CSE 332 Summer 2024 Lecture 18: ForkJoin, Maps, Reductions

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Parallelism Vs. Concurrency (with Potatoes)

- Sequential:
  - The task is completed by just one processor doing one thing at a time
  - There is one cook who peels all the potatoes
- Parallelism:
  - One task being completed by may threads
  - Recruit several cooks to peel a lot of potatoes faster
- Concurrency:
  - Parallel tasks using a shared resource
  - Several cooks are making their own recipes, but there is only 1 oven

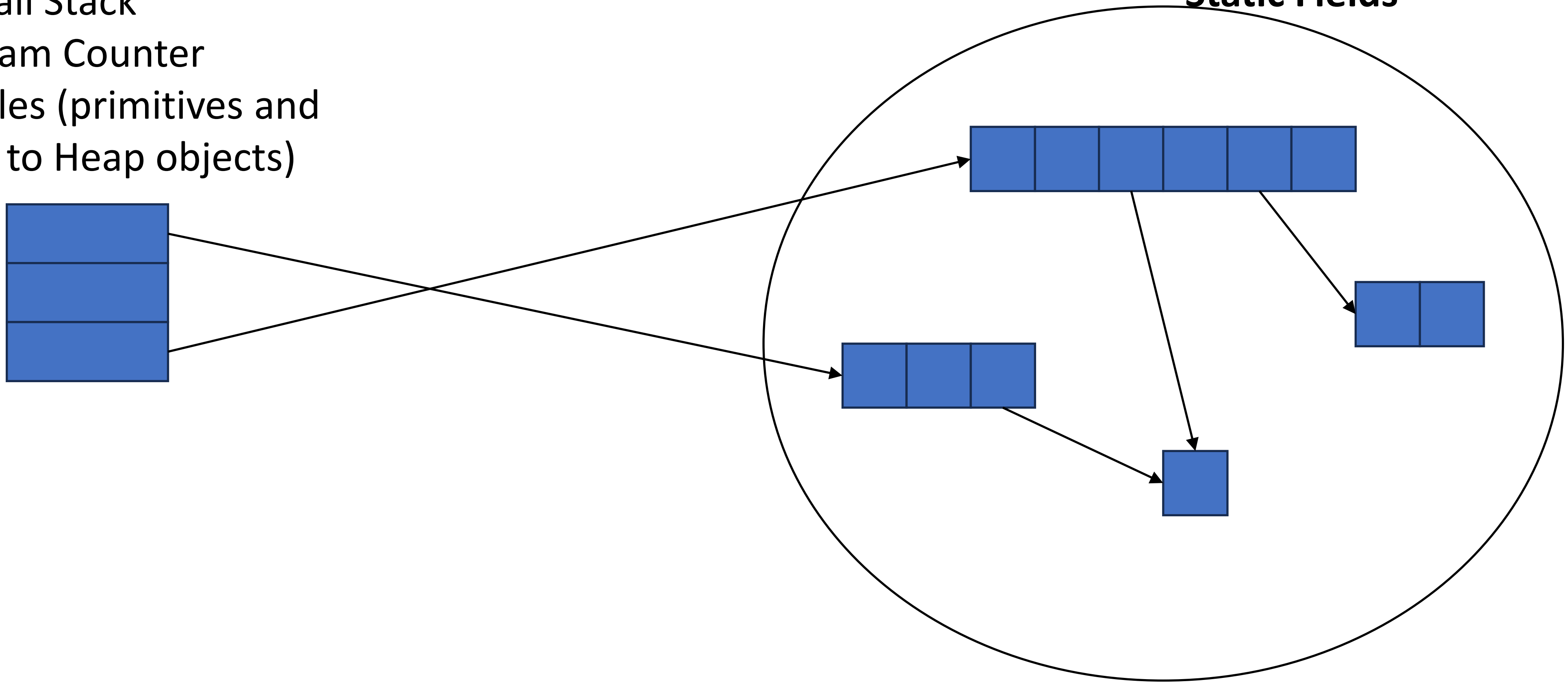
New Story of Code Execution

- Old Story:
  - One program counter (current statement executing)
  - One call stack (with each stack frame holding local variables)
  - Objects in the heap created by memory allocation (i.e., new)
    - (nothing to do with data structure called a heap)
- New Story:
  - Collection of threads each with its own:
    - Program Counter
    - Call Stack
    - Local Variables
    - References to objects in a shared heap

