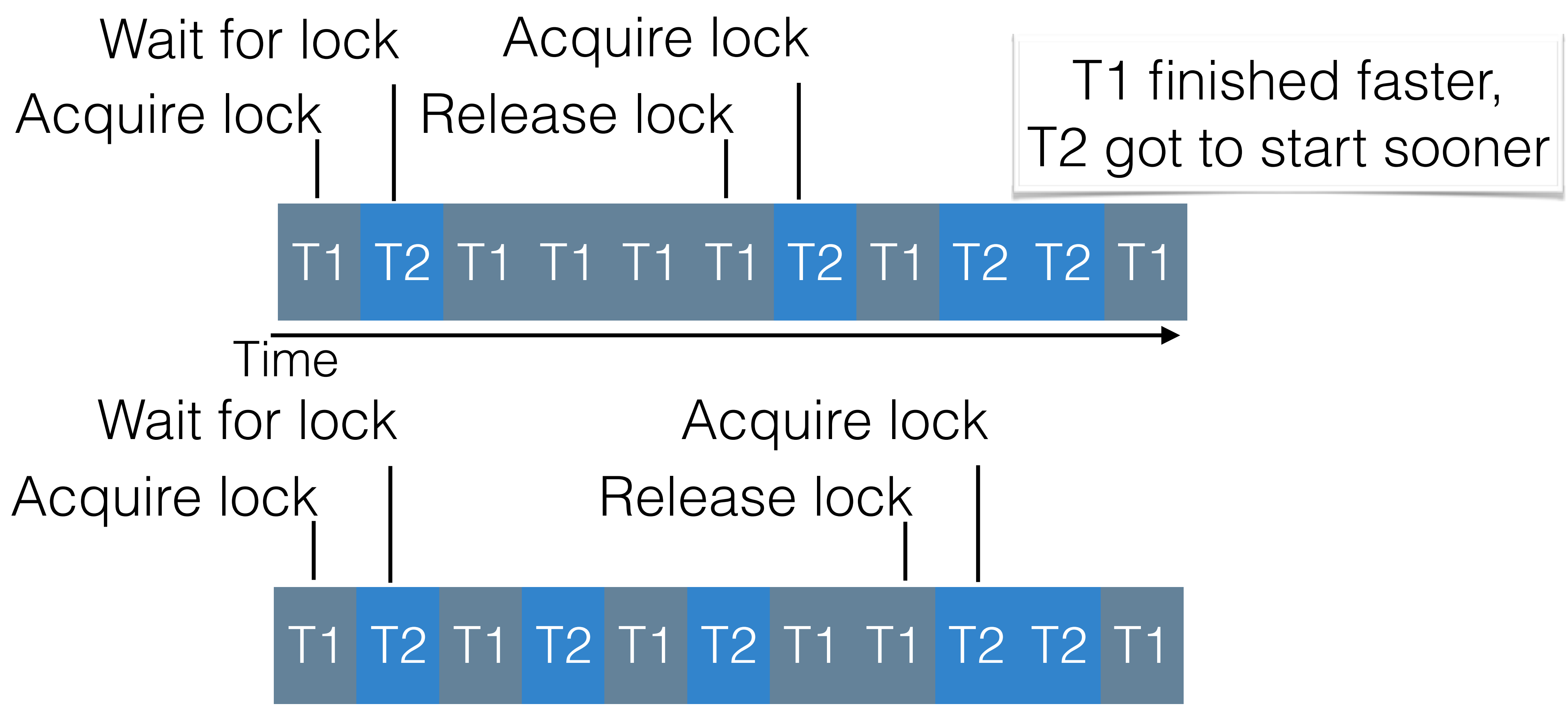
Busy Waiting

```
while(true) {
    flag[i] = true;
    turn = j;
    while(flag[j] && turn == j); //wait if j is in its critical section
    //critical section
    flag[i] = false; //signal we are done
    //do anything else that is not in critical section
}
```



Locks

- Most systems have some hardware support for implementing this, based on **locks**
- This tells the OS and processor that when a thread is waiting for a lock, **not to bother running it** until it can receive the lock



