CSE 332
Data Structures & Parallelism

Introduction to Multithreading & Fork-Join Parallelism

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Updates

- Project 2 due THURSDAY
  - Up to 2 late days available
- Project 3 will be released on Thursday as well

- Ex7 Sorting due TOMORROW
- Ex8 Dijkstra’s due next Tuesday
- Regrade requests open for the midterm

Changing a major assumption

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

Removing this assumption creates major challenges & opportunities

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

How did we get here?

Writing correct and efficient multithreaded code is often much more difficult than for single-threaded (i.e., sequential) code

- Especially in common languages like Java and C
- So typically stay sequential if possible

From roughly 1980-2005, desktop computers got exponentially faster at running sequential programs

- About twice as fast every couple years

But nobody knows how to continue this

- Increasing clock rate generates too much heat
- Relative cost of memory access is too high
- But we can keep making "wires exponentially smaller" (Moore's "Law"), so put multiple processors on the same chip ("multicore")

What to do with multiple processors?

Your computer and phone probably have at least 4-8 processors

- Wait a few years and it will be 16, 32, …
- The chip companies have decided to do this (not a "law")

What can you do with them?

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

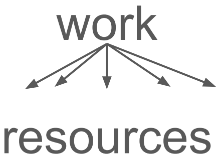
Parallelism vs. Concurrency

Note: Terms not yet standard but the perspective is essential

- Many programmers confuse these concepts

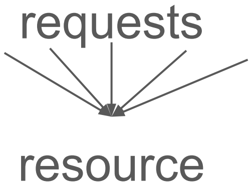
Parallelism:

Use extra resources to solve a problem faster



Concurrency:

Correctly and efficiently manage access to shared resources



There is some connection:

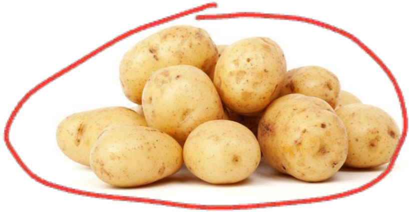
- Common to use threads for both
- If parallel computations need access to shared resources, then the concurrency needs to be managed

An analogy

A program is like a recipe for a cook

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

Parallelism: (Let’s get the job done faster!)



- 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: (We need to manage a shared resource)

- 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

Parallelism Example

Pseudocode for array sum:
(note FORALL doesn't exist)

```
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;
}
```

Pseudocode for a hashtable:

Concurrency Example

```
class Hashtable<K,V> {
  …
  void insert(K key, V value) {
    int bucket = …;
    prevent-other-inserts/lookups in table[bucket]
    do the insertion
    re-enable access to table[bucket]
  }
  V lookup(K key) {
    (similar to insert, but can allow concurrent
    lookups to same bucket)
  }
}
```

Shared Memory with Threads

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

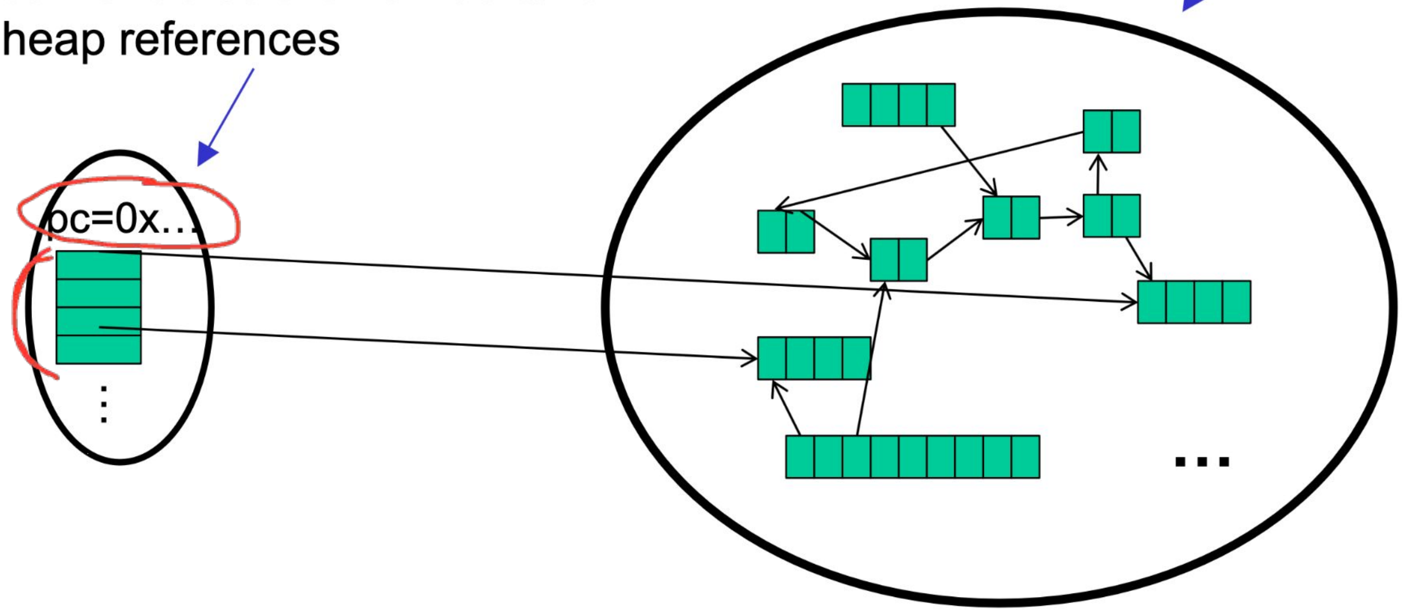
New story:

