

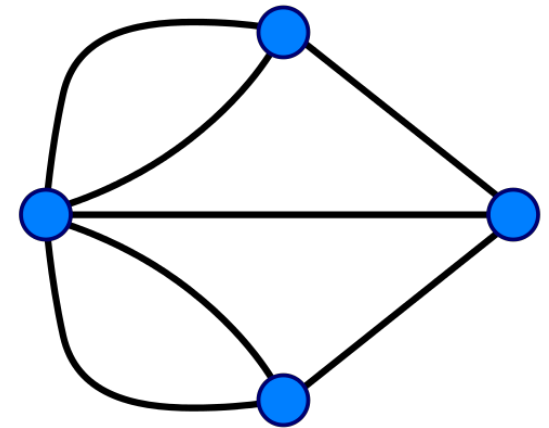
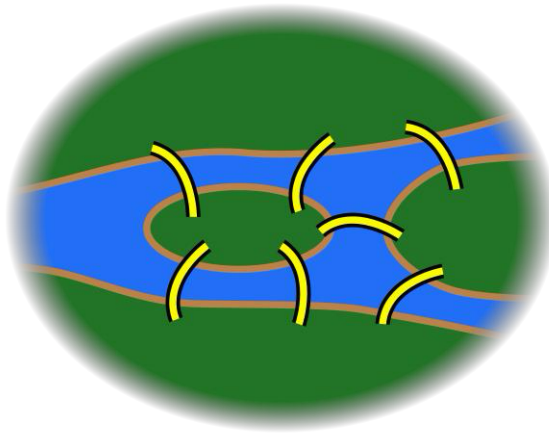
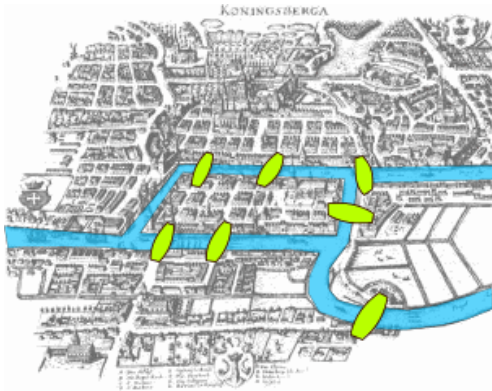
# Lecture 9: Graph

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Bo Tang @ SUSTech, Fall 2024

# Seven Bridges of Königsberg

- ◆ City A was set on both sides of the River, and included two large islands which were connected to each other by seven bridges. The problem was to devise a walk through the city that would cross each of those bridges once and only once.



- ◆ Eulerian path (In Chinese: 一笔画问题)

# Our Roadmap

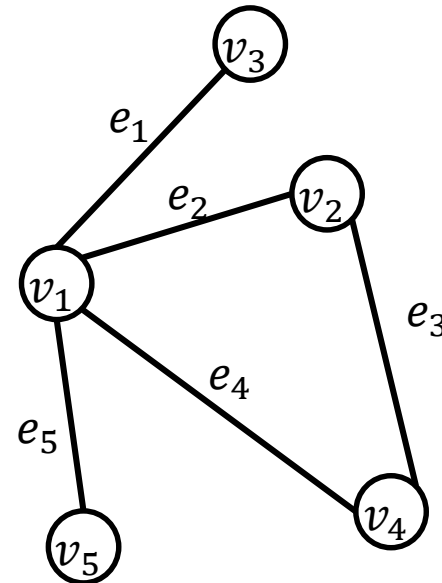
- ◆ Graph Concepts
- ◆ Graph Traversal
  - ◆ Breath First Search (SSSP)
  - ◆ Depth First Search (DAG, topological sort)
- ◆ Shortest Path Algorithm (SP)
- ◆ Minimum Spanning Tree (MST)
- ◆ Strongly Connected Component (SCC)

# Undirected Graph

- ◆ An undirected graph is a pair of  $(V, E)$  where:
  - ◆  $V$  is a set of elements, each of which called a node
  - ◆  $E$  is a set of unordered pairs  $\{u, v\}$  such that  $u$  and  $v$  are nodes
- ◆ A node may also be called a vertex. We will refer to  $V$  as the vertex set or the node set of graph, and  $E$  the edge set.

