COMP 322: Fundamentals of Parallel Programming

Lecture 7: Memory Models (contd), Futures --- Tasks with Return Values

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Goals for Today's Lecture

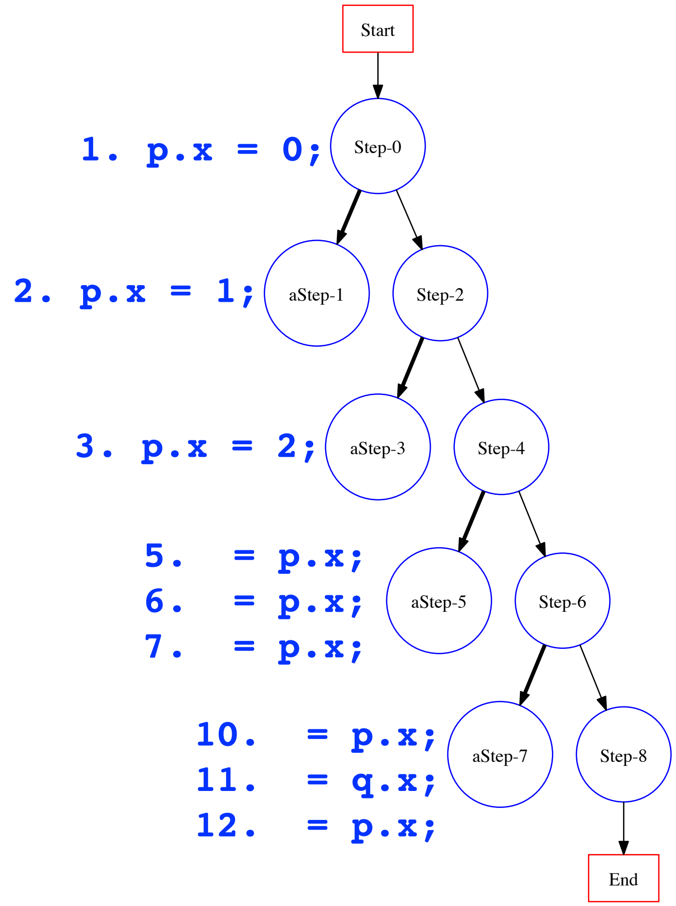
- <u>Code Transformations and Memory Consistency Models</u>
- Futures --- Tasks with Return Values

Memory Consistency Models (Recap)

- A memory consistency model, or <u>memory model</u>, is the part of a programming language specification that defines what write values a read may see in the presence of data races.

<u>Example HJ program:</u>

```
1.  p.x = 0; q = p;
2.  async p.x = 1; // Task T1
3.  async p.x = 2; // Task T2
4.  async { // Task T3
5.    System.out.println("First read = " + p.x);
6.    System.out.println("Second read = " + p.x);
7.    System.out.println("Third read = " + p.x)
8.  }
9.  async { // Task T4
10.   System.out.println("First read = " + p.x);
11.   System.out.println("Second read = " + q.x);
12.   System.out.println("Third read = " + p.x);
13. }
```

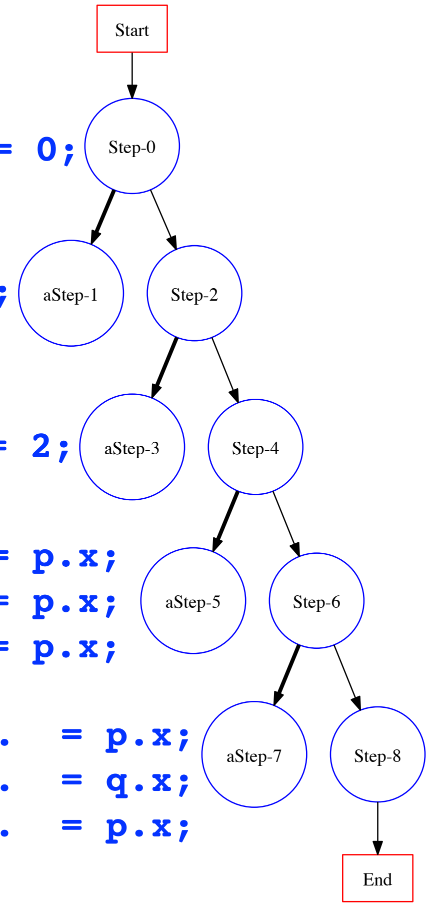


Memory Consistency Models (Recap)

- A memory consistency model, or <u>memory model</u>, is the part of a programming language specification that defines what write values a read may see in the presence of data races.

