CSE373: Data Structures & Algorithms
Lecture 23: Introduction to Multithreading & Fork-Join Parallelism

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Admin

- HW 6 due Wednesday
- Final exam on Friday
- Final review session 7 pm on Wednesday

So far most or all of your study of computer science has assumed

One thing happened at a time

Called sequential programming – everything part of one sequence

It’s all been lies!

Well, not all lies…

But most computers these days have multiple cores, and most languages support using them.

Removing this assumption creates major challenges & opportunities

- Divide work among threads of execution and coordinate (synchronize) among them
- Parallel activity provide speed-up (more throughput: work done per unit time)
- May need to support concurrent access to data (multiple threads operating on data at the same time)

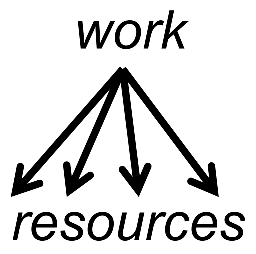
What to do with multiple processors?

- Run multiple totally different programs at the same time
  – Already do that? Yes, with time-slicing
- Do multiple things at once in one program
  – Requires rethinking everything from asymptotic complexity to how to implement data-structure operations

Parallelism vs. Concurrency

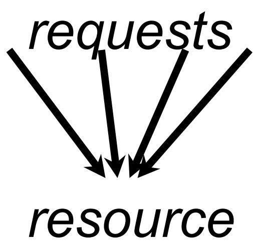
Parallelism:

Use extra resources to solve a problem faster



Concurrency:

Correctly and efficiently manage access to shared resources



There is some connection:

- Common to use *threads* for both
- If parallel computations need access to shared resources, then the concurrency needs to be managed

We will focus on parallelism, avoiding concurrency issues

An analogy

CS1 idea: A program is like a recipe for a cook

- One cook who does one thing at a time! (*Sequential*)

Parallelism:

- Have lots of potatoes to slice?
- Hire helpers, hand out potatoes and knives
- But too many chefs and you spend all your time coordinating

Concurrency:

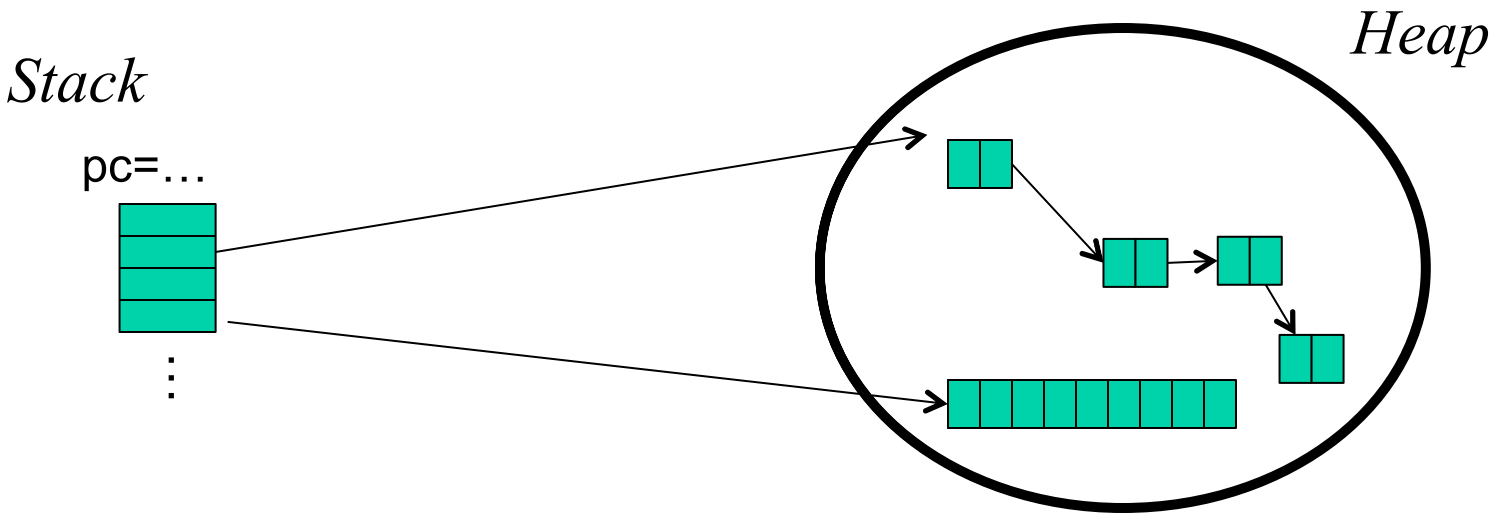
- Lots of cooks making different things, but only 4 stove burners
- Want to allow access to all 4 burners, but not cause spills or incorrect burner settings

Shared memory

The model we will assume is shared memory with explicit 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* - belong to the class and not an instance (or object) of the class. Only one for all instances of a class.