- 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 values to some shared location that another thread reads from

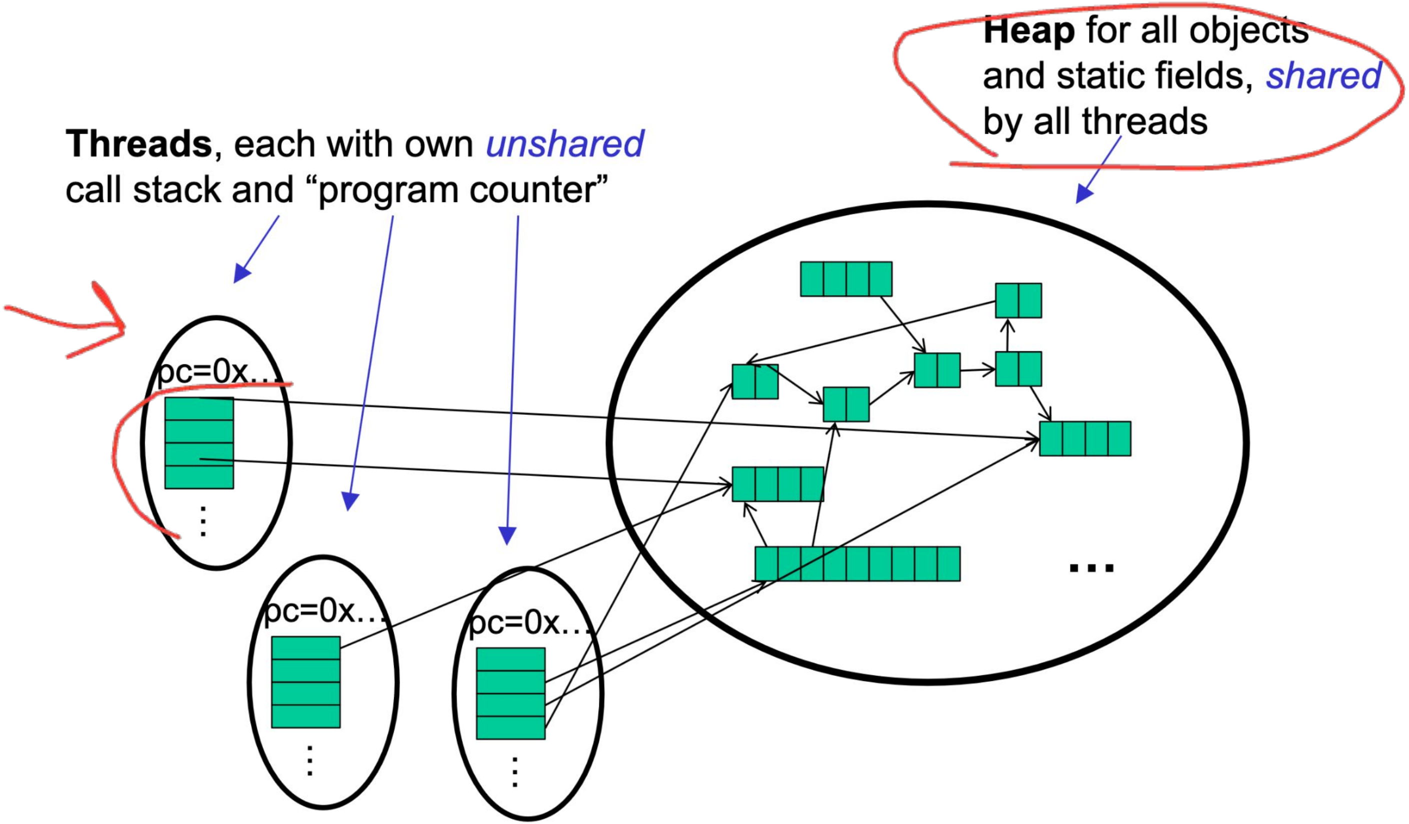
Old Story: one call stack, one pc

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

Heap for all objects and static fields



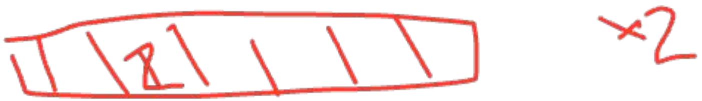
New Story: Shared memory with Threads



Other models

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

- Message-passing: Each thread has its own collection of objects. Communication is via explicitly sending/receiving messages
  - Cooks working in separate kitchens, mail around ingredients
- Dataflow: Programmers write programs in terms of a DAG. A node executes after all of its predecessors in the graph
  - Cooks wait to be handed results of previous steps
- 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

