COMP 322: Fundamentals of Parallel Programming

Lecture 12: Finish Accumulators, Forall Statements & Barriers

Vivek Sarkar

Department of Computer Science, Rice University

vsarkar@rice.edu

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Goals for Today's Lecture

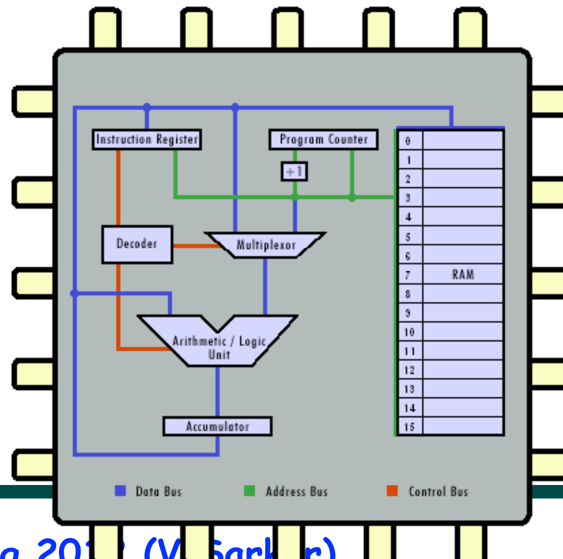
- Finish Accumulators
- Forall statements and barriers

Summing Values from Multiple Async's using AtomicInteger (Recap from Lecture 6)

```
import java.util.concurrent.atomic.AtomicInteger;
// Example 1: compute sum from async tasks in a loop
AtomicInteger a1 = new AtomicInteger();
  finish while(...)
   async { ...; elem = ...; a1.addAndGet(elem); ...; }
int sum1 = a1.get(); // returns sum from while loop
// Example 2: compute sum in a recursive method
AtomicInteger a2 = new AtomicInteger();
void visit(...)
{ ...; elem = ...; a2.addAndGet(elem);
  async visit(...); ...;
}
... finish visit(...); ...
int sum2 = a2.get(); // returns sum from while loop
```

From Atomic Variables to Accumulators

- **Atomic variables are overkill if you just want the final sum**
  - Semantic issues: programs that read the return value of methods like addAndGet() are nondeterministic in general
  - Performance issues: atomic variable can be a sequential bottleneck
- **Instead, need a construct that just returns the final sum without revealing intermediate values**
- **Historically, this pattern has been captured by “accumulators” in computer instructions and programming languages**
  - Load value from memory/register into accumulator
  - Add values into accumulator
  - Load value from accumulator into memory/register



Finish Accumulators in HJ

- Creation

```
accumulator ac = accumulator.factory.accumulator(operator, type);
```

  - operator can be Operator.SUM, Operator.PROD, Operator.MIN, or Operator.MAX
  - type can be int.class or double.class
  - extensions to support generic types, and user-defined operators and types are in progress

- Accumulation

```
ac.put(data);
```

  - data must be of type java.lang.Number, int, or double

- Retrieval

```
Number n = ac.get();
```

  - get() can only be performed outside finish scope that ac is registered with
  - result from get() must be deterministic if HJ program does not use atomic or isolated constructs and is data-race-free

Replacing AtomicInteger by Finish Accumulators in Examples 1 & 2

```
// Example 1: compute sum from async tasks in a loop
accumulator ac1 = accumulator.factory.accumulator
                     (accumulator.Operator.SUM, int.class);
finish (ac1) // permits ac.put() by async tasks in finish
  while(...) async { ...; elem = ...; ac1.put(elem); ...; }
int sum1 = ac1.get().intValue(); // returns sum from while loop
// Example 2: compute sum in a recursive method
accumulator ac1 = accumulator.factory.accumulator
                     (accumulator.Operator.SUM, int.class);
finish (ac2) visit(ac2, ...);
int sum2 = ac2.get().intValue(); // returns sum from visit()
...
void visit(accumulator ac2, ...)
{ ...; elem = ...; ac2.put(elem);
  async visit(...); ...;
}
```

