COMP 322: Fundamentals of Parallel Programming

https://wiki.rice.edu/confluence/display/PARPROG/COMP322

Lecture 13: Barrier Synchronization (contd)

Vivek Sarkar
Department of Computer Science
Rice University
vsarkar@rice.edu

Announcements

- Homework 4 due by 5pm on Wednesday, Feb 16th
  - We will try and return graded homeworks by Feb 23rd
- Guest lecture on Bitonic Sort by John Mellor-Crummey on Friday, Feb 18th
- Feb 23rd lecture will be a Midterm Review
- No lecture on Friday, Feb 25th since midterm is due that day
  - Midterm will be a 2-hour take-home written exam
  - Will be given out at lecture on Wed, Feb 23rd
  - Must be handed in by 5pm on Friday, Feb 25th

Acknowledgments for Today's Lecture

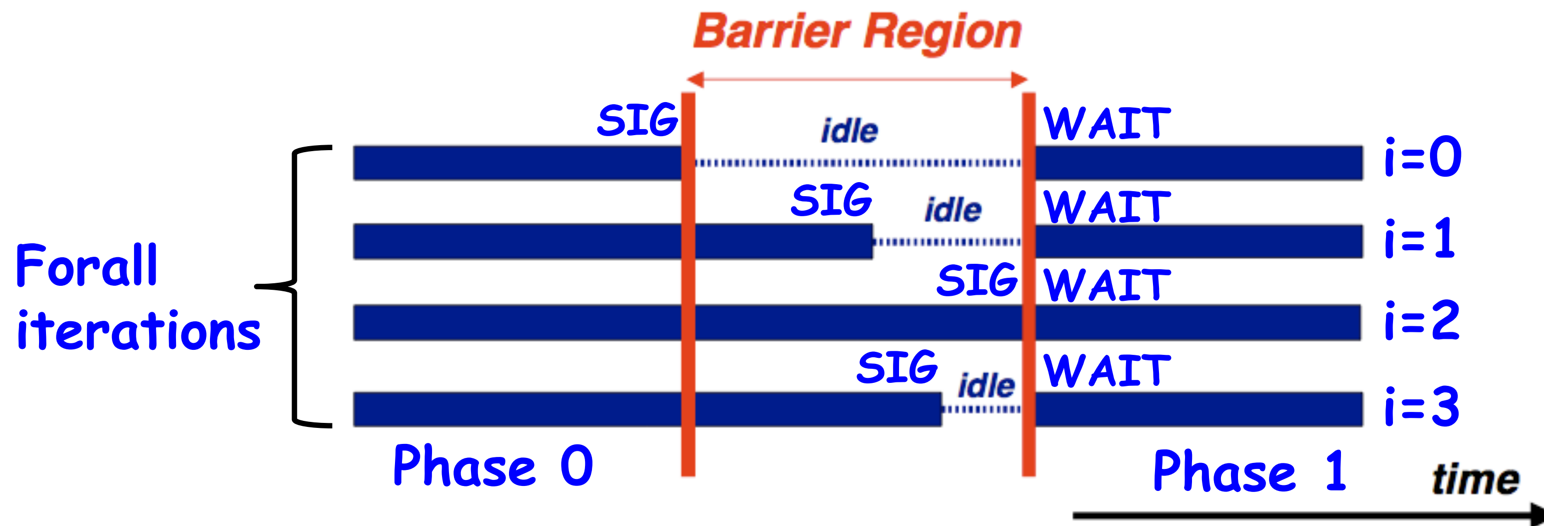
- "Principles of Parallel Programming", Calvin Lin & Lawrence Snyder, Addison-Wesley, 2009
  - Includes resources available at http://www.pearsonhighered.com/educator/academic/product/0,3110,0321487907,00.html
- Handout for Lectures 12 and 13

Barrier Synchronization using HJ's "next" statement (recap of Hello-Goodbye example)

