COMP 322: Fundamentals of Parallel Programming

Lecture 13: Forall and Barriers (contd), Data-driven tasks

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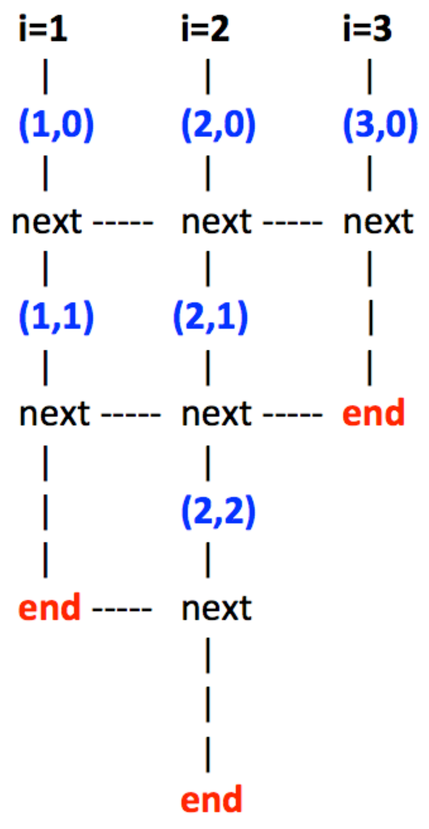
Worksheet #12: Forall Loops and Barriers

1) Draw a “barrier matching” figure similar to slide 14 for the code fragment below.

```
String[] a = { “ab”, “cde”, “f” };
. . . int m = a.length; . . .
forall (point[i] : [1:m]) {
   for (int j = 0; j < a[i-1].length(); j++) {
     // forall iteration i is executing phase j
     System.out.println("(" + i + "," + j + ")");
     next;
   }
 }
```

Solution



Outline of Today's Lecture

- <u>**Barrier Synchronization in Forall Loops (contd)**</u>
- **Dataflow Computing, Data-Driven Futures (DDFs) and Data-Driven Tasks (DDTs)**

Acknowledgments

- COMP 322 Module 1 handout, Chapters 10, 11

One-Dimensional Iterative Averaging: chunkedForkJoin version with *chunked for-forall-for* structure (Recap)

```
double[] gVal=new double[n+2]; double[] gNew=new double[n+2];
gVal[0] = 0; gVal[n+1] = 1; // boundary condition
int nc = Runtime.getNumOfWorkers(); // number of chunks
double[] myVal = gVal; double[] myNew = gNew;
for (point [iter] : [0:m-1]) {
  // Compute MyNew as function of input array MyVal
  forall (point [jj] : [0:nc-1]) {
    for(point [j] : getChunk([1:n],nc,jj))
      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
  } // forall
  temp=myVal; myVal=myNew; myNew=temp;// Swap myVal & myNew;
  // myNew becomes input array for next iteration
} // for
```

This program creates m*nc async tasks

One-Dimensional Iterative Averaging: Barrier version with *chunked forall-for-for+next* structure (Recap)

```
double[] gVal=new double[n+2]; double[] gNew=new double[n+2]; gVal[n+1] = 1;
int nc = Runtime.getNumWorkers();
forall (point [jj]:[0:nc-1]) { // Chunked forall is now the outermost loop
  double[] myVal = gVal; double[] myNew = gNew; // Copy of myVal/myNew pointers
  for (point [iter] : [0:m-1]) {
    // Compute MyNew as function of input array MyVal
    for (point [j]:getChunk([1:n],nc,jj)) // Iterate within chunk
       myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
    next; // Barrier before executing next iteration of iter loop
    // Swap local pointers, myVal and myNew
    double[] temp=myVal; myVal=myNew; myNew=temp;
    // myNew becomes input array for next iter
  } // for
} // forall
```

This program creates nc async tasks, and performs m*nc barrier operations

What just happened?