Deadlocks & Starvation

- Starvation: one or more threads are blocked from gaining access to a resource, and hence, can't make progress
- Deadlock: Two or more threads are waiting for the others to do something
    - T1: Has lock 1, needs lock 2
    - T2: Has lock 2, needs lock 1
    - Hence, neither T1 nor T2 can execute

Locking in Java

- Most locks are *reentrant*: if you hold it, and ask for it again, you don't have to wait (because you already have it)
- Basic primitives:
  - `synchronized{}`
  - `wait`
  - `notify`
- Plus…
  - `Lock` API… `lock.lock()`, `lock.unlock()`
  - The *preferred* way

Synchronized methods in Java

```java
public synchronized static void increment()
{
    i = i + 1;
}
```

Result: Before entering **`increment()`**, thread gets a lock on the Class object of **`increment()`**

wait and notify()

- Two mechanisms to enable coordination between multiple threads using the same monitor (target of synchronized)
- While holding a monitor on an object, a thread can **wait** on that monitor, which will temporarily release it, and put that thread to sleep
- Another thread can then acquire the monitor, and can **notify** a waiting thread to resume and re-acquire the monitor

wait and notify() example

Only one thread can be in put or take of the same queue

```
public class BlockingQueue<T> {

    private Queue<T> queue = new LinkedList<T>();
    private int capacity;

    public BlockingQueue(int capacity) {
        this.capacity = capacity;
    }

    public synchronized void put(T element) throws InterruptedException {
        while(queue.size() == capacity) {
            wait();
        }

        queue.add(element);
        notify(); // notifyAll() for multiple producer/consumer threads
    }

    public synchronized T take() throws InterruptedException {
        while(queue.isEmpty()) {
            wait();
        }

        T item = queue.remove();
        notify(); // notifyAll() for multiple producer/consumer threads
        return item;
    }
}
```

Synchronized methods in Java

```
public synchronized static void increment()
{
    i = i + 1;
}
```

Result: Before entering **`increment()`**, thread gets a lock on the Class object of **`increment()`**

```
public synchronized static void incrementOther()
{
    j = j + 1;
}
```

Result: Before entering **`incrementOther()`**, thread gets a lock on the Class object of **`incrementOther()`**

Problem?

Synchronized blocks in Java

- Can also use *any* object as that monitor

```
static Object someObject = new Object();
public static void increment()
{
    synchronized(someObject){
        i = i + 1;
    }
}
static Object someOtherObject = new Object();
public static void incrementOther()
{
    synchronized(someOtherObject){
        j = j + 1;
    }
}
```

Now, two different threads could call **`increment()`** and **`incrementOther()`** at the same time

Java Lock API

- `Synchronized` gets messy: what happens when you need to synchronize many operations? What if we want more complicated locking?
- `ReentrantLock`: same semantics as synchronized
- `ReadWriteLock`: allows many readers simultaneously, but writes are exclusive

```
static ReentrantLock lock = new ReentrantLock();
public static void increment()
{
    lock.lock();
    try{
        i = i + 1;
    } finally{
        lock.unlock();
    }
}
```

Java Lock API

```
static ReadWriteLock lock = new ReentrantReadWriteLock();
static int i;
public static void increment()
{
    lock.writeLock().lock();
    try{
        i = i + 1;
    } finally{
        lock.writeLock().unlock();
    }
}
public static int getI()
{
    lock.readLock().lock();
    try{
        return i;
    } finally{
        lock.readLock().unlock();
    }
}
```

Locking Granularity

- BIG design question in writing concurrent programs: how many locks should you have?
- Example: Distributed filesystem
  - It would be *correct* to block all clients from reading *any* file, when one client writes a file
  - However, this would not be performant at all!
  - It would be much better to instead lock on *individual files*
- More locks -> more complicated semantics and tricky to avoid deadlocks, races

