



CSE 332: Data Structures & Parallelism

Lecture 16: Parallel Prefix, Pack, and Sorting

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Outline

Done:

- Simple ways to use parallelism for counting, summing, finding
- Analysis of running time and implications of Amdahl's Law

Now: Clever ways to parallelize more than is intuitively possible

- **Parallel prefix:**
 - This “key trick” typically underlies surprising parallelization
 - Enables other things like **packs (aka filters)**
- **Parallel sorting:** quicksort (not in place) and mergesort
 - Easy to get a little parallelism
 - With cleverness can get a lot

The prefix-sum problem

Given `int[] input`, produce `int[] output` where:

$$\text{output}[i] = \text{input}[0] + \text{input}[1] + \dots + \text{input}[i]$$

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

Sequential can be a CSE142 exam problem:

```
int[] prefix_sum(int[] input){
    int[] output = new int[input.length];
    output[0] = input[0];
    for(int i=1; i < input.length; i++)
        output[i] = output[i-1] + input[i];
    return output;
}
```

Does not seem parallelizable

- Work: $O(n)$, Span: $O(n)$
- *This algorithm* is sequential, but a *different algorithm* has Work: $O(n)$, Span: $O(\log n)$

Parallel prefix-sum

- The parallel-prefix algorithm does two passes
 - Each pass has $O(n)$ work and $O(\log n)$ span
 - So in total there is $O(n)$ work and $O(\log n)$ span
 - So like with array summing, parallelism is $n/\log n$
 - An exponential speedup
- First pass builds a tree bottom-up: the “up” pass
- Second pass traverses the tree top-down: the “down” pass

Local bragging

Historical note:

- Original algorithm due to R. Ladner and M. Fischer at UW in 1977
- Richard Ladner joined the UW faculty in 1971 and hasn't left



1968? 1973?



recent

Parallel Prefix: The Up Pass

We build want to build a binary tree where

- Root has sum of the range $[x,y)$
- If a node has sum of $[lo,hi)$ and $hi > lo$,
 - Left child has sum of $[lo,middle)$
 - Right child has sum of $[middle,hi)$
 - A leaf has sum of $[i,i+1)$, which is simply $input[i]$

It is critical that we actually create the tree as we will need it for the down pass

- We do not need an actual linked structure
- We could use an array as we did with heaps

Analysis of first step: Work = Span =

The algorithm, part 1

Specifically.....

1. Propagate 'sum' up: Build a binary tree where
 - Root has sum of `input[0] .. input[n-1]`
 - Each node has sum of `input[l0] .. input[hi-1]`
 - Build up from leaves; `parent.sum=left.sum+right.sum`
 - A leaf's sum is just its value; `input[i]`

This is an easy fork-join computation: combine results by actually building a binary tree with all the sums of ranges

