COMP 322: Fundamentals of Parallel Programming

Lecture 3: Multiprocessor Scheduling

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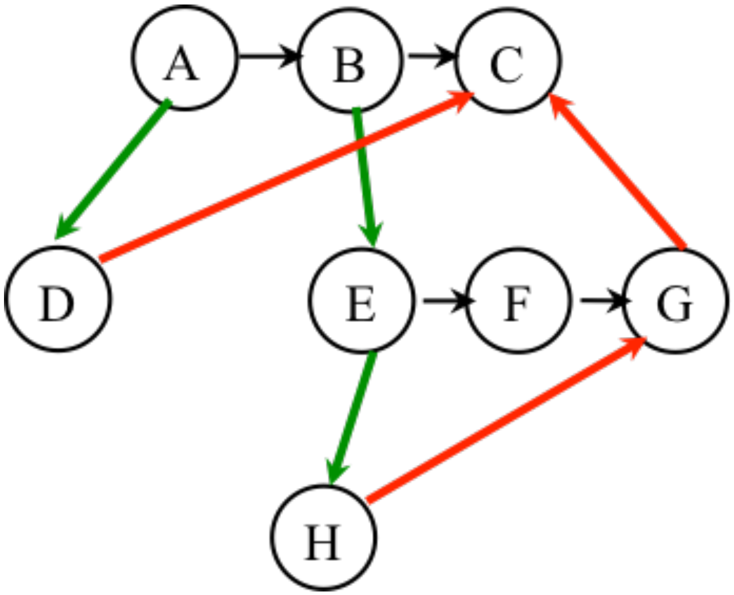
One Possible Solution to Worksheet 2 (Reverse Engineering a Computation Graph)




```
A();
finish { // F1
  async D();
  B();
  async {
    E();
    finish { // F2
      async H();
       F();
    } // F2
    G();
   }
} // F1
C();
```

Observations:

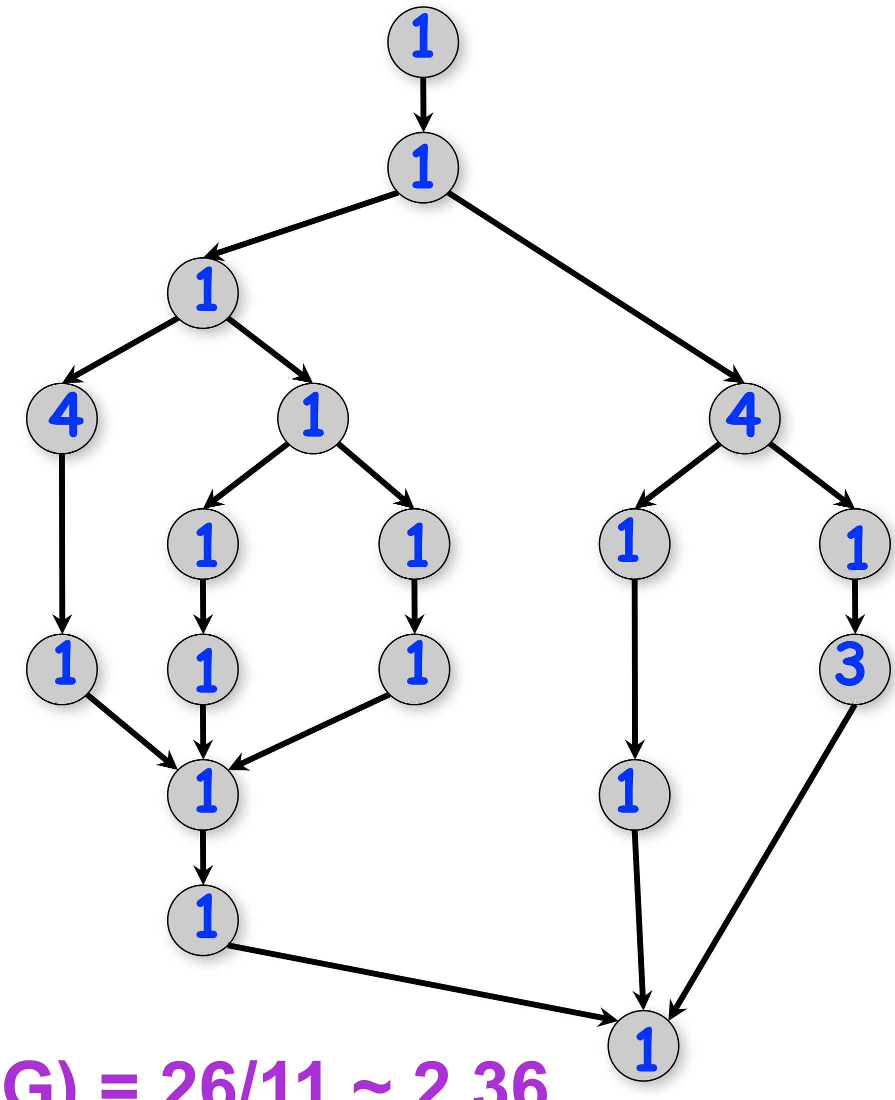
- Any node with out-degree > 1 must be an async (must have an outgoing spawn edge)
- Any node with in-degree > 1 must be an end-finish (must have an incoming join edge
- Adding or removing transitive edges does not impact ordering constraints