Access Rules for Finish Accumulators

- Accumulator put() and get() operations can be performed by
  - Task that created the accumulator (owner)
  - Any async task in a finish scope that is registered on accumulator e.g.,"finish (ac)"
  - If a get() operation is performed by a non-owner task inside a finish scope, the value returned is the value on entry to the finish scope

Example with Multiple Finish Accumulators

```
// T1 allocates accumulator a and b
accumulator a = accumulator.factory.accumulator(SUM, int.class);
accumulator b = accumulator.factory.accumulator(MIN, double.class);
// T1 can invoke put()/get() on a and b any time
a.put(1); // adds 1 to accumulator a
Number v1 = a.get(); // Returns 1
// T1 creates a finish scope registered on a and b
finish (a, b) {
  // Any task can invoke put() within the finish
  b.put(2.5); // min operation with accumulator b
  finish { // Inner finish inherits registrations for a & b
    async a.put(2);
    b.put(1.5);
  }
  // Unlikely case: if a task invokes get() within the finish,
  // the value returned value is that on entry to the finish
  Number v2 = a.get(); // Returns 1
}
// T1 obtains overall sum and min values after end-finish
Number v3 = a.get(); // Returns 1 + 2 = 3
Number v4 = b.get(); // Returns min(2.5,1.5) = 1.5
```

Error Conditions with Finish Accumulators

1. Non-owner task cannot access accumulators outside registered finish

```
// T1 allocates accumulator a
accumulator a = accumulator.factory.accumulator(...);
async { // T2 cannot access a
  a.put(1); Number v1 = a.get();
}
```

2. Non-owner task cannot register accumulators with a finish

```
// T1 allocates accumulator a
accumulator a = accumulator.factory.accumulator(...);
async {
  // T2 cannot register a with finish
  finish (a) { async a.put(1);  }
}
```

Solution Counting Pattern using Finish Accumulators (NQueens revisited)

```
static accumulator a;
. . .
a = accumulator.factory.accumulator(SUM, int.class);
finish(a) nqueens_kernel(new int[0], 0);
System.out.println("No. of solutions = " + a.get().intValue())
. . .
void nqueens_kernel(int [] a, int depth) {
  if (size == depth) a.put(1);
  else
    /* try each possible position for queen at depth */
    for (int i =  0; i < size; i++) async {
      /* allocate a temporary array and copy array a into it */
      int [] b = new int [depth+1];
      System.arraycopy(a, 0, b, 0, depth);
      b[depth] = i;
      if (ok(depth+1,b)) nqueens_kernel(b, depth+1);
    } // for-async
} // nqueens_kernel()
```

Current Implementation of Finish Accumulators in HJ

- Work-sharing runtime ("eager" accumulation)
  - Each finish accumulator is implemented using java.util.concurrent atomic objects
  - Finish accumulators support operations not supported by AtomicInteger
    - Operator.PROD, Operator.MIN, Operator.MAX
    - Implementations of these operations is analogous to that of AtomicInteger operations
- Work-stealing runtime ("lazy" accumulation)
  - Create an array of accumulators, one per worker
    - accumulator must be allocated with extra "true" parameter

      e.g., `accumulator.factory.accumulator(SUM, int.class, true);`
  - Each task updates the accumulator for its worker
  - At end-finish of registrations scope, the array is reduced to a single value

Atomic Variables vs. Accumulators

Atomic variables

- Pros:
  - simple construct that can be used anywhere in HJ code
  - supports nondeterminism e.g., work-sharing example in Lecture 6
- Cons:
  - can be a sequential bottleneck with large number of simultaneous parallel accesses
  - supports nondeterminism

Finish accumulators

- Pros:
  - integration with finish structure guarantees determinism and reduces errors
  - supports more reduction operations (max, min, product) than AtomicInteger
  - lazy implementation with work-stealing schedulers is more scalable than AtomicInteger operations
- Con:
  - does not support nondeterminism

Goals for Today's Lecture

- Finish Accumulators
- Forall statements and barriers

HJ's forall statement = finish + forasync + barriers

Goal 1 (minor): replace common finish-forasync idiom by forall
e.g., replace

```
finish forasync (point [I,J] : [0:N-1,0:N-1])
  for (point[K] : [0:N-1])
    C[I][J] += A[I][K] * B[K][J];
```

by

```
forall (point [I,J] : [0:N-1,0:N-1])
  for (point[K] : [0:N-1])
    C[I][J] += A[I][K] * B[K][J];
```

