COMP 322: Fundamentals of Parallel Programming

Lecture 20: Barrier Synchronization with Phasers

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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)

```
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*
  — Problem: Need to communicate local sq values from first forall to the second

```
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)

```
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 2: 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 2
2. int[] sq = new int[m];
3. forall (0, m - 1, (i) -> {
4.    sq[i] = i*i;
5.    System.out.println("Hello from task with square = " + sq[i] );
6. });
7. forall (0, m - 1, (i) -> {
8.   System.out.println("Goodbye from task with square = " + sq[i]);
9. });
```


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 3: insert a "barrier" ("next" statement) between the hello's and goodbye's

```
1. // APPROACH 3
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. });
```

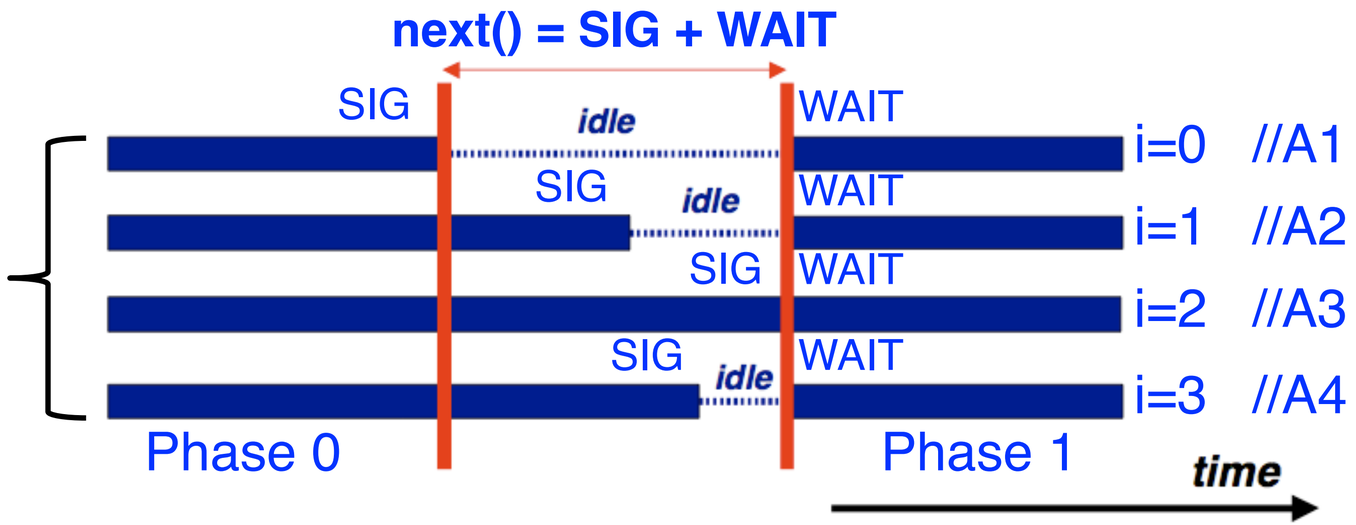
Phase 0

Phase 1

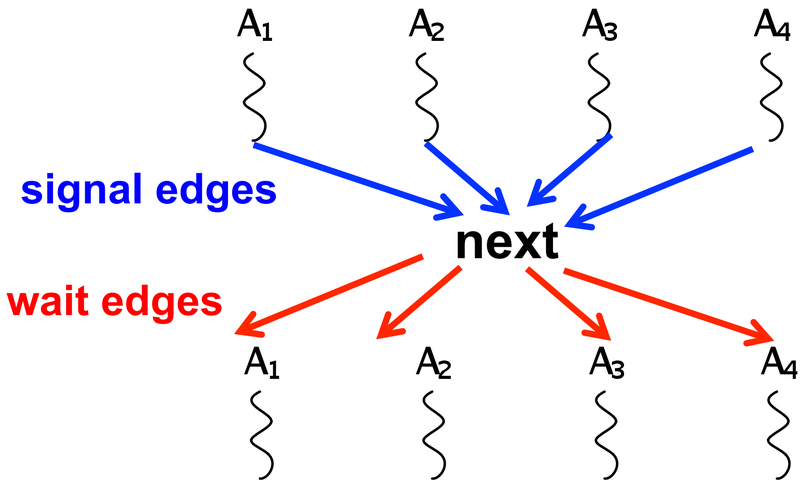
- next -> each forallPhased iteration waits at barrier until all iterations arrive (previous phase is completed), after which the next phase can start
  - —Scope of next is the closest enclosing forallPhased statement
  - —If a forallPhased iteration terminates before executing "next", then the other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

