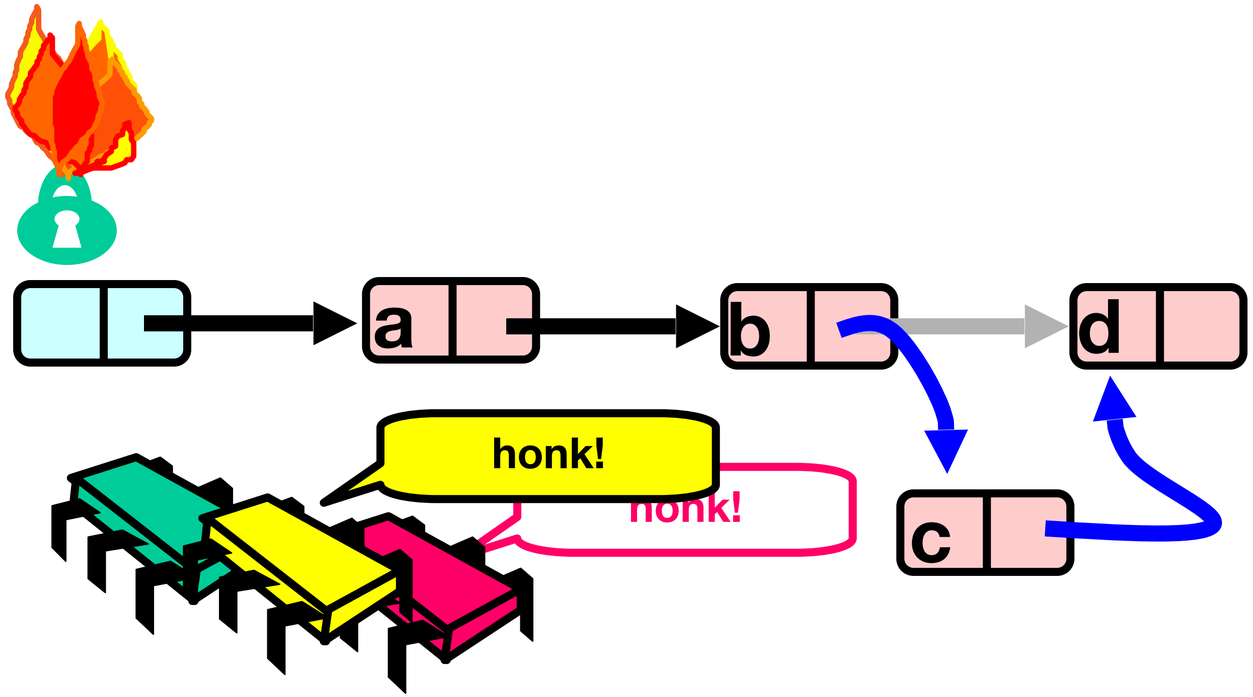
Concurrent Programming Models

CS 475, Spring 2019
Concurrent & Distributed Systems

GEORGE MASON UNIVERSITY

With material from Herlihy & Shavit, Art of Multiprocessor Programming

Review: Course Grained Locking

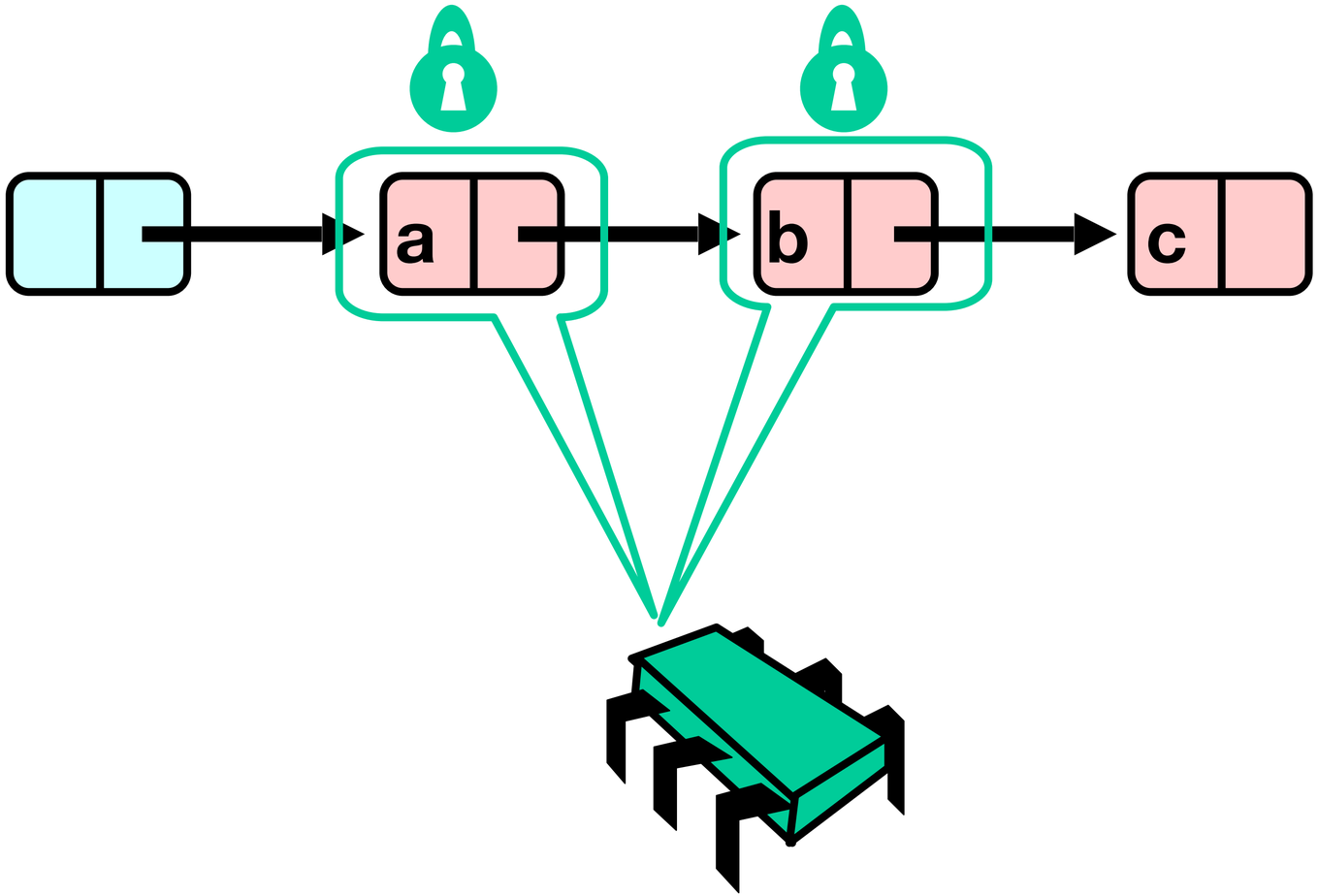


Simple but hotspot + bottleneck

Review: Fine-Grained Synchronization

- Instead of using a single lock ..
- Split object into
  - Independently-synchronized components
- Methods conflict when they access
  - The same component …
  - At the same time

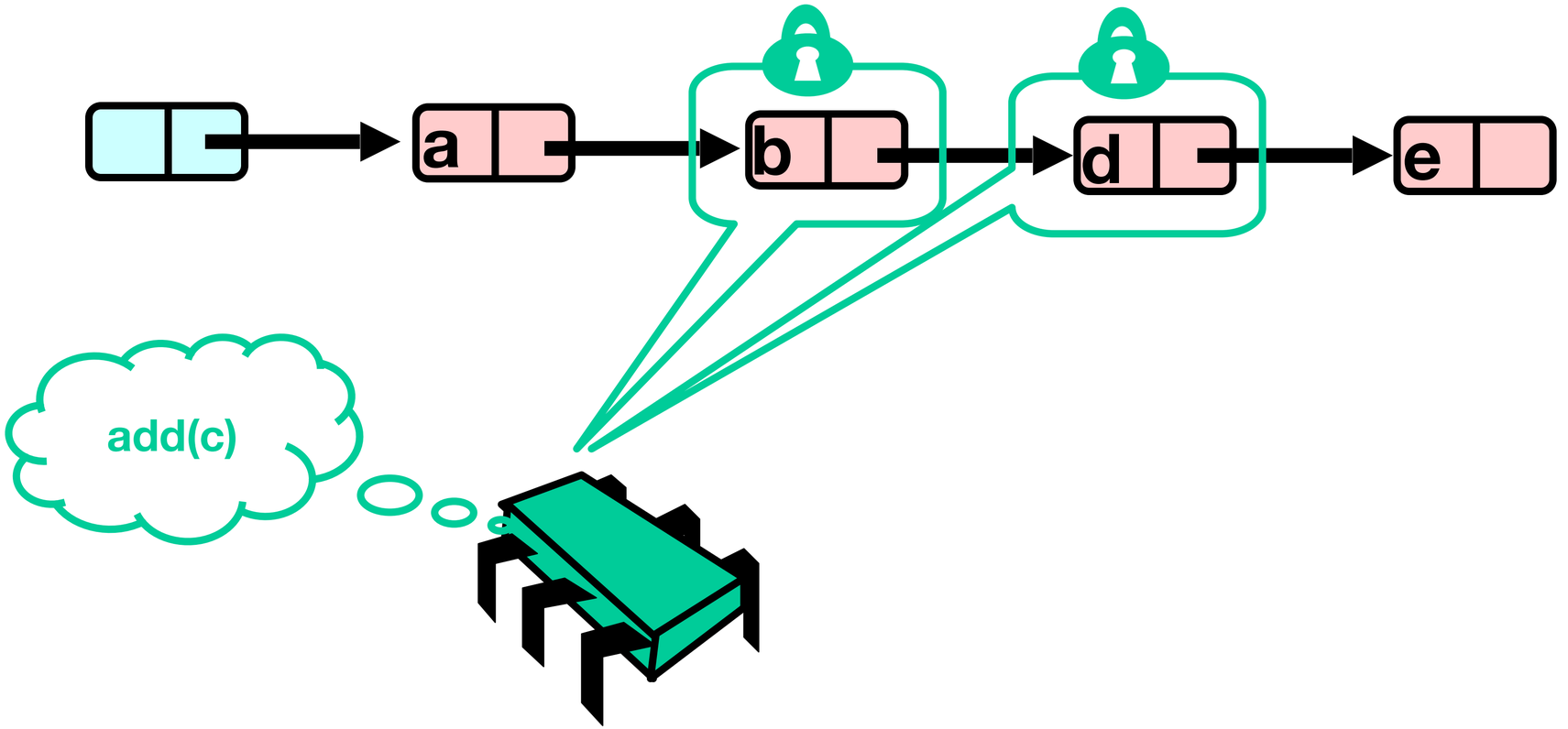
Review: Fine Grained Locking List



Review: Optimistic Synchronization

- Search without locking …
- If you find it, lock and check …
  - OK: we are done
  - Oops: start over
- Evaluation
  - Usually cheaper than locking
  - Mistakes are expensive

