COMP 322: Fundamentals of Parallel Programming

Lecture 13: Parallelism in Java Streams, Parallel Prefix Sums

Zoran Budimlić and Mack Joyner
{zoran, mjoyner}@rice.edu

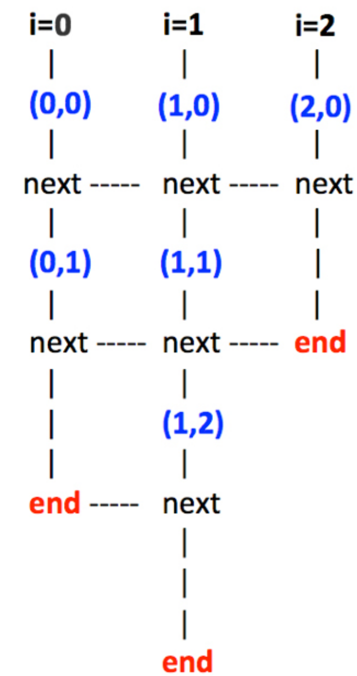
http://comp322.rice.edu

Worksheet #12: Forall Loops and Barriers

Draw a “barrier matching” figure similar to lecture 12 slide 11 for the code fragment below.

```
String[] a = { “ab”, “cde”, “f” };
. . . int m = a.length; . . .
forallPhased (0, m-1, (i) -> {
  for (int j = 0; j < a[i].length(); j++) {
    // forall iteration i is executing phase j
    System.out.println("(" + i + "," + j + ")");
    next();
  }
});
```

Solution



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)
                                .mapToInt(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, user-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.

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

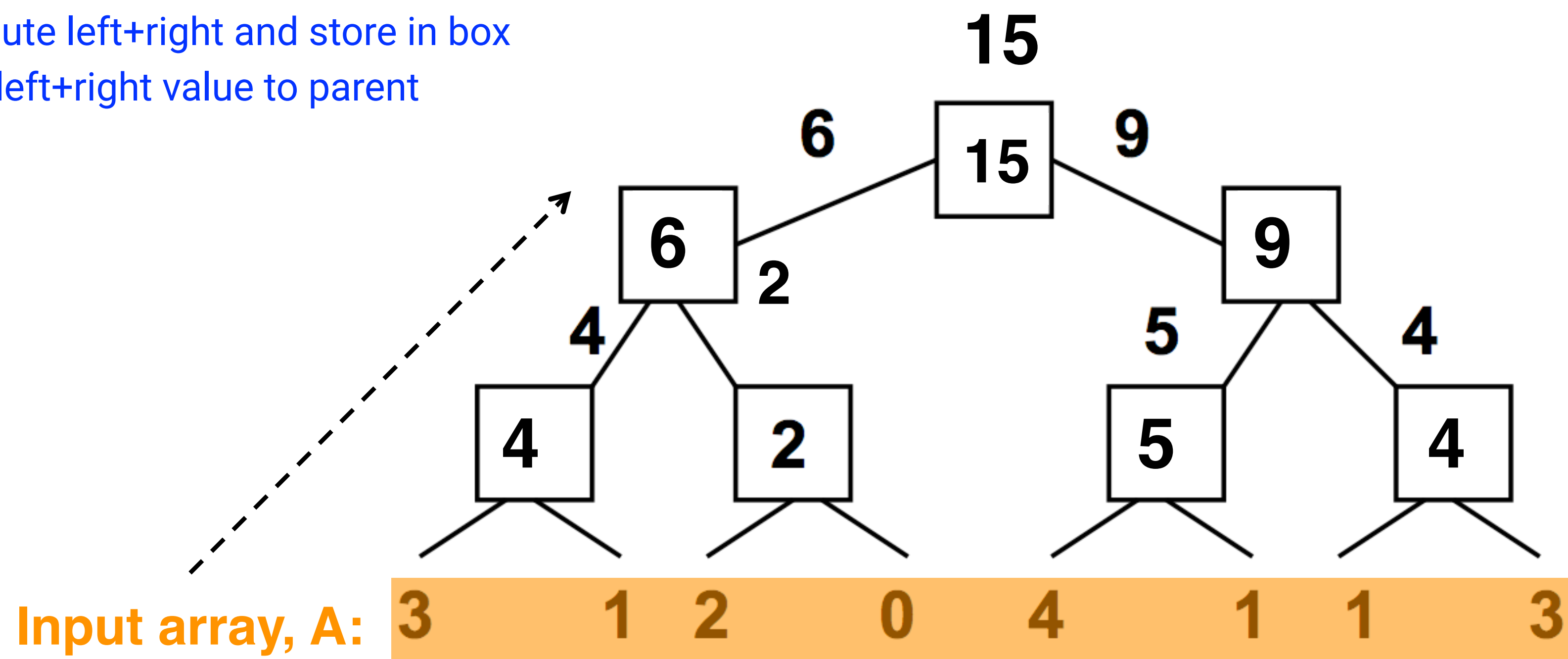
Approach:

