# COMP 322: Fundamentals of Parallel Programming

## Lecture 9: Async, Finish, Data-Driven Tasks

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# Async and Finish Statements for Task Creation and Termination

**async S**

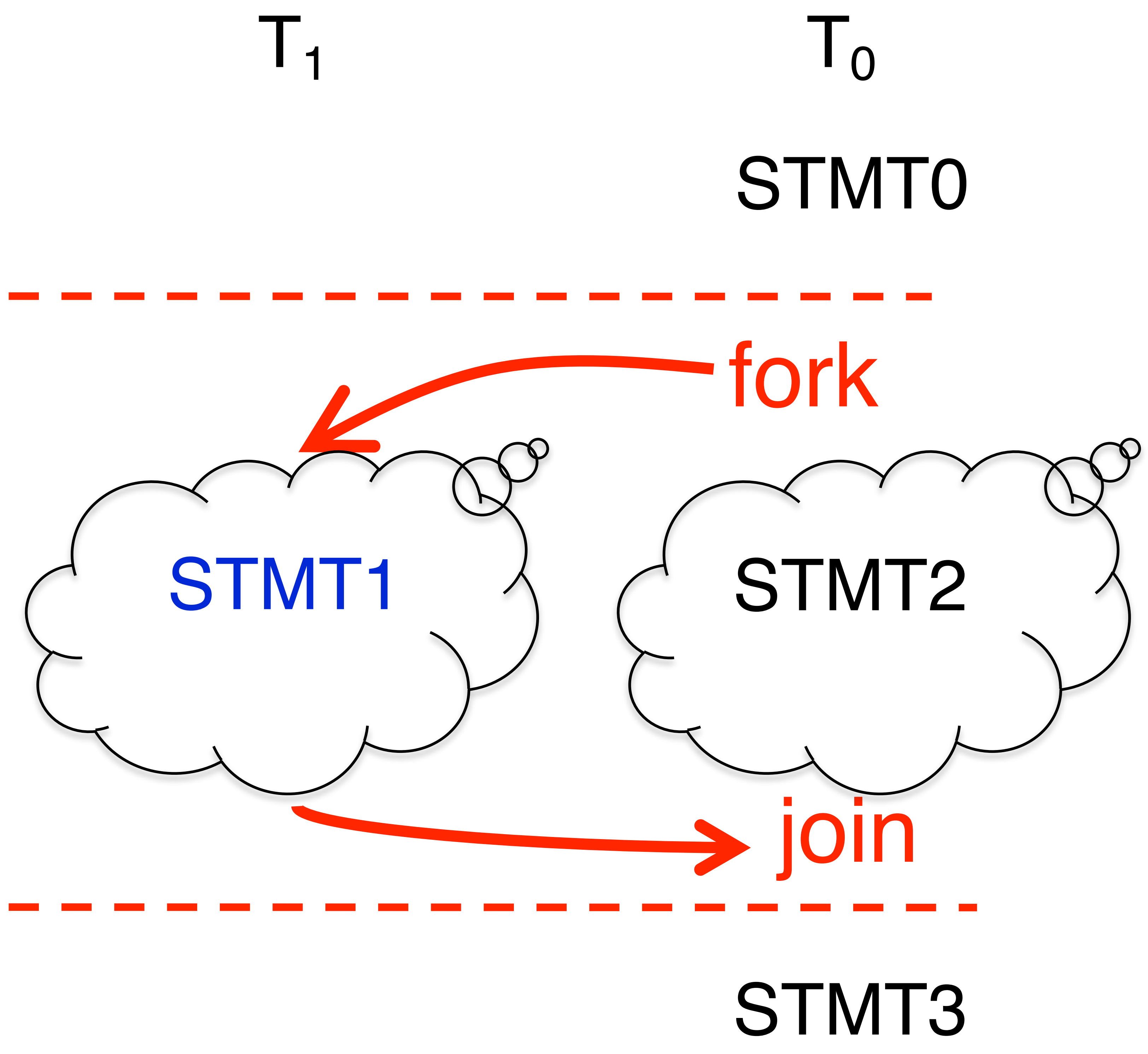
- Creates a new child task that executes statement S

```
// T0(Parent task)
STMT0;
finish {   //Begin finish
  async {
    STMT1; //T1(Child task)
  }
  STMT2;   //Continue in T0

}          //End finish (wait for T1)
STMT3;     //Continue in T0
```