The following reads are prohibited by Sequential Consistency (SC), but permitted by the Java Memory Model (JMM) and Habanero-Java Memory Model (HJMM)

```
1. p.x = 0;
2. p.x = 1;
3. p.x = 2;
0    5.  = p.x;
0    6.  = p.x;
0    7.  = p.x;
1    10.  = p.x;
2    11.  = q.x;
1    12.  = p.x;
```



Semantics-Preserving Code Transformations in Sequential Programs

- A Code Transformation is said to be semantics-preserving if the transformed program, P', exhibits the same Input-Output behavior as the original program, P
- For <u>sequential</u> programs, many local transformations are guaranteed to be semantics-preserving regardless of the context
  - e.g., replacing the second access of an object field or array element by a local variable containing the result of the first access, if there are no possible updates between the two accesses

P

```
static void foo(T p, T q) {
  System.out.println(p.x);
  System.out.println(q.x);
  System.out.println(p.x);
}
```

P'

```
static void foo(T p, T q) {
  int xLocal = p.x
  System.out.println(xLocal);
  System.out.println(q.x);
  System.out.println(xLocal);
}
```

Semantics-Preserving Code Transformations in Parallel Programs

- **Question:** What should we expect if we perform a Code Transformation on a sequential region of a parallel program, if the transformation is knoen to be semantics-preserving for sequential programs?
- **Answer:** The transformation should be semantics-preserving for the parallel program if there are no data races. Otherwise, it depends on the memory model!

P

```
p.x = 0; q = p;
async p.x = 1;
async p.x = 2;
async foo(p, p);
async foo(p, q);
. . .
static void foo(T p, T q) {
  System.out.println(p.x);
  System.out.println(q.x);
  System.out.println(p.x);
}
```

Is this a legal transformation?

It may result in the following output:
0 0 0
1 2 1

P'

```
p.x = 0; q = p;
async p.x = 1;
async p.x = 2;
async foo(p, p);
async foo(p, q);
. . .
static void foo(T p, T q) {
  int xLocal = p.x
  System.out.println(xLocal);
  System.out.println(q.x);
  System.out.println(xLocal);
}
```

==> Code transformation is legal for JMM & HJMM, but not for SC !

Summary of Memory Model Discussion

- Memory model specifies rules for what write values can be seen by reads in the presence of data races
  - In the absence of data races, program semantics specifies exactly one write for each read
- A local code transformation performed on a sequential code region may be semantics-preserving for sequential programs, but not necessarily for parallel programs
  - Stronger memory models (e.g., SC) are more restrictive about permissible read sets than weaker memory models (e.g., JMM, HJMM), and thus more restrictive about allowing transformations
- Different memory models are appropriate for different levels of the software stack
  - e.g., SC at the OS/HW level, JMM at the thread level, HJMM at the task level

HJMM
JMM
SC

Goals for Today's Lecture

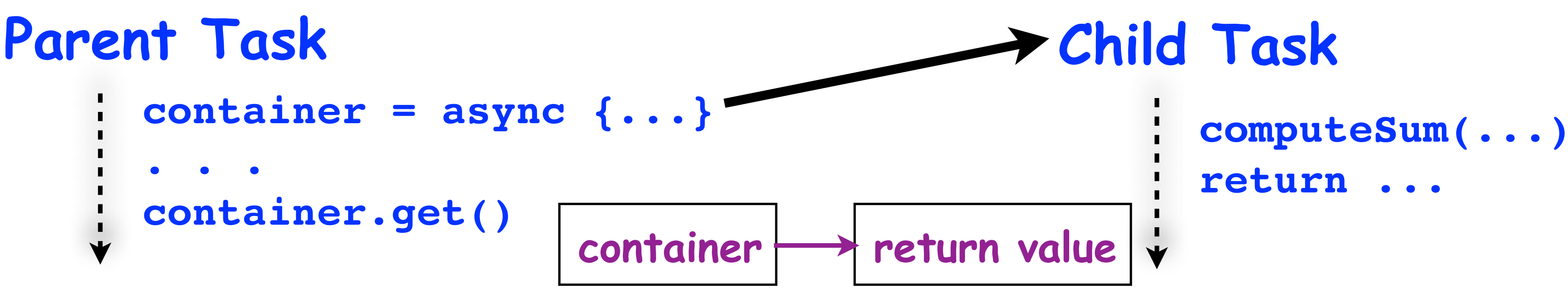
- Code Transformations and Memory Consistency Models
- Futures --- Tasks with Return Values