Java Basics

First learn some basics built into Java via `java.lang.Thread`

- Then a better library for parallel programming

To get a new thread running:

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"

magic

What if we instead called the `run` method of `C`?

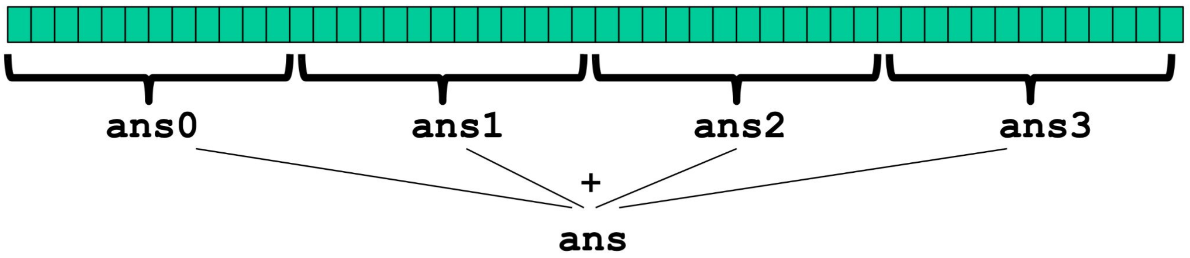
- This would just be a normal method call, in the current thread

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



- 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, Part 1

```
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 - field used to communicate
               //          across threads
  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, continued (wrong)

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

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)

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

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)

fork join

```
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
    ans += ts[i].ans;
    ts[i].join(); // wait for helper to finish!
  }
  return ans;
}
```

synch

Fourth attempt (better!)

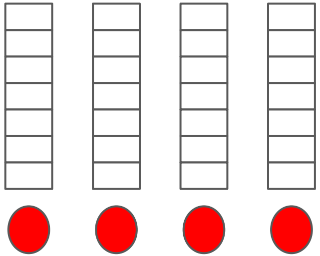
```
int sum(int[] arr, int numTs) { // parameterize by # of threads
  int len = arr.length;
  int ans = 0;
  SumThread[] ts = new SumThread[numTs];
  for(int i=0; i < numTs; i++) {
    ts[i] = new SumThread(arr,i*len/numTs,(i+1)*len/numTs);
    ts[i].start();
  }
  for(int i=0; i < numTs; i++) {
   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

(think of a “unit of work” as 1 second)

Problem 1: processors available to ME

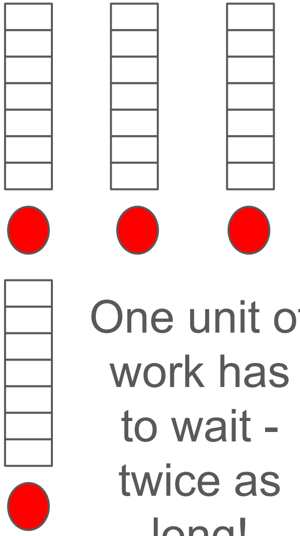
24 units of work

4 processors



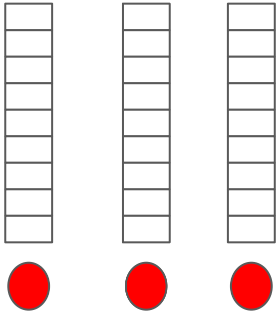
6 units of work per processor

If 1 of those 4 processors is busy with other work



One unit of work has to wait - twice as long!