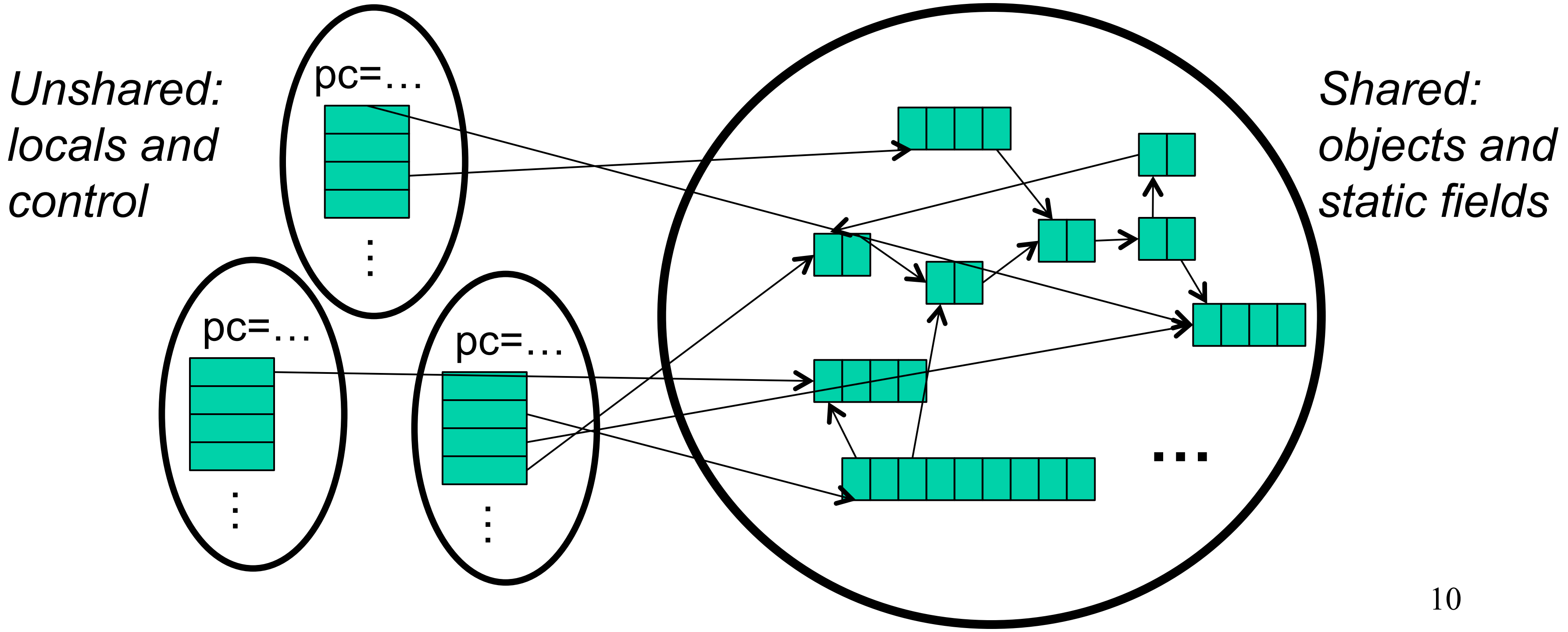


Shared memory

The model we will assume is shared memory with explicit threads

New story:

- A set of *threads*, each with its own program counter & call stack
  - No access to another thread's local variables
- Threads can (implicitly) share static fields / objects
  - To *communicate*, write somewhere another thread reads


Unshared: locals and control
pc=…
pc=…
pc=…
Shared: objects and static fields
…

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)*
  - A way for one thread to wait for another to finish
  - [Other features needed in practice for concurrency]

Java basics

Learn **`java.lang.Thread`**

– In real life, use Java 7’s ForkJoin Framework instead!

To get a new thread running:

1. Define a subclass **`t`** of **`java.lang.Thread`**, overriding **`run`**
2. Create an object of class **`t`**
3. Call that object’s **`start`** method
    - **`start`** sets off a new thread, using **`run`** as its “main”

