Principles of Software Construction: Objects, Design and Concurrency

The Perils of Concurrency, Part 3 (Can't live with it, can't live without it.)

15-214

toad

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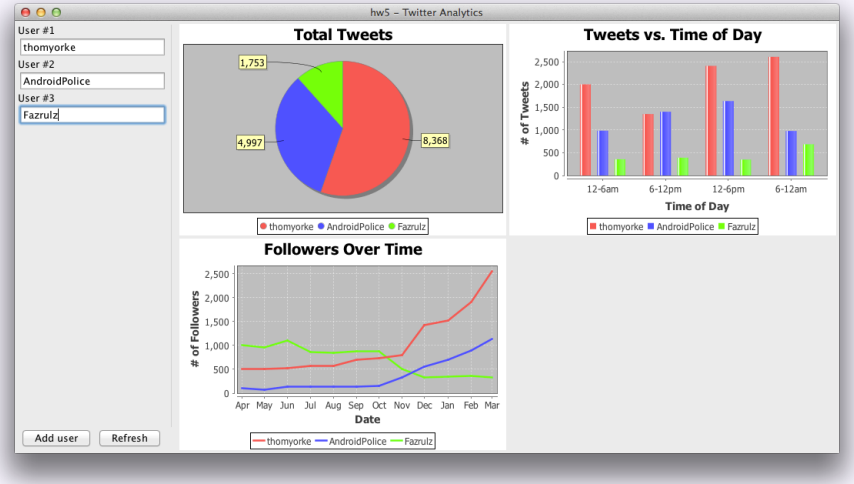
Christian Kästner **Charlie Garrod**

School of Computer Science
isr institute for SOFTWARE RESEARCH

Administrivia

- Homework 5: The Framework Strikes Back
  - 5a presentations tomorrow!
    - Two tracks; we will send room assignments soon



Key topics from last Thursday

Avoiding deadlock with restarts

- One option: If thread needs a lock out of order, restart the thread
  - Get the new lock in order this time
- Another option: Arbitrarily kill and restart long-running threads
- Optimistic concurrency control
  - e.g., with a copy-on-write system
  - Don't lock, just detect conflicts later
    - Restart a thread if a conflict occurs

Another concurrency problem: livelock

- In systems involving restarts, *livelock* can occur
  - Lack of progress due to repeated restarts
- *Starvation*: when some task(s) is(are) repeatedly restarted because of other tasks

Today: More concurrency

- Java tools for managing concurrency
  - Classic concurrent data structures
- Higher-level concurrent algorithms
- Thursday: More Java tools…

Concurrency control in Java

- Using primitive synchronization, you are responsible for correctness:
  - Avoiding race conditions
  - Progress (avoiding deadlock and livelock)
- Java provides tools to help:
  - `volatile` fields
  - `java.util.concurrent.atomic`
  - `java.util.concurrent`

The Java *happens-before* relation

- Java guarantees a transitive, consistent order for some memory accesses
  - Within a thread, one action *happens-before* another action based on the usual program execution order
  - Release of a lock *happens-before* acquisition of the same lock
  - `Object.notify` *happens-before* `Object.wait` returns
  - `Thread.start` *happens-before* any action of the started thread
  - Write to a `volatile` field *happens-before* any subsequent read of the same field
  - …
- Assures ordering of reads and writes
  - A race condition can occur when reads and writes are not ordered by the happens-before relation

The `java.util.concurrent.atomic` package

- Concrete classes supporting atomic operations
  - `AtomicInteger`

```
int  get();
void set(int newValue);
int  getAndSet(int newValue);
int  getAndAdd(int delta);
…
```

