Lecture 05: Computation Graphs and Ideal Parallelism

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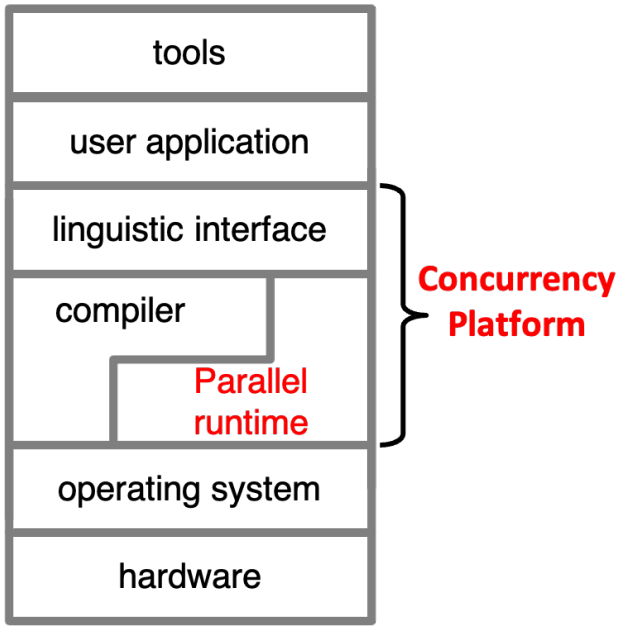
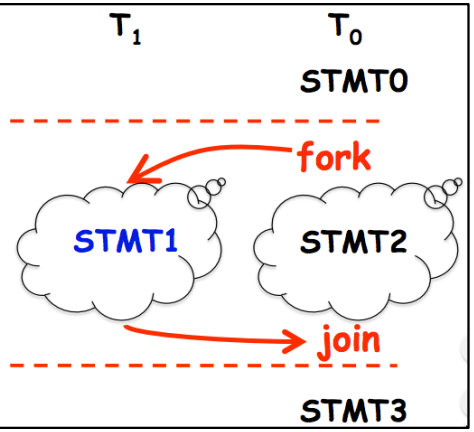
Last Lecture




```
finish {
        async { Wash your clothes in washing machine }
        async { Complete your MPPRS project deadline
}
finish {
        async { Watch movies on laptop }
        async { Talk to father
                Talk to mother }
        async { Buy fruits online using your smartphone }
        async { Make your bed }
}
Post on Facebook that you are done with all your tasks!
```

```
// T0 (Parent task)
STMT0;
finish {    //Begin finish
  async {
    STMT1; //T1 (Child task)
  }
  STMT2;    //Continue in T0
            //Wait for T1
}           //End finish
STMT3;      //Continue in T0
```



Today's Class

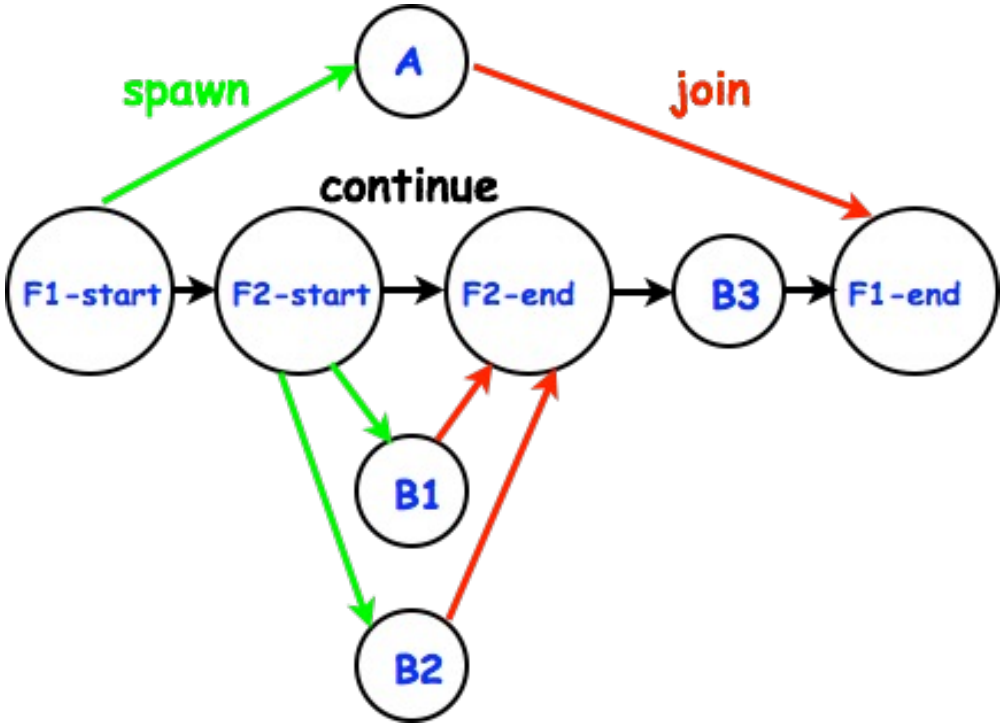
- Computation graph
  - Ideal parallelism
  - Introduction to data races
- Quiz-1

