Topological Sort

In this topic, we will discuss:

- Motivations
- Review the definition of a directed acyclic graph (DAG)
- Describe a topological sort and applications
- Prove the existence of topological sorts on DAGs
- Describe an abstract algorithm for a topological sort
- Do a run-time and memory analysis of the algorithm
- Describe a concrete algorithm
- Define critical times and critical paths

11.4.1

Motivation

Given a set of tasks with dependencies,

is there an order in which we can complete the tasks?

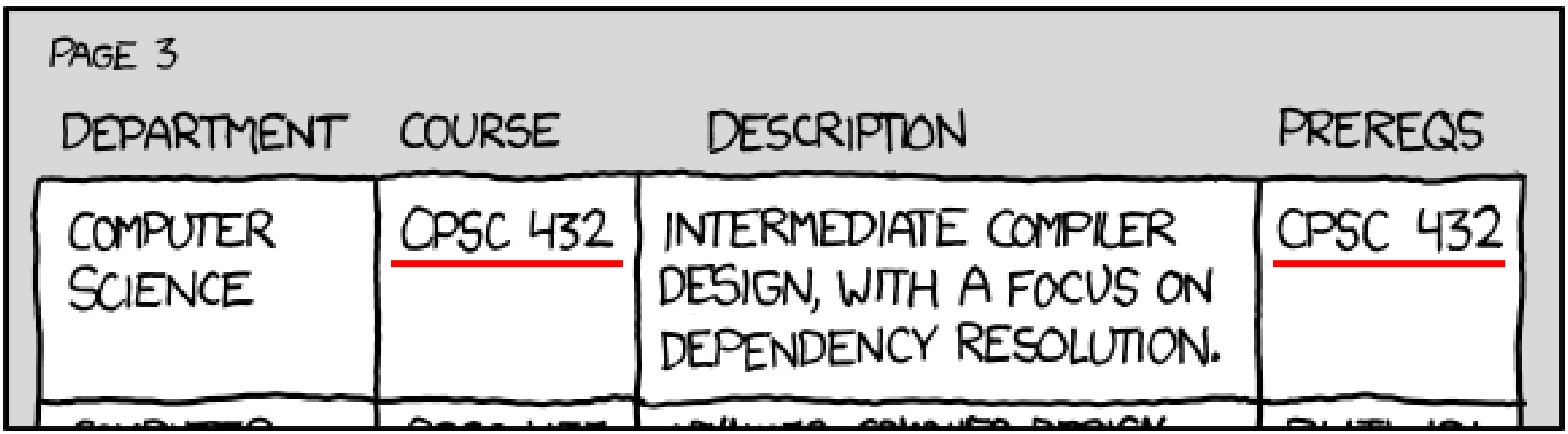
Dependencies form a partial ordering

– A partial ordering on a finite number of objects can be represented as a directed acyclic graph (DAG)

11.4.1

Motivation

Cycles in dependencies can cause issues...



http://xkcd.com/754/

11.4.2

Restriction of paths in DAGs

In a DAG, given two different vertices v_j and v_k, there cannot both be a path from v_j to v_k and a path from v_k to v_j

Proof:

– Assume otherwise; thus there exists two paths:

$$(v_j, v_{1,1}, v_{1,2}, v_{1,3}, \ldots, v_k)$$

$$(v_k, v_{2,1}, v_{2,2}, v_{2,3}, \ldots, v_j)$$

From this, we can construct the path

$$(v_j, v_{1,1}, v_{1,2}, v_{1,3}, \ldots, v_k, v_{2,1}, v_{2,2}, v_{2,3}, \ldots, v_j)$$

This a path is a cycle, but this is an *acyclic* graph

$\therefore$ contradiction

11.4.3

Definition of topological sorting

A topological sorting of the vertices in a DAG is an ordering

$$v_1, v_2, v_3, \ldots, v_{|V|}$$

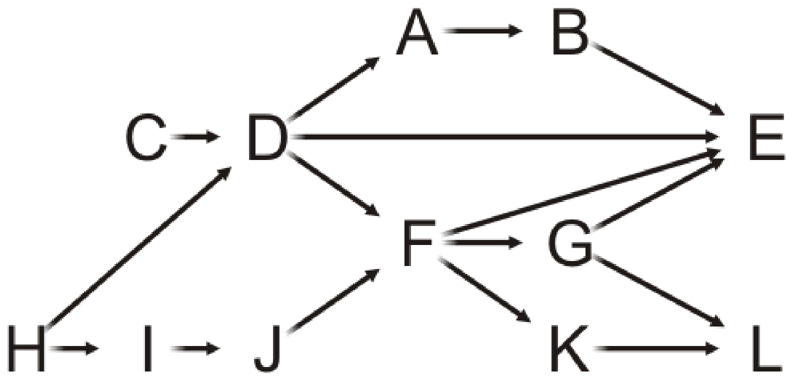
such that v_j appears before v_k if there is a path from v_j to v_k

11.4.3

Definition of topological sorting

Given this DAG, a topological sort is

H, C, I, D, J, A, F, B, G, K, E, L

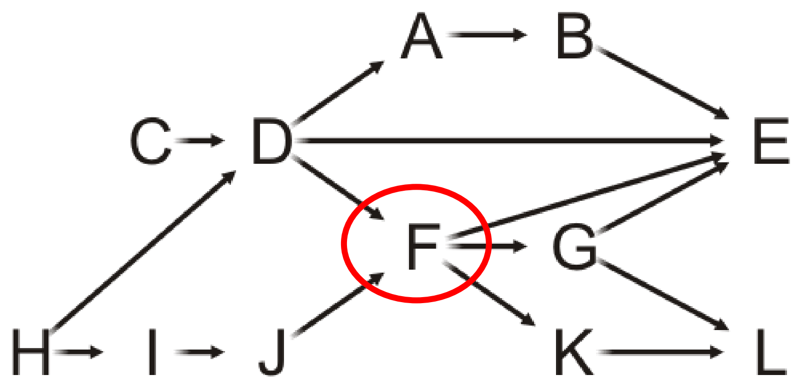


11.4.3

Example

For example, there are paths from H, C, I, D and J to F, so all these must come before F in a topological sort

H, **C**, **I**, **D**, **J**, A, **F**, B, G, K, E, L



Clearly, this sorting need not be unique

11.4.3

Applications

Consider the course instructor getting ready for a dinner out

He must wear the following:

- jacket, shirt, briefs, socks, tie, etc.

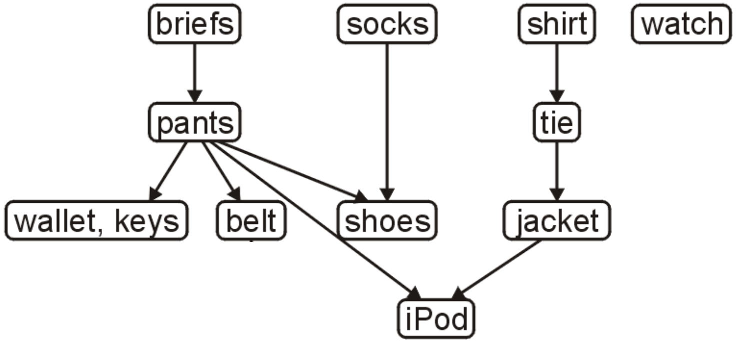
There are certain constraints:

- the pants really should go on after the briefs,
- socks are put on before shoes

http://www.idealliance.org/proceedings/xml03/slides/mansfield&otkunc/Paper/03-02-04.html

Applications

The following is a task graph for getting dressed:



One topological sort is:

briefs, pants, wallet, keys, belt, socks, shoes, shirt, tie, jacket, iPod, watch

A more reasonable topological sort is:

briefs, socks, pants, shirt, belt, tie, jacket, wallet, keys, iPod, watch, shoes

11.4.3

Applications

C++ header and source files have `#include` statements

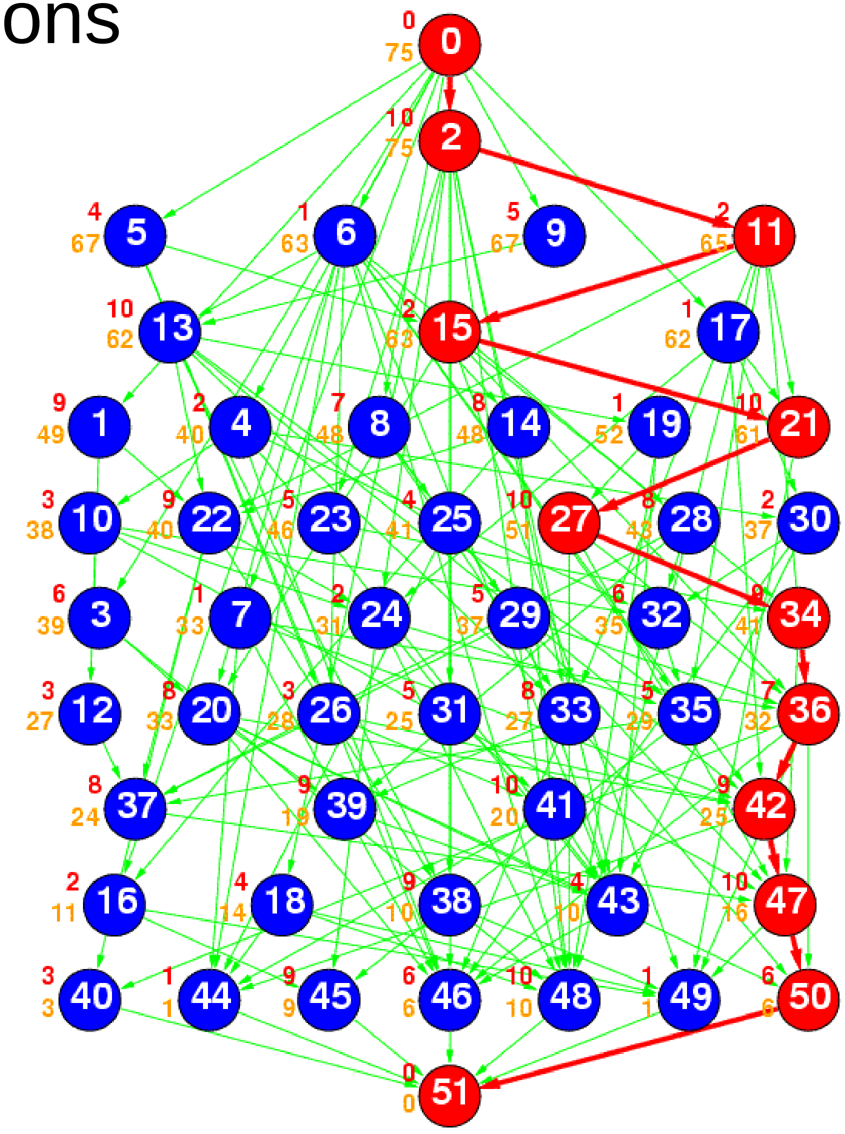
- A change to an included file requires a recompilation of the current file
- On a large project, it is desirable to recompile only those source files that depended on those files which changed
- For large software projects, full compilations may take hours

11.4.3

Applications

The following is a DAG representing a number of tasks

- The green arrows represent dependencies
- The numbering indicates a topological sort of the tasks



Ref: The Standard Task Graph
http://www.kasahara.elec.waseda.ac.jp/schedule/

11.4.4

Topological Sort

Theorem:

A graph is a DAG if and only if it has a topological sorting

Proof strategy:

Such a statement is of the form $a \leftrightarrow b$ and this is equivalent to:

$a \rightarrow b$ and $b \rightarrow a$

11.4.4

Topological Sort

First, we need a two lemmas:

- A DAG always has at least one vertex with in-degree zero
  - That is, it has at least one *source*

Proof:

- If we cannot find a vertex with in-degree zero, we will show there must be a cycle
- Start with any vertex and define a list $L = (v)$
- Then iterate this loop $|V|$ times:
  - Given the list L, the first vertex ℓ_1 does not have in-degree zero
  - Find any vertex w such that (w, ℓ_1) is an edge
  - Create a new list $L = (w, \ell_1, \ldots, \ell_k)$
- By the pigeon-hole principle, at least one vertex must appear twice
  - This forms a cycle; hence a contradiction, as this is a DAG

$\therefore$ we can always find a vertex with in-degree zero

11.4.4

Topological Sort

First, we need a two lemmas:

– Any sub-graph of a DAG is a DAG

Proof:

– If a sub-graph has a cycle, that same cycle must appear in the super-graph
– We assumed the super-graph was a DAG
– This is a contradiction

∴ the sub-graph must be a DAG

11.4.4

Topological Sort

We will start with showing $a \rightarrow b$:

If a graph is a DAG, it has a topological sort

By induction:

A graph with one vertex is a DAG and it has a topological sort

Assume a DAG with n vertices has a topological sort

A DAG with $n + 1$ vertices must have at least one vertex v of in-degree zero

Removing the vertex v and consider the vertex-induced sub-graph with the remaining n vertices

- If this sub-graph has a cycle, so would the original graph—contradiction
- Thus, the graph with n vertices is also a DAG, therefore it has a topological sort

Add the vertex v to the start of the topological sort to get one for the graph of size $n + 1$

11.4.4

Topological Sort

Next, we will show that $b \rightarrow a$:

If a graph has a topological ordering, it must be a DAG

We will show this by showing the contrapositive: $\neg a \rightarrow \neg b$:

If a graph is not a DAG, it does not have a topological sort

By definition, it has a cycle: $(v_1, v_2, v_3, \ldots, v_k, v_1)$

- In any topological sort, v_1 must appear before v_2, because (v_1, v_2) is a path
- However, there is also a path from v_2 to v_1: $(v_2, v_3, \ldots, v_k, v_1)$
- Therefore, v_2 must appear in the topological sort before v_1

This is a contradiction, therefore the graph cannot have a topological sort

$\therefore$ A graph is a DAG if and only if it has a topological sorting

11.4.5

Topological Sort

Idea:

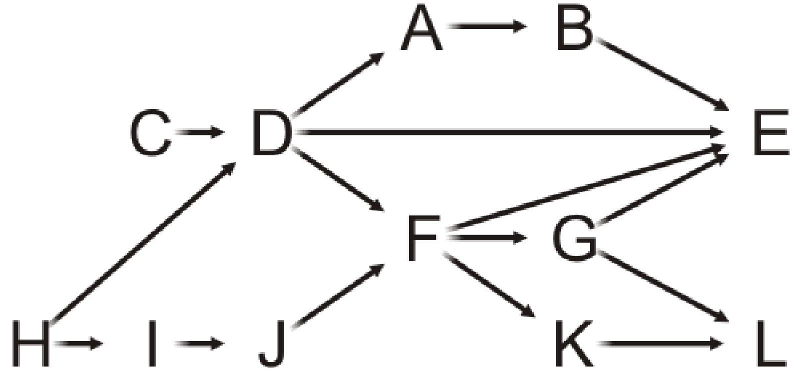
– Given a DAG V, make a copy W and iterate:
  - Find a vertex v in W with in-degree zero
  - Let v be the next vertex in the topological sort
  - Continue iterating with the vertex-induced sub-graph $W \setminus \{v\}$

11.4.5.1

Example

On this graph, iterate the following $|V| = 12$ times

- Choose a vertex v that has in-degree zero
- Let v be the next vertex in our topological sort
- Remove v and all edges connected to it

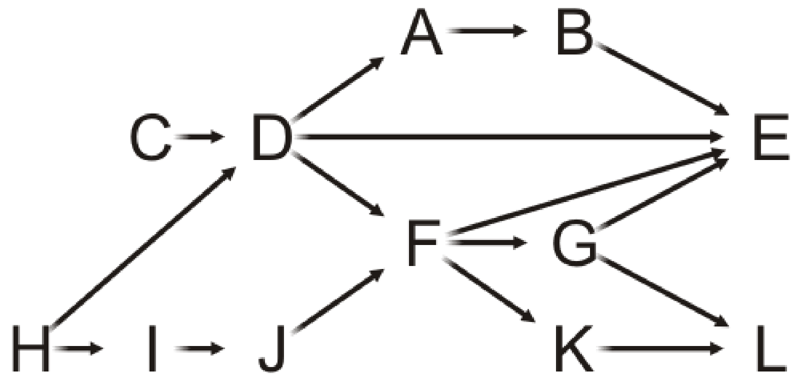


11.4.5.1

Example

Let's step through this algorithm with this example

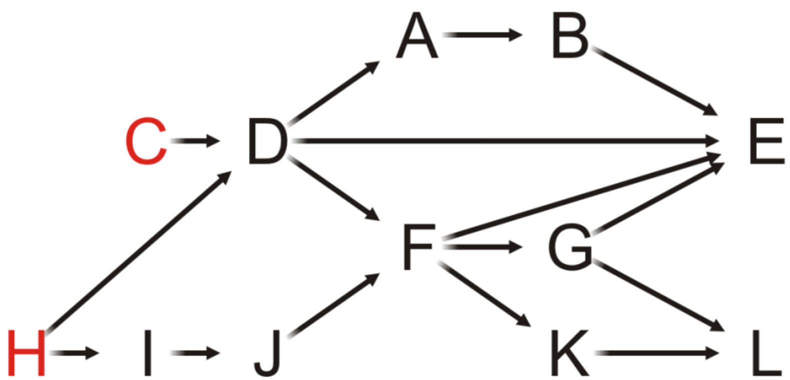
- Which task can we start with?



11.4.5.1

Example

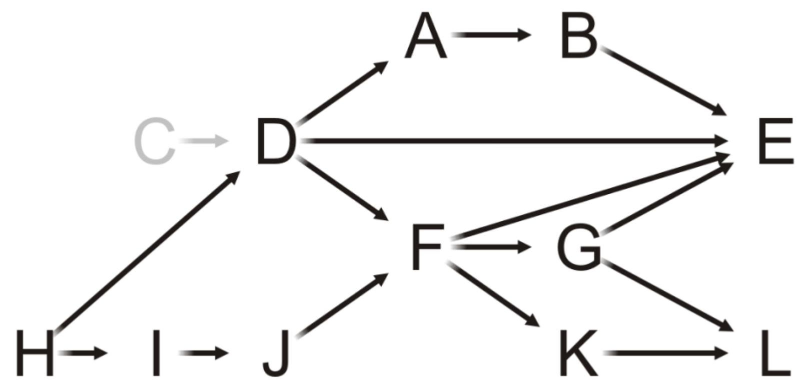
Of Tasks C or H, choose Task C



11.4.5.1

Example

Having completed Task C, which vertices have in-degree zero?