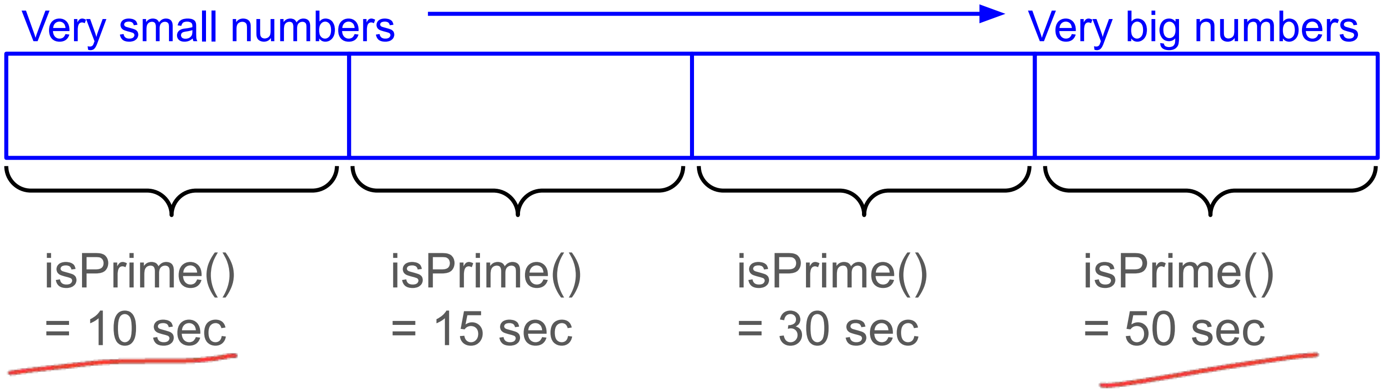
If we had optimally distributed work



8 units of work per processor

Problem 2: unequal work

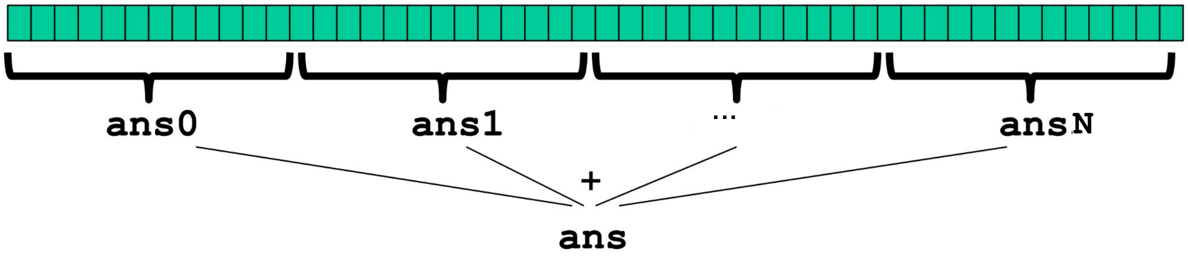
For some problems, dividing the array “equally” may result in subproblems that take significantly different amounts of time.



Solution attempt #1

The counterintuitive (?) solution to all these problems is to *cut up our problem into **many** pieces*, far more than the number of processors

- But this will require changing our algorithm
- And for constant-factor reasons, abandoning Java's threads



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

BUT naive 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 the “combining of results” part of the code will have `arr.length / 1000` additions

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

In the extreme, suppose we create one thread per element – If we use a for loop to combine the results, we have N iterations

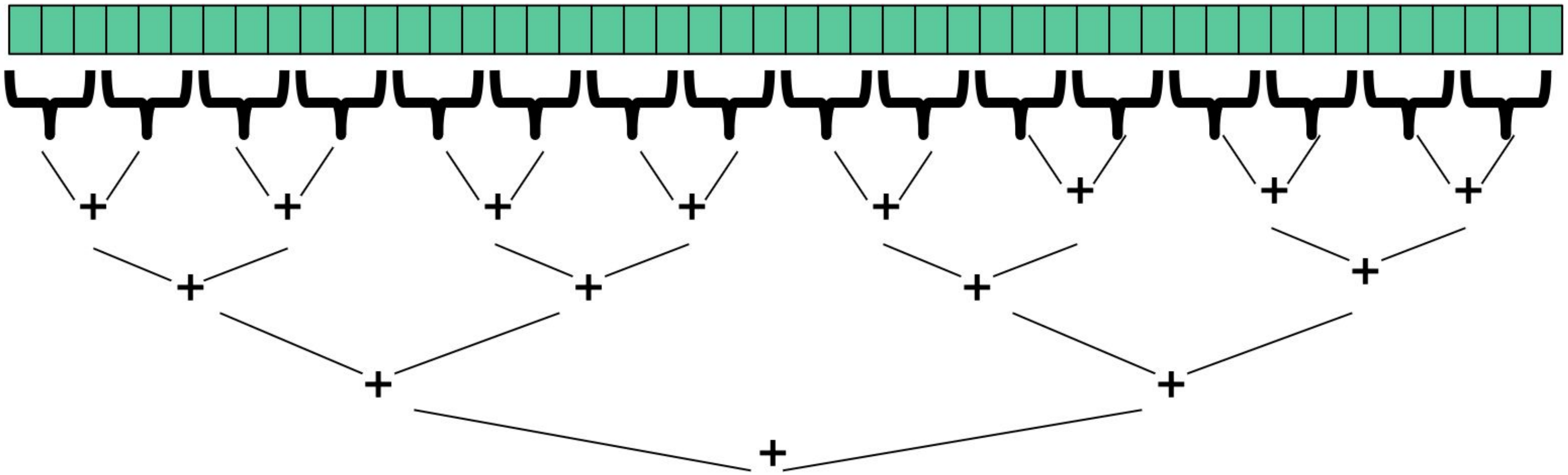
- In either case we get a $\Theta(N)$ algorithm with the combining of results as the bottleneck….

