



CSE 332: Data Structures & Parallelism

Lecture 15: Analysis of Fork-Join Parallel Programs

Ruth Anderson
Winter 2022

Outline

Done:

- How to use `fork` and `join` to write a parallel algorithm
- Why using divide-and-conquer with lots of small tasks is best
 - Combines results in parallel

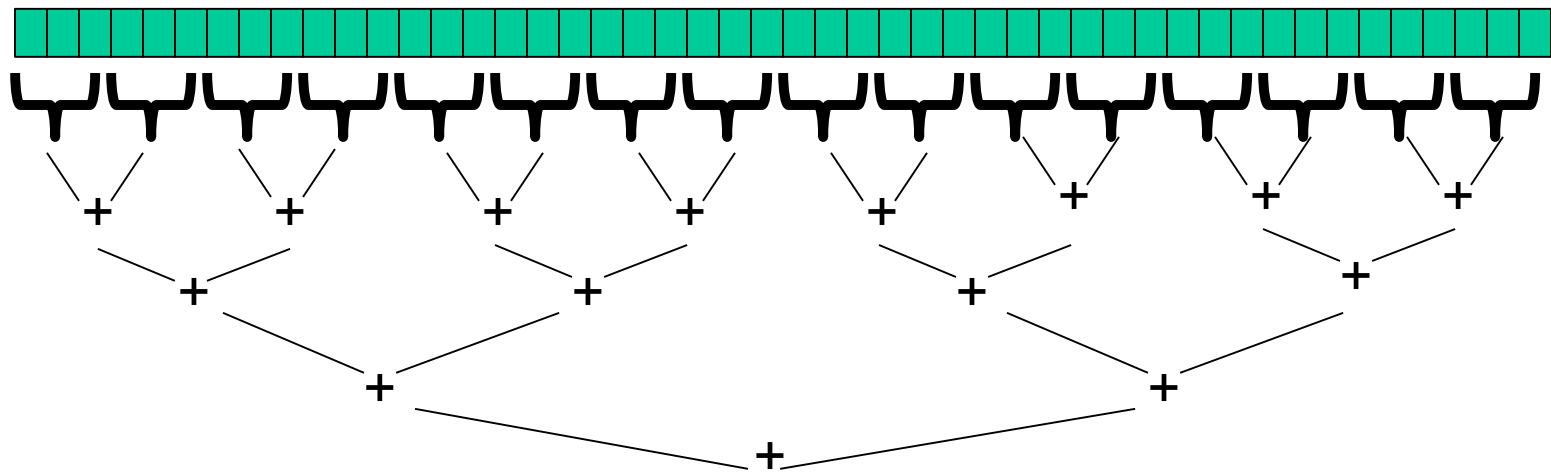
Now:

- More examples of simple parallel programs
- Arrays & balanced trees support parallelism better than linked lists
- Asymptotic analysis for fork-join parallelism
- Amdahl's Law

What else looks like this?

Saw summing an array went from $O(n)$ sequential to $O(\log n)$ parallel (assuming **a lot** of processors and very large n)

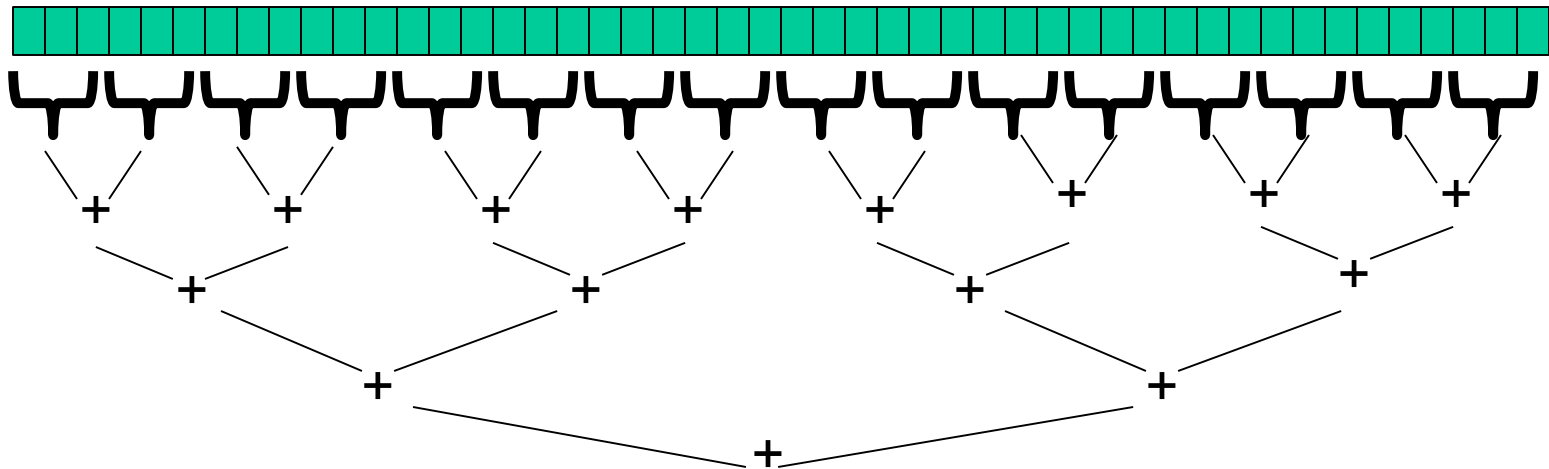
- Exponential speed-up in theory ($n / \log n$ grows exponentially)