chunkedForkJoin version:

```
5. for (point [iter] : [0:m-1])
7.   forall (point [jj] : [0:nc-1]) {
8,9.     for(point [j] : getChunk([1:n],nc,jj)) { ... }
10.  } // forall
     . . .
13. } // for
```

barrier version:

```
3. forall (point [jj]:[0:nc-1]))
5.   for (point [iter] : [0:m-1]) {
       . . .
7,8.   for (point [j]:getChunk([1:n],nc,jj)) { ... } // for
9.     next;
       . . .
13,   } // for
15. } // forall
```

Single Program Multiple Data (SPMD) Parallel Programming Model

Basic idea

- Run the same code (program) on P workers
- Use the "rank" --- an ID ranging from 0 to (P-1) --- to determine what data is processed by which worker
  - —Hence, "single-program" and "multiple-data"
  - —Rank is equivalent to index in a top-level "forall (point[i] : [0:P-1])" loop
- Lower-level programming model than dynamic async/finish parallelism
  - —Programmer's code is essentially at the worker level (each forall iteration is like a worker), and work distribution is managed by programmer by using barriers and other synchronization constructs
  - —Harder to program but can be more efficient for restricted classes of applications (e.g. for OneDimAveraging, but not for nqueens)
- Convenient for hardware platforms that are not amenable to efficient dynamic task parallelism
  - —General-Purpose Graphics Processing Unit (GPGPU) accelerators
  - —Distributed-memory parallel machines

One-Dimensional Iterative Averaging: Barrier version with *chunked forall-for-for+next* structure is an SPMD program

```
double[] gVal=new double[n+2]; double[] gNew=new double[n+2]; gVal[n+1] = 1;
int nc = Runtime.getNumWorkers();
forall (point [jj]:[0:nc-1]) { // Chunked forall is now the outermost loop
  double[] myVal = gVal; double[] myNew = gNew; // Copy of myVal/myNew pointers
  for (point [iter] : [0:m-1]) {
    // Compute MyNew as function of input array MyVal
    for (point [j]:getChunk([1:n],nc,jj)) // Iterate within chunk
       myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
    next; // Barrier before executing next iteration of iter loop
    // Swap local pointers, myVal and myNew
    double[] temp=myVal; myVal=myNew; myNew=temp;
    // myNew becomes input array for next iter
  } // for
} // forall
```

Instead of async-finish, this SPMD version of OneDimAveraging creates one task per worker, uses getChunk() to distribute work, and use barriers to synchronize workers.

Motivation for “single” statement with barriers --- Hello Goodbye Example revisited (Listing 36)

- **Goal: rewrite Hello-Goodbye example so as to print a single log message in between phases**
- **Simple solution: add a second barrier and designate a specific forall task to print the log message between those two barriers**

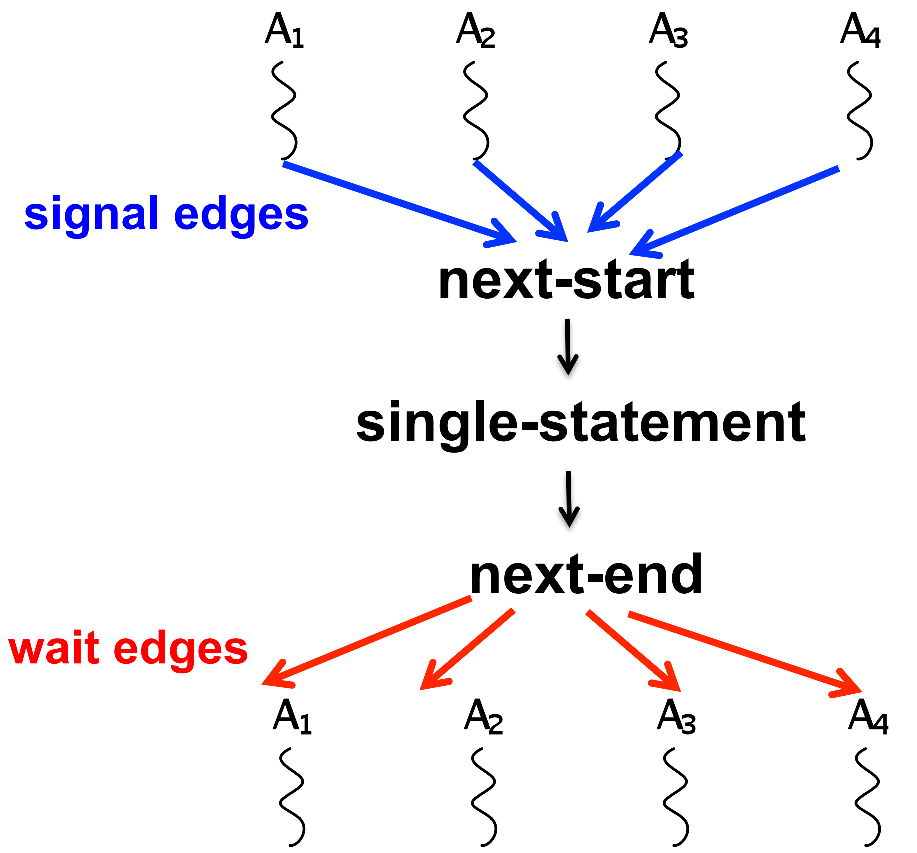
```
// Listing 36 in Module 1 handout
forall (point[i] : [0:m-1]) {
 int sq = i*i;
 System.out.println(“Hello from task with square = “ + sq);
 next; // Barrier
 if (i==0) System.out.println(“LOG: Between Hello & Goodbye phases”));
 next; // Barrier
 System.out.println(“Goodbye from task with square = “ + sq);
}
```