- ◆ Example:

- ◆  $V = \{v_1, v_2, v_3, v_4, v_5\}$
- ◆  $E = \{e_1, e_2, e_3, e_4, e_5\}$

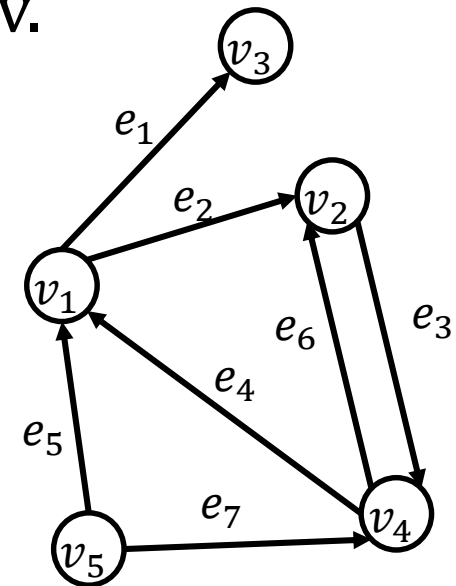


# Directed Graph

- ◆ An directed graph is a pair of  $(V, E)$  where:
  - ◆  $V$  is a set of elements, each of which called a node
  - ◆  $E$  is a set of unordered pairs  $\{u, v\}$  where  $u$  and  $v$  are nodes, we say there is a directed edge from  $u$  to  $v$ .
- ◆ A directed edge  $(u, v)$  is said to be an outgoing edge of  $u$ , and incoming edge of  $v$ . Accordingly,  $v$  is an out-neighbor of  $u$ , and  $u$  is in-neighbor of  $v$ .
- ◆ Note that every edge has a direction.

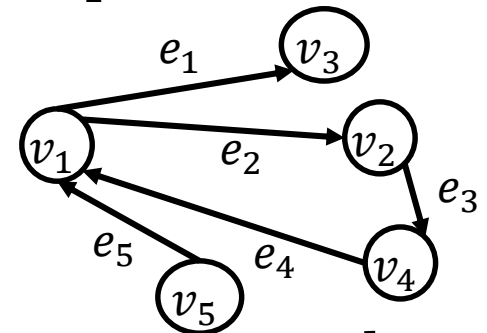
- ◆ Example:

- ◆  $V = \{v_1, v_2, v_3, v_4, v_5\}$
- ◆  $E = \{e_1, e_2, e_3, e_4, e_5, e_6, e_7\}$
- ◆  $e_3 = \{v_2, v_4\}$
- ◆  $e_6 = \{v_4, v_2\}$



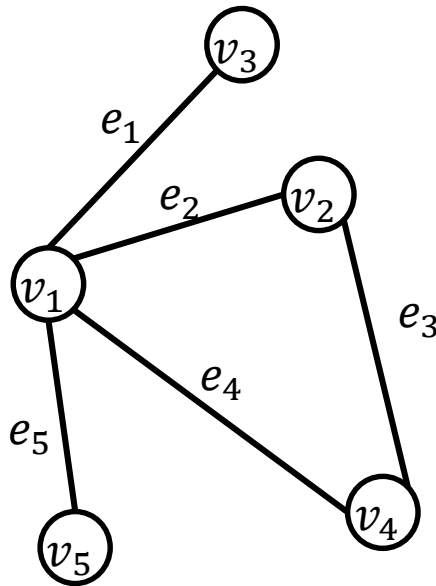
# Definitions in Graph

- ◆ Let  $G = (V, E)$  be a graph. A path in  $G$  is a sequence of nodes  $(v_1, v_2, \dots, v_k)$  such that
  - ◆ For every  $i \in [1, k - 1]$ , there is an edge between  $v_i$  and  $v_{i+1}$ .
- ◆ A cycle in  $G$  is a trail in which the only repeated vertices are the first and last vertices.
- ◆ Example:
  - ◆ Cycle:  $(v_1, v_2, v_4, v_1)$ ; Path:  $(v_5, v_1, v_2, v_4)$
- ◆ In an undirected graph, the degree of vertex  $u$  is the number of edges of  $u$
- ◆ In a directed graph, the out-degree of a vertex  $u$  is the number of outgoing edges of  $u$ , and its in-degree is the number of its incoming edges