Extending Async Tasks with Return Values

- Example Scenario in PseudoCode

```
// Parent task creates child async task
container = async<int>  { return computeSum(X, low, mid); };
. . .
// Later, parent examines the return value
int sum = container.get();
```

- Two key issues to be addressed:
  1) Distinction between container and value in container
  2) Synchronization to avoid race condition in container accesses



HJ Futures: Tasks with Return Values

`async<T> { <Stmt-Block> }`

- Creates a new child task that executes Stmt-Block, which must terminate with a return statement returning a value of type T
- Async expression returns a reference to a container of type future<T>
- Values of type future<T> can only be assigned to final variables

`Expr.get()`

- Evaluates Expr, and blocks if Expr's value is unavailable
- Expr must be of type future<T>
- Return value from Expr.get() will then be T
- Unlike finish which waits for all tasks in the finish scope, a get() operation only waits for the specified async expression

Example: Two-way Parallel Array Sum using Future Tasks

```
// Parent Task T1 (main program)
// Compute sum1 (lower half) and sum2 (upper half) in parallel
final future<int> sum1 = async<int> { // Future Task T2
  int sum = 0;
  for(int i=0 ; i < X.length/2 ; i++) sum += X[i];
  return sum;
}; //NOTE: semicolon needed to terminate assignment to sum1
final future<int> sum2 = async<int> { // Future Task T3
  int sum = 0;
  for(int i=X.length/2 ; i < X.length ; i++) sum += X[i];
  return sum;
}; //NOTE: semicolon needed to terminate assignment to sum2
//Task T1 waits for Tasks T2 and T3 to complete
int total = sum1.get() + sum2.get();
```

Why are these semicolons needed?

Future Task Declarations and Uses

- Variable of type future<T> is a reference to a future object
  - Container for return value of T from future task
  - The reference to the container is also known as a "handle"
- Two operations that can be performed on variable V1 of type future<T1> (assume that type T2 is a subtype of type T1):
  - Assignment: V1 can be assigned value of type future<T2>
  - Blocking read: V1.get() waits until the future task referred to by V1 has completed, and then propagates the return value
- Future task body must start with a type declaration, async<T1>, where T1 is the type of the task's return value
- Future task body must consist of a statement block enclosed in { } braces, terminating with a return statement