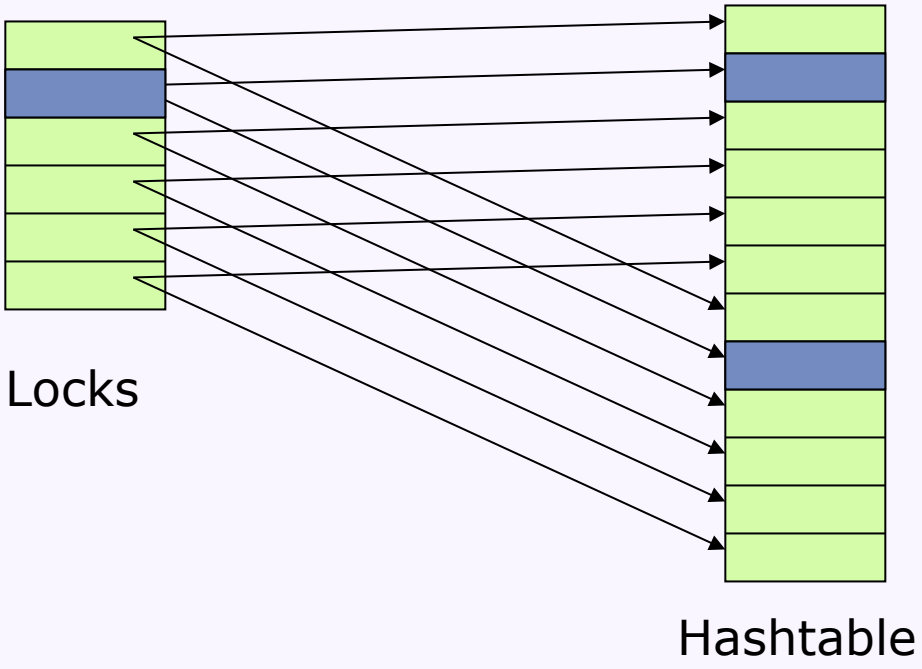
  - `AtomicIntegerArray`
  - `AtomicBoolean`
  - `AtomicLong`
  - …

The `java.util.concurrent` package

- Interfaces and concrete thread-safe data structure implementations
  - `ConcurrentHashMap`
  - `BlockingQueue`
    - `ArrayBlockingQueue`
    - `SynchronousQueue`
  - `CopyOnWriteArrayList`
  - …
- Other tools for high-performance multi-threading
  - `ThreadPools` and `Executor` services
  - `Locks` and `Latches`

java.util.concurrent.ConcurrentHashMap

- Implements `java.util.Map<K,V>`
  - High concurrency lock striping
    - Internally uses multiple locks, each dedicated to a region of the hash table
    - Locks just the part of the table you actually use
    - You use the `ConcurrentHashMap` like any other map…



java.util.concurrent.BlockingQueue

- Implements `java.util.Queue<E>`
- `java.util.concurrent.SynchronousQueue`
  - Each `put` directly waits for a corresponding `poll`
  - Internally uses `wait/notify`
- `java.util.concurrent.ArrayBlockingQueue`
  - `put` blocks if the queue is full
  - `poll` blocks if the queue is empty
  - Internally uses `wait/notify`