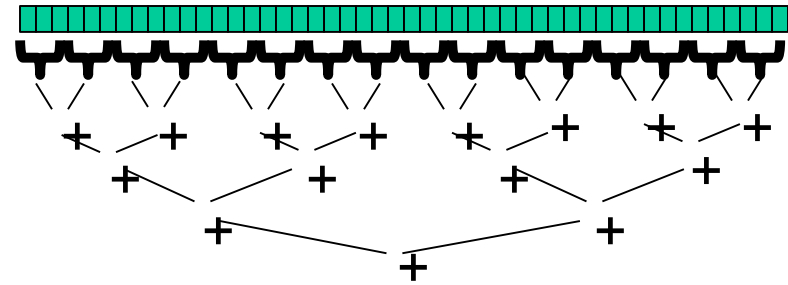
- Anything that can use results from two halves and merge them in $O(1)$ time has the same property...

Extending Parallel Sum

- We can tweak the ‘parallel sum’ algorithm to do all kinds of things; just specify 2 parts (usually)
 - Describe how to compute the result at the ‘cut-off’
(Sum: Iterate through sequentially and add them up)
 - Describe how to merge results
(Sum: Just add ‘left’ and ‘right’ results)



Examples



- Parallelization (for some algorithms)
 - Describe how to compute result at the ‘cut-off’
 - Describe how to merge results
- How would we do the following (assuming data is given as an array)?
 1. Maximum or minimum element
 2. Is there an element satisfying some property (e.g., is there a 17)?
 3. Left-most element satisfying some property (e.g., first 17)
 4. Smallest rectangle encompassing a number of points
 5. Counts; for example, number of strings that start with a vowel
 6. Are these elements in sorted order?

Reductions

- This class of computations are called **reductions**
 - We ‘reduce’ a large array of data to a single item
 - Produce single answer from collection via an **associative operator**
 - Examples: max, count, leftmost, rightmost, sum, product, ...
- Note: Recursive results don’t have to be single numbers or strings. They can be arrays or objects with multiple fields.
 - Example: create a Histogram of test results from a much larger array of actual test results
- While many can be parallelized due to nice properties like associativity of addition, some things are inherently sequential
 - How we process `arr[i]` may depend entirely on the result of processing `arr[i-1]`

Even easier: Maps (Data Parallelism)

- A `map` operates on each element of a collection independently to create a new collection of the same size
 - No combining results
 - For arrays, this is so trivial some hardware has direct support
- Canonical example: Vector addition

```
int[] vector add(int[] arr1, int[] arr2) {  
    assert (arr1.length == arr2.length);  
    result = new int[arr1.length];  
    FORALL(i=0; i < arr1.length; i++) {  
        result[i] = arr1[i] + arr2[i];  
    }  
    return result;  
}
```

