

COMP 322: Fundamentals of Parallel Programming

Lecture 21: 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. });

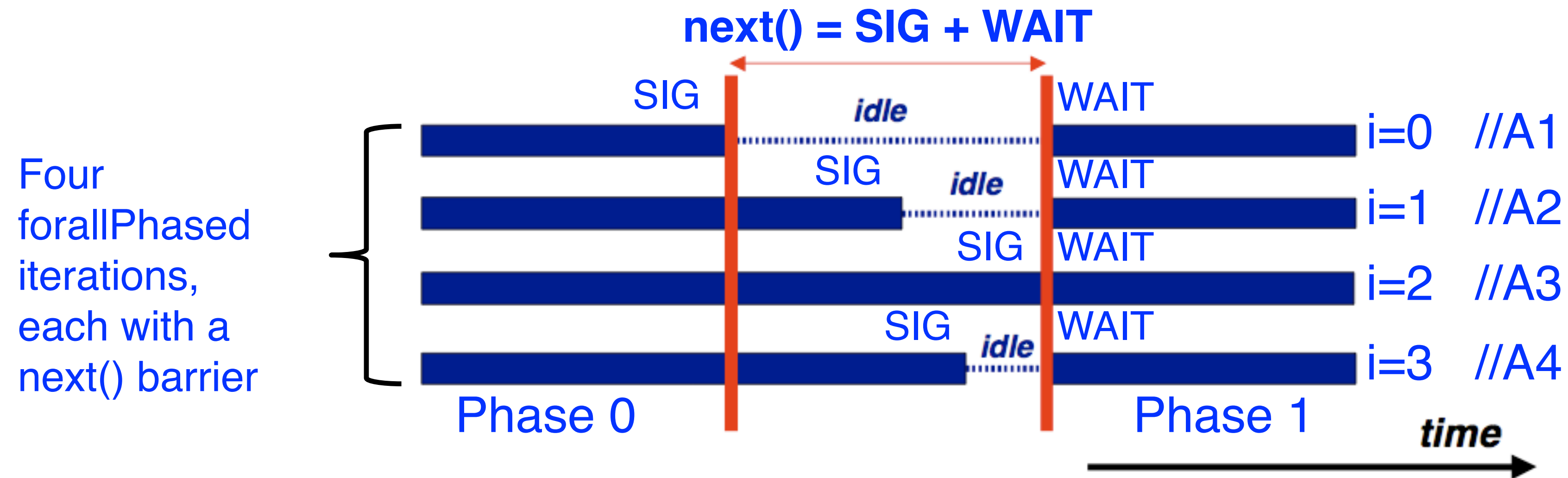
} **Phase 0**

} **Phase 1**

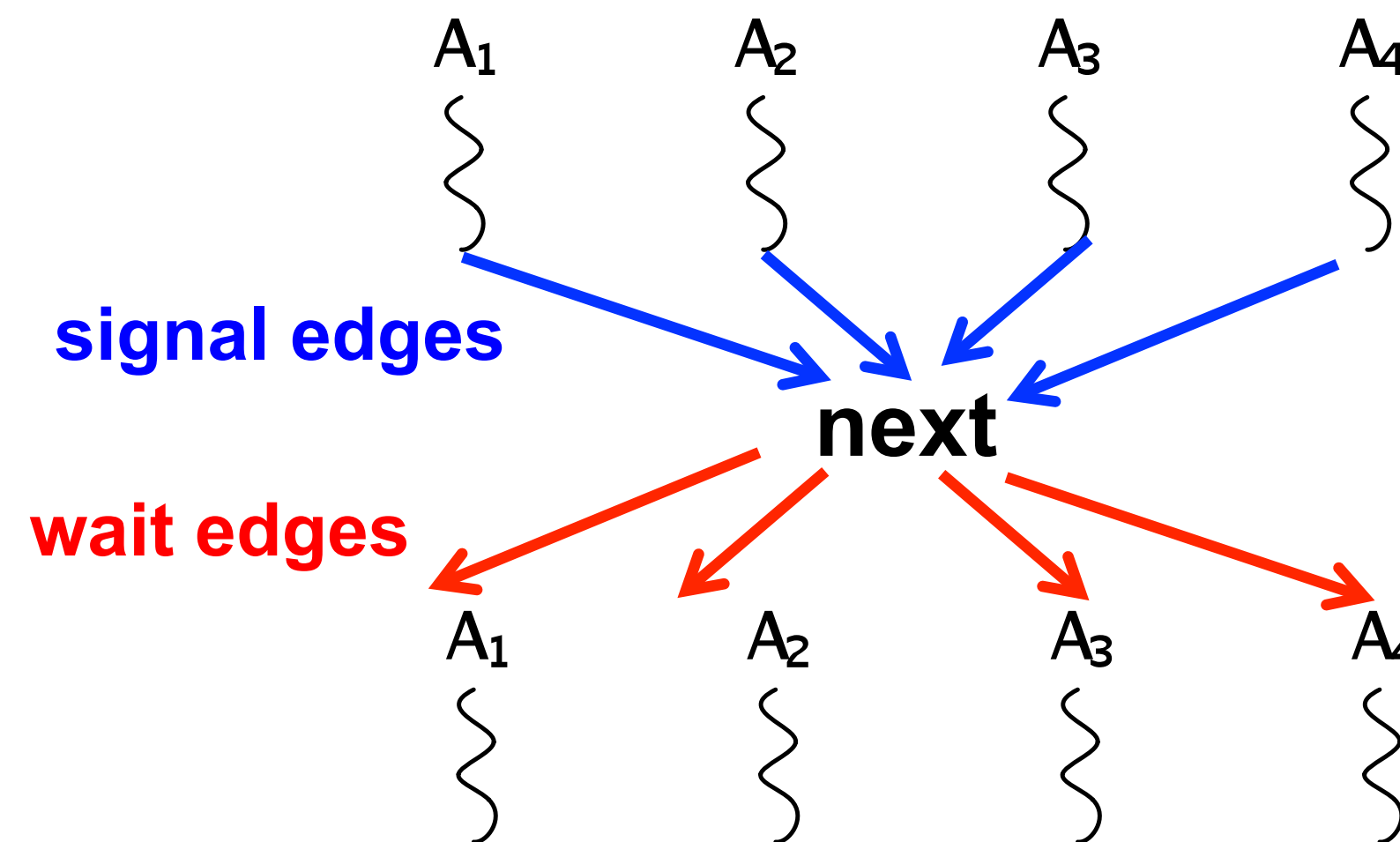
- **next** -> each forallPhased iteration waits at barrier until all iterations arrive (previous phase is completed), after which the next phase can start
 - Scope of next is the closest enclosing forallPhased statement
 - If a forallPhased iteration terminates before executing “next”, then the other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