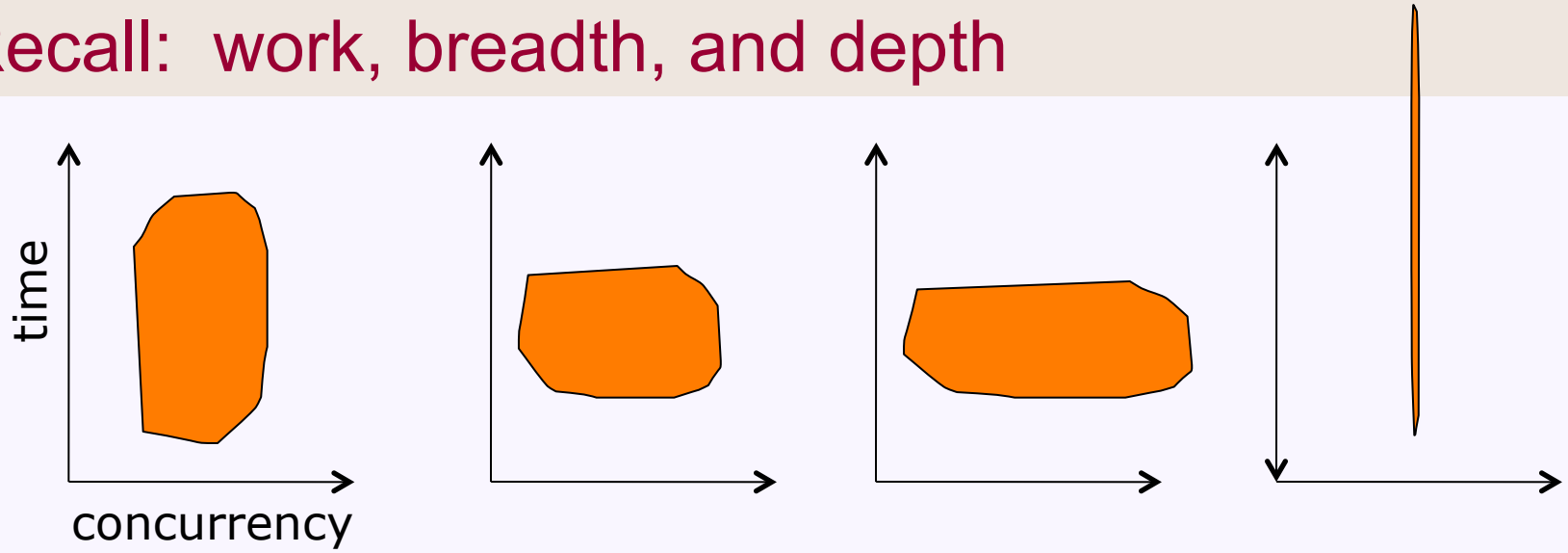
The `CopyOnWriteArrayList`

- Implements `java.util.List<E>`
- All writes to the list copy the array storing the list elements

The power of immutability

- Data is *mutable* if it can change over time. Otherwise it is *immutable*.
  - Data declared as `final` is always immutable
- After immutable data is initialized, it is immune from race conditions

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

Concurrency at the language level

- Consider:

```
int sum = 0;
Iterator i = list.iterator();
while (i.hasNext()) {
    sum += i.next();
}
```

- In python:

```
sum = 0;
for item in lst:
    sum += item
```

Parallel quicksort in Nesl

```
function quicksort(a) =
  if (#a < 2) then a
  else
   let pivot   = a[#a/2];
       lesser  = {e in a| e < pivot};
       equal   = {e in a| e == pivot};
       greater = {e in a| e > pivot};
       result  = {quicksort(v): v in [lesser,greater]};
   in result[0] ++ equal ++ result[1];
```

- Operations in {} occur in parallel
- What is the total work? What is the depth?
  - What assumptions do you have to make?

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
```

A better parallel prefix sums algorithm

- 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:

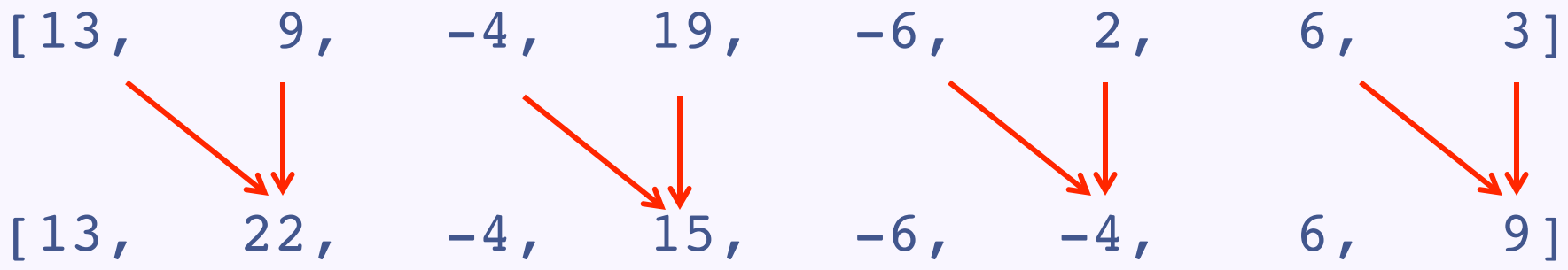
```
prefix_sums(x):
  for d in 0 to (lg n)-1:              // d is depth
    parallelfor i in 2^d-1 to n-1, by 2^(d+1):
      x[i+2^d] = x[i] + x[i+2^d]