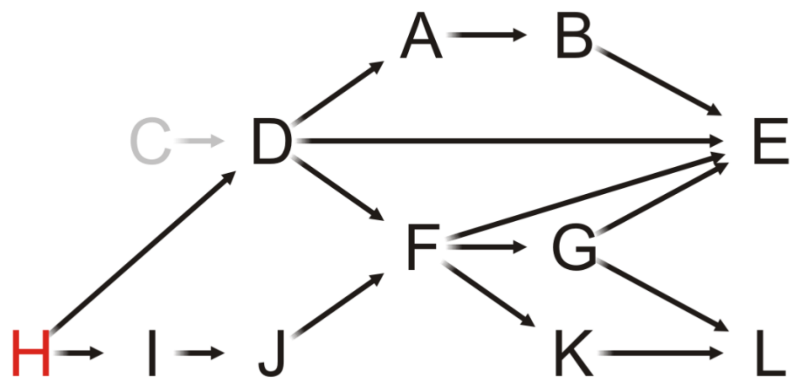


C

11.4.5.1

Example

Only Task H can be completed, so we choose it

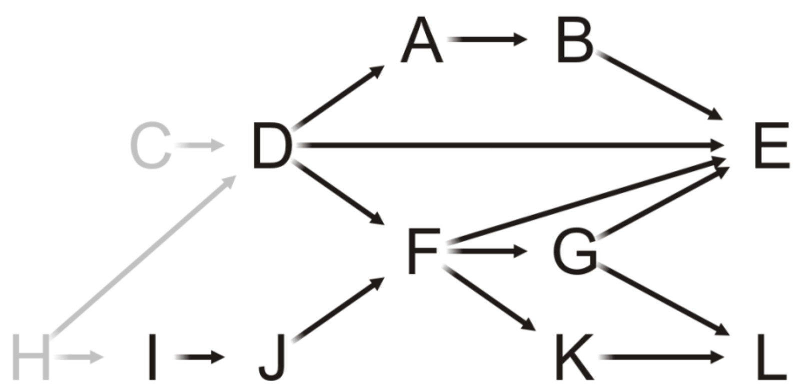


C

11.4.5.1

Example

Having removed H, what is next?



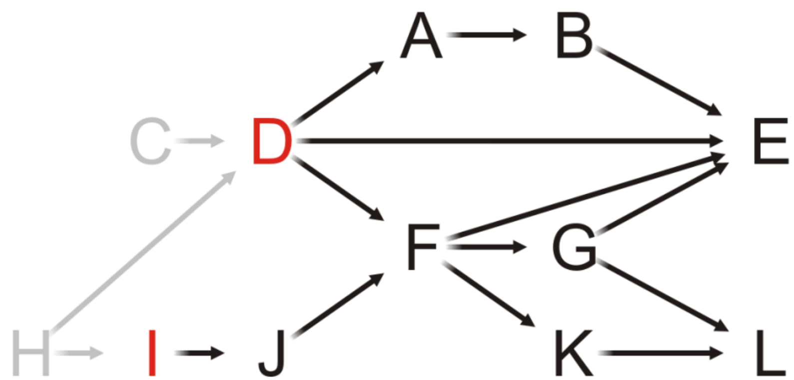
C, H

11.4.5.1

Example

Both Tasks D and I have in-degree zero

– Let us choose Task D

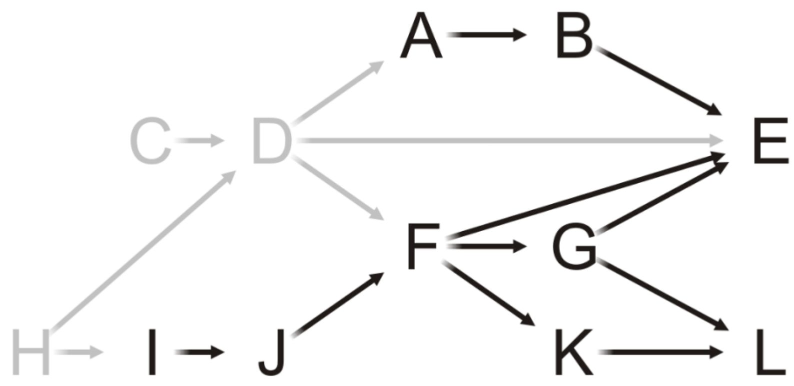


C, H

11.4.5.1

Example

We remove Task D, and now?



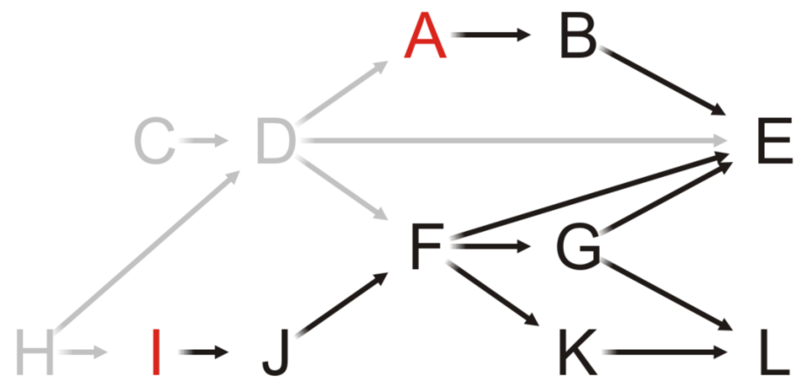
C, H, D

11.4.5.1

Example

Both Tasks A and I have in-degree zero

– Let’s choose Task A

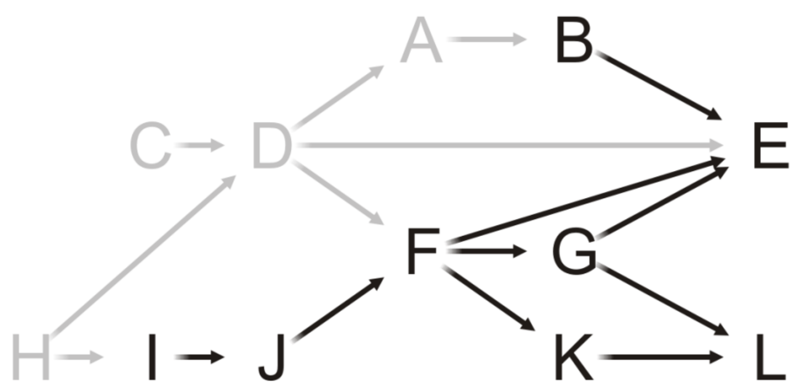


C, H, D

11.4.5.1

Example

Having removed A, what now?

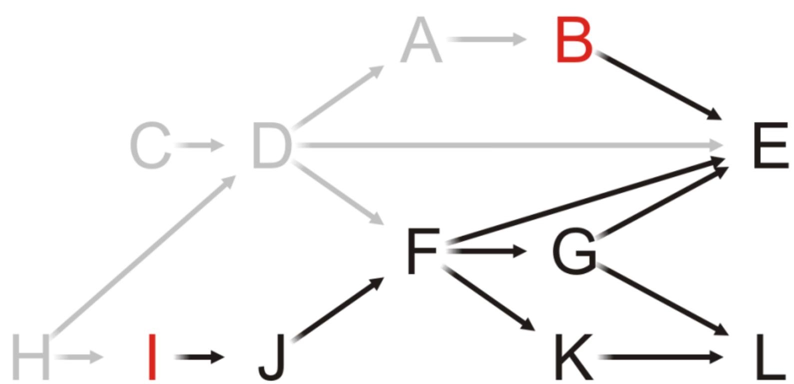


C, H, D, A

11.4.5.1

Example

Both Tasks B and I have in-degree zero
- Choose Task B



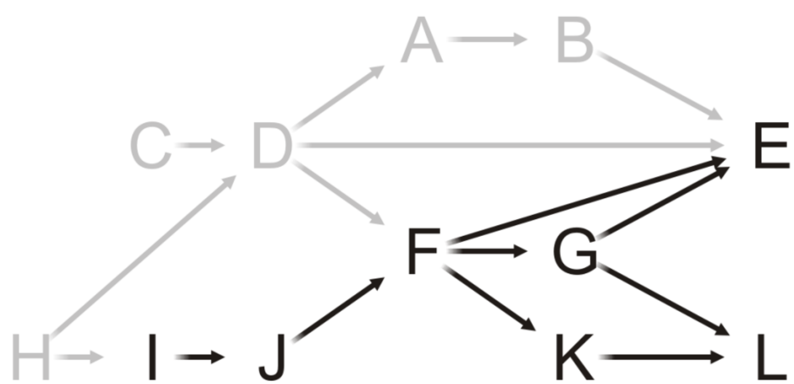
C, H, D, A

11.4.5.1

Example

Removing Task B, we note that Task E still has an in-degree of two

– Next?

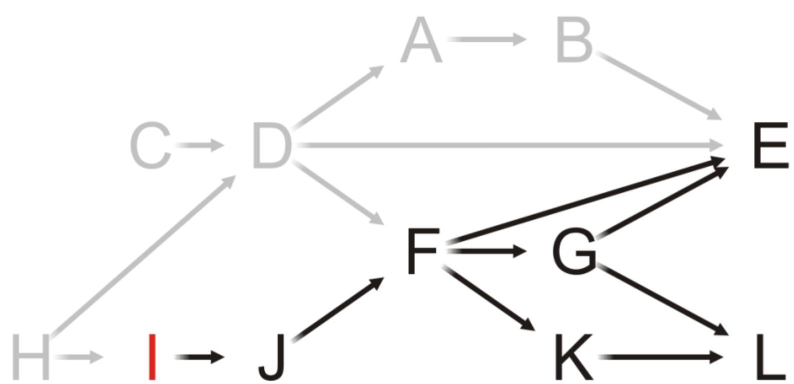


C, H, D, A, B

11.4.5.1

Example

As only Task I has in-degree zero, we choose it

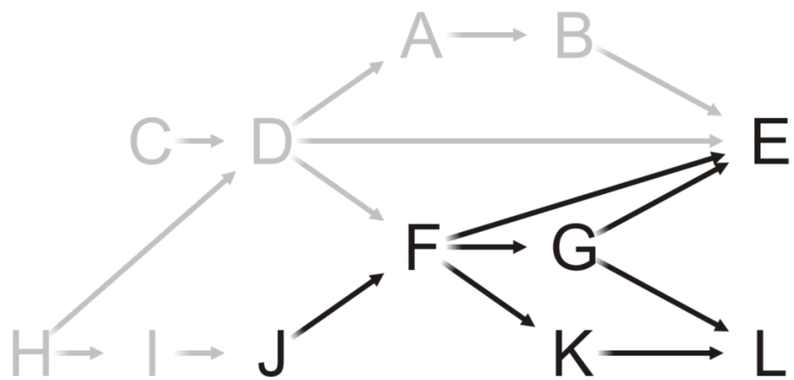


C, H, D, A, B

11.4.5.1

Example

Having completed Task I, what now?

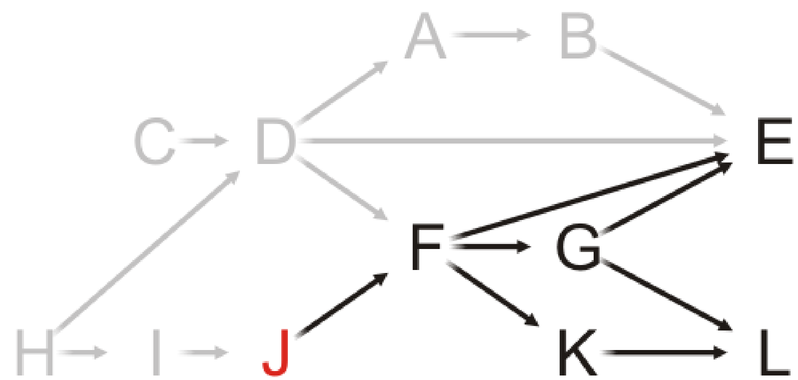


C, H, D, A, B, I

11.4.5.1

Example

Only Task J has in-degree zero: choose it

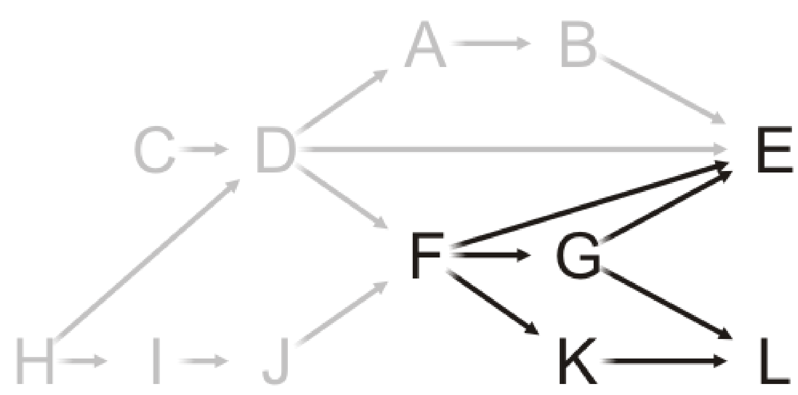


C, H, D, A, B, I

11.4.5.1

Example

Having completed Task J, what now?

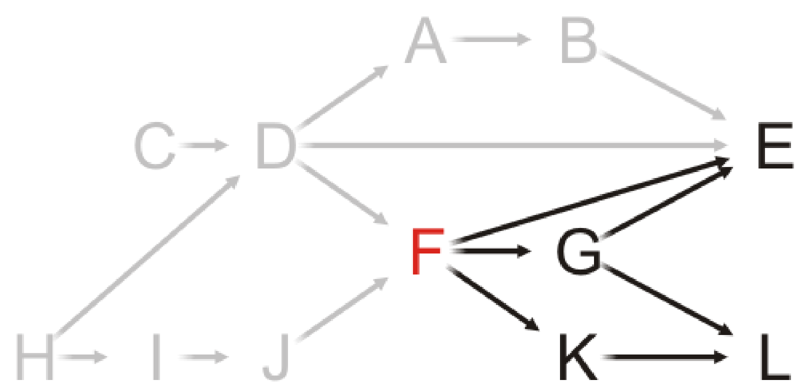


C, H, D, A, B, I, J

11.4.5.1

Example

Only Task F can be completed, so choose it

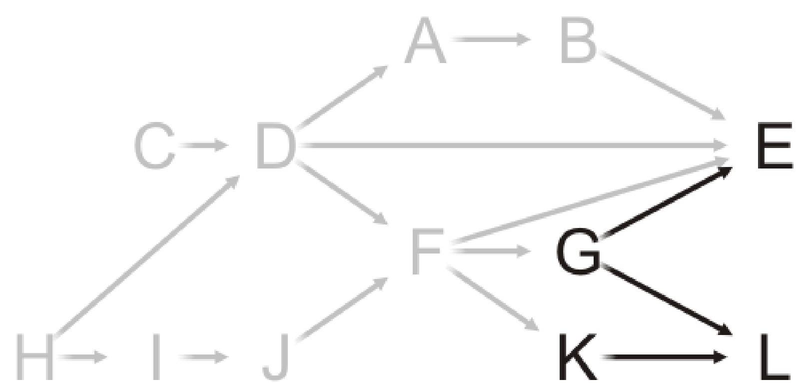


C, H, D, A, B, I, J

11.4.5.1

Example

What choices do we have now?



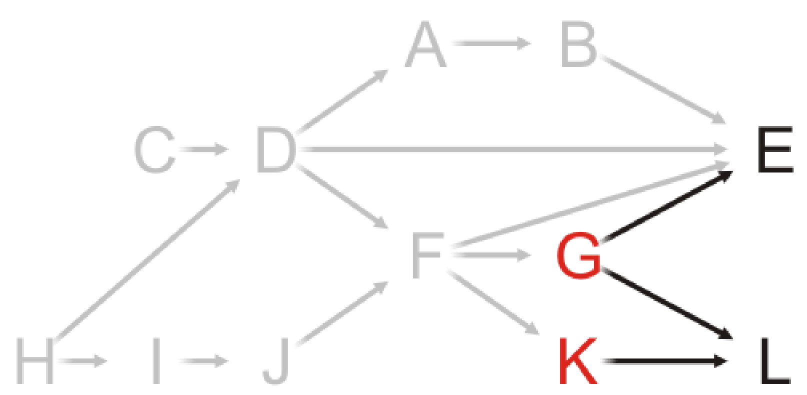
C, H, D, A, B, I, J, F

11.4.5.1

Example

We can perform Tasks G or K

– Choose Task G

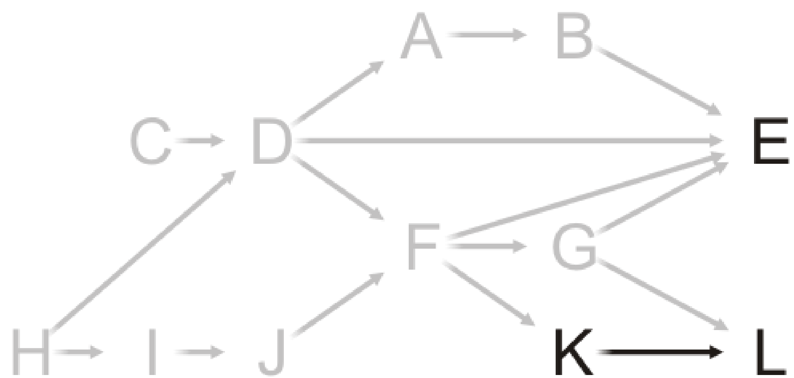


C, H, D, A, B, I, J, F

11.4.5.1

Example

Having removed Task G from the graph, what next?

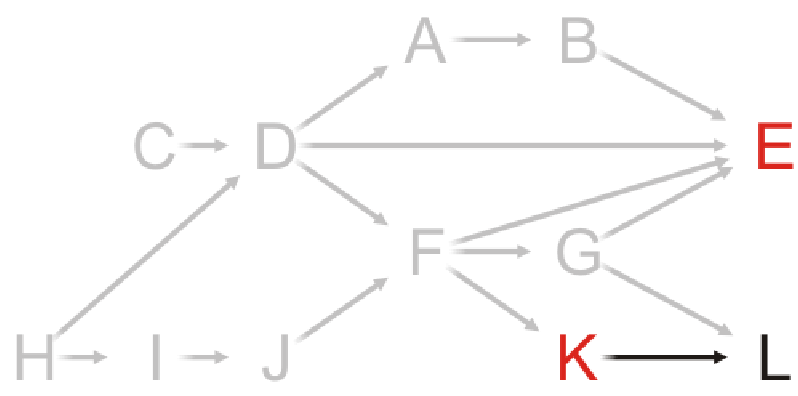


C, H, D, A, B, I, J, F, G

11.4.5.1

Example

Choosing between Tasks E and K, choose Task E

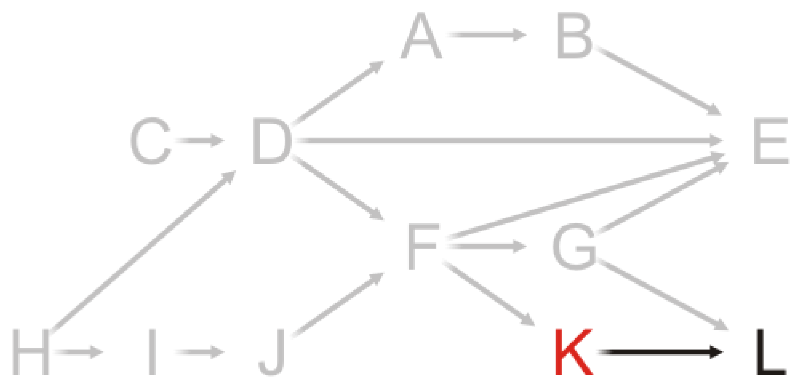


C, H, D, A, B, I, J, F, G

11.4.5.1

Example

At this point, Task K is the only one that can be run

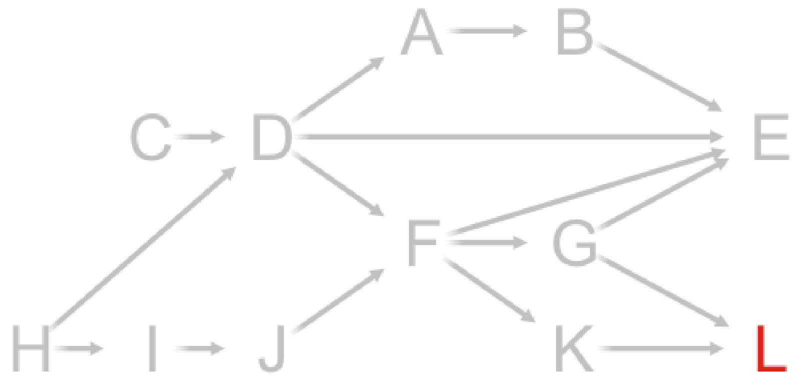


C, H, D, A, B, I, J, F, G, E

11.4.5.1

Example

And now that both Tasks G and K are complete, we can complete Task L

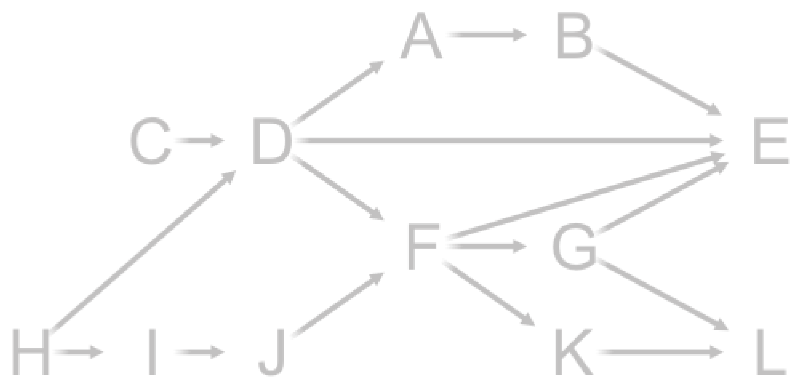


C, H, D, A, B, I, J, F, G, E, K

11.4.5.1

Example

There are no more vertices left



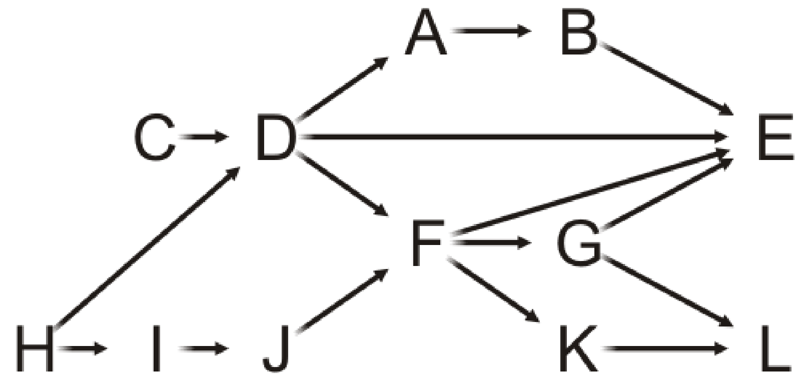
C, H, D, A, B, I, J, F, G, E, K, L

11.4.5.1

Example

Thus, one possible topological sort would be:

C, H, D, A, B, I, J, F, G, E, K, L



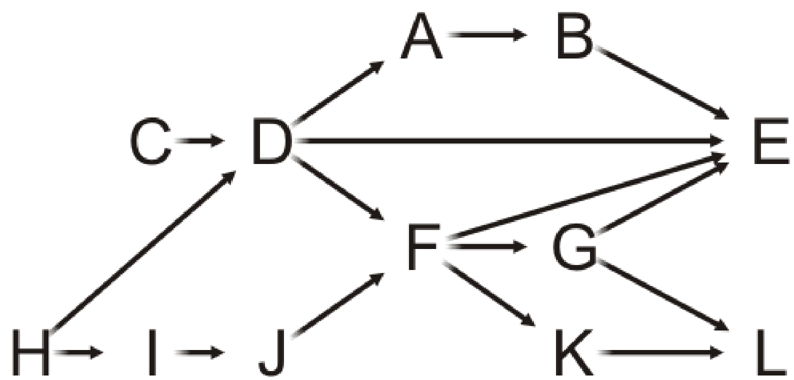
11.4.5.1

Example

Note that topological sorts need not be unique:

C, H, D, A, B, I, J, F, G, E, K, L

H, I, J, C, D, F, G, K, L, A, B, E

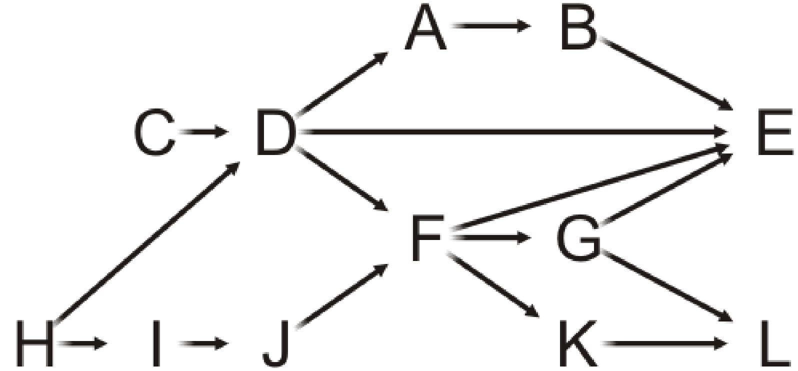


11.4.6

Analysis

What are the tools necessary for a topological sort?

- We must know and be able to update the in-degrees of each of the vertices
- We could do this with a table of the in-degrees of each of the vertices
- This requires $\Theta(|V|)$ memory

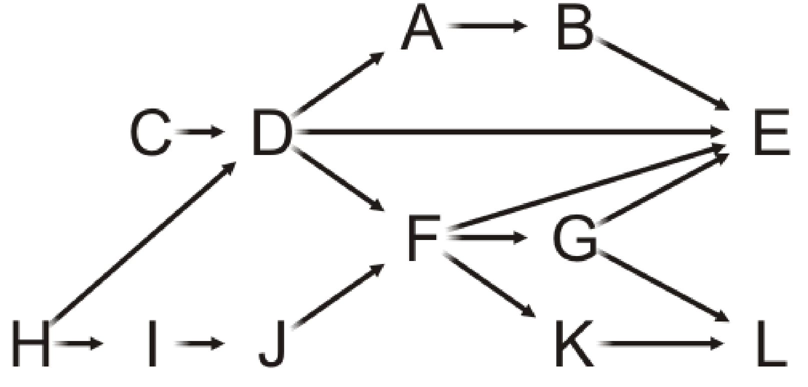


A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

11.4.6

Analysis

We must iterate at least $|V|$ times, so the run-time must be $\Omega(|V|)$



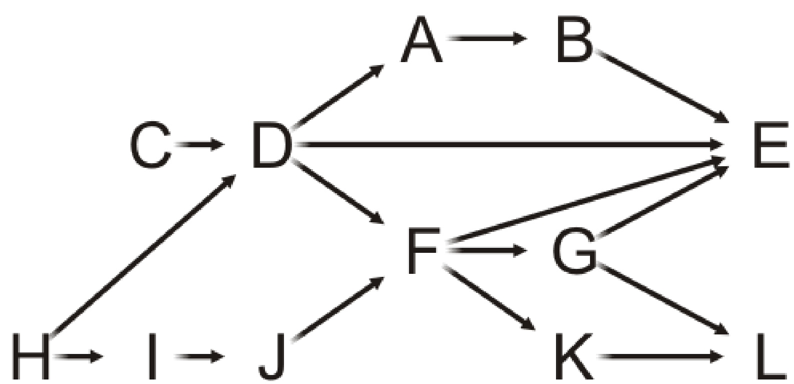
A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

11.4.6

Analysis

We need to find vertices with in-degree zero

- We could loop through the array with each iteration
- The run time would be $O(|V|^2)$



A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

11.4.6

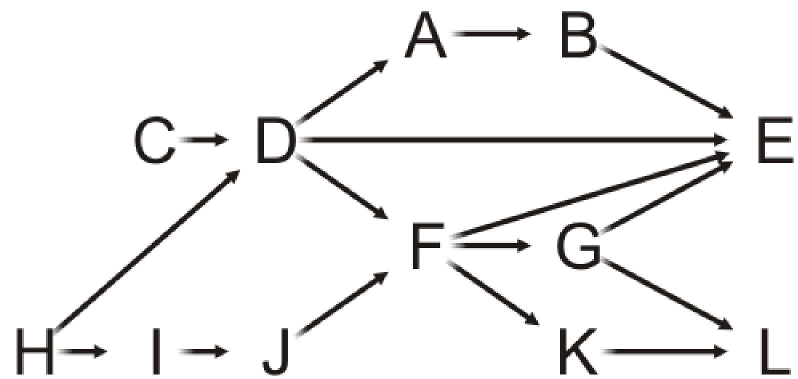
Analysis

What did we do with tree traversals?

– Use a queue (or other container) to temporarily store those vertices with in-degree zero

– Each time the in-degree of a vertex is decremented to zero, push it onto the queue

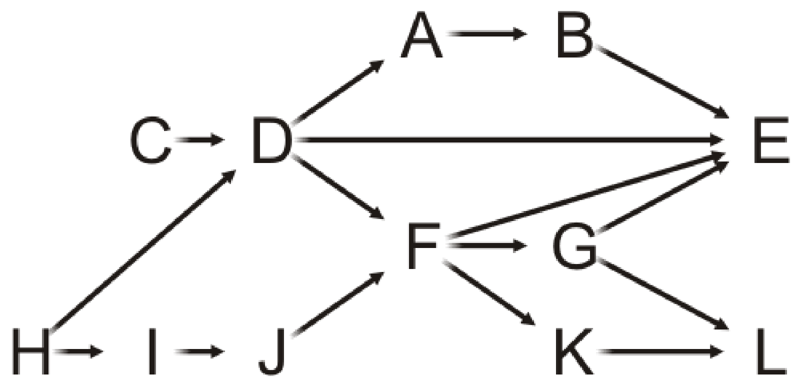
A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2



Analysis

What are the run times associated with the queue?

- Initially, we must scan through each of the vertices: $\Theta(|V|)$
- For each vertex, we will have to push onto and pop off the queue once, also $\Theta(|V|)$



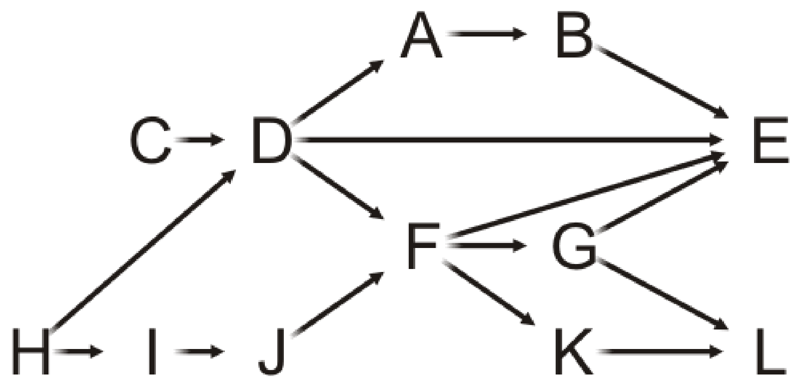
A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

11.4.6

Analysis

Finally, each value in the in-degree table is associated with an edge

- Here, $|E| = 16$
- Each of the in-degrees must be decremented to zero
- The run time of these operations is $\Omega(|E|)$
- If we are using an adjacency matrix: $\Theta(|V|^2)$
- If we are using an adjacency list: $\Theta(|E|)$



A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	+ 2
	16

11.4.6

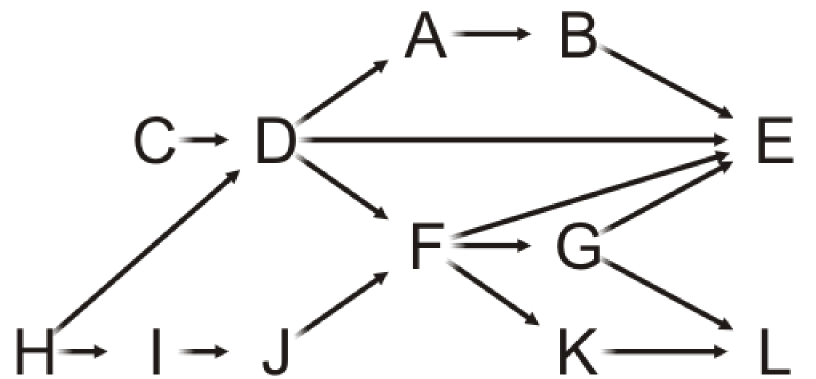
Analysis

Therefore, the run time of a topological sort is:

$\Theta(|V| + |E|)$ if we use an adjacency list

$\Theta(|V|^2)$ if we use an adjacency matrix

and the memory requirements is $\Theta(|V|)$



A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

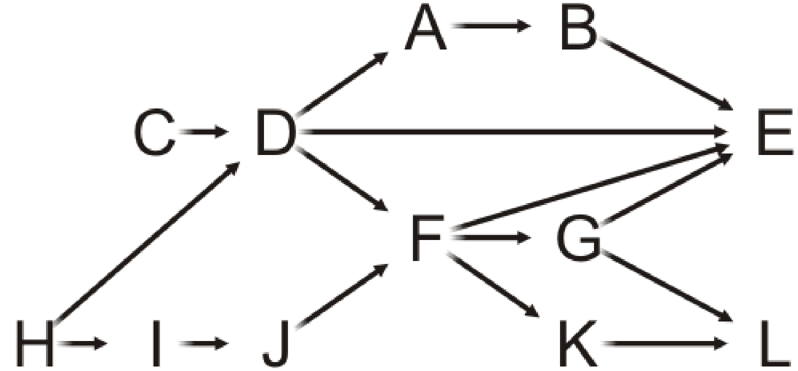
11.4.6

Analysis

What happens if at some step, all remaining vertices have an in-degree greater than zero?

– There must be at least one cycle within that sub-set of vertices

Consequence: we now have an $\Theta(|V| + |E|)$ algorithm for determining if a graph has a cycle



A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

11.4.7

Implementation

Thus, to implement a topological sort:

- Allocate memory for and initialize an array of in-degrees
- Create a queue and initialize it with all vertices that have in-degree zero

While the queue is not empty:

- Pop a vertex from the queue
- Decrement the in-degree of each neighbor
- Those neighbors whose in-degree was decremented to zero are pushed onto the queue

11.4.7

Implementation

We will, however, use a trick with our queue

- Initialization

```
Type array[vertex_size()];
int ihead = 0, itail = -1;
```

- Testing if empty:

```
ihead == itail + 1
```

- For push

```
++itail;
array[itail] = next vertex;
```

- For pop

```
Type current_top = array[ihead];
++ihead;
```

11.4.7

Implementation

Because we place each vertex into the queue exactly once

- We must never resize the array
- We do not have to worry about the queue cycling

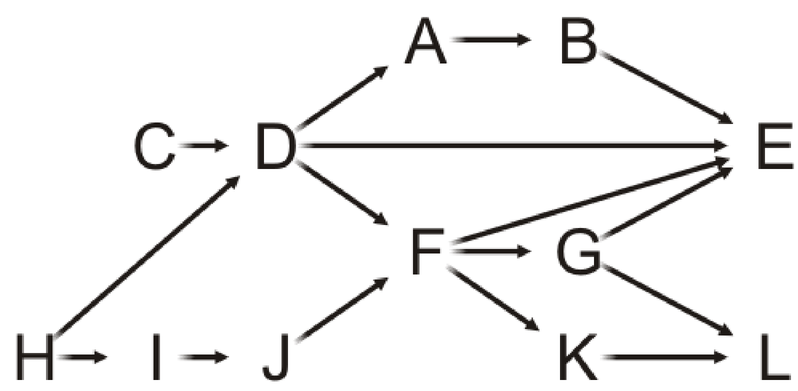
Most importantly, however, because of the properties of a queue

- When we finish, the underlying array stores the topological sort

Example

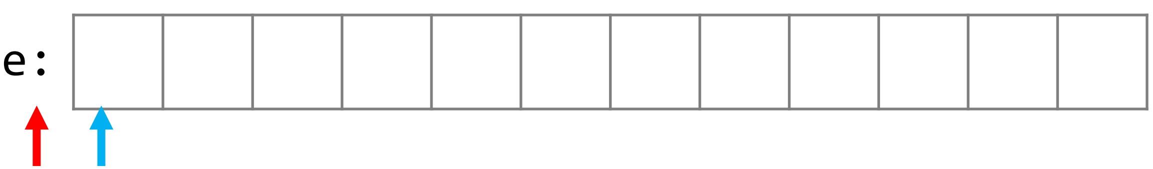
With the previous example, we initialize:

- The array of in-degrees
- The queue



A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

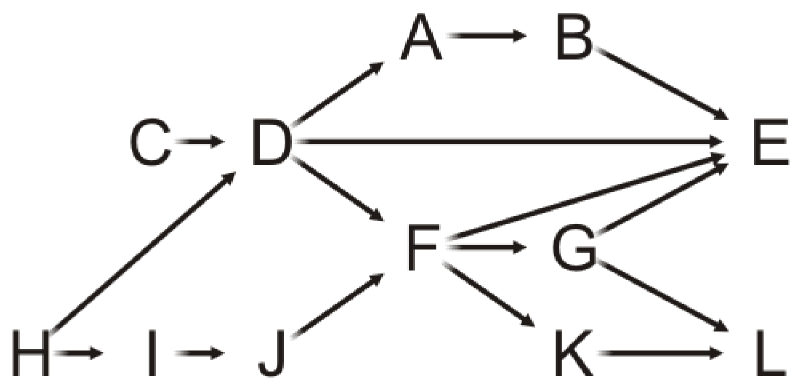
Queue:



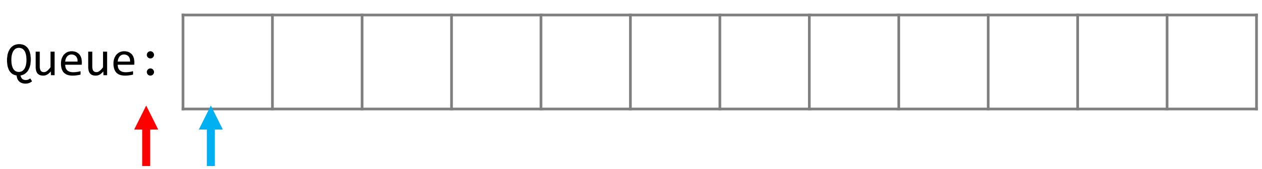
The queue is empty

Example

Stepping through the table, push all source vertices into the queue



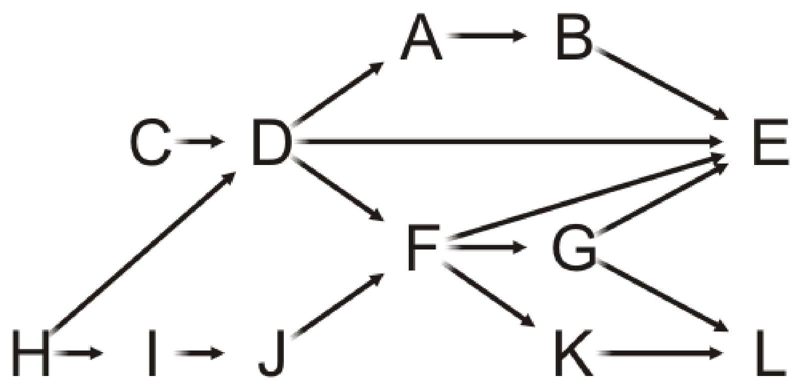
A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2