Comparison of Future Task and Regular Async Versions of Two-Way Array Sum

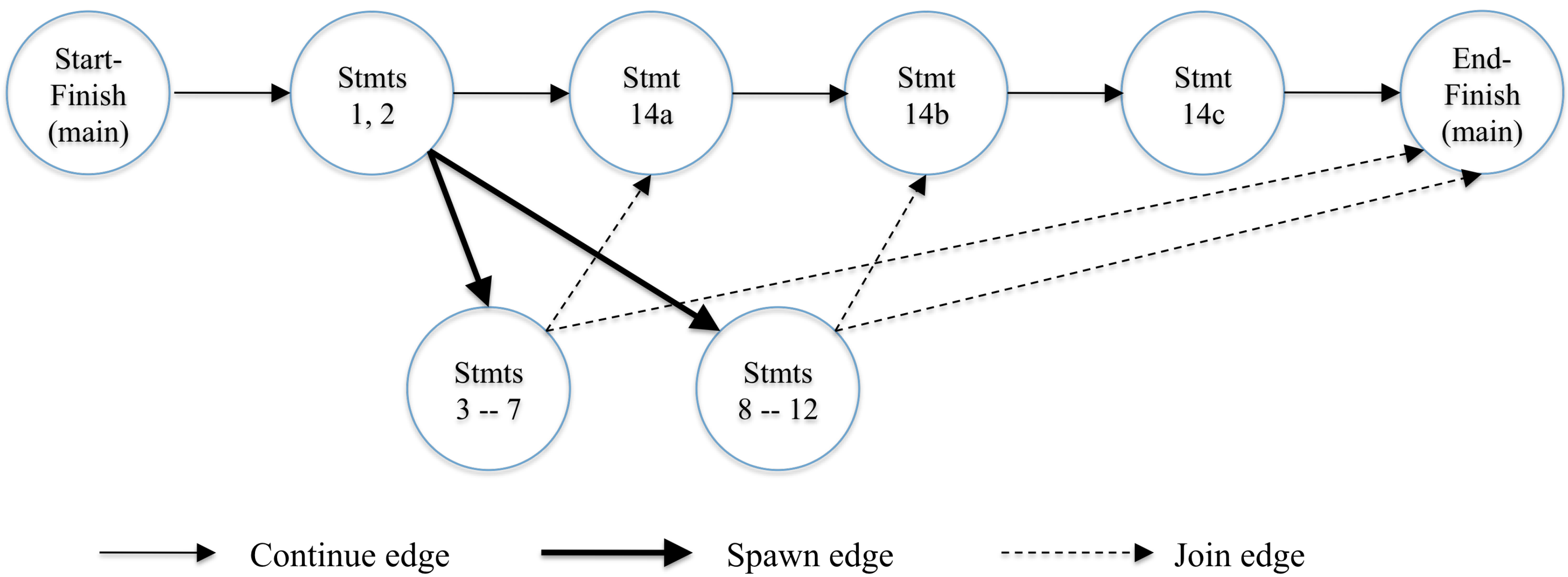
- Future task version initializes two references to future objects, sum1 and sum2, and both are declared as final
- No finish construct needed in this example
  - Instead parent task waits for child tasks by performing sum1.get() and sum2.get()
- Guaranteed absence of race conditions in Future Task example
  - No race on sum because it is a local variable in tasks T2 and T3
  - No race on future variables, sum1 and sum2, because of blocking-read semantics

Computation Graph Extensions for Future Tasks

- Since a get() is a blocking operation, it must occur on boundaries of CG nodes/steps
  - May require splitting a statement into sub-statements e.g.,
    - 14: int sum = sum1.get() + sum2.get();