**finish S**

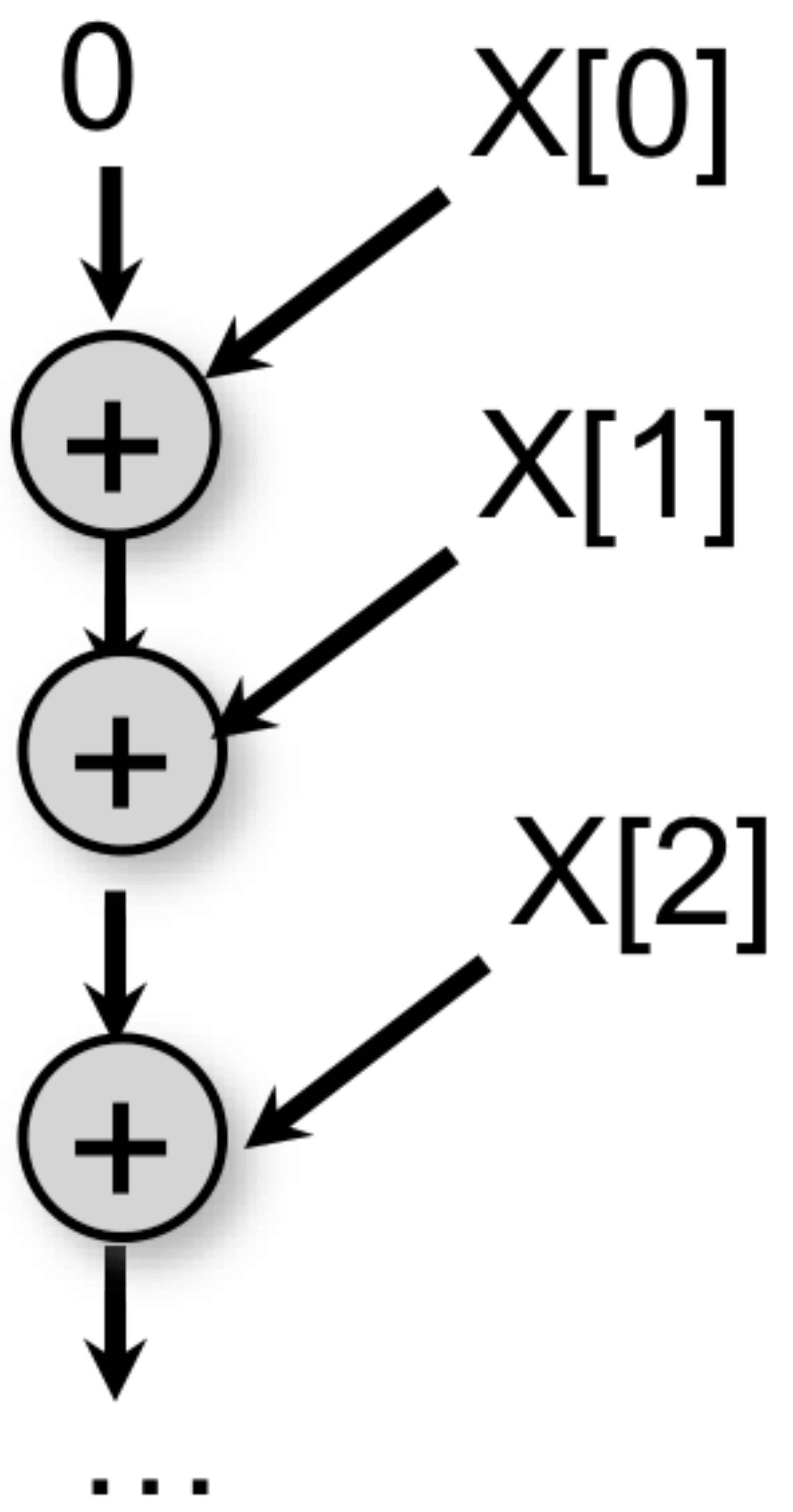
- Execute S, but wait until *all* asyncs in S's scope have terminated.