Ordering Constraints and Transitive Edges in a Computation Graph

- The primary purpose of a computation graph is to determine if an ordering constraint exists between two steps (nodes)
  - —Observation: Node A must be performed before node B if there is a path of directed edges from A and B
- An edge, X →Y, in a computation graph is said to be *transitive* if there exists a path of directed edges from X to Y that does not include the X →Y edge
  - —Observation: Adding or removing a transitive edge does not change the ordering constraints in a computation graph

Ideal Parallelism (Recap)

- Define ideal parallelism of Computation Graph G 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) = 26

CPL(G) = 11

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

What is the critical path length of this parallel computation?

```
finish { // F1
  async A; // Boil water & pasta (20)
  finish { // F2
    async B1; // Chop veggies (5)
    async B2; // Brown meat (10)
  } // F2
  B3; // Make pasta sauce (5)
} // F1
```

Step B1

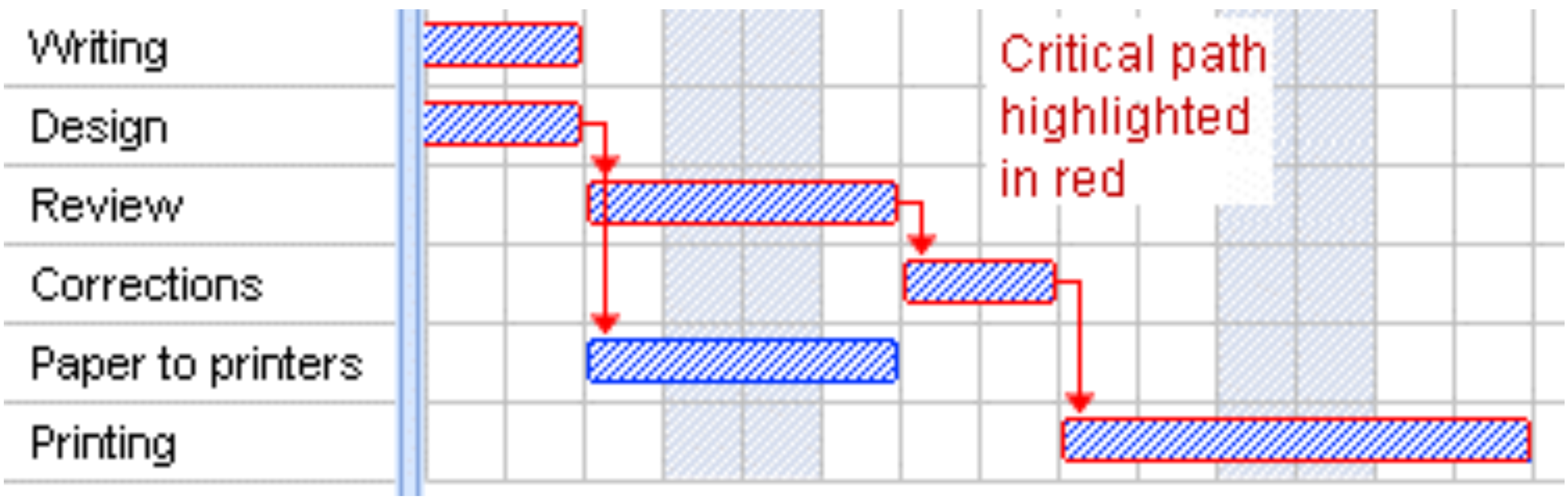
Step B2

Step B3

Step A

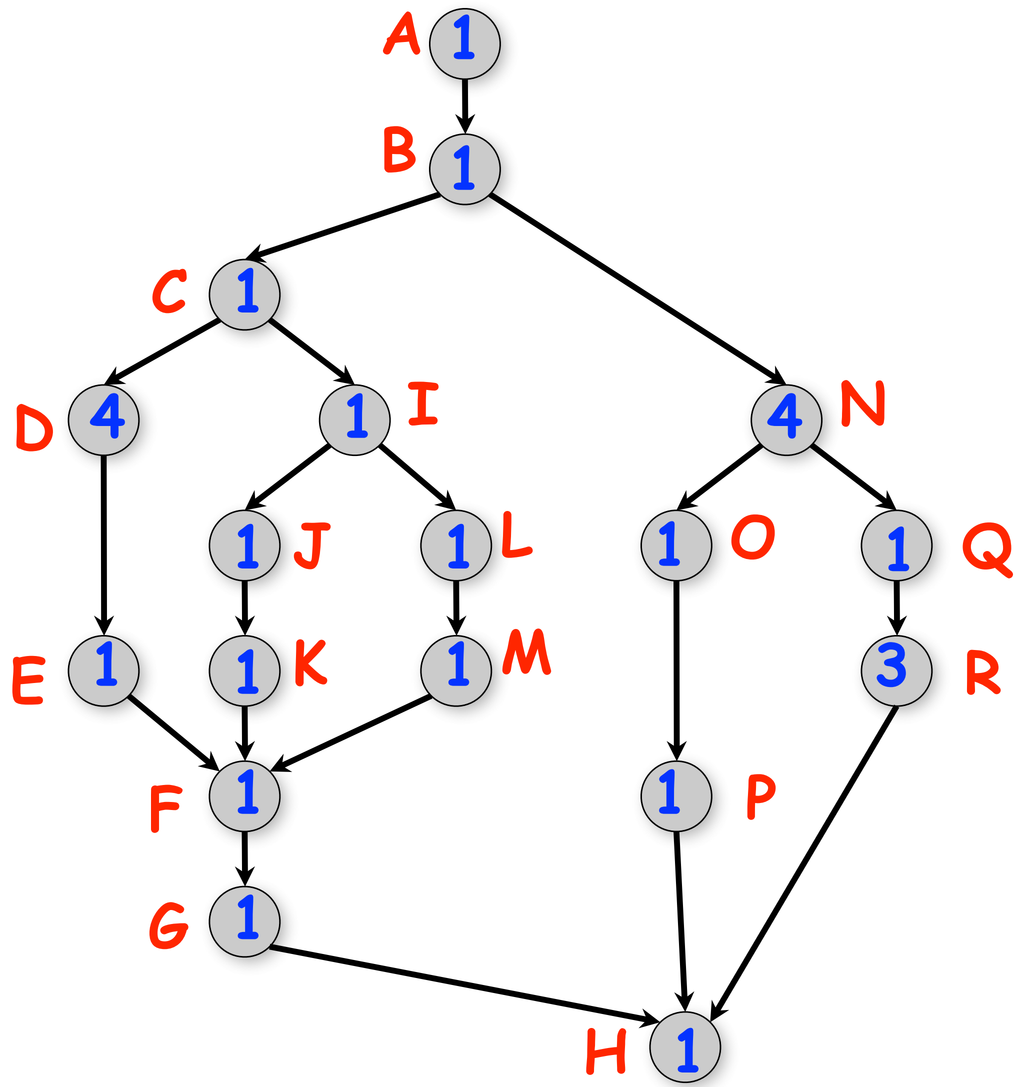
Computation Graphs are used in Project Scheduling as well

- Computation graphs are referred to as "Gantt charts" in project management
- Sample project for preparing a printed document
  —Source: http://www.gantt.com/creating-gantt-charts.htm



Scheduling of a Computation Graph on a fixed number of processors: Example

node label = time(N), for all nodes N in the graph



Start time	Proc 1	Proc 2	Proc 3
0	A		
1	B		
2	C	N	
3	D	N	I
4	D	N	J
5	D	N	K
6	D	Q	L
7	E	R	M
8	F	R	O
9	G	R	P
10	H		
11	Completion time = 11		

NOTE: this schedule achieved a completion time of 11. Can we do better?