Impact of barrier on scheduling forallPhased iterations



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

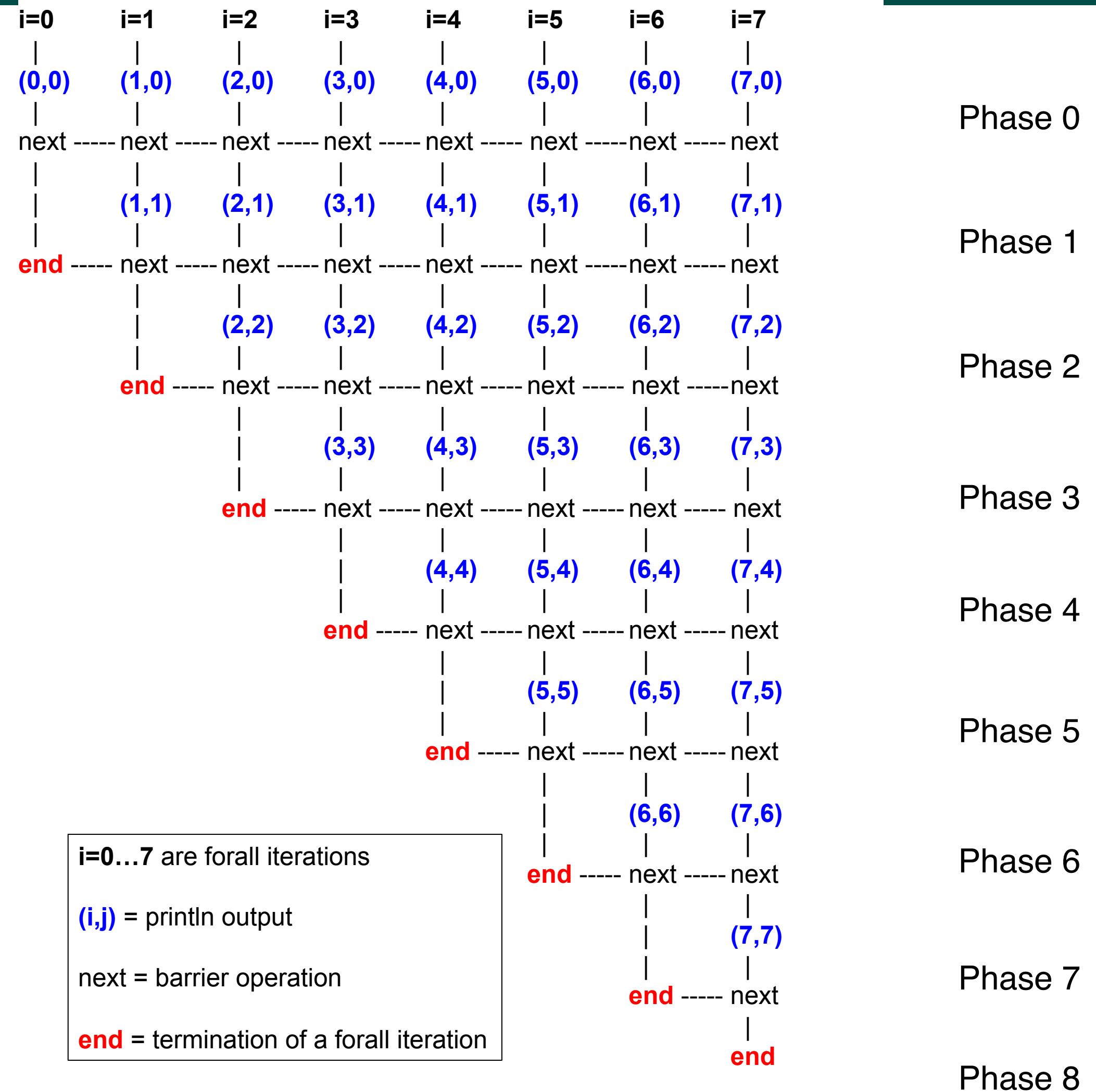
```
1. forallPhased (0, m - 1, (i) -> {
2.   forseq (0, i, (j) -> {
3.     // forall iteration i is executing phase j
4.     System.out.println("(" + i + "," + j + ")");
5.     next();
6.   }); //forseq-j
7. }); //forall-i
```

- 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]);
```

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



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]);
```

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