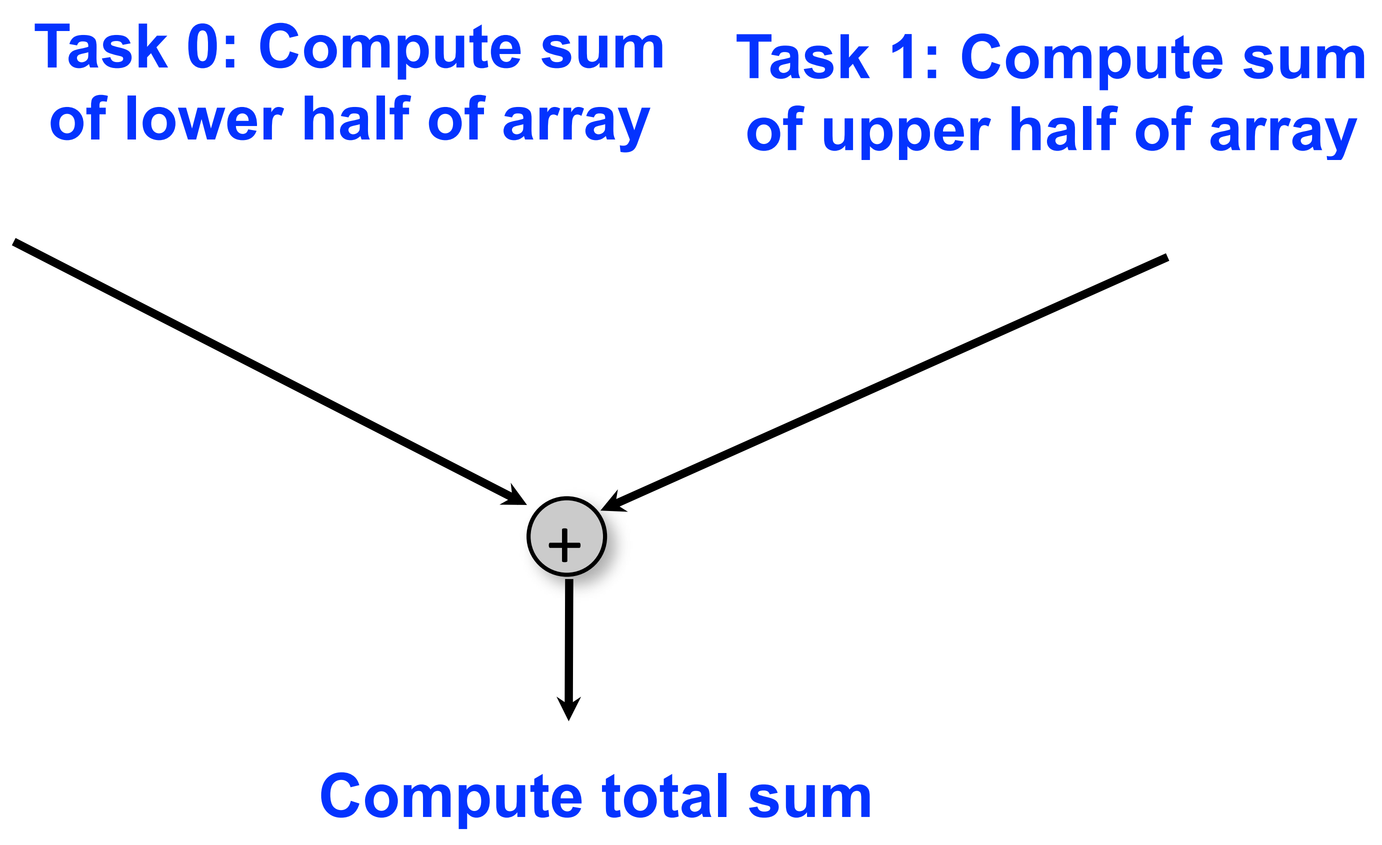
# Example of a Sequential Program: Computing sum of array elements

**Algorithm 1: Sequential ArraySum**

**Input**: Array of numbers, $X$.
**Output**: $sum$ = sum of elements in array $X$.
$sum \leftarrow 0$;
**for** $i \leftarrow 0$ **to** $X.length - 1$ **do**
  $sum \leftarrow sum + X[i]$;
**return** $sum$;