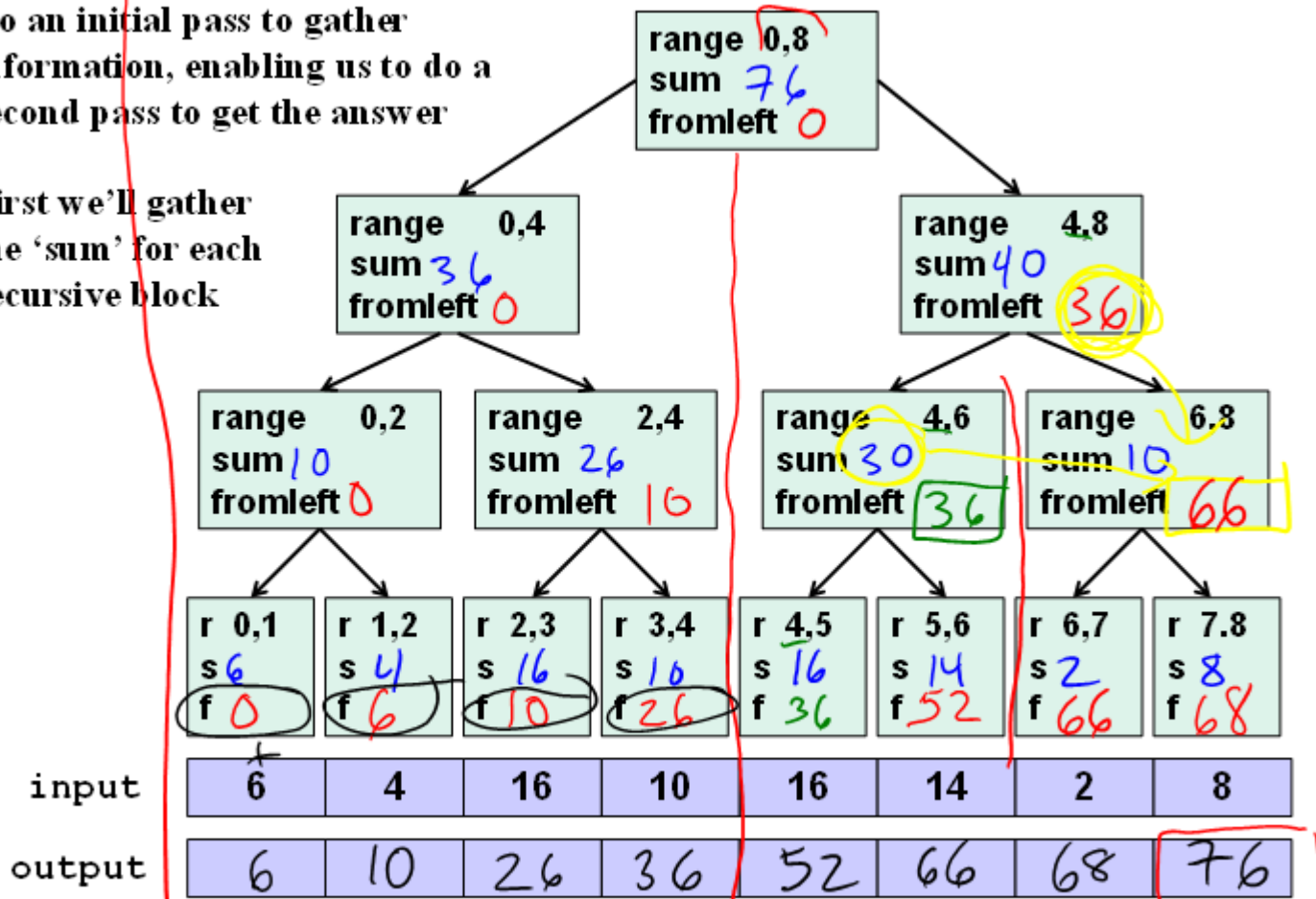
- Tree built bottom-up in parallel
- Could be more clever; ex. Use an array as tree representation like we did for heaps

Analysis of first step: $O(n)$ work, $O(\log n)$ span

