COMP 322: Fundamentals of Parallel Programming

Lecture 15: Point-to-Point Synchronization with Phasers

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Outline of Today's Lecture

- **Point-to-Point Synchronization with Phasers**
- **Signal statement and split-phase barriers**

Acknowledgments

- COMP 322 Module 1 handout, Chapter 12

Phasers: a unified construct for barrier and point-to-point synchronization (Recap)

- HJ phasers unify barriers with point-to-point synchronization
- Examples in Lecture 14 motivated the need for "point-to-point" synchronization
  - With barriers, phase i of a task waits for *all* tasks associated with the same barrier to complete phase i-1
  - With phasers, phase i of a task can select a subset of tasks to wait for
- Phaser properties
  - Support for barrier and point-to-point synchronization
  - Support for dynamic parallelism --- the ability for tasks to drop phaser registrations on termination (end), and for new tasks to add phaser registrations (async phased)
  - A task may be registered on multiple phasers in different modes
  - Deadlock freedom --- a next operation will not lead to a situation where all active tasks are blocked indefinitely
  - Support for phaser accumulators --- reductions that can be performed with phasers

Simple Example with Four Async Tasks and One Phaser (Listing 43)

```
1. finish {
2.   ph = new phaser(); // Default mode is SIG_WAIT
3.   async phased(ph<phaserMode.SIG>){ //A1 (SIG mode)
4.     doA1Phase1(); next;
5.     doA1Phase2(); }
6.   async phased { //A2 (default SIG_WAIT mode from parent)
7.     doA2Phase1(); next;
8.     doA2Phase2(); }
9.   async phased { //A3 (default SIG_WAIT mode from parent)
10.    doA3Phase1(); next;
11.    doA3Phase2(); }
12.  async phased(ph<phaserMode.WAIT>){ //A4 (WAIT mode)
13.    doA4Phase1(); next; doA4Phase2(); }
14. }
```