# Parallelization Strategy for 2 cores (Two-way Parallel Array Sum)




Basic idea:

- Decompose problem into two tasks for partial sums
- Combine results to obtain final answer
- Parallel divide-and-conquer pattern

# Two-way Parallel Array Sum using async & finish constructs

**Algorithm 2: Two-way Parallel ArraySum**

**Input**: Array of numbers, $X$.
**Output**: $sum$ = sum of elements in array $X$.

```
// Start of Task T1 (main program)
sum1 ← 0; sum2 ← 0;
// Compute sum1 (lower half) and sum2 (upper half) in parallel.
finish{
    async{
        // Task T2
        for i ← 0 to X.length/2 − 1 do
            sum1 ← sum1 + X[i];
    };
    async{
        // Task T3
        for i ← X.length/2 to X.length − 1 do
            sum2 ← sum2 + X[i];
    };
};
// Task T1 waits for Tasks T2 and T3 to complete
// Continuation of Task T1
sum ← sum1 + sum2;
return sum;
```

# Two-way Parallel Array Sum using async & finish constructs

**Algorithm 2: Two-way Parallel ArraySum**

**Input**: Array of numbers, $X$.
**Output**: $sum$ = sum of elements in array $X$.

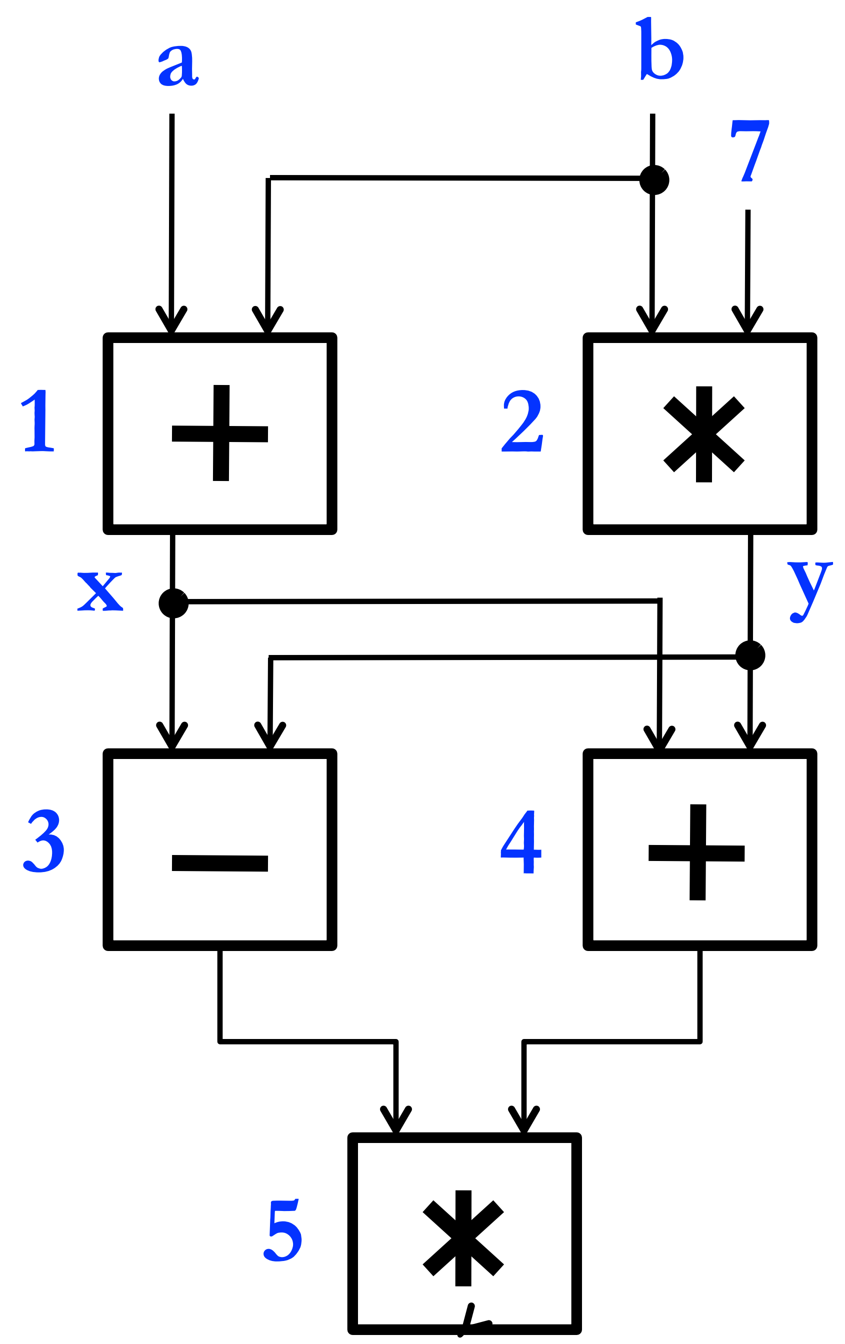
```
// Start of Task T1 (main program)
sum1 ← 0; sum2 ← 0;
// Compute sum1 (lower half) and sum2 (upper half) in parallel.
finish{
    async{
        // Task T2
        for i ← 0 to X.length/2 − 1 do
            sum1 ← sum1 + X[i];
    };
    async{
        // Task T3
        for i ← X.length/2 to X.length − 1 do
            sum2 ← sum2 + X[i];
    };
};
foo();
sum ← sum1 + sum2;
return sum;
```