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 POOL = new ForkJoinPool();
int[] add(int[] arr1, int[] arr2) {
    assert (arr1.length == arr2.length);
    int[] ans = new int[arr1.length];
    POOL.invoke(new VecAdd(0, arr1.length, ans, arr1, arr2));
    return ans;
}
```

Maps and reductions

Maps and reductions: the “workhorses” of parallel programming

- By far the two most important and common patterns
 - Two more-advanced patterns in next lecture
- Learn to recognize when an algorithm can be written in terms of maps and reductions
- Use maps and reductions to describe (parallel) algorithms
- Programming them becomes “trivial” with a little practice
 - Exactly like sequential for-loops seem second-nature

Map vs reduce in ForkJoin framework

- In our examples:
- Reduce:
 - Parallel-sum extended RecursiveTask
 - Result was returned from compute()
- Map:
 - Class extended was RecursiveAction
 - Nothing returned from compute()
 - In the above code, the 'answer' array was passed in as a parameter
- Doesn't *have* to be this way
 - Map can use RecursiveTask to, say, return an array
 - Reduce could use RecursiveAction; depending on what you're passing back via RecursiveTask, could store it as a class variable and access it via 'left' or 'right' when done

Digression: MapReduce on clusters

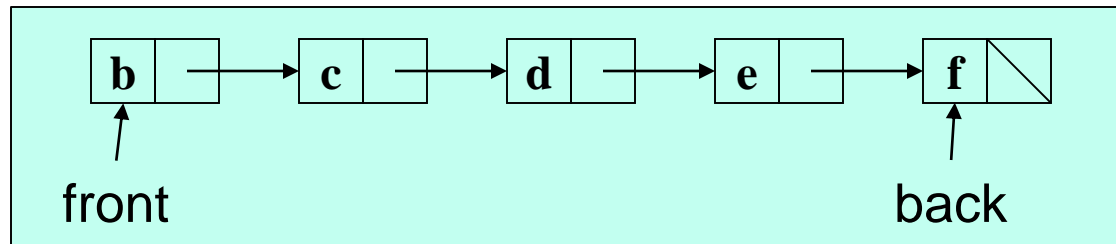
- You may have heard of Google's "map/reduce"
 - Or the open-source version Hadoop
- Idea: Perform maps/reduces on data using many machines
 - The system takes care of distributing the data and managing fault tolerance
 - You just write code to map one element and reduce elements to a combined result
- Separates how to do recursive divide-and-conquer from what computation to perform
 - Old idea in higher-order functional programming transferred to large-scale distributed computing
 - Complementary approach to declarative queries for databases

Trees

- Maps and reductions work just fine on balanced trees
 - Divide-and-conquer each child rather than array sub-ranges
 - Correct for unbalanced trees, but won't get much speed-up
- Example: minimum element in an unsorted but balanced binary tree in $O(\log n)$ time given enough processors
- How to do the sequential cut-off?
 - Store number-of-descendants at each node (easy to maintain)
 - Or could approximate it with, e.g., AVL-tree height

Linked lists

- Can you parallelize maps or reduces over linked lists?
 - Example: Increment all elements of a linked list
 - Example: Sum all elements of a linked list
 - Parallelism still beneficial for expensive per-element operations



- Once again, data structures matter!