- **More efficient solution: use next-with-single**

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 37 in Module 1 handout
forall (point[i] : [0:m-1]) {
  int sq = i*i;
  System.out.println(“Hello from task with square = “ + sq);
  next { // next-with-single statement
    System.out.println(“LOG: Between Hello & Goodbye phases”);
  }
  System.out.println(“Goodbye from task with square = “ + sq);
}
```

One-Dimensional Iterative Averaging with Single Statement and global gVal & gNew fields

```
static double[] gVal=new double[n+2];
static double[] gNew=new double[n+2];
. . .
gVal[n+1] = 1; // Boundary condition
int nc = Runtime.getNumWorkers();
forall (point [jj]:[0:nc-1]) { // forall is now outermost loop
   for (point [iter] : [0:m-1]) {
    // Compute Gnew as function of input array Gval
    for (point [j]:getChunk([1:n],nc,jj)) // Iterate within chunk
       gNew[j] = (gVal[j-1] + gVal[j+1])/2.0;
    // Use next-with-single
    next {double[] temp=gVal; gVal=gNew; gNew=temp;} // single
    // gNew becomes input array for next iter
  } // for
} // forall
```

Outline of Today's Lecture

- **Barrier Synchronization in Forall Loops (contd)**

- **<u>Dataflow Computing, Data-Driven Futures (DDFs) and Data-Driven Tasks (DDTs)</u>**

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Dataflow Computing

- **Original idea: replace machine instructions by a small set of dataflow operators**

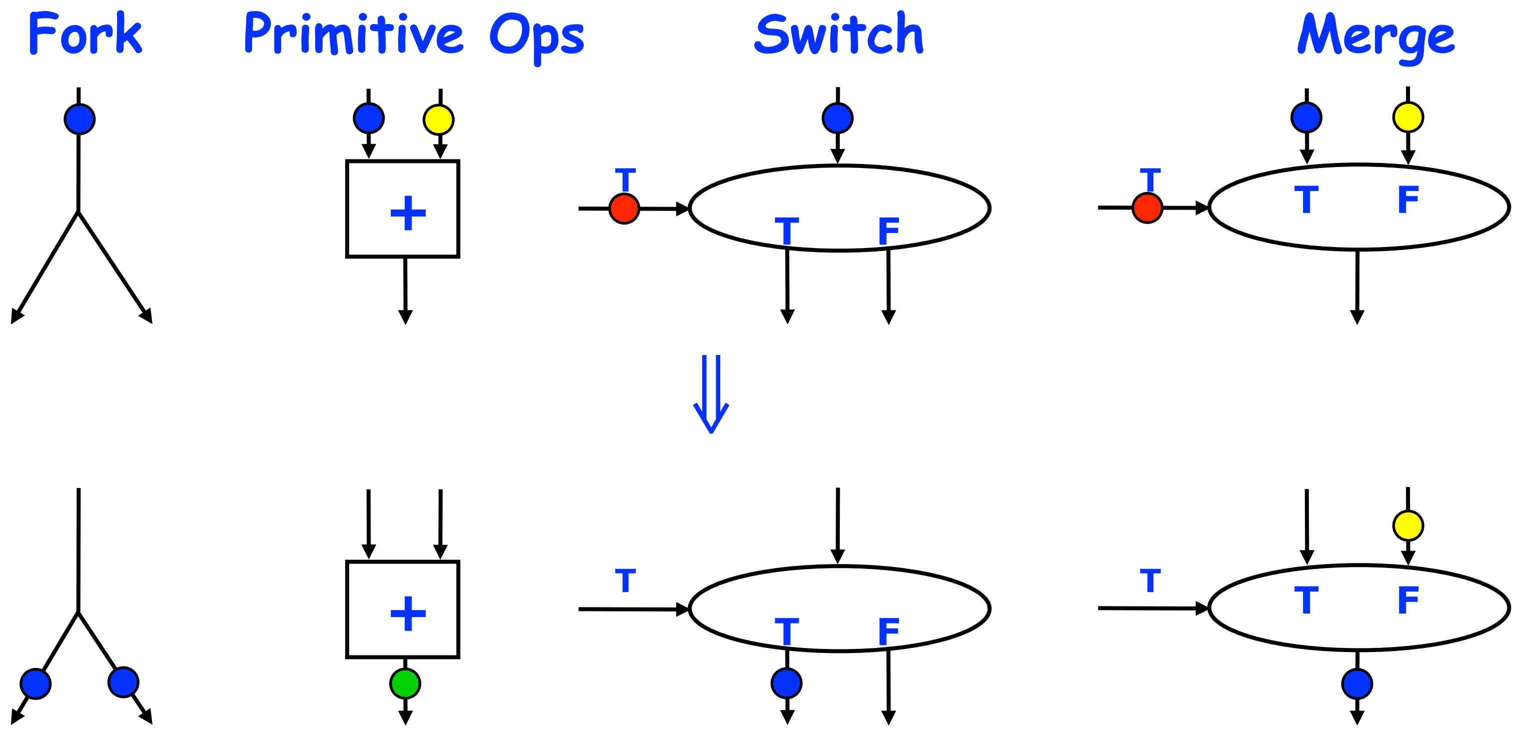
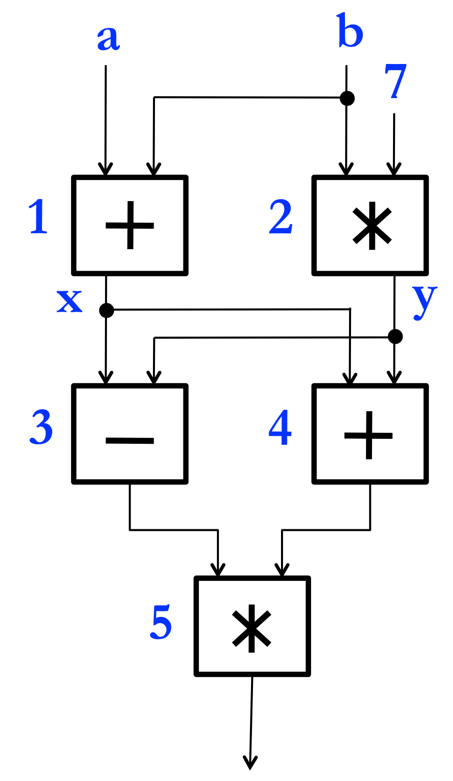


Figure 37: Example instruction sequence and its dataflow graph