The (completely non-obvious) idea:

Do an initial pass to gather information, enabling us to do a second pass to get the answer

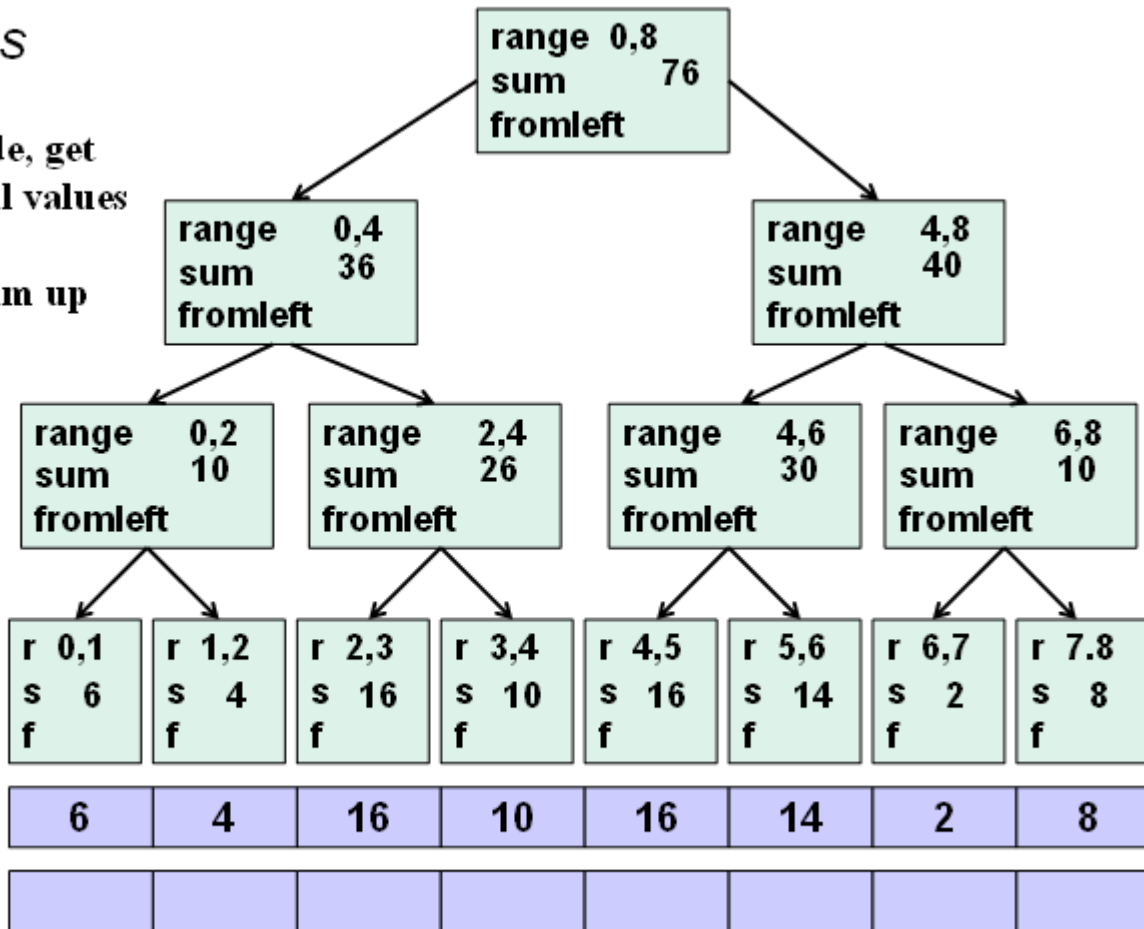
First we'll gather the 'sum' for each recursive block