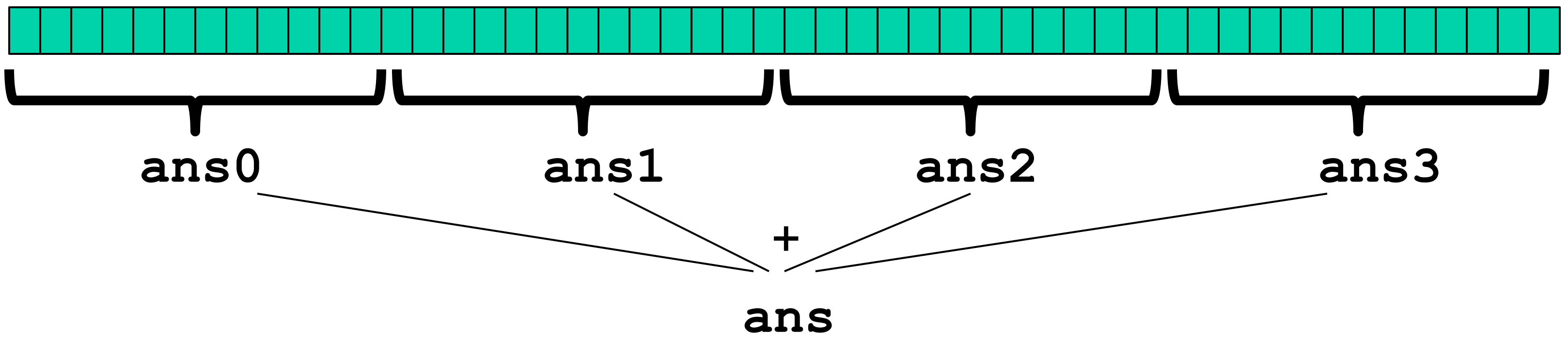
What if we instead called the **`run`** method of **`t`**?

– This would just be a normal method call, in the current thread

Let’s see how to share memory and coordinate via an example…

Parallelism idea

- Example: Sum elements of a large array
- Idea: Have 4 threads simultaneously sum 1/4 of the array
  - Warning: This is an inferior first approach, but it's usually good to start with something naïve works



  - Create 4 *thread objects*, each given a portion of the work
  - Call **`start()`** on each thread object to actually *run* it in parallel
  - *Wait* for threads to finish using **`join()`**
  - Add together their 4 answers for the *final result*

First attempt: create Thread subclass

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

  int lo; // arguments
  int hi;
  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

First attempt, continued (wrong)

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

```
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);
  for(int i=0; i < 4; i++) // combine results
    ans += ts[i].ans;
  return ans;
}
```

Second attempt (still wrong)

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

```
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(); // start not run
  }
  for(int i=0; i < 4; i++) // combine results
    ans += ts[i].ans;
  return ans;
}
```

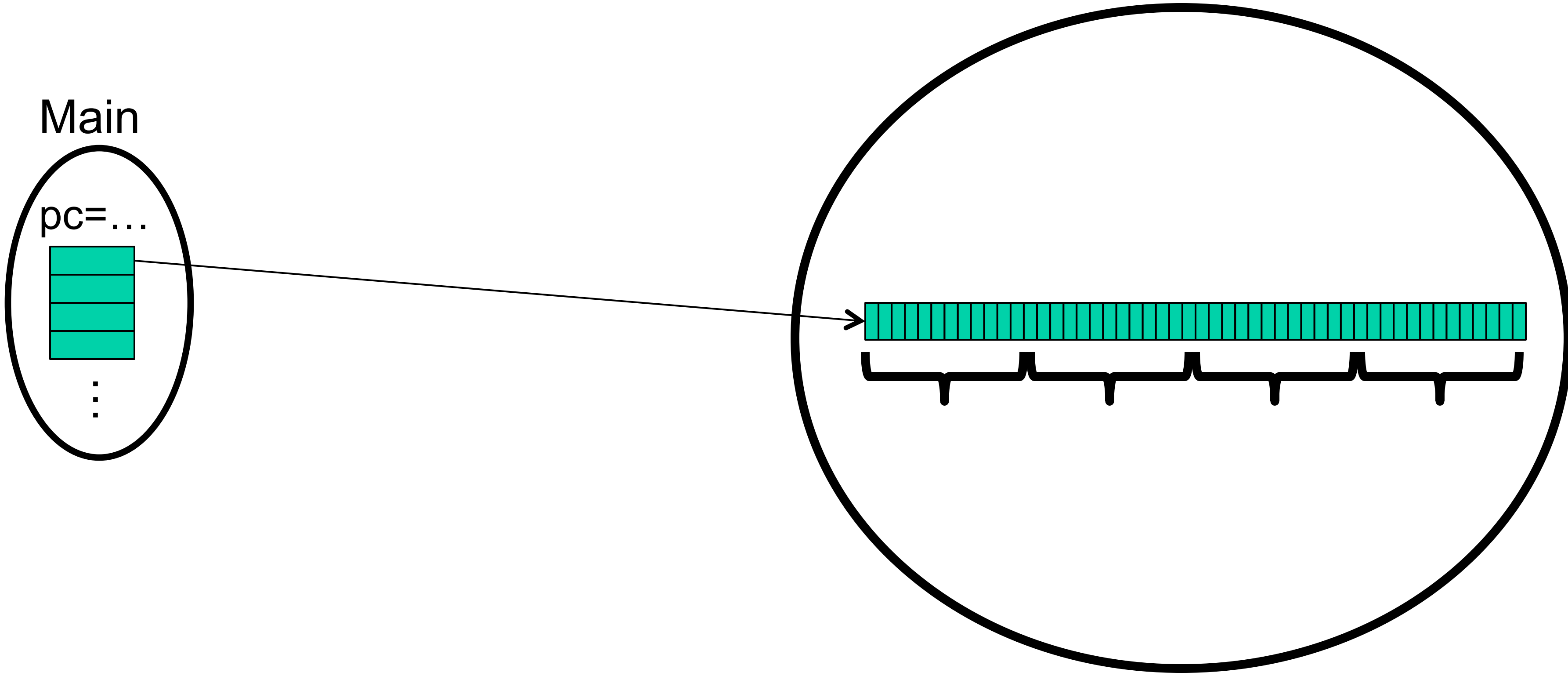
Third attempt (correct in spirit)