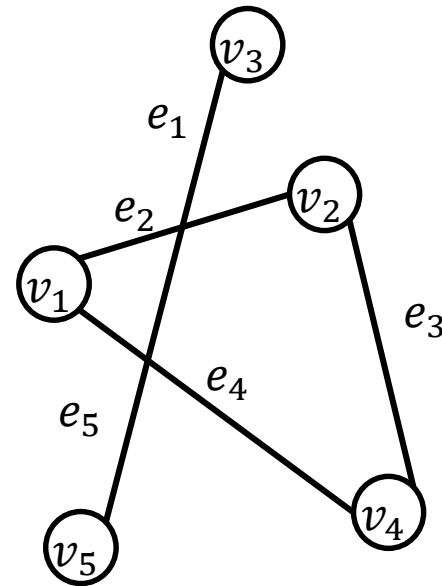


# Connected Graph

- ◆ An undirected graph  $G=(V,E)$  is connected if, for any two distinct vertices  $u$  and  $v$ ,  $G$  has a path from  $u$  to  $v$ .



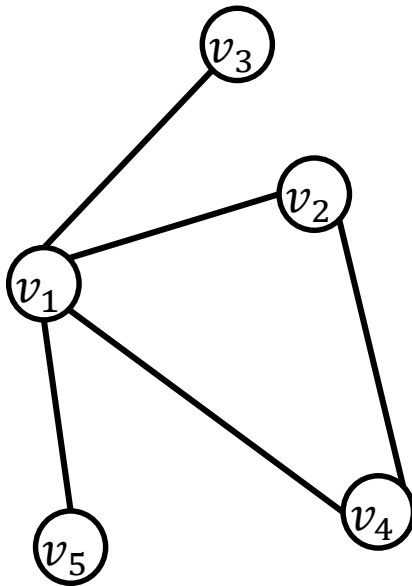
connected



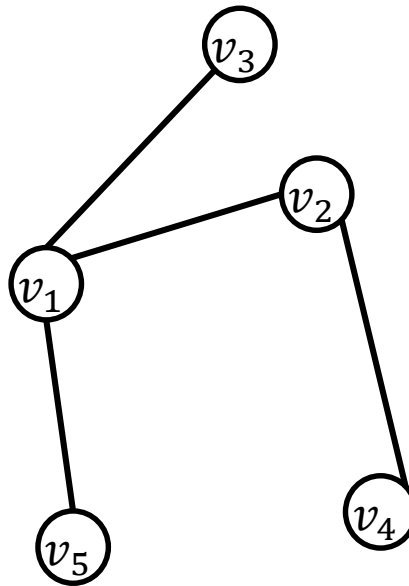
not connected

# Graph vs. Tree vs. Forest

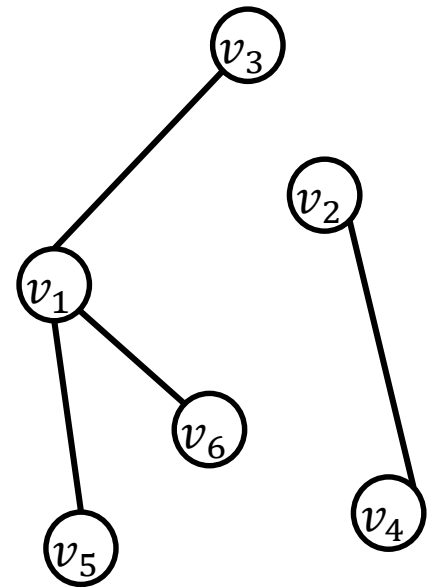
- ◆ A tree is a connected undirected graph contains no cycles.
- ◆ Forest is a set of disjoint trees.