Impact of barrier on scheduling forallPhased iterations

Four forallPhased iterations, each with a next() barrier



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/Module0.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
```

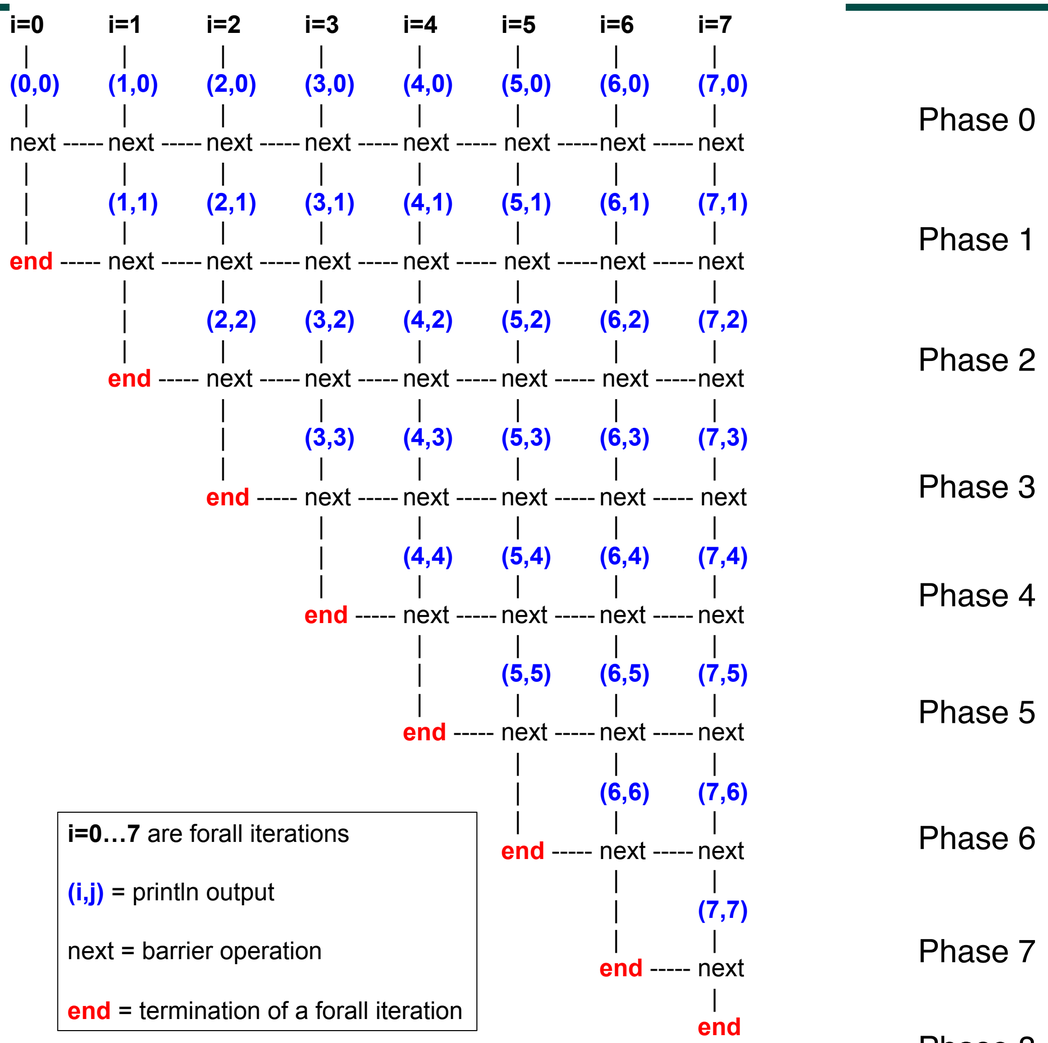

Observation 2: If a forall iteration terminates before “next”, then other iterations do not wait for it

```
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]);
```

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