The queue is empty

Example

Stepping through the table, push all source vertices into the queue



A	1
B	1
C	**0**
D	2
E	4
F	2
G	1
H	**0**
I	1
J	1
K	1
L	2

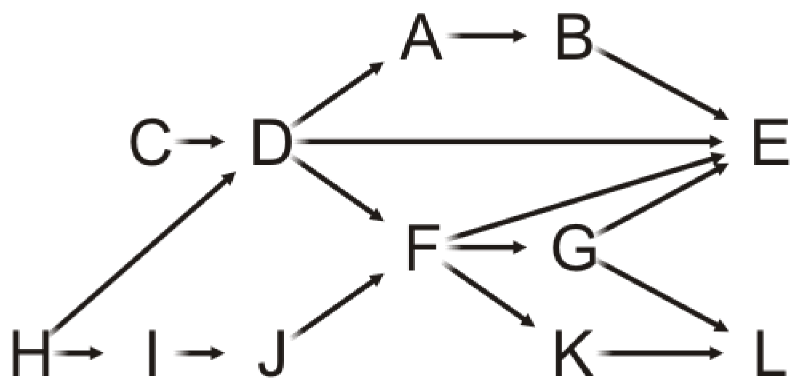
Queue:

C	**H**										

The queue is empty

Example

Pop the front of the queue



Queue:

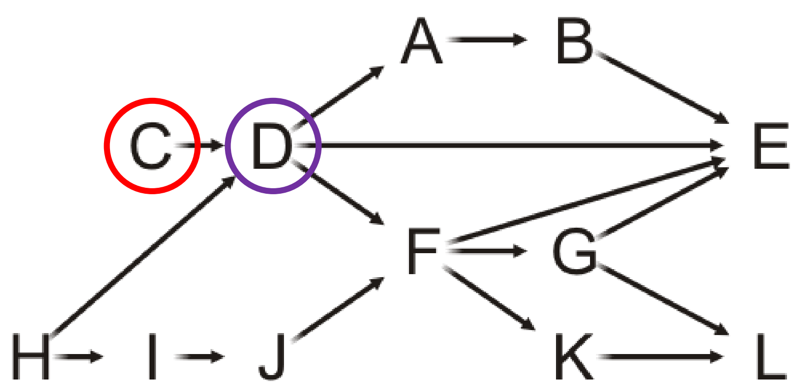
C	H										

A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

Example

Pop the front of the queue

– C has one neighbor: D



Queue:

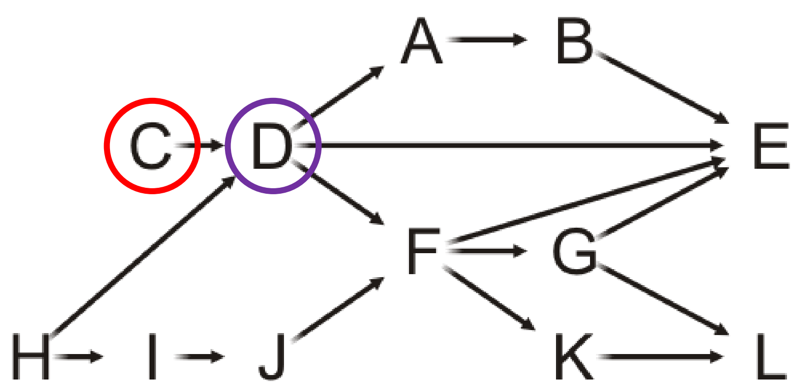
C	H										

A	1
B	1
C	0
D	2
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

Example

Pop the front of the queue

- C has one neighbor: D
- Decrement its in-degree



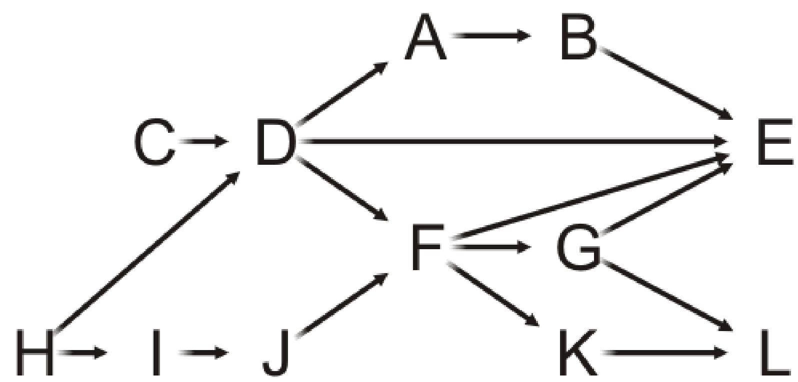
A	1
B	1
C	**0**
D	**1**
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

Queue:

C	H										

Example

Pop the front of the queue



A	1
B	1
C	0
D	1
E	4
F	2
G	1
H	0
I	1
J	1
K	1
L	2

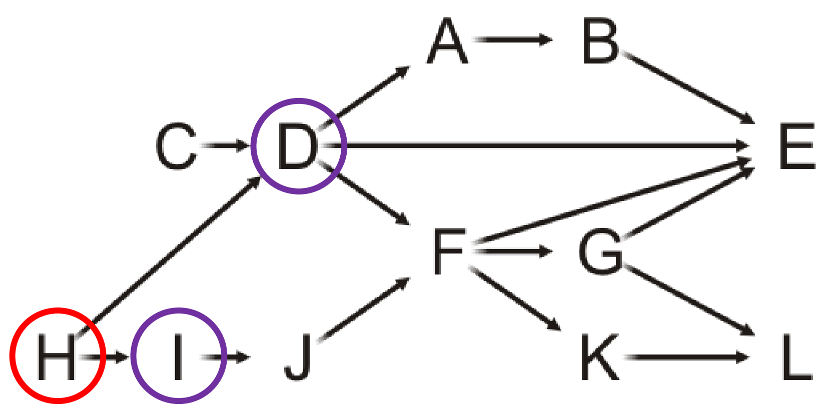
Queue:

C	H										

Example

Pop the front of the queue

– H has two neighbors: D and I



Queue:

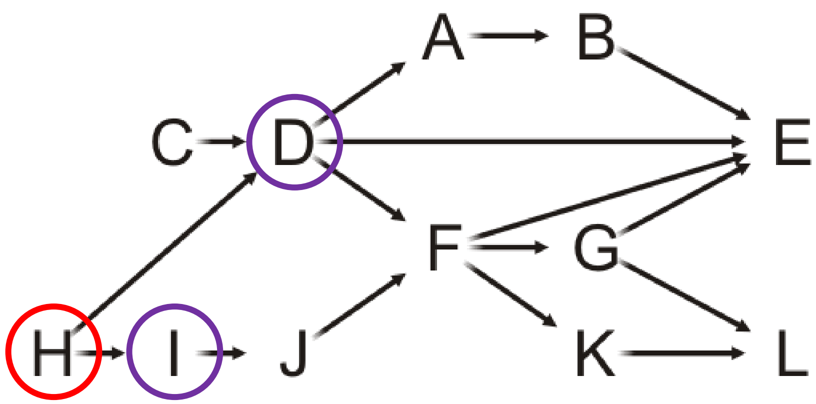
C	H										

A	1
B	1
C	0
D	**1**
E	4
F	2
G	1
H	**0**
I	**1**
J	1
K	1
L	2

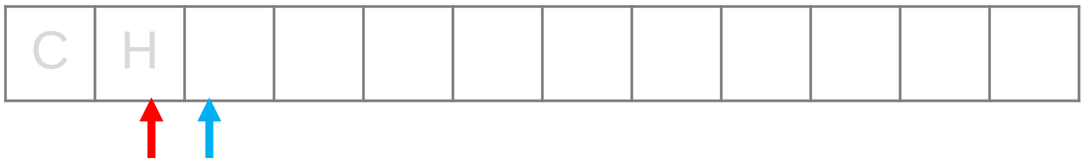
Example

Pop the front of the queue

- H has two neighbors: D and I
- Decrement their in-degrees



Queue:

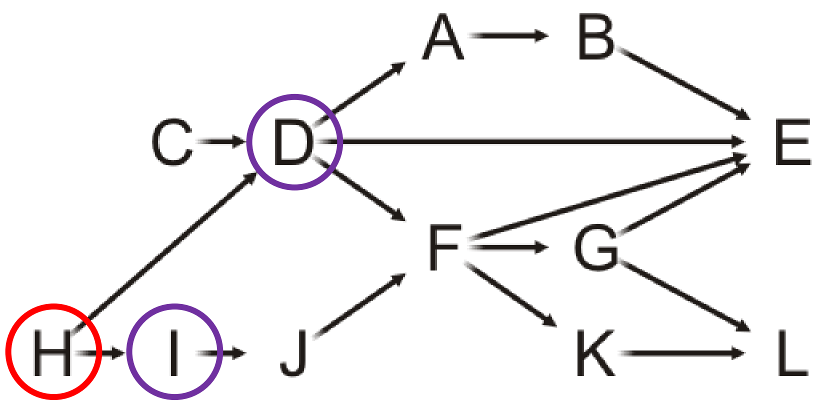


A	1
B	1
C	0
D	**0**
E	4
F	2
G	1
H	**0**
I	**0**
J	1
K	1
L	2

Example

Pop the front of the queue

- H has two neighbors: D and I
- Decrement their in-degrees
  - Both are decremented to zero, so push them onto the queue



Queue:

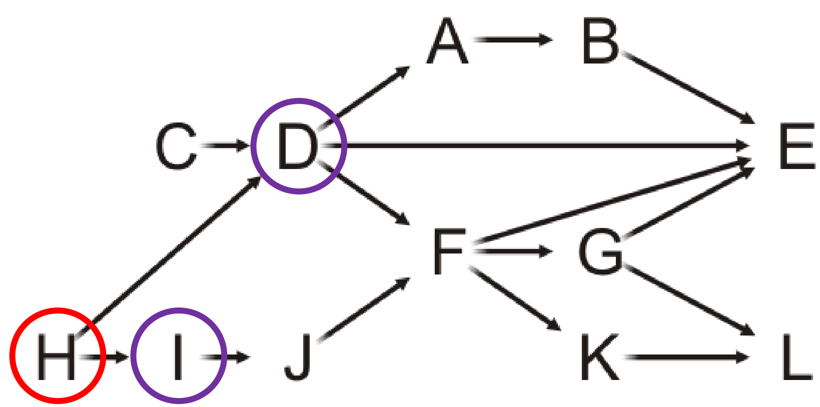
C	H										

A	1
B	1
C	0
D	**0**
E	4
F	2
G	1
H	**0**
I	**0**
J	1
K	1
L	2

Example

Pop the front of the queue

- H has two neighbors: D and I
- Decrement their in-degrees
  - Both are decremented to zero, so push them onto the queue



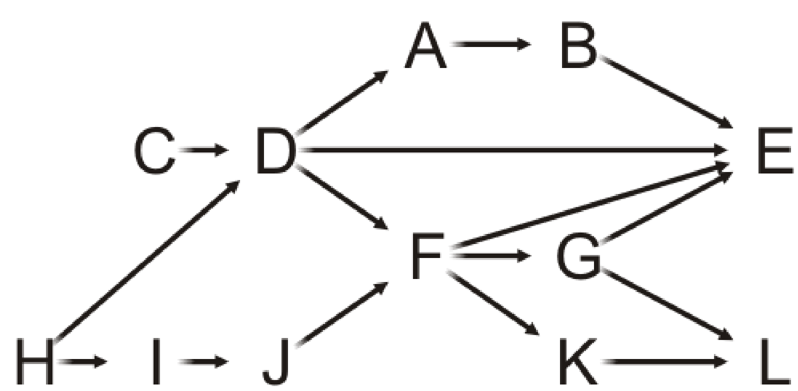
A	1
B	1
C	0
D	**0**
E	4
F	2
G	1
H	**0**
I	**0**
J	1
K	1
L	2

Queue:

C	H	D	I								

Example

Pop the front of the queue



A	1
B	1
C	0
D	0
E	4
F	2
G	1
H	0
I	0
J	1
K	1
L	2

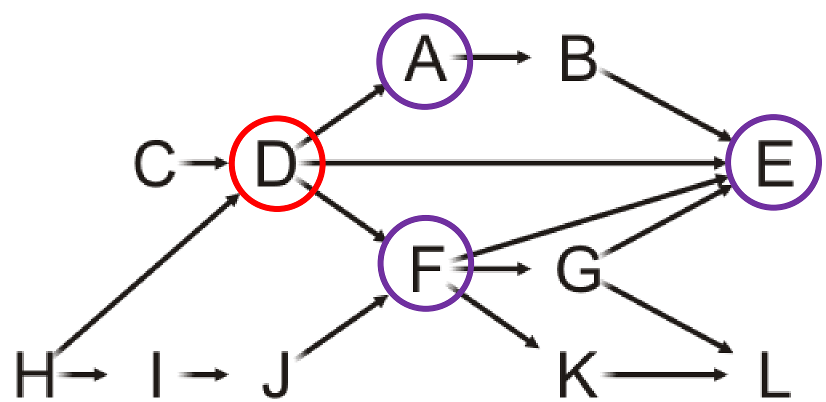
Queue:

C	H	D	I								

Example

Pop the front of the queue

- D has three neighbors: A, E and F



Queue:

C	H	D	I								

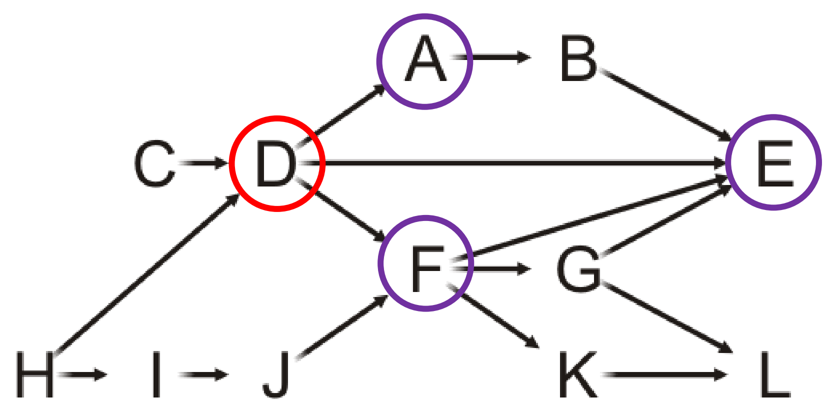
A	**1**
B	1
C	0
D	**0**
E	**4**
F	**2**
G	1
H	0
I	0
J	1
K	1
L	2

Example

Pop the front of the queue

- D has three neighbors: A, E and F
- Decrement their in-degrees

A	0
B	1
C	0
D	0
E	3
F	1
G	1
H	0
I	0
J	1
K	1
L	2



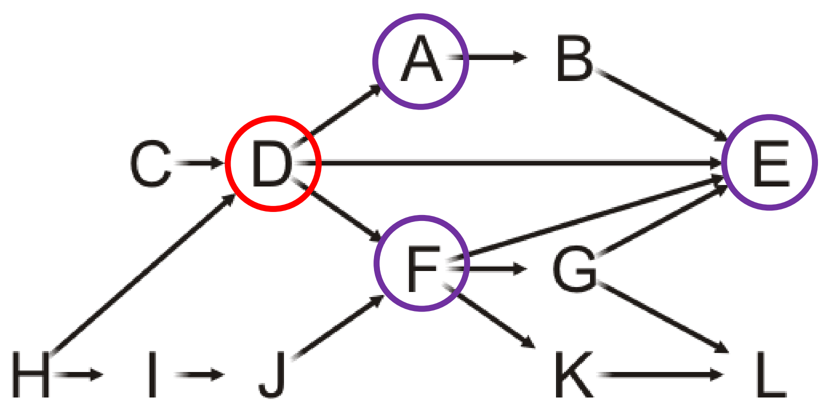
Queue:

C	H	D	I								

Example

Pop the front of the queue

- D has three neighbors: A, E and F
- Decrement their in-degrees
  - A is decremented to zero, so push it onto the queue



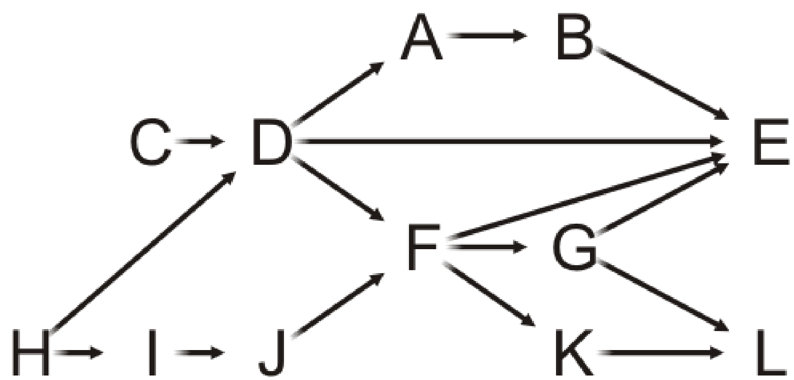
Queue:

C	H	D	I	A							

A	**0**
B	1
C	0
D	**0**
E	**3**
F	**1**
G	1
H	0
I	0
J	1
K	1
L	2

Example

Pop the front of the queue



Queue:

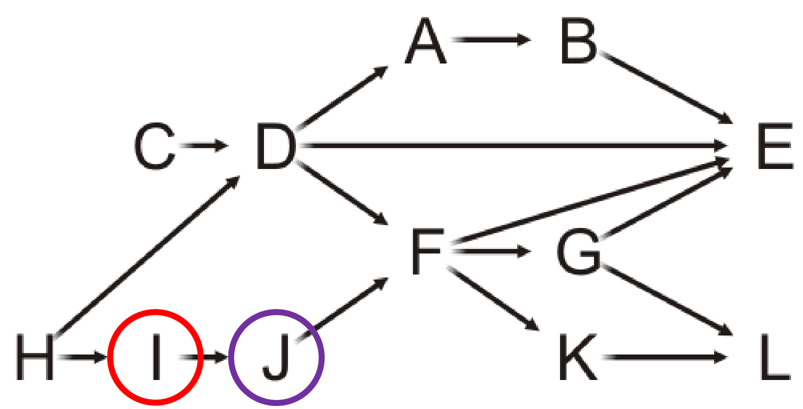
C	H	D	I	A							

A	0
B	1
C	0
D	0
E	3
F	1
G	1
H	0
I	0
J	1
K	1
L	2

Example

Pop the front of the queue

- I has one neighbor: J



A	0
B	1
C	0
D	0
E	3
F	1
G	1
H	0
I	**0**
J	**1**
K	1
L	2

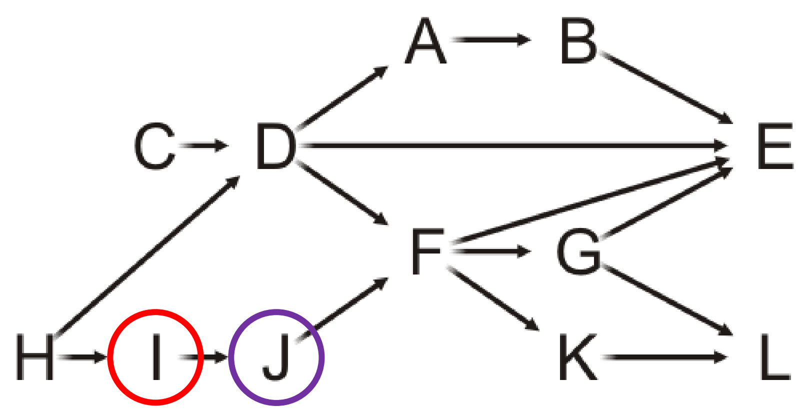
Queue:

C	H	D	I	A							

Example

Pop the front of the queue

- I has one neighbor: J
- Decrement its in-degree



Queue:

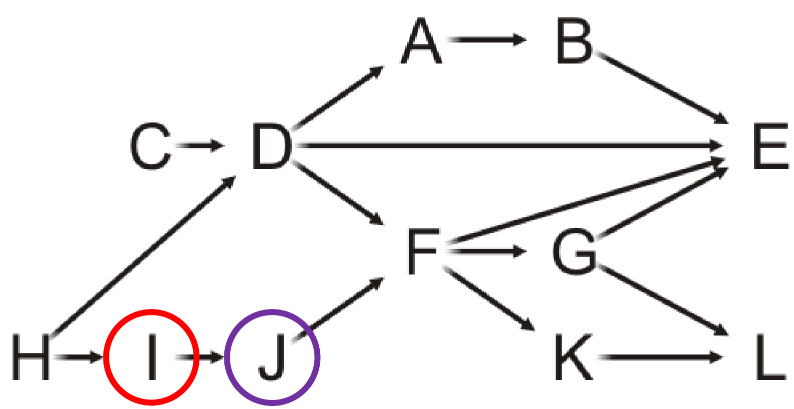
C	H	D	I	A							

A	0
B	1
C	0
D	0
E	3
F	1
G	1
H	0
I	**0**
J	**0**
K	1
L	2

Example

Pop the front of the queue

- I has one neighbor: J
- Decrement its in-degree
  - J is decremented to zero, so push it onto the queue



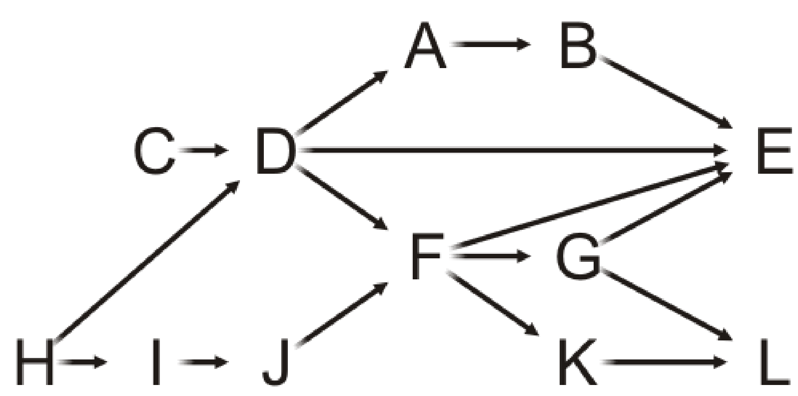
Queue:

C	H	D	I	A	J						

A	0
B	1
C	0
D	0
E	3
F	1
G	1
H	0
I	**0**
J	**0**
K	1
L	2

Example

Pop the front of the queue



A	0
B	1
C	0
D	0
E	3
F	1
G	1
H	0
I	0
J	0
K	1
L	2

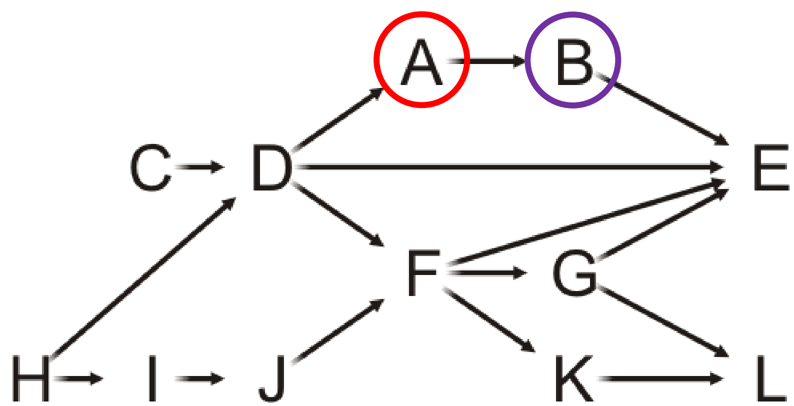
Queue:

C	H	D	I	A	J						

Example

Pop the front of the queue

– A has one neighbor: B



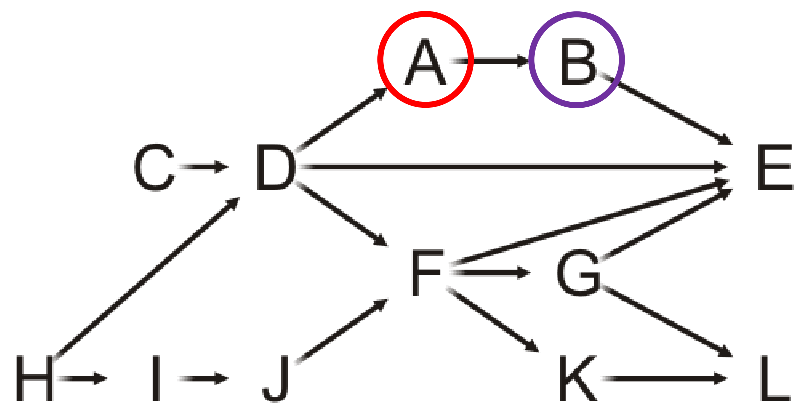
Queue:

C	H	D	I	A	J						

A	**0**
B	**1**
C	0
D	0
E	3
F	1
G	1
H	0
I	0
J	0
K	1
L	2

Example

Pop the front of the queue
- A has one neighbor: B
- Decrement its in-degree



A	0
B	0
C	0
D	0
E	3
F	1
G	1
H	0
I	0
J	0
K	1
L	2

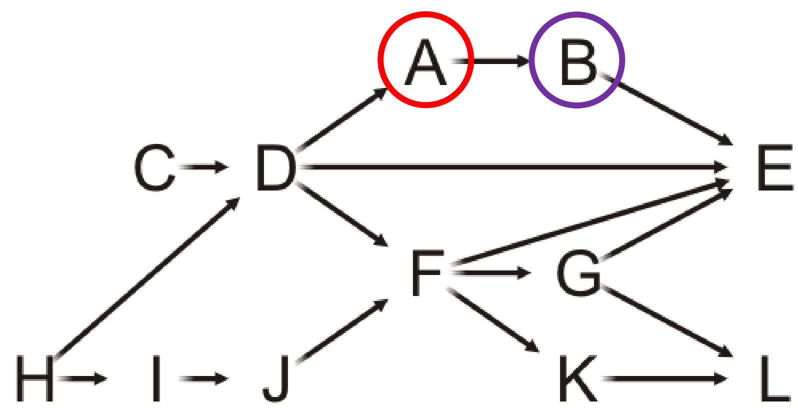
Queue:

C	H	D	I	A	J						

Example

Pop the front of the queue

- A has one neighbor: B
- Decrement its in-degree
  - B is decremented to zero, so push it onto the queue



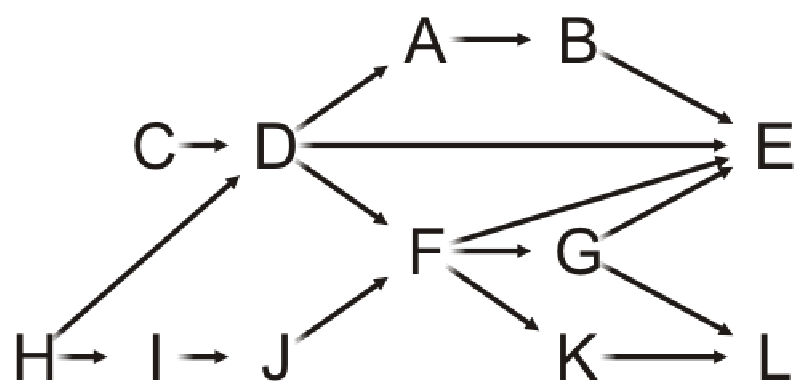
Queue:

C	H	D	I	A	J	B					

A	**0**
B	**0**
C	0
D	0
E	3
F	1
G	1
H	0
I	0
J	0
K	1
L	2

Example

Pop the front of the queue



Queue:

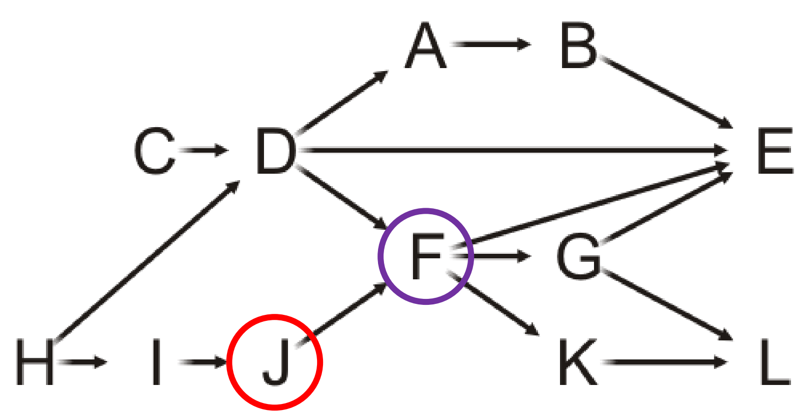
C	H	D	I	A	J	B					

A	0
B	0
C	0
D	0
E	3
F	1
G	1
H	0
I	0
J	0
K	1
L	2

Example

Pop the front of the queue

– J has one neighbor: F



Queue:

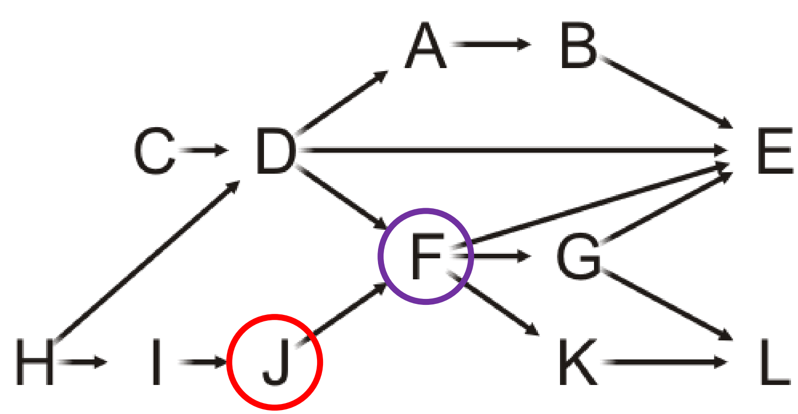
C	H	D	I	A	J	B					

A	0
B	0
C	0
D	0
E	3
F	**1**
G	1
H	0
I	0
J	**0**
K	1
L	2

Example

Pop the front of the queue

- J has one neighbor: F
- Decrement its in-degree



Queue:

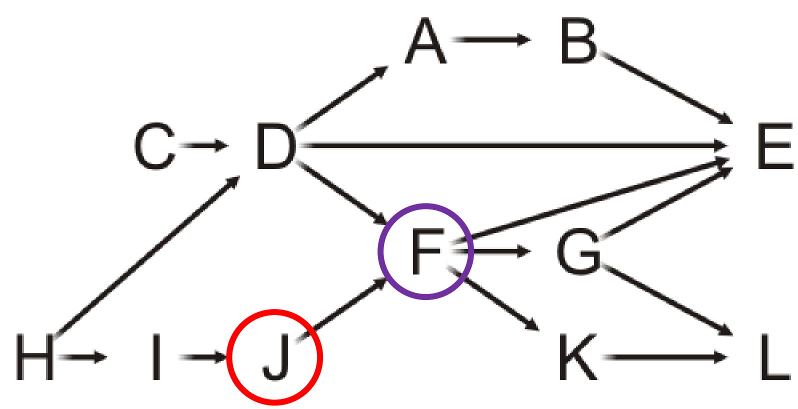
C	H	D	I	A	J	B					

A	0
B	0
C	0
D	0
E	3
F	0
G	1
H	0
I	0
J	0
K	1
L	2

Example

Pop the front of the queue

- J has one neighbor: F
- Decrement its in-degree
  - F is decremented to zero, so push it onto the queue



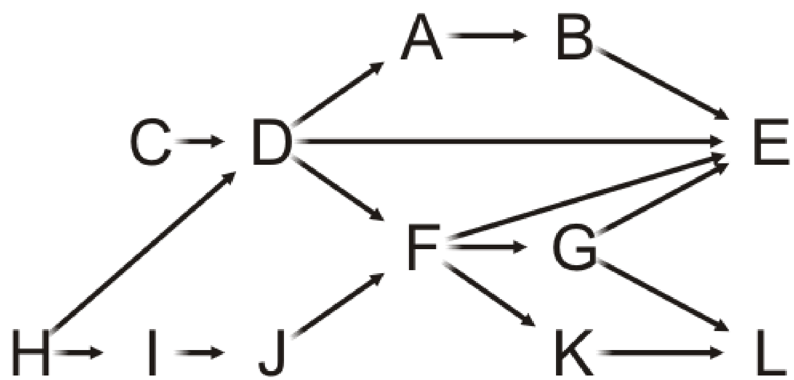
Queue:

C	H	D	I	A	J	B	F				

A	0
B	0
C	0
D	0
E	3
F	**0**
G	1
H	0
I	0
J	**0**
K	1
L	2

Example

Pop the front of the queue



Queue:

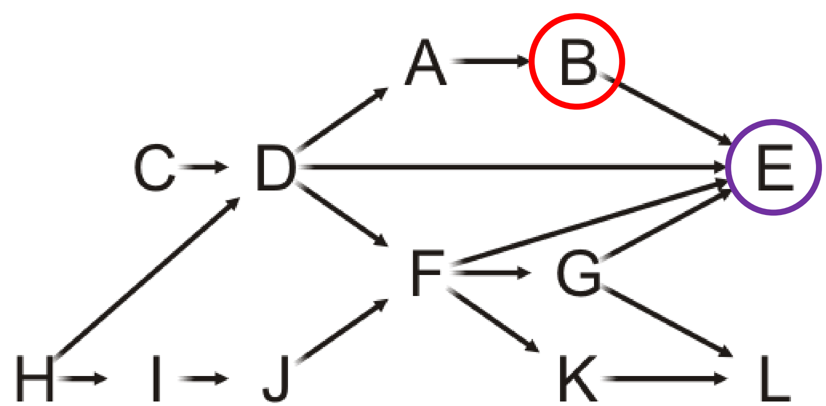
C	H	D	I	A	J	B	F				

A	0
B	0
C	0
D	0
E	3
F	0
G	1
H	0
I	0
J	0
K	1
L	2

Example

Pop the front of the queue

- B has one neighbor: E



A	0
B	**0**
C	0
D	0
E	**3**
F	0
G	1
H	0
I	0
J	0
K	1
L	2

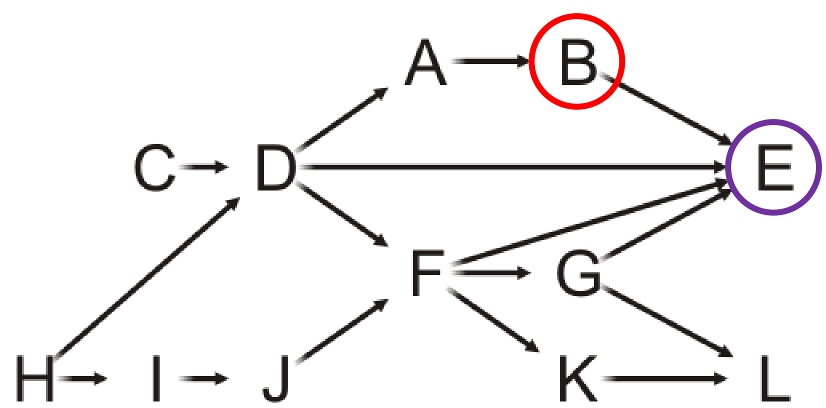
Queue:

C	H	D	I	A	J	B	F				

Example

Pop the front of the queue

- B has one neighbor: E
- Decrement its in-degree



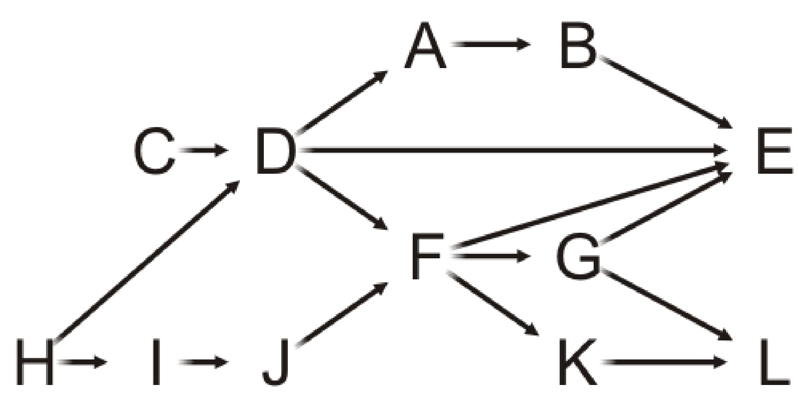
A	0
B	**0**
C	0
D	0
E	**2**
F	0
G	1
H	0
I	0
J	0
K	1
L	2

Queue:

C	H	D	I	A	J	B	F				

Example

Pop the front of the queue



A	0
B	0
C	0
D	0
E	2
F	0
G	1
H	0
I	0
J	0
K	1
L	2

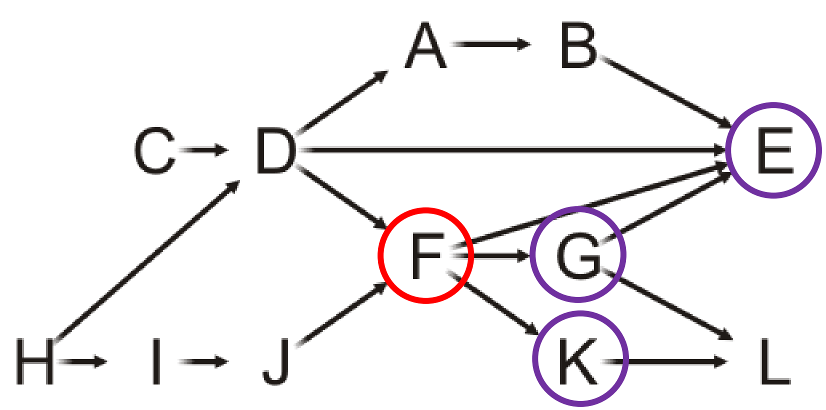
Queue:

C	H	D	I	A	J	B	F				

Example

Pop the front of the queue

– F has three neighbors: E, G and K



Queue:

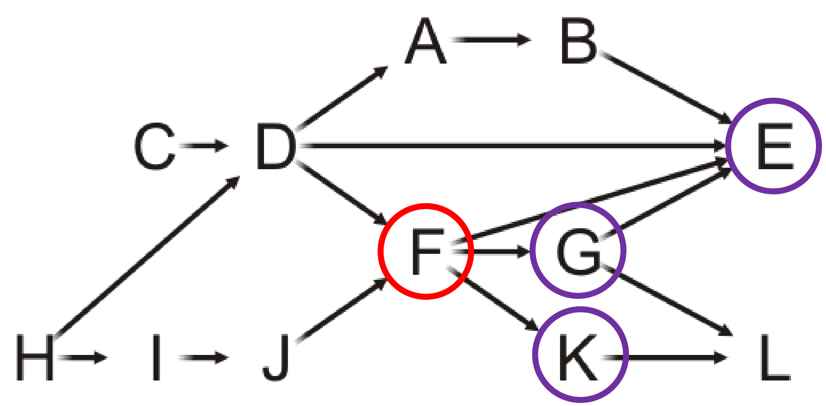
C	H	D	I	A	J	B	F				

A	0
B	0
C	0
D	0
E	**2**
F	**0**
G	**1**
H	0
I	0
J	0
K	**1**
L	2

Example

Pop the front of the queue

- F has three neighbors: E, G and K
- Decrement their in-degrees



Queue:

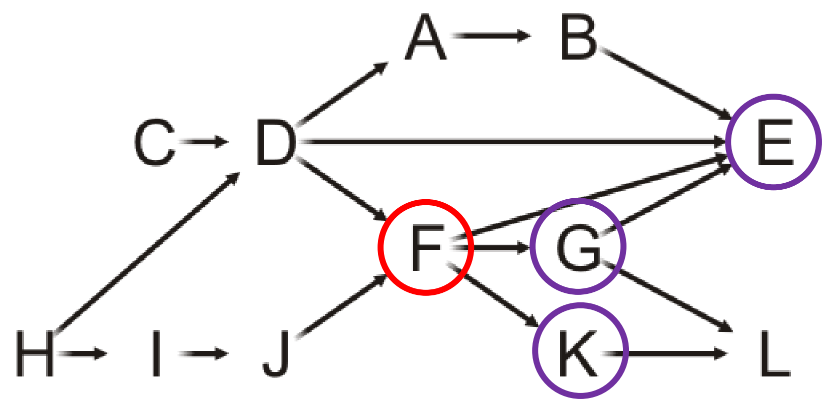
C	H	D	I	A	J	B	F				

A	0
B	0
C	0
D	0
E	**1**
F	**0**
G	**0**
H	0
I	0
J	0
K	**0**
L	2

Example

Pop the front of the queue

- F has three neighbors: E, G and K
- Decrement their in-degrees
  - G and K are decremented to zero, so push them onto the queue



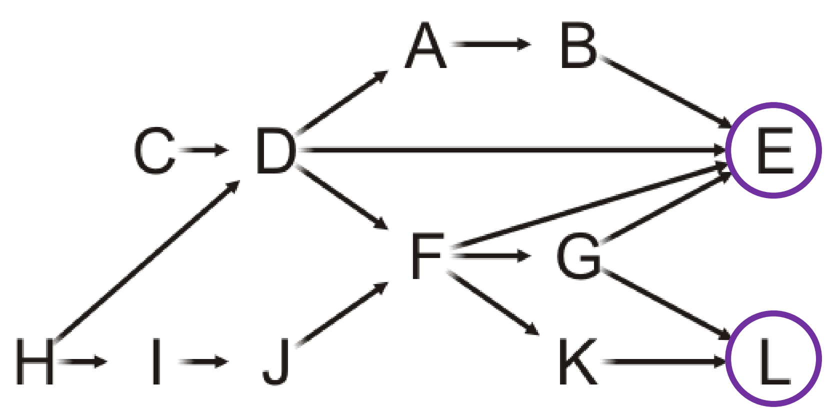
A	0
B	0
C	0
D	0
E	**1**
F	**0**
G	**0**
H	0
I	0
J	0
K	**0**
L	2

Queue:

C	H	D	I	A	J	B	F	G	K		

Example

Pop the front of the queue



Queue:

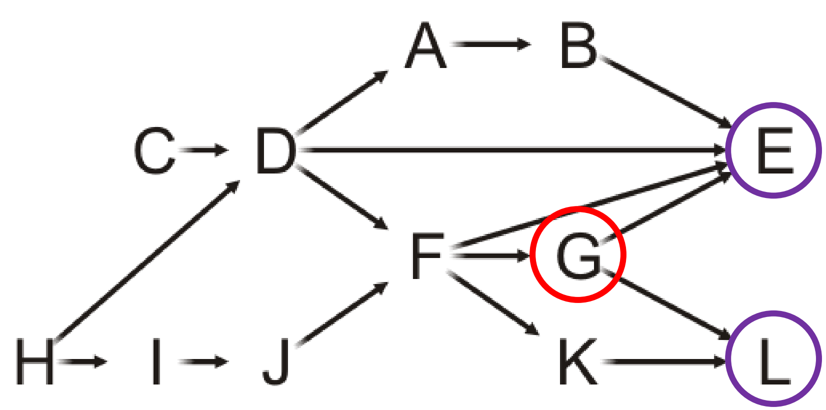
C	H	D	I	A	J	B	F	G	K		

A	0
B	0
C	0
D	0
E	1
F	0
G	0
H	0
I	0
J	0
K	0
L	2

Example

Pop the front of the queue

– G has two neighbors: E and L



A	0
B	0
C	0
D	0
E	**1**
F	0
G	**0**
H	0
I	0
J	0
K	0
L	**2**

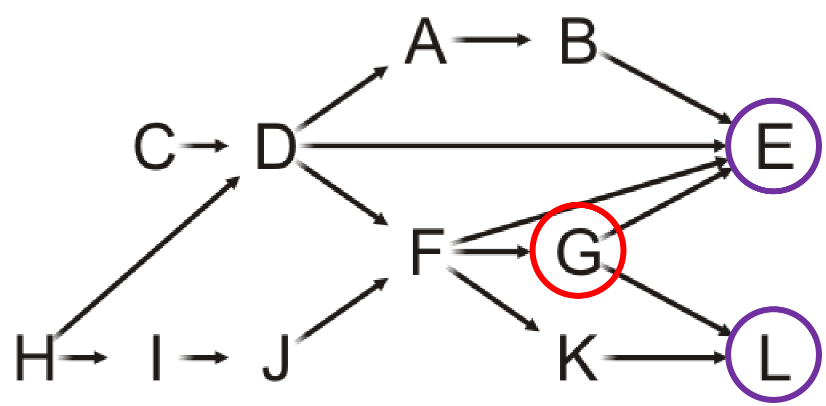
Queue:

C	H	D	I	A	J	B	F	G	K		

Example

Pop the front of the queue

- G has two neighbors: E and L
- Decrement their in-degrees



Queue:

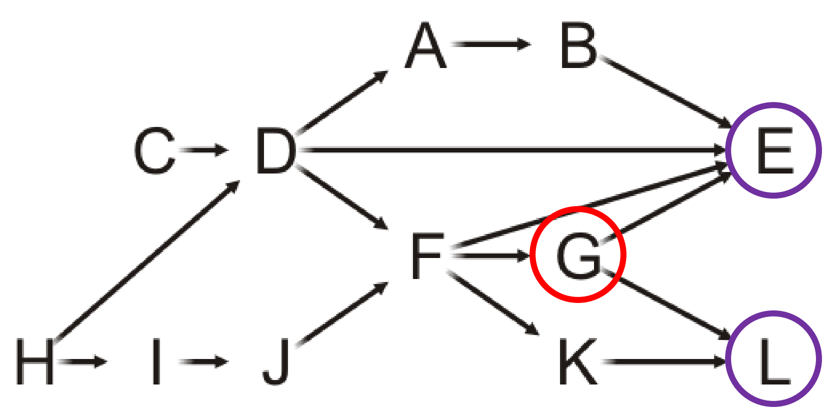
C	H	D	I	A	J	B	F	G	K		

A	0
B	0
C	0
D	0
E	**0**
F	0
G	**0**
H	0
I	0
J	0
K	0
L	**1**

Example

Pop the front of the queue

- G has two neighbors: E and L
- Decrement their in-degrees
  - E is decremented to zero, so push it onto the queue



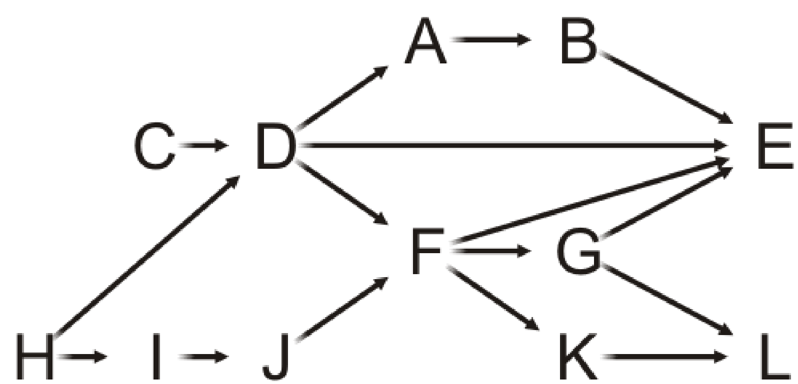
Queue:

C	H	D	I	A	J	B	F	G	K	E	

A	0
B	0
C	0
D	0
E	**0**
F	0
G	**0**
H	0
I	0
J	0
K	0
L	**1**

Example

Pop the front of the queue



Queue:

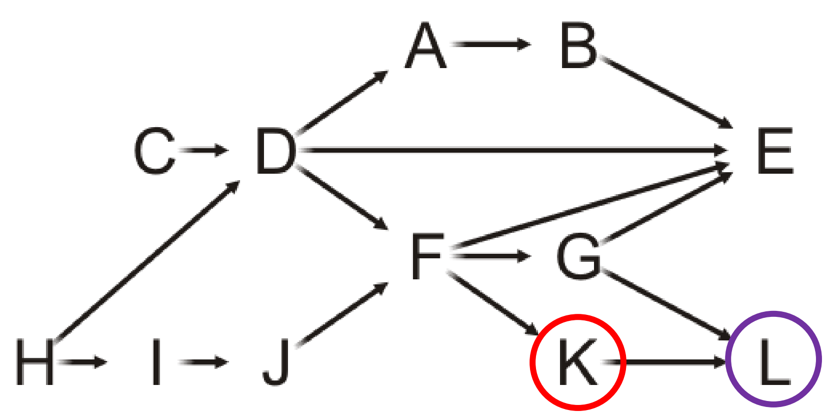
C	H	D	I	A	J	B	F	G	K	E	

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	0
L	1

Example

Pop the front of the queue

– K has one neighbors: L



Queue:

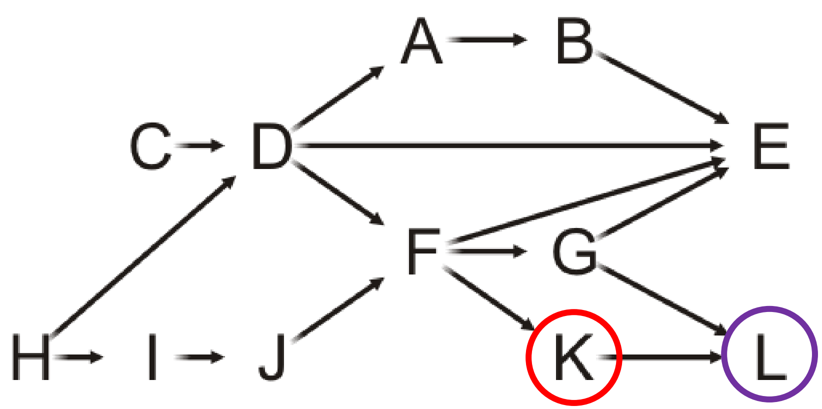
C	H	D	I	A	J	B	F	G	K	E	

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	**0**
L	**1**

Example

Pop the front of the queue

- K has one neighbors: L
- Decrement its in-degree



Queue:

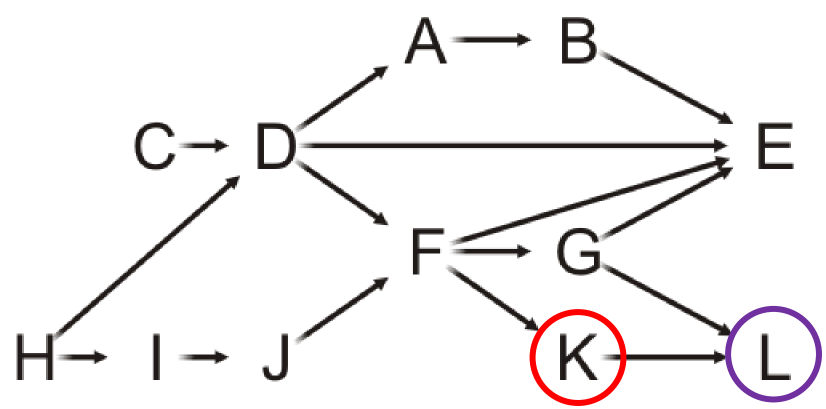
C	H	D	I	A	J	B	F	G	K	E	

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	**0**
L	**0**

Example

Pop the front of the queue

- K has one neighbors: L
- Decrement its in-degree
  - L is decremented to zero, so push it onto the queue



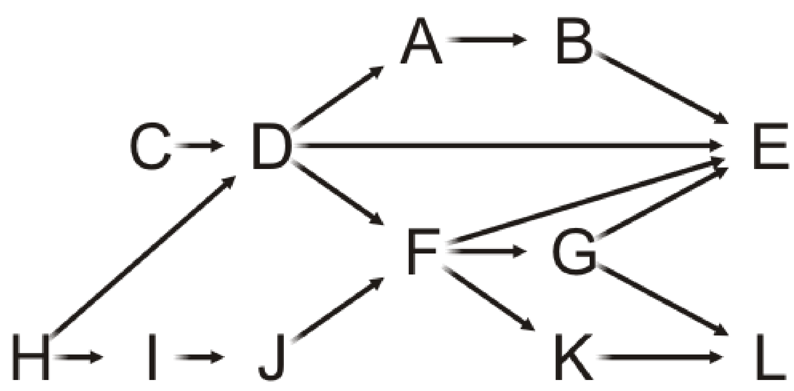
Queue:

C	H	D	I	A	J	B	F	G	K	E	L

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	**0**
L	**0**

Example

Pop the front of the queue



Queue:

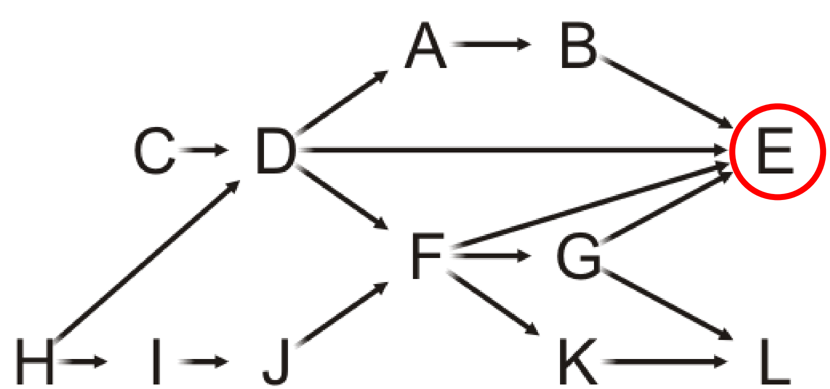
C	H	D	I	A	J	B	F	G	K	E	L

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	0
L	0

Example

Pop the front of the queue

- E has no neighbors—it is a *sink*



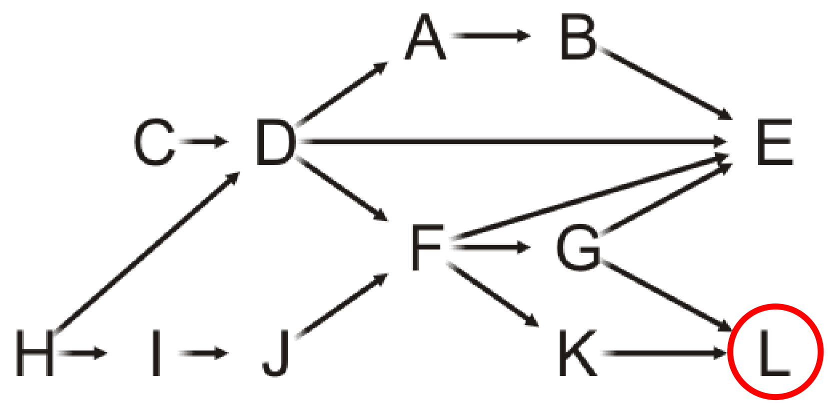
Queue:

C	H	D	I	A	J	B	F	G	K	E	L

A	0
B	0
C	0
D	0
E	**0**
F	0
G	0
H	0
I	0
J	0
K	0
L	0

Example

Pop the front of the queue



Queue:

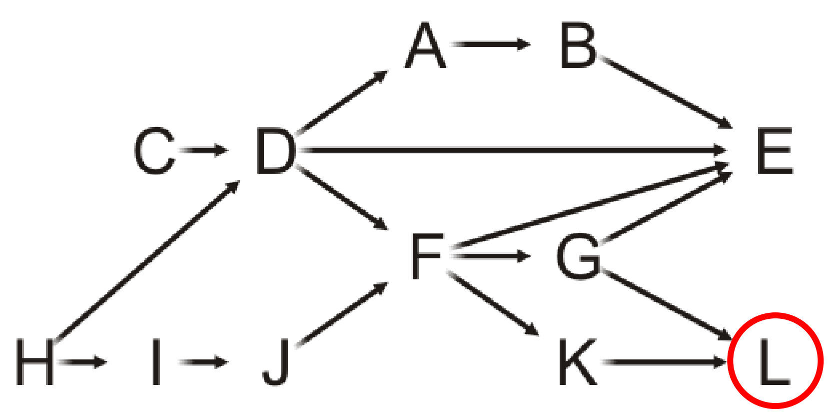
C	H	D	I	A	J	B	F	G	K	E	L

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	0
L	0

Example

Pop the front of the queue

– L has no neighbors—it is also a *sink*



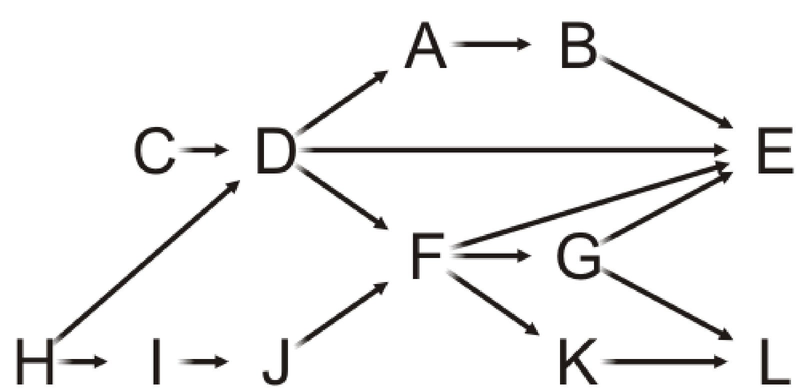
Queue:

C	H	D	I	A	J	B	F	G	K	E	L

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	0
L	**0**

Example

The queue is empty, so we are done



Queue:

C	H	D	I	A	J	B	F	G	K	E	L

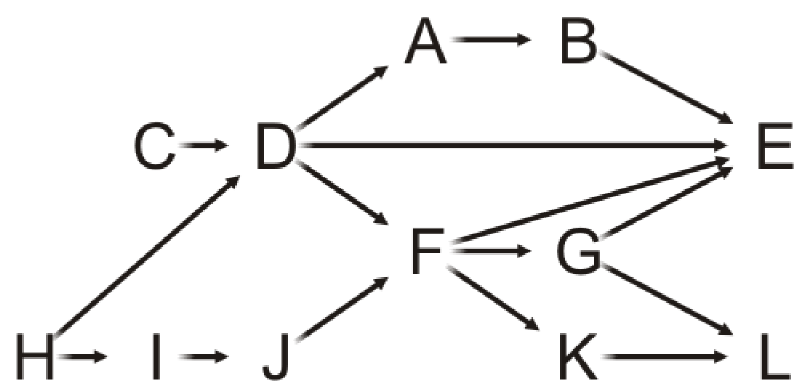
A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	0
L	0

Example

We deallocate the memory for the temporary in-degree array

The array stores the topological sorting

A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	0
L	0



C	H	D	I	A	J	B	F	G	K	E	L

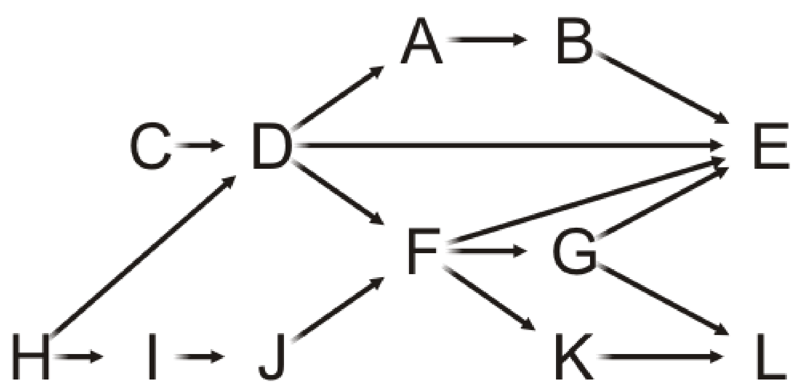
Example

We deallocate the memory for the temporary in-degree array

The array used for the queue stores the topological sort

– Note the difference in order from our previous sort?