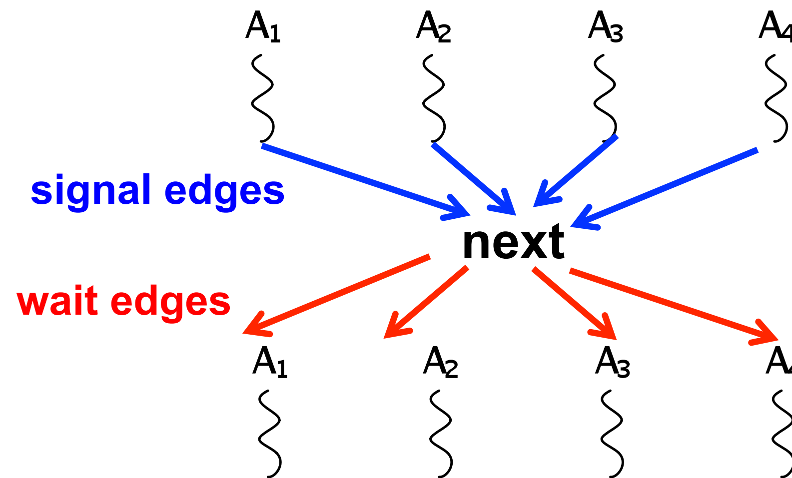
```
rank.count = 0; // rank object contains an int field, count
forall (point [i] : [0:m-1]) {
  int r;
  isolated {r = rank.count++;}                              } Phase 0
  System.out.println("Hello from task ranked " + r);
  next; // Acts as barrier between phases 0 and 1
  System.out.println("Goodbye from task ranked " + r);     } Phase 1
}
```

- **next** → each forall iteration suspends at next until all iterations arrive (complete previous phase), after which the phase can be advanced
  - Observation 1: Scope of synchronization is the closest enclosing forall statement
  - Observation 2: If a forall iteration terminates before executing "next", then the other iterations do not wait for it
  - Observation 3: Different forall iterations may perform "next" at different program points e.g., consider a conditional based on the forall index value

Impact of barrier on scheduling forall iterations



Modeling a next operation in the computation graph



Observation 1: Scope of synchronization for "next" is closest enclosing forall statement

```
forall (point [i] : [0:m-1]) {
  System.out.println("Starting forall iteration " + i);
  next; // Acts as barrier for forall-i
  forall (point [j] : [0:n-1]) {
    System.out.println("Hello from task (" + i + ","
                                + j + ")");
    next; // Acts as barrier for forall-j
    System.out.println("Goodbye from task (" + i + ","
                                + j + ")");
  } // forall-j
  next; // Acts as barrier for forall-i
  System.out.println("Ending forall iteration " + i);
} // forall-i
```