  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]`

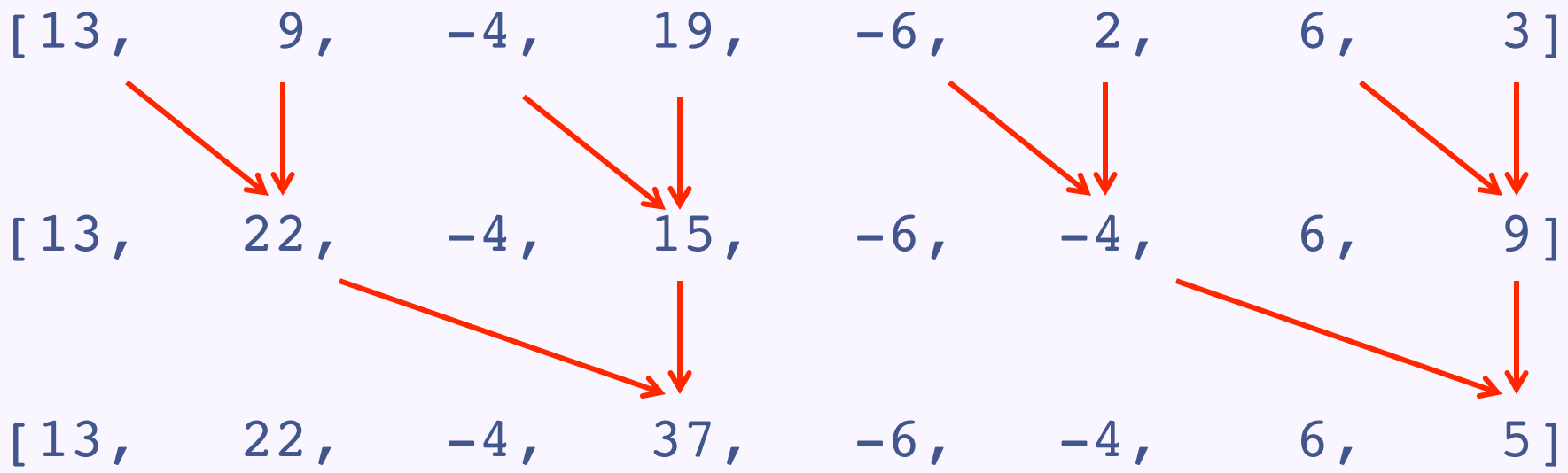
A better parallel prefix sums algorithm, part 1