Graph, not tree



Graph, tree



Graph, forest

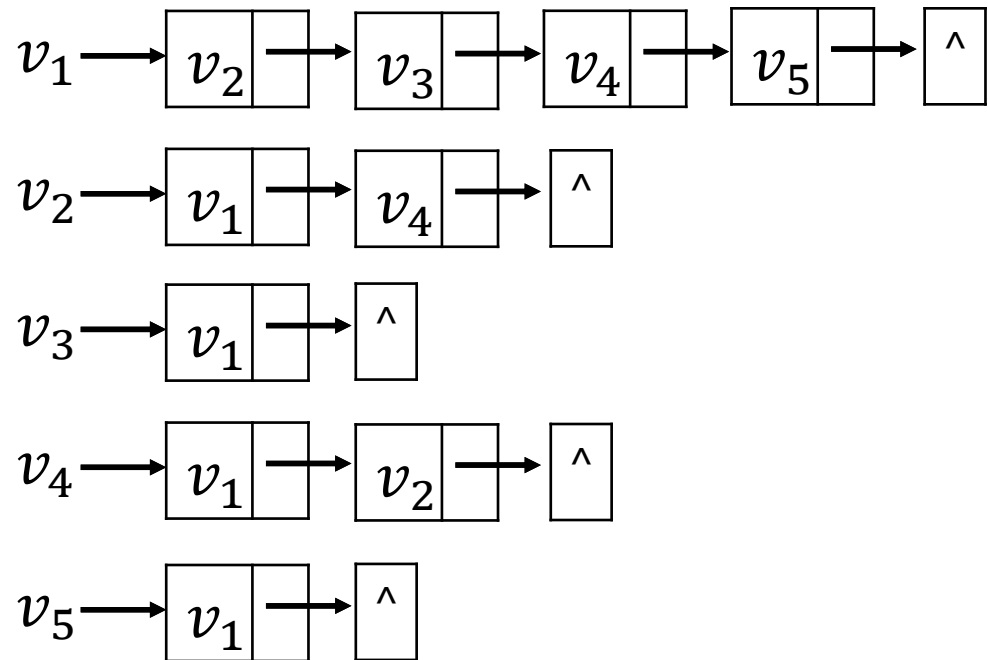
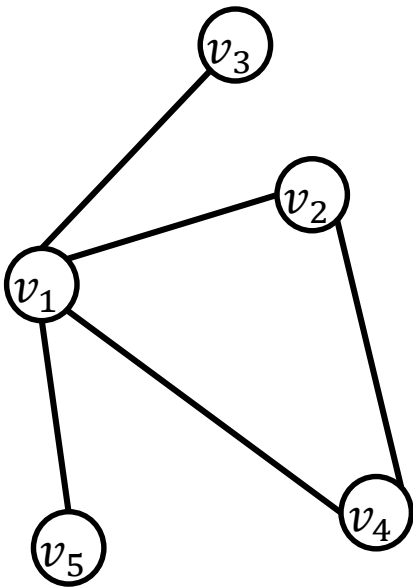


# Graph Representation

- ◆ We discuss two common way to store a graph:
  - ◆ Adjacency list
  - ◆ Adjacency matrix
- ◆ In both cases, we represent each vertex in  $V$  using a unique id in  $1, 2, \dots, |V|$