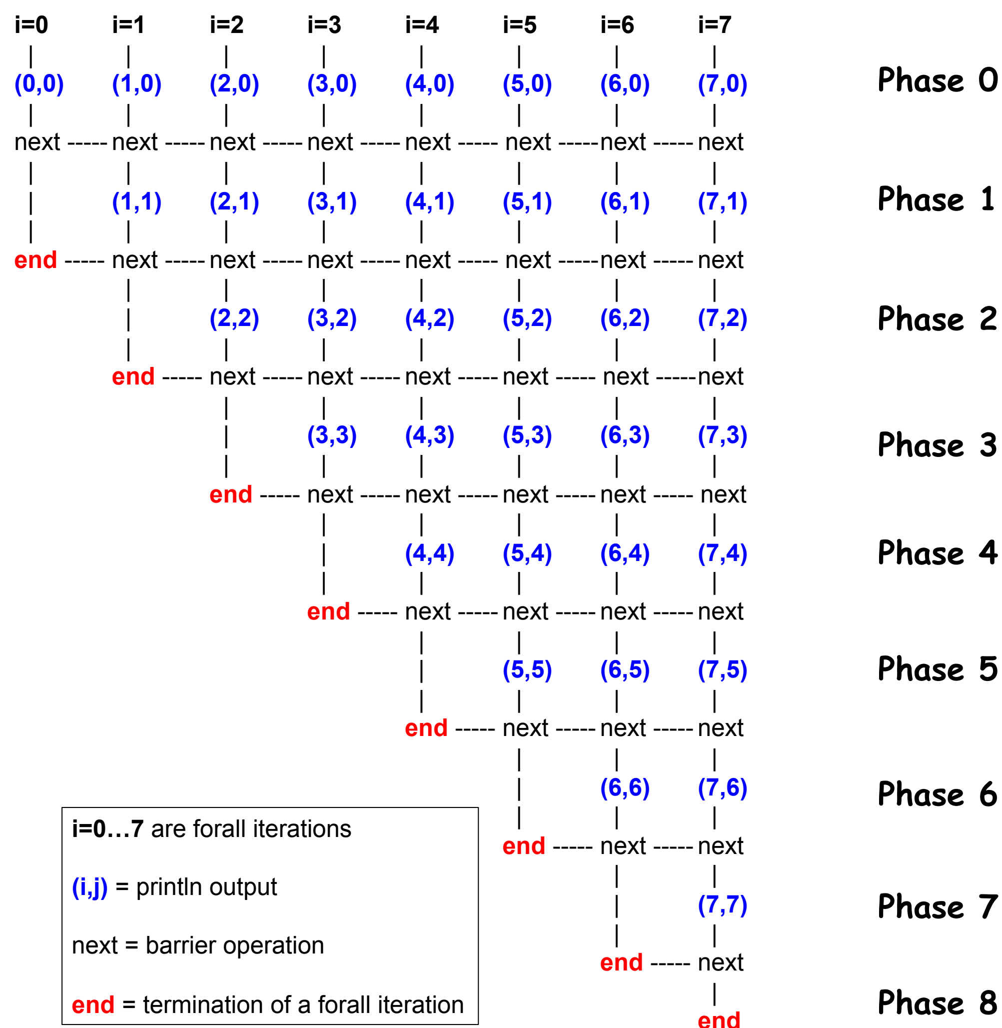
Observation 2: If a forall iteration terminates before "next", then other iterations do not wait for it

```
1. forall (point[i] : [0:m-1]) {
2.   for (point[j] : [0:i]) {
3.     // Forall iteration i is executing phase j
4.     System.out.println("(" + i + "," + j + ")");
5.     next;
6.   }
7. }
```

- Outer forall-i loop has m iterations, 0…m-1
- Inner sequential j loop has i+1 iterations, 0…i
- Line 4 prints (task,phase) = (i, j) before performing a next operation.
- Iteration i = 0 of the forall-i loop prints (0, 0), performs a next, and then terminates. Iteration i = 1 of the forall-i loop prints (1,0), performs a next, prints (1,1), performs a next, and then terminates. And so on.

Illustration of previous example

- Iteration i=0 of the forall-i loop prints (0, 0) in Phase 0, performs a next, and then ends Phase 1 by terminating.
- Iteration i=1 of the forall-i loop prints (1,0) in Phase 0, performs a next, prints (1,1) in Phase 1, performs a next, and then ends Phase 2 by terminating.
- And so on until iteration i=8 ends an empty Phase 8 by terminating



Observation 3: Different forall iterations may perform "next" at different program points

```
1.  forall (point[i] : [0:m-1]) {
2.    if (i % 2 == 1) { // i is odd
3.      oddPhase0(i);
4.      next;
5.      oddPhase1(i);
6.    } else { // i is even
7.      evenPhase0(i);
8.      next;
9.      evenPhase1(i);
10.   } // if-else
11. } // forall
```

- Barrier operation synchronizes odd-numbered iterations at line 4 with even-numbered iterations in line 8
- next statement may even be in a method such as oddPhase1()

Recap: incorrect translation of PRAM Array sum algorithm to task-parallel program

```
1.  forall (point[i] : [0:n/2-1]) {
2.    for (point[j] : [0:ceilLog2(n)-1]) {
3.      int exp2j = 1<<j;
4.      if (i % exp2j == 0 && 2*i+exp2j < n)
5.        A[2*i] = A[2*i] + A[2*i+exp2j]
6.    } // for
7.  } // forall
8.  static int ceilLog2(int n) { // returns 0 if n <= 0
9.    int r=0; while (n > 1) { r++; n = n >> 1; } return r;
10. }
```

Is there a data race in this program?

If so, why was the PRAM algorithm correct?

