COMP 322: Fundamentals of Parallel Programming

Lecture 11: Iteration Grouping, Barrier Synchronization

Mack Joyner
mjoyner@rice.edu

http://comp322.rice.edu

Solution to Worksheet #10: One-dimensional Iterative Averaging Example

1) Assuming n=9 and the input array below, perform a "half-iteration" of the iterative averaging example by only filling in the blanks for odd values of j in the myNew[] array (different from the real algorithm). Recall that the computation is "myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;"

index, j	0	1	2	3	4	5	6	7	8	9	10
myVal	0	0	0.2	0	0.4	0	0.6	0	0.8	0	1
myNew	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

2) Will the contents of myVal[] and myNew[] change in further iterations?

No, this represents the converged value (equilibrium/fixpoint).

3) Write the formula for the final value of myNew[i] as a function of i and n. In general, this is the value that we will get if m (= #iterations in sequential for-iter loop) is large enough.

After a sufficiently large number of iterations, the iterated averaging code will converge with myNew[i] = myVal[i] = i / (n+1)

Announcements & Reminders

- Quiz for Unit 2 (topics 2.1 - 2.8) is available on Canvas, due by 11:59pm on Friday, Feb. 26th
- Hw #2 due Wednesday, Mar. 3rd at 11:59pm
- Lab #3 due Thursday, Mar. 4th at 2pm
- Midterm Exam on Thursday, Mar. 11th at 7pm

HJ code for One-Dimensional Iterative Averaging

```
1.// Intialize m, n, myVal, newVal
2.m = … ; n = … ;
3.float[] myVal = new float[n+2];
4.float[] myNew = new float[n+2];
5.forseq(0, m-1, (iter) -> {
6.  // Compute MyNew as function of input array MyVal
7.    forall(1, n, (j) -> { // Create n tasks
8.        myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
9.    }); // forall
10.  // What is the purpose of line 11 below?
11.  float[] temp=myVal; myVal=myNew; myNew=temp;
12.}); // forseq
```

What about Overheads?

- It is inefficient to create `forall` iterations in which each iteration (`async` task) does very little work
- An alternate approach is “iteration grouping” or “loop chunking”
  - —e.g., replace

```
forall(0, 99, (i) -> BODY(i)); // 100 tasks
```

  - —by

```
forall(0, 3, (ii) -> { // 4 tasks
// Each task executes a “chunk” of 25 iterations
    forseq(25*ii, 25*(ii+1)-1, (i) -> BODY(i));

}); // forall
```

  - —This is better, but it’s still inconvenient for the programmer to do the “iteration grouping” or “loop chunking” explicitly

forallChunked APIs

- forallChunked(int s0, int e0, int chunkSize, edu.rice.hj.api.HjProcedure<Integer> body)
- Like forall(int s0, int e0, edu.rice.hj.api.HjProcedure<Integer> body)
- but `forallChunked` includes chunkSize as the third parameter
  - e.g., replace

```
forall(0, 99, (i) -> BODY(i)); // 100 tasks
```

  - by

```
forallChunked(0, 99, 100/4, (i)->BODY(i));
```


```
1.int nc = numWorkerThreads();
2. … // Initializations
3.forseq(0, m-1, (iter) -> {
4.  // Compute MyNew as function of input array MyVal
5.    forallChunked(1, n, n/nc, (j) -> { // Create n/nc tasks
6.      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
7.    }); // forallChunked
8.  // Swap myVal & myNew;
9.  float[] temp=myVal; myVal=myNew; myNew=temp;
10.  // myNew becomes input array for next iteration
11.}); // forseq
```


Barrier Synchronization: Hello-Goodbye Forall Example (Pseudocode)

```
forall (0, m - 1, (i) -> {
  int sq = i*i;  // NOTE: video used lookup(i) instead
  System.out.println("Hello from task with square = " + sq);
  System.out.println("Goodbye from task with square = " + sq);
});
```

Sample output for m = 4:

```
Hello from task with square = 0
Hello from task with square = 1
Goodbye from task with square = 0
Hello from task with square = 4
Goodbye from task with square = 4
Goodbye from task with square = 1
Hello from task with square = 9
Goodbye from task with square = 9
```


Hello-Goodbye Forall Example (contd)

```
forall (0, m - 1, (i) -> {
  int sq = i*i;
  System.out.println("Hello from task with square = " + sq);
  System.out.println("Goodbye from task with square = " + sq);
});
```