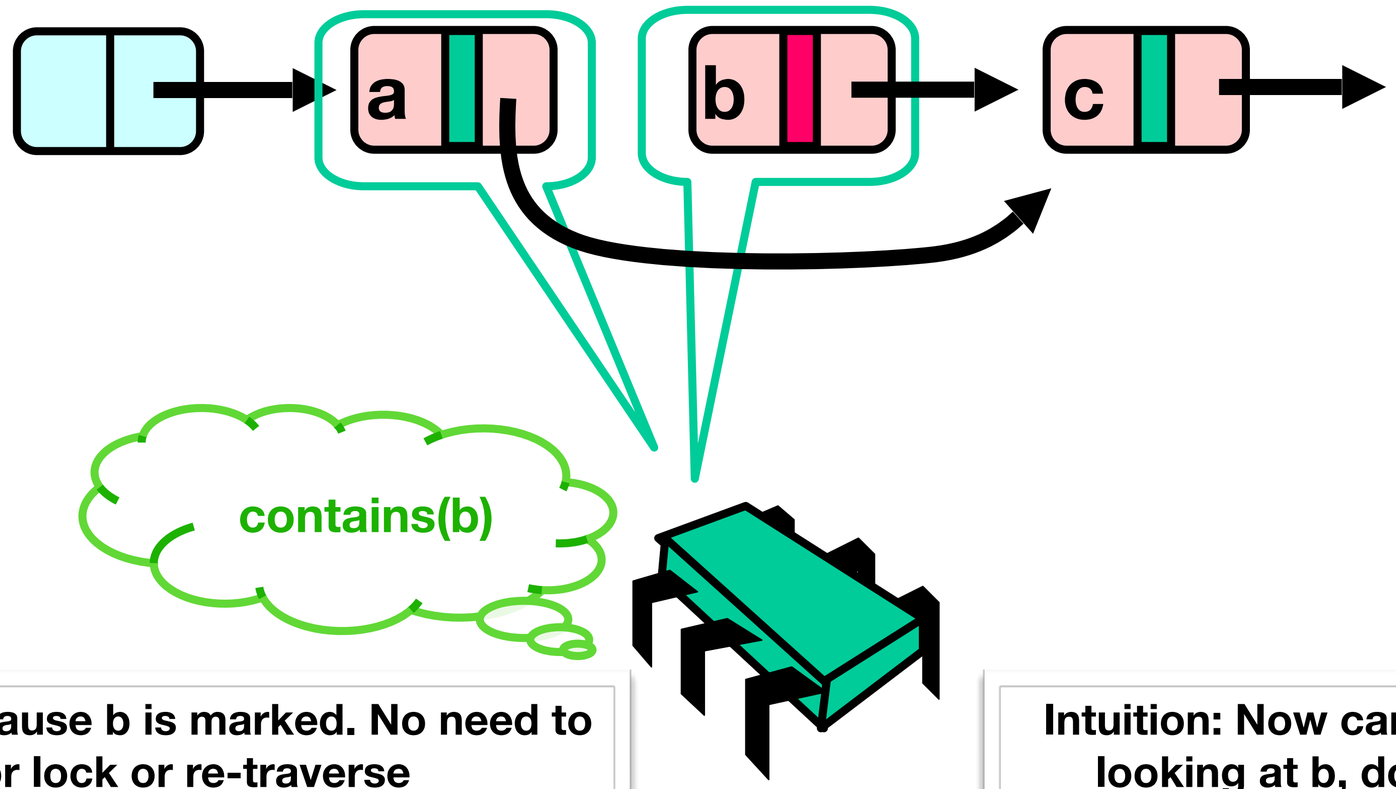
Review: Optimistic List



Review: Lazy Synchronization

- Postpone hard work
- Removing components is tricky
  - Logical removal
    - Mark component to be deleted
  - Physical removal
    - Do what needs to be done

Review: Lazy List



Returns false, because b is marked. No need to validate or lock or re-traverse

Intuition: Now can judge if b is in list ONLY by looking at b, don't also need to look at a

Today

- How do we increase performance with parallelism?
- How do we split up our program into concurrent sections effectively?
- Different models for parallel computation
- Reading: H&S 16.1, 16.2

Designing for Performance

- What factors can impact performance?
  - Limits imposed by physics
  - Limits imposed by technology
  - Limits imposed by economics
- These limits can force us to make tradeoffs
  - Smaller chips are faster, but harder to dissipate heat
  - Need to serve X clients, can only spend Y on CPUs

Performance Metrics

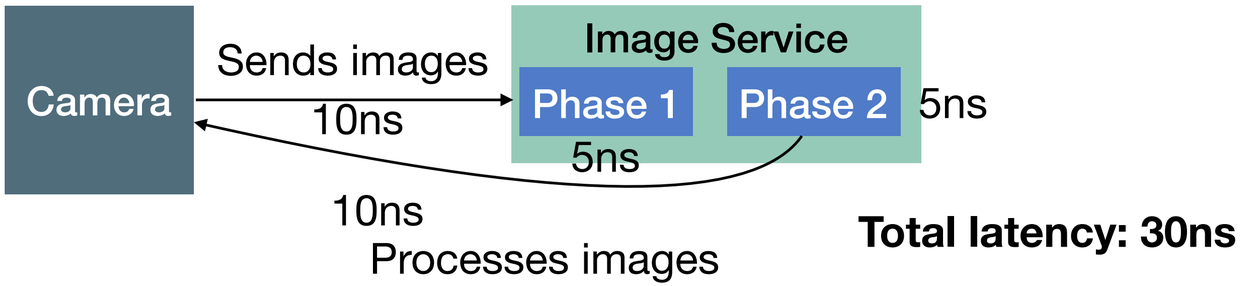
- Capacity
  - Consistent measure of a service's size or amount of resources
- Utilization
  - Percentage of that resource used for a workload
- Latency
  - How long it takes an input to propagate through a system and generate an output
- Throughput
  - Work done per time

Adjusted by buying more resources

Adjusted by thinking hard about the problem

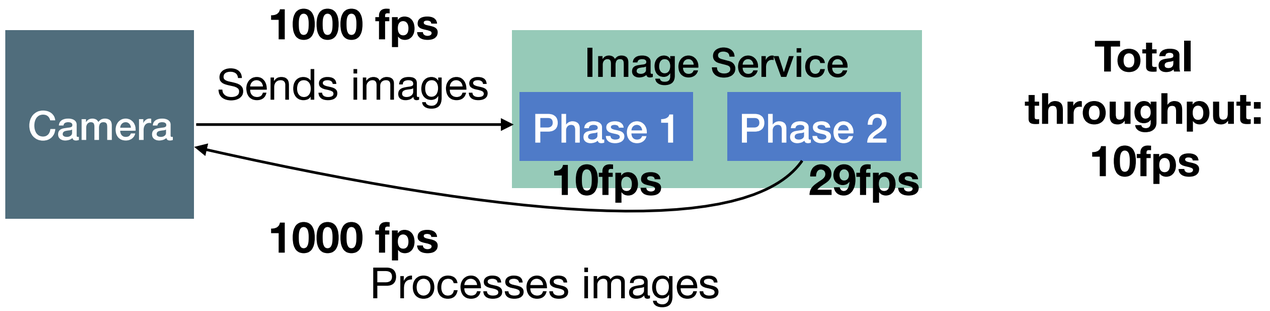
Latency

- In client/server model, latency is simply: time between client sending request and receiving response
- What contributes to latency?
  - Latency sending the message
  - Latency processing the message
  - Latency sending the response
- Adding pipelined components -> latency is cumulative



Throughput

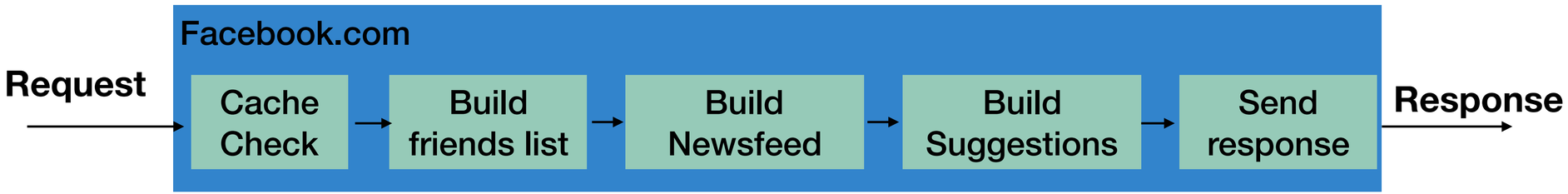
- Measure of the rate of useful work done for a given workload
- Example:
  - Throughput is camera frames processed/second
- When adding multiple pipelined components -> throughput is the minimum value



Designing for Performance

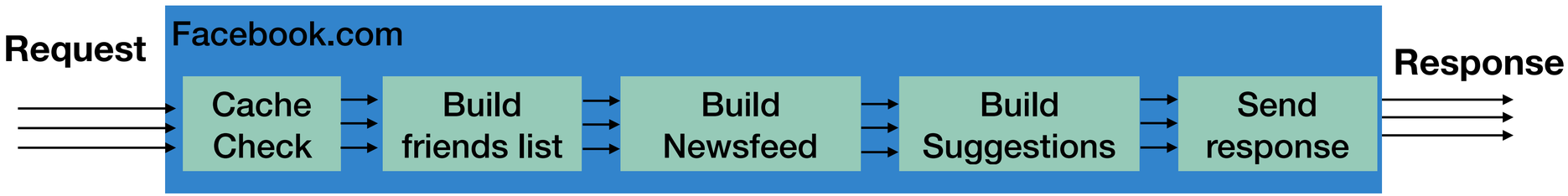
- Measure system to find which aspect of performance is lacking (throughput or latency)
- Measure each component to identify bottleneck
- Identify if fixing that bottleneck will realistically improve system performance
- Measure improvement
- Repeat

Improving Throughput



Improving Throughput

- Introduce concurrency into our pipeline
- Each stage runs in its own thread (or many threads, perhaps)
- If a stage completes its task, it can start processing the next request right away
  - E.g. our system will process multiple requests at the same time



Reducing Latency

- Often more challenging than increasing throughput
  - Examples:
    - Physical - Speed of light (network transmissions over long distances)
    - Algorithmic - Looking up an item in a hash table is limited by hash function
    - Economic - Adding more RAM gets expensive

Latency & Stock Trading

- Buy low/sell high
- Most of skill is in knowing what a stock will do **before** your competitors

Latency & Stock Trading

- Algorithmic trading -> computer programs look at various factors, place trades automatically
- Example:
  - President Trump tweets positively about a company -> price goes up
  - Write a script to check twitter for company mentions, immediately buy/sell stock
  - Get in and out before it hits CNN!
  - https://www.npr.org/sections/money/2017/04/07/522897876/meet-botus-planet-money-s-stock-trading-twitter-bot

Latency & Stock Trading

- This only works if you can make your trades **before** other people find out
- What if you set up this bot in Chicago, and I set one up in NYC?
  - I would beet you to it, every time.

Latency & Stock Trading

- What is the speed of light?
  - ~300,000 km/sec
- How fast does your CPU execute an instruction?
  - 0.33 nanoseconds (say, 3Ghz CPU)
- How far does light travel in 1 CPU cycle?
  - 10 cm
- How many instructions does your CPU execute in the time it takes light to travel from Chicago to NYC and back?
  - ~700 miles -> 7.4msec -> 22 million instructions
- Being in NYC would let me execute 22 million instructions in the time it took you to send your stock order to NYC and get a response!

Reducing Latency with $$$$

- People actually care a LOT about the latency between NYC and Chicago, because commodities are traded in Chicago and stocks are traded in NYC
  - Changes to commodities prices (e.g. **ethanol**) can dramatically impact price of some stocks

Reducing Latency with $$$$

- It's not quite as simple as 700 miles -> 7.4msec
- There are streams, mountains, etc… more like 1,000 miles
- Light is refracted in a fiber optic cable is ~31% slower
- What do we do if money is no object?

Reducing Latency with Billions of Dollars

ORIGINAL CABLE

Technology
Buried fiber-optic cable

Completion
Mid-1980s

Path length
~ 1,000 miles

Round-trip time for data
14.5
milliseconds and up

Approach
Multiple routes followed the easiest rights-of-way—along rail lines. But that means time-sucking jogs and detours.

SPREAD NETWORKS

Technology
Buried fiber-optic cable

Completion
August 2010

Path length
825 miles

Round-trip time for data
13.1
milliseconds

Approach
Spread bought its own rights-of-way, avoiding a Philadelphia-ward dip in favor of a shorter path northwest through central Pennsylvania.

MCKAY BROTHERS

Technology
Microwave beams through air

Completion
July 4, 2012

Path length
744 miles

Round-trip time for data
9
milliseconds

Approach
Microwaves generally move faster than photons in optical fiber, and McKay's network uses just 20 towers on a nearly perfect great circle.