- Computes the partial sums in a more useful manner



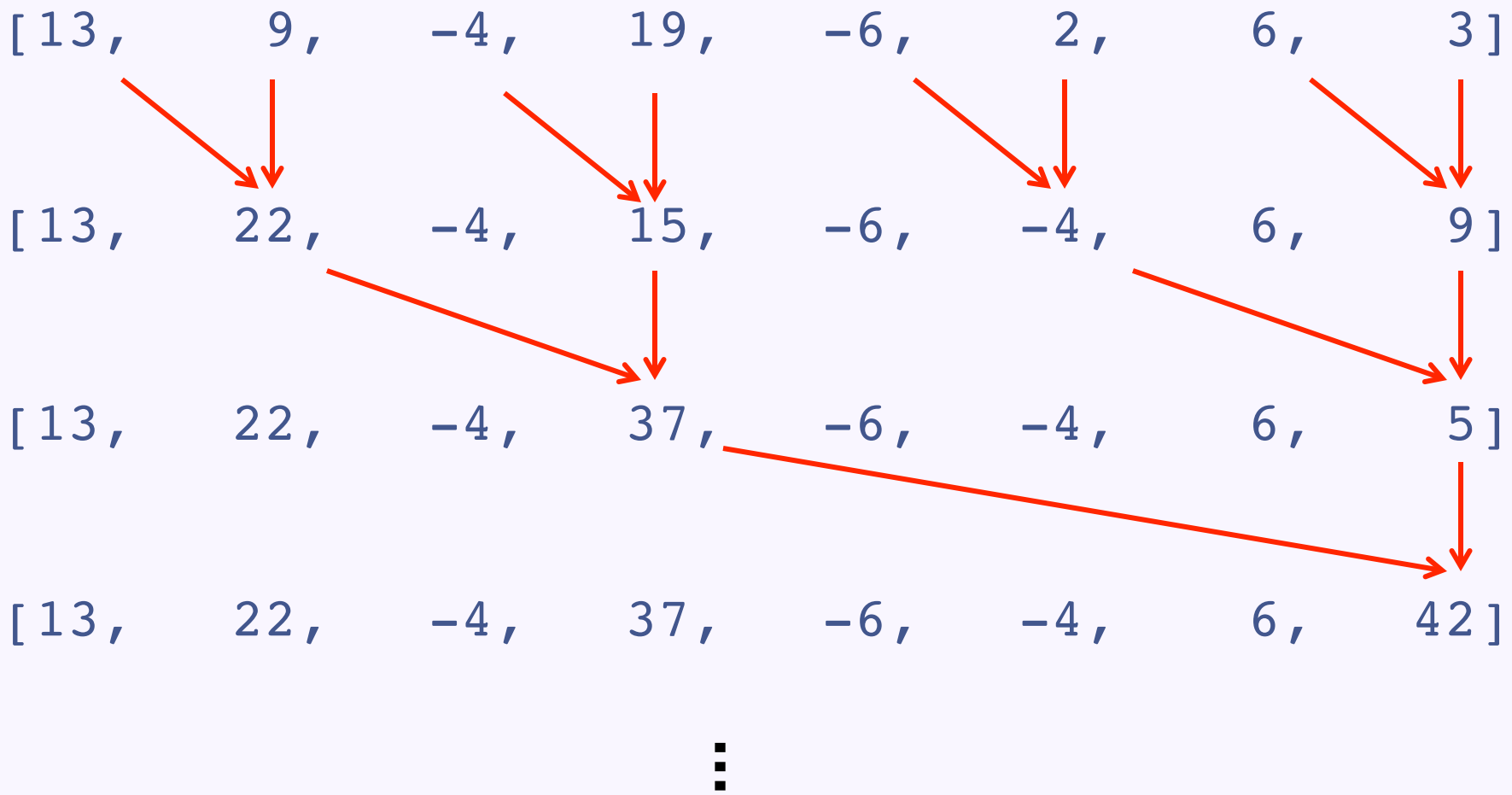
A better parallel prefix sums algorithm, part 1