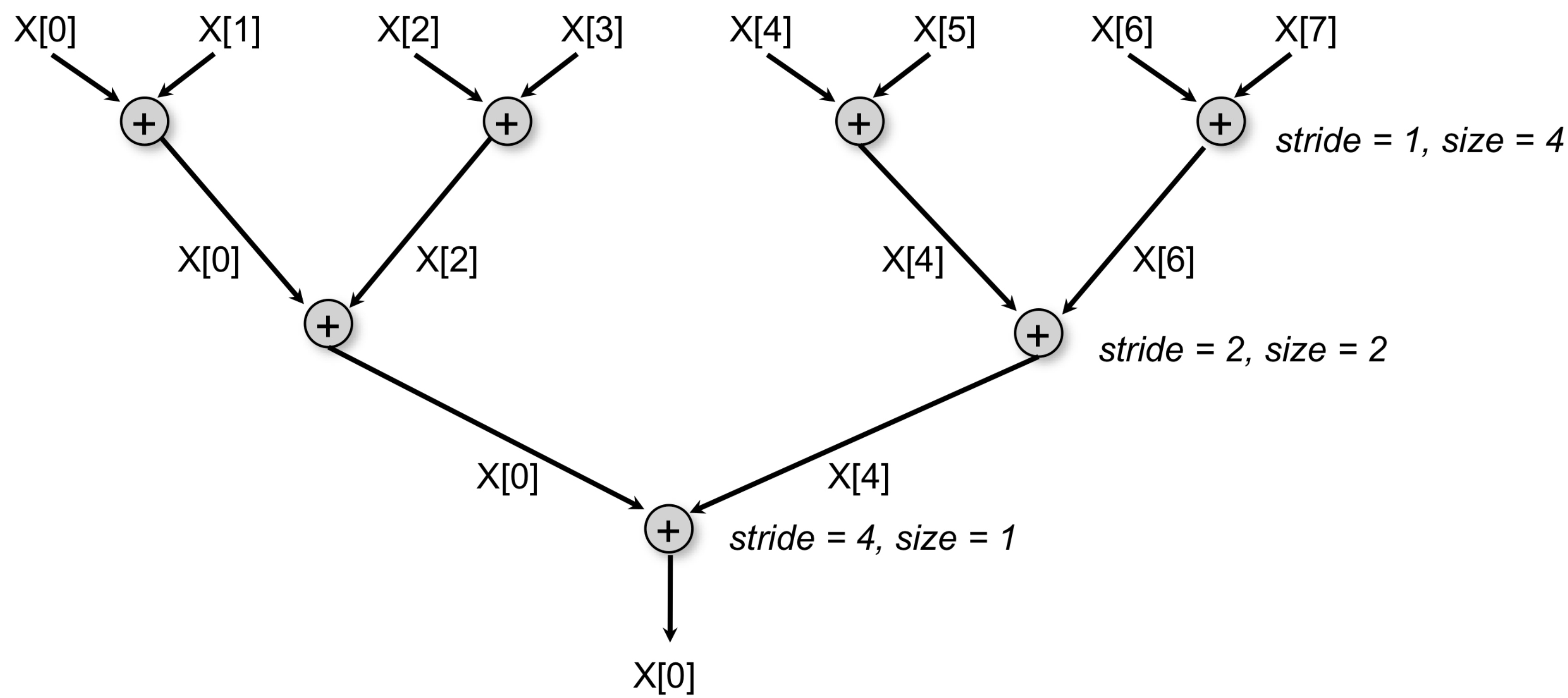
    can be split into three sub-statements
    - 14a int temp1 = sum1.get();
    - 14b int temp2 = sum2.get();
    - 14c int sum = temp1 + temp2;
- Spawn edge connects parent task to child future task, as before
- Join edge connects end of future task to Immediately Enclosing Finish (IEF), as before
- Additional join edges are inserted from end of future task to each get() operation on future object

Computation Graph for Two-way Parallel Array Sum using Future Tasks



NOTE: Generation of computation graphs and data race detection in current HJ implementation do not support futures as yet

Reduction Tree Schema in ArraySum1 (Recap)



Questions:

- How can we implement this schema using future tasks instead?
- Can we avoid overwriting elements of array X?

Array Sum using Future Tasks (ArraySum2)

