COMP 322: Fundamentals of Parallel Programming

Lecture 22: Parallelism in Java Streams, Parallel Prefix Sums

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Worksheet #21 solution: Abstract Metrics with Isolated Constructs

Q: Compute the WORK and CPL metrics for this program. Indicate if your answer depends on the execution order of isolated constructs.

```
finish(() -> {
    for (int i = 0; i < 5; i++) {
        async(() -> {
            doWork(2);
            isolated(() -> { doWork(1); });
            doWork(2);
        }); // async
    } // for
}); // finish
```

Answer: WORK = 25, CPL = 9. These metrics do not depend on the execution order of isolated constructs.

How Java Streams addressed pre-Java-8 limitations of Java Collections

1. Iteration had to be performed explicitly using for/foreach loop, e.g.,

```
// Iterate through students (collection of Student objects)
for (Student s in students) System.out.println(s);
```

⇒ **Simplified using Streams as follows**

```
students.stream().foreach(s -> System.out.println(s));
```

2. Overhead of creating intermediate collections

```
List<Student> activeStudents = new ArrayList<Student>();
for (Student s in students)
    if (s.getStatus() == Student.ACTIVE) activeStudents.add(s);
for (Student a in activeStudents) totalCredits += a.getCredits();
```

⇒ **Simplified using Streams as follows**

```
totalCredits = students.stream().filter(s -> s.getStatus() == Student.ACTIVE)
                       .map(a -> a.getCredits()).sum();
```

3. Complexity of parallelism simplified (for example) by replacing stream() by parallelStream()

Java 8 Streams Cheat Sheet

Definitions

- ✓ A stream **is** a pipeline of functions that can be evaluated.
- ✓ Streams **can** transform data.
- ✗ A stream **is not** a data structure.
- ✗ Streams **cannot** mutate data.

Intermediate operations

- Always return streams.
- Lazily executed.

Common examples include:

Function	Preserves count	Preserves type	Preserves order
map	✓	✗	✓
filter	✗	✓	✓
distinct	✗	✓	✓
sorted	✓	✓	✗
peek	✓	✓	✓

Stream examples

Get the unique surnames in uppercase of the first 15 book authors that are 50 years old or over.

```
library.stream()
      .map(book -> book.getAuthor())
      .filter(author -> author.getAge() >= 50)
      .map(Author::getSurname)
      .map(String::toUpperCase)
      .distinct()
      .limit(15)
      .collect(toList());
```

Compute the sum of ages of all female authors younger than 25.

```
library.stream()
      .map(Book::getAuthor)
      .filter(a -> a.getGender() == Gender.FEMALE)
      .map(Author::getAge)
      .filter(age -> age < 25)
      .reduce(0, Integer::sum):
```

Terminal operations

- Return concrete types or produce a side effect.
- Eagerly executed.

Common examples include:

Function	Output	When to use
reduce	concrete type	to cumulate elements
collect	list, map or set	to group elements
forEach	side effect	to perform a side effect on elements

Parallel streams

Parallel streams use the common ForkJoinPool for threading.

```
library.parallelStream()...
```

or intermediate operation:

```
IntStream.range(1, 10).parallel()...
```

Useful operations

Grouping:

```
library.stream().collect(
    groupingBy(Book::getGenre));
```

Stream ranges:

```
IntStream.range(0, 20)...
```

Infinite streams:

```
IntStream.iterate(0, e -> e + 1)...
```

Max/Min:

```
IntStream.range(1, 10).max();
```

FlatMap:

```
twitterList.stream()
      .map(member -> member.getFollowers())
      .flatMap(followers -> followers.stream())
      .collect(toList());
```

Pitfalls

- ✗ Don't update shared mutable variables i.e.

```
List<Book> myList = new ArrayList<>();
library.stream().forEach
    (e -> myList.add(e));
```

- ✗ Avoid blocking operations when using parallel streams.