A better idea: Divide and Conquer!

1) Divide problem into pieces recursively:

- Start with full problem at root
- Halve and make new thread until size is at some cutoff

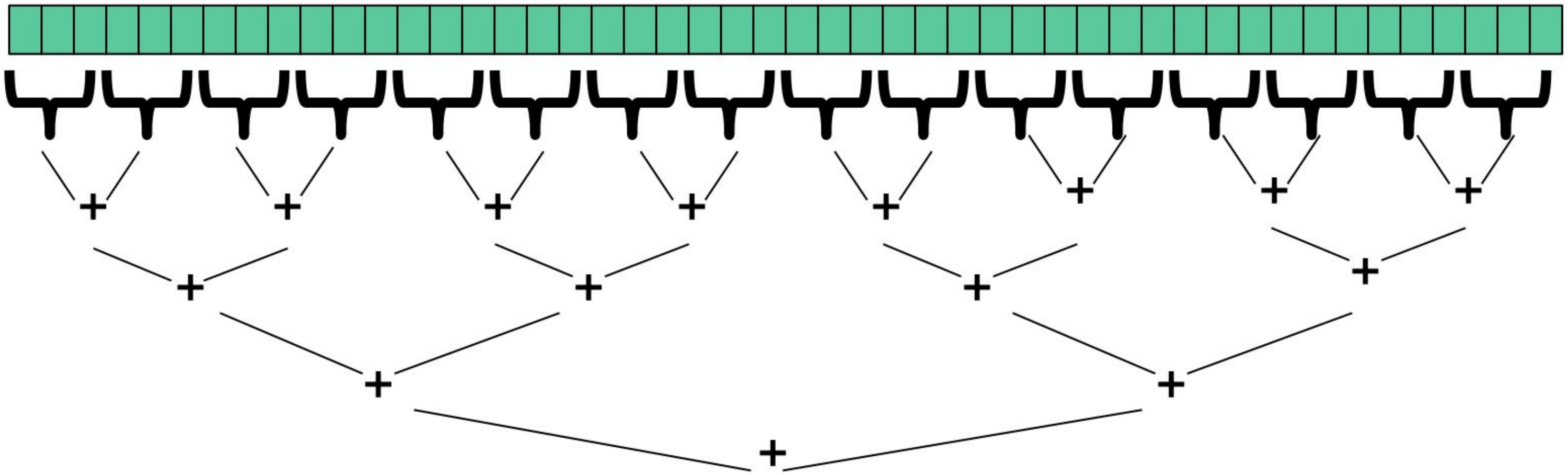
2) Combine answers in pairs as we return from recursion (see diagram)