Old Story

Call Stack
Program Counter
Local Variables (primitives and references to Heap objects)

Heap Containing Objects and Static Fields



New Story

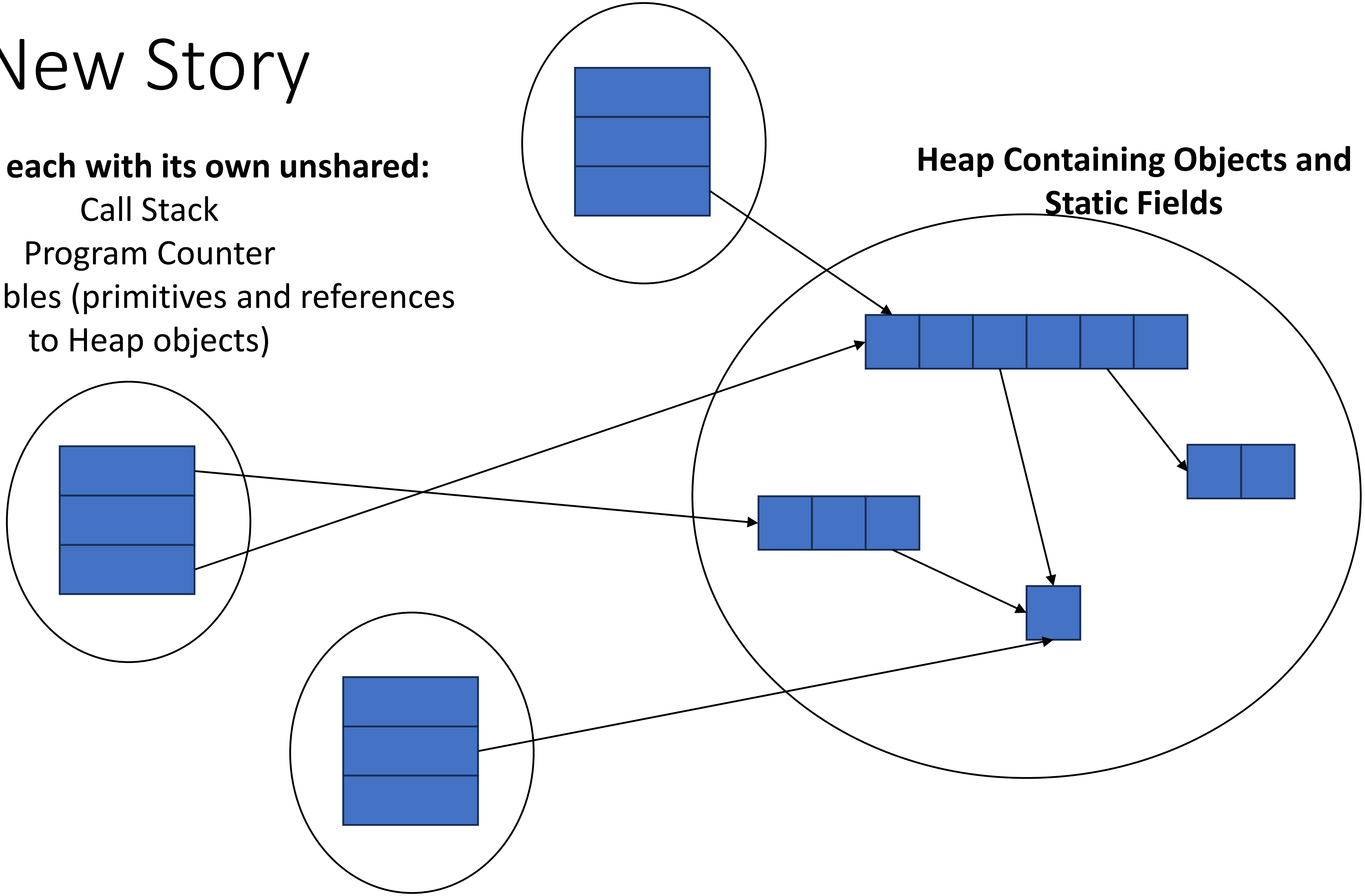
Threads, each with its own unshared:

Call Stack

Program Counter

Local Variables (primitives and references to Heap objects)