- For parallelism, balanced trees generally better than lists so that we can get to all the data exponentially faster $O(\log n)$ vs. $O(n)$
 - Trees have the same flexibility as lists compared to arrays (in terms of say inserting an item in the middle of the list)

Analyzing algorithms

- How to measure efficiency?
 - Want asymptotic bounds
 - Want to analyze the algorithm without regard to a specific number of processors
 - The key “magic” of the ForkJoin Framework is getting expected run-time performance asymptotically optimal for the available number of processors
 - So we can analyze algorithms assuming this guarantee

Work and Span

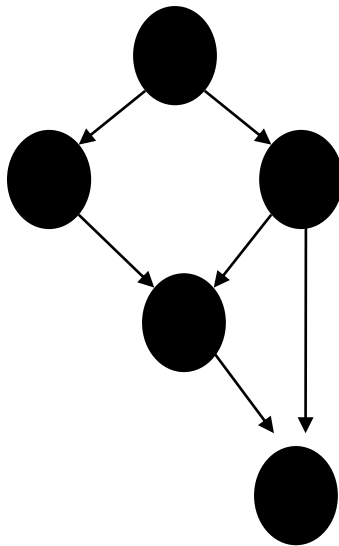
Let T_P be the running time if there are P processors available

Two key measures of run-time:

- **Work:** How long it would take 1 processor = T_1
 - Just “sequentialize” the recursive forking
 - Cumulative work that all processors must complete
- **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
 - Notice in this example having $> n/2$ processors is no additional help
 - Also called “critical path length” or “computational depth”

The DAG (Directed Acyclic Graph)

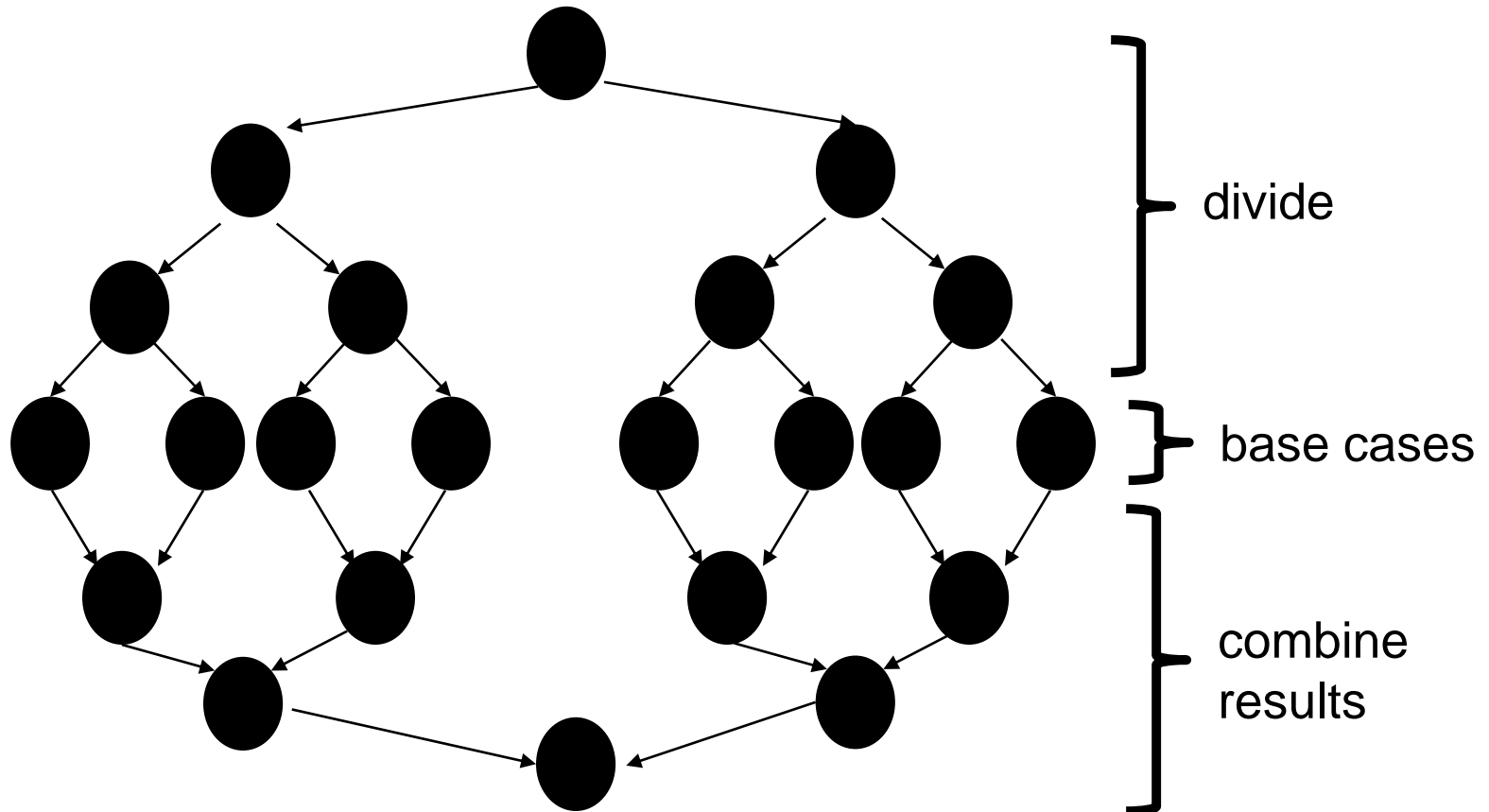
- A program execution using `fork` and `join` can be seen as a DAG
- [A DAG is a graph that is directed (edges have direction (arrows)), and those arrows do not create a cycle (ability to trace a path that starts and ends at the same node).]
 - **Nodes:** Pieces of work
 - **Edges:** Source must finish before destination starts



- A `fork` “ends a node” and makes two outgoing edges
 - New thread
 - Continuation of current thread
- A `join` “ends a node” and makes a node with two incoming edges
 - Node just ended
 - Last node of thread joined on

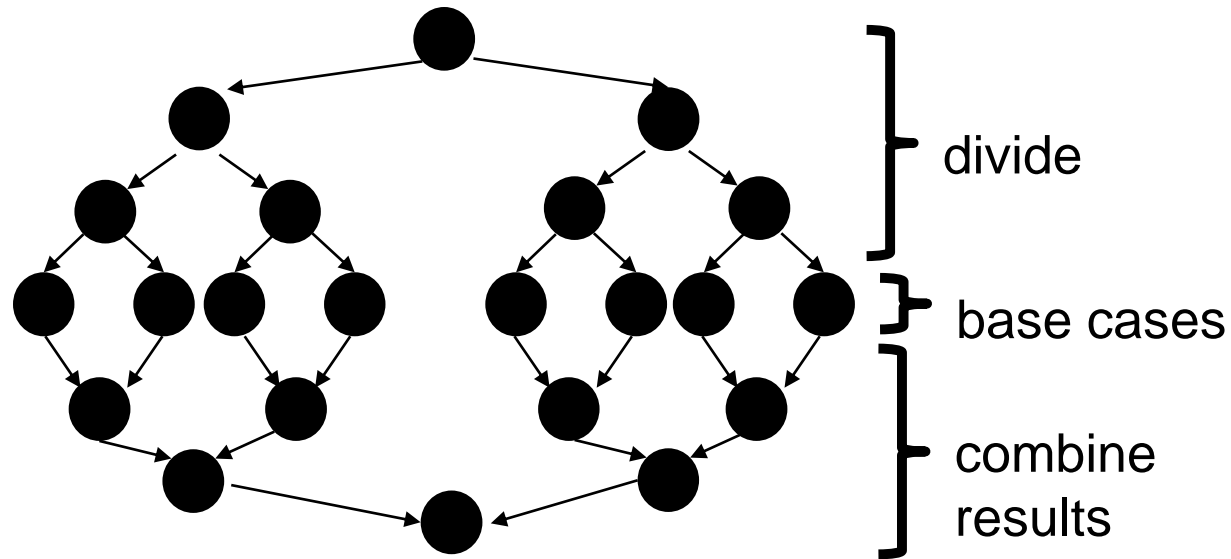
Our simple examples

- `fork` and `join` are very flexible, but divide-and-conquer maps and reductions use them in a very basic way:
 - A tree on top of an upside-down tree



Our simple examples, in more detail

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”

More interesting DAGs?

- The DAGs are not always this simple
- Example:
 - Suppose combining two results might be expensive enough that we want to parallelize each one
 - Then each node in the inverted tree on the previous slide would itself expand into another set of nodes for that parallel computation

Connecting to performance

- Recall: T_P = running time if there are P processors available
- Work = T_1 = sum of run-time of all nodes in the DAG
 - That lonely processor does everything
 - Any topological sort is a legal execution
 - $O(n)$ for simple maps and reductions
