Principles of Software Construction: Objects, Design and Concurrency

The Perils of Concurrency, Part 4 (Can't live with it, can't live without it.)

15-214

toad

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Administrivia

- Homework 5: The Framework Strikes Back
  - 5a presentations yesterday!

Key topics from Tuesday

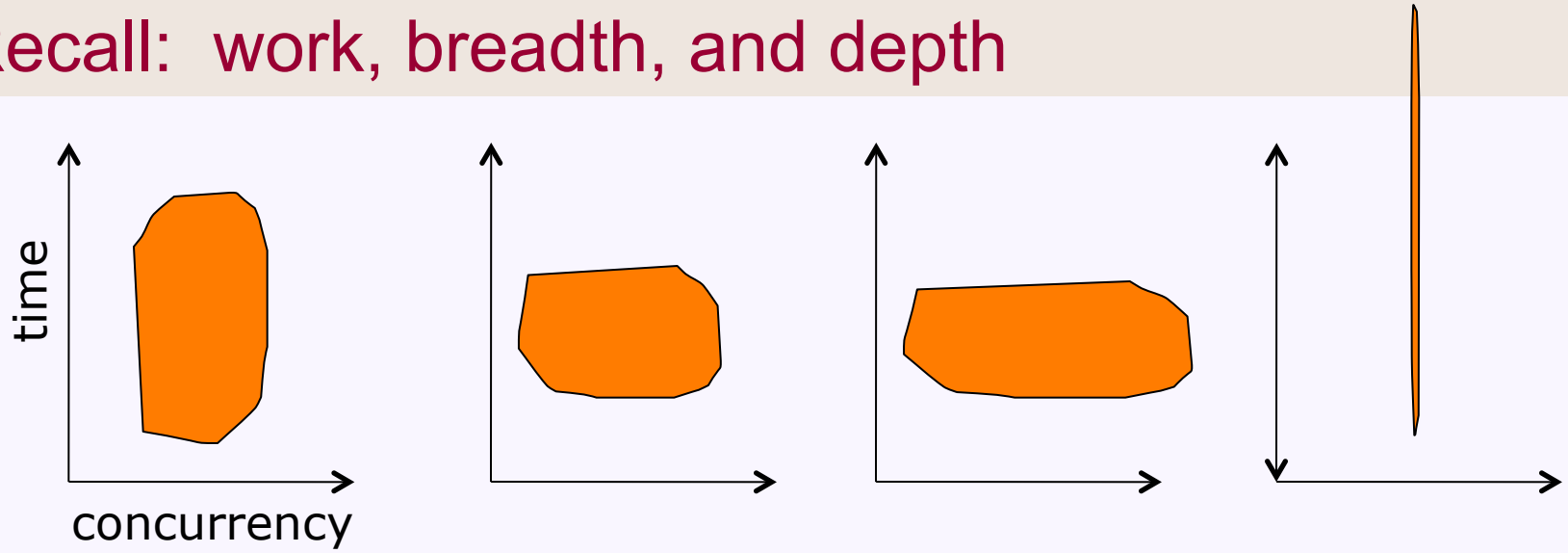
Today: In the trenches of parallelism

- A concurrent implementation of prefix-sums

Today: In the trenches of parallelism

- A concurrent implementation of prefix-sums
- Also: Java I/O fundamentals

Recall: work, breadth, and depth



- Work: total effort required
  - area of the shape
- Breadth: extent of simultaneous activity
  - width of the shape
- Depth (or span): length of longest computation
  - height of the shape

Prefix sums (a.k.a. inclusive scan)

- Goal: given array `x[0…n-1]`, compute array of the sum of each prefix of `x`

```
[ sum(x[0…0]),
  sum(x[0…1]),
  sum(x[0…2]),
  …
  sum(x[0…n-1]) ]
```

- e.g., `x = [13, 9, -4, 19, -6, 2, 6, 3]`

  prefix sums: `[13, 22, 18, 37, 31, 33, 39, 42]`

Parallel prefix sums

- Intuition: If we have already computed the partial sums `sum(x[0…3])` and `sum(x[4…7])`, then we can easily compute `sum(x[0…7])`
- Code:

```
prefix_sums(x):
  for d in 0 to (lg n)-1:              // d is depth
    parallelfor i in 2^d to n-1:
      newx[i] = x[i-2^d] + x[i]
    x = newx
```

- How good is this?