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

```
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;
}
```

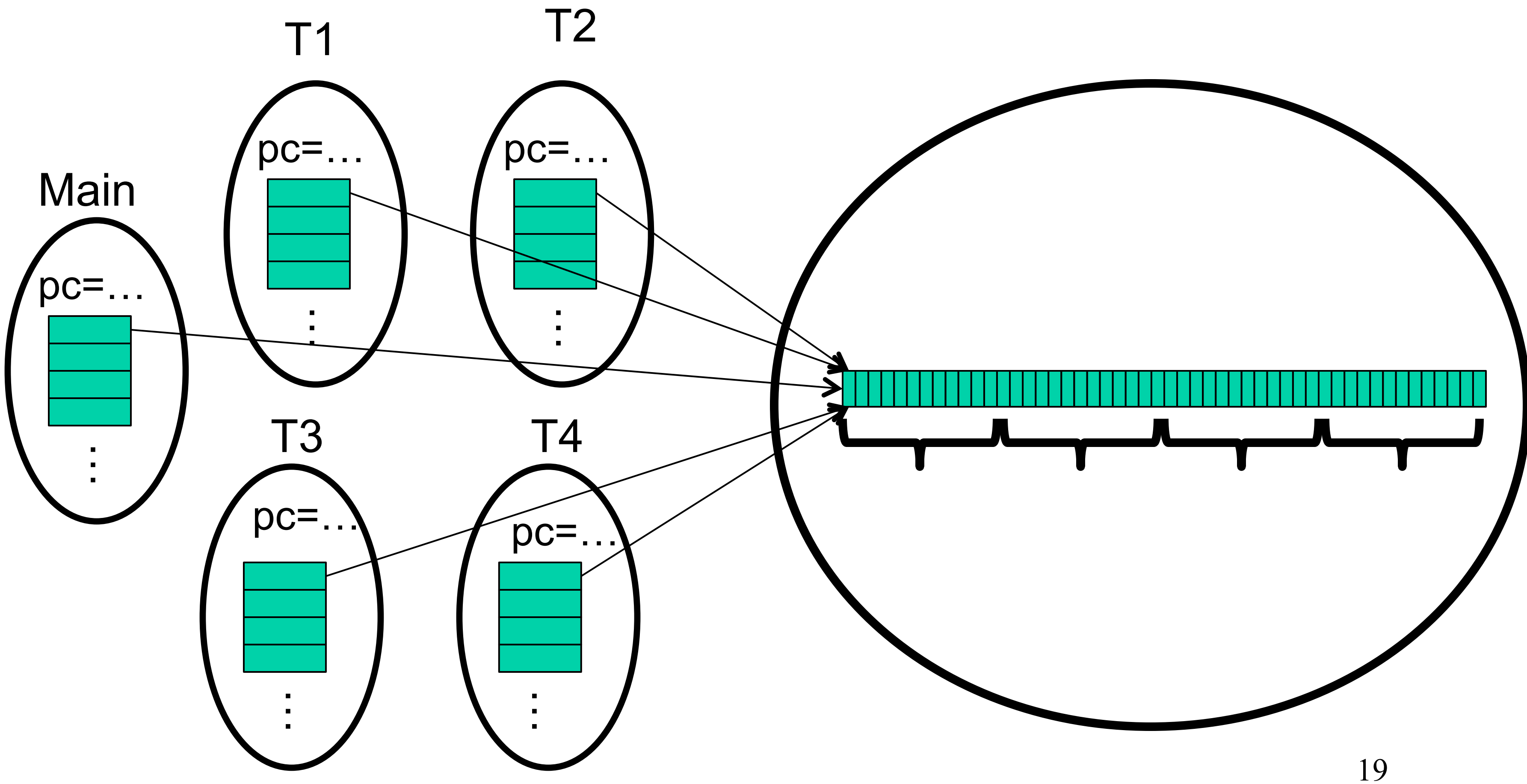
What's Happening?