First pass

For each node, get the sum of all values in its range; propagate sum up from leaves

Will work like parallel sum, but recording intermediate information



The algorithm, part 2

2. Propagate 'fromleft' down:

- Root given a `fromLeft` of 0
- Node takes its `fromLeft` value and
 - Passes its left child the same `fromLeft`
 - Passes its right child its `fromLeft` plus its left child's `sum` (as stored in part 1)
- At the leaf for array position `i`,
`output[i] = fromLeft + input[i]`

This is an easy fork-join computation: traverse the tree built in step 1 and produce no result (the leaves assign to `output`)

- Invariant: `fromLeft` is sum of elements left of the node's range

Analysis of first step: $O(n)$ work, $O(\log n)$ span

Analysis of second step: $O(n)$ work, $O(\log n)$ span

Total for algorithm: $O(n)$ work, $O(\log n)$ span

The algorithm, part 2

2. Propagate 'fromleft' down:

- Root given a `fromLeft` of 0
- Node takes its `fromLeft` value and
 - Passes its left child the same `fromLeft`
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- At the leaf for array position `i`,
`output[i]=fromLeft+input[i]`

This is an easy fork-join computation: traverse the tree built in step 1 and produce no result (the leaves assign to `output`)

- Invariant: `fromLeft` is sum of elements left of the node's range

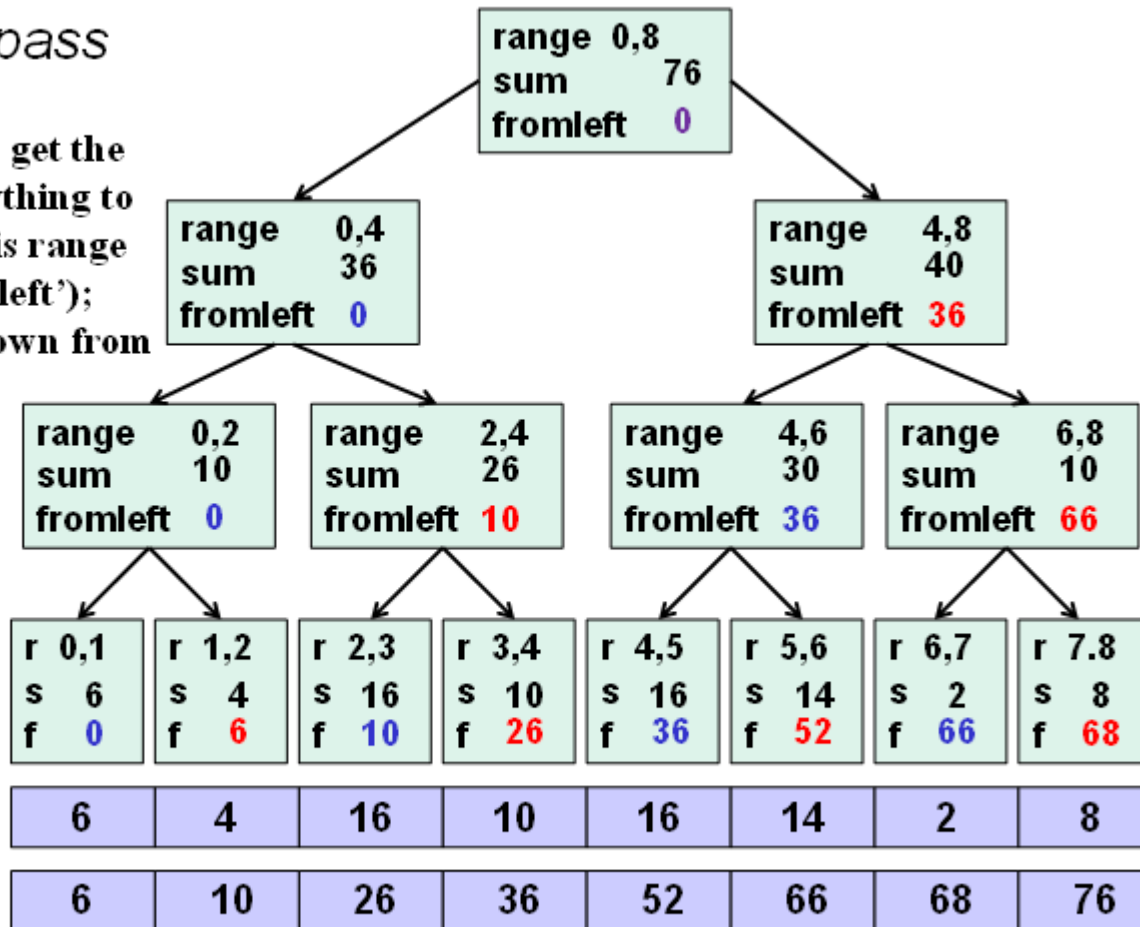
Analysis of first step: $O(n)$ work, $O(\log n)$ span

Analysis of second step: $O(n)$ work, $O(\log n)$ span

Total for algorithm: $O(n)$ work, $O(\log n)$ span

Second pass

Using 'sum', get the sum of everything to the left of this range (call it 'fromleft'); propagate down from root



Sequential cut-off

Adding a sequential cut-off isn't too bad:

- **Step One:** Propagating Up the `sums`:
 - Have a leaf node just hold the sum of a range of values instead of just one array value (Sequentially compute sum for that range)
 - The tree itself will be shallower
- **Step Two:** Propagating Down the `fromLefts`:
 - Have leaf compute prefix sum sequentially over its `[lo,hi)`:

```
output[lo] = fromLeft + input[lo];
for(i=lo+1; i < hi; i++)
    output[i] = output[i-1] + input[i]
```

Parallel prefix, generalized

Just as sum-array was the simplest example of a common pattern, prefix-sum illustrates a pattern that arises in many, many problems

- Minimum, maximum of all elements *to the left of i*
- Is there an element *to the left of i* satisfying some property?
- Count of elements *to the left of i* satisfying some property
 - This last one is perfect for an efficient parallel pack...
 - Perfect for building on top of the “parallel prefix trick”

Pack (think "Filter")

[Non-standard terminology]

Given an array **input**, produce an array **output** containing only elements such that $f(\text{element})$ is **true**

Example: **input** [17, 4, 6, 8, 11, 5, 13, 19, 0, 24]
 0 1 2 3 4 5 6 7 8 9
 T F F F T F T T F T
f: "is element > 10"
output [17, 11, 13, 19, 24]
 0 1 2 3 4

Parallelizable?

- Determining whether an element belongs in the output is easy
- But determining where an element belongs in the output is hard; seems to depend on previous results...