# Two-way Parallel Array Sum using futures

```
// Parent Task T1 (main program)
// Compute sum1 (lower half) & sum2 (upper half) in parallel
var sum1 = future(() -> { // Future Task T2
     int sum = 0;
     for (int i = 0; i < X.length / 2; i++) sum += X[i];
     return sum;
});
var sum2 = future(() -> { // Future Task T3
     int sum = 0;
     for (int i = X.length / 2; i < X.length; i++) sum += X[i];
     return sum;
});
foo();
int total = sum1.get() + sum2.get();
```

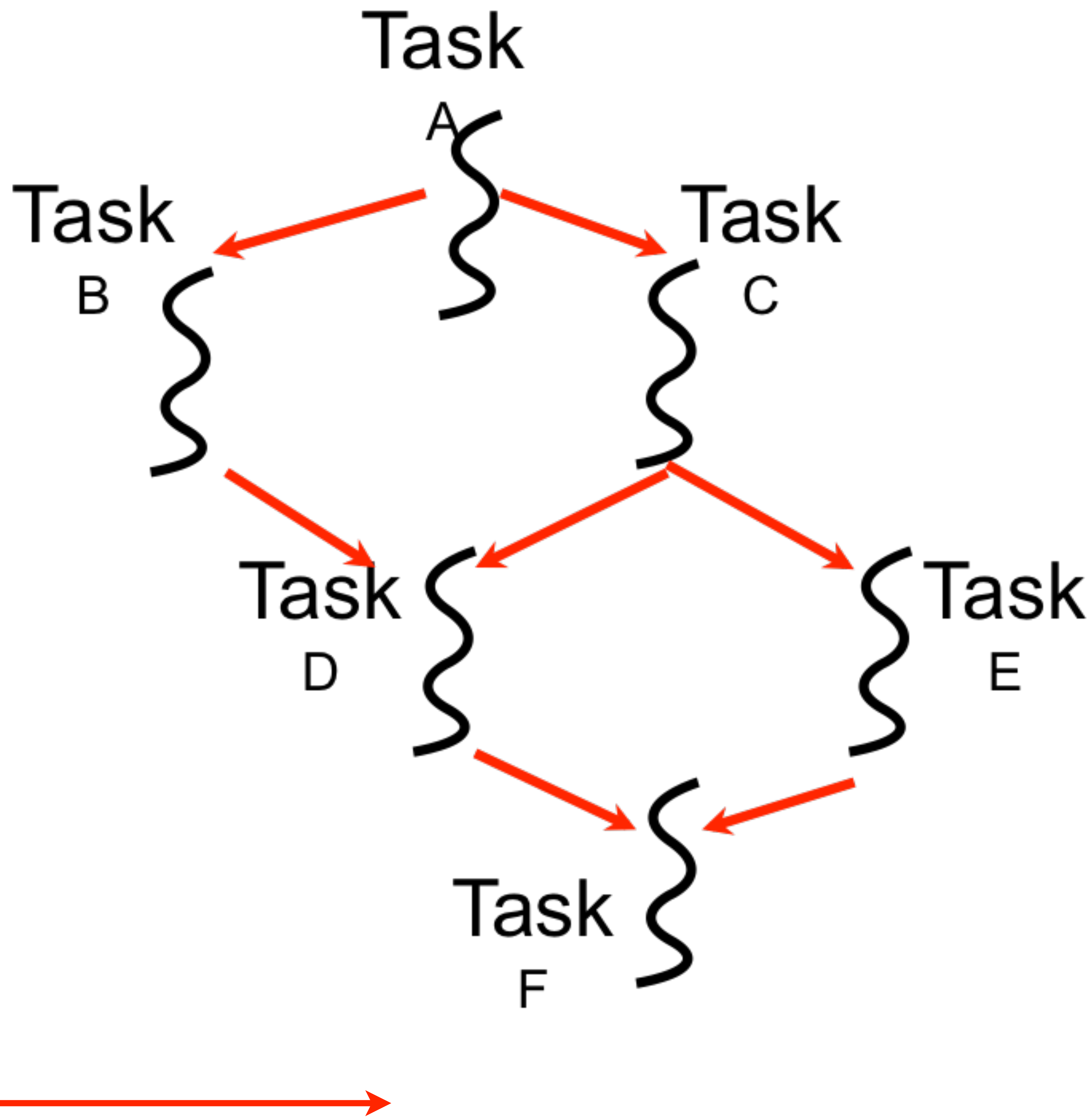
# Example instruction sequence and its dataflow graph