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- How good is this?
  - Work: O(n lg n)
  - Depth O(lg n)

A better parallel prefix sums algorithm

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- Code:

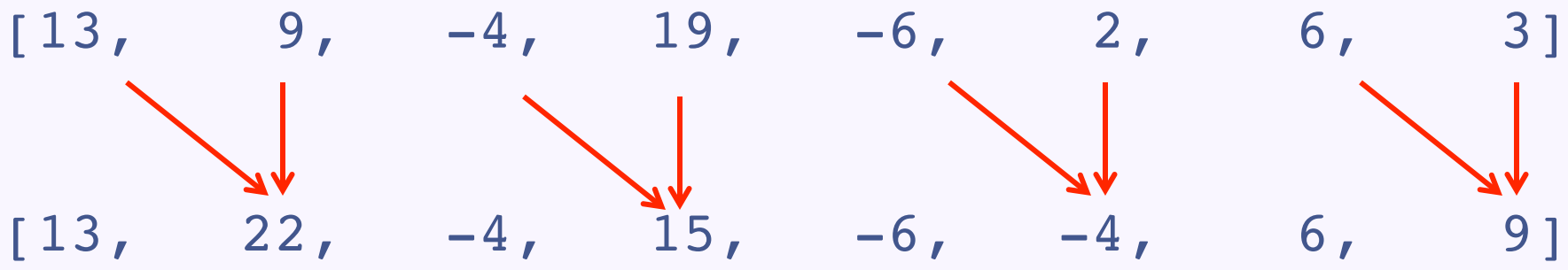
```
prefix_sums(x):
  for d in 0 to (lg n)-1:              // d is depth
    parallelfor i in 2^d-1 to n-1, by 2^(d+1):
      x[i+2^d] = x[i] + x[i+2^d]

  for d in (lg n)-1 to 0:
    parallelfor i in 2^d-1 to n-1-2^d, by 2^(d+1):
      if (i-2^d >= 0):
        x[i] = x[i] + x[i-2^d]
```

- e.g., `x = [13, 9, -4, 19, -6, 2, 6, 3]`

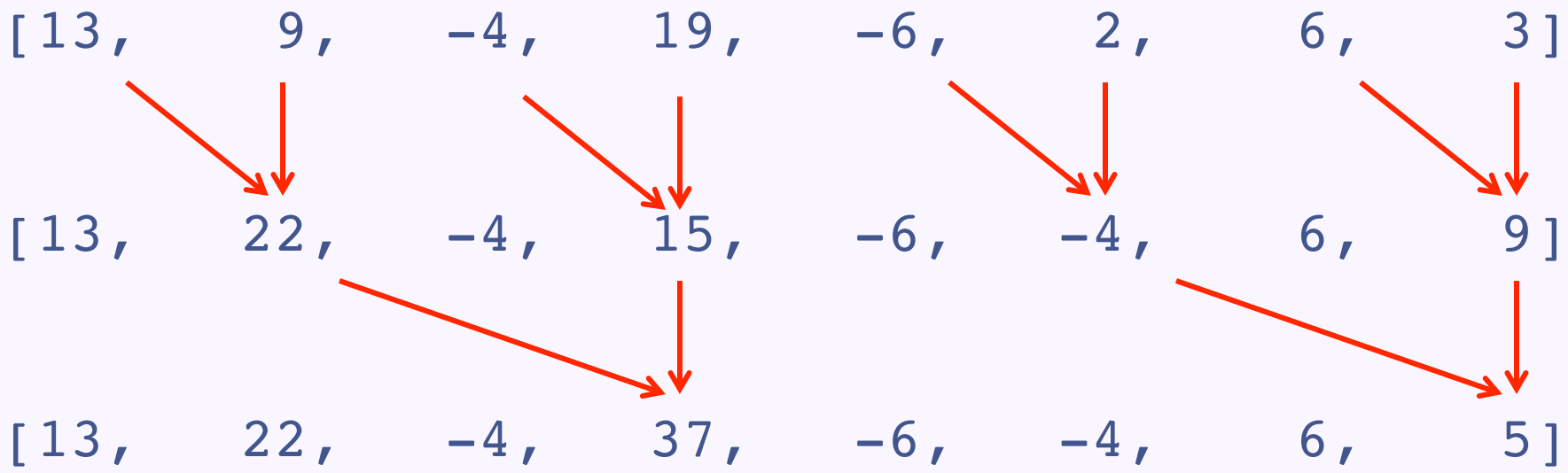
A better parallel prefix sums algorithm, part 1