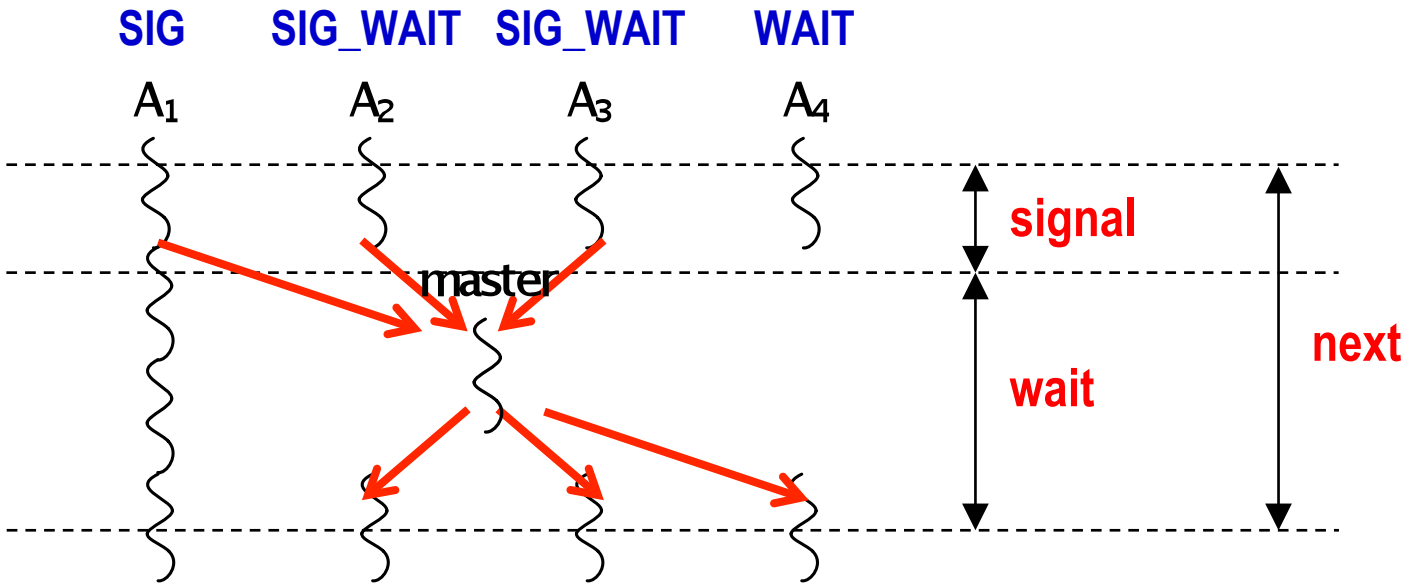

Simple Example with Four Async Tasks and One Phaser (Figure 48)

Semantics of next depends on registration mode

SIG_WAIT: **next = signal + wait**

SIG: **next = signal**

WAIT: **next = wait**



A master thread (worker) gathers all signals and broadcasts a barrier completion

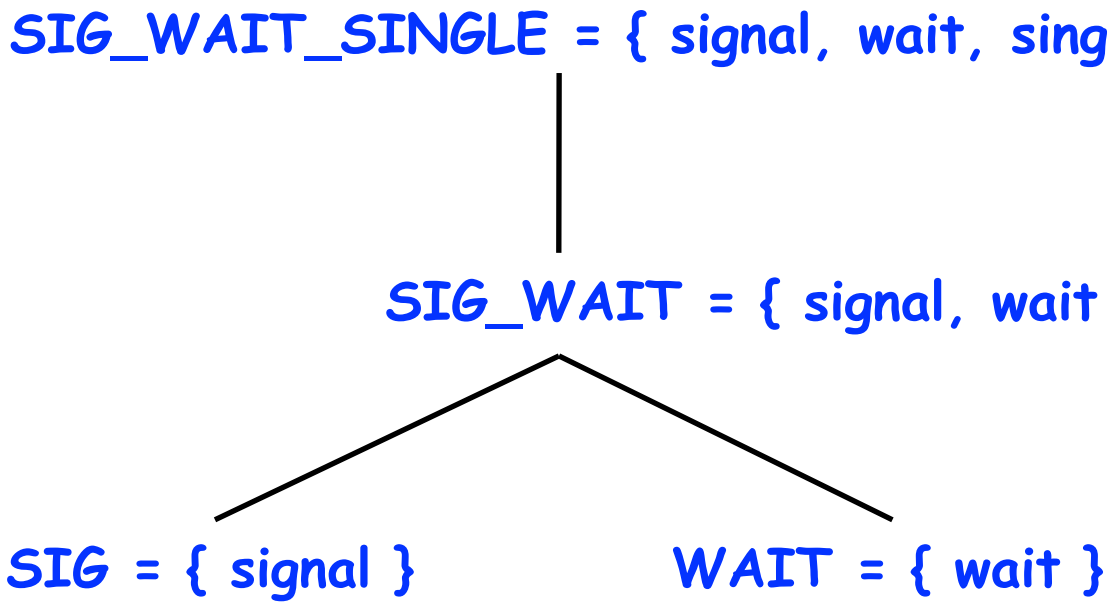
Summary of Phaser Construct

- Phaser allocation
  - phaser ph = new phaser(mode);
    - Phaser ph is allocated with registration mode
    - Phaser lifetime is limited to scope of Immediately Enclosing Finish (IEF)
- Registration Modes
  - phaserMode.SIG, phaserMode.WAIT, phaserMode.SIG_WAIT, phaserMode.SIG_WAIT_SINGLE
    - NOTE: phaser WAIT is unrelated to Java wait/notify (which we will study later)
- Phaser registration
  - async phased (ph_1<$mode_1$>, ph_2<$mode_2$>, …) <stmt>
    - Spawned task is registered with ph_1 in $mode_1$, ph_2 in $mode_2$, …
    - Child task's capabilities must be subset of parent's
    - async phased <stmt> propagates all of parent's phaser registrations to child
- Synchronization
  - next;
    - Advance each phaser that current task is registered on to its next phase
    - Semantics depends on registration mode
    - Barrier is a special case of phaser, which is why *next* is used for both

So, what is a phaser and how does it work?