1. Start with one thread



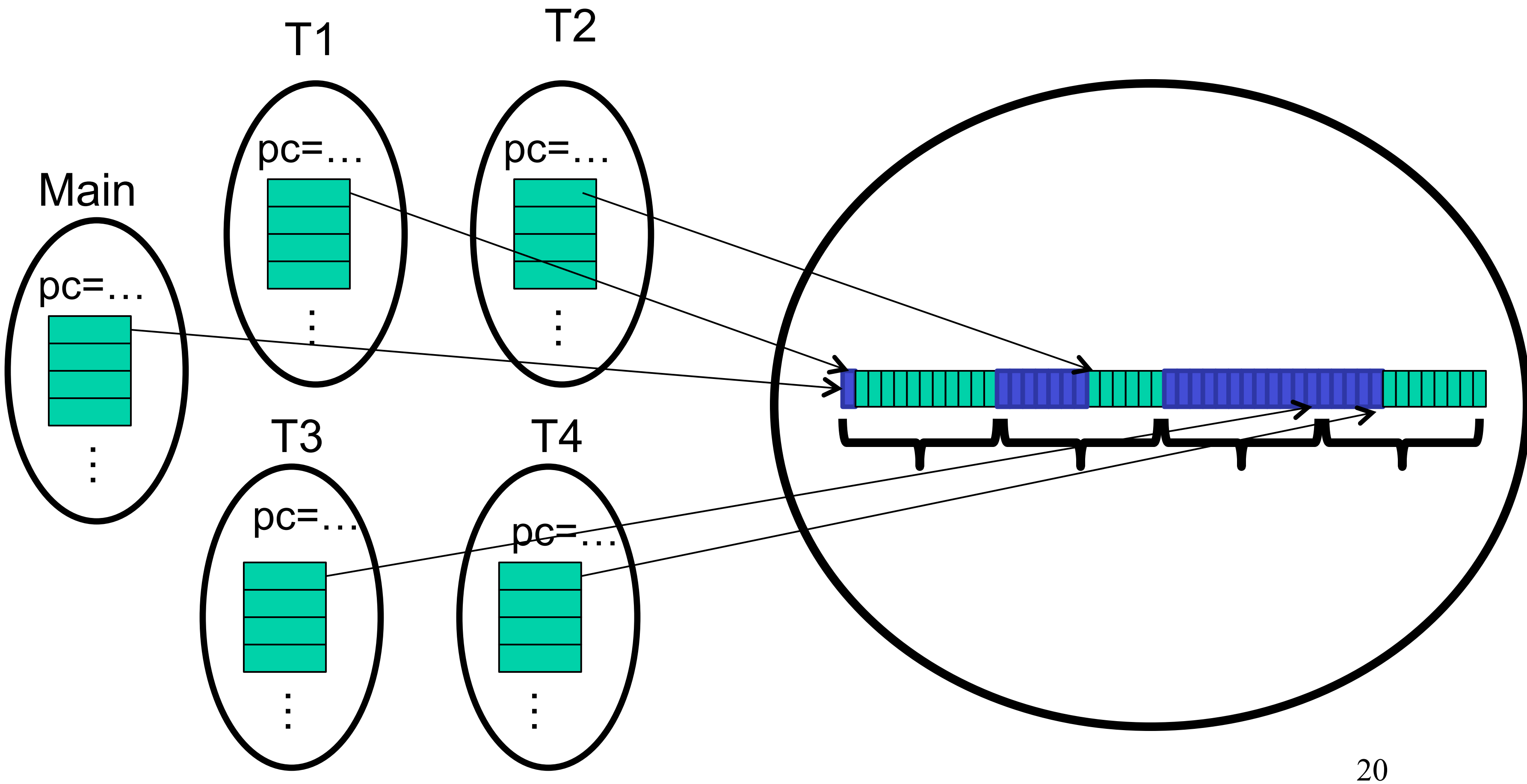
What's Happening?