# Adjacency List: Undirected $G$

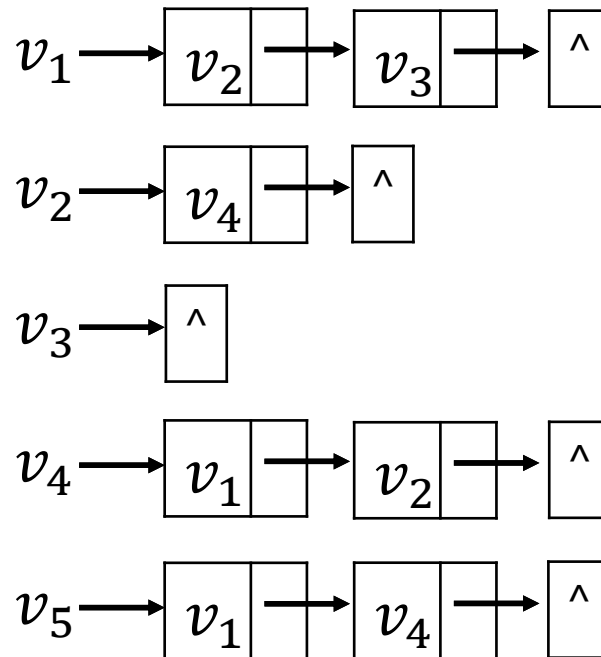
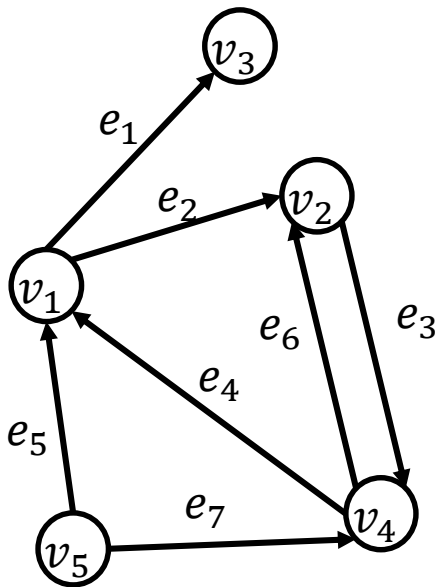
- Each vertex  $u \in V$  is associated with a linked list that enumerates all the vertices that are connected to  $u$ .



- Space =  $O(|V| + |E|)$

# Adjacency List: Directed G

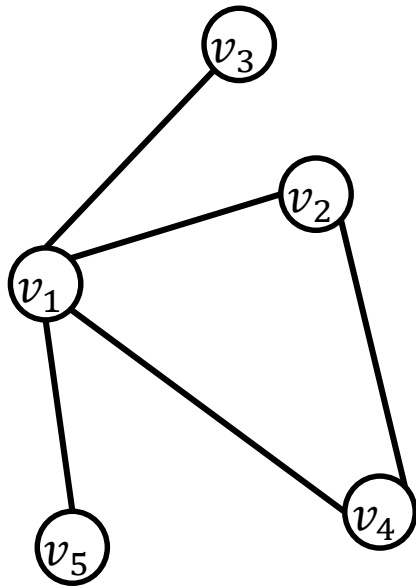
- Each vertex  $u \in V$  is associated with a linked list that enumerates all the vertices  $v \in V$  that there is an edge from  $u$  to  $v$ .



- Space =  $O(|V| + |E|)$

# Adjacency Matrix: Undirected $G$

- ◆ A  $|V| \times |V|$  matrix  $A$  where  $A[u,v] = 1$  if  $(u,v) \in E$ , or 0 otherwise

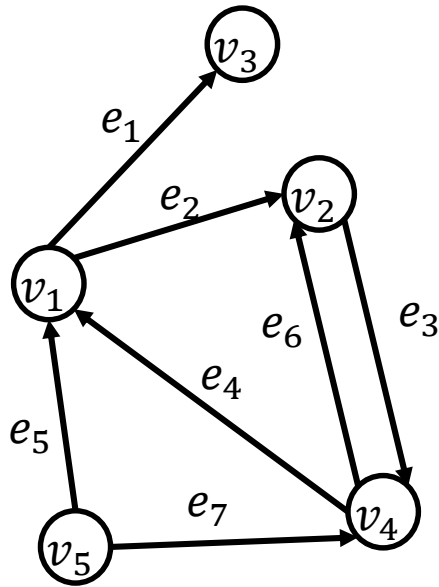


	$v_1$	$v_2$	$v_3$	$v_4$	$v_5$
$v_1$	0	1	1	1	1
$v_2$	1	0	0	1	0
$v_3$	1	0	0	0	0
$v_4$	1	1	0	0	0
$v_5$	1	0	0	0	0

