CSE 332: Data Structures and Parallelism

Fall 2022

Richard Anderson

Lecture 19: Introduction to Parallelism

Course Schedule

- Lectures 1- 16: Traditional Data Structures
- Lectures 17-18: Intro to Graphs
- Lectures 19-21: Parallelism
- Lectures 22-23: Concurrency
- Lectures 24-27: Graph Algorithms
- Lectures 28-29: Theory of NP-Completeness

Announcements

- Read parallel computing notes by Dan Grossman 2.1-3.4
- Midterm
  - Stats: Median – 72, Mean 70.8, SD 15.7
- Projects
  - Project 3 – Parallel Implementation of Bellman-Ford algorithm

Sequential Summation

- Sum up N numbers in an array
  - Complexity?

Parallel Sum

- Sum up N numbers in an array
  - with two processors

Parallel Sum

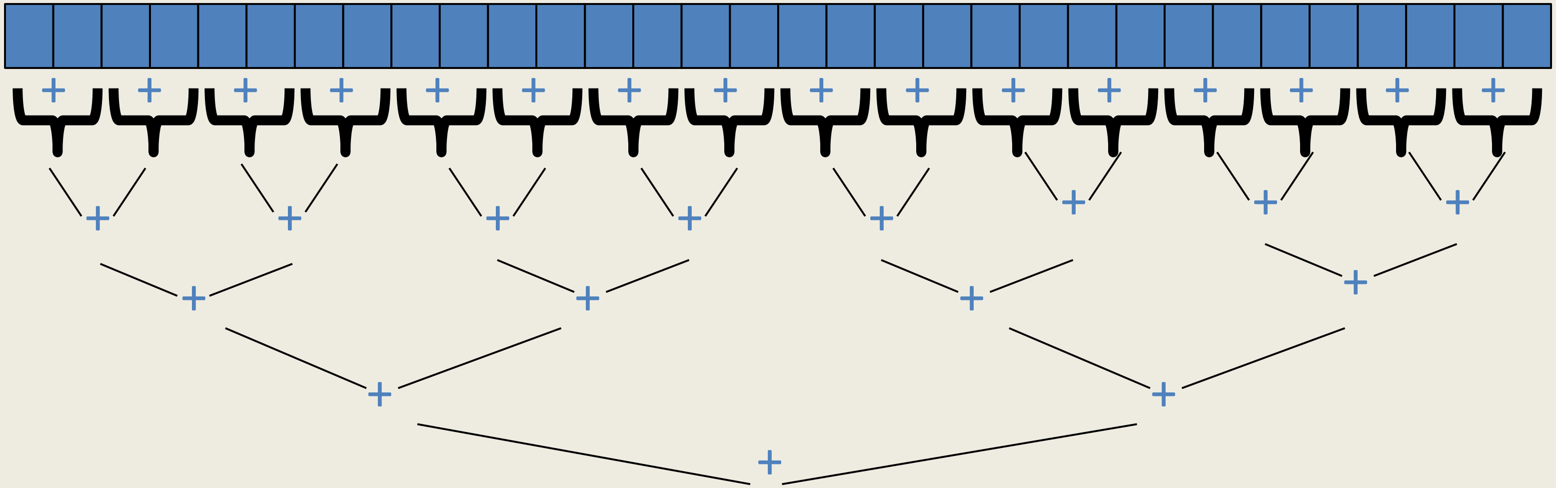
- Sum up N numbers in an array
  - with ten processors

Parallel Sum

- Sum up N numbers in an array
  - with N processors?

Parallel Sum

- Sum up N numbers in an array



- Complexity?
- How many processors?
- Faster with infinite processors?