TRADEWORX

Technology
Microwave beams through air

Completion
Winter 2012

Path length
~ 731 miles

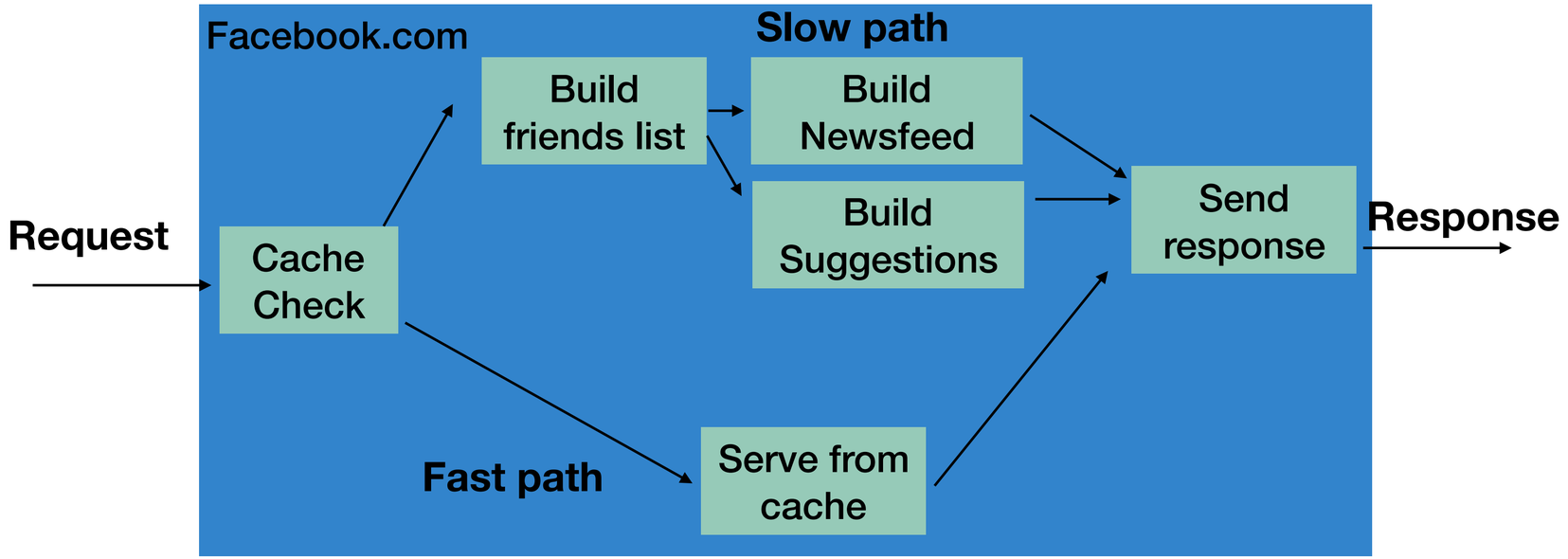
Round-trip time for data
8.5
milliseconds (est.)

Approach
Tradeworx is highly secretive, but the company is open about the price of a subscription: $250,000 a year.

https://www.zerohedge.com/news/chicago-new-york-and-back-85-milliseconds

Reducing Latency without lots of $$$

- Approach: use **concurrency**
- Limited by serial section



Exploiting Concurrency

- These examples are at a very high level (components in a large server system)
- For this lecture, we'll focus on smaller, more concrete examples
- First: Matrix Multiplication

$$(C) = (A) \bullet (B)$$

Matrix Multiplication

$$c_{ij} = \sum_{k=0}^{N-1} a_{ki} * b_{jk}$$

Matrix Multiplication

```
class Worker extends Thread {
  int row, col;
  Worker(int row, int col) {
    this.row = row; this.col = col;
  }
  public void run() {
    double dotProduct = 0.0;
    for (int i = 0; i < n; i++)
      dotProduct += a[row][i] * b[i][col];
    c[row][col] = dotProduct;
  }}}
```

Matrix Multiplication

```
class Worker extends Thread {
  int row, col;
  Worker(int row, int col) {
    this.row = row; this.col = col;
  }
  public void run() {
    double dotProduct = 0.0;
    for (int i = 0; i < n; i++)
      dotProduct += a[row][i] * b[i][col];
    c[row][col] = dotProduct;
  }}}
```

a thread

Matrix Multiplication

```
class Worker extends Thread {
  int row, col;
  Worker(int row, int col) {
    this.row = row; this.col = col;
  }
  public void run() {
    double dotProduct = 0.0;
    for (int i = 0; i < a[0].length; i++)
      dotProduct += a[row][i] * b[i][col];
    c[row][col] = dotProduct;
  }}}
```

Which matrix entry to compute

Matrix Multiplication

```
class Worker extends Thread {
  int row, col;
  Worker(int row, int col) {
    this.row = row; this.col = col;
  }
  public void run() {
    double dotProduct = 0.0;
    for (int i = 0; i < n; i++)
      dotProduct += a[row][i] * b[i][col];
    c[row][col] = dotProduct;
  }}}
```

Actual computation

Matrix Multiplication

```
  void multiply() {
    Worker[][] worker = new Worker[n][n];
    for (int row …)
      for (int col …)
        worker[row][col] = new Worker(row,col);
    for (int row …)
      for (int col …)
        worker[row][col].start();
    for (int row …)
      for (int col …)
        worker[row][col].join();
}
```

Matrix Multiplication

```
void multiply() {
  Worker[][] worker = new Worker[n][n];
  for (int row …)
    for (int col …)
      worker[row][col] = new Worker(row,col);
  for (int row …)
    for (int col …)
      worker[row][col].start();
  for (int row …)
    for (int col …)
      worker[row][col].join();
}
```

Create nxn threads

Matrix Multiplication

```
void multiply() {
  Worker[][] worker = new Worker[n][n];
  for (int row …)
    for (int col …)
      worker[row][col] = new Worker(row,col);
  for (int row …)
    for (int col …)
      worker[row][col].start();
  for (int row …)
    for (int col …)
      worker[row][col].join();
}
```

Start them

Matrix Multiplication

```
void multiply() {
  Worker[][] worker = new Worker[n][n];
  for (int row …)
    for (int col …)
      worker[row][col] = new Worker(row,col);
  for (int row …)
    for (int col …)
      worker[row][col].start();
  for (int row …)
    for (int col …)
      worker[row][col].join();
}
```

Start them

Wait for them to finish

Matrix Multiplication

```
void multiply() {
  Worker[][] worker = new Worker[n][n];
  for (int row …)
    for (int col …)
      worker[row][col] = new Worker(row,col);
  for (int row …)
    for (int col …)
      worker[row][col].start();
  for (int row …)
    for (int col …)
      worker[row][col].join();
}
```

Start them

What's wrong with this picture?

Wait for them to finish

Thread Overhead

- Threads Require resources
  - Memory for stacks
  - Setup, teardown
- Scheduler overhead
- Worse for short-lived threads

Thread Pools

- More sensible to keep a pool of long-lived threads
- Threads assigned short-lived tasks
  - Runs the task
  - Rejoins pool
  - Waits for next assignment

Thread Pool = Abstraction

- Insulate programmer from platform
  - Big machine, big pool
  - And vice-versa
- Portable code
  - Runs well on any platform
  - No need to mix algorithm/platform concerns

ExecutorService Interface

- In java.util.concurrent
  - Task = **Runnable** object
    - If no result value expected
    - Calls **run()** method.
  - Task = **Callable<T>** object
    - If result value of type **T** expected
    - Calls **T call()** method.
    - Interesting question: how do you get the return value from call?

Future<T>

```
Callable<T> task = …;
…
Future<T> future = executor.submit(task);
…
T value = future.get();
```

Future<T>

```
Callable<T> task = …;
…
Future<T> future = executor.submit(task);
…
T value = future.get();
```

Submitting a Callable<T> task returns a Future<T> object

Future<T>

```
Callable<T> task = …;
…
Future<T> future = executor.submit(task);
…
T value = future.get();
```

The Future's get() method blocks until the value is available

Future<?>

```
Runnable task = …;
…
Future<?> future = executor.submit(task);
…
future.get();
```

Future<?>

```
Runnable task = …;
…
Future<?> future = executor.submit(task);
…
future.get();
```

Submitting a Runnable task returns a Future<?> object

Future<?>

```
Runnable task = …;
…
Future<?> future = executor.submit(task);
…
future.get();
```

The Future's get() method blocks until the computation is complete

Note

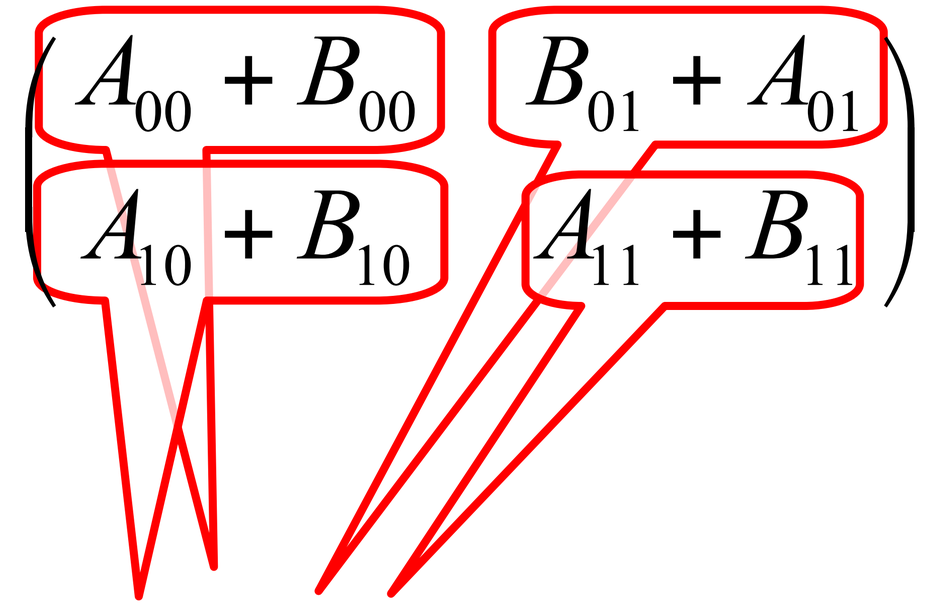
- Executor Service submissions
  - Like Maryland traffic signs
  - Are purely advisory in nature
- The executor
  - Like the Maryland driver
  - Is free to ignore any such advice
  - And could execute tasks sequentially …

Matrix Addition

$$\begin{pmatrix} C_{00} & C_{00} \\ C_{10} & C_{10} \end{pmatrix} = \begin{pmatrix} A_{00} + B_{00} & B_{01} + A_{01} \\ A_{10} + B_{10} & A_{11} + B_{11} \end{pmatrix}$$

Matrix Addition

$$\begin{pmatrix} C_{00} & C_{00} \\ C_{10} & C_{10} \end{pmatrix} = \begin{pmatrix} A_{00} + B_{00} & B_{01} + A_{01} \\ A_{10} + B_{10} & A_{11} + B_{11} \end{pmatrix}$$



4 parallel additions

Matrix Addition Task

```
class AddTask implements Runnable {
   Matrix a, b; // multiply this!
   public void run() {
     if (a.dim == 1) {
      c[0][0] = a[0][0] + b[0][0]; // base case
     } else {
      (partition a, b into half-size matrices a_ij and b_ij)
      Future<?> f_00 = exec.submit(add(a_00,b_00));
      …
      Future<?> f_11 = exec.submit(add(a_11,b_11));
      f_00.get(); …; f_11.get();
      …
     }}
```

This is not real Java code (see book)

Matrix Addition Task

```
class AddTask implements Runnable {
   Matrix a, b; // multiply this!
   public void run() {
    if (a.dim == 1) {
     c[0][0] = a[0][0] + b[0][0]; // base case
    } else {
     (partition a, b into half-size matrices a_ij and b_ij)
     Future<?> f00 = exec.submit(add(a00,b00));
     …
     Future<?> f11 = exec.submit(add(a11,b11));
     f00.get(); …; f11.get();
     …
    }}
```

Base case: add directly

Matrix Addition Task

```
class AddTask implements Runnable {
   Matrix a, b; // multiply this!
   public void run() {
     if (a.dim == 1) {
      c[0][0] = a[0][0] + b[0][0]; // base case
     } else {
      (partition a, b into half-size matrices a_ij and b_ij)
      Future<?> f00 = exec.submit(add(a00,b00));
      …
      Future<?> f11 = exec.submit(add(a11,b11));
      f00.get(); …; f11.get();
      …
     }}
```