I/O

- OS manages all access to network, filesystem, memory
- I/O is typically *synchronous*
    - Program requests some I/O, then waits
    - Eventually, the I/O completes, and the program resumes
- Storage hierarchy:
    - Main memory
    - SSD
    - Magnetic (hard disks)
    - Network
- Exposed interfaces: files (local), sockets (remote hosts)

Nonblocking & Asynchronous I/O

- Blocking: Your thread is suspended until I/O is completed (e.g. read(), write() are not instantaneous so you wait)
- Nonblocking: I/O calls return only as much as they can
    - select() to find if there is data then read() or write() it if it’s there
- Asynchronous: Process runs while I/O occurs
    - Can be very tricky to do correctly

Files

- File:
  - Name
  - Size (bytes)
  - Create/Access/Modification Time
  - Contents (binary)
- Directory:
  - Maintains a list of the files (and their metadata) in that directory

File Operations

- Create
- Read, Write
  - OS normally provides this functionality with small buffers, CFS simplifies this for you to read/write an entire file at once
- Delete
- Truncate
  - CFS simplifies this by turning it into a write with no contents
- Open, close file
- Open, close directory

Open file locking

- When a file is opened, it can *also* be locked on
- In CFS (the homeworks for this course), opening a file will *always* acquire a lock in the following ways:
    - Several processes can read a file concurrently
    - Only one process can write a file at a time; no process can read that file simultaneously

