COMP 322: Fundamentals of Parallel Programming

Lecture 2: Computation Graphs, Ideal Parallelism

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Async and Finish Statements for Task Creation and Termination (Recap)

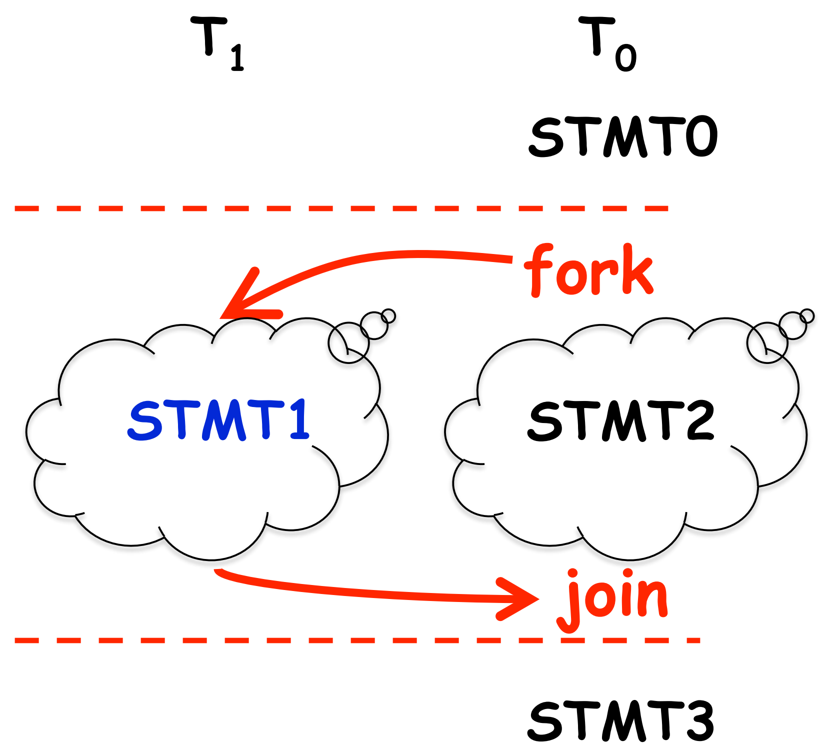
async S

- Creates a new child task that executes statement S

finish S

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

```
// 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
```



One Possible Solution to Worksheet 1 (Parallel Matrix Multiplication)