Correct translation of PRAM Array sum algorithm to HJ using for-forall structure

```
1. for (point[j] : [0:ceilLog2(n)-1]) {
2.   forall (point[i] : [0:n/2-1]) {
3.     int exp2j = 1<<j;
4.     if (i % exp2j == 0 && 2*i+exp2j < n)
5.       A[2*i] = A[2*i] + A[2*i+exp2j]
6.   } // forall
7. } // for
```

- Moving the forall loop inside the for loop inserts implicit finish after each step (lines 3, 4, 5)
- Think of a PRAM program as sequential at the outer level, while executing each step as a forall loop across all processors

Correct translation of PRAM Array sum algorithm to HJ using forall-for-next

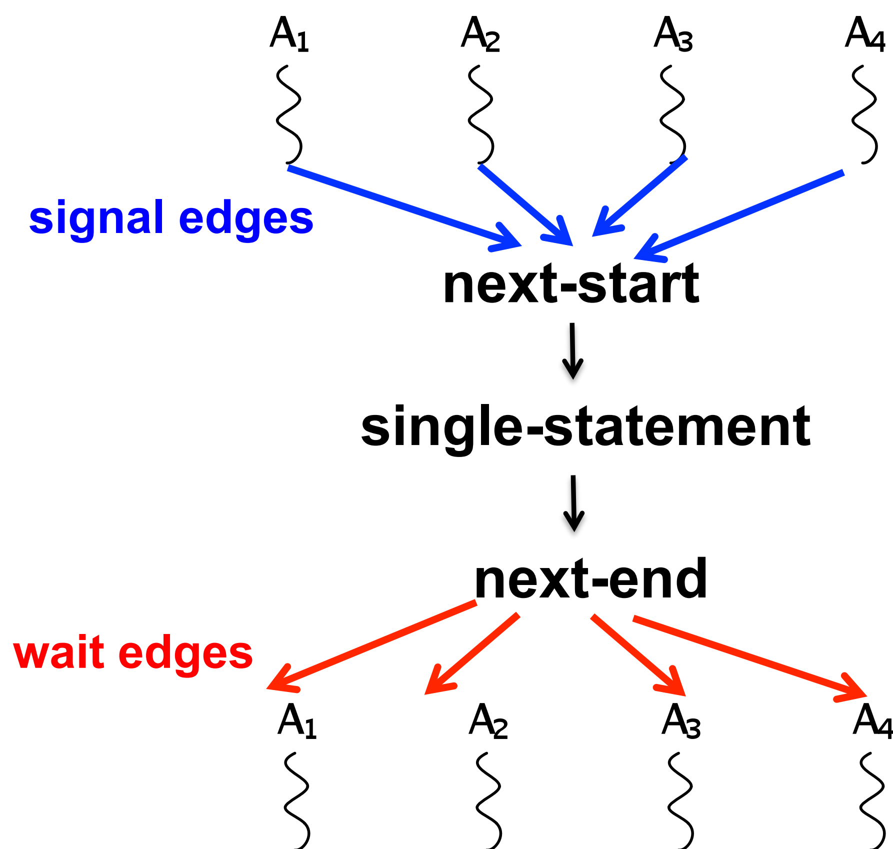
```
1. forall (point[i] : [0:n/2-1]) {
2.   for (point[j] : [0:ceilLog2(n)-1]) {
3.     int exp2j = 1<<j;
4.     if (i \% exp2j == 0 && 2*i+exp2j < n)
5.       A[2*i] = A[2*i] + A[2*i+exp2j]
6.     next; // barrier ensures lock-step semantics
7.   } // for
8. } // forall
```

- You can also think of a PRAM program as parallel at the outer level with a barrier (next) operation at each step to synchronize all processors

Next-with-Single Statement

next <single-stmt> is a barrier in which single-stmt is performed exactly once after all tasks have completed the previous phase and before any task begins its next phase.