Which Statements can Potentially Execute in Parallel with Each Other?

```
finish {                // F1-start
    async A;
    finish {            // F2-start
        async B1;
        async B2;
    }                   // F2-end
    B3;
}                       // F1-end
```

Key idea: If two statements, X and Y, have *no path of directed edges* from one to the other, then they can run in parallel with each other.

Computation Graph



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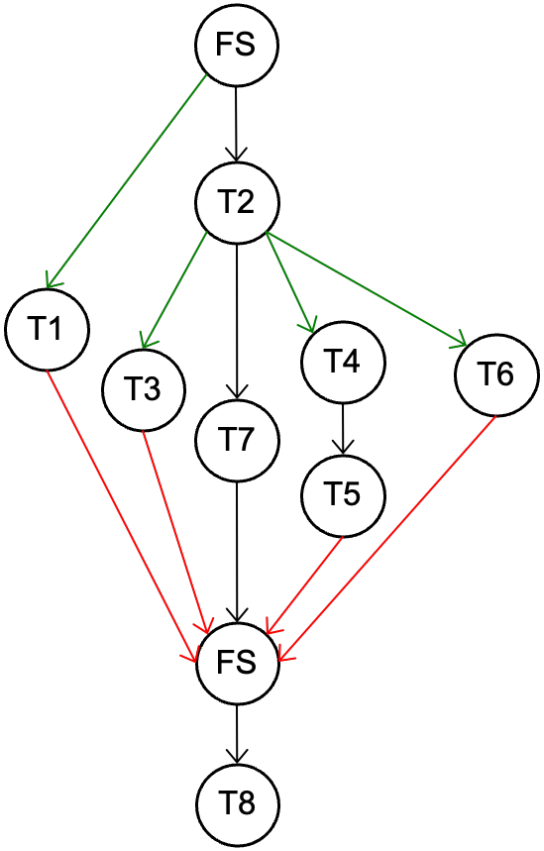
Question: Draw Computation Graph for this Parallel Computation

```
finish {                                                          // FS
    async { Wash your clothes in washing machine }                // T1
          Complete your MPPRS project deadline                    // T2
    async { Watch movies on laptop }                              // T3
    async { Talk to father                                        // T4
          Talk to mother }                                        // T5
    async { Buy fruits online using your smartphone }             // T6
          Make your bed                                           // T7
}                                                                 // FE
Post on Facebook that you are done with all your tasks!           // T8
```



Computation Graphs

- A Computation Graph (CG) captures the dynamic execution of a parallel program, for a specific input
- CG nodes are "steps" in the program's execution
  - A step is a sequential sub-computation without any async, begin-finish and end-finish operations
- CG edges represent ordering constraints
  - "Continue" edges define sequencing of steps within a task
    - Only one outgoing edge from a node
  - "Spawn" edges connect parent tasks to child async tasks
    - When there are more than one outgoing edge from a node (one of them must be a spawn)
  - "Join" edges connect the end of each async task to its IEF's end-finish operations
    - Incoming edge on a node
- All computation graphs must be acyclic
  - It is not possible for a node to depend on itself
- Computation graphs are examples of "directed acyclic graphs" (dags)

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Execution Time Analysis for Computation Graphs

Define

- TIME(N) = execution time of a node 'N'
- WORK(G) = sum of TIME(N), for all nodes 'N' in CG 'G'
  - WORK(G) is the total work to be performed in G
- CPL(G) = length of a longest path in CG 'G', when adding up execution times of all nodes in the path
  - Such paths are called *critical paths*
  - CPL(G) is the length of these paths (critical path length, also referred to as the ***span*** of the graph)
  - CPL(G) is also the smallest possible execution time for the computation graph