- 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)

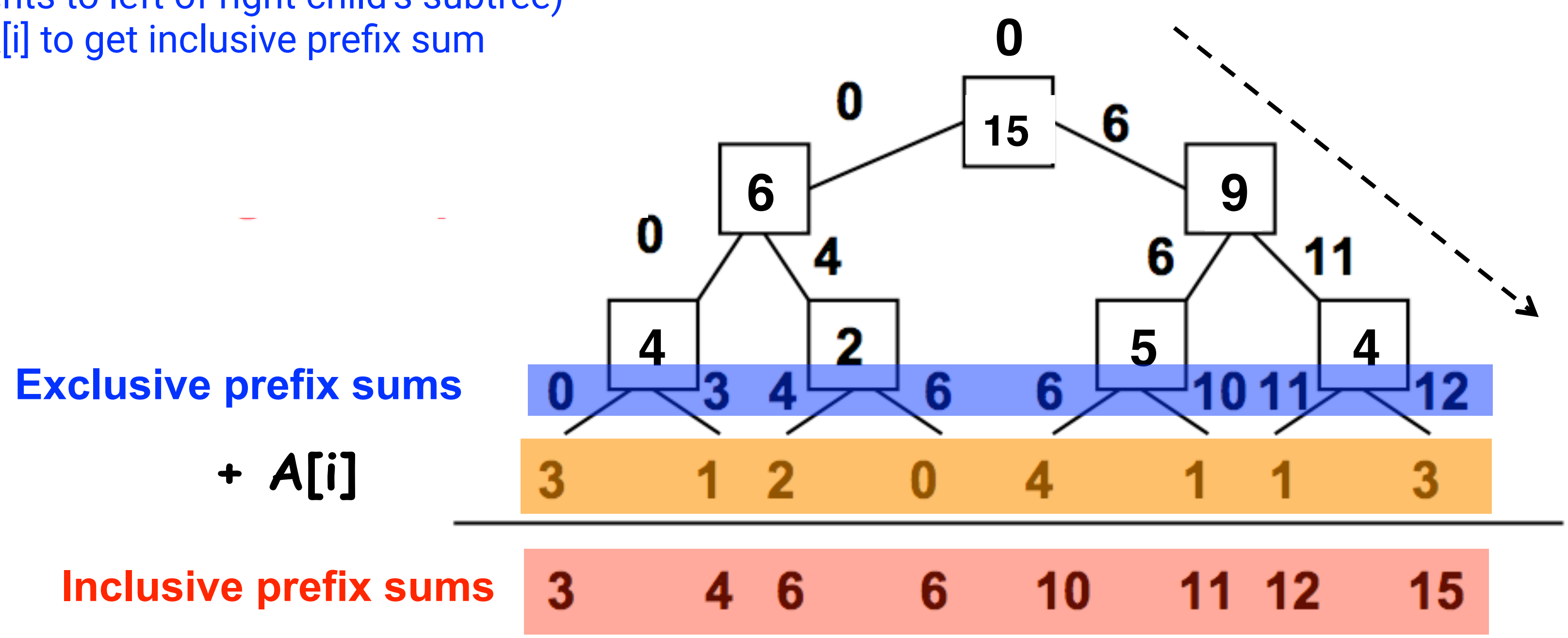
Upward sweep is just like Parallel Reduction, except that partial sums are also stored along the way

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];
}
```

Announcements & Reminders

- HW2 is available and due today by 11:59pm
- HW3 will be available today and due March 21st (two intermediate checkpoints!)
- Quiz for Unit 2 (topics 2.1 - 2.6) is available on Canvas, and due by 11:59pm on Monday
- Watch the topic 3.5, 3.6 videos for the next lecture
- Use Piazza (public or private posts, as appropriate) for all communications re. COMP 322
- See Office Hours link on course web site for latest office hours schedule.

Worksheet #13:
Parallelism in Java Streams, Parallel Prefix Sums

Name: ______________________________ Netid: ________________

1. What output will the following Java Streams code print?
2. Which stream operation in this example could benefit from a parallel prefix sum implementation, and why? (Assume a larger array when answering this question, so that overheads of parallelism are not an issue.)