Parallel Algorithms

- So far, we have assumed:

  One thing happens at a time

- What if we want to implement algorithms with multiple "processors"
  - How do we model parallel computing
  - How do we program parallel computers

Parallel Computation

- There is nothing new about parallel computation
- Hardware design and architecture have always been about parallelism
  - Parallelism has been central to computer performance
- Parallel algorithms have been an area of study since the late 1970s
- Hardware trends
  - Multiple cores in processors
  - Can no longer make components smaller to make them faster – need to make more of them

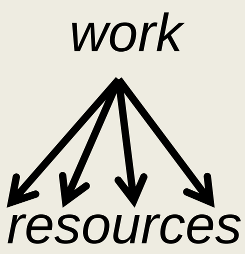
Who Implements Parallelism

- User
- Application
- Operating System
- Programming Language, Compiler
- Algorithm
- Processor Hardware

Parallelism vs. Concurrency

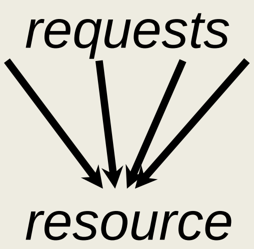
Parallelism:

Use extra resources to solve a problem faster



Concurrency:

Manage access to shared resources



Shared Memory with Threads

Old story: A running program has

- 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)
- *Static fields*

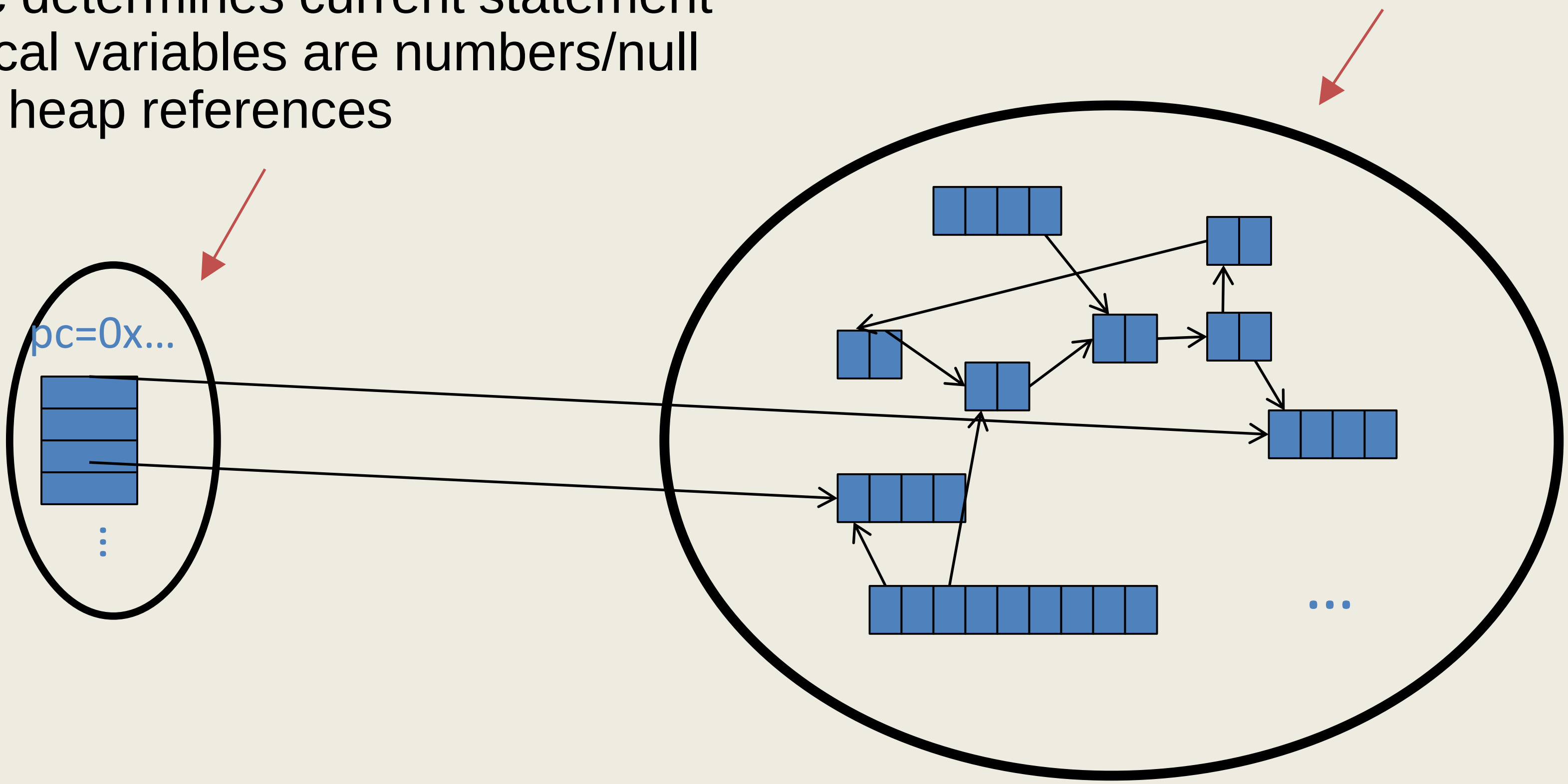
New story:

- A set of *threads*, each with its own program counter & call stack
  - No access to another thread's local variables
- Threads can share static fields / objects
  - To *communicate*, write values to some shared location that another thread reads from

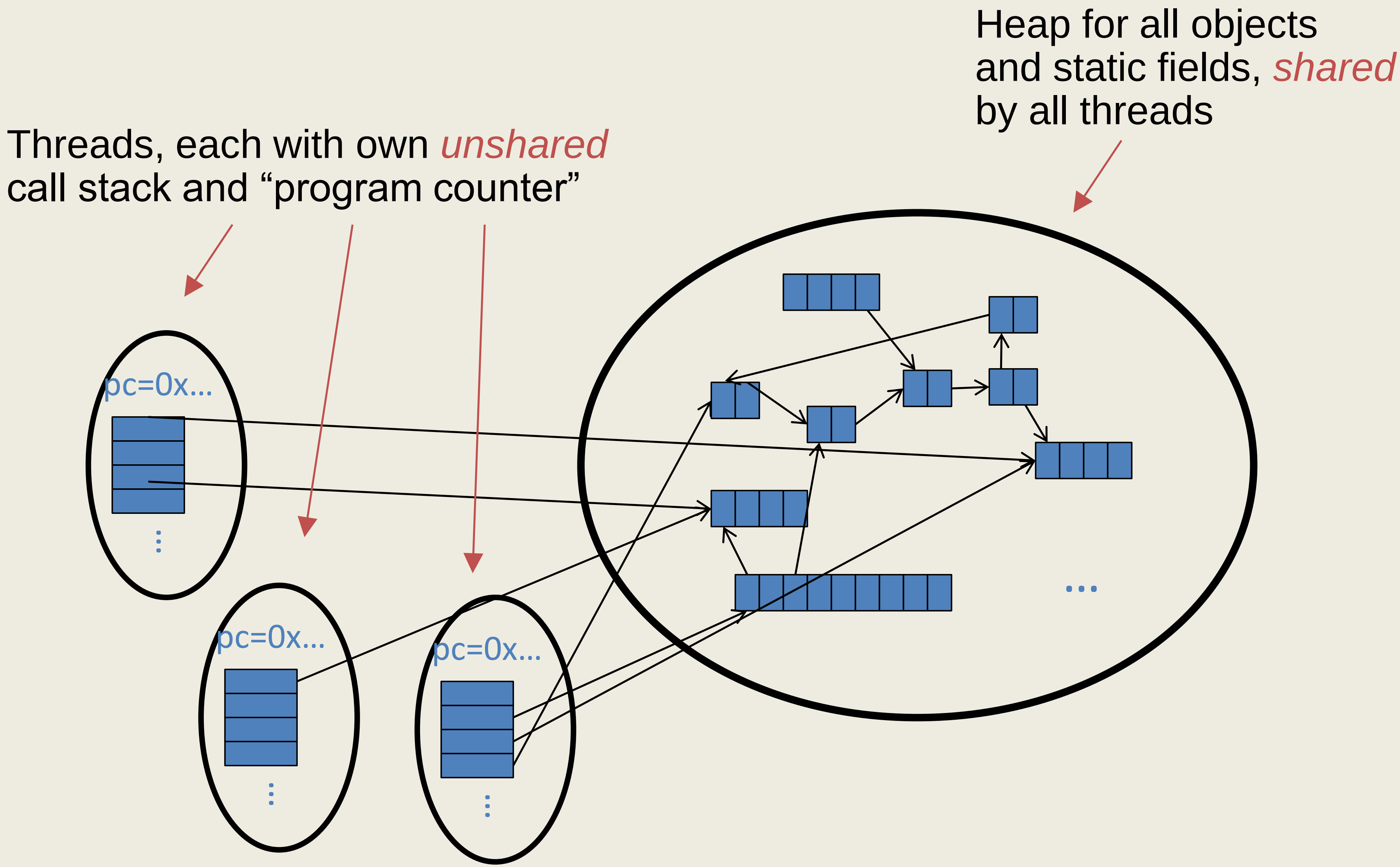
Old Story: one call stack, one pc

- Call stack with local variables
- pc determines current statement
- local variables are numbers/null or heap references

Heap for all objects and static fields



New Story: Shared Memory with Threads



Other models

We will focus on shared memory, but you should know several other models exist and have their own advantages **(see notes)**

- Synchronous Shared Memory: Processors execute same instructions and access shared memory

- Message-passing: Each thread has its own collection of objects. Communication is via explicitly sending/receiving messages

- Dataflow: Programmers write programs in terms of a DAG.
  A node executes after all of its predecessors in the graph

- Data parallelism: Have primitives for things like “apply function to every element of an array in parallel”