C, H, D, A, B, I, J, F, G, E, K, L



C	H	D	I	A	J	B	F	G	K	E	L

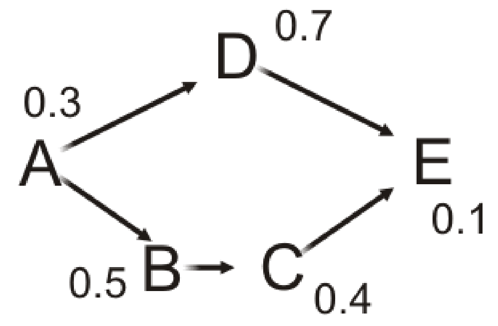
A	0
B	0
C	0
D	0
E	0
F	0
G	0
H	0
I	0
J	0
K	0
L	0

11.4.8

Critical path

Suppose each task has a performance time associated with it

– If the tasks are performed serially, the time required to complete the last task equals to the sum of the individual task times



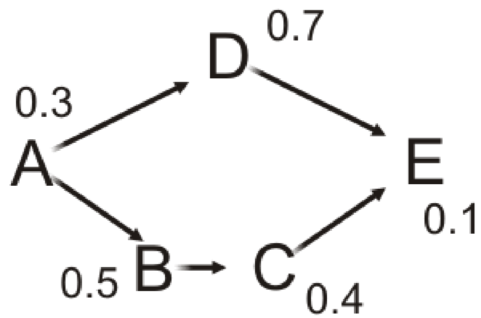
– These tasks require $0.3 + 0.7 + 0.5 + 0.4 + 0.1 = 2.0$ s to execute serially

11.4.8

Critical path

Suppose two tasks are ready to execute

- We could perform these tasks in parallel



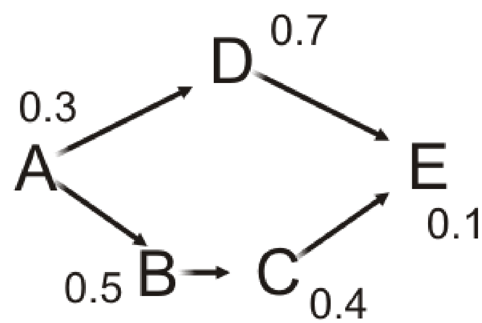
- Computer tasks can be executed in parallel (multi-processing)
- Different tasks can be completed by different teams in a company

11.4.8

Critical path

Suppose Task A completes

– We can now execute Tasks B and D in parallel



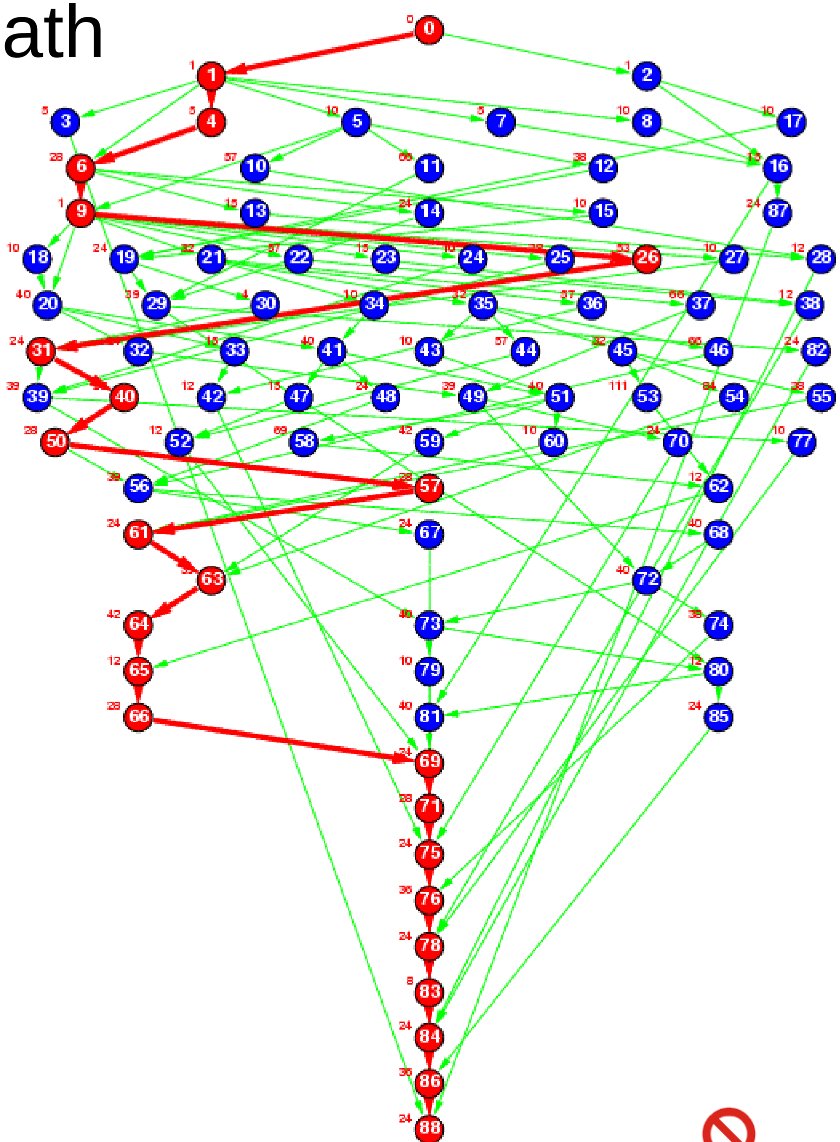
– However, Task E cannot execute until Task C completes, and Task C cannot execute until Task B completes
  - The least time in which these five tasks can be completed is

$$0.3 + 0.5 + 0.4 + 0.1 = 1.3 \text{ s}$$

  - This is called the *critical time of all tasks*
  - The path (A, B, C, E) is said to be the *critical path*

11.4.8

Critical path



- The program described previously shows the critical path in red
  - We will define the *critical time* of each task to be the earliest time that it could be completed after the start of execution

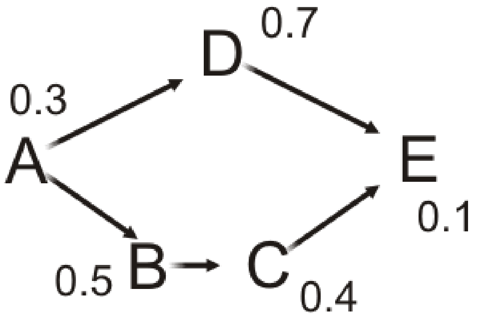
Ref: The Standard Task Graph
http://www.kasahara.elec.waseda.ac.jp/schedule/

11.4.8

Finding the critical path

Tasks that have no prerequisites have a critical time equal to the time it takes to complete that task

For tasks that depend on others, the critical time will be:
- The maximum critical time that it takes to complete a prerequisite
- Plus the time it takes to complete this task



In this example, the critical times are:
- Task A completes in 0.3 s
- Task B must wait for A and completes after 0.8 s
- Task D must wait for A and completes after 1.0 s
- Task C must wait for B and completes after 1.2 s
- Task E must wait for both C and D, and completes after

$$\max(1.0, 1.2) + 0.1 = 1.3 \text{ s}$$

11.4.8.1

Finding the critical path

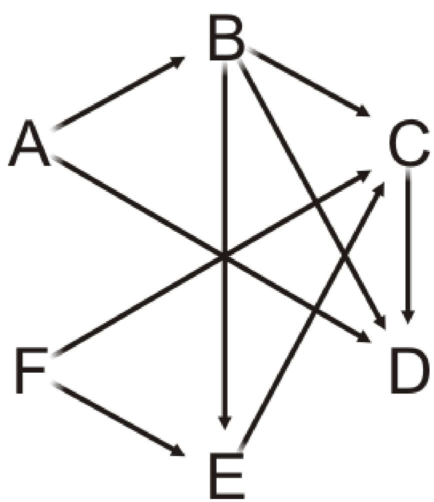
Thus, we require more information:

- We must know the execution time of each task
- We will have to record the critical time for each task
  - Initialize these to zero
- We will need to know the previous task with the longest critical time to determine the critical path
  - Set these to null

11.4.8.2

Finding the critical path

Suppose we have the following times for the tasks



Queue

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	0.0	Ø
B	1	6.1	0.0	Ø
C	3	4.7	0.0	Ø
D	3	8.1	0.0	Ø
E	2	9.5	0.0	Ø
F	0	17.1	0.0	Ø

11.4.8.2

Finding the critical path

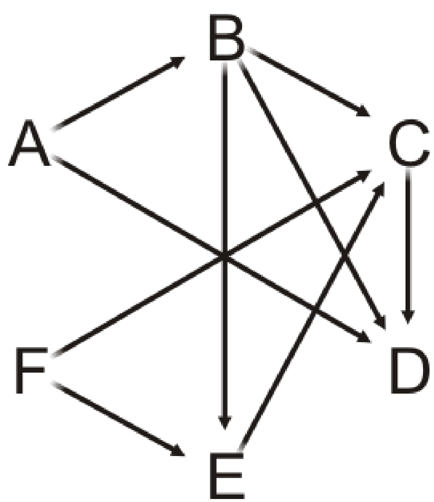
Each time we pop a vertex v, in addition to what we already do:

- For v, add the task time onto the critical time for that vertex:
  - That is the critical time for v
- For each adjacent vertex w:
  - If the critical time for v is greater than the currently stored critical time for w
    - Update the critical time with the critical time for v
    - Set the previous pointer to the vertex v

11.4.8.2

Finding the critical path

So we initialize the queue with those vertices with in-degree zero



Queue

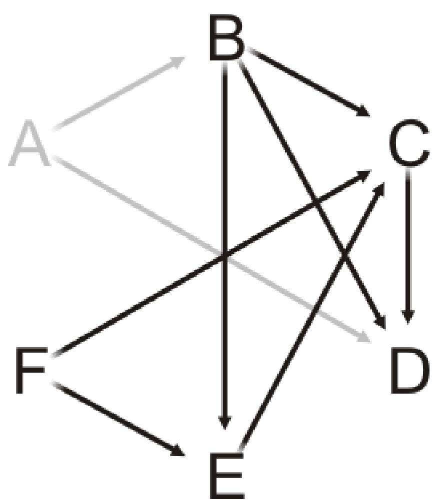
A	**F**		

Task	In-degree	Task Time	Critical Time	Previous Task
A	**0**	5.2	0.0	Ø
B	1	6.1	0.0	Ø
C	3	4.7	0.0	Ø
D	3	8.1	0.0	Ø
E	2	9.5	0.0	Ø
F	**0**	17.1	0.0	Ø

11.4.8.2

Finding the critical path

Pop Task A and update its critical time 0.0 + 5.2 = 5.2



Queue

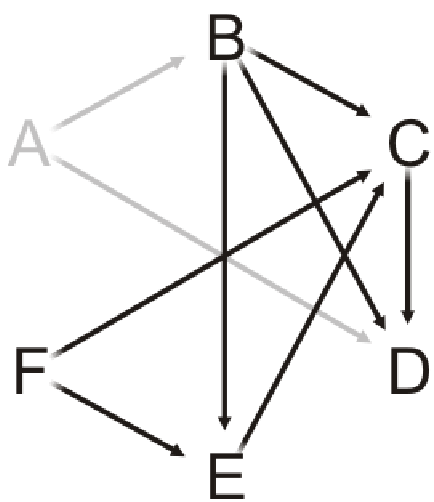
F			

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	0.0	Ø
B	1	6.1	0.0	Ø
C	3	4.7	0.0	Ø
D	3	8.1	0.0	Ø
E	2	9.5	0.0	Ø
F	0	17.1	0.0	Ø

11.4.8.2

Finding the critical path

Pop Task A and update its critical time 0.0 + 5.2 = 5.2



Queue

F			

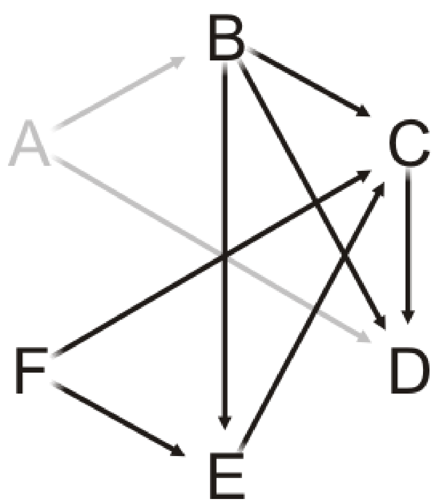
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	**5.2**	Ø
B	1	6.1	0.0	Ø
C	3	4.7	0.0	Ø
D	3	8.1	0.0	Ø
E	2	9.5	0.0	Ø
F	0	17.1	0.0	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task A:

– Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

F			

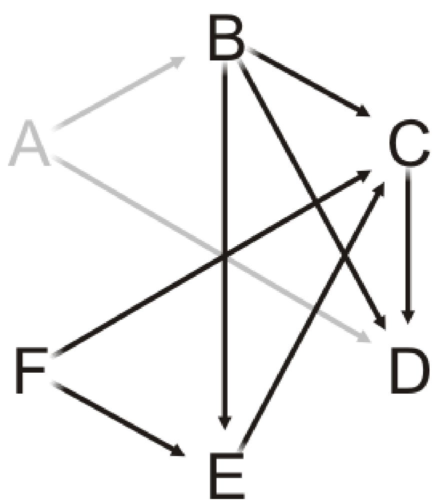
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	1	6.1	0.0	Ø
C	3	4.7	0.0	Ø
D	3	8.1	0.0	Ø
E	2	9.5	0.0	Ø
F	0	17.1	0.0	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task A:

– Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

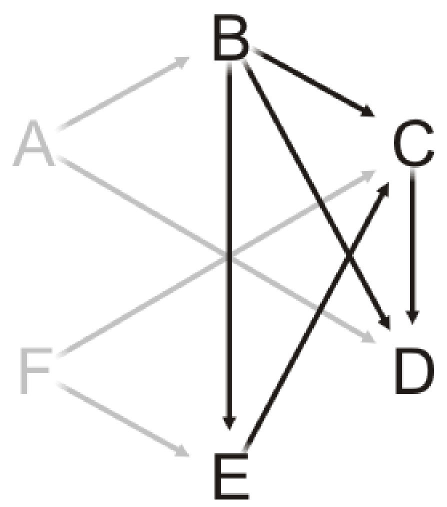
F	**B**		

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	**0**	6.1	**5.2**	**A**
C	3	4.7	0.0	Ø
D	**2**	8.1	**5.2**	**A**
E	2	9.5	0.0	Ø
F	0	17.1	0.0	Ø

11.4.8.2

Finding the critical path

Pop Task F and update its critical time 0.0 + 17.1 = 17.1



Queue

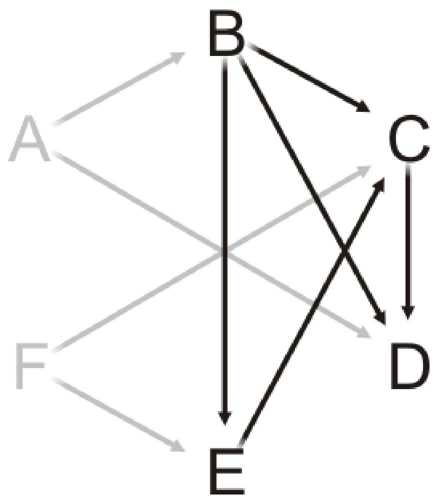
B			

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	5.2	A
C	3	4.7	0.0	Ø
D	2	8.1	5.2	A
E	2	9.5	0.0	Ø
F	0	17.1	0.0	Ø

11.4.8.2

Finding the critical path

Pop Task F and update its critical time 0.0 + 17.1 = 17.1



Queue

B			

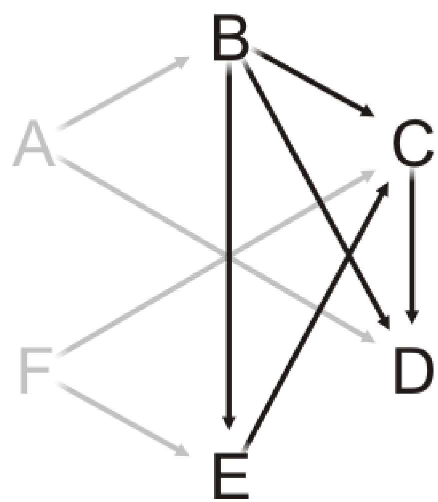
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	5.2	A
C	3	4.7	0.0	Ø
D	2	8.1	5.2	A
E	2	9.5	0.0	Ø
F	0	17.1	**17.1**	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task F:

- Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

B			

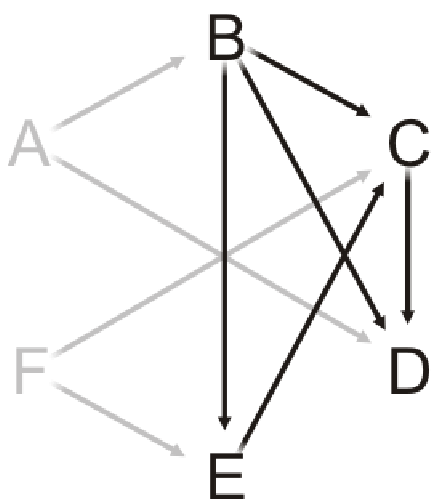
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	5.2	A
C	3	4.7	0.0	Ø
D	2	8.1	5.2	A
E	2	9.5	0.0	Ø
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task F:

- Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

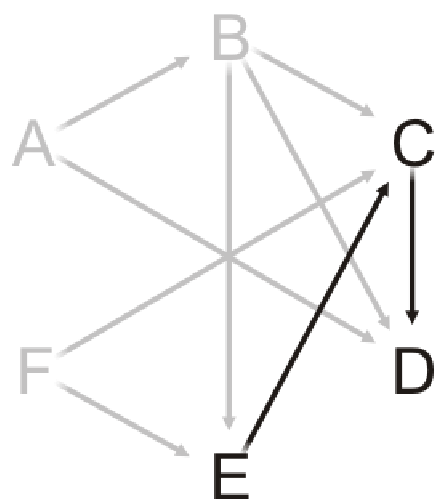
B			

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	5.2	A
C	**2**	4.7	**17.1**	**F**
D	2	8.1	5.2	A
E	**1**	9.5	**17.1**	**F**
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task B and update its critical time 5.2 + 6.1 = 11.3