Heap Containing Objects and Static Fields



Needs from Our Programming Language

- A way to create multiple things running at once
  - Threads
- Ways to share memory
  - References to common objects
- Ways for threads to synchronize
  - For now, just wait for other threads to finish their work

Parallelism Example (not real code)

- Goal: Find the sum of an array
- Idea: 4 processors will each find the sum of one quarter of the array, then we can add up those 4 results

```
int sum(int[] arr){
   res = new int[4];
   len = arr.length;
   FORALL(i=0; i < 4; i++) {   //parallel iterations
      res[i] = sumRange(arr,i*len/4,(i+1)*len/4);
   }
   return res[0]+res[1]+res[2]+res[3];
}

int sumRange(int[] arr, int lo, int hi) {
   result = 0;
   for(j=lo; j < hi; j++)
      result += arr[j]; return result;
}
```

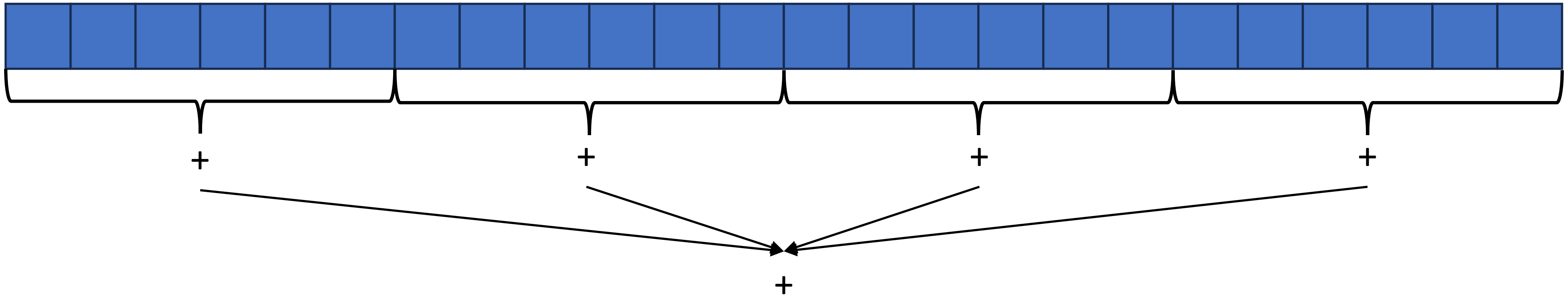
Note: This FORALL construct does not exist, but it’s similar to how we’ll actually do it.

Java.lang.Thread

- To run a new thread:
  1. Define a subclass **C** of java.lang.Thread, overriding **run**
  2. Create an object of class **C**
  3. Call that object's **start** method
     - **start** sets off a new thread, using **run** as its "main"
- Calling "**run**" directly causes the program to execute "**run**" sequentially

Back to Summing an Array

- Goal: Find the sum of an array
- Idea: 4 threads each find the sum of one quarter of the array
- Process:
  - Create 4 thread objects, each given a portion of the work
  - Call start() on each thread object to run it in parallel
  - Wait for threads to finish using join()
  - Add together their 4 answers for the final result



First Attempt (part 1, Defining Thread Object)

```
class SumThread extends java.lang.Thread {
    int lo;     // fields, assigned in the constructor
    int hi;     // so threads know what to do.
    int[] arr;
    int ans = 0; // result

    SumThread(int[] a, int l, int h) {
        lo=l; hi=h; arr=a;
    }

    public void run() { //override must have this type
        for(int i=lo; i < hi; i++)
            ans += arr[i];
    }
```

First Attempt (part 2, Creating Thread Objects)

```
static int parallelSum(int[] arr){ // this method could be anywhere
        int len = arr.length;
        int ans = 0;
        SumThread[] threads = new SumThread[4];
        for(int i=0; i < 4; i++) // create threads
                threads[i] = new SumThread(arr, i*len/4, (i+1)*len/4);
        // more stuff to follow
}
```

```
class SumThread extends java.lang.Thread {
        int lo, int hi, int[] arr; // fields to know what to do
        int ans = 0; // result
        SumThread(int[] a, int l, int h) { … }
        public void run(){ … } // override
}
```