2. Main thread reaches sum() method, creates 4 new threads



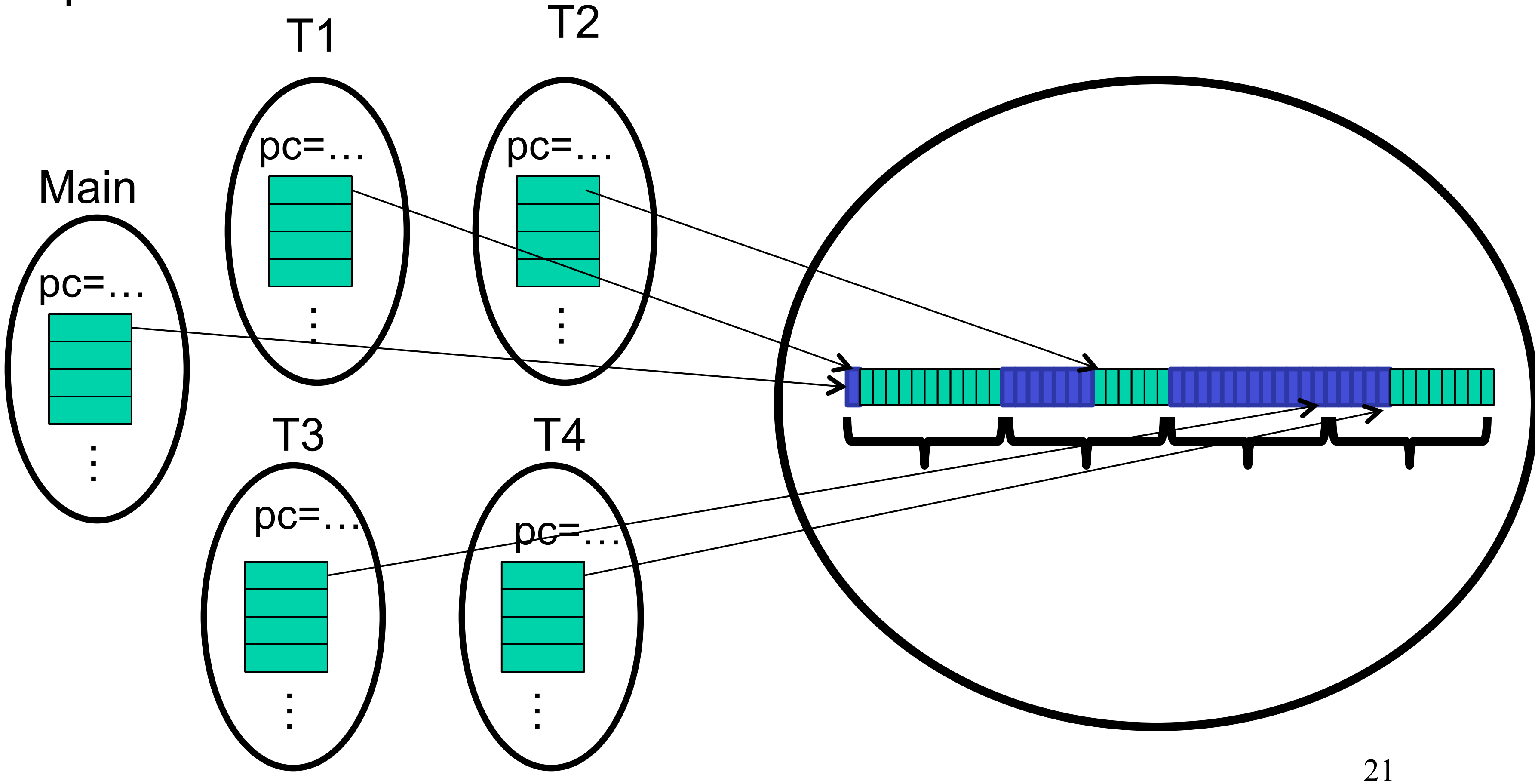
What's Happening?

3. Each new thread begins its start() method, and iterates over its section of the array



What's Happening?

4. Each new thread may end at different times, so the main thread must wait until they are all done(calls join()) before summing them up



Join (not the most descriptive word)

- The `join` method is valuable for coordinating this kind of computation
  - Caller blocks until/unless the receiver is done executing (meaning the call to `run` returns)
  - Else we would have a race condition on `ts[i].ans` (answer would depend on what finishes first)

- This style of parallel programming is called "fork/join"

- Java detail: code has 1 compile error because `join` may throw `java.lang.InterruptedException`
  - In basic parallel code, should be fine to catch-and-exit

Shared memory?

- Fork-join programs (thankfully) do not require much focus on sharing memory among threads

- But in languages like Java, there is memory being shared. In our example:
  - **`lo`**, **`hi`**, **`arr`** fields written by "main" thread, read by helper thread
  - **`ans`** field written by helper thread, read by "main" thread

- When using shared memory, you must avoid race conditions
  - We will stick with **`join`** to do so

How many threads to use?