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

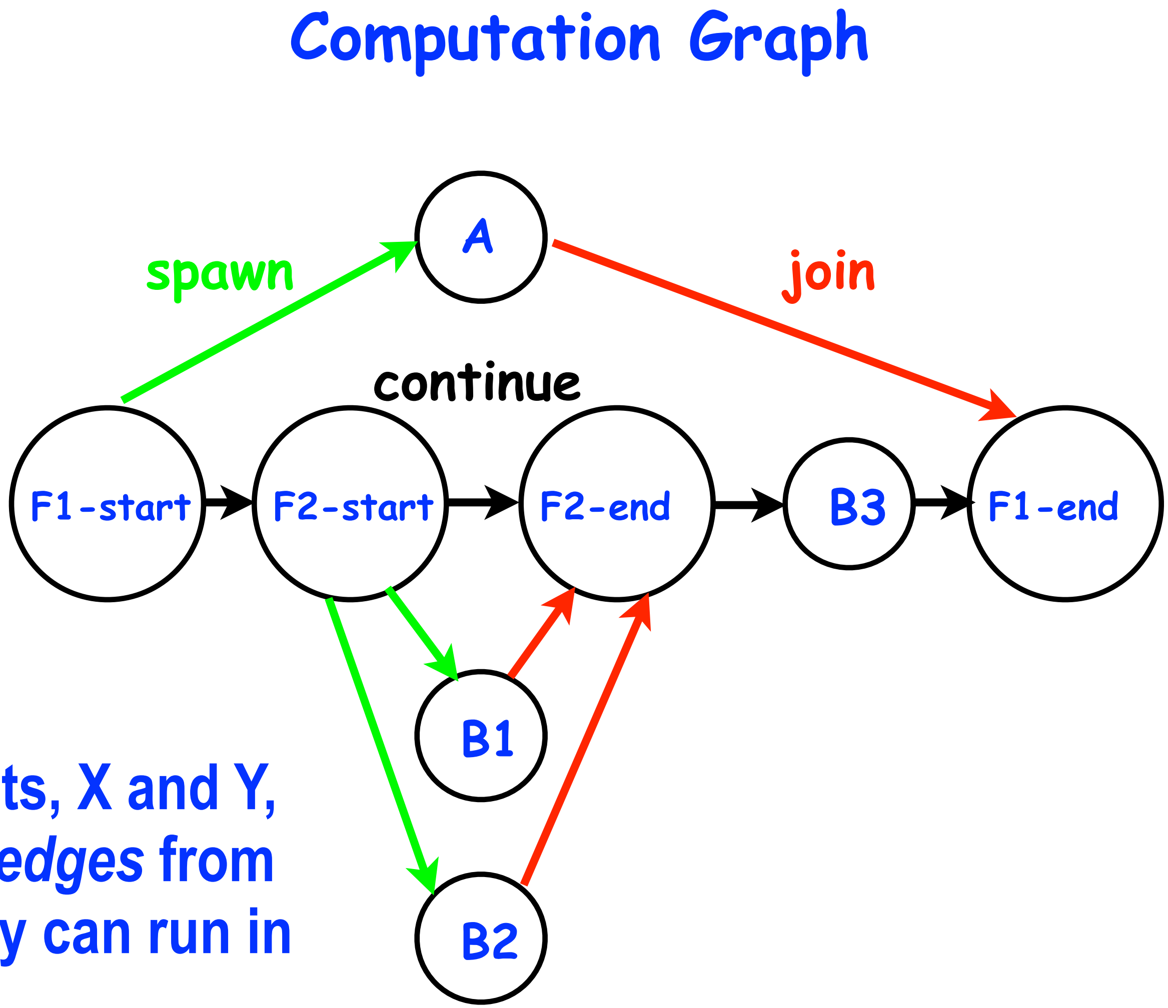
This program generates N^2 parallel async tasks, one to compute each C[i][j] element of the output array. Additional parallelism can be exploited within the inner k loop, but that would require more changes than inserting async & finish.

Is this a correct solution for Worksheet 1?

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

Which statements can potentially be executed in parallel with each other?

```
1.   finish { // F1
2.     async A;
3.     finish { // F2
4.       async B1;
5.       async B2;
6.     } // F2
7.     B3;
8.   } // F1
```



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 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 subcomputation without any async, begin-finish and end-finish operations
- CG edges represent ordering constraints
  — "Continue" edges define sequencing of steps within a task
  — "Spawn" edges connect parent tasks to child async tasks
  — "Join" edges connect the end of each async task to its IEF's end-finish operations
- 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)

Complexity Measures for Computation Graphs

Define

- TIME(N) = execution time of 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)
  - CPL(G) is also the smallest possible execution time for the computation graph

What is the critical path length of this parallel computation?

```
finish { // F1
  async A; // Boil pasta
  finish { // F2
    async B1; // Chop veggies
    async B2; // Brown meat
  } // F2
  B3; // Make pasta sauce
} // F1
```