- Question: how can we transform this code so as to ensure that all tasks say hello before *any* tasks say goodbye?
- Statements in red below will need to be moved to solve this problem

Hello from task with square = 0
Hello from task with square = 1
Goodbye from task with square = 0
Hello from task with square = 4
Goodbye from task with square = 4
Goodbye from task with square = 1
Hello from task with square = 9
Goodbye from task with square = 9

Hello-Goodbye Forall Example (contd)

```
forall (0, m - 1, (i) -> {
  int sq = i*i;
  System.out.println("Hello from task with square = " + sq);
  System.out.println("Goodbye from task with square = " + sq);
});
```

- Question: how can we transform this code so as to ensure that all tasks say hello before any tasks say goodbye?
- *Approach 1: Replace the forall loop by two forall loops, one for the hello's and one for the goodbye's*
  - What's the problem here?

```
1. // APPROACH 1
2. forall (0, m - 1, (i) -> {
3.  int sq = i*i;
4.  System.out.println("Hello from task with square = " + sq);
5. });
6. forall (0, m - 1, (i) -> {
7.  System.out.println("Goodbye from task with square = " + sq);
8. });
```


Hello-Goodbye Forall Example (contd)

- Question: how can we transform this code so as to ensure that all tasks say hello before any tasks say goodbye, without having to change the local variable?
- Approach 2: insert a “barrier” (“next” statement) between the hello’s and goodbye’s

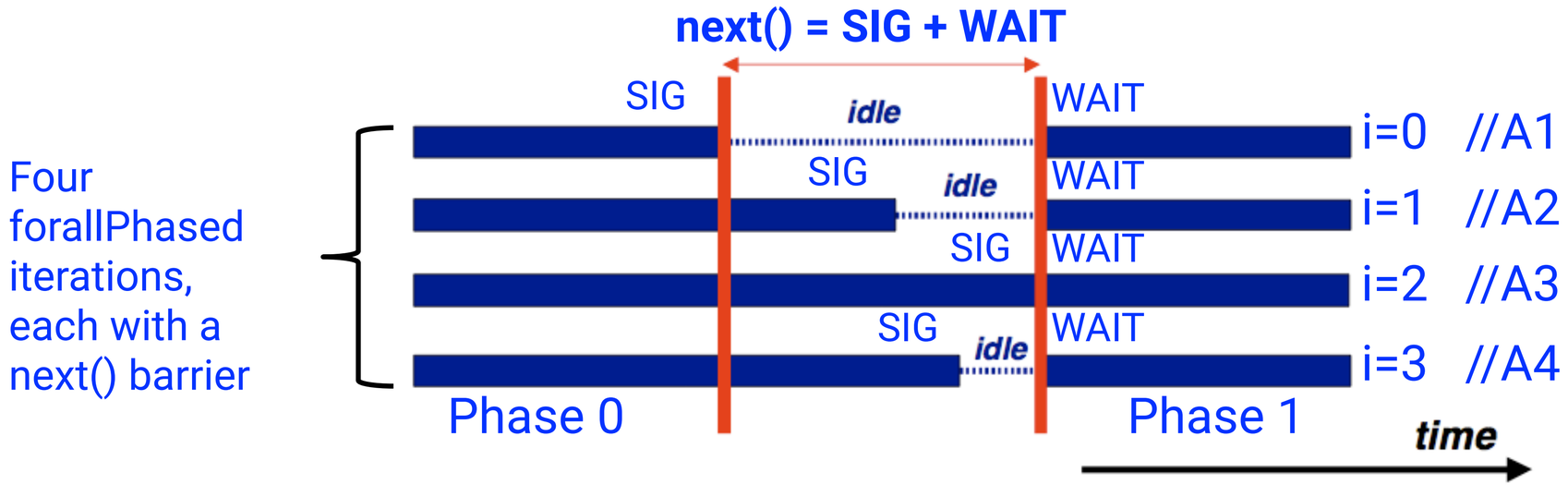
```
1. // APPROACH 2
2. forallPhased (0, m - 1, (i) -> {
3.   int sq = i*i;
4.   System.out.println(“Hello from task with square = “ + sq);
5.   next(); // Barrier
6.   System.out.println(“Goodbye from task with square = “ + sq);
7. });
```