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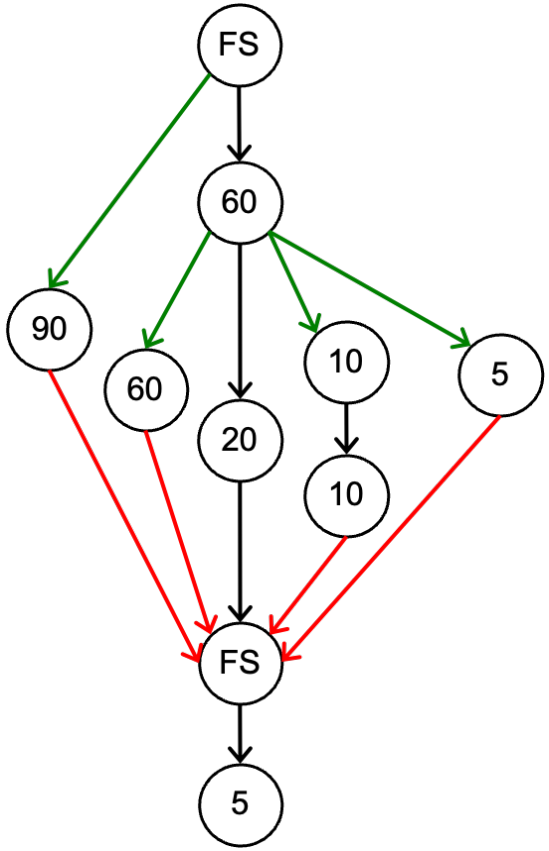
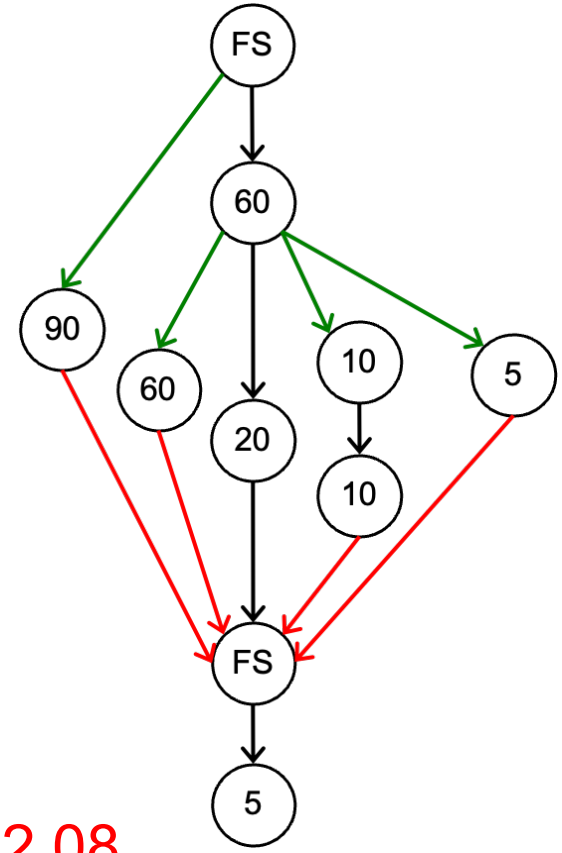
Question: What is the Critical Path Length of this Parallel Computation?

```
finish {                                                    // FS
    async { Wash your clothes in washing machine }          // T1
          Complete your MPPRS project deadline              // T2
    async { Watch movies on laptop }                        // T3
    async { Talk to father                                  // T4
          Talk to mother }                                  // T5
    async { Buy fruits online using your smartphone }       // T6
          Make your bed                                     // T7
}                                                           // FE
Post on Facebook that you are done with all your tasks!     // T8
```



Ideal Parallelism

- Define ideal parallelism of Computation G Graph as the ratio, WORK(G)/CPL(G)
- Ideal Parallelism only depends on the computation graph, and is the speedup that you can obtain with an unbounded number of processors



Example:

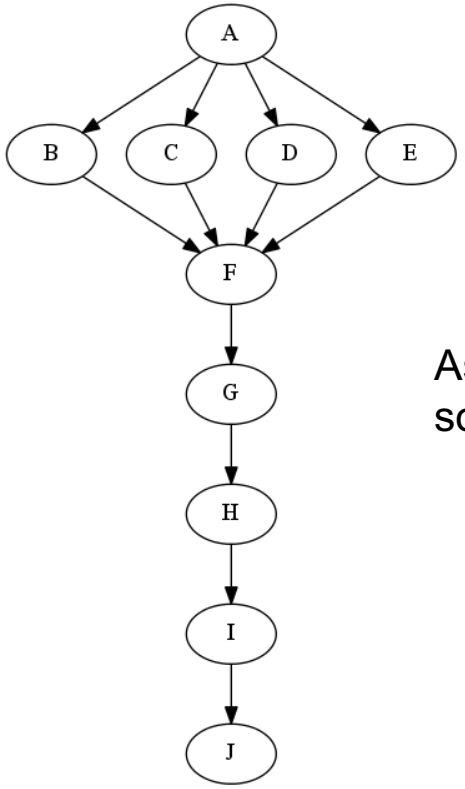
WORK(G) = 260

CPL(G) = 125

Ideal Parallelism = WORK(G)/CPL(G) = 260/125 ~ 2.08

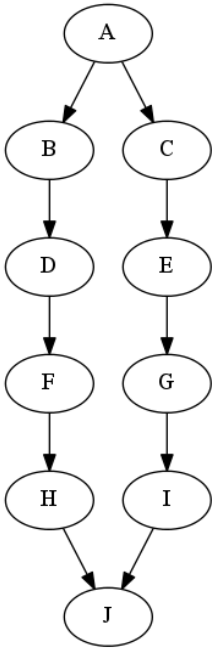
Question: Which Computation Graph has more Ideal Parallelism?

Computation Graph 1



Assume that all nodes have TIME = 1, so WORK = 10 for both graphs

Computation Graph 2



Data Races

- A data race occurs on location L in a program execution with computation graph CG if there exist steps (nodes) S1 and S2 in CG such that:
  1. S1 does not depend on S2 and S2 does not depend on S1, i.e., S1 and S2 can potentially execute in parallel, and
  2. Both S1 and S2 read or write L, and at least one of the accesses is a write.
- A data-race is usually considered an error. The result of a read operation in a data race is undefined. The result of a write operation is undefined if there are two or more writes to the same location.
  - Note that our definition of data race includes the case that both S1 and S2 write the same value in location L, even if that may not be considered an error.
- Above definition includes all "**potential**" data races i.e., we consider it to be a data race even if S1 and S2 end up executing on the same processor.

Question: Locate the Data Race Bug

```
...
double a[SIZE];
sum1 = sum2 = 0;

    async { for(int i=0; i<SIZE/2; i++) sum1 += a[i]; }
    async { for(int i=SIZE/2; i<SIZE; i++) sum2+=a[i]; }

double sum = sum1 + sum2;
```

Data race bug! Reads and writes can occur in parallel on sum1 and sum2, in this example!

ArraySum Example

```
...
double a[SIZE];
sum1 = sum2 = 0;
finish {
    async { for(int i=0; i<SIZE/2; i++) sum1 += a[i]; }
    async { for(int i=SIZE/2; i<SIZE; i++) sum2+=a[i]; }
}
double sum = sum1 + sum2; // Now gives correct result
```

In this situation, finish was able to resolve the Data Race..

How to Parallelize Matrix Multiplication ?

```
for (int i = 0 ; i < N ; i++)
  for (int j = 0 ; j < N ; j++)

      for (int k = 0 ; k < N ; k++)

        C[i][j] = C[i][j] + A[i][k] * B[k][j];
```

Is this a Correct Solution ?

```
finish {
  for (int i = 0 ; i < N ; i++)
    for (int j = 0 ; j < N ; j++)

        for (int k = 0 ; k < N ; k++)
              async {
          C[i][j] = C[i][j] + A[i][k] * B[k][j];
      } // async
} // finish
```

Data race bug! Reads and writes can occur in parallel on the same C[i][j] location, in this example!

One Possible Solution

```
finish {
  for (int i = 0 ; i < N ; i++)
    for (int j = 0 ; j < N ; j++)
      async {
        for (int k = 0 ; k < N ; k++)

          C[i][j] = C[i][j] + A[i][k] * B[k][j];
      } // async
} // finish
```

In this situation, by changing the position of async we are able to resolve the data race..

This program generates N2 parallel async tasks, one to compute each C[i][j] element of the output array.

What to do in Case of Valid Data Races that Cannot be Resolved with just async-finish ?

- We saw in Lecture 02 that we were able to resolve the data races between Pthreads by using pthread_mutex_locks/pthread_mutex_unlock
- It is perfectly legal to do this even in case of async-finish programs, but that's not productivity!
  - Highly prone to deadlocks and performance loss
  - In later lectures we will see a better way that provides both productivity and performance

Next Lecture

- Greedy scheduling of computation graphs