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




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

# Macro-Dataflow Programming




Communication via "single-assignment" variables

- "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 (like futures)
  - 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)

```
final HjDataDrivenFuture<T1> ddfA = newDataDrivenFuture();
```

- Allocate an instance of a data-driven-future object (container)
- Object in container must be of type T1, and can only be assigned once via put() operations
- HjDataDrivenFuture extends the HjFuture interface

```
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

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

asyncAwait(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”)
- Alternatively, you can pass a list to asyncAwait
- Await clause can be used to implement “nodes” and “edges” in a computation graph

ddfA.get()

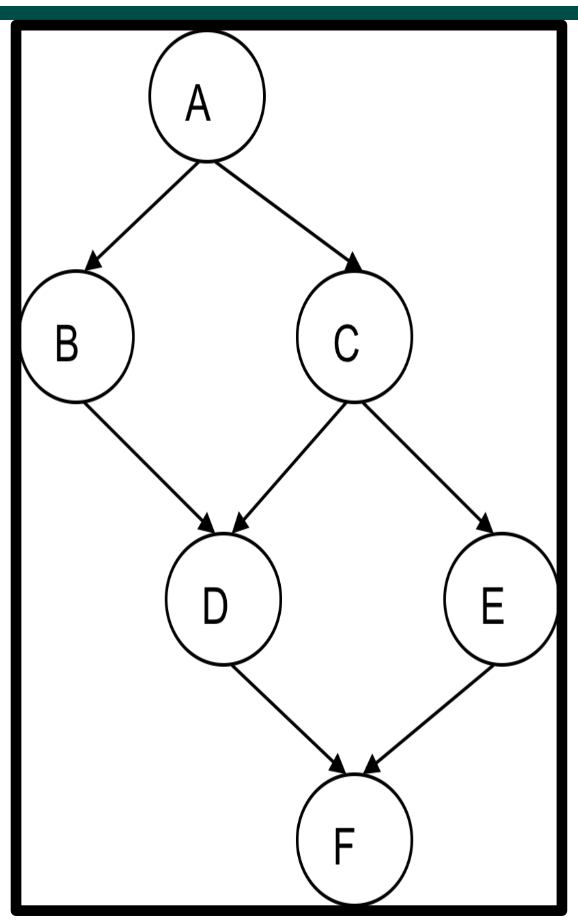
- Return value (of type T1) stored in ddfA
- Throws an exception if put() has not been performed

ddfA.safeGet()

- Doesn’t throw an exception
  - Should be performed by async’s that contain ddfA in their await clause, or if there’s some other synchronization to guarantee that the put() was performed

# Converting previous Future example to Data-Driven Futures and AsyncAwait Tasks