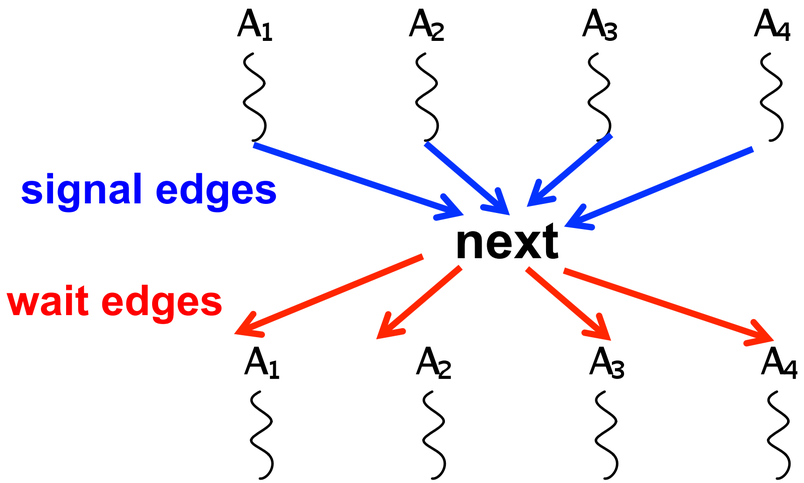
Phase 0 (lines 3–4)

Phase 1 (lines 5–6)

- next -> each forallPhased iteration waits at barrier until all iterations arrive (previous phase is completed), after which the next phase can start
  - Scope of next is the closest enclosing forallPhased statement
  - If a forallPhased iteration terminates before executing “next”, then the other iterations don’t wait for it

Impact of barrier on scheduling forallPhased iterations





next() operation is modeled in the Computation Graph using *signal* and *wait* edges

forallPhased API's in HJlib

http://www.cs.rice.edu/~vs3/hjlib/doc/edu/rice/hj/Module1.html

- `static void forallPhased(int s0, int e0, edu.rice.hj.api.HjProcedure<java.lang.Integer> body)`
- `static <T> void forallPhased(java.lang.Iterable<T> iterable, edu.rice.hj.api.HjProcedure<T> body)`
- `static void next()`

- NOTE:
  - All forallPhased API's include an implicit finish at the end (just like a regular forall)
  - Calls to next() are only permitted in forallPhased(), not in forall()

Observation 1: Scope of synchronization for “next” barrier is its closest enclosing forallPhased statement

```
1. forallPhased (0, m - 1, (i) -> {
2.  println(“Starting forall iteration ” + i);
3.  next(); // Acts as barrier for forallPhased-i
4.  forallPhased (0, n - 1, (j) -> {
5.    println(“Hello from task (“ + i + “,” + j + “)”);
6.    next(); // Acts as barrier for forallPhased-j
7.    println(“Goodbye from task (“ + i + “,” + j + “)”);
8.  } // forallPhased-j
9.  next(); // Acts as barrier for forallPhased-i
10. println(“Ending forallPhased iteration ” + i);
11.}); // forallPhased-i
```