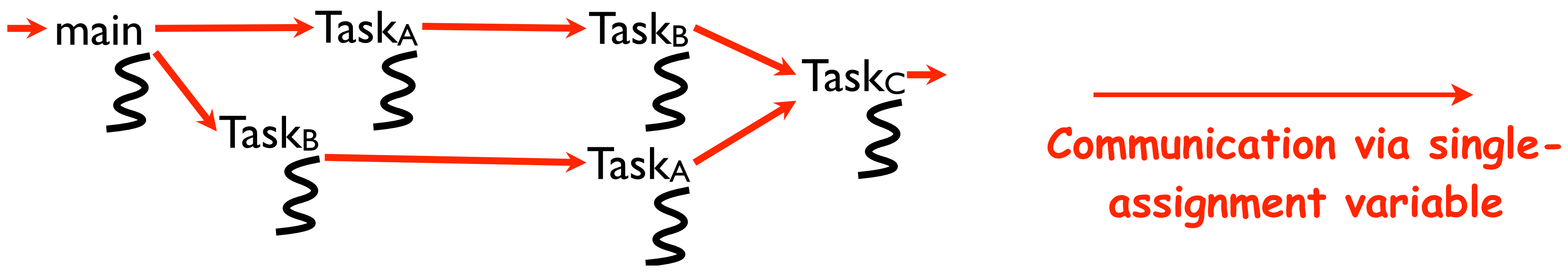
```
x = a + b;
y = b * 7;
z = (x-y) * (x+y);
```



An operator executes when all its input values are present; copies of the result value are distributed to the destination operators.

No separate control flow

Macro-Dataflow Programming



- "Macro-dataflow" = extension of dataflow model from instruction-level to task-level operations
- General idea: build an arbitrary task graph, but restrict all inter-task communications to single-assignment variables
  - Static dataflow ==> graph fixed when program execution starts
  - Dynamic dataflow ==> graph can grow dynamically
- Semantic guarantees: race-freedom, determinism
  - Deadlocks are possible due to unavailable inputs (but they are deterministic)

Extending HJ Futures for Macro-Dataflow: Data-Driven Futures (DDFs) and Data-Driven Tasks (DDTs)

`ddfA = new DataDrivenFuture<T1>();`

- Allocate an instance of a data-driven-future object (container)
- Object in container must be of type T1

`async await(ddfA, ddfB, …) Stmt`

- Create a new data-driven-task to start executing Stmt after all of ddfA, ddfB, … become available (i.e., after task becomes "enabled")

`ddfA.put(V) ;`

- Store object V (of type T1) in ddfA, thereby making ddfA available
- Single-assignment rule: at most one put is permitted on a given DDF

ddfA.get()

- Return value (of type T1) stored in ddfA
- Can only be performed by async's that contain ddfA in their await clause (hence no blocking is necessary for DDF gets)

Implementing Future Tasks using DDFs

- **Future version**