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15

```
j = 0
for i = 1 to n:
  if (input[i] > 10) {
    output[j] = input[i];
    j++;
  }
}
```

Parallel Pack = (Soln)

In this example,
Filter =
element > 10

parallel map + parallel prefix + parallel map

1. **Parallel map** to compute a **bit-vector** for true elements:

input [17, 4, 6, 8, 11, 5, 13, 19, 0, 24]

bits [1, 0, 0, 0, 1, 0, 1, 1, 0, 1]

0 1 2 3 4 5 6 7 8 9

2. **Parallel-prefix** sum on the bit-vector:

bitsum [1, 1, 1, 1, 2, 2, 3, 4, 4, 5]

0 1 2 3 4 5 6 7 8 9

3. **Parallel map** to produce the output:

output [17, 11, 13, 19, 24]

0 1 2 3 4

```
output = new array of size bitsum[n-1]
```

```
FORALL(i=0; i < input.length; i++){
```

```
  if (bit[i] == 1) {
```

```
    output[bitsum[i]-1] = input[i];
```

```
  }
```

```
}
```

11/06/2017

Parallel Pack =

parallel map + parallel prefix + parallel map

In this example,
Filter =
element > 10

1. **Parallel map** to compute a **bit-vector** for true elements:

input [17, 4, 6, 8, 11, 5, 13, 19, 0, 24]

bits [1, 0, 0, 0, 1, 0, 1, 1, 0, 1]

2. **Parallel-prefix** sum on the bit-vector:

bitsum [1, 1, 1, 1, 2, 2, 3, 4, 4, 5]

3. **Parallel map** to produce the output:

output [17, 11, 13, 19, 24]

```
output = new array of size bitsum[n-1]
FORALL(i=0; i < input.length; i++){
    if(bits[i]==1)
        output[bitsum[i]-1] = input[i];
}
```

Pack comments

- First two steps can be combined into one pass
 - Just using a different base case for the prefix sum
 - No effect on asymptotic complexity
- Can also combine third step into the down pass of the prefix sum
 - Again no effect on asymptotic complexity
- Analysis: $O(n)$ work, $O(\log n)$ span
 - 2 or 3 passes, but 3 is a constant 😊
- Parallelized packs will help us parallelize quicksort...

Sequential Quicksort review

Recall quicksort was sequential, in-place, expected time $O(n \log n)$

- | | Best / expected case work |
|--|----------------------------------|
| 1. Pick a pivot element | $O(1)$ |
| 2. Partition all the data into: | $O(n)$ |
| A. The elements less than the pivot | |
| B. The pivot | |
| C. The elements greater than the pivot | |
| 3. Recursively sort A and C | $2T(n/2)$ |

Recurrence (assuming a good pivot):

$$T(0)=T(1)=1$$
$$T(n)=\underline{O(n)} + 2T\left(\frac{n}{2}\right)$$

Run-time: $O(n \log n)$

How should we parallelize this?

Review: Really common recurrences

Should know how to solve recurrences but also recognize some really common ones:

$T(n) = O(1) + T(n-1)$	linear
$T(n) = O(1) + 2T(n/2)$	linear
$T(n) = O(1) + T(n/2)$	logarithmic
$T(n) = O(1) + 2T(n-1)$	exponential
$T(n) = O(n) + T(n-1)$	quadratic
$T(n) = O(n) + T(n/2)$	linear
$T(n) = O(n) + 2T(n/2)$	$O(n \log n)$

Note big-Oh can also use more than one variable

- Example: can sum all elements of an n -by- m matrix in $O(nm)$

Parallel Quicksort (version 1)

	Best / expected case work
1. Pick a pivot element	$O(1)$
2. Partition all the data into:	$O(n)$
A. The elements less than the pivot	
B. The pivot	
C. The elements greater than the pivot	
3. Recursively sort A and C	$2T(n/2)$

First: Do the two recursive calls in parallel

- Work: $O(n \log n)$
- Span: now recurrence takes the form:

Span:
$$T(n) = O(n) + T\left(\frac{n}{2}\right)$$
$$= O(n)$$

Parallel Quicksort (version 1) (Soln)

	Best / expected case <i>work</i>
1. Pick a pivot element	$O(1)$
2. Partition all the data into:	$O(n)$
A. The elements less than the pivot	
B. The pivot	
C. The elements greater than the pivot	
3. Recursively sort A and C	$2T(n/2)$

First: Do the two recursive calls in parallel

- **Work:** unchanged of course, $O(n \log n)$
- **Span:** now recurrence takes the form:
$$T(n) = O(n) + 1T(n/2) = O(n)$$
Span: $O(n)$
- So parallelism (i.e., work/span) is $O(\log n)$

Doing better

- $O(\log n)$ speed-up with an infinite number of processors is okay, but a bit underwhelming
 - Sort 10^9 elements 30 times faster
- Google searches strongly suggest quicksort cannot do better because the partition cannot be parallelized
 - The Internet has been known to be wrong 😊
 - But we need auxiliary storage (no longer in place)
 - In practice, constant factors may make it not worth it, but remember Amdahl's Law...(exposing parallelism is important!)
- Already have everything we need to parallelize the partition...