Step B1

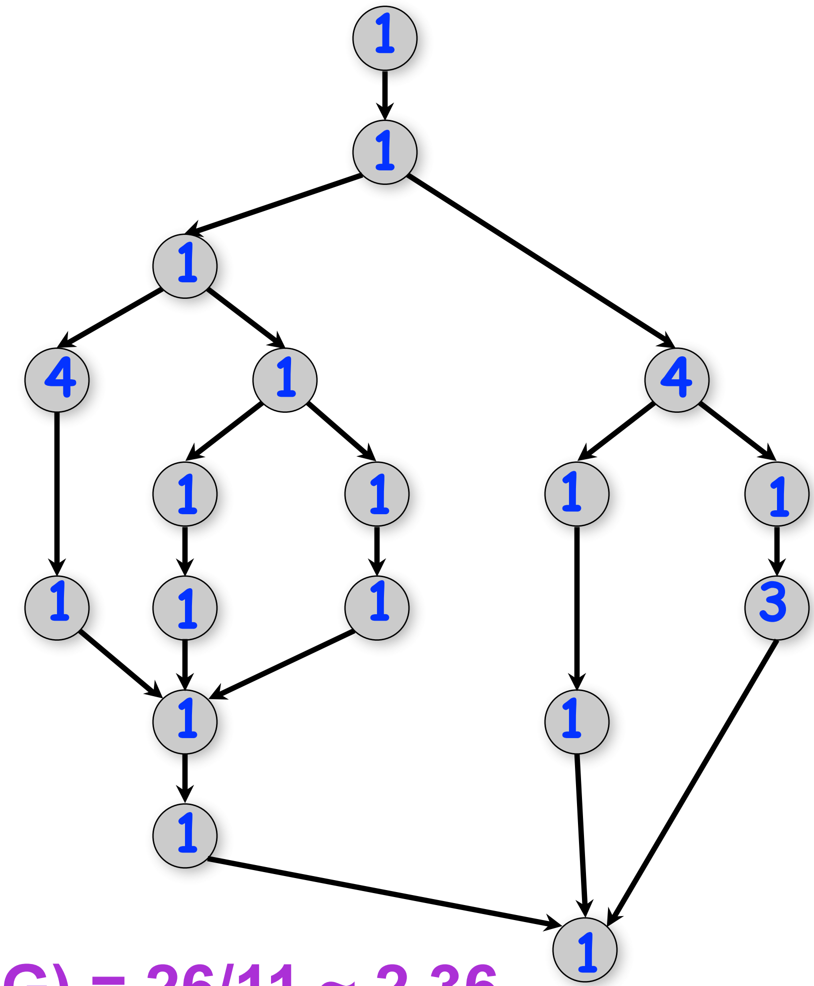
Step B2

Step B3

Step A

Ideal Parallelism

- Define ideal parallelism of Computation G Graph as the ratio, WORK(G)/CPL(G)
- Ideal Parallelism is independent of the number of processors that the program executes on, and only depends on the computation graph