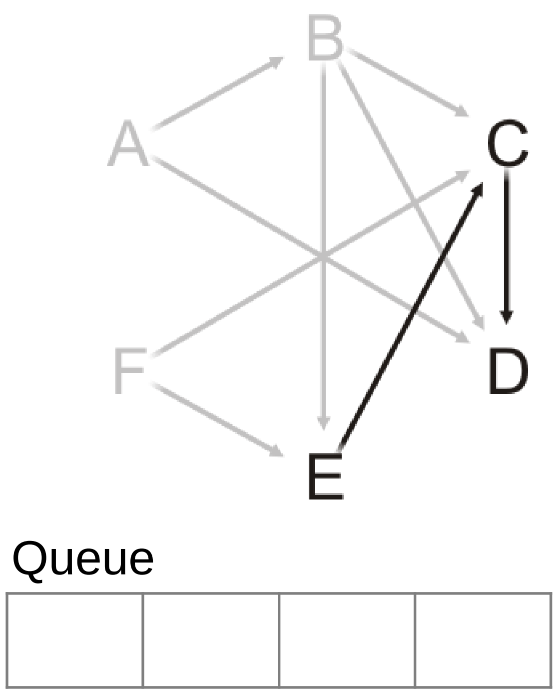
Queue

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	5.2	A
C	2	4.7	17.1	F
D	2	8.1	5.2	A
E	1	9.5	17.1	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task B and update its critical time 5.2 + 6.1 = 11.3



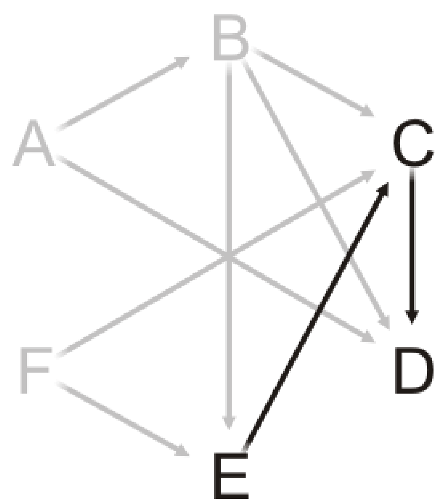
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	**11.3**	A
C	2	4.7	17.1	F
D	2	8.1	5.2	A
E	1	9.5	17.1	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task B:

– Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

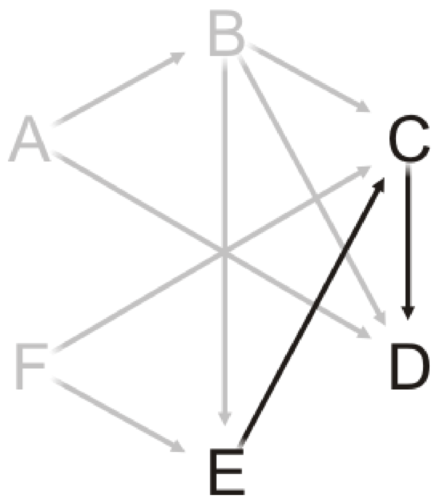
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	2	4.7	17.1	F
D	2	8.1	5.2	A
E	1	9.5	17.1	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task B:

- Decrement the in-degree, push if necessary, and check if we must update the critical time
- Both C and E are waiting on F



Queue

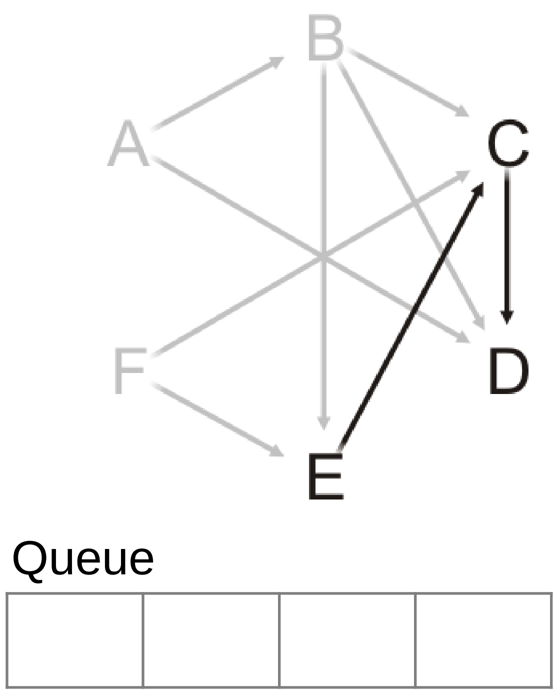
E			

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	**1**	4.7	17.1	F
D	**1**	8.1	**11.3**	**B**
E	**0**	9.5	17.1	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task E and update its critical time 17.1 + 9.5 = 26.6

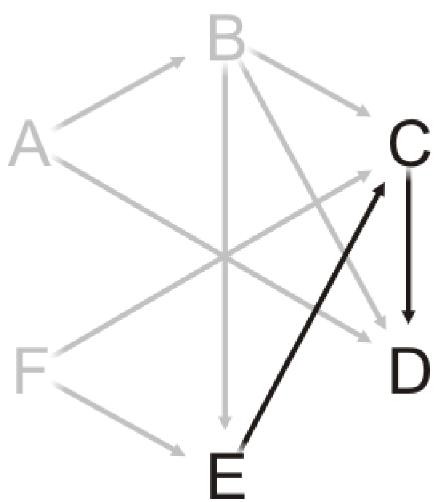


Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	1	4.7	17.1	F
D	1	8.1	11.3	B
E	0	9.5	17.1	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task E and update its critical time 17.1 + 9.5 = 26.6



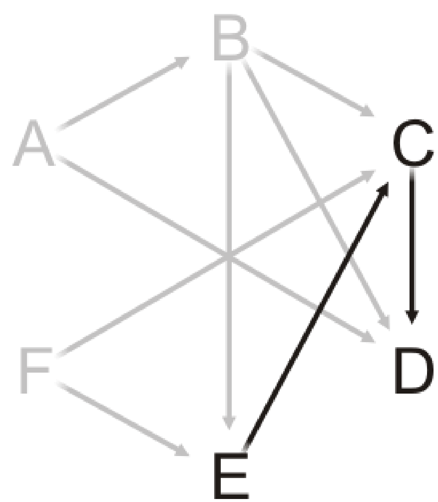
Queue

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	1	4.7	17.1	F
D	1	8.1	11.3	B
E	0	9.5	**26.6**	F
F	0	17.1	17.1	Ø

Finding the critical path

For each neighbor of Task E:

- Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

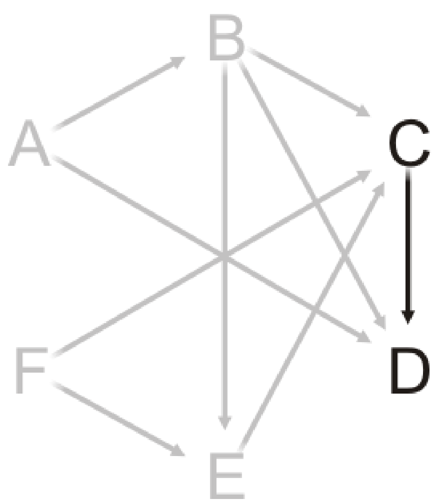
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	1	4.7	17.1	F
D	1	8.1	11.3	B
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task E:

- Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

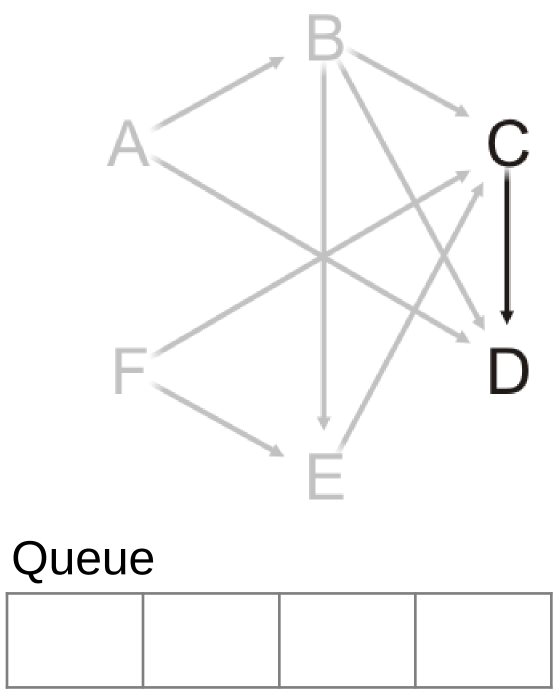
C			

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	**0**	4.7	**26.6**	**E**
D	1	8.1	11.3	B
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task C and update its critical time 26.6 + 4.7 = 31.3

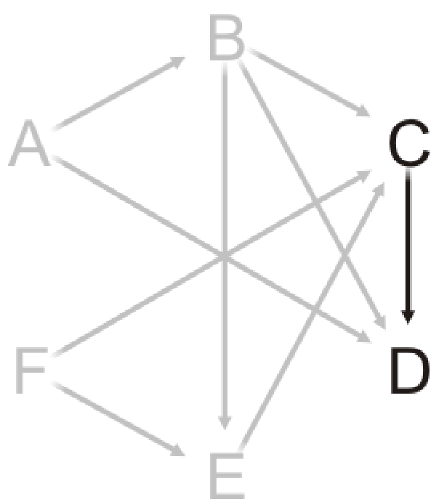


Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	26.6	E
D	1	8.1	11.3	B
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task C and update its critical time 26.6 + 4.7 = 31.3



Queue

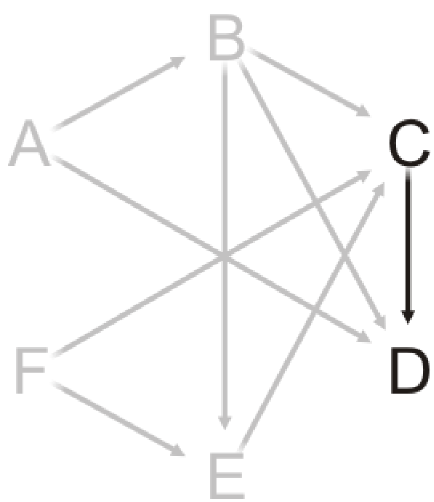
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	**31.3**	E
D	1	8.1	11.3	B
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task C:

– Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

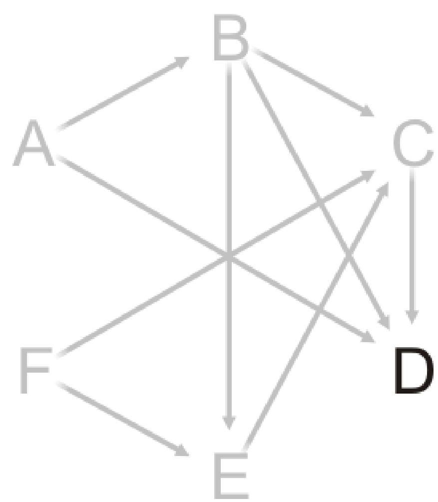
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	31.3	E
D	1	8.1	11.3	B
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

For each neighbor of Task C:

- Decrement the in-degree, push if necessary, and check if we must update the critical time



Queue

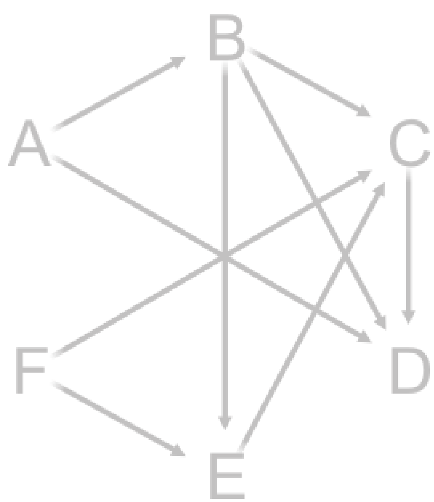
D			

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	31.3	E
D	**0**	8.1	**31.3**	**C**
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task D and update its critical time 31.3 + 8.1 = 39.4



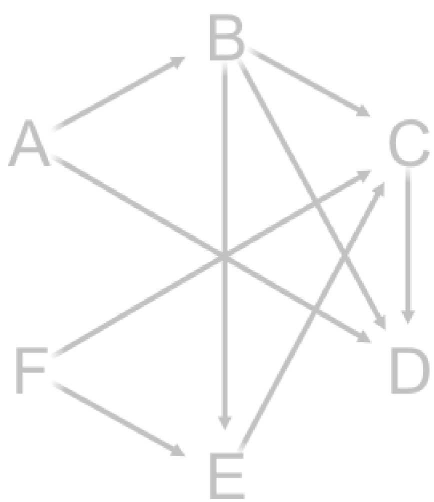
Queue

Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	31.3	E
D	0	8.1	31.3	C
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Pop Task D and update its critical time 31.3 + 8.1 = 39.4



Queue

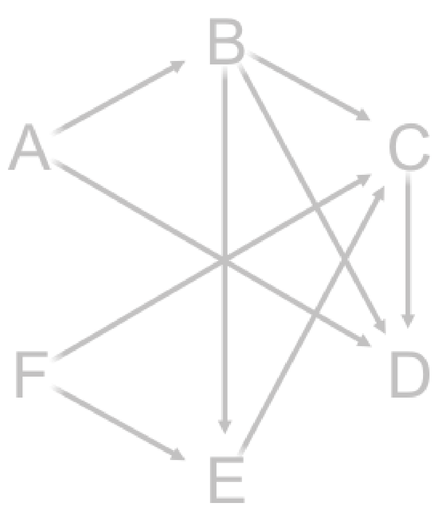
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	31.3	E
D	0	8.1	**39.4**	C
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Task D has no neighbors and the queue is empty

– We are done



Queue

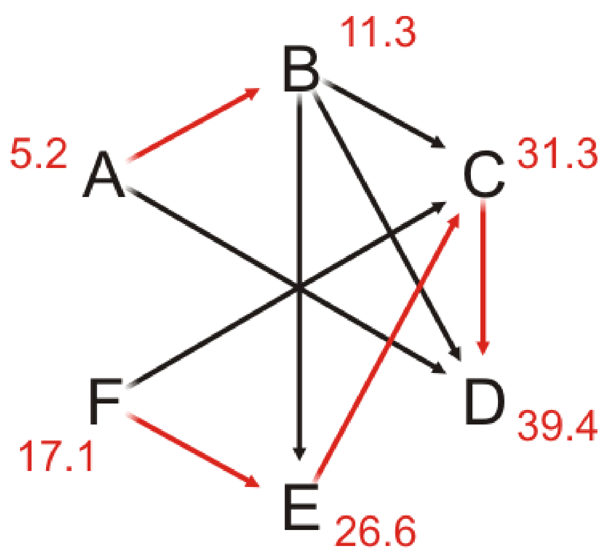
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	31.3	E
D	0	8.1	39.4	C
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Task D has no neighbors and the queue is empty

- We are done



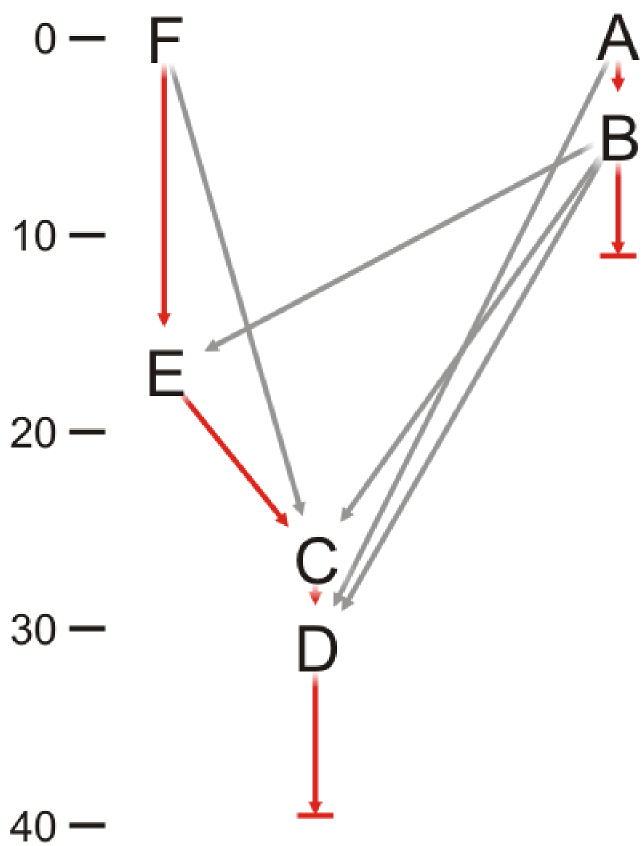
Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	31.3	E
D	0	8.1	39.4	C
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

We can also plot the completing of the tasks tasks in time

– We need to be able to execute two tasks in parallel for this example

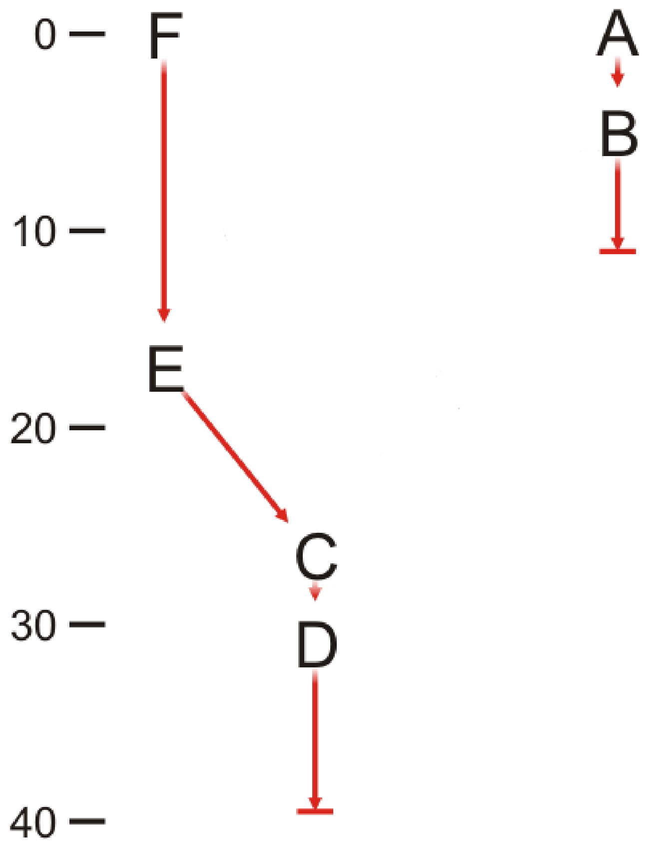


Task	In-degree	Task Time	Critical Time	Previous Task
A	0	5.2	5.2	Ø
B	0	6.1	11.3	A
C	0	4.7	31.3	E
D	0	8.1	39.4	C
E	0	9.5	26.6	F
F	0	17.1	17.1	Ø

11.4.8.2

Finding the critical path

Incidentally, the task and previous task defines a forest using the parental tree data structure



Task	Previous Task
A	Ø
B	A
C	E
D	C
E	F
F	Ø

Summary

In this topic, we have discussed topological sorts

- Sorting of elements in a DAG
- Implementation
  - A table of in-degrees
  - Select that vertex which has current in-degree zero
- We defined critical paths
  - The implementation requires only a few more table entries

References

Wikipedia, http://en.wikipedia.org/wiki/Topological_sorting

[1] Cormen, Leiserson, and Rivest, *Introduction to Algorithms*, McGraw Hill, 1990, §11.1, p.200.

[2] Weiss, Data Structures and Algorithm Analysis in C++, 3rd Ed., Addison Wesley, §9.2, p.342-5.