Several reasons why this is a poor parallel algorithm

1. Want code to be reusable and efficient across platforms
   - “Forward-portable” as core count grows
   - So at the *very* least, parameterize by the 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;
}
```

How many threads to use?

2. Want to use (only) processors "available to you *now*"
   - Not used by other programs or threads in your program
     - Maybe caller is also using parallelism
     - Available cores can change even while your threads run

```
// numThreads == numProcessors is bad
// if some are needed for other things
int sum(int[] arr, int numTs){
  …
}
```

How many threads to use?

3. Though unlikely for **`sum`**, in general subproblems may take significantly different amounts of time

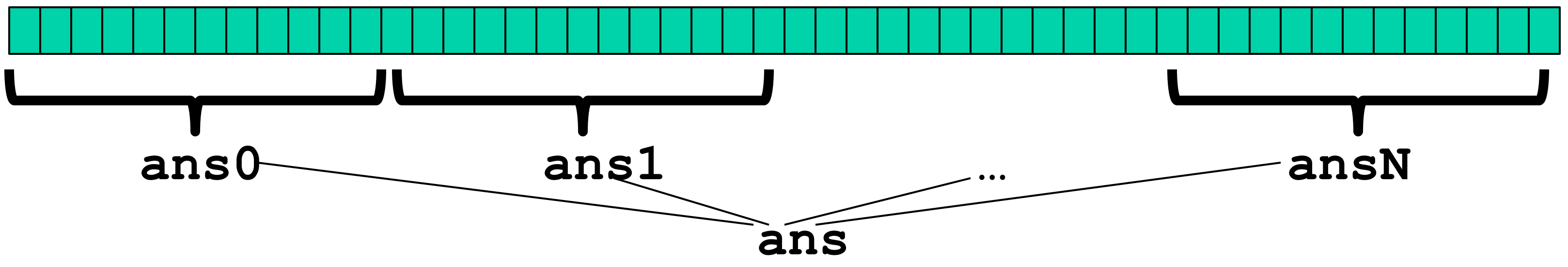
   – Example: Apply method **`f`** to every array element, but maybe **`f`** is much slower for some data items
     - Example: Is a large integer prime?

   – If we create 4 threads and all the slow data is processed by 1 of them, we won't get nearly a 4x speedup
     - Example of a load imbalance

How many threads to use?

The solution to all these problems is to use lots of threads, far more than the number of processors

- But this will require changing our algorithm
- [And using a different Java library]



1. Forward-portable: Lots of helpers each doing a small piece
2. Processors available: Hand out “work chunks” as you go
3. Load imbalance: No problem if slow thread scheduled early enough
   - Variation probably small anyway if pieces of work are small

Naïve algorithm is poor

Suppose we create 1 thread to process every 1000 elements

```
int sum(int[] arr){
  …
  int numThreads = arr.length / 1000;
  SumThread[] ts = new SumThread[numThreads];
  …
}
```

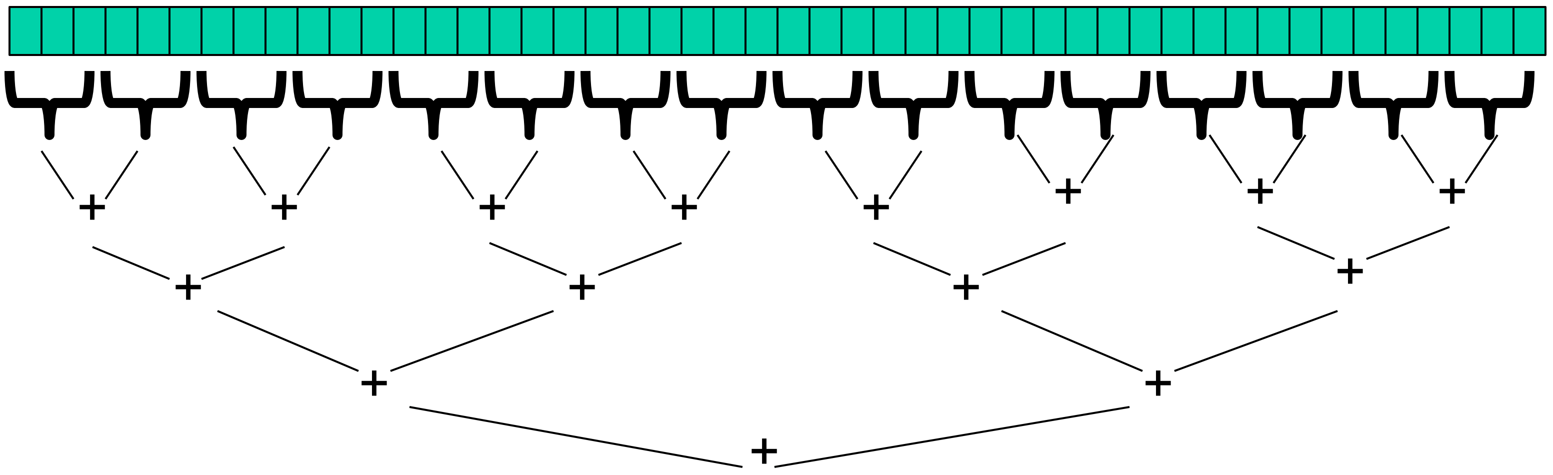
Then combining results will have **`arr.length / 1000`** additions

- Linear in size of array (with constant factor 1/1000)
- Previously we had only 4 pieces (constant in size of array)

In the extreme, if we create 1 thread for every 1 element, the loop to combine results has length-of-array iterations

- Just like the original sequential algorithm

A better idea



This is straightforward to implement using divide-and-conquer

- Parallelism for the recursive calls
- Each thread creates two new threads, lets them run and then sums up their answer
- Below some threshold (when the array gets small enough) thread just runs

Divide-and-conquer to the rescue!