- Computes the partial sums in a more useful manner



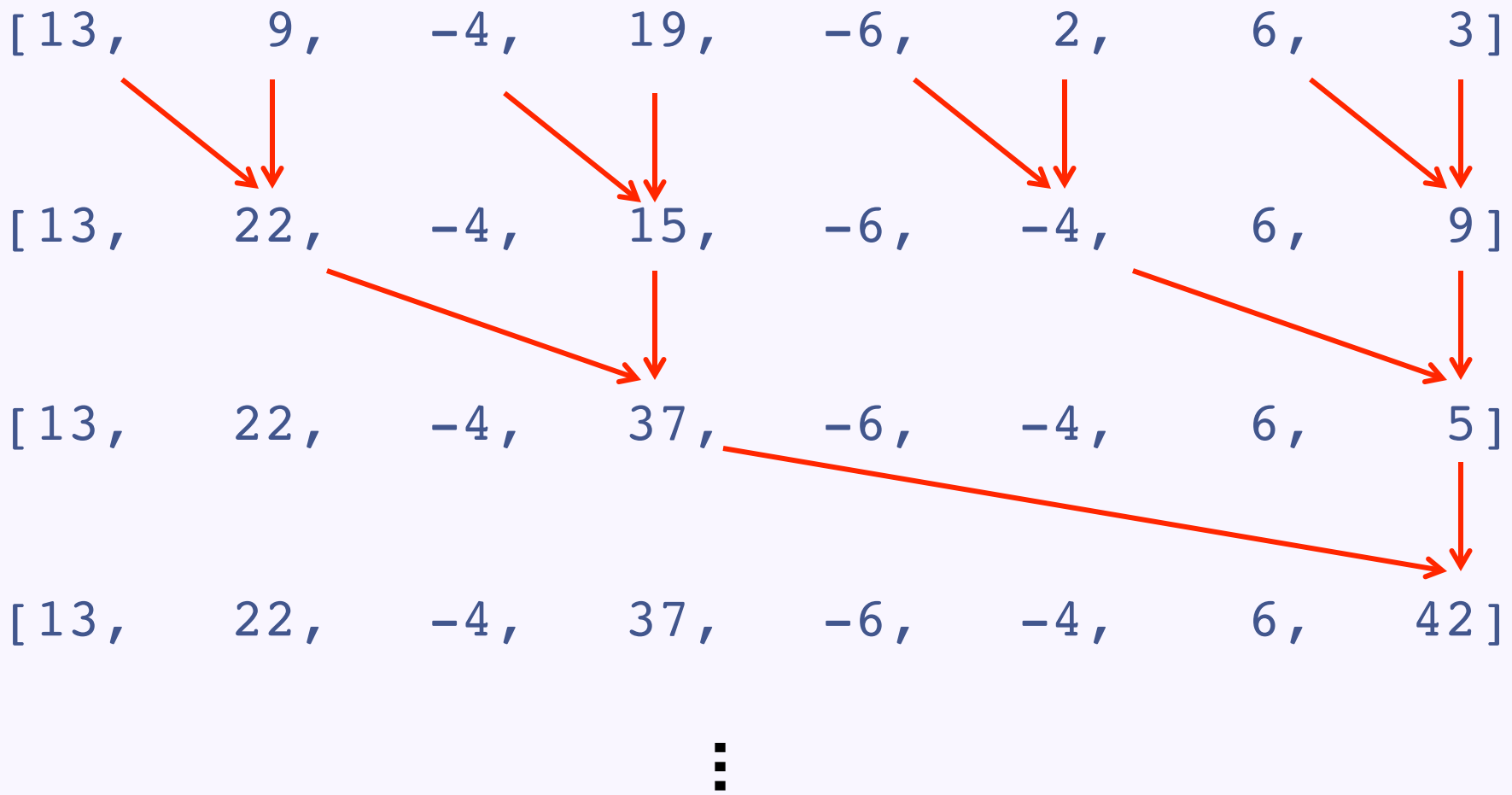
A better parallel prefix sums algorithm, part 1