First Attempt (part 3, Running Thread Objects)

```
static int parallelSum(int[] arr){ // this method could be anywhere
        int len = arr.length;
        int ans = 0;
        SumThread[] threads = new SumThread[4];
        for(int i=0; i < 4; i++){ // create threads, do parallel computations
                threads[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
                threads[i].start(); // start not run
        }
        for(int i=0; i < 4; i++) // combine results
                ans += threads[i].ans;
        return ans;
}
```

```
class SumThread extends java.lang.Thread {
        int lo, int hi, int[] arr; // fields to know what to do
        int ans = 0; // result
        SumThread(int[] a, int l, int h) { … }
        public void run(){ … } // override
}
```

First Attempt (part 4, Synchronizing)

```
static int parallelSum(int[] arr){ // this method could be anywhere
        int len = arr.length;
        int ans = 0;
        SumThread[] threads = new SumThread[4];
        for(int i=0; i < 4; i++){ // do parallel computations
                threads[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
                threads[i].start(); // start not run
        }
        for(int i=0; i < 4; i++){ // combine results
                threads[i].join(); // wait for thread to finish!
                ans += threads[i].ans;
        }
        return ans;
}
```

```
class SumThread extends java.lang.Thread {
        int lo, int hi, int[] arr; // fields to know what to do
        int ans = 0; // result
        SumThread(int[] a, int l, int h) { … }
        public void run(){ … } // override
}
```

Join

- Causes program to pause until the other thread completes its **run** method
- Avoids a **race condition**
  - Without join the other thread's **ans** field may not have its final answer yet

Adding More Parallelism!

Different machines have different numbers of processors!

Making the thread count a parameter helps make your program more efficient and reusable across computers

```
static int parallelSum(int[] arr, int numTs){
    int len = arr.length;
    int ans = 0;
    SumThread[] threads = new SumThread[numTs];
    for(int i=0; i < numTs; i++){ // do parallel computations
        threads[i] = new SumThread(arr, i*len/numTs, (i+1)*len/numTs);
        threads[i].start(); // start not run
    }
    for(int i=0; i < numTs; i++) {// combine results
        threads[i].join(); // wait for thread to finish!
        ans += threads[i].ans;
    }
    return ans;
}
```

Flaws With this Attempt

- Even If we make the number of threads equal to the number of processors, the OS is doing time slicing, so we might not have all processors available right now
- For some problems, not all subproblems will take the same amount of time:
  - E.g. determining whether all integers in an array are prime.

One Potential Solution: More Threads!

- Identify an “optimal” workload per thread
  - E.g. maybe it’s not worth splitting the work if the array is shorter than 1000
- Split the array into chunks using this “sequential Cutoff”
  - numTs = len/SEQ_CUTOFF;
- Problem: One process is still responsible for summing all len/1000 results
  - Process is still linear time

A Better Solution: Divide and Conquer!

- Idea: Each thread checks its problem size. If its smaller than the sequential cutoff, it will sum everything sequentially. Otherwise it will split the problem in half across two separate threads.

Merge Sort

5	8	2	9	4	1

5

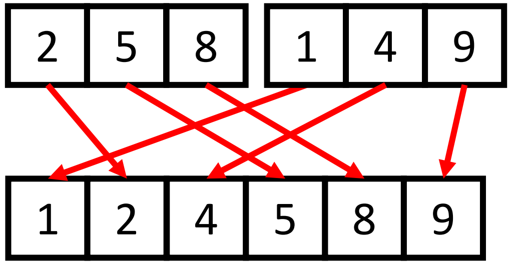
- **Base Case**:
  - If the list is of length 1 or 0, it’s already sorted, so just return it