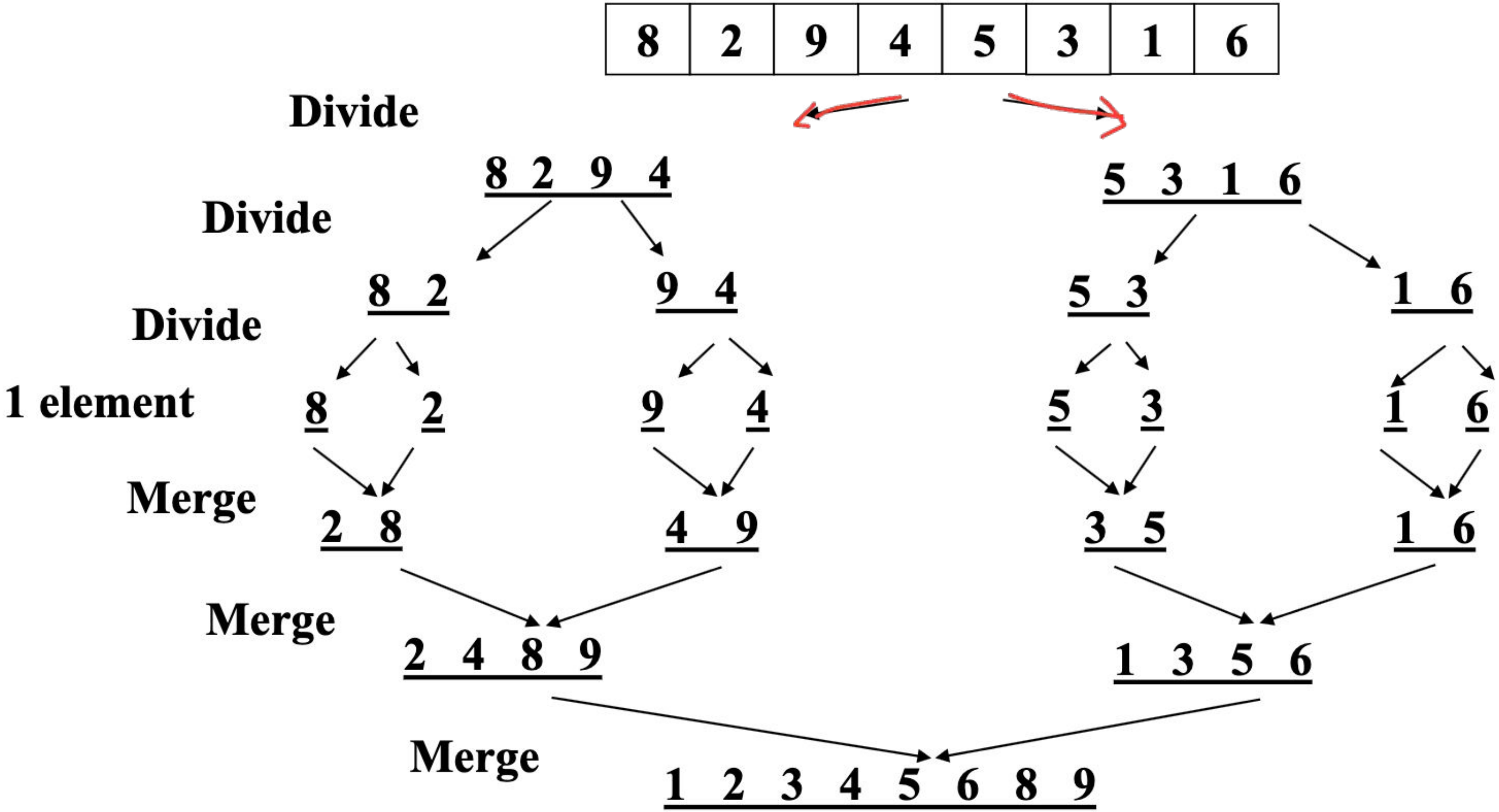
A better idea: Divide and Conquer!

This will start small, and ‘grow’ threads to fit the problem. This is straightforward to implement using divide-and-conquer.