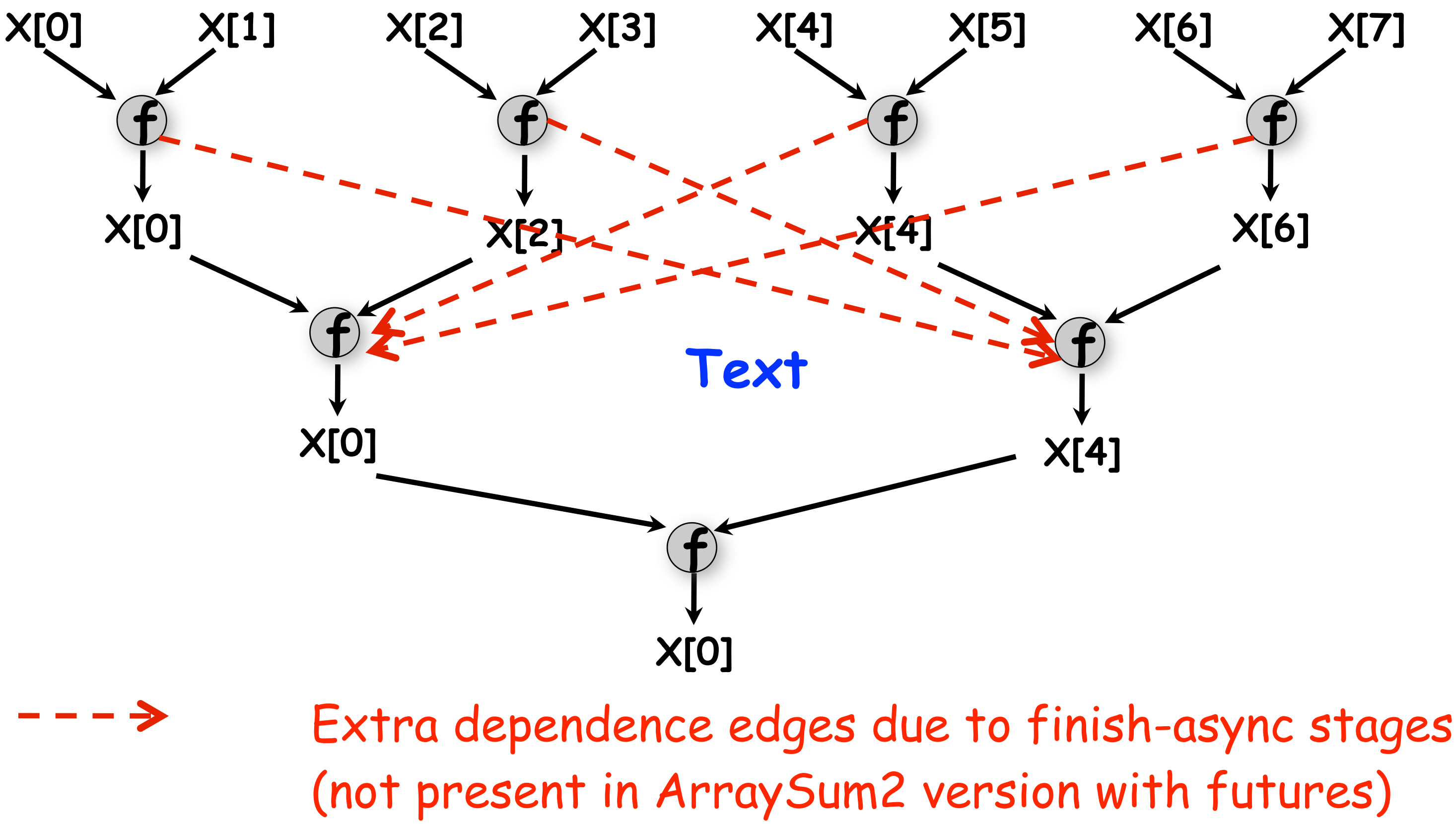
Recursive divide-and-conquer pattern

```
static int computeSum(int[] X, int lo, int hi) {
  if ( lo > hi ) return 0;
  else if ( lo == hi ) return X[lo];
  else {
    int mid = (lo+hi)/2;
    final future<int> sum1 =
          async<int> { return computeSum(X, lo, mid); };
    final future<int> sum2 =
         async<int> { return computeSum(X, mid+1, hi); };
   // Parent now waits for the container values
    return sum1.get() + sum2.get();
   }
 } // computeSum
int sum = computeSum(X, 0, X.length-1); // main program
```

Extension of ArraySum2 to reduce an arbitrary associative function, f

```
static int reduce(int[] X, int lo, int hi) {
  if ( lo > hi ) return identity();
  else if ( lo == hi ) return X[lo];
  else {
    int mid = (lo+hi)/2;
    final future<int> sum1 =
      async<int> {return computeSum(X, lo, mid);};
    final future<int> sum2 =
      async<int> {return computeSum(X, mid+1, hi);};
    return f(sum1.get(), sum2.get());
  }
} // computeSum
int retVal = reduce(X, 0, X.length-1); // main program
```

Extra dependences in ArraySum1 program (for-finish-for-async)



- **Which of ArraySum1 or ArraySum2 will perform better if the time taken by the reduction operator depends on its inputs e.g., as in WordCount ?**

Why must Future References be declared as final?

```
static future<int> f1=null;

static future<int> f2=null;


void main(String[] args) {

   f1 = async<int> {return a1();};

   f2 = async<int> {return a2();};
```

```
int a1() { // Task T1
 while (f2 == null); // spin loop
  return f2.get(); //T1 waits for T2
}


int a2() { // Task T2
  while (f1 == null); // spin loop
  return f1.get(); //T2 waits for T1
}
```

cyclic wait condition

- Above situation cannot arise in HJ because f1 and f2 must be final
- Final declaration ensures that variable (handle) cannot be modified after initialization
- WARNING: such spin loops are an example of bad parallel programming practice in application code (they should only be used by expert systems programmers, and even then sparingly)
  - Their semantics depends on the memory model!