__Example__:

WORK(G) = 26

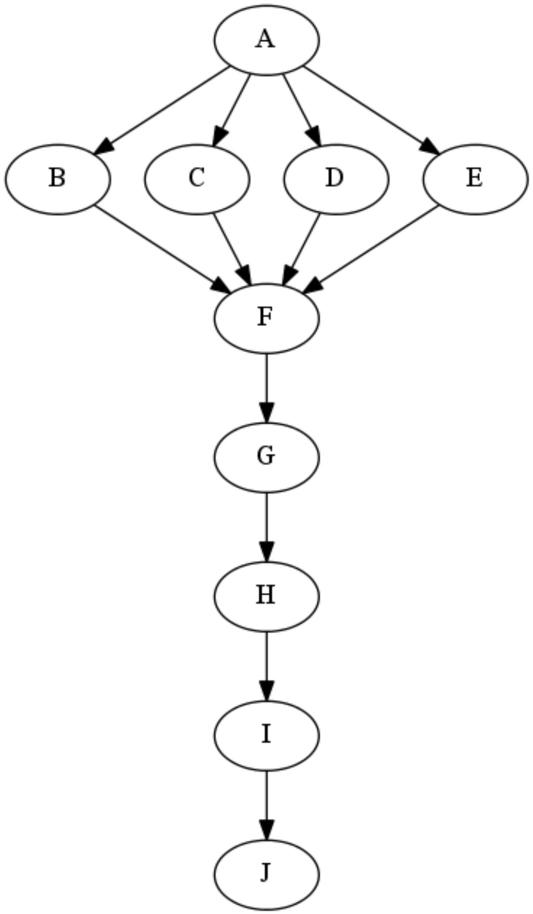
CPL(G) = 11

Ideal Parallelism = WORK(G)/CPL(G) = 26/11 ~ 2.36

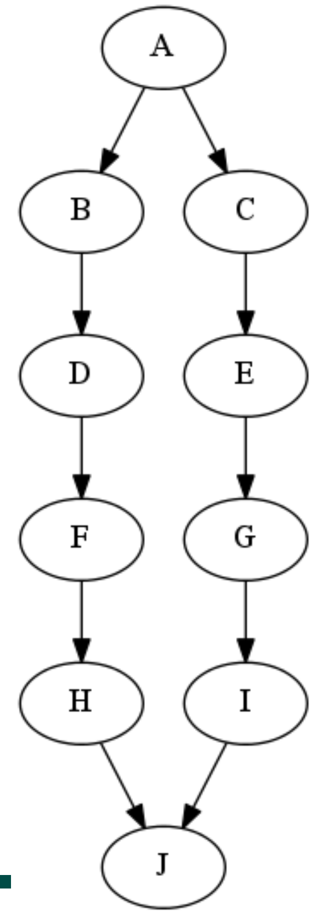
Which Computation Graph has more ideal parallelism?

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

Computation Graph 1



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 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.
- Above definition includes all "potential" data races i.e., we consider it to be a data race even if S1 and S2 execute on the same processor.

Reminders

- IMPORTANT:
  - Send email to comp322-staff@mailman.rice.edu if you did NOT receive a welcome email from us
    - Bring your laptop to this week's lab at 7pm TODAY (Section A01: DH 1064, Section A02: DH 1070)
  - Watch videos for topics 1.2 & 1.3 for next lecture on Wednesday
- Complete each week's assigned quizzes on edX by 11:59pm that Friday. This week, you should submit quizzes for lecture & demonstration videos for topics 1.1, 1.2, 1.3, 1.4
- HW1 will be assigned on Jan 16th and be due on Jan 28th
- See course web site for work assignments and due dates
  - https://wiki.rice.edu/confluence/display/PARPROG/COMP322

BACKUP SLIDES START HERE

String Search Problem

- **Inputs**
  - —text: a long string with N characters to search in
  - —pattern: a short string of M characters to search for
- **Output**
  - —Existence of an occurrence (boolean value)
- **Example**
  - —text: "abacadabrabracabracadababacadabrabracabracadabrabrabr"
  - —pattern: aca
  - —output: true (pattern found)
- **Applications**
  - —Word processing, virus scans, information retrieval, computational biology, web search engines, ...
- **Variations**
  - —Count of occurrences, index of any occurrence, indices of all occurrences

Brute Force Sequential Algorithm for String Search

```
public static boolean search(char[] pattern, char[] text) {
    int M = pattern.length; int N = text.length;
    boolean found = false;
    for (int i = 0; i <= N - M; i++) {
      int j; // search for pattern starting at text[i]
      for (j = 0; j < M; j++) {
        // Count each char comparison as 1 unit of work
        if (text[i+j] != pattern[j]) break;
      } // for (j = ... )
      if (j == M) found = true; // found at offset i
    }
    return found;
}
```

What is the complexity (work) of this algorithm?