- Span = T_∞ = sum of run-time of all nodes on the most-expensive path in the DAG
 - Note: costs are on the nodes not the edges
 - Our infinite army can do everything that is ready to be done, but still has to wait for earlier results
 - $O(\log n)$ for simple maps and reductions

Definitions

A couple more terms:

- **Speed-up** on P processors: T_1 / T_P
- If speed-up is P as we vary P , we call it **perfect linear speed-up**
 - Perfect linear speed-up means doubling P halves running time
 - Usually our goal; hard to get in practice
- **Parallelism** is the maximum possible speed-up: T_1 / T_∞
 - At some point, adding processors won't help
 - What that point is depends on the span

Parallel algorithms is about decreasing span without increasing work too much

Optimal T_P : Thanks ForkJoin library!

- So we know T_1 and T_∞ but we want T_P (e.g., $P=4$)
- Ignoring memory-hierarchy issues (caching), T_P can't beat
 - T_1 / P why not?
 - T_∞ why not?

- So an *asymptotically* optimal execution would be:

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

- First term dominates for small P , second for large P
- The ForkJoin Framework gives an *expected-time guarantee* of asymptotically optimal!
 - Expected time because it flips coins when *scheduling*
 - How? For an advanced course (few need to know)
 - Guarantee requires a few assumptions about your code...

Division of responsibility

- Our job as ForkJoin Framework users:
 - Pick a good algorithm, write a program
 - When run, program creates a DAG of things to do
 - *Make all the nodes a small-ish and approximately equal amount of work*
- The framework-writer's job:
 - Assign work to available processors to avoid **idling**
 - Let framework-user ignore all **scheduling** issues
 - Keep constant factors low
 - Give the **expected-time optimal guarantee** assuming framework-user did his/her job

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

Examples

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

- In the algorithms seen so far (e.g., sum an array):
 - $T_1 = O(n)$
 - $T_\infty = O(\log n)$
 - So expect (ignoring overheads): $T_P = O(n/P + \log n)$
- Suppose instead:
 - $T_1 = O(n^2)$
 - $T_\infty = O(n)$
 - So expect (ignoring overheads): $T_P = O(n^2/P + n)$

And now for the bad news...

- So far: talked about a parallel program in terms of **work** and **span**
- In practice, it's common that your program has:
 - a) parts that **parallelize well**:
 - Such as maps/reduces over arrays and trees
 - b) ...and parts that **don't parallelize at all**:
 - Such as reading a linked list, getting input, or just doing computations where each step needs the results of previous step