```
Arrays
  .asList(“a1", "a2", "b1", "c2", "c1")
  .parallelStream()
  .filter(s -> s.startsWith(“c"))
  .sorted()
  .map(String::toUpperCase)
  .forEach(System.out::println);
```

Backup Slides

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

Example Applications of Parallel Prefix Algorithm

- Prefix Max with Index of First Occurrence: given an input array A, output an array X of objects such that X[i].max is the maximum of elements A[0…i] and X[i].index contains the index of the first occurrence of X[i].max in A[0…i]
  - Homework 2 includes this problem just for the entire array (not intermediate prefix "sums")
- Filter and Packing of Strings: given an input array A identify elements that satisfy some desired property (e.g., uppercase), and pack them in a new output array. (First create a 0/1 array for elements that satisfy the property, and then compute prefix sums to identify locations of elements to be packed.)
  - Useful for parallelizing partitioning step in Parallel Quicksort algorithm (Approaches 2 and 3)

Use of Prefix Sums to parallelize partition() in Quicksort (Approach 2, Summary of Listing 30)

```
1.  partition(int[] A, int M, int N) { // choose pivot from M..N
2.   forall (point [k] : [0:N-M]) { // parallel loop
3.    lt[k] = (A[M+k] < A[pivot] ? 1 : 0);  // bit vector with < comparisons
4.    eq[k] = (A[M+k] == A[pivot] ? 1 : 0); // bit vector with = comparisons
5.    gt[k] = (A[M+k] > A[pivot] ? 1 : 0);  // bit vector with > comparisons
6.    buffer[k] = A[M+k];                   // Copy A[M..N] into buffer
7.   }
8.   ... Copy lt, eq, gt, into ltPS, eqPS, gtPS before step 9 ...
9.   final int ltCount = computePrefixSums(ltPS); //update lt with prefix sums
10. final int eqCount = computePrefixSums(eqPS); //update eq with prefix sums
11. final int gtCount = computePrefixSums(gtPS); //update gt with prefix sums
12. // Parallel move from buffer into A
13. forall (point [k] : [0:N-M]) {
14.   if(lt[k]==1) A[M+ltPS[k]-1] = buffer[k];
15.   else if(eq[k]==1) A[M+ltCount+eqPS[k]-1] = buffer[k];
16.   else A[M+ltCount+eqCount+gtPS[k]-1] = buffer[k];
17.  }
18.  . . .
19.}  // partition
```

Examples of Intermediate Operations

- filter
- map
- mapTo... (Int, Long or Double)
- flatMap
- flatMapTo... (Int, Long or Double)
- distinct
- sorted
- peek
- limit
- skip
- sequential
- parallel
- unordered
- onClose

Examples of Terminal Operations

- forEach
- forEachOrdered
- toArray
- reduce
- collect
- min
- max
- count
- anyMatch
- allMatch
- noneMatch
- findFirst
- findAny iterator
- spliterator

Overview of Java Streams

- Definition: a possibly-infinite sequence of elements supporting sequential or parallel aggregate operations
- possibly-infinite: elements are processed lazily
- sequential or parallel: two kinds of streams
- aggregate: operations act on the entire stream
  - contrast: iterators
- Some stream sources
  Invoking .stream() or .parallelStream() on any Collection Invoking .lines() on a BufferedReader
  Generating from a function: Stream.generate(Supplier<T> s)
- Intermediate operations
  Produce one stream from another Examples: map, filter, sorted, ...
- Each stream is used only once, with an intermediate or terminal operation
- Terminal operations
  Extract a value or a collection from a stream Examples: reduce, collect, count, findAny

Example: what will this code print?

```
List<String> myList =
    Arrays.asList("a1", "a2", "b1", "c2", "c1");

myList
    .stream()
    .filter(s -> s.startsWith("c"))
    .map(String::toUpperCase)
    .sorted()
    .forEach(System.out::println);
```

Pitfalls when using Java Streams

- Blocking calls in Stream computation
- Can only operate on a stream once
  - java.lang.IllegalStateException: stream has already been operated upon or closed
- Creation of infinite streams
- Modifying backing collection when processing a stream