Parallel partition (not in place)

Partition all the data into:

- A. The elements less than the pivot
- B. The pivot
- C. The elements greater than the pivot

- This is just two packs!
 - We know a pack is $O(n)$ work, $O(\log n)$ span
 - Pack elements less than pivot into left side of aux array
 - Pack elements greater than pivot into right side of aux array
 - Put pivot between them and recursively sort
 - With a little more cleverness, can do both packs at once but no effect on asymptotic complexity
- With $O(\log n)$ span for partition, the total span for quicksort is
$$T(n) = O(\log n) + T\left(\frac{n}{2}\right) = O(\log^2 n)$$

Parallel partition (not in place) (Soln)

Partition all the data into:

- A. The elements less than the pivot**
- B. The pivot**
- C. The elements greater than the pivot**

- This is just two packs!
 - We know a pack is $O(n)$ work, $O(\log n)$ span
 - Pack elements less than pivot into left side of aux array
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$$T(n) = O(\log n) + 1T(n/2) = O(\log^2 n)$$

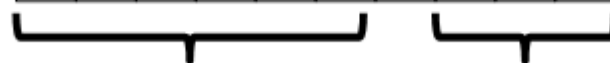
Parallel Quicksort Example (version 2)

- Step 1: pick pivot as median of three

8	1	4	9	0	3	5	2	7	6
---	---	---	---	---	---	---	---	---	---

- Steps 2a and 2c (combinable): pack less than, then pack greater than into a second array
 - Fancy parallel prefix to pull this off (not shown)

1	4	0	3	5	2				
1	4	0	3	5	2	6	8	9	7



- Step 3: Two recursive sorts in parallel
 - Can sort back into original array (like in mergesort)

Parallelize Mergesort?

Recall mergesort: sequential, **not**-in-place, worst-case $O(n \log n)$

- | | |
|----------------------------------|-----------|
| 1. Sort left half and right half | $2T(n/2)$ |
| 2. Merge results | $O(n)$ |

Just like quicksort, doing the two recursive sorts in parallel changes the recurrence for the **Span** to $T(n) = O(n) + 1T(n/2) = O(n)$

- Again, **Work** is $O(n \log n)$, and
- parallelism is $\text{work/span} = O(\log n)$
- To do better, *need to parallelize the merge*
 - The trick won't use parallel prefix this time...

Parallelizing the merge

Need to merge two *sorted* subarrays (may not have the same size)

0	1	4	8	9
---	---	---	---	---

2	3	5	6	7
---	---	---	---	---

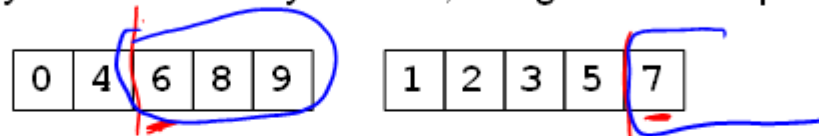
Idea: Suppose the larger subarray has m elements. In parallel:

- Merge the first $m/2$ elements of the larger half with the “appropriate” elements of the smaller half
- Merge the second $m/2$ elements of the larger half with the rest of the smaller half

Parallelizing the merge (in more detail)

Need to merge two **sorted** subarrays (may not have the same size)

Idea: Recursively divide subarrays in half, merge halves in parallel



Suppose the larger subarray has m elements. In parallel:

- Pick the **median** element of the larger array (here 6) in constant time
- In the other array, use binary search to find the first element greater than or equal to that median (here 7)

Then, in parallel:

- Merge half the larger array (from the median onward) with the upper part of the shorter array
- Merge the lower part of the larger array with the lower part of the shorter array

Example: Parallelizing the Merge

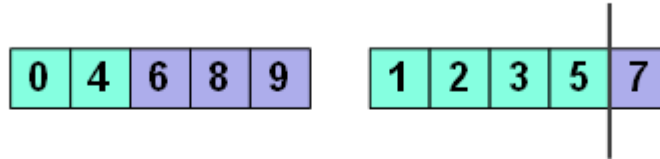
0	4	6	8	9	1	2	3	5	7
---	---	---	---	---	---	---	---	---	---