- A phaser is a synchronization *object* --- you can allocate as many phasers as you choose, and also build arrays/collections of phasers
- The task that allocates a phaser is automatically *registered* on the phaser in the mode specified in the constructor (SIG_WAIT is the default mode)
- A task can be registered on *multiple phasers in different modes*, specified in its "async phased" clause or due to its phaser allocations
- A "next" operation performs *all signal operations followed by all wait operations*, according to the task's phaser registrations
  - Ordering of signal-wait avoids deadlock
  - Degenerates gracefully when wait set or signal set is empty
- A registration on phaser ph in mode m can only be included in "async phased" if the parent was also registered on ph with mode m (*capability rule*)
- Phaser lifetime is limited to scope of Immediately Enclosing Finish (IEF) for the allocation i.e., if phaser ph is allocated in finish scope F, then the task executing F *must drop any registration that it has on ph when reaching the end-finish point for F*

Capability Hierarchy



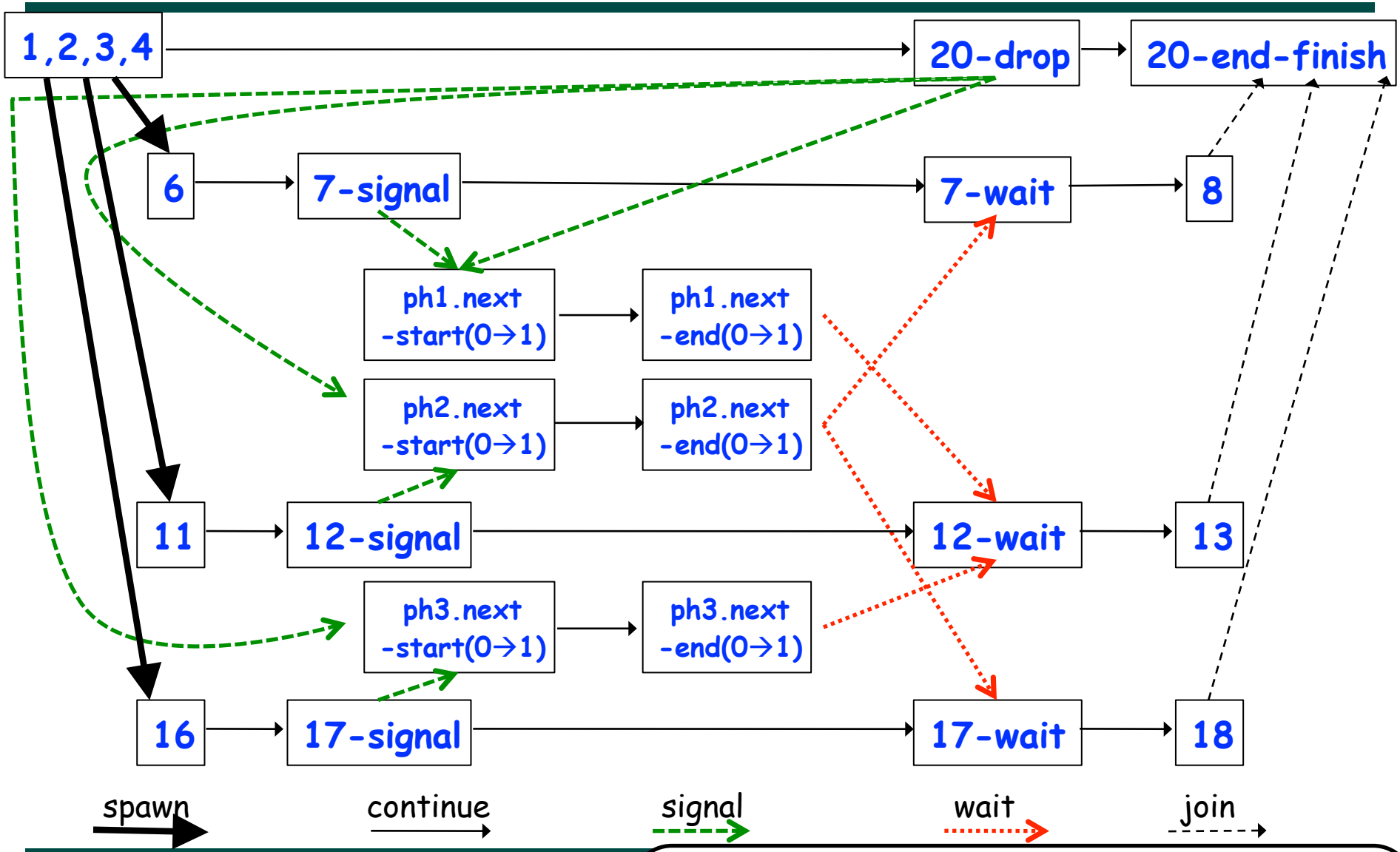
- A task can be registered in one of four modes with respect to a phaser: SIG_WAIT_SINGLE, SIG_WAIT, SIG, or WAIT. The mode defines the set of capabilities — signal, wait, single — that the task has with respect to the phaser. The subset relationship defines a natural hierarchy of the registration modes. A task can drop (but not add) capabilities after initialization.