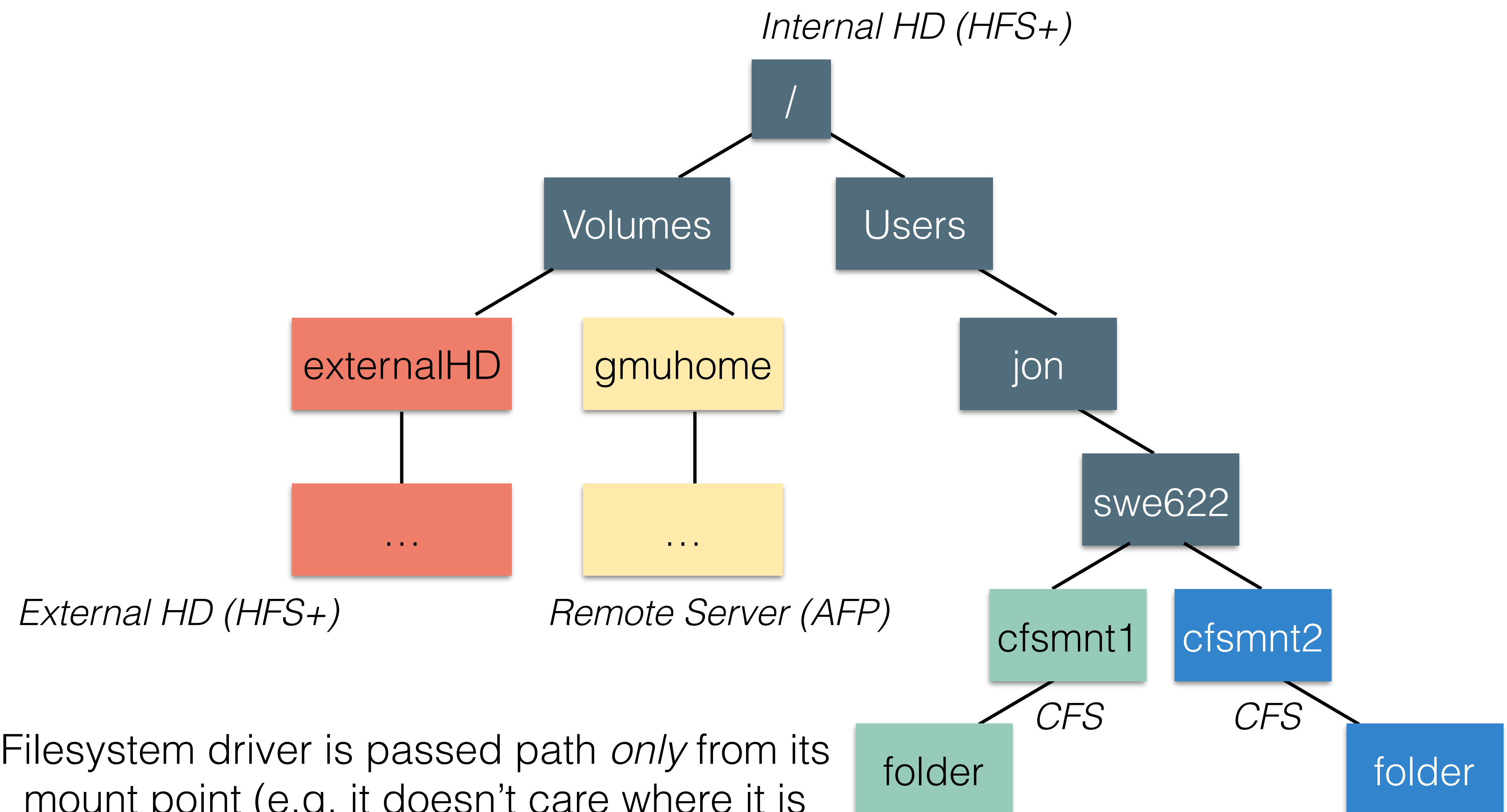
Directory Structure

- Directories contain information about the files in them
- Directories can be nested
- Operations on directories:
  - Create file
  - List files
  - Delete file
  - Rename file

Filesystems

- Define how files and directory structure is maintained
- Exposes this information to the OS via a standard interface (driver)
- OS can provide user with access to that filesystem when it is **mounted**
- (Example: NFS, AFP, SMB… CFS)

Mounting Filesystems



Filesystem driver is passed path *only* from its mount point (e.g. it doesn't care where it is mounted)

Sockets

- Basic abstraction for network communication
- Server socket: listens on an IP Address + network port
- Client socket: connects to some IP address + network port

TCP & UDP

- The two underlying protocols that almost every network are built upon
- TCP: server acknowledges receipt of packet to client
- UDP: no acknowledgement -> less overhead, less reliable
- Note: TCP doesn't guarantee your message will get there - just that you will probably know if it doesn't

Sockets in Java

- java.net.Socket: client TCP socket
- java.net.ServerSocket: server TCP socket
    - Server listens for connections, client establishes them
- java.net.DatagramSocket: UDP socket
    - UDP is connectionless, so no difference between client/server