Parallel Algorithm for String Search

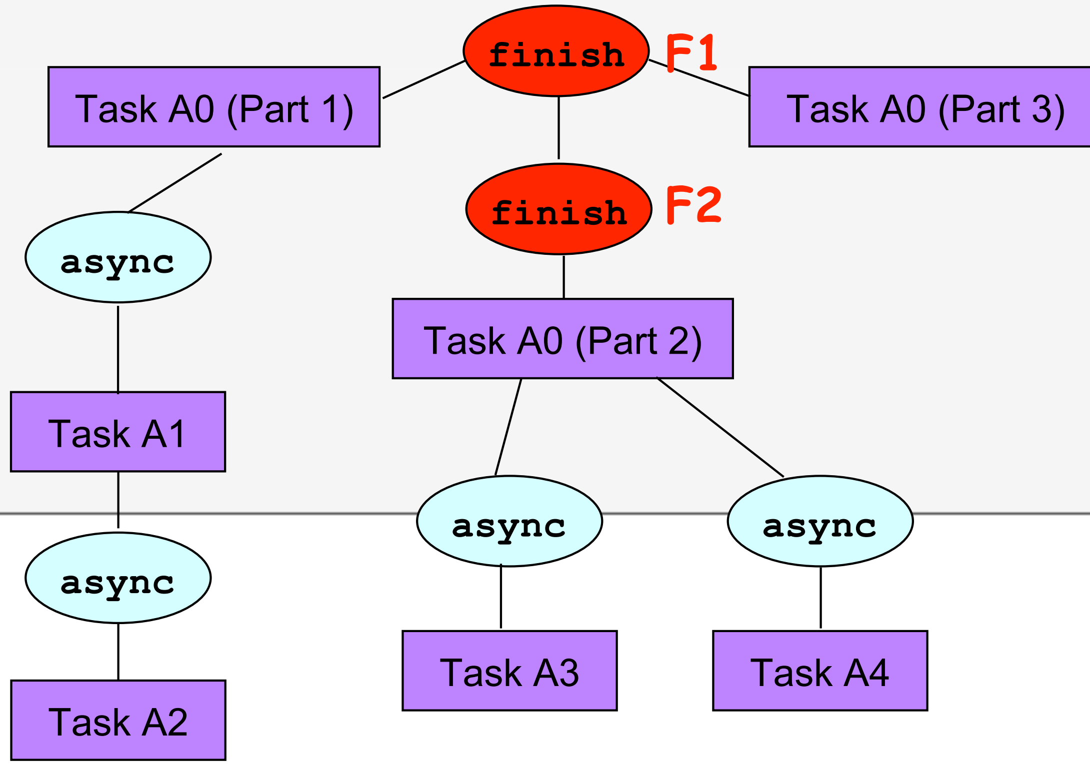
- Consider a parallel algorithm in which each i iteration is spawned as a separate async task
- For this above algorithm (assuming N >> M)
  - —WORK ~ M*N,
  - —CPL ~ M
  - —Ideal Parallelism ~ N
- Big-O notation: We say that a cost function Cost(n) is “order f(n)”, or simply “O(f (n))” (read “Big-O of f (n))”) if
  - —Cost(n) < factor * f (n), for sufficiently large n, for some constant factor
- If we consider M to be a constant in the String Search example then WORK = O(N), CPL = O(1), and Ideal Parallelism = O(N)

Course Announcements

- All Unit 1 lecture and demonstration quizzes are due by Jan 24th
  - Quizzes are still being uploaded into edX (see schedule on wiki)
- Homework 1 will be assigned on Jan 17th, and will be due on Jan 31st
- We will begin including programming exercises as in-class activities starting Jan 17th
  - Please bring laptops to class with HJlib set up for the exercises. Laptops can be shared within groups.
- Next week's schedule (Jan 20-24)
  - No lecture on Monday (MLK Jr Day)
  - No lab next week on Monday or Wednesday
  - We will have lectures on Wednesday & Friday as usual

Dynamic Finish-Async nesting structure and Immediately Enclosing Finish (IEF)

```
finish { // F1
  // Part 1 of Task A0
  async {A1; async A2;}
  finish { // F2
    // Part 2 of Task A0
    async A3;
    async A4;
  }
  // Part 3 of Task A0
}
```



- IEF(A3) = IEF(A4) = F2
- IEF(A1) = IEF(A2) = F1
- Module 1 handout: Listing 6 & Figure 7