Left-Right Neighbor Synchronization Example for m=3 (Listing 46)

```
1  finish { // Task T0
2   phaser ph1 = new phaser(phaserMode.SIG_WAIT);
3   phaser ph2 = new phaser(phaserMode.SIG_WAIT);
4   phaser ph3 = new phaser(phaserMode.SIG_WAIT);
5   async phased(ph1<phaserMode.SIG>, ph2<phaserMode.WAIT>)
6   { doPhase1(1); // Task T1
7     next; // Signals ph1, and waits on ph2
8     doPhase2(1);
9   }
10  async phased(ph2<phaserMode.SIG>,ph1<phaserMode.WAIT>,ph3<phaserMode.WAIT>)
11  { doPhase1(2); // Task T2
12    next; // Signals ph2, and waits on ph1 and ph3
13    doPhase2(2);
14  }
15  async phased(ph3<phaserMode.SIG>, ph2<phaserMode.WAIT>)
16  { doPhase1(3); // Task T3
17    next; // Signals ph3, and waits on ph2
18    doPhase2(3);
19  }
20 } // finish
```

Listing 46: Example of left-right neighbor synchronization for $m = 3$ case

Computation Graph for m=3 example (Figure 49)



Let's try another phaser example in Worksheet 15!

Adding Phaser Operations to the Computation Graph

CG node = step

Step boundaries are induced by continuation points

- async: source of a spawn edge
- end-finish: destination of join edges
- future.get(): destination of a join edge
- signal, drop: source of signal edges
- wait: destination of wait edges
- next: modeled as signal + wait

CG also includes an unbounded set of pairs of phase transition nodes for each phaser ph allocated during program execution

- ph.next-start(i→i+1) and ph.next-end(i→i+1)