- ◆  $A$  must be symmetric
- ◆ Space =  $O(|V|^2)$

# Adjacency Matrix: Directed G

- Defined in the same way as in the undirected graph



	$v_1$	$v_2$	$v_3$	$v_4$	$v_5$
$v_1$	0	1	1	0	0
$v_2$	0	0	0	1	0
$v_3$	0	0	0	0	0
$v_4$	1	1	0	0	0
$v_5$	1	0	0	1	0

- A may not be symmetric.
- Space =  $O(|V|^2)$

# Our Roadmap

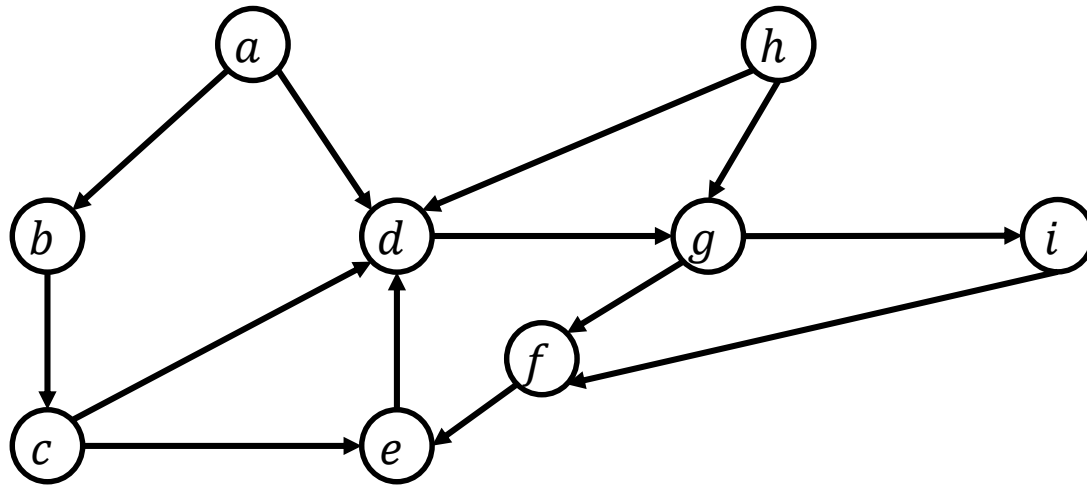
- ◆ Graph Concepts
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- ◆ Minimum Spanning Tree (MST)
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# Shortest Path



- ◆ Let  $G = (V, E)$  be a directed graph. A path in  $G$  is a sequence of nodes  $(v_1, v_2, \dots, v_k)$  such that
  - ◆ For every  $i \in [1, k - 1]$ , there is an edge between  $v_i$  and  $v_{i+1}$ .
  - ◆ E.g.,  $(v_1, v_2), (v_2, v_3), \dots, (v_{k-1}, v_k)$
  - ◆ Sometimes, we also denote the path as  $v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_k$
- ◆ The path is said to be from  $v_1$  to  $v_k$ , the length of the path is  $k - 1$ .
- ◆ Given two vertices  $u, v \in V$ , a shortest path from  $u$  to  $v$  is a path from  $u$  to  $v$  that has the minimum length among all the paths from  $u$  to  $v$ .
- ◆ If there is no path from  $u$  to  $v$ , then  $v$  is said to be unreachable from  $u$ .

# Shortest Path Example




- ◆ There are several path from a to g:
  - ◆  $a \rightarrow b \rightarrow c \rightarrow d \rightarrow g$  (length 4)
  - ◆  $a \rightarrow b \rightarrow c \rightarrow e \rightarrow d \rightarrow g$  (length 5)
  - ◆  $a \rightarrow d \rightarrow g$  (length 2)
- ◆ The last one is a shortest path. In this case, the shortest path is unique.
- ◆ Note that h is unreachable from a.