Our Needs

To write a shared-memory parallel program, need new primitives from a programming language or library

- Ways to create and *run multiple things at once*
  - Let's call these things **threads**
- Ways for threads to *share memory*
  - Often just have threads with references to the same objects
- Ways for threads to *coordinate (a.k.a. synchronize)*
  - For now, a way for one thread to wait for another to finish
  - Other primitives when we study concurrency

Threads vs. Processors

What happens if you start 5 threads on a machine with only 4 processors?

Threads vs. Processors

For sum operation:

- with 3 processors available,
  using 4 threads would take 50% more time than 3 threads

Fork-Join Parallelism

1. Define thread
   - Java: define subclass of `java.lang.Thread`, override `run`

2. Fork: instantiate a thread and start executing
   - Java: create thread object, call `start()`

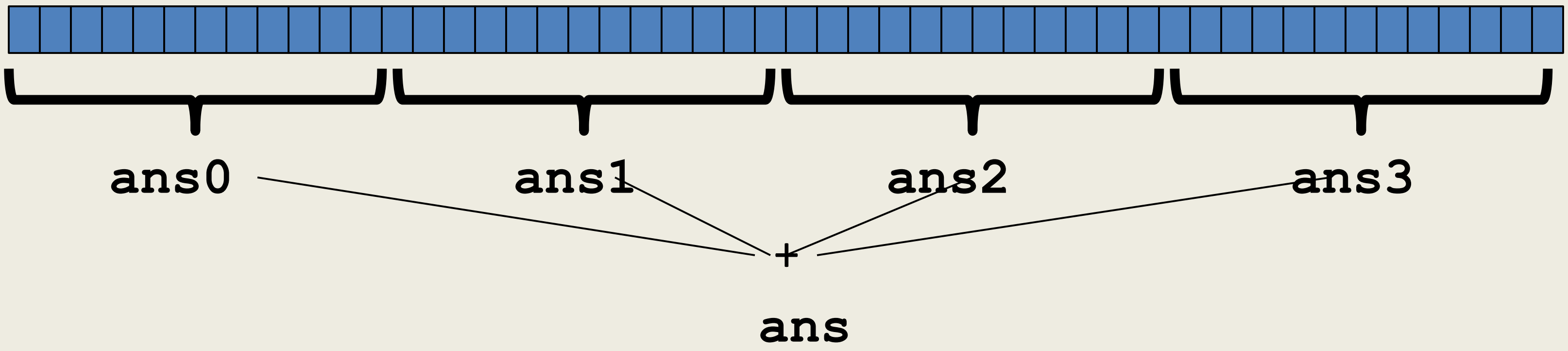
3. Join: wait for thread to terminate
   - Java: call `join()` method, which returns when thread finishes