```
final future<T> f = async<T> { return g(); };
S1
... = f.get();
S2
S3
```

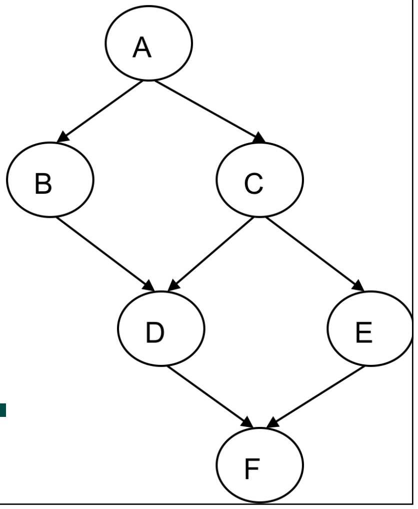
- **DDF version**

```
DataDrivenFuture<T> f = new DataDrivenFuture<T>();
async { f.put(g()) };
S1
finish async await(f) {
  ... = f.get();
  S2 // DDT must include full continuation starting
  S3 // with S2
}
```

Use of DDFs with dummy objects (like future<void>)

```
finish {
  DataDrivenFuture ddfA = new DataDrivenFuture();
  DataDrivenFuture ddfB = new DataDrivenFuture();
  DataDrivenFuture ddfC = new DataDrivenFuture();
  DataDrivenFuture ddfD = new DataDrivenFuture();
  DataDrivenFuture ddfE = new DataDrivenFuture();
  async { ... ; ddfA.put(""); } // Task A
  async await(ddfA) { ... ;  ddfB.put(""); } // Task B
  async await(ddfA) { ... ;  ddfC.put(""); } // Task C
  async await(ddfB,ddfC) { ... ;  ddfD.put(""); } // Task D
  async await(ddfC) { ... ;  ddfE.put(""); } // Task E
  async await(ddfD,ddfE) { ... } // Task F
} // finish
```

- **This example uses an empty string as a dummy object**



Differences between Futures and DDFs/DDTs

- Consumer task blocks on get() for each future that it reads, whereas async-await does not start execution till all DDFs are available
- Future tasks cannot deadlock, but it is possible for a DDT to block indefinitely (“deadlock”) if one of its input DDFs never becomes available
- DDTs and DDFs are more general than futures
  - —Producer task can only write to a single future object, where as a DDT can write to multiple DDF objects
  - —The choice of which future object to write to is tied to a future task at creation time, where as the choice of output DDF can be deferred to any point with a DDT
- DDTs and DDFs can be more implemented more efficiently than futures
  - —An “async await” statement does not block the worker, unlike a future.get()
  - —You will never see the following message with “async await”
    - – “ERROR: Maximum number of hj threads per place reached”

Two Exception (error) cases for DDFs that do not occur in futures

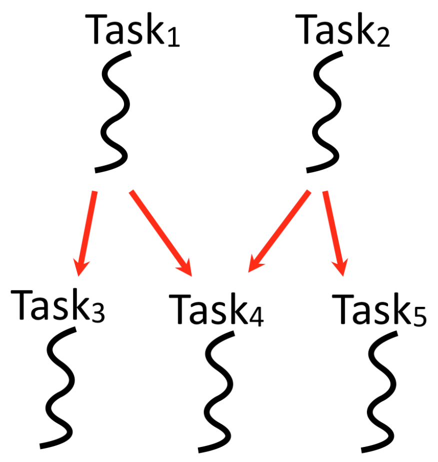
- **Case 1:** If two put's are attempted on the same DDF, an exception is thrown because of the violation of the single-assignment rule
  - There can be at most one value provided for a future object (since it comes from the producer task's return statement)
