CSE 332:
Analysis of Fork-Join Parallel Programs

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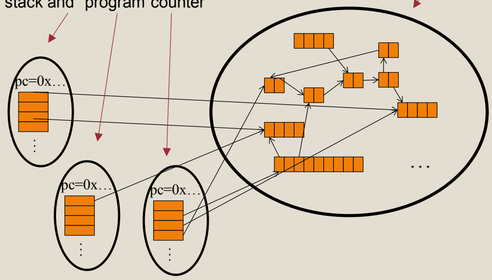
New Story: Shared Memory with Threads

Heap for all objects and static fields, *shared* by all threads

Threads, each with own *unshared* call stack and "program counter"



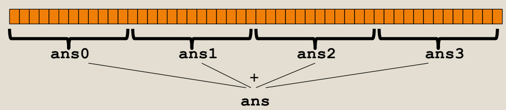
Fork-Join Parallelism

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 ¼ of the array



– Create 4 *thread objects*, each given ¼ 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];
  }
}
```

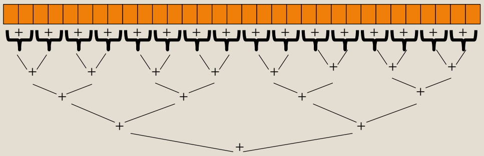
Because we must override a no-arguments/no-result run, we use fields to communicate across threads

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;
}
```

Recall: Parallel Sum

- Sum up N numbers in an array



- Let's implement this with threads...

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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

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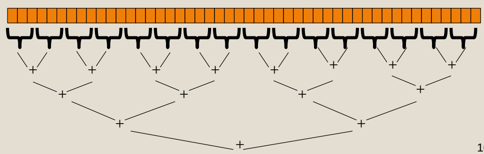
Divide-and-conquer

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 +)



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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

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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`

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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 7 standard libraries
    - (Also available for Java 6 as a downloaded `.jar` file)
  - 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
    - …

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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"

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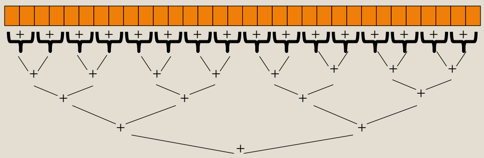
Fork Join Framework Version:

```
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
}
```

Parallel Sum

- Sum up N numbers in an array



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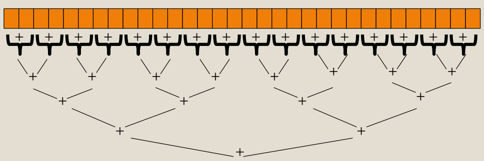
Parallel Max?



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Reductions

- Same trick works for many tasks, e.g.,
  - is there an element satisfying some property (e.g., prime)
  - left-most element satisfying some property (e.g., first prime)
  - smallest rectangle encompassing a set of points (proj3)
  - counts: number of strings that start with a vowel
  - are these elements in sorted order?
- Called a reduction, or reduce operation
  - reduce a collection of data items to a single item
    - result can be more than a single value, e.g., produce histogram from a set of test scores
- Very common parallel programming pattern

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Parallel Vector Scaling

- Multiply every element in the array by 2

Maps

- A map operates on each element of a collection of data to produce a new collection of the same size
  - each element is processed independently of the others, e.g.
    - vector scaling
    - vector addition
    - test property of each element (is it prime)
    - uppercase to lowercase
    - …
- Another common parallel programming pattern

Maps in ForkJoin Framework

```
class VecAdd extends RecursiveAction {
  int lo; int hi; int[] res; int[] arr1; int[] arr2;
  VecAdd(int l,int h,int[] r,int[] a1,int[] a2){ … }
  protected void compute(){
    if(hi – lo < SEQUENTIAL_CUTOFF) {
      for(int i=lo; i < hi; i++)
        res[i] = arr1[i] + arr2[i];
    } else {
      int mid = (hi+lo)/2;
      VecAdd left = new VecAdd(lo,mid,res,arr1,arr2);
      VecAdd right= new VecAdd(mid,hi,res,arr1,arr2);
      left.fork();
      right.compute();
      left.join();
    }
  }
}
static final ForkJoinPool fjPool = new ForkJoinPool();
int[] add(int[] arr1, int[] arr2){
  assert (arr1.length == arr2.length);
  int[] ans = new int[arr1.length];
  fjPool.invoke(new VecAdd(0,arr.length,ans,arr1,arr2);
  return ans;
}
```