Above uses basic thread library build into Java

Later we'll introduce a better ForkJoin Java library designed for parallel programming

Sum with Threads

For starters: have 4 threads simultaneously sum one quarter of the array



- Create 4 *thread objects*, each given one quarter of the array
- 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

Part 1: define thread class

```
class SumThread extends java.lang.Thread {

  int lo; // fields, passed to 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];
  }
}
```

Because we must override a no-arguments/no-result run,

we use fields to communicate across threads

Part 2: sum routine

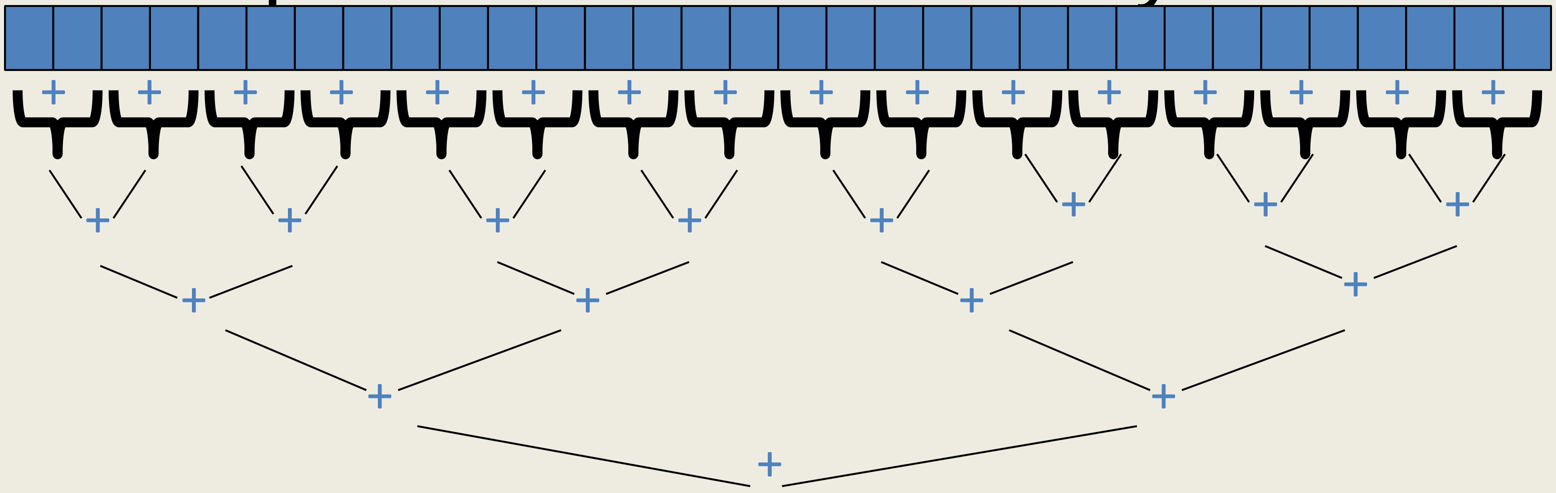
```
int sum(int[] arr){// can be a static method
  int len = arr.length;
  int ans = 0;
  SumThread[] ts = new SumThread[4];
  for(int i=0; i < 4; i++){// do parallel computations
    ts[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
    ts[i].start();
  }
  for(int i=0; i < 4; i++) { // combine results
    ts[i].join(); // wait for helper to finish!
    ans += ts[i].ans;
  }
  return ans;
}
```

Parameterizing by number of threads

```
int sum(int[] arr, int numTs){
  int ans = 0;
  SumThread[] ts = new SumThread[numTs];
  for(int i=0; i < numTs; i++){
   ts[i] = new SumThread(arr,(i*arr.length)/numTs,
                             ((i+1)*arr.length)/numTs);
   ts[i].start();
  }
  for(int i=0; i < numTs; i++) {
    ts[i].join();
    ans += ts[i].ans;
  }
  return ans;
}
```

Recall: Parallel Sum

- Sum up N numbers in an array



- Let's implement this with threads...