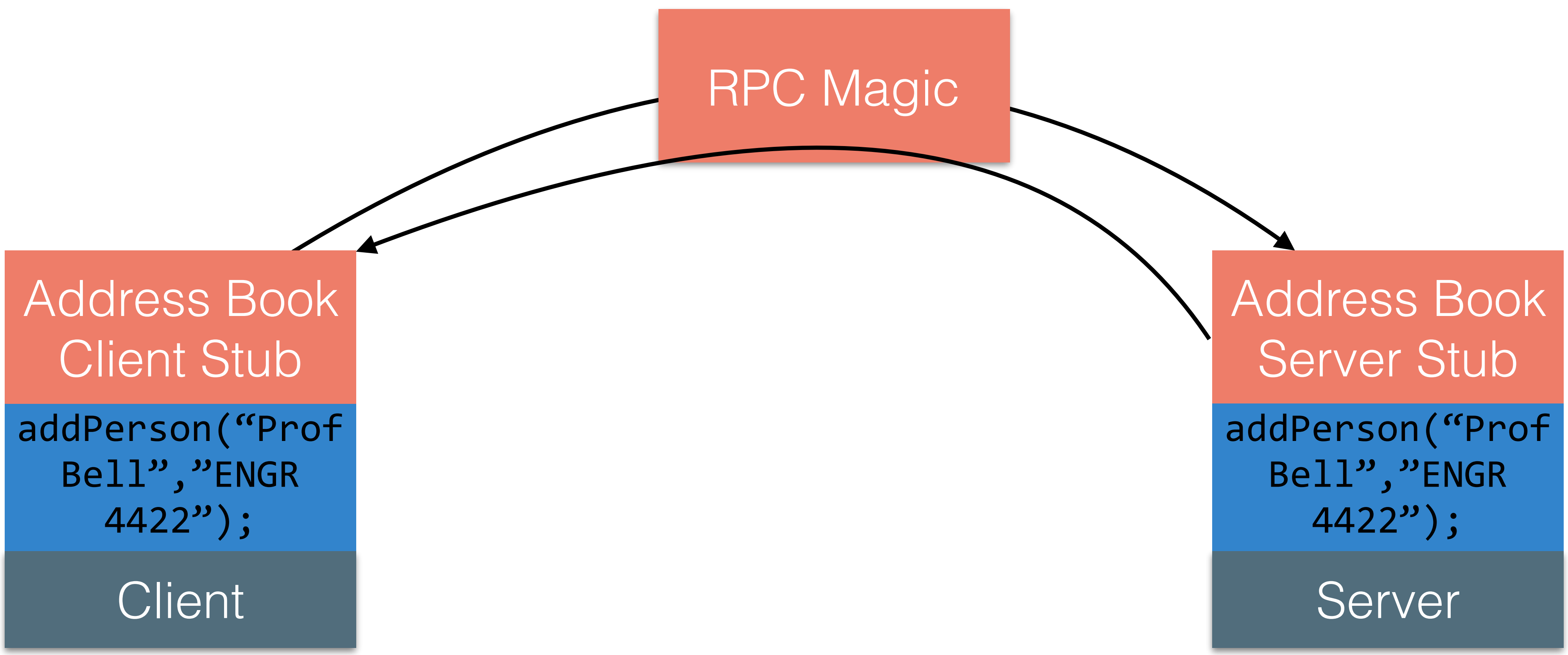
Abstractions

- Using sockets directly is annoying - very low level, likely someone else already figured out a way to solve your problem and their fix is bug free
- High level protocols:
  - FTP, SMTP
  - HTTP (REST, SOAP and other web service stuff)
- For general purpose, lower level:
  - RPC - Remote Procedure Call, and for Java: RMI - Remote Method Invocation
  - Language agnostic: Google ProtocolBuffers

Remote Procedure Calls

- Example: Address book
- We’ll store our address book on a server
- But to simplify writing the code, can we pretend that the address book is stored on the client?
- RPC
  - Client program will think it’s directly talking to the server
  - Server program will think it’s directly talking to the client
  - In reality, there’s a ton of glue in between them