```
finish(() -> {
  final HjDataDrivenFuture<Void> ddfA = newDataDrivenFuture();
  final HjDataDrivenFuture<Void> ddfB = newDataDrivenFuture();
  final HjDataDrivenFuture<Void> ddfC = newDataDrivenFuture();
  final HjDataDrivenFuture<Void> ddfD = newDataDrivenFuture();
  final HjDataDrivenFuture<Void> ddfE = newDataDrivenFuture();
  asyncAwait(ddfA, () -> { ... ;  ddfB.put(…); }); // Task B
  asyncAwait(ddfA, () -> { ... ;  ddfC.put(…); }); // Task C
  asyncAwait(ddfB, ddfC, ()->{ ... ; ddfD.put(…); }); // Task D
  asyncAwait(ddfC, () -> { ... ;  ddfE.put(…); }); // Task E
  asyncAwait(ddfD, ddfE, () -> { ... }); // Task F
  // Note that creating a "producer" task after its "consumer"
  // task is permitted with DDFs & DDTs, but not with futures
  async(() -> { ... ; ddfA.put(…); }); // Task A
}); // finish
```



# What is Deadlock?

- A parallel program execution contains a deadlock if some task's execution remains incomplete due to it being *blocked indefinitely* awaiting some condition
- Example of a program with a deadlocking execution

```
final HJDataDrivenFuture<Object> left = newDataDrivenFuture();
final HJDataDrivenFuture<Object> right = newDataDrivenFuture();
finish {
  asyncAwait ( left ) right.put(rightBuilder()); // Task1
  asyncAwait ( right ) left.put(leftBuilder()); // Task2
}
```

- In this case, Task1 and Task2 are in a deadlock cycle.
- HJ-Lib has a deadlock detection debug option, which can be enabled as follows:
  - System.setProperty(HjSystemProperty.trackDeadlocks.propertyKey(), "true");
  - Throws an edu.rice.hj.runtime.util.DeadlockException when deadlock detected

# Implementing Future Tasks using DDTs

- Future version

```
var f = future(() -> { return g(); });
S1
async(() -> {
  ... = f.get(); // blocks if needed
  S2;
  S3;
});
```

- DDT version

```
var f = newDataDrivenFuture();
async(() -> { f.put(g()) });
S1
asyncAwait(f, () -> {
  ... = f.safeGet(); // does not need to block -- why?
  S2;
  S3;
});
```

# Differences between Futures and DDTs

- Consumer task blocks on get() for each future that it reads, whereas async-await does not start execution till all futures are available
- Future tasks cannot deadlock, but it is possible for a DDT to block indefinitely ("deadlock") if one of its input futures never becomes available
- DDTs and DDFs are more general than futures
  - Producer task can only write to a single future object, whereas 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
  - Consumer DDTs can be created before the producer tasks
- DDTs and DDFs can be implemented more efficiently than futures
  - An "asyncAwait" statement does not block the worker, unlike a future.get()

# Two Exception (error) cases for DDFs that cannot occur with 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 (cannot be reproduced with futures)

- A parallel program execution contains a deadlock if some task's execution remains incomplete due to it being *blocked indefinitely* awaiting some condition

```
var left = newDataDrivenFuture();
var right = newDataDrivenFuture();
finish(() -> {
  asyncAwait(left, () -> {
     right.put(rightWriter()); });
  asyncAwait(right, () -> {
     left.put(leftWriter()); });
});
```

**Can you think of a deadlock example or explain why it can't happen?**

- HJ-Lib has deadlock detection mode
- Enabled using:
  - System.setProperty(HjSystemProperty.trackDeadlocks.propertyKey(), "true");
  - Throws an edu.rice.hj.runtime.util.DeadlockException when deadlock detected

# Announcements & Reminders

- Regular office hour schedule can be found at Office Hours link on course web site
- Hw #1 is due Friday, Feb. 4th by 11:59pm
- Quiz #2 is due Sunday, Feb. 6th by 11:59pm