Constant-time operation

Matrix Addition Task

```
class AddTask implements Runnable {
   Matrix a, b; // multiply this!
   public void run() {
     if (a.dim == 1) {
      c[0][0] = a[0][0] + b[0][0]; // base case
     } else {
      (partition a, b into half-size matrices a_ij and b_ij)
     Future<?> f00 = exec.submit(add(a00,b00));
     …
     Future<?> f11 = exec.submit(add(a11,b11));
      f00.get(); …; f11.get();
      …
     }}
```

Submit 4 tasks

Matrix Addition Task

```
class AddTask implements Runnable {
   Matrix a, b; // multiply this!
   public void run() {
     if (a.dim == 1) {
      c[0][0] = a[0][0] + b[0][0]; // base case
     } else {
      (partition a, b into half-size matrices a_ij and b_ij)
      Future<?> f00 = exec.submit(add(a00,b00));
      …
      Future<?> f11 = exec.submit(add(a11,b11));
      f00.get(); …; f11.get();
      …
     }}
```

Let them finish

Dependencies

- Matrix example is not typical
- Tasks are independent
  - Don’t need results of one task …
  - To complete another
- Often tasks are not independent

Fibonacci

$$F(n) \begin{cases} 1 \text{ if } n = 0 \text{ or } 1 \\ F(n-1) + F(n-2) \text{ otherwise} \end{cases}$$

- Note: potential parallelism, but subject to dependencies

Disclaimer

- This Fibonacci implementation is
  - Egregiously inefficient
    - So don't deploy it!
  - But illustrates our point
    - How to deal with dependencies

Multithreaded Fibonacci

```
class FibTask implements Callable<Integer> {
  static ExecutorService exec =
Executors.newCachedThreadPool();
  int arg;
  public FibTask(int n) {
    arg = n;
  }
  public Integer call() {
    if (arg > 2) {
      Future<Integer> left  = exec.submit(new FibTask(arg-1));
      Future<Integer> right = exec.submit(new FibTask(arg-2));
      return left.get() + right.get();
    } else {
      return 1;
    }}}
```

Multithreaded Fibonacci

```
class FibTask implements Callable<Integer> {
  static ExecutorService exec =
Executors.newCachedThreadPool();
  int arg;
  public FibTask(int n) {
    arg = n;
  }
  public Integer call() {
    if (arg > 2) {
      Future<Integer> left  = exec.submit(new FibTask(arg-1));
      Future<Integer> right = exec.submit(new FibTask(arg-2));
      return left.get() + right.get();
    } else {
      return 1;
    }}}
```

Parallel calls

Multithreaded Fibonacci

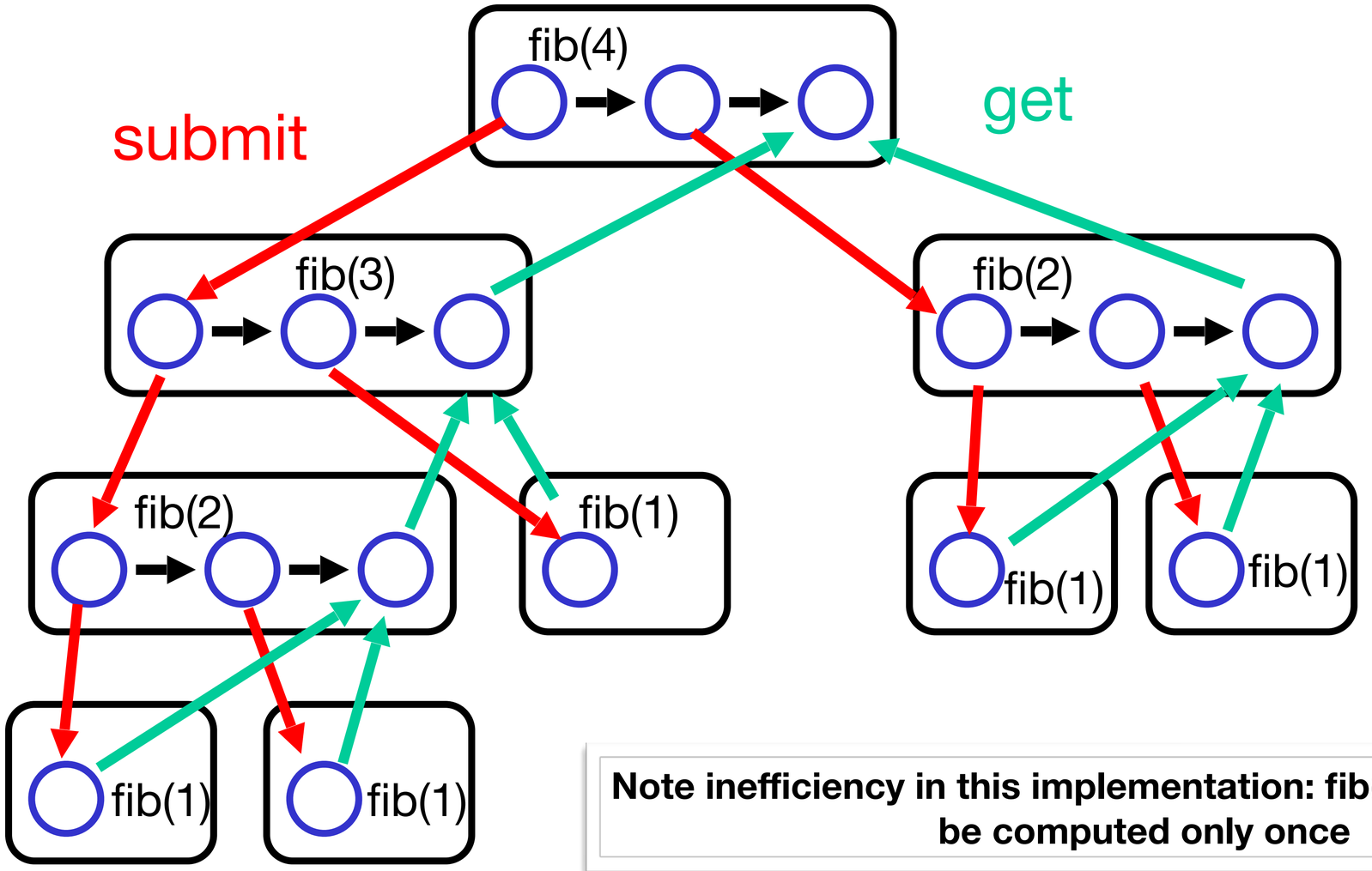
```
class FibTask implements Callable<Integer> {
  static ExecutorService exec =
Executors.newCachedThreadPool();
  int arg;
  public FibTask(int n) {
    arg = n;
  }
  public Integer call() {
    if (arg > 2) {
      Future<Integer> left = exec.submit(new FibTask(arg-1));
      Future<Integer> right = exec.submit(new FibTask(arg-2));
      return left.get() + right.get();
    } else {
      return 1;
    }}}
```

Pick up & combine results

Dynamic Behavior

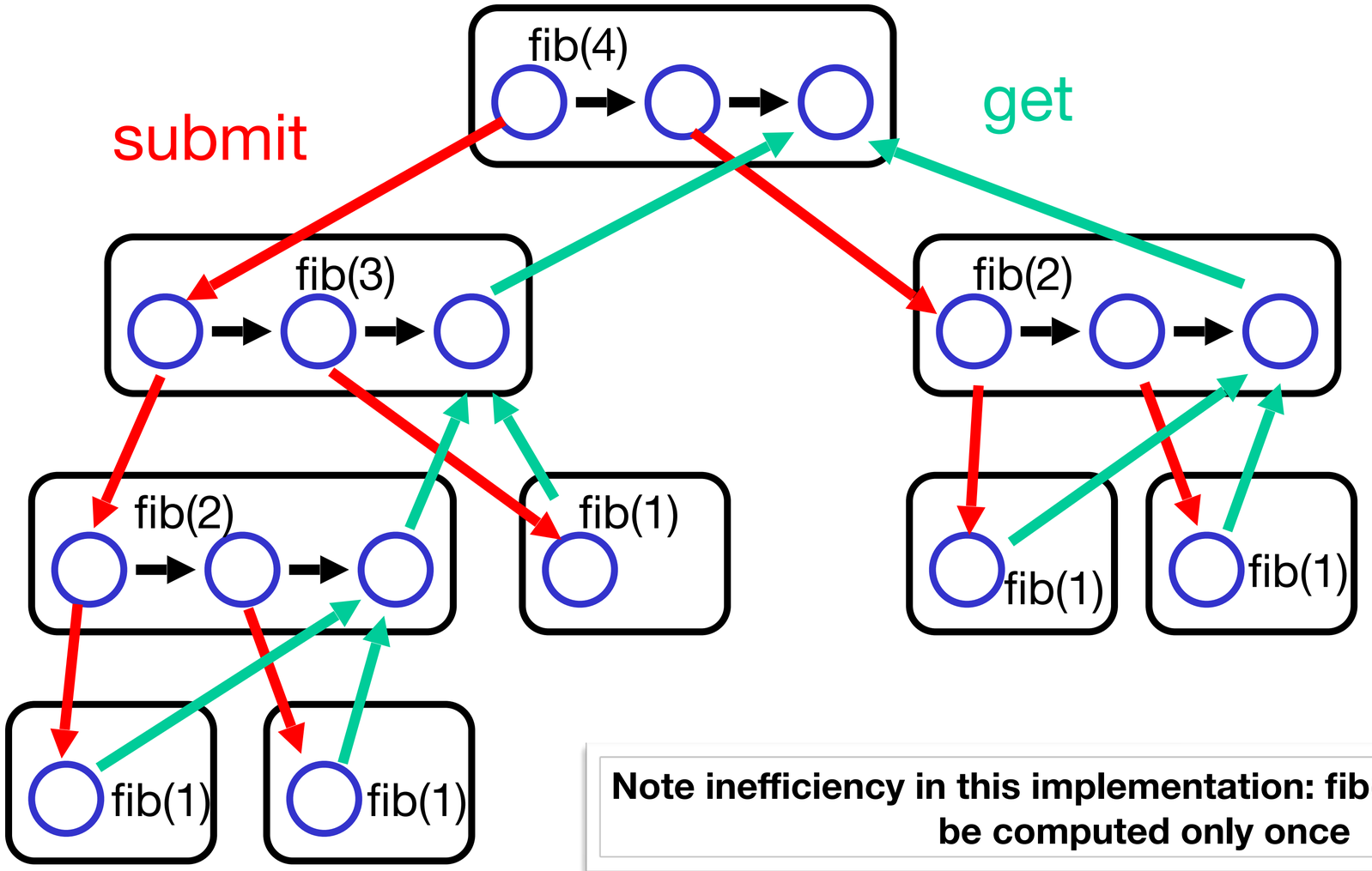
- Multithreaded program is
  - A directed acyclic graph (DAG)
  - That unfolds dynamically
- Each node is
  - A single unit of work

Fib DAG



Note inefficiency in this implementation: fib(2)'s result should be computed only once