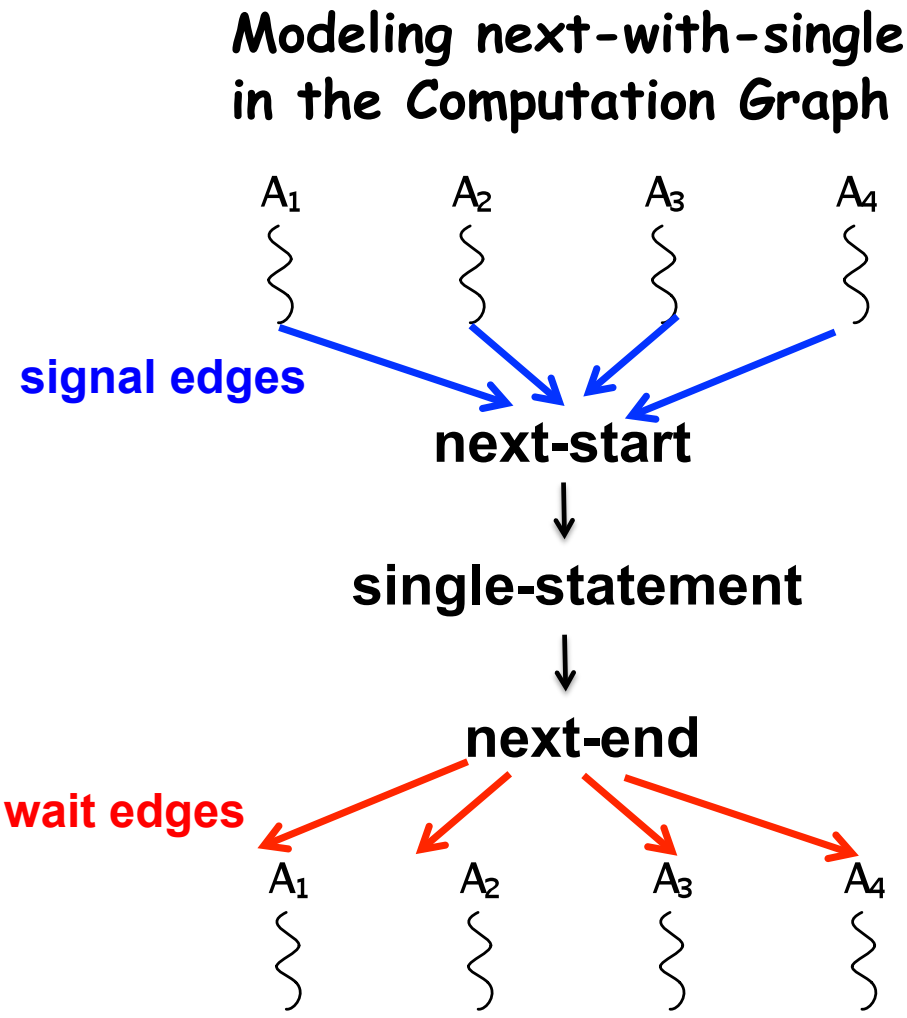
Adding Phaser Operations to the Computation Graph (contd)

CG edges enforce ordering constraints among the nodes

- continue edges capture sequencing of steps within a task
- spawn edges connect parent tasks to child async tasks
- join edges connect descendant tasks to their Immediately Enclosing Finish (IEF) operations and to get() operations for future tasks
- signal edges connect each signal or drop operation to the corresponding phase transition node, ph.next-start(i→i+1)
- wait edges connect each phase transition node, ph.next-end(i→i+1) to corresponding wait or next operations
- single edges connect each phase transition node, ph.next-start(i→i+1) to the start of a single statement instance, and from the end of that single statement to the phase transition node, ph.next-end(i→i+1)

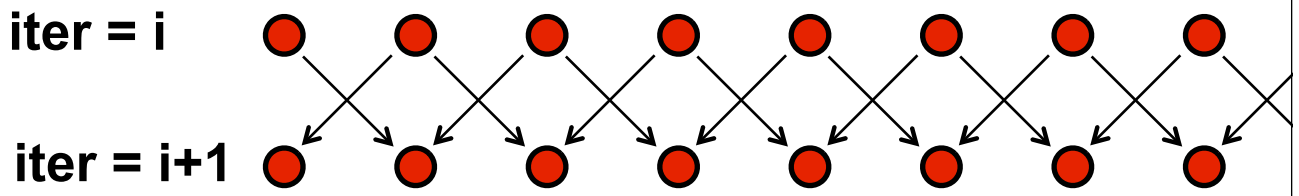
Next-with-Single Statement (for SIG_WAIT_SINGLE registration mode)

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.