Goal 2 (major): Also support "barrier" synchronization

Hello-Goodbye Forall Example

```
AtomicInteger rank = new AtomicInteger();
forall (point[i] : [0:m-1]) {
  int r = rank.getAndIncrement();
  System.out.println("Hello from task ranked " + r);
  System.out.println("Goodbye from task ranked " + r);
}
```

- Sample output for m = 4

  Hello from task ranked 0

  Hello from task ranked 1

  Goodbye from task ranked 0

  Hello from task ranked 2

  Goodbye from task ranked 2

  Goodbye from task ranked 1

  Hello from task ranked 3

  Goodbye from task ranked 3

Hello-Goodbye Forall Example (contd)

```
AtomicInteger rank = new AtomicInteger();
forall (point[i] : [0:m-1]) {
  int r = rank.getAndIncrement();
  System.out.println("Hello from task ranked " + r);
  System.out.println("Goodbye from task ranked " + r);
}
```

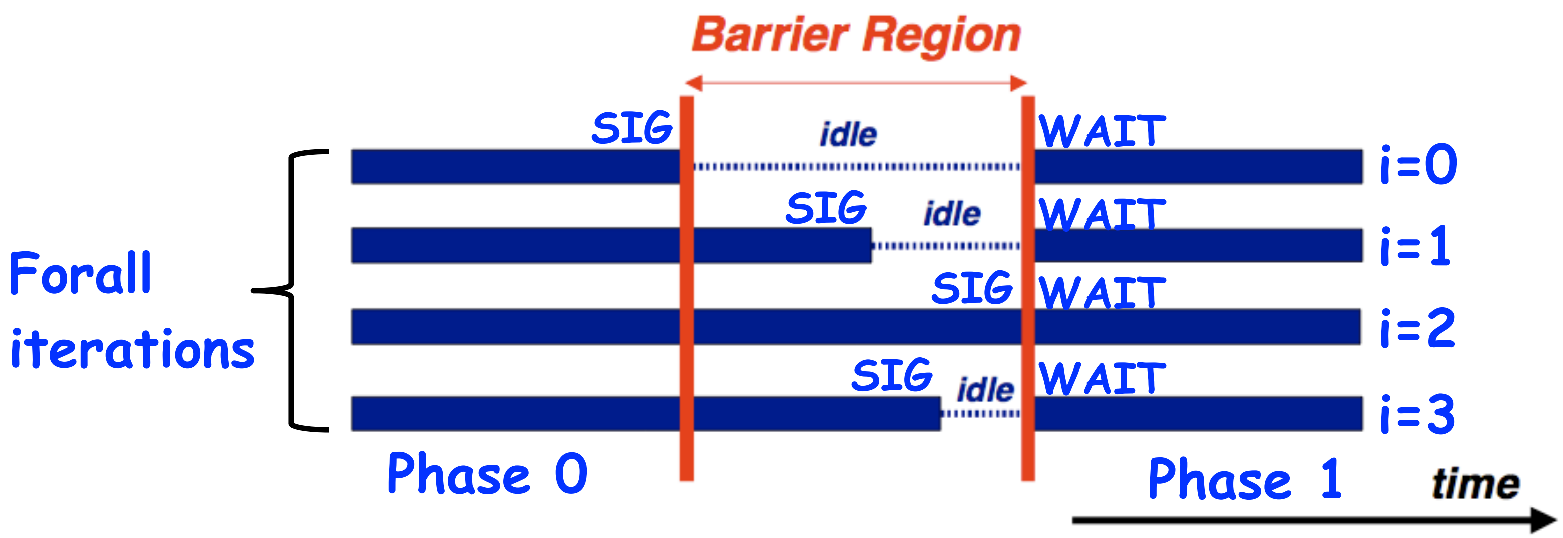
- Question: how can we transform this code so as to ensure that all tasks say hello before any tasks say goodbye?
- Approach 1: Replace the forall loop by two forall loops, one for the hello's and one for the goodbye's
  - Need to communicate local r values from one forall to the next
- Approach 2: insert a "barrier" between the hello's and goodbye's
  - "next" statement in HJ's forall loops