5	8	2	9	4	1

- **Divide**:
  - Split the list into two “sublists” of (roughly) equal length

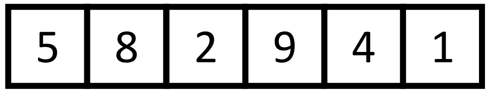
2	5	8	1	4	9

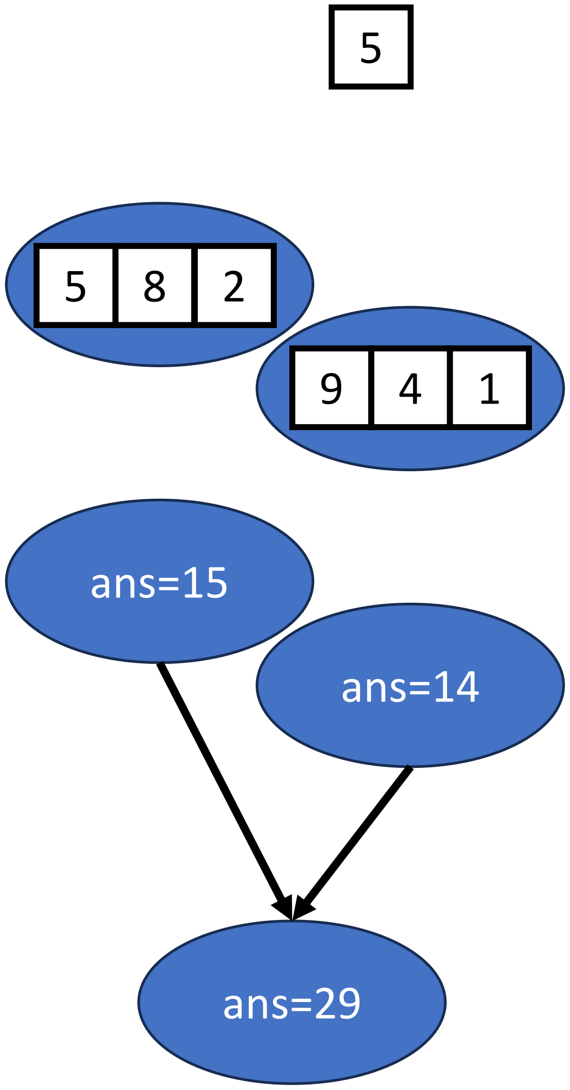
- **Conquer**:
  - Sort both lists recursively



- **Combine**:
  - **Merge** sorted sublists into one sorted list

Parallel Sum





- **Base Case:**
  - If the list's length is smaller than the Sequential Cutoff, find the sum sequentially
- **Divide:**
  - Split the list into two "sublists" of (roughly) equal length, create a thread to sum each sublist.
- **Conquer:**
  - Call **start()** for each thread
- **Combine:**
  - Sum together the answers from each thread

Divide and Conquer with Threads

```
class SumThread extends java.lang.Thread {
        public void run(){ // override
                if(hi – lo < SEQUENTIAL_CUTOFF) // “base case”
                        for(int i=lo; i < hi; i++) ans += arr[i];
                else {
                        SumThread left = new SumThread(arr,lo,(hi+lo)/2); // divide
                        SumThread right= new SumThread(arr,(hi+lo)/2,hi); // divide
                        left.start(); // conquer
                        right.start(); // conquer
                        left.join(); // don’t move this up a line – why?
                        right.join();
                        ans = left.ans + right.ans; // combine
                }
        }
}
int sum(int[] arr){ // just make one thread!
        SumThread t = new SumThread(arr,0,arr.length);
        t.run();
        return t.ans; }
```

Small optimization

- Instead of calling two separate threads for the two subproblems, create one parallel thread (using **start**) and one sequential thread (using **run**)

Divide and Conquer with Threads (optimized)

```
class SumThread extends java.lang.Thread {
	public void run(){ // override
		if(hi – lo < SEQUENTIAL_CUTOFF) // “base case”
			for(int i=lo; i < hi; i++) ans += arr[i];
		else {
			SumThread left = new SumThread(arr,lo,(hi+lo)/2); // divide
			SumThread right= new SumThread(arr,(hi+lo)/2,hi); // divide
			left.start(); // conquer
			right.run(); // conquer
			left.join(); // don’t move this up a line – why?
			//right.join();
			ans = left.ans + right.ans; // combine
		}
	}
}
int sum(int[] arr){ // just make one thread!
	SumThread t = new SumThread(arr,0,arr.length);
	t.run();
	return t.ans; }
```

ForkJoin Framework

- This strategy is common enough that Java (and C++, and C#, and…) provides a library to do it for you!