# Single Source Shortest Path

- ◆ Let  $G=(V,E)$  be a directed graph with unit weight in each edge, and  $s$  be a vertex in  $V$ . The goal of the single source shortest path (SSSP) problem is to find, for every other vertex  $t \in V \setminus \{s\}$ , a shortest path from  $s$  to  $t$ , unless  $t$  is unreachable from  $s$ .
- ◆ Next, we will describe the breadth first search (BFS) algorithm to solve the problem in  $O(|V|+|E|)$  time, which is clearly optimal (because any algorithm must at least see every vertex and every edge once in the worst case).

# Single Source Shortest Path

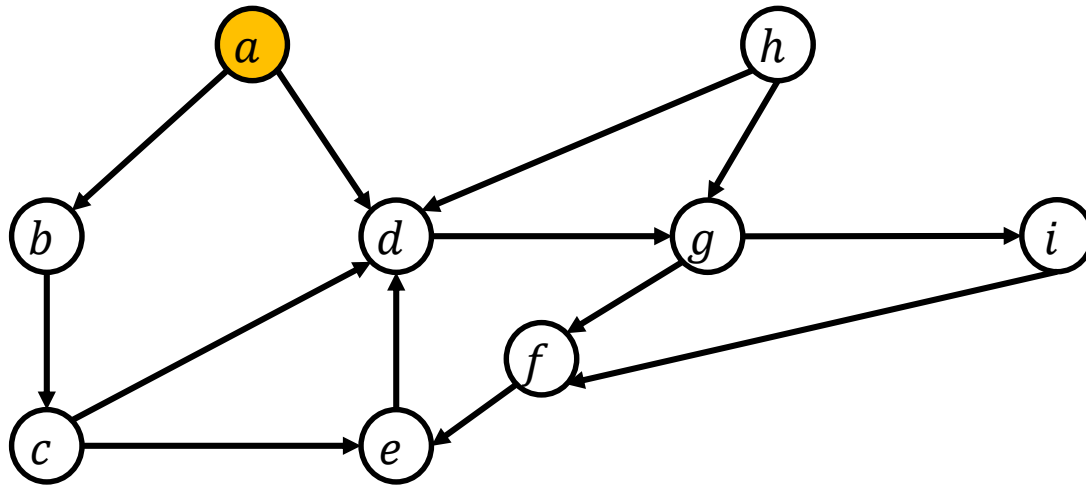
- ◆ How do you solve it? 
- ◆ At first glance, this may look surprising because the total length of all the shortest paths may reach  $\Omega(|V|^2)$  even when  $|E|=O(|V|)$ ! So shouldn't the algorithm need  $\Omega(|V|^2)$  time just to output all these shortest paths in the worst case?
- ◆ The answer, interestingly, is no. As will see, BFS encodes all the shortest paths in a BFS tree compactly, which uses only  $O(|V|)$  space, and can be output in  $O(|V|+|E|)$  time.

# Breadth First Search

- ◆ At the beginning, color all vertices in graph white. And create an empty BFS tree  $T$ .
- ◆ Create a queue  $Q$ . Insert the source vertex  $s$  into  $Q$ , and color it yellow (which means “in the queue”)
- ◆ Make  $s$  the root of  $T$ .

# Breadth First Search Example

- Suppose that source vertex is  $a$ .