Barrier Synchronization: HJ's "next" statement

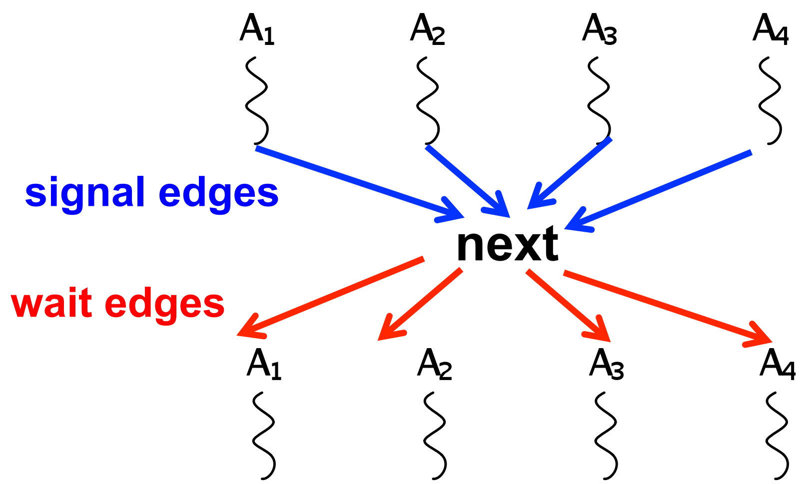
```
AtomicInteger rank = new AtomicInteger();
forall (point[i] : [0:m-1]) {
   int r = rank.getAndIncrement();                          } Phase 0
   System.out.println("Hello from task ranked " + r);
  next; // Acts as barrier between phases 0 and 1
  System.out.println("Goodbye from task ranked " +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

- *next* ➔ each forall iteration suspends at next until all iterations arrive (complete previous phase), after which the phase can be advanced
  - If a forall iteration terminates before executing "next", then the other iterations do not wait for it
  - Scope of synchronization is the closest enclosing forall statement
  - Special case of "phaser" construct (will be covered in following lectures)

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
```