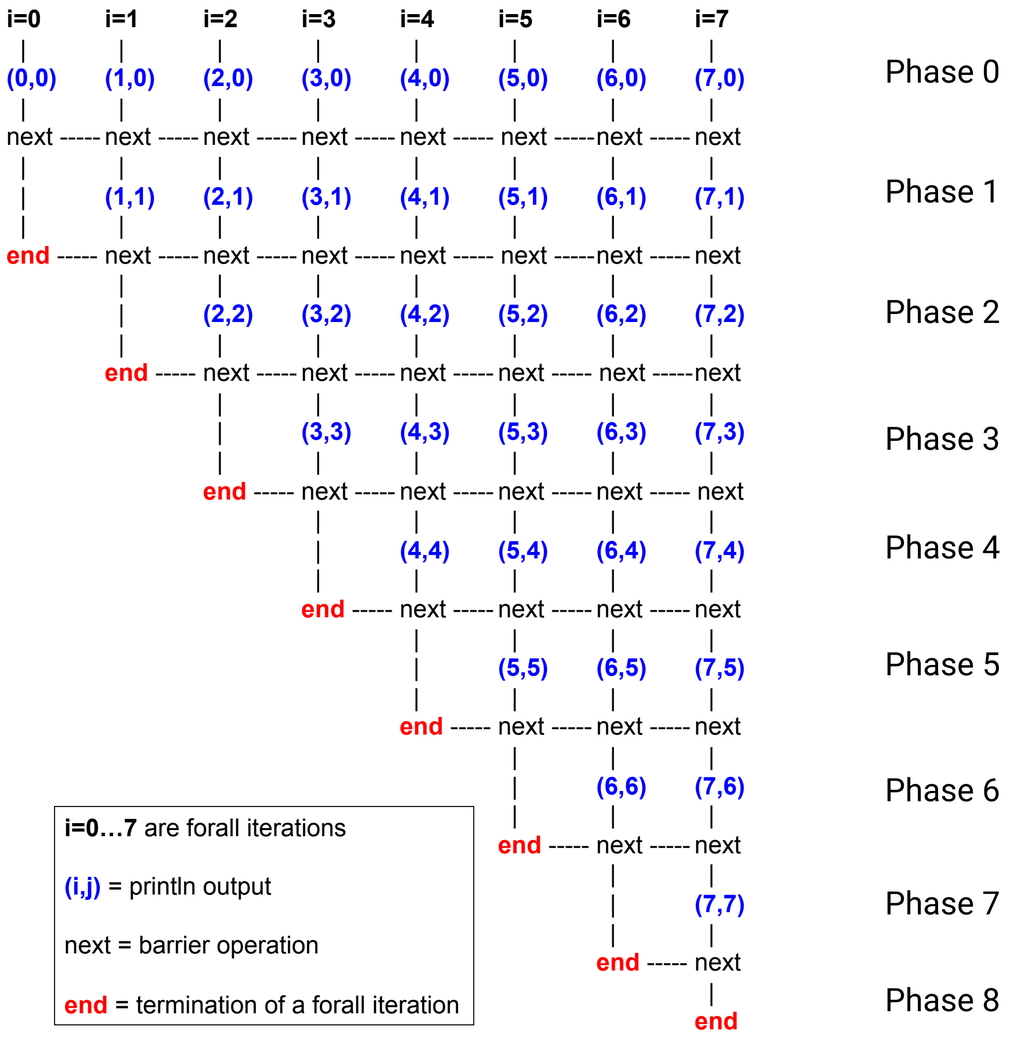
Observation 2: If a forall iteration terminates before “next”, then other iterations do not wait for it

```
1.  forallPhased (0, m - 1, (i) -> {
2.    forseq (0, i, (j) -> {
3.      // forall iteration i is executing phase j
4.      System.out.println("(" + i + "," + j + ")");
5.      next();
6.    }); //forseq-j
7.  }); //forall-i
```

- 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.

Barrier Matching for previous example

- Iteration i=0 of the forallPhased-i loop prints (0, 0) in Phase 0, performs a next, and then ends Phase 1 by terminating.
- Iteration i=1 of the forallPhased-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 forallPhased iterations may perform “next” at different program points

```
1.  forallPhased (0, m-1, (i) -> {
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
```

Barriers are not statically scoped — matching barriers may come from different program points, and may even be in different methods!

- Barrier operation synchronizes odd-numbered iterations at line 4 with even-numbered iterations in line 8
- One reason why barriers are “less structured” than finish, async, future

Parallelizing loops in Matrix Multiplication example using forall

```
1. // Parallel version using forall
2.  forall(0, n-1, 0, n-1, (i, j) -> {
3.       c[i][j] = 0;
4.    });
5.  forall(0, n-1, 0, n-1, (i, j) -> {
6.     forseq(0, n-1, (k) -> {
7.        c[i][j] += a[i][k] * b[k][j];
8.      });
9.   });
10. // Print first element of output matrix
11. println(c[0][0]);
```

$$c[i,j] = \sum_{0 \le k < n} a[i,k] * b[k,j]$$

Parallelizing loops in Matrix Multiplication example using forall

```
1. // Parallel version using forall
2.  forallPhased(0, n-1, 0, n-1, (i, j) -> {
3.       c[i][j] = 0;
4.       next();
5.       forseq(0, n-1, (k) -> {
6.         c[i][j] += a[i][k] * b[k][j];
7.       });
8.   });
9. // Print first element of output matrix
10. println(c[0][0]);
```

$$c[i,j] = \sum_{0 \le k < n} a[i,k] * b[k,j]$$

Worksheet #11: Forall Loops and Barriers

Draw a “barrier matching” figure similar to slide 17 for the code fragment below.

```
1. String[] a = { “ab”, “cde”, “f” };
2. . . . int m = a.length; . . .
3. forallPhased (0, m-1, (i) -> {
4.   for (int j = 0; j < a[i].length(); j++) {
5.     // forallPhased iteration i is executing phase j
6.     System.out.println("(" + i + "," + j + “)");
7.     next();
8.   }
9. });
```