- Computes the partial sums in a more useful manner



A better parallel prefix sums algorithm, part 1

- Computes the partial sums in a more useful manner



A better parallel prefix sums algorithm, part 2

- Now unwinds to calculate the other sums

A better parallel prefix sums algorithm, part 2

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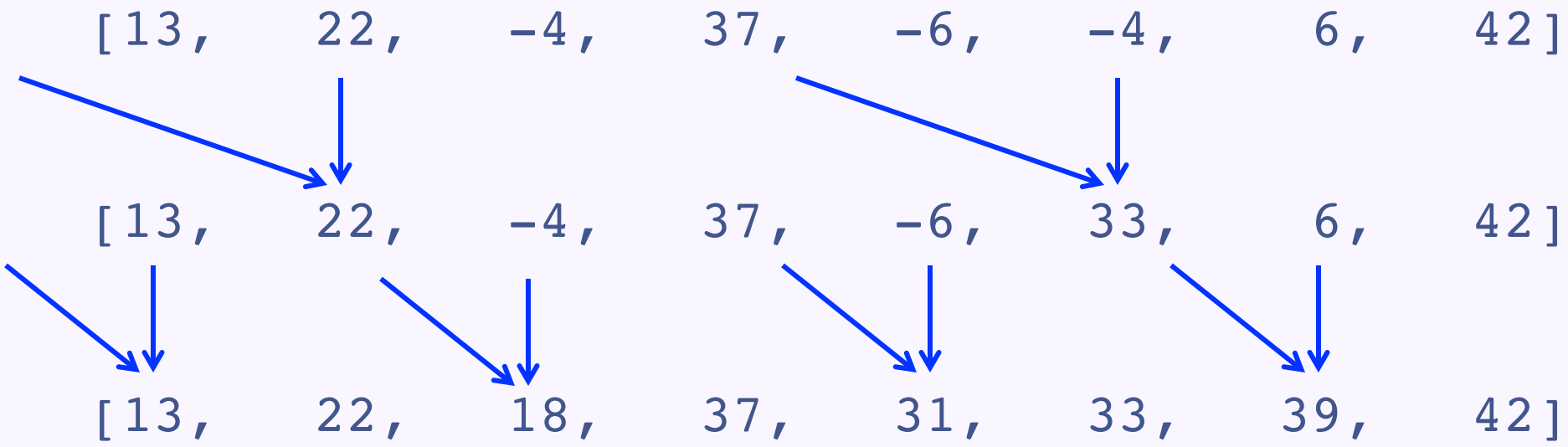

- Recall, we started with:

[13, 9, -4, 19, -6, 2, 6, 3]

A better parallel prefix sums algorithm, in code

- An iterative Java-esque implementation:

```
void computePrefixSums(long[] a) {
  for (int gap = 1; gap < a.length; gap *= 2) {
    parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
      a[i+gap] = a[i] + a[i+gap];
    }
  }
  for (int gap = a.length/2; gap > 0; gap /= 2) {
    parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
      a[i] = a[i] + ((i-gap >= 0) ? a[i-gap] : 0);
    }
  }
```

A better parallel prefix sums algorithm, in code

- A recursive Java-esque implementation:

```
void computePrefixSumsRecursive(long[] a, int gap) {
  if (2*gap – 1 >= a.length) {
    return;
  }

  parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
    a[i+gap] = a[i] + a[i+gap];
  }

  computePrefixSumsRecursive(a, gap*2);

  parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
    a[i] = a[i] + ((i-gap >= 0) ? a[i-gap] : 0);
  }
}
```

A better parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Depth: O(lg n)
- See Main.java, PrefixSumsNonSequentialImpl.java