Example: Parallelizing the Merge

0	4	6	8	9	1	2	3	5	7
---	---	---	---	---	---	---	---	---	---

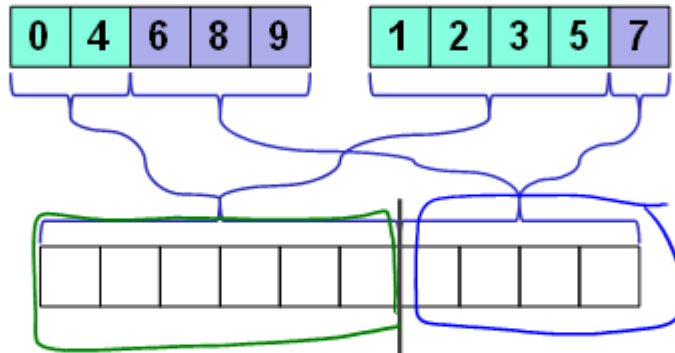
1. Get median of bigger half: $O(1)$ to compute **middle index**

Example: Parallelizing the Merge



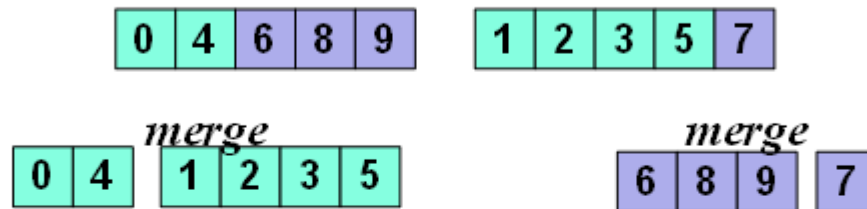
1. Get median of bigger half: $O(1)$ to compute middle index
2. Find how to split the smaller half at the same value:
 $O(\log n)$ to do binary search on the sorted small half

Example: Parallelizing the Merge



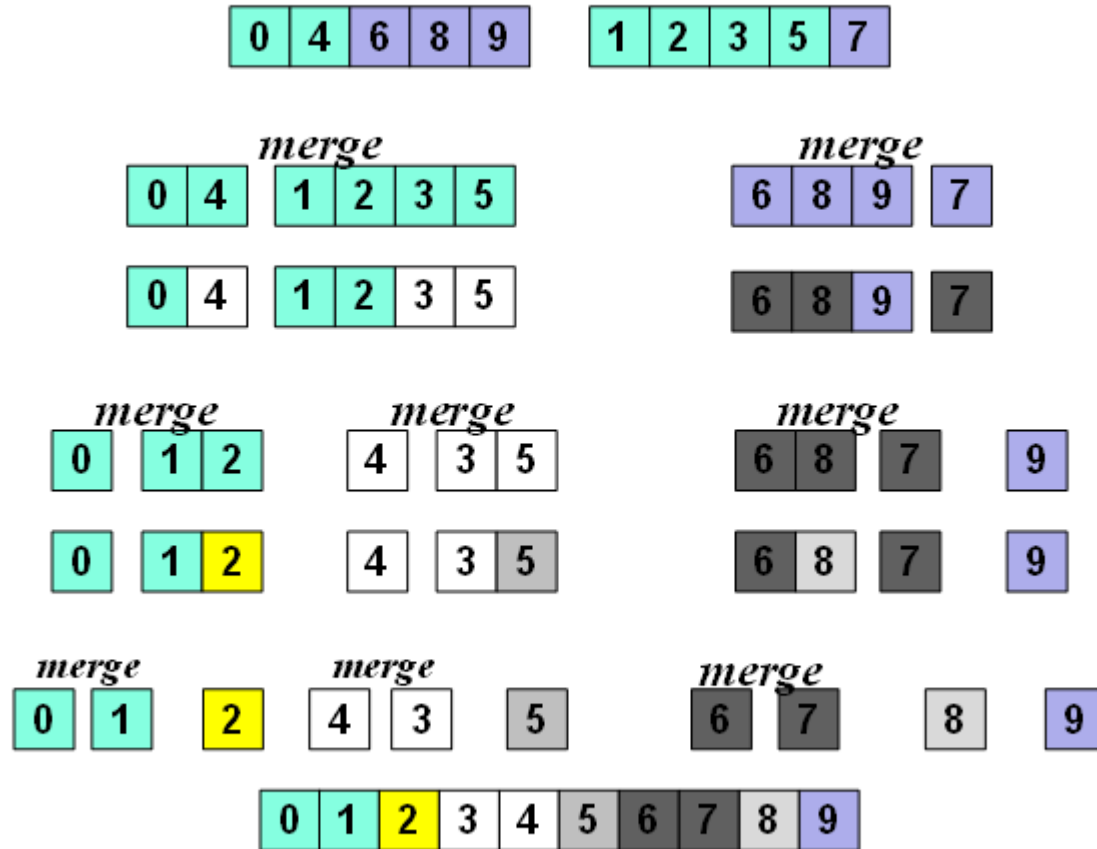
1. Get median of bigger half: $O(1)$ to compute middle index
2. Find how to split the smaller half at the same value: $O(\log n)$ to do binary search on the sorted small half
3. Size of two sub-merges conceptually splits output array: $O(1)$