Arrows Reflect Dependencies

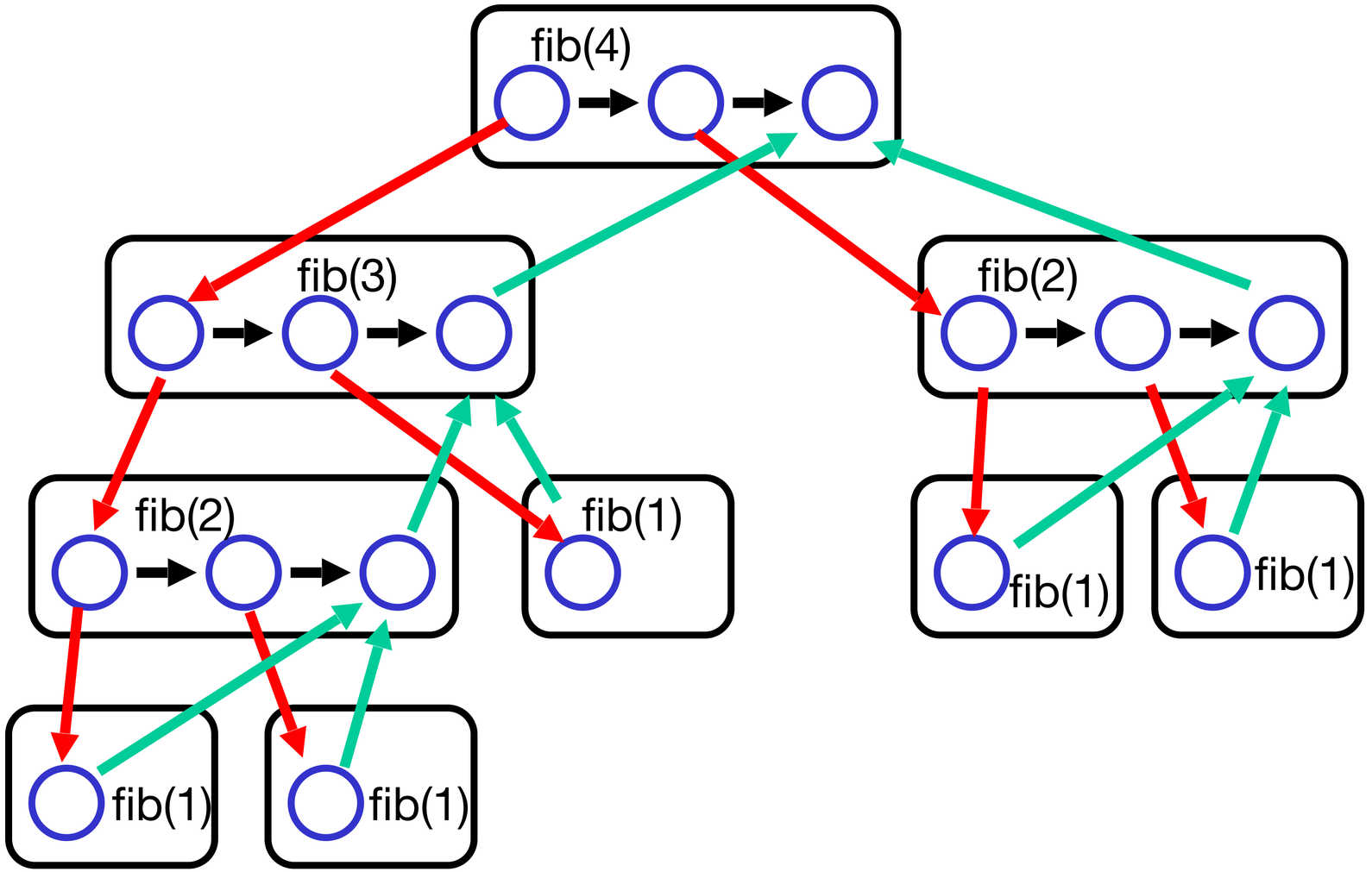


Note inefficiency in this implementation: fib(2)'s result should be computed only once

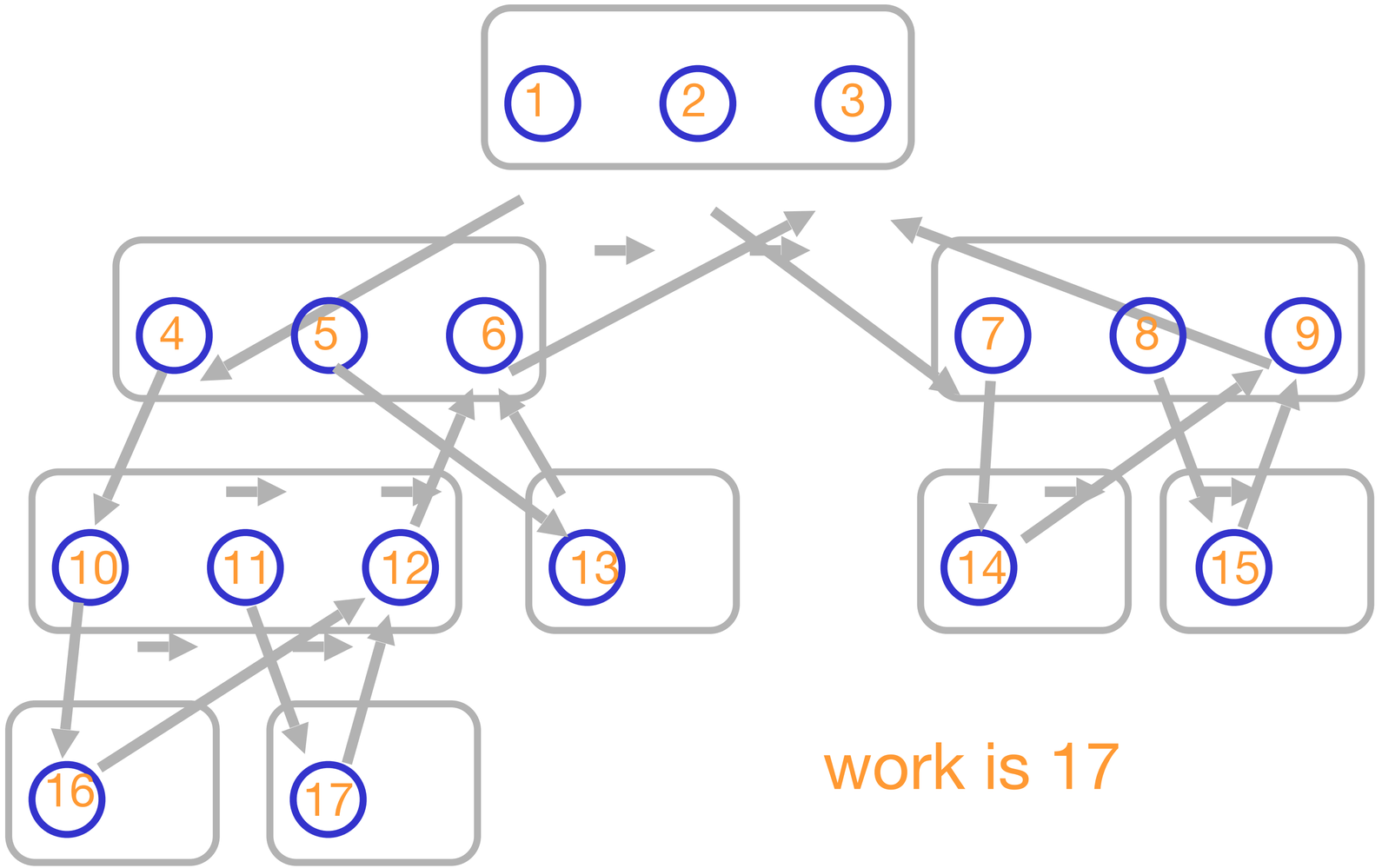
How Parallel is That?

- Define work:
  - Total time on one processor
- Define critical-path length:
  - Longest dependency path
  - Can’t beat that!