Goal: parallelize PrefixSumsNonSequentialImpl

- Specifically, parallelize the parallelizable loops

```
parfor(int i=gap-1; i+gap<a.length; i += 2*gap) {
  a[i+gap] = a[i] + a[i+gap];
}
```

- Partition into multiple segments, run in different threads

```
for(int i=left+gap-1; i+gap<right; i += 2*gap) {
  a[i+gap] = a[i] + a[i+gap];
}
```

Recall the Java primitive concurrency tools

- The `java.lang.Runnable` interface

```
void          run();
```

- The `java.lang.Thread` class

```
Thread(Runnable r);
void          start();
static void   sleep(long millis);
void          join();
boolean       isAlive();
static Thread currentThread();
```

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- The `java.util.concurrent.Callable<V>` interface
  - Like `java.lang.Runnable` but can return a value

```
V             call();
```

A framework for asynchronous computation

- The `java.util.concurrent.Future<V>` interface

```
V       get();
V       get(long timeout, TimeUnit unit);
boolean isDone();
boolean cancel(boolean mayInterruptIfRunning);
boolean isCancelled();
```

- The `java.util.concurrent.ExecutorService` interface

```
Future           submit(Runnable task);
Future<V>        submit(Callable<V> task);
List<Future<V>> invokeAll(Collection<Callable<V>>
                                          tasks);

Future<V>        invokeAny(Collection<Callable<V>>
                                          tasks);
```

`Executors` for common computational patterns

- From the `java.util.concurrent.Executors` class

```
static ExecutorService newSingleThreadExecutor();
static ExecutorService newFixedThreadPool(int n);
static ExecutorService newCachedThreadPool();
static ExecutorService newScheduledThreadPool(int n);
```

- See NetworkServer.java

Fork/Join: another common computational pattern

- In a long computation:
  - Fork a thread (or more) to do some work
  - Join the thread(s) to obtain the result of the work

Fork/Join: another common computational pattern

- In a long computation:
  - Fork a thread (or more) to do some work
  - Join the thread(s) to obtain the result of the work
- The `java.util.concurrent.ForkJoinPool` class
  - Implements `ExecutorService`
  - Executes `java.util.concurrent.ForkJoinTask<V>` or `java.util.concurrent.RecursiveTask<V>` or `java.util.concurrent.RecursiveAction`

The `RecursiveAction` abstract class

```
public class MyActionFoo extends RecursiveAction {
    public MyActionFoo(…) {
      store the data fields we need
    }

    @Override
    public void compute() {
      if (the task is small) {
        do the work here;
        return;
      }

      invokeAll(new MyActionFoo(…),   // smaller
                new MyActionFoo(…),   // tasks
                …);                   // …
    }
}
```

A ForkJoin example

- See PrefixSumsParallelImpl.java, PrefixSumsParallelLoop1.java, and PrefixSumsParallelLoop2.java
- See the processor go, go go!

A better parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Depth: O(lg n)
- See PrefixSumsSequentialImpl.java

A better parallel prefix sums algorithm

- How good is this?
  - Work: O(n)
  - Depth: O(lg n)
- See PrefixSumsSequentialImpl.java
  - n-1 additions
  - Memory access is sequential
- For PrefixSumsNonsequentialImpl.java
  - About 2n useful additions, plus extra additions for the loop indexes
  - Memory access is non-sequential
- The punchline: Constants matter.

Today: In the trenches of parallelism

- A concurrent implementation of prefix-sums
- Also: Java I/O fundamentals

System.out is a java.io.PrintStream

- `java.io.PrintStream`: Allows you to conveniently print common types of data

```
void close();
void flush();
void print(String s);
void print(int i);
void print(boolean b);
void print(Object o);
…
void println(String s);
void println(int i);
void println(boolean b);
void println(Object o);
…
```

The fundamental I/O abstraction: a stream of data

- `java.io.InputStream`

```
void           close();
abstract int   read();
int            read(byte[] b);
```

- `java.io.OutputStream`

```
void           close();
void           flush();
abstract void  write(int b);
void           write(byte[] b);
```