One-Dimensional Iterative Averaging with Point-to-Point Synchronization (w/o chunking)

```
1. double[] gVal=new double[n+2]; double[] gNew=new double[n+2];
2. gVal[n+1] = 1; gNew[n+1] = 1;
3. phaser ph = new phaser[n+2];
4. finish { // phasers must be allocated in finish scope
5.   forall(point [i]:[0:n+1]) ph[i] = new phaser();
6.   forasync(point [j]:[1:n]) phased(ph[j]<phaserMode.SIG>,
7.                    ph[j-1]<phaserMode.WAIT>,ph[j+1]<phaserMode.WAIT>){
8.     double[] myVal = gVal; double[] myNew = gNew; // Local pointers
9.     for (point [iter] : [0:numIters-1]) {
10.      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
11.      next; // Point-to-point synchronization
12.      // Swap myVal and myNew
13.      double[] temp=myVal; myVal=myNew; myNew=temp;
14.      // myNew becomes input array for next iter
15.    } // for-iter
16.  } // forasync-j
17.} // finish
```



forall barrier is just an implicit phaser

```
1. forall (point[i,j] : [iLo:iHi,jLo:jHi]) {
2.   S1; next; S2; next{...}
3.  }

is equivalent to

4. finish {
5.   // Implicit phaser for forall barrier
6.   phaser ph = new phaser(phaserMode.SIG_WAIT_SINGLE);
7.   forasync(point[i,j] : [iLo:iHi,jLo:jHi])
8.     phased(phaserMode.SIG_WAIT_SINGLE){
9.       S1; next; S2; next{...}
10.     } // next statements in async refer to ph
11. }
```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- **Signal statement and split-phase barriers**

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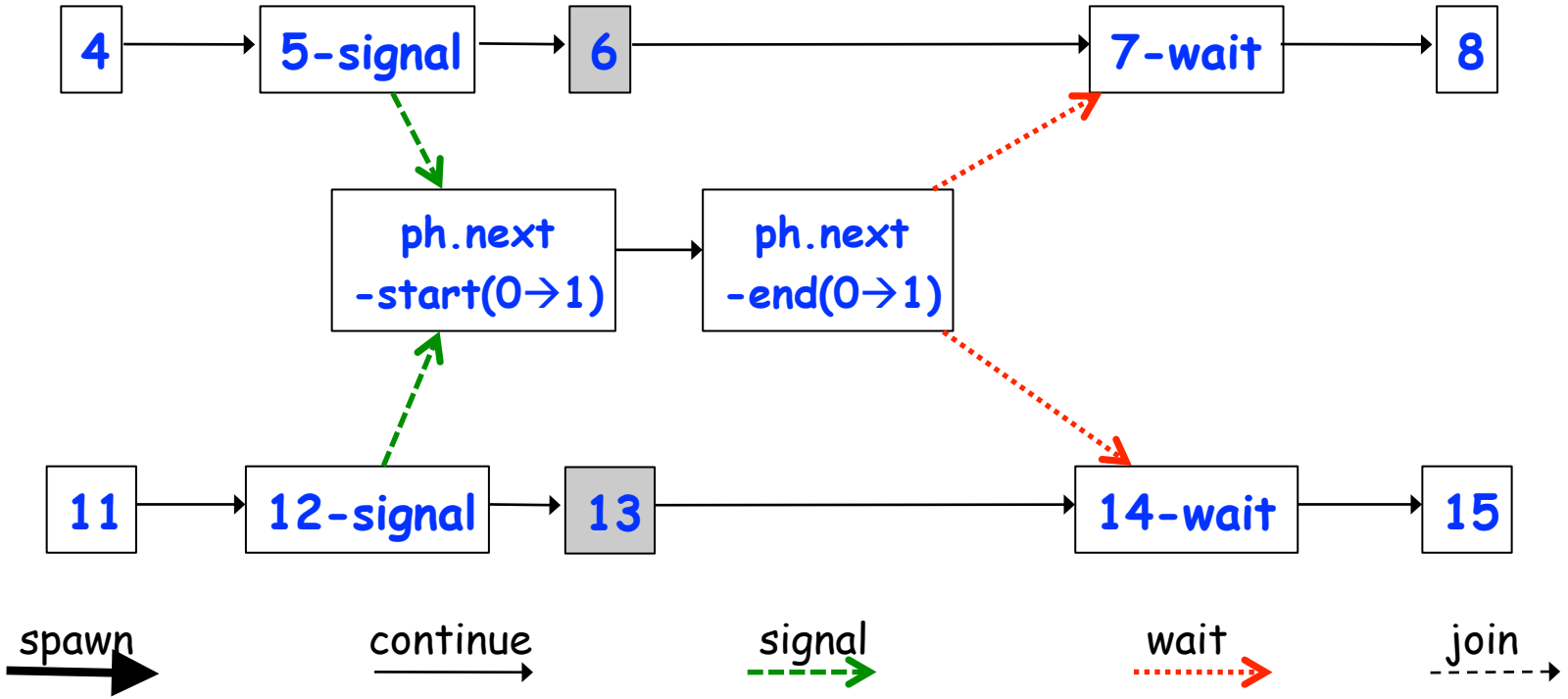
Signal statement