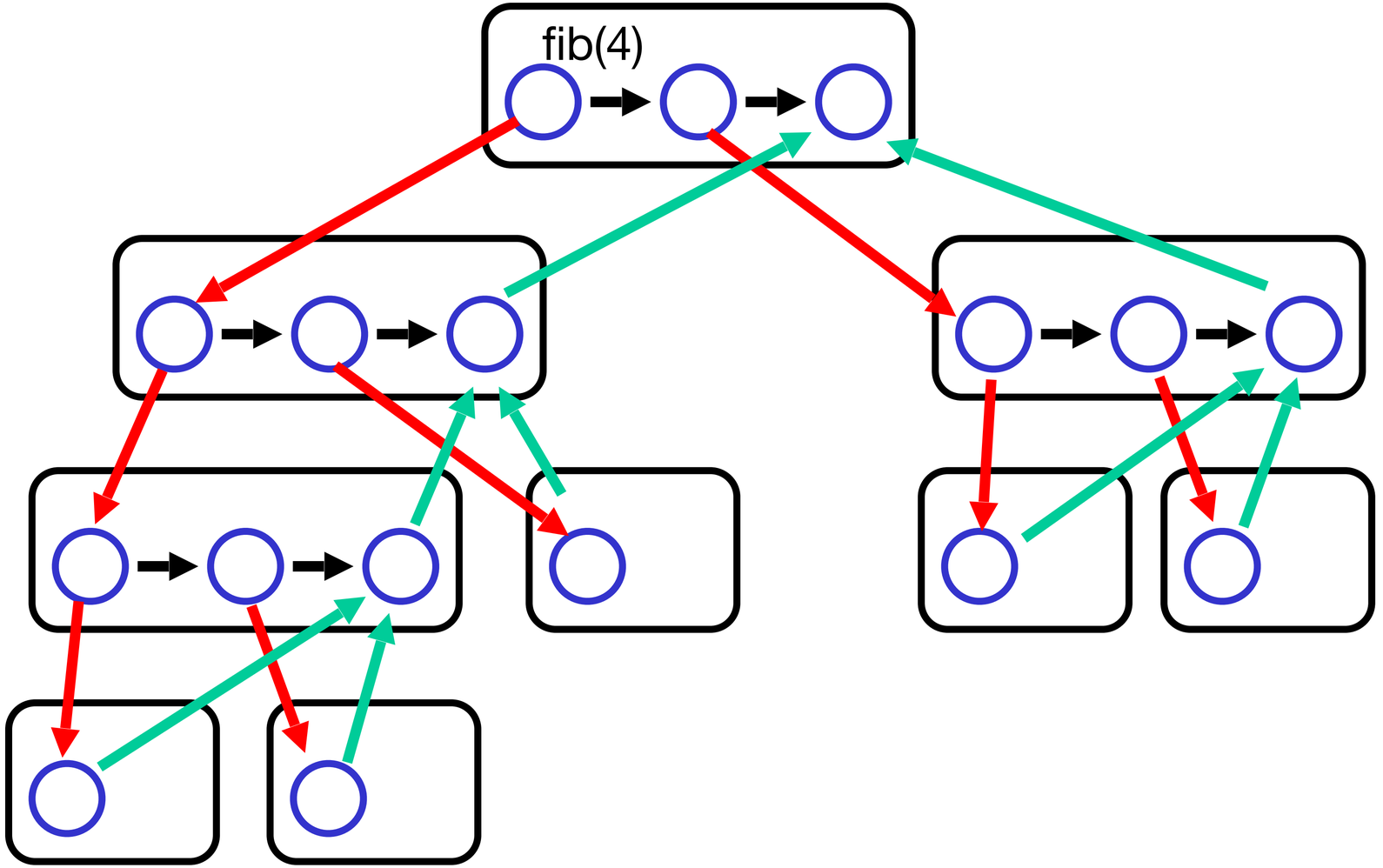
Fib Work



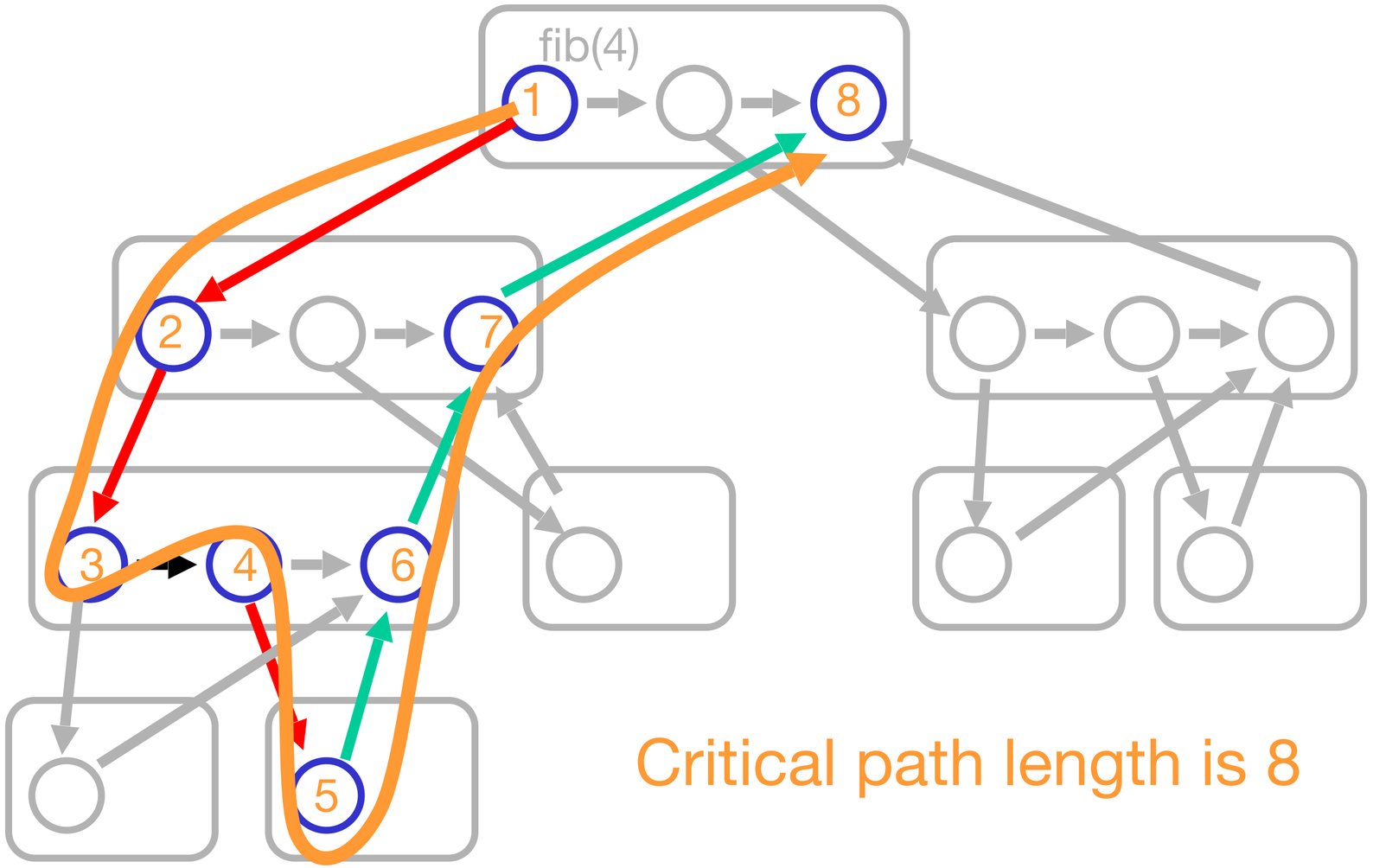
Fib Work



Fib Critical Path



Fib Critical Path



Critical path length is 8

Notation Watch

- T_P = time on P processors
- T_1 = work (time on 1 processor)
- T_∞ = critical path length (time on ∞ processors)

Simple Bounds

- $T_P \geq T_1/P$
  - In one step, can't do more than P work
- $T_P \geq T_\infty$
  - Can't beat infinite resources

More Notation Watch

- Speedup on P processors
  - Ratio T_1/T_P
  - How much faster with P processors
- Linear speedup
  - $T_1/T_P = \Theta(P)$
- Max speedup (average parallelism)
  - T_1/T_∞

Matrix Addition

$$\begin{pmatrix} C_{00} & C_{00} \\ C_{10} & C_{10} \end{pmatrix} = \begin{pmatrix} A_{00} + B_{00} & B_{01} + A_{01} \\ A_{10} + B_{10} & A_{11} + B_{11} \end{pmatrix}$$

Matrix Addition

$$\begin{pmatrix} C_{00} & C_{00} \\ C_{10} & C_{10} \end{pmatrix} = \begin{pmatrix} A_{00} + B_{00} & B_{01} + A_{01} \\ A_{10} + B_{10} & A_{11} + B_{11} \end{pmatrix}$$

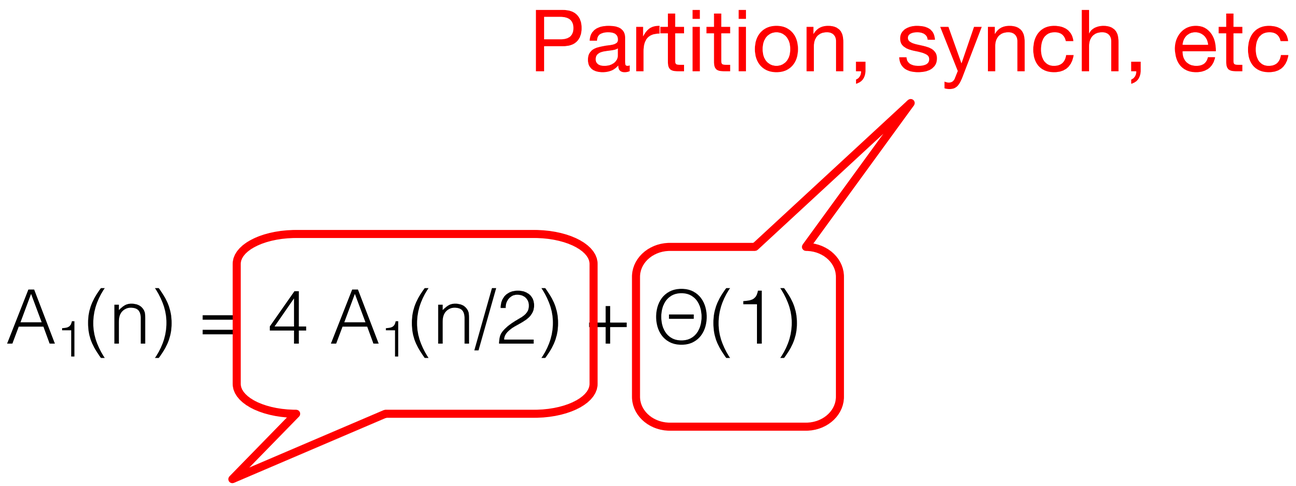
4 parallel additions

Addition

- Let $A_P(n)$ be running time
  - For n x n matrix
  - on P processors
- For example
  - $A_1(n)$ is work
  - $A_\infty(n)$ is critical path length

Addition

- Work is



Addition

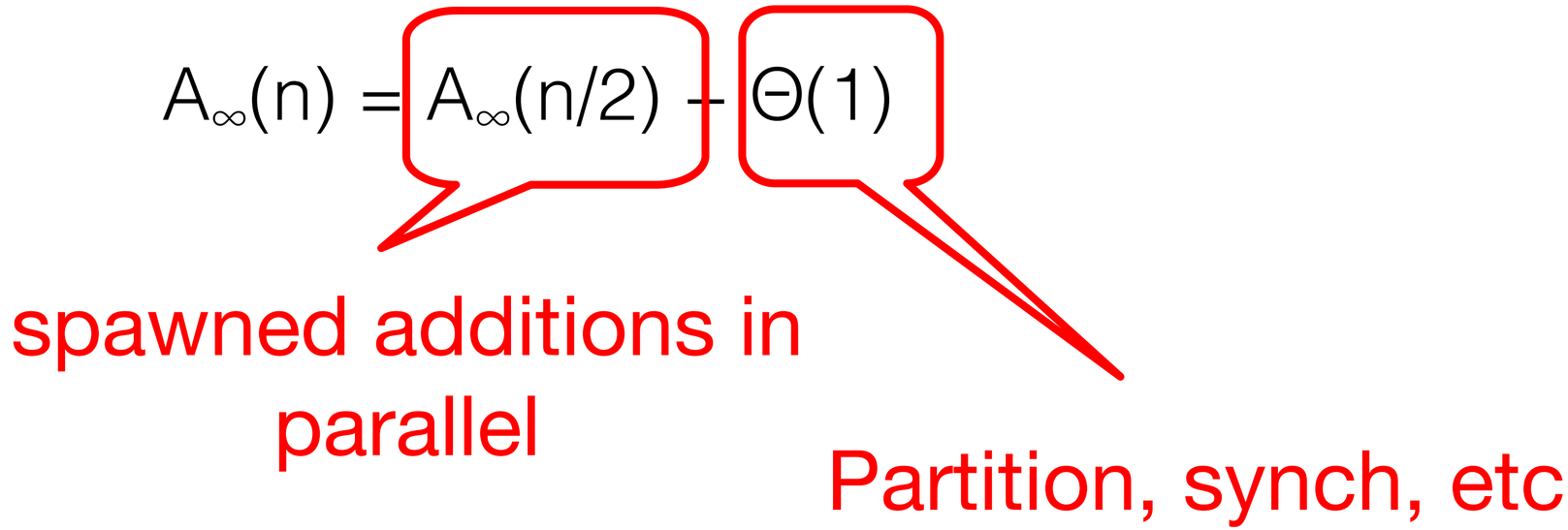
- Work is

$$A_1(n) = 4\,A_1(n/2) + \Theta(1)$$
$$= \Theta(n^2)$$

Same as double-loop summation

Addition

- Critical Path length is



Addition

- Critical Path length is

$$A_\infty(n) = A_\infty(n/2) + \Theta(1)$$
$$= \Theta(\log n)$$

Matrix Multiplication Redux

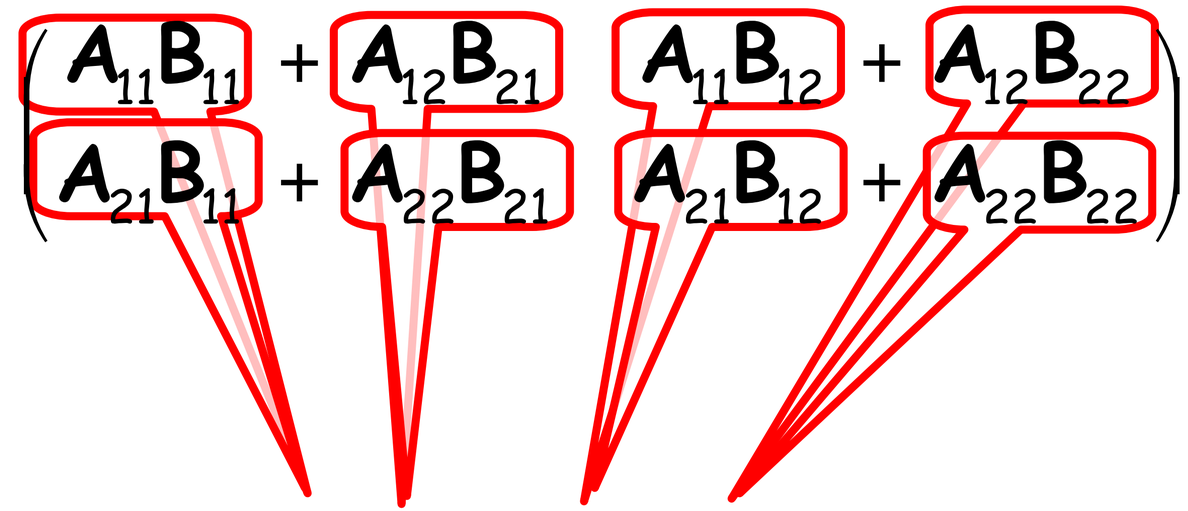
$$(C) = (A) \bullet (B)$$

Matrix Multiplication Redux

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \cdot \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$$