Example: Parallelizing the Merge



1. Get median of bigger half: $O(1)$ to compute middle index
2. Find how to split the smaller half at the same value:
 $O(\log n)$ to do binary search on the sorted small half
3. Two sub-merges conceptually splits output array: $O(1)$
4. Do two submerges in parallel

Example: Parallelizing the Merge

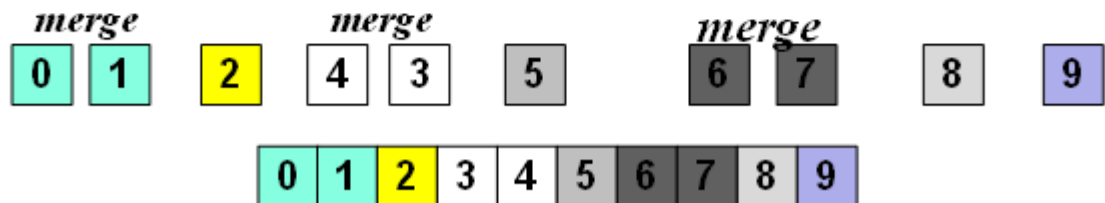


Example: Parallelizing the Merge



When we do each merge in parallel:

- we split the bigger array in half
- use binary search to split the smaller array
- And in base case we do the copy



Parallel Merge Pseudocode

```
Merge(arr[], left1, left2, right1, right2, out[], out1, out2)
```

```
    int leftSize = left2 - left1
```

```
    int rightSize = right2 - right1
```

```
    // Assert: out2 - out1 = leftSize + rightSize
```

```
    // We will assume leftSize > rightSize without loss of generality
```

```
    if (leftSize + rightSize < CUTOFF)
```

```
        sequential merge and copy into out[out1..out2]
```

```
    int mid = (left2 - left1) / 2
```

```
    - binarySearch arr[right1..right2] to find j such that
```

```
        arr[j] ≤ arr[mid] ≤ arr[j+1]
```

```
    - Merge(arr[], left1, mid, right1, j, out[], out1, out1+mid+j)
```

```
    - Merge(arr[], mid+1, left2, j+1, right2, out[], out1+mid+j+1, out2)
```

Analysis

- Sequential mergesort:
 $T(n) = 2T(n/2) + O(n)$ which is $O(n \log n)$
- Doing the *two recursive calls in parallel* but a sequential merge:
Work: same as sequential
Span: $T(n) = 1T(n/2) + O(n)$ which is $O(n)$
- Parallel merge makes **work** and **span** harder to compute...
 - Each merge step does an extra $O(\log n)$ binary search to find how to split the smaller subarray
 - To merge n elements total, do two smaller merges of possibly different sizes
 - But worst-case split is $(3/4)n$ and $(1/4)n$
 - Happens when the two subarrays are of the same size ($n/2$) and the “smaller” subarray splits into two pieces of the most uneven sizes possible: one of size $n/2$, one of size 0



Analysis continued

For just a parallel merge of n elements:

- **Work** is $T(n) = T(3n/4) + T(n/4) + O(\log n)$ which is $O(n)$
- **Span** is $T(n) = T(3n/4) + O(\log n)$, which is $O(\log^2 n)$
- (neither bound is immediately obvious, but "trust me")

Binary Search

So for mergesort with parallel merge overall:

- **Work** is $T(n) = 2T(n/2) + O(n)$, which is $O(n \log n)$
- **Span** is $T(n) = T(n/2) + O(\log^2 n)$, which is $O(\log^3 n)$

parallel merge

So parallelism (work / span) is $O(n / \log^2 n)$

- Not quite as good as quicksort's $O(n / \log n)$
 - But (unlike Quicksort) this is a worst-case guarantee
- And as always this is just the asymptotic result