- 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

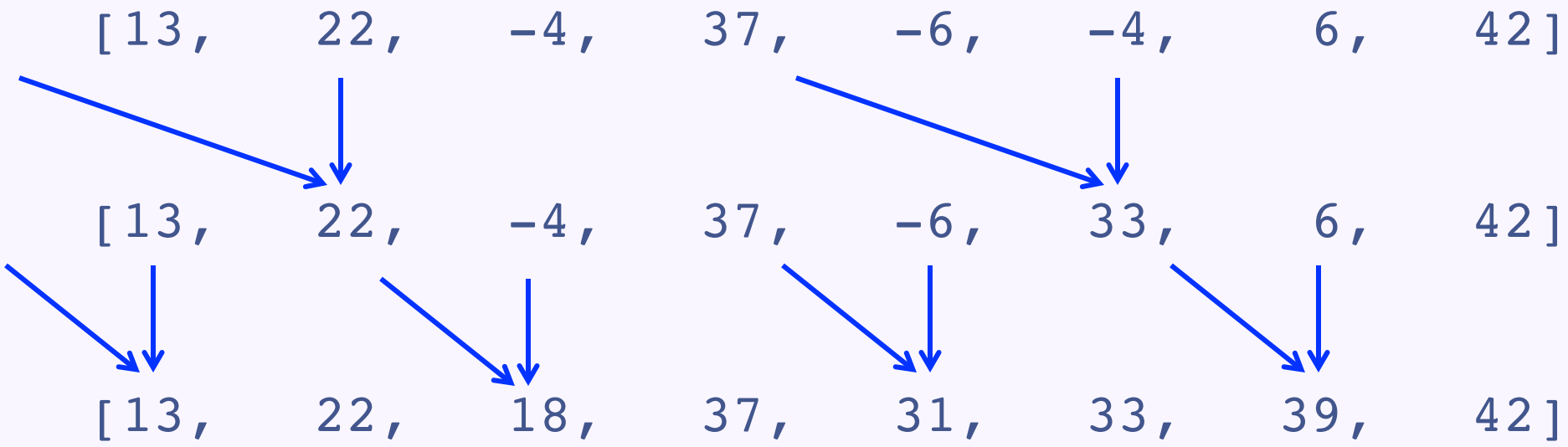


A better parallel prefix sums algorithm, part 2

- Now unwinds to calculate the other sums

A better parallel prefix sums algorithm, part 2

- Now unwinds to calculate the other sums



- 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?
  - O(n) work, O(lg n) depth

A better parallel prefix sums algorithm

- How good is this?
  - O(n) work, O(lg n) depth
  - About 2n useful additions, plus extra additions for the loop indexes
  - Converts sequential memory access into non-sequential memory access
- See PrefixSums.java, PrefixSumsSequentialImpl.java, PrefixSumsNonSequentialImpl.java, and Main.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];
}
```

Goal: parallelize PrefixSumsNonSequentialImpl

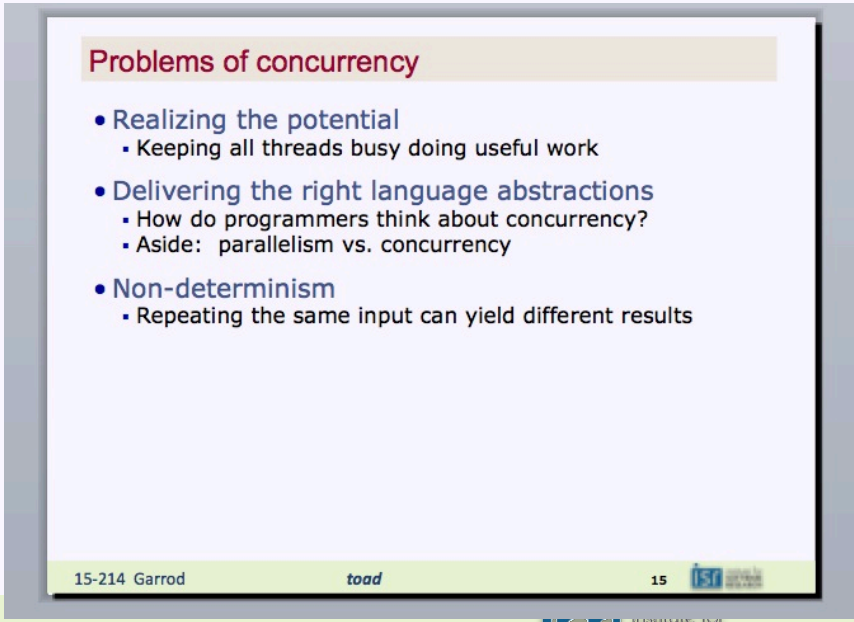
- Specifically, parallelize the parallelizable loops

```
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];
}
```

- Caveats:
  - We know we can't beat the sequential implementation on my 4-core computer



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();
```

Recall the Java primitive concurrency tools

- The `java.lang.Runnable` interface

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void          run();
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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 (but not today)

Fork/Join: another common computational pattern

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

Fork/Join: another common computational pattern

- In a long computation:
  - Fork one (or more) thread(s) 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 RecursiveActionImpl
                              extends RecursiveAction {
    public RecursiveActionImpl(…) {
      store the data fields we need
    }

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

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

A ForkJoin example

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

Thursday:

- More Java tools for managing concurrency