First Phase …

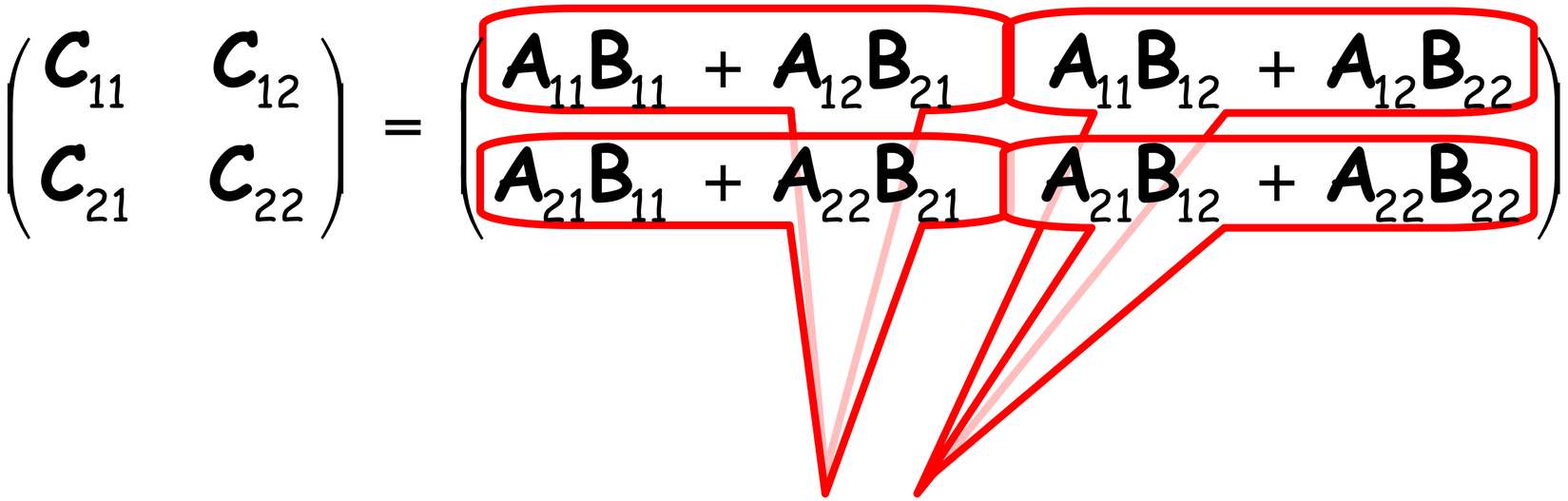
$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} A_{11}B_{11} + A_{12}B_{21} & A_{11}B_{12} + A_{12}B_{22} \\ A_{21}B_{11} + A_{22}B_{21} & A_{21}B_{12} + A_{22}B_{22} \end{pmatrix}$$



8 multiplications

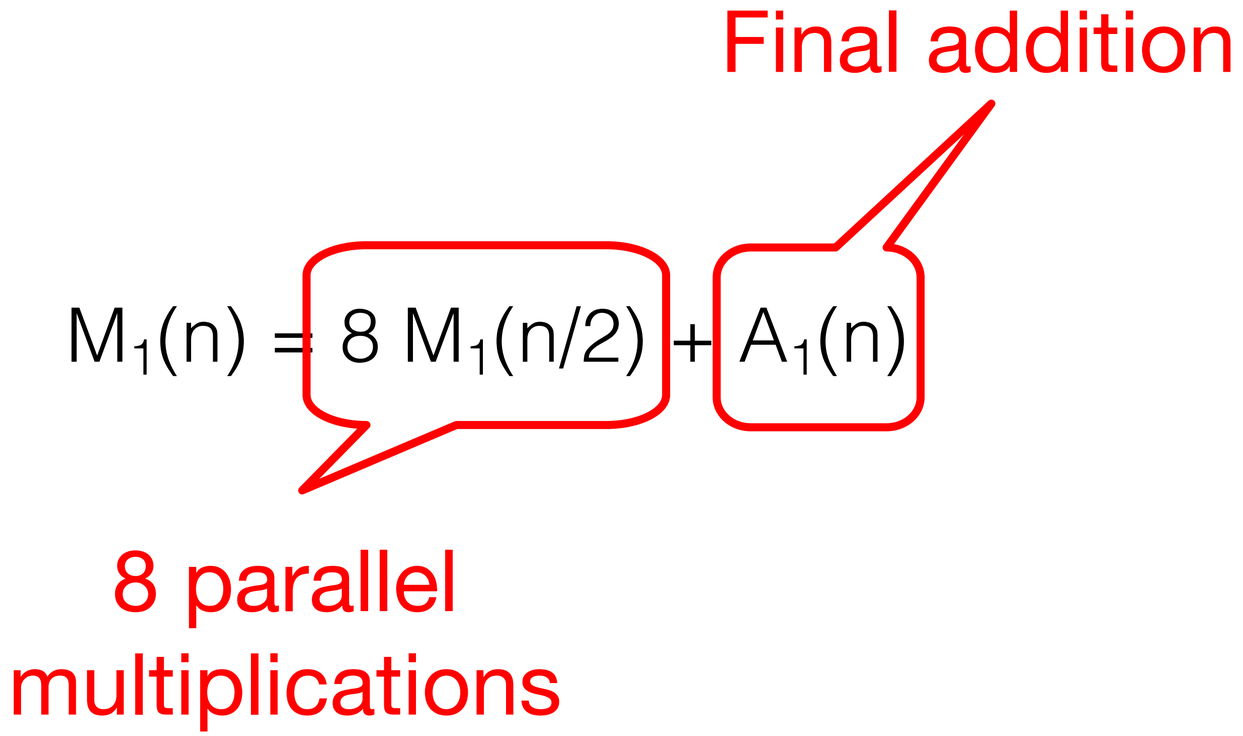
Second Phase …

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} A_{11}B_{11} + A_{12}B_{21} & A_{11}B_{12} + A_{12}B_{22} \\ A_{21}B_{11} + A_{22}B_{21} & A_{21}B_{12} + A_{22}B_{22} \end{pmatrix}$$



Multiplication

- Work is



Multiplication

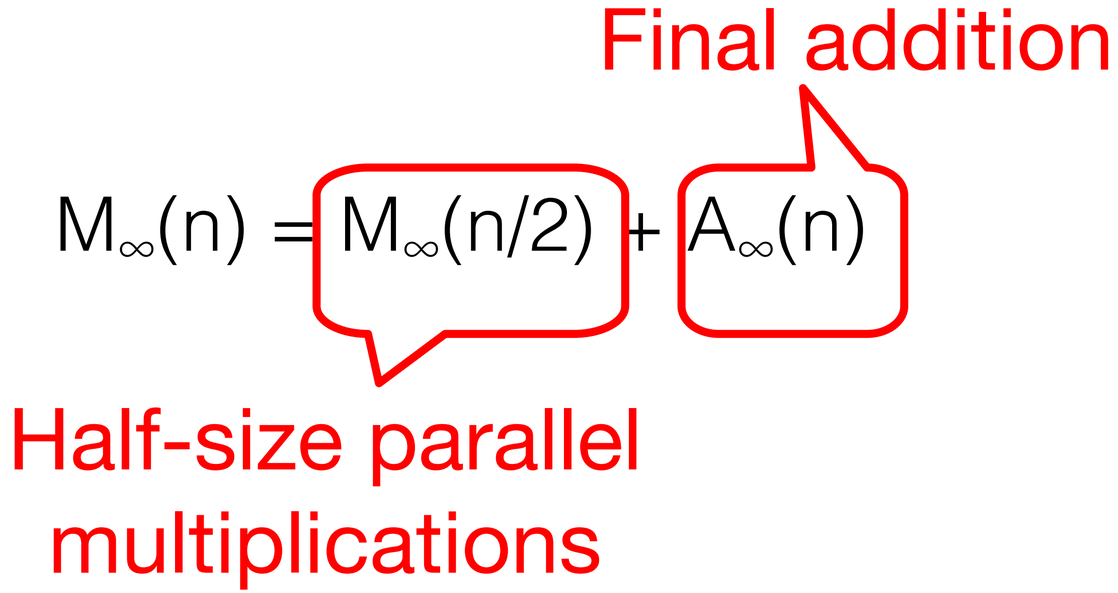
- Work is

$$M_1(n) = 8\,M_1(n/2) + \Theta(n^2)$$
$$= \Theta(n^3)$$

Same as serial triple-nested loop

Multiplication

- Critical path length is



Multiplication

- Critical path length is

$$
\begin{aligned}
M_\infty(n) &= M_\infty(n/2) + A_\infty(n) \\
&= M_\infty(n/2) + \Theta(\log n) \\
&= \Theta(\log^2 n)
\end{aligned}
$$

Parallelism

- $M_1(n)/ M_\infty(n) = \Theta(n^3/\log^2 n)$
- To multiply two 1000 x 1000 matrices
  - $1000^3/10^2=10^7$
- Much more than number of processors on any real machine

Shared-Memory Multiprocessors

- Parallel applications
  - Do not have direct access to HW processors
- Mix of other jobs
  - All run together
  - Come & go dynamically
- Hence, we have **no control** over how many processors we get at any given point
- Instead, shoot for the best parallelism that we can get given however many processors we actually get

Concurrent Programming Models

Asynchronous Programming

- AKA event-driven programming
- A paradigm that lends itself well to scaling, especially in a multi-stage systems (like the example with Facebook)
- Allows us to think about **what** is done, **abstract** away **how** it is done
- We will discuss two asynchronous models: **streams,** and **Promises**, **neither of which** make you think about threads (or locks?)

Streams

- Java 8 introduced the concept of **Streams**
- A stream is a sequence of objects
- Streams have functions that you can perform on them, which are (mostly) **non-interfering** and **stateless**
  - Non-interfering: Does not modify the actual stream
  - Stateless: Each time the function is called on the same data, get same result
- Example:

```
IntStream.range(1, 1000000) //Generate a stream of all ints 1 - 1m
.filter(x -> isPrime(x)) //Retain only values that pass some expensive isPrime function
.forEach(System.out::println); //For each value returned by filter, print it
```

Sidebar: Lambdas

- I don't know if you have seen this before

```
IntStream.range(1, 1000000)
.filter(x -> isPrime(x))
.forEach(System.out::println);
```

- This line is called a lambda expression
- We should have shown it to you before, because it's a core part of Java syntax since Java 8 was released in 2014
- Effectively, think of this as shorthand for:

```
IntStream.range(1, 1000000)
.filter(new IntPredicate() {
    @Override
    public boolean test(int x) {
        return isPrime(x);
    }
})
.forEach(System.out::println);
```

- In fact, javac generates exactly the long-hand code for that shorthand (but that println is cool, right?)

Streams

```
IntStream.range(1, 1000000) //Generate a stream of all ints 1 - 1m
.filter(x -> isPrime(x)) //Retain only values that pass some expensive isPrime function
.forEach(System.out::println); //For each value returned by filter, print it
```

- Why use the stream interface instead of

```
for(int i = 1; i < 1000000; i++)
    if(isPrime(x))
        System.out.println(x);
```

- Who wants to write the parallel version of this?

```
IntStream.range(1, 1000000) //Generate a stream of all ints 1 - 1m
.filter(x -> isPrime(x)) //Retain only values that pass some expensive isPrime function
.parallel() //Do the filtering in parallel
.forEach(System.out::println); //For each value returned by filter, print it
```

- The magic works as long as isPrime is stateless!

Streams - what can't be parallelized

- Interference

```
List<String> list = new ArrayList<>(Arrays.asList("Luke", "Leia", "Han"));
list.stream()
.peek(name -> {
    if (name.equals("Han")) {
        list.add("Chewie"); // Adds to list that we are peeking into
    }
})
.forEach(i -> {});
```

- Stateful

```
boolean tooBusy = false;
public void isPrime(int x)
{
    if(tooBusy)
        return false;//don't bother running if another thread set tooBusy
    else
        //do a sieve of erasthenes
}
```

- Side effects

```
List<Integer> list = new ArrayList<>(
Arrays.asList(1,3,5,7,9,11,13,15,17,19));
List<Integer> result = new ArrayList<>();
list.parallelStream()
.filter(x -> isPrime(x))
.forEach(x -> result.add(x)); //Changing external state, which may not (is not) thread safe
```

Streams under the hood

- Just adding more parallel() doesn't always make it faster! (see: law of leaky abstractions)
- There is some overhead to how a parallel operation occurs
- Internally, Java keeps a pool of **worker threads** (rather than make new threads for each parallel task)
- Streams use a special kind of pool, called a **ForkJoinPool**

Fork/Join Programming

- Special kind of task - fork() defines how to create subtasks, join() defines how to combine the results
- Similar to map/reduce, but not distributed
- For streams:
  - **Fork** a task into subtasks for many threads to work on
  - **Join** the results together

Fork/Join Programming

- Obligatory array sum example

```
class Sum extends RecursiveTask<Long> {
    static final int SEQUENTIAL_THRESHOLD = 5000;

    int low;
    int high;
    int[] array;

    Sum(int[] arr, int lo, int hi) {
        array = arr;
        low   = lo;
        high  = hi;
    }

    protected Long compute() {
        if(high - low <= SEQUENTIAL_THRESHOLD) {
            long sum = 0;
            for(int i=low; i < high; ++i)
                sum += array[i];
            return sum;
        } else {
            int mid = low + (high - low) / 2;
            Sum left  = new Sum(array, low, mid);
            Sum right = new Sum(array, mid, high);
            left.fork();
            long rightAns = right.compute();
            long leftAns  = left.join();
            return leftAns + rightAns;
        }
    }

    static long sumArray(int[] array) {
        return ForkJoinPool.commonPool().invoke(new Sum(array,0,array.length));
    }
}
```