Code looks something like this (using Java Threads)

```
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
    if(hi – lo < SEQUENTIAL_CUTOFF)
      for(int i=lo; i < hi; i++)
        ans += arr[i];
    else {
      SumThread left = new SumThread(arr,lo,(hi+lo)/2);
      SumThread right= new SumThread(arr,(hi+lo)/2,hi);
      left.start();
      right.start();
      left.join(); // don't move this up a line – why?
      right.join();
      ans = left.ans + right.ans;
    }
  }
}
int sum(int[] arr){ // just make one thread!
   SumThread t = new SumThread(arr,0,arr.length);
   t.run();
   return t.ans;
}
```

Recursive problem decomposition

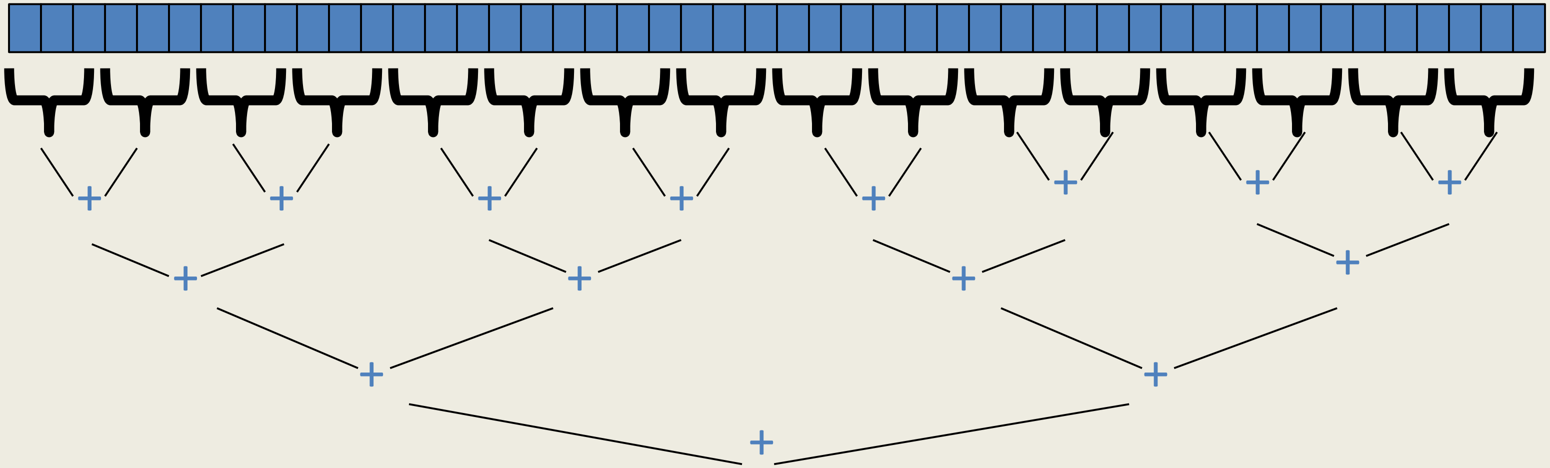
- Thread: sum range [0,10)
  - Thread: sum range [0,5)
    - Thread: sum range [0,2)
      - Thread: sum range [0,1) (return arr[0])
      - Thread: sum range [1,2) (return arr[1])
      - add results from two helper threads
    - Thread: sum range [2,5)
      - Thread: sum range [2,3) (return arr[2])
      - Thread: sum range [3,5)
        - Thread: sum range [3,4) (return arr[3])
        - Thread: sum range [4,5) (return arr[4])
        - add results from two helper threads
      - add results from two helper threads
    - add results from two helper threads
  - Thread: sum range [5,10)
    - Thread: sum range [5,7)
      - Thread: sum range [5,6) (return arr[5])
      - Thread: sum range [6,7) (return arr[6])
      - add results from two helper threads
    - Thread: sum range [7,10)
      - Thread: sum range [7,8) (return arr[7])
      - Thread: sum range [8,10)
        - Thread: sum range [8,9) (return arr[8])
        - Thread: sum range [9,10) (return arr[9])
        - add results from two helper threads
      - add results from two helper threads
  - add results from two helper threads