```java
class SumThread extends java.lang.Thread {
  int lo; int hi; int[] arr; // arguments
  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){
   SumThread t = new SumThread(arr,0,arr.length);
   t.run();
   return t.ans;
}
```

Divide-and-conquer to the rescue!

```
class SumThread extends java.lang.Thread {
  int lo; int hi; int[] arr; // arguments
  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);
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      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){
   SumThread t = new SumThread(arr,0,arr.length);
   t.run();
   return t.ans;
}
```
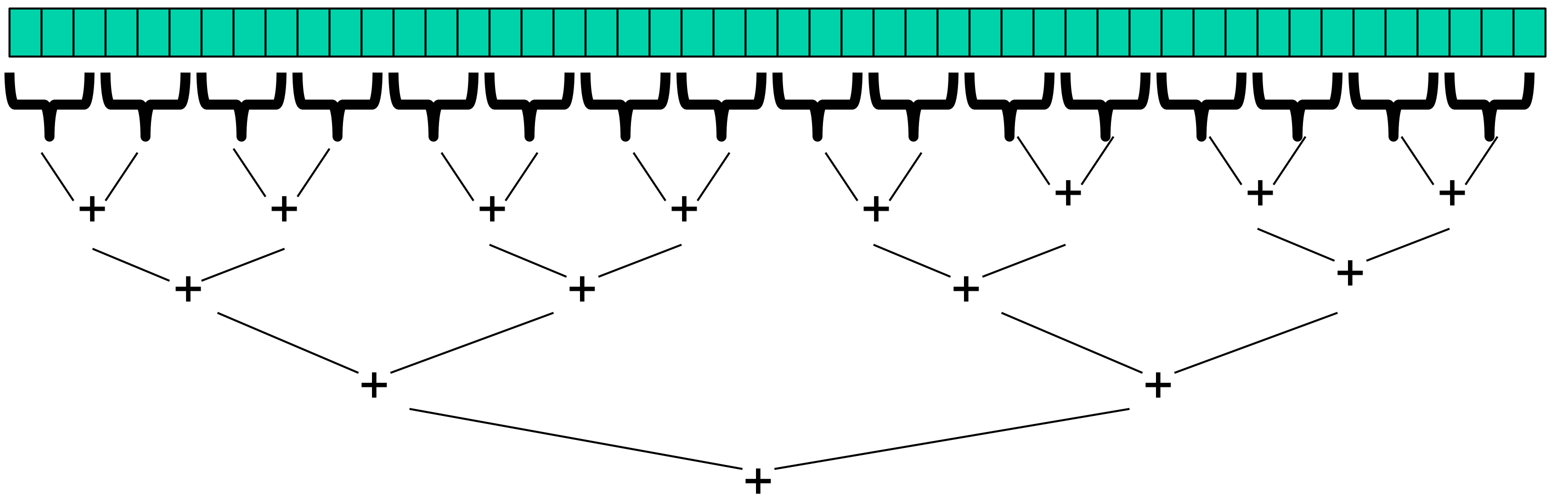

Divide-and-conquer really works

- Divide-and-conquer parallelizes the result-combining
  - *If* you have enough processors, total time is height of the tree: *O*(`log` *n*) (optimal, exponentially faster than sequential *O*(*n*))



Being realistic

- In theory, you can divide down to single elements, do all your result-combining in parallel and get optimal speedup (P is number of processors)
  - Total time $O(n/P + \log n)$

- In practice, creating all those threads and communicating swamps the savings, so:
  - Use a *sequential cutoff*, typically around 500-1000
    - Eliminates *almost all* the recursive thread creation (bottom levels of tree)
  - Instead of creating two recursive threads; create one and do the other "yourself"
    - Cuts the number of threads created by another 2x

Being realistic, part 2

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

- The ForkJoin Framework is designed to meet the needs of divide-and-conquer fork-join parallelism
  - In the Java 7 standard libraries
  - Library's implementation is a fascinating but advanced topic
    - Next lecture will discuss its guarantees, not how it does it
  - Names of methods and how to use them slightly different