- **Case 2:** If a get is attempted by a task on a DDF that was not in the task's await list, then an exception is thrown because DDF's do not support blocking gets
  - Futures support blocking gets

Deadlock example with DDTs

```
DataDrivenFuture left = new DataDrivenFuture();
DataDrivenFuture right = new DataDrivenFuture();
finish {
  async await(left) right.put(rightWriter());
  async await(right) left.put(leftWriter());
}
```

Another Example with DDTs and DDFs

```
DataDrivenFuture left = new DataDrivenFuture();
DataDrivenFuture right = new DataDrivenFuture();
finish {
  async await(left) leftReader(left); // Task3
  async await(right) rightReader(right); // Task5
  async await(left,right)
          bothReader(left,right); // Task4
  async left.put(leftWriter()); // Task1
  async right.put(rightWriter());// Task2
}
```



- **await clauses capture data flow relationships**

Interesting example. Let's discuss it further in Worksheet 13!

Implementing DDFs/DDTs using Future tasks

Shown for completeness, but not recommend for performance ...

- DDF version

```
DataDrivenFuture f1 = new DataDrivenFuture();
DataDrivenFuture f2 = new DataDrivenFuture();
async { f1.put(g()) }; async { f2.put(h()) };
// async doesn't start till f1 & f2 are available
async await (f1, f2) {
  ... = f1.get() + f2.get(); };
```

- Future version

```
final future<int> f1 = async<int> { return g(); };
final future<int> f2 = async<int> { return h(); };
// Async may block at each get() operation
async { ... = f1.get() + f2.get(); };
```

Worksheet #12: Forall Loops and Barriers

Name 1: ______________________ Name 2: ______________________

For the example below, will reordering the five async statements change the meaning of the program? If so, show two orderings that exhibit different behaviors. If not, explain why not. (You can use the space below this slide for your answer.)

```
DataDrivenFuture left = new DataDrivenFuture();
DataDrivenFuture right = new DataDrivenFuture();
finish {
  async await(left) leftReader(left); // Task3
  async await(right) rightReader(right); // Task5
  async await(left,right)
        bothReader(left,right); // Task4
  async left.put(leftWriter()); // Task1
  async right.put(rightWriter());// Task2
}
```