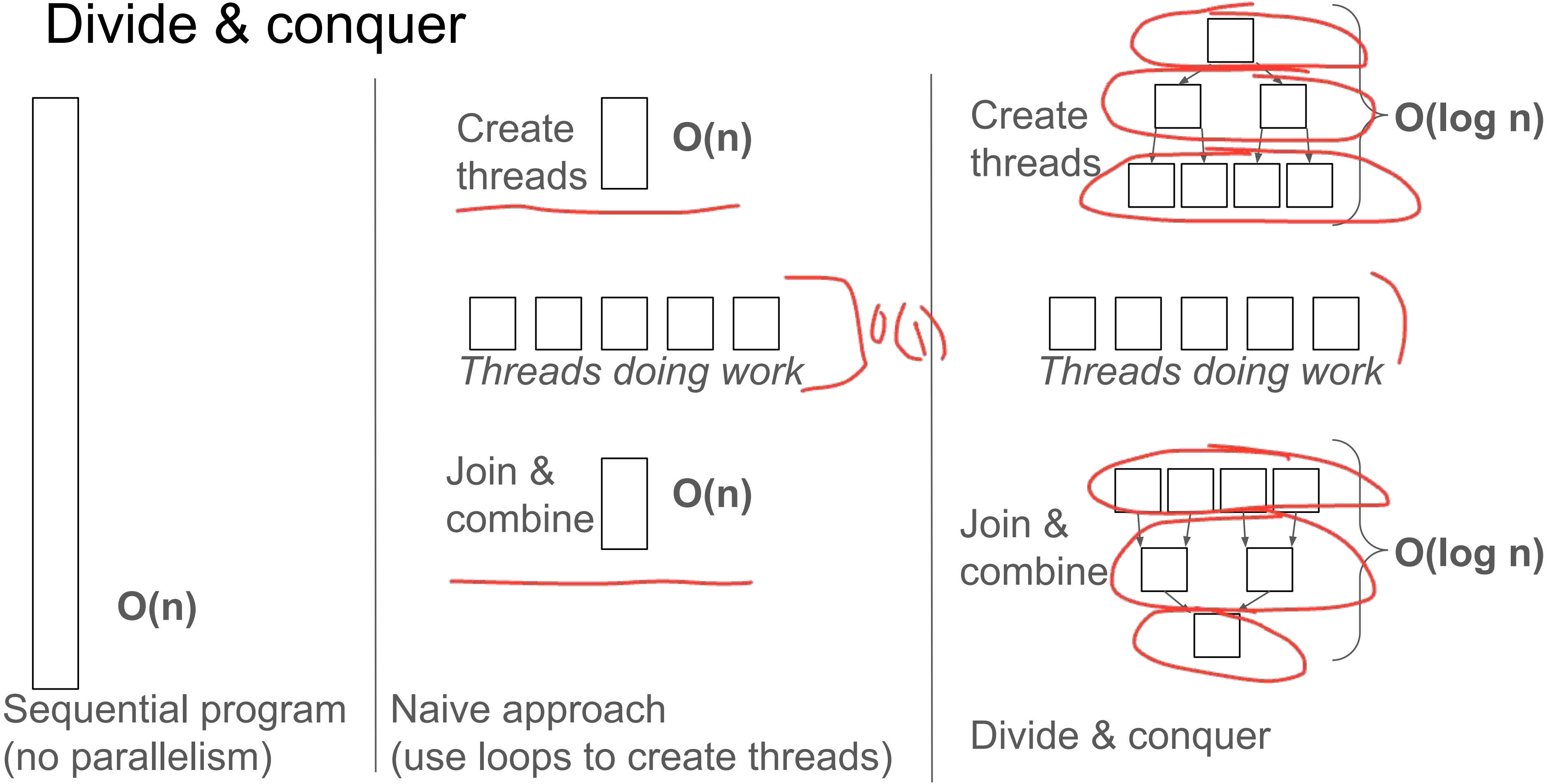
- Parallelism for the recursive calls



Remember mergesort?



Divide & conquer



Fifth attempt (still using Java Threads)

```java
class SumThread extends java.lang.Thread {
  int lo; int hi; int[] arr;
  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;
    }
  }
}
```

```java
int sum(int[] arr){
  // just make one thread!
  SumThread t =
    new SumThread(arr,0,arr.length);
  t.run();
  return t.ans;
}
```

rec

Being realistic

In theory, you can divide down to single elements, do all your result-combining in parallel and get optimal speedup

- Total time **O(n / numProcessors + log n)**

In practice, creating all those threads and communicating swamps the savings, so do two things to help:

1. Use a *sequential cutoff*, typically around 500-1000
   - Eliminates almost all the recursive thread creation (bottom levels of tree)
   - Exactly like quicksort switching to insertion sort for small subproblems, but more important here
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

order of last 4 lines is critical – why?

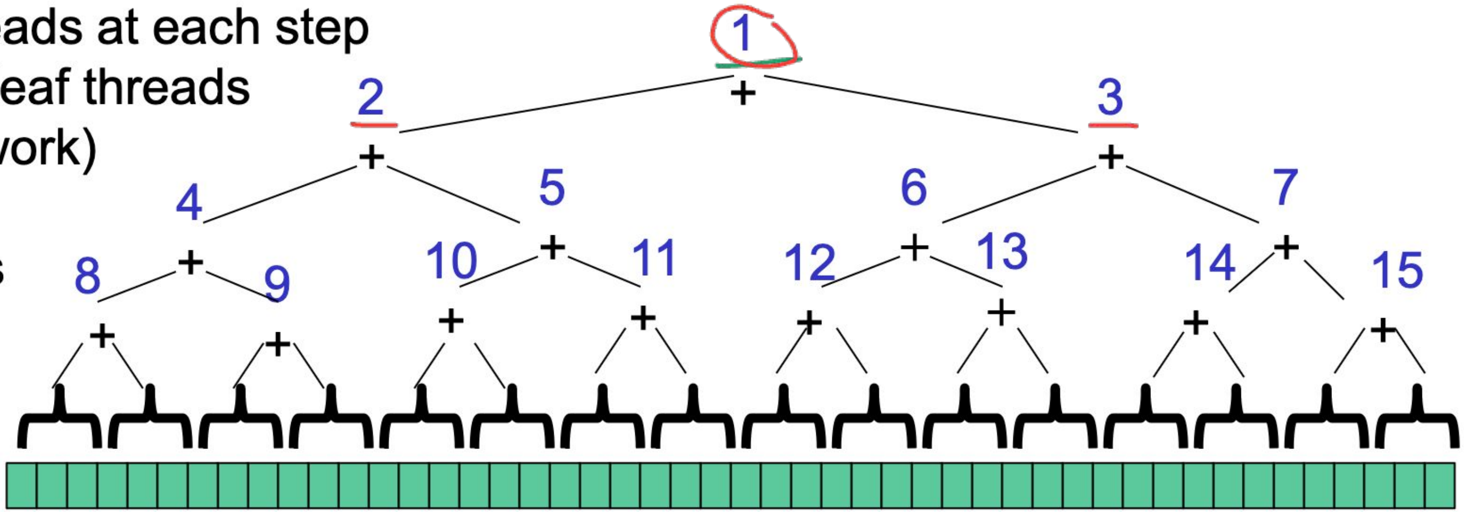
Half the threads!

```
// wasteful, don't
SumThread left = …
SumThread right = …
left.start();
right.start();
left.join();
right.join();
ans=left.ans+right.ans;
```