What you would do in Threads	What to instead in ForkJoin
Subclass **Thread**	Subclass **RecursiveTask<V>**
Override **run**	Override **compute**
Store the answer in a field	Return a V from compute
Call **start**	Call **fork**
join synchronizes only	**join** synchronizes and returns the answer
Call **run** to execute sequentially	Call **compute** to execute sequentially
Have a topmost thread and call **run**	Create a pool and call **invoke**

Divide and Conquer with ForkJoin

```
class SumTask extends RecursiveTask<Integer> {
	int lo; int hi; int[] arr; // fields to know what to do
	SumTask(int[] a, int l, int h) { … } // constructor
	protected Integer compute(){ // return answer
		if(hi – lo < SEQUENTIAL_CUTOFF) {  // base case
			int ans = 0; // local var, not a field
			for(int i=lo; i < hi; i++) {
				ans += arr[i]; return ans; }
		else {
			SumTask left = new SumTask(arr,lo,(hi+lo)/2); // divide
			SumTask right= new SumTask(arr,(hi+lo)/2,hi); // divide
			left.fork(); // execute the left compute in parallel(conquer)
			int rightAns = right.compute(); //do right compute sequentially (conquer)
			int leftAns = left.join(); // wait for result from left, save return value to a variable
			return leftAns + rightAns; // combine
		}
	}
}
```

Divide and Conquer with ForkJoin (continued)

```
static final ForkJoinPool POOL = new ForkJoinPool();
static int parallelSum(int[] arr){
        SumTask task = new SumTask(arr,0,arr.length)
        return POOL.invoke(task); // invoke returns the value compute returns
}
```

Find Max with ForkJoin

```
class MaxTask extends RecursiveTask<Integer> {
        int lo; int hi; int[] arr; // fields to know what to do
        SumTask(int[] a, int l, int h) { … }
        protected Integer compute(){// return answer
                if(hi – lo < SEQUENTIAL_CUTOFF) {  // base case
                        int ans = Integer.MIN_VALUE; // local var, not a field
                        for(int i=lo; i < hi; i++) {
                                ans = Math.max(ans, arr[i]);}
                        return ans;
                else {
                        MaxTask left = new MaxTask(arr,lo,(hi+lo)/2); // divide
                        MaxTask right= new MaxTask(arr,(hi+lo)/2,hi); // divide
                        left.fork(); // fork a thread and calls compute (conquer)
                        int rightAns = right.compute(); //call compute directly (conquer)
                        int leftAns = left.join(); // get result from left
                        return Math.max(rightAns, leftAns); // combine
                }
        }
}
```

Other Problems that can be solved similarly

- Element Search
  - Is the value 17 in the array?
- Counting items with a certain property
  - How many elements of the array are divisible by 5?
- Checking if the array is sorted
- Find the smallest rectangle that covers all points in the array
- Find the first thing that satisfies a property
  - What is the leftmost item that is divisible by 20?

Reductions

- All examples of a category of computation called a reduction
  - We “reduce” all elements in an array to a single item
  - Requires operation done among elements is associative
    - $(x + y) + z = x + (y + z)$
  - The “single item” can itself be complex
    - E.g. create a histogram of results from an array of trials

Map

- Perform an operation on each item in an array to create a new array of the same size
- Examples:
  - Vector addition:
    - sum[i] = arr1[i] + arr2[i]
  - Function application:
    - out[i] = f(arr[i]);

Map with ForkJoin

```
class AddTask extends RecursiveAction {
        int lo; int hi; int[] arr; // fields to know what to do
        AddTask(int[] a, int[] b, int[] sum, int l, int h) { … }
        protected void compute(){// return answer
                if(hi – lo < SEQUENTIAL_CUTOFF) {  // base case
                        for(int i=lo; i < hi; i++) {
                                sum[i] = a[i] + b[i];}
                else {
                        AddTask left = new AddTask(a,b,sum,lo,(hi+lo)/2); // divide
                        AddTask right= new AddTask(a,b,sum,(hi+lo)/2,hi); // divide
                        left.fork(); // fork a thread and calls compute (conquer)
                        right.compute(); //call compute directly (conquer)
                        left.join(); // get result from left
                        return; // combine
                }
        }
}
```

Map with ForkJoin (continued)

```
static final ForkJoinPool POOL = new ForkJoinPool();
int[] add(int[] a, int[] b){
	int[] ans = new int[a.length];
	AddTask task = new AddTask(a, b, ans, 0, a.length)
	POOL.invoke(task);
	return ans;
}
```

Maps and Reductions

- “Workhorse” constructs in parallel programming
- Many problems can be written in terms of maps and reductions
- With practice, writing them will become second nature
  - Like how over time for loops and if statements have gotten easier

Section

- Working with examples of ForkJoin
- Make sure to bring your laptops!
    - And charge it!