Promises & CompleteableFutures

- What if we want to run some task, and do stuff while we are waiting for it to be done?
- You COULD do it with a complicated combination of **synchronized**, **wait**, and **notify**
- You can use the **Promise** abstraction instead
  - Called a **CompletableFuture** in Java 8

```
CompletableFuture<String> future = CompletableFuture.supplyAsync(() -> {
    try {
        TimeUnit.SECONDS.sleep(1);
    } catch (InterruptedException e) {
        throw new IllegalStateException(e);
    }
    return "Result of the asynchronous computation";
});
// Block and get the result of the Future
String result = future.get();
System.out.println(result);
```

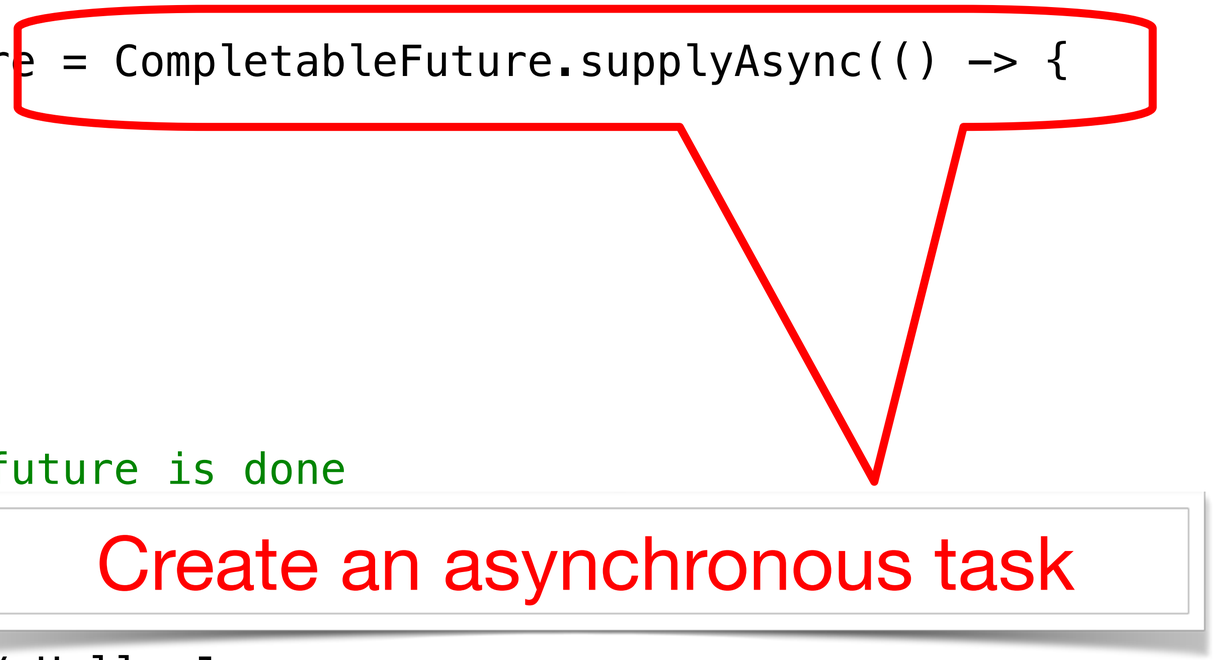
- Just like Future's from before, but supports *chaining*

Chaining CompletableFuture

```
CompletableFuture<String> whatsYourNameFuture = CompletableFuture.supplyAsync(() -> {
    try {
        TimeUnit.SECONDS.sleep(1);
    } catch (InterruptedException e) {
        throw new IllegalStateException(e);
    }
    return "Jon";
});
// Chain on some more code to run when the future is done
CompletableFuture<String> greetingFuture = whatsYourNameFuture.thenApply(returnValue -> {
    return “Hello, ” + returnValue;
});
System.out.println(greetingFuture.get()); // Hello Jon
```

Chaining CompletableFuture

```
CompletableFuture<String> whatsYourNameFuture = CompletableFuture.supplyAsync(() -> {
    try {
        TimeUnit.SECONDS.sleep(1);
    } catch (InterruptedException e) {
        throw new IllegalStateException(e);
    }
    return "Jon";
});
// Chain on some more code to run when the future is done
CompletableFuture<String> greetingFuture =
    return “Hello, ” + returnValue;
});
System.out.println(greetingFuture.get()); // Hello Jon
```



Chaining CompletableFuture

Task will return string “Jon” eventually

```
CompletableFuture.supplyAsync(() -> {
    try {
        TimeUnit.SECONDS.sleep(1);
    } catch (InterruptedException e) {
        throw new IllegalStateException(e);
    }
    return "Jon";
});
// Chain on some more code to run when the future is done
CompletableFuture<String> greetingFuture = whatsYourNameFuture.thenApply(returnValue -> {
    return “Hello, ” + returnValue;
});
System.out.println(greetingFuture.get()); // Hello Jon
```

Chaining CompletableFuture

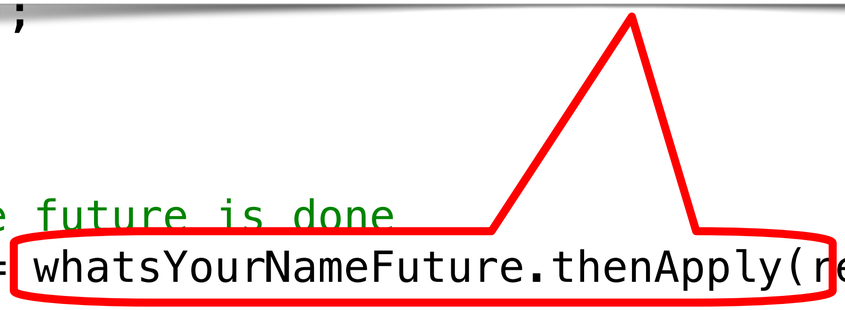
Task will return string “Jon” eventually

```
CompletableFuture.supplyAsync(() -> {
    try {
        TimeUnit.SECONDS.sleep(1);
    } catch (InterruptedException e) {
        throw new IllegalStateException(e);
    }
    return "Jon";
});
// Chain on some more code to run when the future is done
CompletableFuture<String> greetingFuture = whatsYourNameFuture.thenApply(returnValue -> {
    return “Hello, ” + returnValue;
});
System.out.println(greetingFuture.get()); // Hello Jon
```

Chaining CompletableFuture

```
CompletableFuture<String> whatsYourName
    try {
        TimeUnit.SECONDS.sleep(1);
    } catch (InterruptedException e) {
        throw new IllegalStateException(e);
    }
    return "Jon";
});
// Chain on some more code to run when the future is done
CompletableFuture<String> greetingFuture = whatsYourNameFuture.thenApply(returnValue -> {
    return “Hello, ” + returnValue;
});
System.out.println(greetingFuture.get()); // Hello Jon
```

Create ANOTHER future that is *chained* to the first



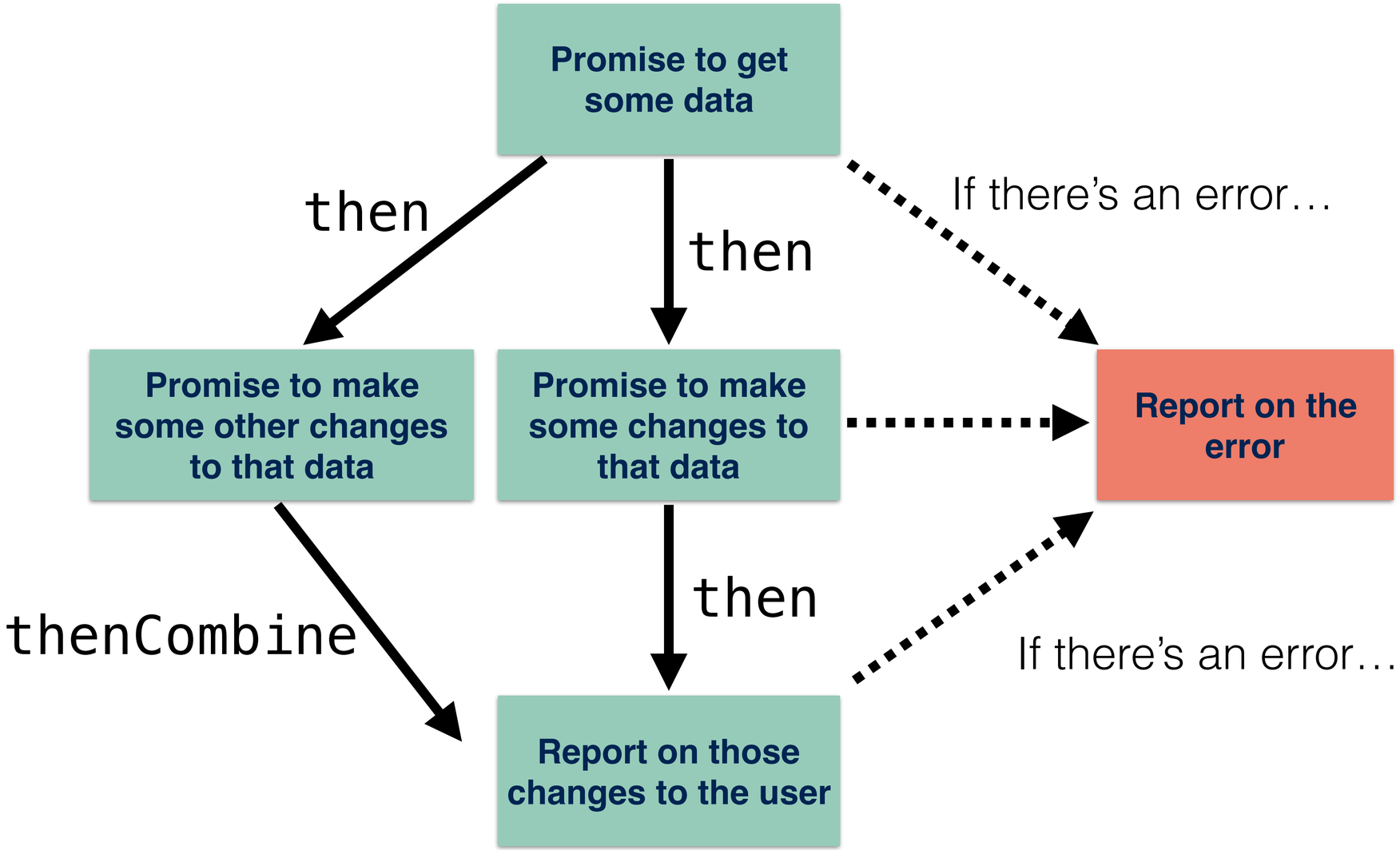
Chaining CompletableFuture

```
CompletableFuture<String> whatsYourNameFuture = CompletableFuture.supplyAsync(() -> {
    try {
        TimeUnit.SECONDS.sleep(1);
    } catch (InterruptedException e) {
        throw new IllegalStateException(e);
    }
    re
});
// Chain on some more code to run when the future is done
CompletableFuture<String> greetingFuture = whatsYourNameFuture.thenApply(returnValue -> {
    return “Hello, ” + returnValue;
});
System.out.println(greetingFuture.get()); // Hello Jon
```

Block the main thread for both futures to finish

Chaining CompletableFutures

- We can **chain** asynchronous activities together with the **thenAccept** term



CompleteableFuture Use-Cases

- Any case where you need to have multiple things happen in the background, but care about the result, and care about them happening in some order
- Asynchronous I/O
  - Read data from a web service
  - Then process it
  - Then save it to a file

CompletableFutures

- Catch errors by providing a callback function for **exceptionally** (called when an exception occurs in any of those threads
- API: https://docs.oracle.com/javase/8/docs/api/java/util/concurrent/CompletableFuture.html

This work is licensed under a Creative Commons Attribution-ShareAlike license