Source: http://zeroturnaround.com/rebellabs/java-8-streams-cheat-sheet/

Parallelism in processing Java Streams

- Parallelism can be introduced at a stream source …
  - e.g., library.parallelStream()…
- … or as an intermediate operation
  - e.g., library.stream().sorted().parallel()…
- Stateful intermediate operations should be avoided on parallel streams …
  - e.g., distinct, sorted, use-written lambda with side effects
- … but stateless intermediate operations work just fine
  - e.g., filter, map
- Parallelism is usually more efficient on unordered streams …
  - e.g., stream created from unordered source (HashSet), or from .unordered() intermediate operation
- … and with unordered collectors
  - e.g., ConcurrentHashMap

Beyond Sum/Reduce Operations — Prefix Sum (Scan) Problem Statement

Given input array A, compute output array X as follows

$$X[i] = \sum_{0 \leq j \leq i} A[j]$$

- The above is an inclusive prefix sum since X[i] includes A[i]
- For an exclusive prefix sum, perform the summation for 0 <=j <i
- It is easy to see that inclusive prefix sums can be computed sequentially in O(n) time …

```
// Copy input array A into output array X
X = new int[A.length]; System.arraycopy(A,0,X,0,A.length);
// Update array X with prefix sums
for (int i=1 ; i < X.length ; i++ ) X[i] += X[i-1];
```

- … and so can exclusive prefix sums

An Inefficient Parallel Algorithm for Exclusive Prefix Sums

```
forall(0, X.length-1, (i) -> {
    // computeSum() adds A[0..i-1]
    X[i] = computeSum(A, 0, i-1);
}
```

Observations:

- **Critical path length, CPL = O(log n)**
- **Total number of operations, WORK = $O(n^2)$**
- **With P = O(n) processors, the best execution time that you can achieve is T_P = max(CPL, WORK/P) = O(n), which is no better than sequential!**

How can we do better?

Assume that input array A = [3, 1, 2, 0, 4, 1, 1, 3]

Define scan(A) = exclusive prefix sums of A = [0, 3, 4, 6, 6, 10, 11, 12]

Hint:

- Compute B by adding pairwise elements in A to get B = [4, 2, 5, 4]
- Assume that we can recursively compute scan(B) = [0, 4, 6, 11]
- How can we use A and scan(B) to get scan(A)?

Another way of looking at the parallel algorithm

Observation: each prefix sum can be decomposed into reusable terms of power-of-2-size e.g.

$$\begin{aligned} X[6] &= A[0]+A[1]+A[2]+A[3]+A[4]+A[5]+A[6] \\ &= (A[0]+A[1]+A[2]+A[3])+(A[4]+A[5])+A[6] \end{aligned}$$