Scheduling of a Computation Graph on a fixed number of processors, P

- Assume that node N takes TIME(N) regardless of which processor it executes on, and that there is no overhead for creating parallel tasks
- A schedule specifies the following for each node
  - —START(N) = start time
  - —PROC(N) = index of processor in range 1...P

  such that
  - —START(i) + TIME(i) <= START(j), for all CG edges from i to j (Precedence constraint)
  - —A node occupies consecutive time slots in a processor (Non-preemption constraint)
  - —All nodes assigned to the same processor occupy distinct time slots (Resource constraint)

Greedy Schedule

- A greedy schedule is one that never forces a processor to be idle when one or more nodes are ready for execution
- A node is ready for execution if all its predecessors have been executed
- Observations
  - —T_1 = WORK(G), for all greedy schedules
  - —T_∞ = CPL(G), for all greedy schedules
- where $T_P(S)$ = execution time of schedule S for computation graph G on P processors

Lower Bounds on Execution Time of Schedules

- Let T_P = execution time of a schedule for computation graph G on P processors
  - T_P can be different for different schedules, for same values of G and P
- Lower bounds for all greedy schedules
  - Capacity bound: $T_P \geq WORK(G)/P$
  - Critical path bound: $T_P \geq CPL(G)$
- Putting them together
  - $T_P \geq \max(WORK(G)/P, CPL(G))$

Upper Bound on Execution Time of Greedy Schedules

Theorem [Graham '66]. Any greedy scheduler achieves

$$T_P \leq WORK(G)/P + CPL(G)$$

Proof sketch:

Define a time step to be complete if P nodes are scheduled at that time, or incomplete otherwise

complete time steps ≤ WORK(G)/P

incomplete time steps ≤ CPL(G)

Start time	Proc 1	Proc 2	Proc 3
0	A		
1	B		
2	C	N	
3	D	N	I
4	D	N	J
5	D	N	K
6	D	Q	L
7	E	R	M
8	F	R	O
9	G	R	P
10	H		
11			

Bounding the performance of Greedy Schedulers

Combine lower and upper bounds to get

$\max(\text{WORK}(G)/P, \text{CPL}(G)) \leq T_P \leq \text{WORK}(G)/P + \text{CPL}(G)$

Corollary 1: Any greedy scheduler achieves execution time T_P that is within a factor of 2 of the optimal time (since max(a,b) and (a+b) are within a factor of 2 of each other, for any $a \geq 0, b \geq 0$).

Corollary 2: Lower and upper bounds approach the same value whenever

- There's lots of parallelism, WORK(G)/CPL(G) >> P
- Or there's little parallelism, WORK(G)/CPL(G) << P

Abstract Performance Metrics (Lab 1)

- Basic Idea
  - Count operations of interest, as in big-O analysis, to evaluate parallel algorithms
  - Abstraction ignores many overheads that occur on real systems
- Calls to doWork()
  - Programmer inserts calls of the form, doWork(N), within a step to indicate abstraction execution of N application-specific abstract operation
    - e.g., in the Homework 1 programming assignment (Parallel Sort), we will include one call to doWork(1) in each call to compareTo(), and ignore the cost of everything else
- Abstract metrics are enabled by calling HjSystemProperty.abstractMetrics.set(true) at start of program execution
- If an HJ program is executed with this option, abstract metrics can be printed at end of program execution with calls to abstractMetrics().totalWork(), abstractMetrics().criticalPathLength(), and abstractMetrics().idealParallelism()

Announcements & Reminders

- **IMPORTANT:**
  - —Watch video & read handout for topic 1.5 for next lecture on Wednesday, Jan 18th
- HW1 was posted on the course web site (http://comp322.rice.edu) on Jan 11th, and is due on Jan 25th
- Quiz for Unit 1 (topics 1.1 - 1.5) is due by Jan 27th on Canvas
- See course web site for all work assignments and due dates
- Use Piazza (public or private posts, as appropriate) for all communications re. COMP 322
- See Office Hours link on course web site for latest office hours schedule. Group office hours are now scheduled during 3pm - 4pm on MWF in DH 3092 (default room but alternate room may need to be used on some days — an announcement will be made in the lecture on those days)