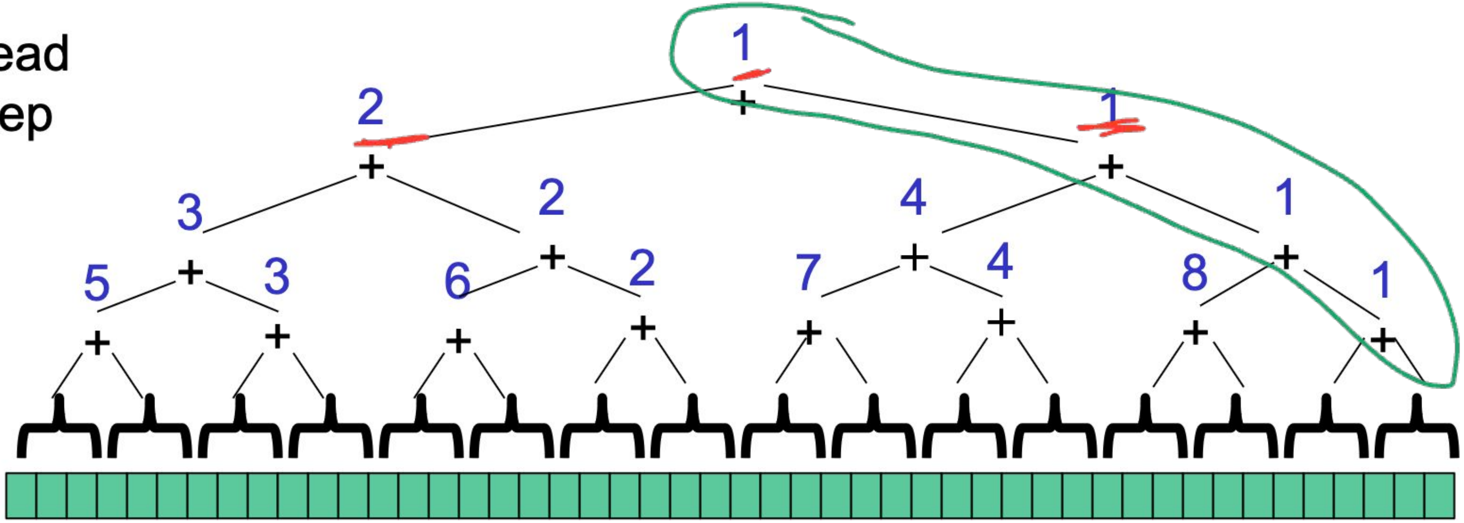
```
// better, do!
SumThread left = …
SumThread right = …
left.start();
right.run(); // normal function call!
left.join();
// no right.join needed
ans=left.ans+right.ans;
```

- If a language had built-in support for fork-join parallelism, I would expect this hand-optimization to be unnecessary
- But the library we are using expects you to do it yourself
  - And the difference is surprisingly substantial
- Again, no difference in theory

2 new threads at each step
(and only leaf threads
do much work)
Total =
15 threads



1 new thread
at each step
Total =
8 threads



That library, finally

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
  - …
- Library's implementation is a fascinating but advanced topic

Different terms, same basic idea

To use the ForkJoin Framework:

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

Java Threads:

Don’t subclass **Thread**
Don’t override **run**
Do not use an **ans** field
Don’t call **start**
Don’t *just* call **join**
answer)
Don’t call **run** to hand-optimize
Don’t have a topmost call to **run**

ForkJoin Framework:

Do subclass **RecursiveTask<V>**
Do override **compute**
Do return a **V** from **compute**
Do call **fork**
Do call **join** (which returns

Do call **compute** to hand-optimize
Do create a pool and call **invoke**

ForkJoin Framework Version *(missing imports)*

```
class SumTask extends RecursiveTask<Integer> {
  int lo; int hi; int[] arr;
  SumTask(int[] a, int l, int h) { ... }
  protected Integer compute() { // override
    if(hi - lo < SEQUENTIAL_CUTOFF)
      int ans = 0; // 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);
      SumTask right =
          new SumTask(arr,(hi+lo)/2,hi);
      left.fork(); // forks a thread and calls compute
      int rightAns = right.compute(); // call directly
      int leftAns = left.join(); // get result from left
      return leftAns + rightAns;
  }
}
```

```
static final ForkJoinPool POOL =
    new ForkJoinPool();

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

Getting good results in practice

- Sequential threshold
  - Library documentation recommends doing approximately 100-5000 basic operations in each “piece” of your algorithm
- Library needs to “warm up”
  - May see slow results before the Java virtual machine re-optimizes the library internals
  - Put your computations in a loop to see the “long-term benefit”