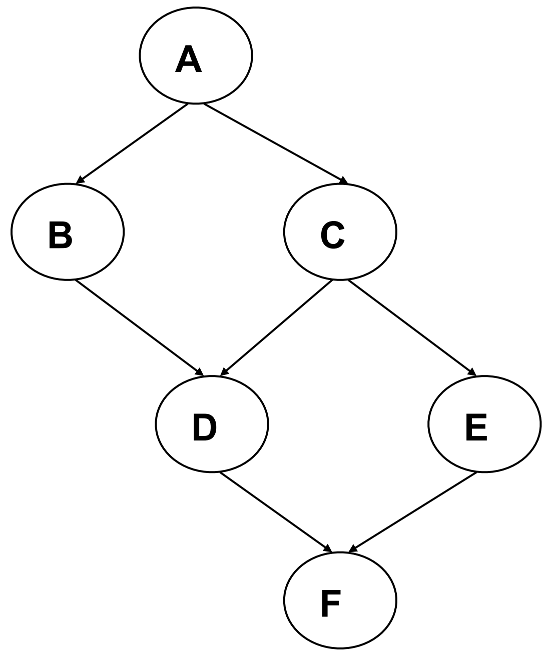
Future Tasks with void Return Type

- Key difference between regular async's and future tasks is that future tasks have a future<T> return value
- We can get an intermediate capability by setting T=void as shown
- Can be useful if a task needs to synchronize on a specific task (instead of finish), but doesn't need a future object to communicate a return value

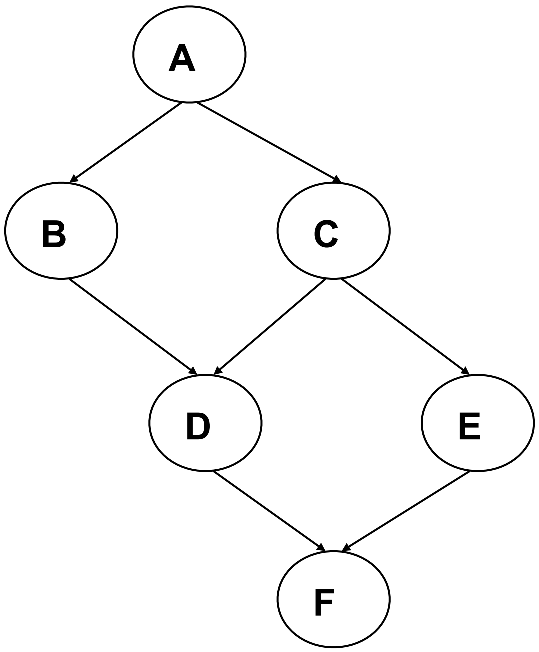
```
sum1 = 0; sum2 = 0; // Task T1
// Assume that sum1 & sum2 are fields
final future<void> a1 = async<void> {
  for (int i=0; i < X.length/2; i++)
    sum1 += X[i]; // Task T2
};
final future<void> a2 = async<void> {
  for (int i=X.length/2; i < X.length; i++)
    sum2 += X[i]; // Task T3
};
//Task T1 waits for Tasks T2 and T3
a1.get(); a2.get();
// Now fields sum1 and sum2 can be read
```

Future Tasks can generate more general Computation Graphs than regular Async Tasks

Can you write a finish-async HJ program that generates the following Computation Graph?



Using Future Tasks to generate previous Computation Graph



Computation Graph

```
// NOTE: return statement is optional
// when return type is void
final future<void> A = async<void>
                     { . . . };
final future<void> B = async<void>
                     { A.get(); . . . };
final future<void> C = async<void>
                     { A.get(); . . . };
final future<void> D = async<void>
                     { B.get(); C.get(); . . . };
final future<void> E = async<void>
                     { C.get(); . . . };
final future<void> F = async<void>
                     { D.get(); E.get(); . . . }
```

Homework 2 Reminder

- Programming assignment, due Monday, Jan 30th
- Post questions on Piazza (preferred), or send email to comp322-staff at mailman.rice.edu
- You should plan to use turn-in script for HW2 submission
  - Contact teaching staff if you cannot access turn-in by following the instructions for Lab 1
- See course web site for penalties for late submissions