Remote Procedure Calls



RPC Magic

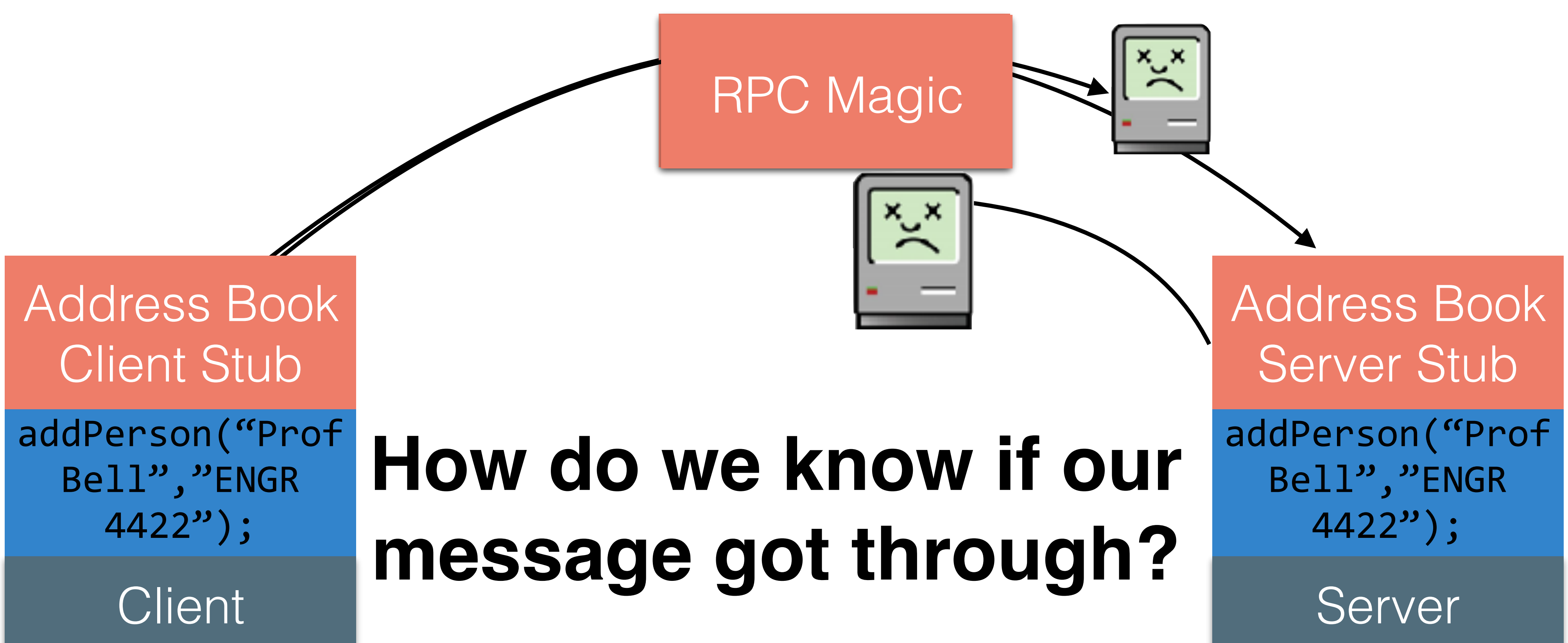
- RPC generates these stubs based on an *interface* that you define
- Many RPC implementations: RMI, CORBA, COM, SOAP
- With Java RMI, we define that interface as literally, an interface, which extends *Remote*
- Java RMI can pass any Java object that is *Serializable*
- In general, deciding how to convert application data into bytes to send over the network is tricky

RPC Challenges

- Communications failures
    - Delayed, lost messages, connection resets
- Machine Failures
    - Server or client fails
    - Was request processed?
- How can we tell if a request was processed?

RPC Challenges

- How do we know that our remote call succeeded?
  - With "call and return" style (as in example) we wait for a response. What if it doesn't come?