- Aside: If you have an `OutputStream` you can construct a `PrintStream`:

```
PrintStream(OutputStream out);
PrintStream(File file);
PrintStream(String filename);
…
```

We typically want structured input, too

- e.g., `java.util.Scanner`

```
Scanner(InputStream source);
Scanner(File source);
void    close();
boolean hasNextInt();
int     nextInt();
boolean hasNextDouble();
double  nextDouble();
boolean hasNextLine();
String  nextLine();
boolean hasNext(Pattern p);
String  next(Pattern p);
…
```

See the FileExample.java demo

- Note the output format

To read and write arbitrary objects

- Your object must implement the `java.io.Serializable` interface
  - Methods: none!
  - If all of your data fields are themselves `Serializable`, Java can automatically serialize your class
    - If not, will get runtime `NotSerializableException`
- See QABean.java and FileObjectExample.java

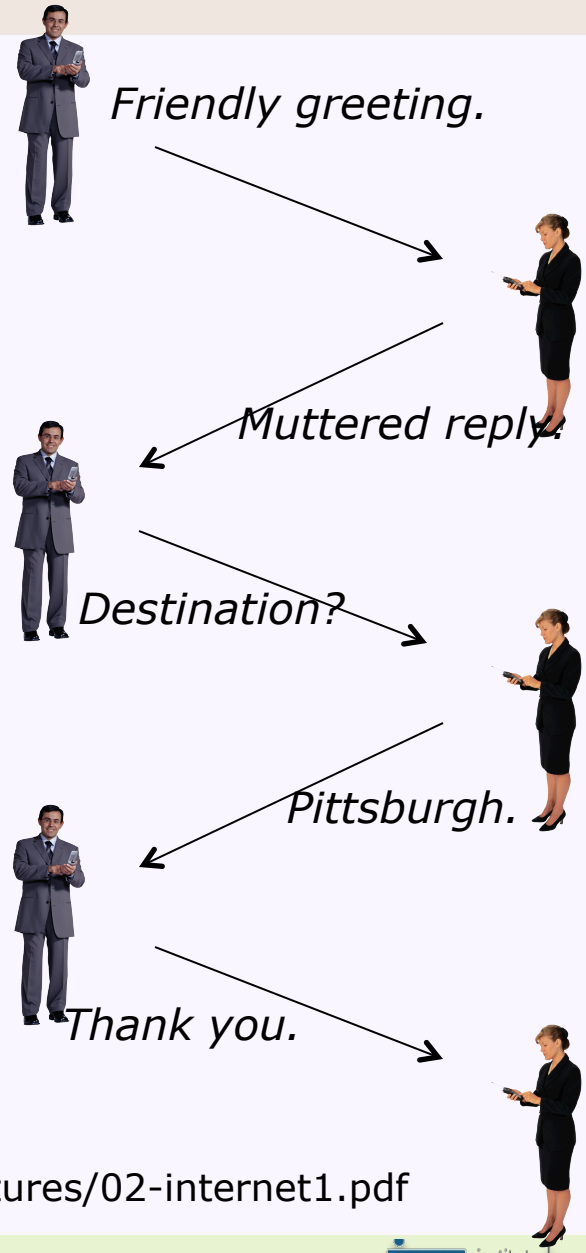
Distributed systems

- Multiple system components (computers) communicating via some medium (the network)
- Challenges:
  - Heterogeneity
  - Scale
  - Geography
  - Security
  - Concurrency
  - Failures

(courtesy of http://www.cs.cmu.edu/~dga/15-440/F12/lectures/02-internet1.pdf

Communication protocols

- Agreement between parties for how communication should take place
  - e.g., buying an airline ticket through a travel agent