Modeling next-with-single in the Computation Graph



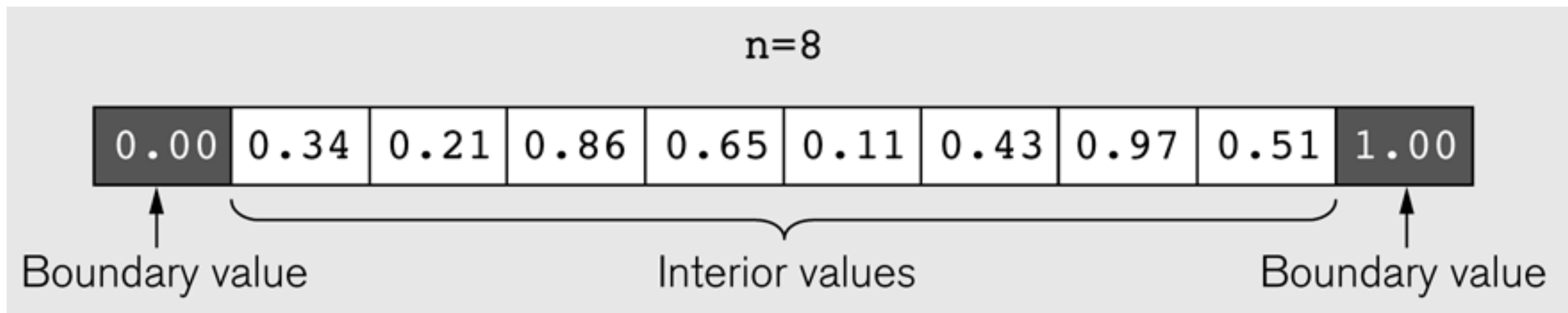
Use of next-with-single to print a log message between Hello and Goodbye phases (Listing 6)

```
1. rank.count = 0; // rank object contains an int field, count
2. forall (point[i] : [0:m-1]) {
3.   // Start of Hello phase
4.   int r;
5.   isolated {r = rank.count++;}
6.   System.out.println("Hello from task ranked " + r);
7.   next { // single statement
8.     System.out.println("LOG: Between Hello & Goodbye Phases");
9.   }
10.  // Start of Goodbye phase
11.  System.out.println("Goodbye from task ranked " + r);
12.} // forall
```

One-Dimensional Iterative Averaging Example

- Initialize a one-dimensional array of (n+2) double's with boundary conditions, myVal[0] = 0 and myVal[n+1] = 1.
- In each iteration, each interior element myVal[i] in 1..n is replaced by the average of its left and right neighbors.
  - Two separate arrays are used in each iteration, one for old values and the other for the new values
- After a sufficient number of iterations, we expect each element of the array to converge to myVal[i] = i/(n+1)
  - In this case, myVal[i] = (myVal[i-1]+myVal[i+1])/2, for all i in 1..n

Illustration of an intermediate step for n = 8 (source: Figure 6.19 in Lin-Snyder book)



HJ code for One-Dimensional Iterative Averaging using nested for-forall structure (Listing 8)

```
1. double[] myVal = new double[n]; myVal[0] = 0; myVal[n+1] = 1;
2. for (point [iter] : [0:iterations-1]) {
3.   // Output array MyNew is computed as function of
4.   // input array MyVal from previous iteration
5.   double[] myNew = new double[n]; myNew[0] = 0; myNew[n+1] = 1;
6.   forall (point [j] : [1:n]) { // Create n tasks
7.      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
8.   } // forall
9.   myVal = myNew; // myNew becomes input array for next iteration
10.} // for
```

- How many tasks does this version create?
- This is an idealized version with no batching of forall iterations and a new array allocation in each iteration of the for-iter loop

HJ code for One-Dimensional Iterative Averaging using nested forall-for-next structure (Listing 9)

```
1. // Assume that myVal and myNew are mutable fields of type double[]
2. myNew = new double[n]; myNew[0] = 0; myNew[n+1] = 1;
3. forall (point [j] : [1:n]) { // Create n tasks
4.   for (point [iter] : [0:iterations-1]) {
5.     next { // single statement
6.       myVal = myNew; //  myNew becomes input array for next iteration
7.       myNew = new double[n]; myNew[0] = 0; myNew[n+1] = 1;
8.     }
9.     myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
10.  } // for
11.} // forall
```

- How many tasks does this version create?
- This version uses next-with-single to synchronize array allocation in each iteration of the for-iter loop