Divide-and-conquer

Same approach useful for many problems beyond sum

- *If* you have enough processors, total time $O(\log n)$
- Next lecture: study reality of **P** << *n* processors

- Will write all our parallel algorithms in this style
  - But using a special fork-join library engineered for this style
    - Takes care of scheduling the computation well
  - Often relies on operations being associative (like +)



Thread Overhead

Creating and managing threads incurs cost

Two optimizations:

1. Use a *sequential cutoff*, typically around 500-1000
   - Eliminates lots of tiny threads

2. Do not create two recursive threads; create one thread and do the other piece of work "yourself"
   - Cuts the number of threads created by another 2x

Half the threads!

order of last 4 lines

Is critical – why?

```
// wasteful: don't
SumThread left  = …
SumThread right = …

left.start();
right.start();


left.join();
right.join();
ans=left.ans+right.ans;
```

```
// better: do!!
SumThread left  = …
SumThread right = …

left.start();
right.run();


left.join();
// no right.join needed
ans=left.ans+right.ans;
```

Note: `run` is a normal function call! execution won't continue until we are done with `run`

Better Java Thread Library

- Even with all this care, Java's threads are too "heavyweight"
  - Constant factors, especially space overhead
  - Creating 20,000 Java threads just a bad idea ☹

- The ForkJoin Framework is designed to meet the needs of divide-and-conquer fork-join parallelism
  - In the Java 8 standard libraries
  - Section will focus on pragmatics/logistics
  - Similar libraries available for other languages
    - C/C++: Cilk (inventors), Intel's Thread Building Blocks
    - C#: Task Parallel Library
    - …

Different terms, same basic idea

To use the ForkJoin Framework:

- A little standard set-up code (e.g., create a **ForkJoinPool**)

Don't subclass **Thread**	Do subclass **RecursiveTask<V>**
Don't override **run**	Do override **compute**
Do not use an **ans** field	Do return a **V** from **compute**
Don't call **start**	Do call **fork**
Don't *just* call **join**	Do call **join** (which returns answer)
Don't call **run** to hand-optimize	Do call **compute** to hand-optimize
Don't have a topmost call to **run**	Do create a pool and call **invoke**

See the web page for (linked in to project 3 description):

"A Beginner's Introduction to the ForkJoin Framework"

Fork Join Framework Version: (missing imports)

```
class SumArray extends RecursiveTask<Integer> {
  int lo; int hi; int[] arr; // fields to know what to do
  SumArray(int[] a, int l, int h) { … }
  protected Integer compute(){// return answer
    if(hi – lo < SEQUENTIAL_CUTOFF) {
      int ans = 0; // local var, not a field
      for(int i=lo; i < hi; i++)
        ans += arr[i];
      return ans;
    } else {
      SumArray left = new SumArray(arr,lo,(hi+lo)/2);
      SumArray right= new SumArray(arr,(hi+lo)/2,hi);
      left.fork(); // fork a thread and calls compute
      int rightAns = right.compute();//call compute directly
      int leftAns  = left.join(); // get result from left
      return leftAns + rightAns;
    }
  }
}
static final ForkJoinPool fjPool = new ForkJoinPool();
int sum(int[] arr){
  return fjPool.invoke(new SumArray(arr,0,arr.length));
      // invoke returns the value compute returns
}
```