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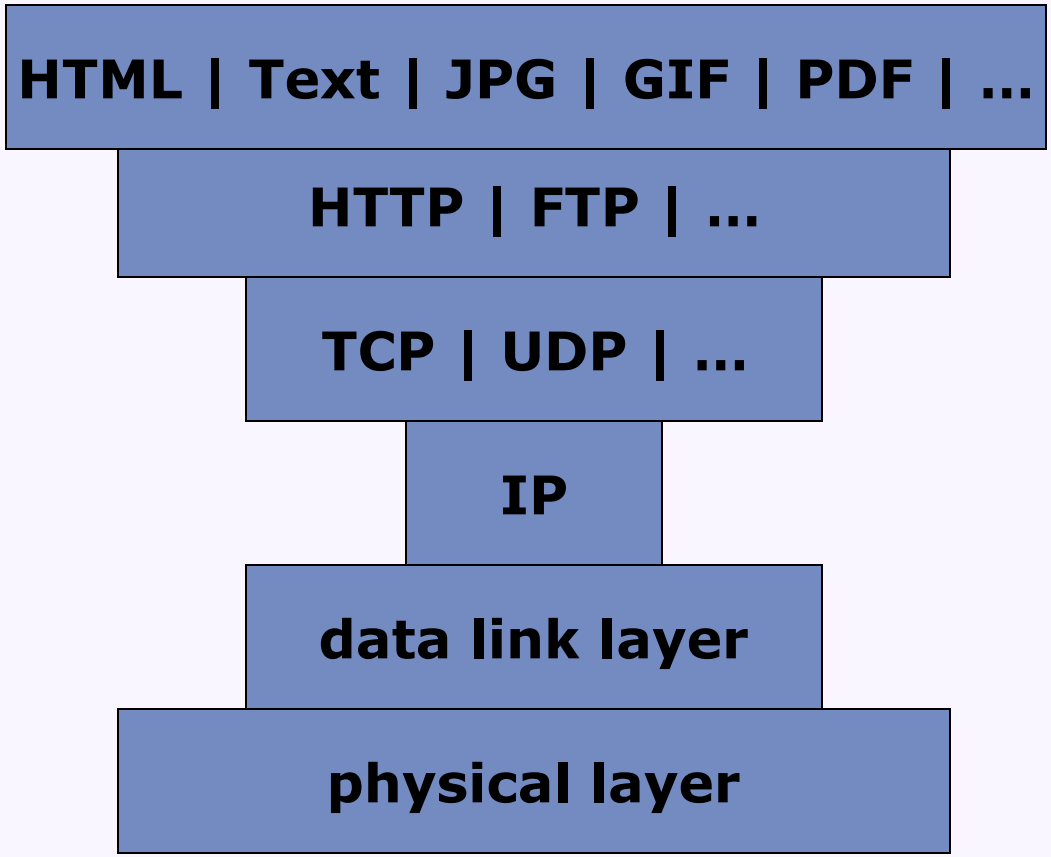
Abstractions of a network connection



Packet-oriented and stream-oriented connections

- UDP: User Datagram Protocol
  - Unreliable, discrete packets of data
- TCP: Transmission Control Protocol
  - Reliable data stream

Internet addresses and sockets

- For IP version 4 (IPv4) host address is a 4-byte number
  - e.g. 127.0.0.1
  - Hostnames mapped to host IP addresses via DNS
  - ~4 billion distinct addresses
- Port is a 16-bit number (0-65535)
  - e.g. 80
  - Assigned conventionally
- In Java:
  - `java.net.InetAddress`
  - `java.net.Inet4Address`
  - `java.net.Inet6Address`
  - `java.net.Socket`
  - `java.net.InetSocket`

Networking in Java

- The java.net.InetAddress:

```
static InetAddress getByName(String host);
static InetAddress getByAddress(byte[] b);
static InetAddress getLocalHost();
```

- The java.net.Socket:

```
Socket(InetAddress addr, int port);
boolean       isConnected();
boolean       isClosed();
void          close();
InputStream   getInputStream();
OutputStream  getOutputStream();
```

- The java.net.ServerSocket:

```
ServerSocket(int port);
Socket        accept();
void          close();
…
```

A simple Sockets demo

- TextSocketClient.java
- TextSocketServer.java
- TransferThread.java

What do you want to do with your distributed system today?

Higher levels of abstraction

- Application-level communication protocols
- Frameworks for simple distributed computation
  - Remote Procedure Call (RPC)
  - Today: Java Remote Method Invocation (RMI)
- Complex computational frameworks
  - e.g., distributed map-reduce

Next week:

- Distributed systems