- These **unparallelized** parts can turn out to be a big bottleneck, which brings us to Amdahl's Law ...

Amdahl's Law (mostly bad news)

Let the **work** (time to run on 1 processor) be 1 unit time

Let **S** be the portion of the execution that can't be parallelized

Then: $T_1 = S + (1-S) = 1$

Suppose we get perfect linear speedup *on the parallel portion*

Then: $T_p = S + (1-S)/P$

So the overall speedup with **P** processors is (Amdahl's Law):

$$T_1 / T_p = 1 / (S + (1-S)/P)$$

And the parallelism (infinite processors) is:

$$T_1 / T_\infty = 1 / S$$

Amdahl's Law Example

Suppose: $T_1 = S + (1-S) = 1$ (aka total program execution time)

$$T_1 = 1/3 + 2/3 = 1$$

$$T_1 = 33 \text{ sec} + 67 \text{ sec} = 100 \text{ sec}$$

Time on P processors: $T_p = S + (1-S)/P$

So: $T_p = 33 \text{ sec} + (67 \text{ sec})/P$

$$T_3 = 33 \text{ sec} + (67 \text{ sec})/3 =$$

Why such bad news?

$$T_1 / T_p = 1 / (S + (1-S)/P)$$

$$T_1 / T_\infty = 1 / S$$

- Suppose 33% of a program is sequential
 - Then a billion processors won't give a speedup over 3!!!
- No matter how many processors you use, your speedup is bounded by the sequential portion of the program.

The future and Amdahl's Law

Speedup: $T_1 / T_p = 1 / (S + (1-S)/P)$

Max Parallelism: $T_1 / T_\infty = 1 / S$

- Suppose you miss the good old days (1980-2005) where 12ish years was long enough to get 100x speedup
 - Now suppose in 12 years, clock speed is the same but you get 256 processors instead of 1
 - What portion of the program must be parallelizable to get 100x speedup?

All is not lost

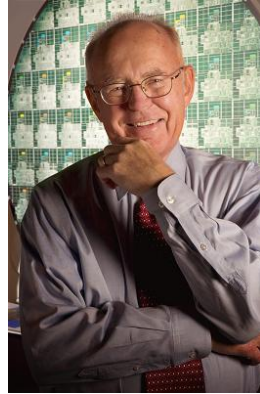
Amdahl's Law is a bummer!

- Unparallelized parts become a bottleneck very quickly
- But it doesn't mean additional processors are worthless
- We can find new parallel algorithms
 - Some things that seem entirely sequential turn out to be parallelizable
 - Eg. How can we parallelize the following?
 - Take an array of numbers, return the 'running sum' array:

input	6	4	16	10	16	14	2	8
output	6	10	26	36	52	66	68	76

- At a glance, not sure; we'll explore this shortly
- We can also change the problem we're solving or do new things
 - Example: Video games use tons of parallel processors
 - They are not rendering 10-year-old graphics faster
 - They are rendering richer environments and more beautiful (terrible?) monsters

Moore and Amdahl



- Moore's "Law" is an **observation** about the progress of the semiconductor industry
 - Transistor density doubles roughly every 18 months
- Amdahl's Law is a **mathematical theorem**
 - Diminishing returns of adding more processors
- Both are incredibly important in designing computer systems