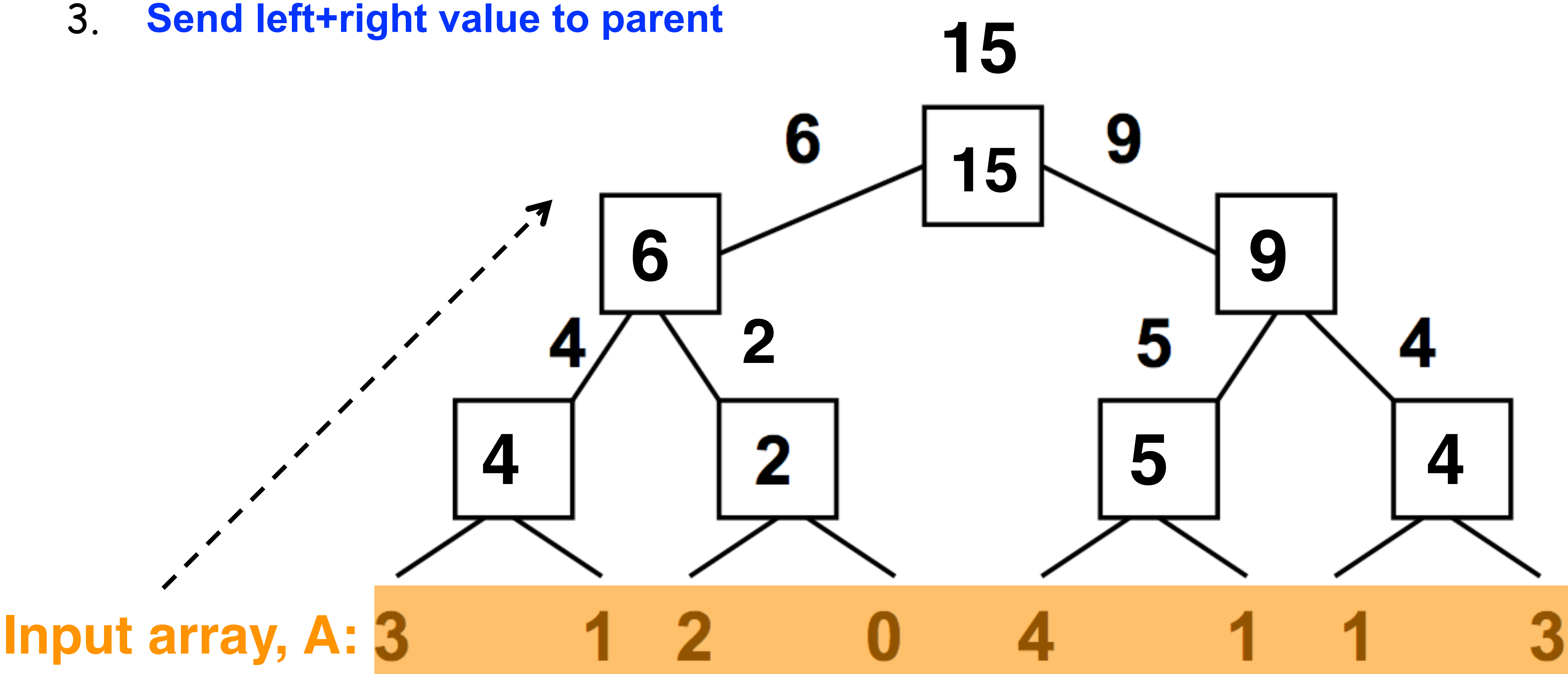
Approach:

- Combine reduction tree idea from Parallel Array Sum with partial sum idea from Sequential Prefix Sum
- Use an “upward sweep” to perform parallel reduction, while storing partial sum terms in tree nodes
- Use a “downward sweep” to compute prefix sums while reusing partial sum terms stored in upward sweep

Parallel Prefix Sum: Upward Sweep (while calling scan recursively)

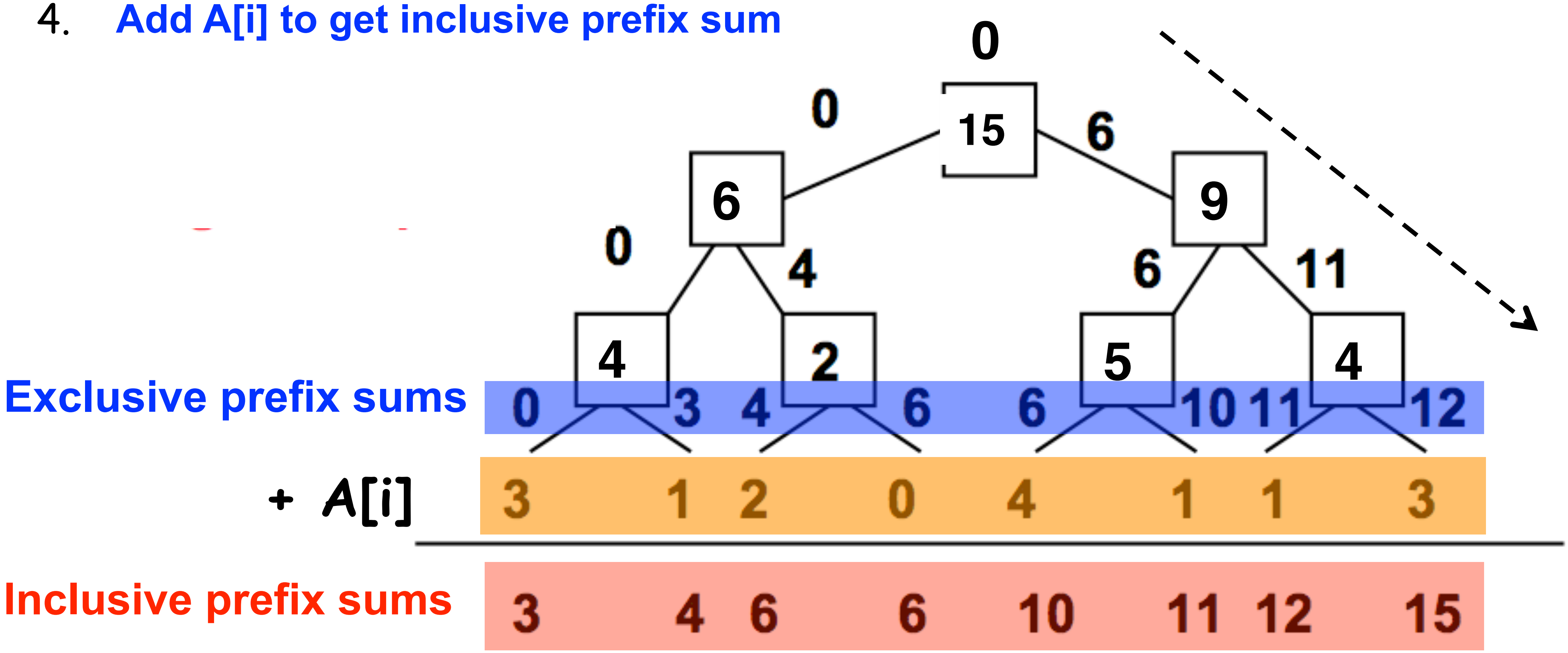
Upward sweep is just like Parallel Reduction, except that partial sums are also stored along the way