- When a task T performs a signal operation, it notifies all the phasers it is registered on that it has completed all the work expected by other tasks in the current phase ("shared" work).
  - —Since signal is a non-blocking operation, an early execution of signal cannot create a deadlock.
- Later, when T performs a next operation, the next degenerates to a wait since a signal has already been performed in the current phase.
- The execution of "local work" between signal and next is performed during phase transition
  - —Referred to as a "split-phase barrier" or "fuzzy barrier"

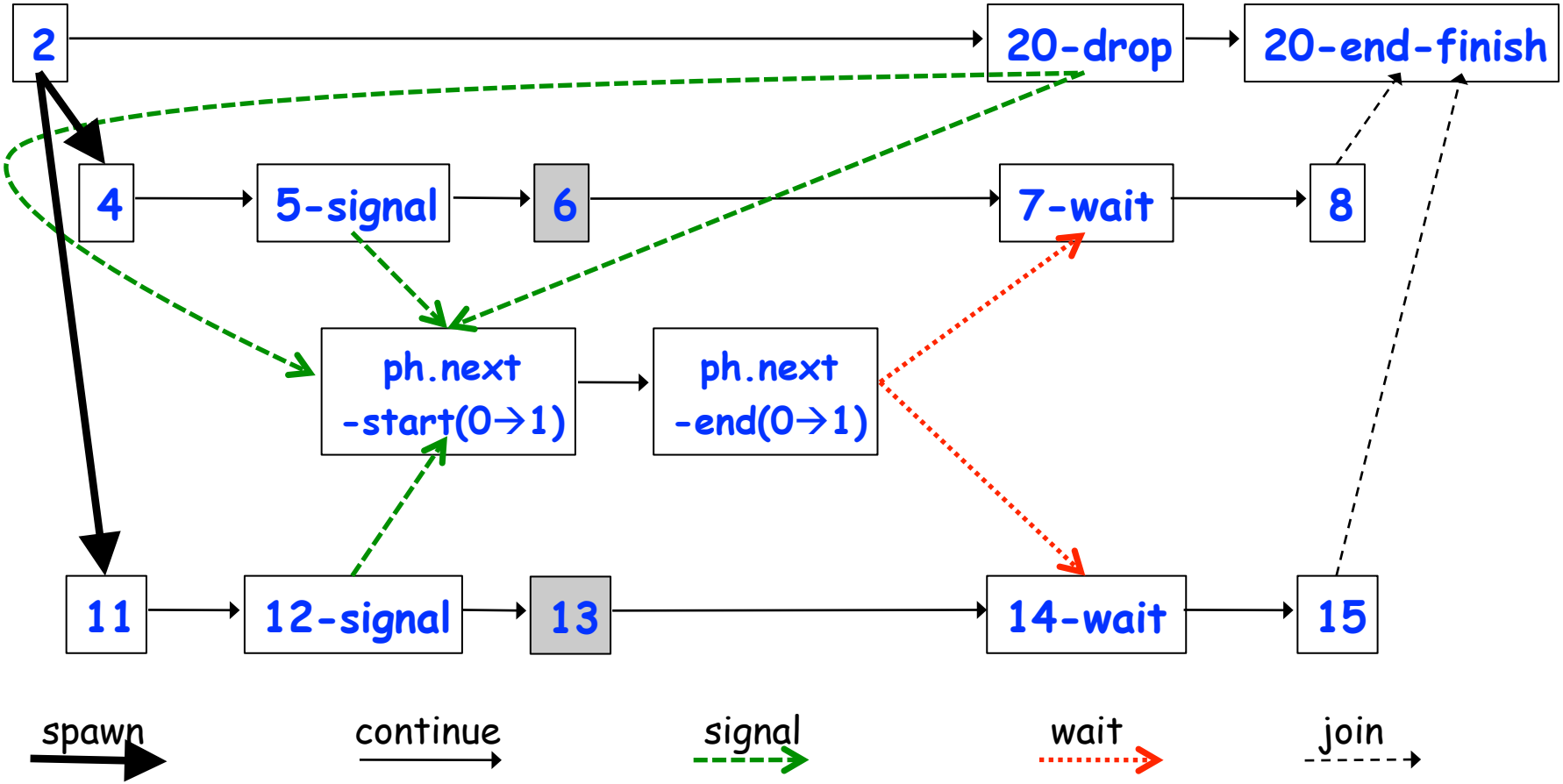
Example of Split-Phase Barrier (Listing 50)

```
1  finish {
2    phaser ph = new phaser(phaserMode.SIG_WAIT);
3    async phased { // Task T1
4      a = ... ;    // Shared work in phase 0
5      signal;      // Signal completion of a's computation
6      b = ... ;    // Local work in phase 0
7      next;        // Barrier -- wait for T2 to compute x
8      b = f(b,x); // Use x computed by T2 in phase 0