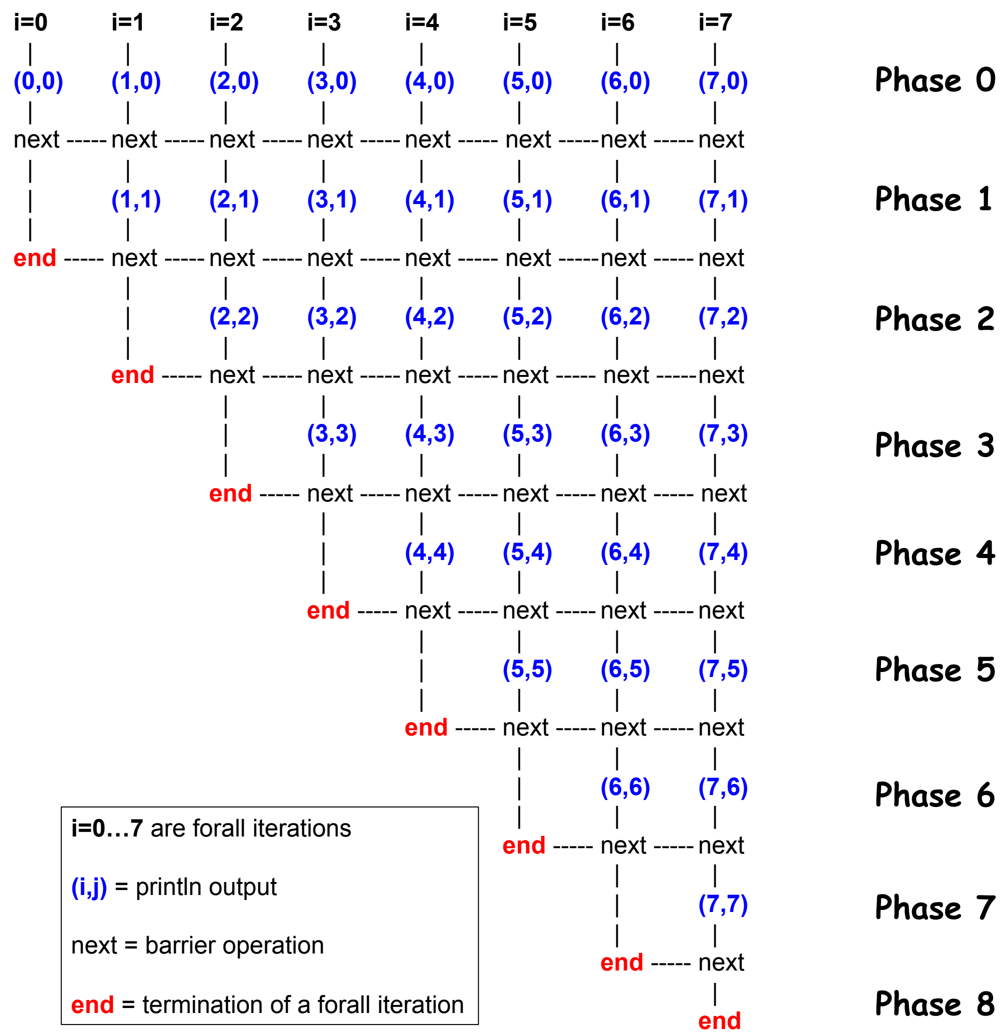
Observation 2: If a forall iteration terminates before "next", then other iterations do not wait for it

```
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 (barrier matching problem)

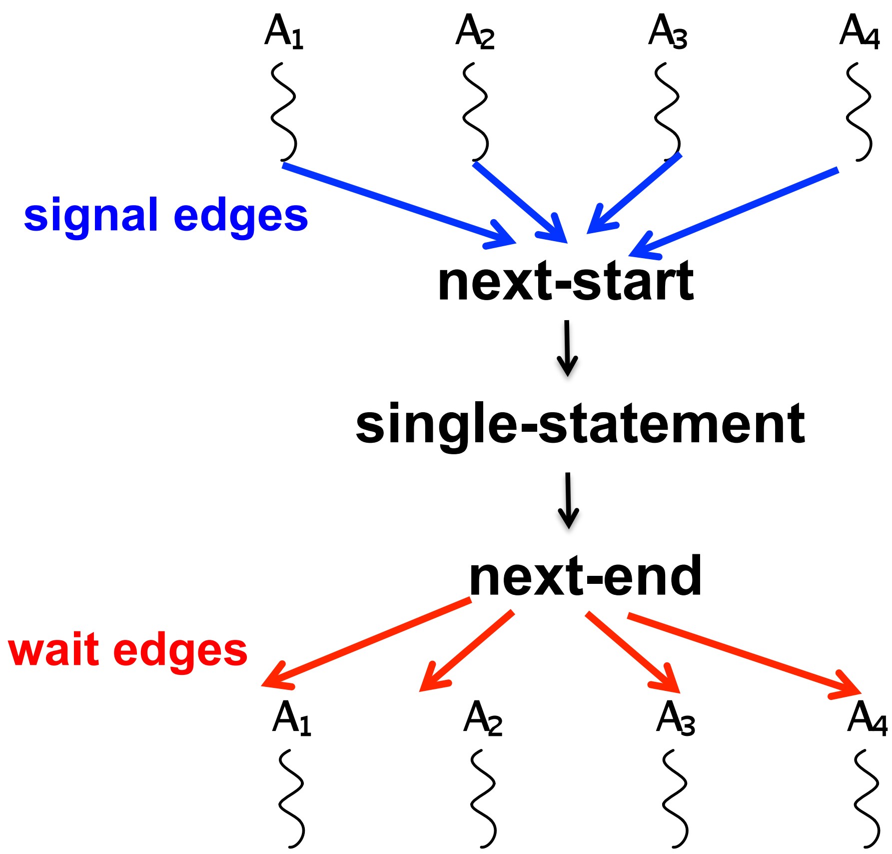
```
1.  forall (point[i] : [0:m-1]) {
2.    if (i % 2 == 1) { // i is odd
3.      oddPhase0(i);
4.      next;
5.      oddPhase1(i);
6.    } else { // i is even
7.      evenPhase0(i);
8.      next;
9.      evenPhase1(i);
10.   } // if-else
11. } // forall
```

- 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()

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)

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