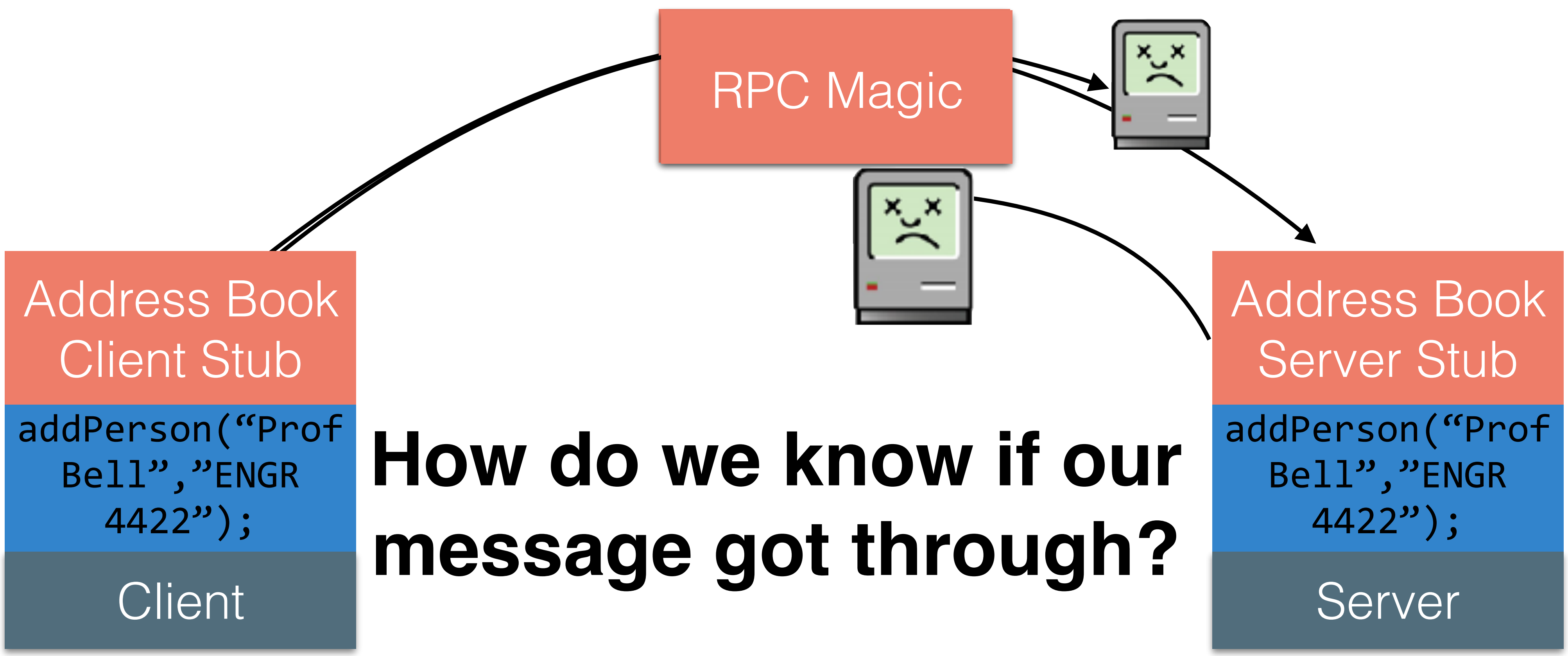


Delivery Semantics

- At least once:
  - Keep sending your call until you hear a response
  - If a failure is transient, then you'll eventually get your message delivered (at least once)
- At most once:
  - Send it once. Hopefully it works. If it didn't?
  - Tricky. Send some sequence number with each message. Server must guarantee it can keep track of all of the messages it received. Each duplicate message indicates what it is duplicating
- Exactly once:
  - Impossible
- The magic is not perfect :)

RPC Challenges

- How do we know that our remote call succeeded?
  - With "call and return" style (as in example) we wait for a response. What if it doesn't come?



How do we know if our message got through?

Message Formats

- Q: How can we make our RPC *cross platform* and *cross language*?
- A: Write our messages in XML/JSON
- Problem: slow, not very friendly
- Answers:
  - Protocol Buffers (Protobuf): efficient, binary, typed, cross platform/language, versioning support
  - Thrift: very similar to Protobuf, *also* provides an RPC implementation (protobuf is just message format)

Java RMI

- Synchronous (client method doesn’t return until server completes)
- At most once delivery
- Hence, in the event of a communication failure, an exception is thrown on your client
- Implications:
  - Client code needs to be aware that failures might happen (and exception might be thrown)
  - Client code needs to have some plan to handle when a message fails to get through (application specific)

Java RMI

- Threading model:
  - What happens when there are multiple simultaneous RMI requests to the same server?
- RMI creates a *thread pool*, a set of threads ready to handle each request
  - Subsequent calls from the same client might or might not use the same thread
  - Subsequent calls from other clients might use the same thread as others
- Implications:
  - Can process multiple requests simultaneously
  - Need to be cognizant of thread safety

Java RMI

```java
public interface AddressBook extends Remote {
   public LinkedList<Person> getAddressBook() throws RemoteException;

   public void addPerson(Person p) throws RemoteException;
}
```

```java
AddressBook book = new AddressBookServer();
AddressBook stub = (AddressBook) UnicastRemoteObject.exportObject(book, 0);
Registry registry = LocateRegistry.createRegistry(port);
registry.rebind("AddressBook", stub);
```

```java
Registry registry = LocateRegistry.getRegistry("localhost", 9000);
AddressBook addressBook = (AddressBook) registry.lookup("AddressBook");
```

Lab: RMI + Threading

Also: need to collect your GitHub IDs