Maps and Reductions

Maps and reductions: the “workhorses” of parallel programming

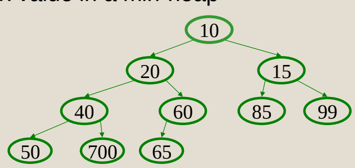
- By far the most important and common patterns
- Learn to recognize when an algorithm can be written in terms of maps and reductions
- makes parallel programming easy (plug and play)

Distributed Map Reduce

- You may have heard of Google’s map/reduce
  - or open-source version called Hadoop
  - powers much of Google’s infrastructure
- Idea: maps/reductions using many machines
  - same principles, applied to distributed computing
  - system takes care of distributing data, fault-tolerance
  - you just write code to handle one element, reduce a collection
- Co-developed by Jeff Dean (UW alum!)

Maps and Reductions on Trees

- Max value in a min-heap



- How to parallelize?
- Is this a map or a reduce?
- Complexity?

Analyzing Parallel Programs

Let T_P be the running time on **P** processors

Two key measures of run-time:
- Work: How long it would take 1 processor = T_1
- Span: How long it would take infinity processors = T_∞
  - The hypothetical ideal for parallelization
  - This is the longest "dependence chain" in the computation
  - Example: $O(\log n)$ for summing an array
  - Also called "critical path length" or "computational depth"

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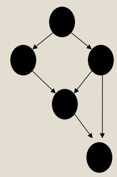
The DAG

- Fork-join programs can be modeled with a DAG
  - nodes: pieces of work
  - edges: order dependencies



A `fork` creates two children
- new thread
- continuation of current thread

A `join` makes a node with two incoming edges
- terminated thread
- continuation of current thread

What's T_1 (work):

What's T_∞ (span):

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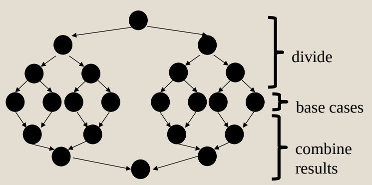
Divide and Conquer Algorithms

Our **`fork`** and **`join`** frequently look like this:



In this context, the span (T_∞) is:
- The longest dependence-chain; longest 'branch' in parallel 'tree'
- Example: $O(\log n)$ for summing an array; we halve the data down to our cut-off, then add back together; $O(\log n)$ steps, O(1) time for each
- Also called "critical path length" or "computational depth"

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Parallel Speed-up

- Speed-up on **P** processors: T_1 / T_P
- If speed-up is **P**, we call it perfect linear speed-up
  - e.g., doubling **P** halves running time
  - hard to achieve in practice
- Parallelism is the maximum possible speed-up: T_1 / T_∞
  - if you had infinite processors

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Estimating T_p

- How to estimate T_P (e.g., P = 4)?
- Lower bounds on T_P (ignoring memory, caching...)
  1. T_∞
  2. T_1 / P
  - which one is the tighter (higher) lower bound?
- The ForkJoin Java Framework achieves the following expected time asymptotic bound:

$$T_P \in O(T_\infty + T_1 / P)$$

  - this bound is optimal

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Amdahl's Law

- Most programs have
  1. parts that parallelize well
  2. parts that don't parallelize at all
- The latter become bottlenecks

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Amdahl's Law

- Let T_1 = 1 unit of time
- Let S = proportion that can't be parallelized

$$1 = \mathbf{T_1 = S + (1 - S)}$$

- Suppose we get perfect linear speedup on the parallel portion:

$$\mathbf{T_P =}$$

- So the overall speed-up on P processors is (Amdahl's Law):

$$\mathbf{T_1 / T_P =}$$

$$\mathbf{T_1 / T_\infty =}$$

- If 1/3 of your program is parallelizable, max speedup is:

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Pretty Bad News

- Suppose 25% of your program is sequential.
  - Then a billion processors won't give you more than a 4x speedup!
- What portion of your program must be parallelizable to get 10x speedup on a 1000 core GPU?
  - 10 <= 1 / (S + (1-S)/1000)
- Motivates minimizing sequential portions of your programs

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Take Aways

- Parallel algorithms can be a big win
- Many fit standard patterns that are easy to implement
- Can't just rely on more processors to make things faster (Amdahl's Law)

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