1. Receive values from left and right children
2. Compute left+right and store in box
3. Send left+right value to parent



Parallel Prefix Sum: Downward Sweep (while returning from recursive calls to scan)

1. Receive value from parent (root receives 0)
2. Send parent's value to LEFT child (prefix sum for elements to left of left child's subtree)
3. Send parent's value+ left child's box value to RIGHT child (prefix sum for elements to left of right child's subtree)
4. Add A[i] to get inclusive prefix sum



Summary of Parallel Prefix Sum Algorithm

- Critical path length, CPL = O(log n)
- Total number of add operations, WORK = O(n)
- Optimal algorithm for P = O(n/log n) processors
  - Adding more processors does not help
- Parallel Prefix Sum has several applications that go beyond computing the sum of array elements
  - Parallel Prefix Sum can be used for any operation that is associative (need not be commutative)
    - In contrast, finish accumulators required the operator to be both associative and commutative

Parallel Filter Operation

[Credits: David Walker and Andrew W. Appel (Princeton), Dan Grossman (U. Washington)]

Given an array `input`, produce an array `output` containing only elements such that `f(elt)` is `true`, i.e., output = input.parallelStream.filter(f).toArray

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

```
f: is elt > 10
output [17, 11, 13, 19, 24]
```

Parallelizable?

- Finding elements for the output is easy
- But getting them in the right place seems hard

Parallel prefix to the rescue

1. Parallel map to compute a bit-vector for true elements (can use Java streams)

```
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 (not available in Java streams)

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

3. Parallel map to produce the output (can use Java streams)

```
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];
}
```

Parallelizing Quicksort (Remember Homework 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)

Simple approach: Do the two recursive calls in parallel

- Work: unchanged at $O(n \log n)$
- Span: now $CPL(n) = O(n) + CPL(n/2) = O(n)$
- So parallelism (i.e., work / span) is $O(\log n)$

Sophisticated approach: use scans for the partition step

- Work: unchanged at $O(n \log n)$
- Span: now $CPL(n) = O(\log n) + CPL(n/2) = O(\log^2 n)$
- So average parallelism (i.e., work / span) is $O(n / \log n)$

Example

- Step 1: pick pivot as median of three

8	1	4	9	0	3	5	2	7	6

- Steps 2: implement partition step as two filter/pack operations that store result in a second array

1	4	0	3	5	2				

1	4	0	3	5	2	6	8	9	7

- Step 3: Two recursive sorts in parallel