9    }
10   async phased { // Task T2
11     x = ... ;    // Shared work in phase 0
12     signal;      // Signal completion of x's computation
13     y = ... ;    // Local work in phase 0
14     next;        // Barrier -- wait for T1 to compute a
15     y = f(y,a); // Use a computed by T1 in phase 0
16   }
17 } // finish
```


Computation Graph for Split-Phase Barrier Example (without async and finish nodes and edges)



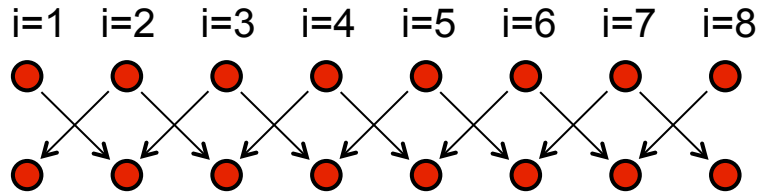
Full Computation Graph for Split-Phase Barrier Example (Figure 52)



Worksheet #15: Left-Right Neighbor Synchronization using Phasers

Name 1: _____

Name 2: _____



Complete the phased clause below to implement the left-right neighbor synchronization shown above

```
1. finish {
2.   phaser[] ph = new phaser[m+2]; // array of phaser objects
3.   for(point [i]:[0:m+1]) ph[i] = new phaser();
4.   for(point [i] : [1:m])
5.    async phased(ph[i-1]<...>, ph[i+1]<...>, ph[i] <...>) {
6.      doPhase1(i);
7.      next;
8.      doPhase2(i);
9.    }
10.}
```