BFS tree

$a$

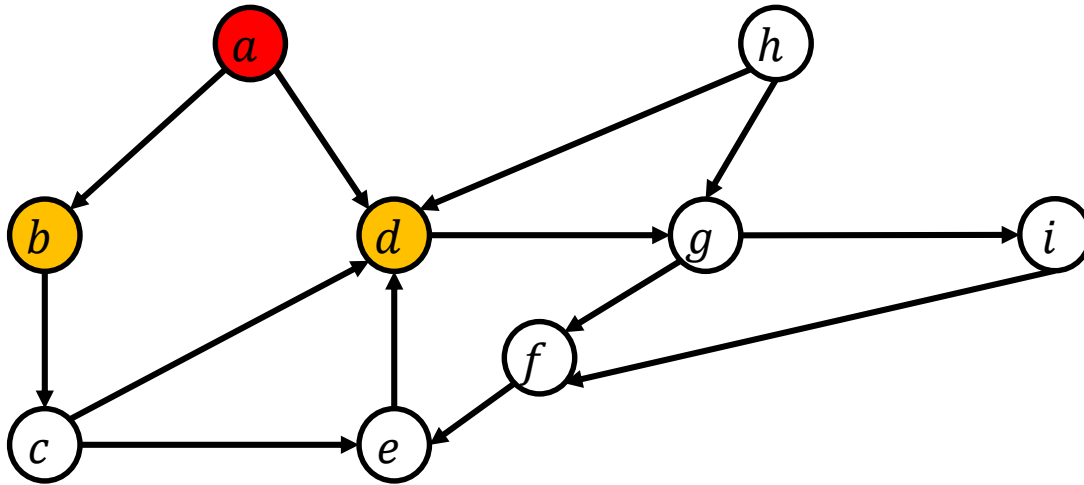
- $Q = (a)$

# Breadth First Search Example

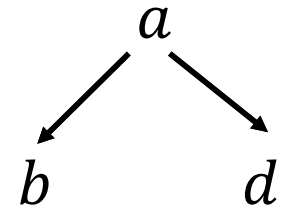
- ◆ Repeat the following until  $Q$  is empty
  - ◆ De-queue from  $Q$  the first vertex  $v$
  - ◆ For every out-neighbor  $u$  of  $v$  that is still white
    - ◆ 2.1 Enqueue  $u$  into  $Q$ , and color  $u$  yellow
    - ◆ 2.2 Make  $u$  a child of  $v$  in the BFS tree  $T$ .
  - ◆ Color  $v$  red (meaning  $v$  is visited)

# Breadth First Search Example

◆ After de-queuing  $a$ :



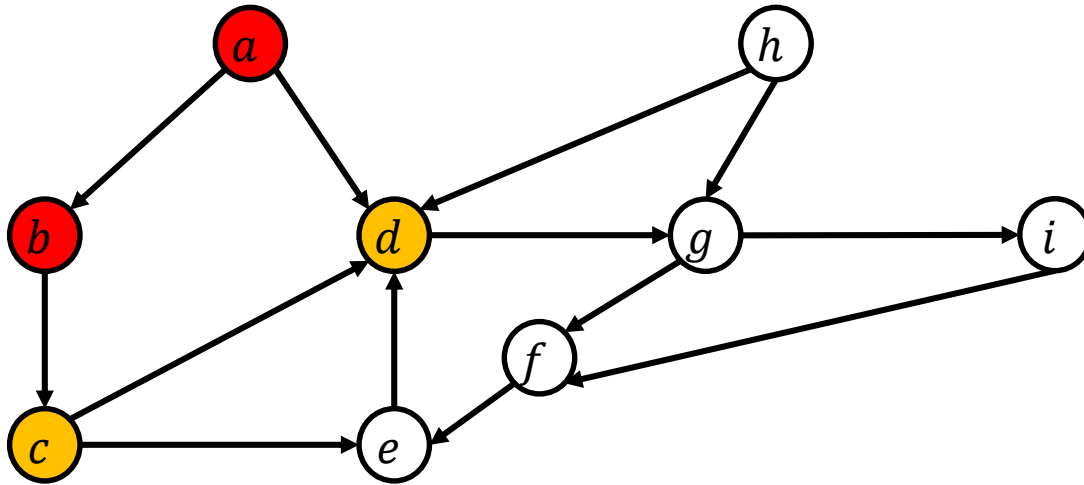
BFS tree



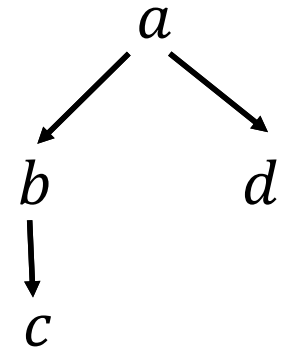
◆  $Q = (b, d)$

# Breadth First Search Example

◆ After dequeuing b:



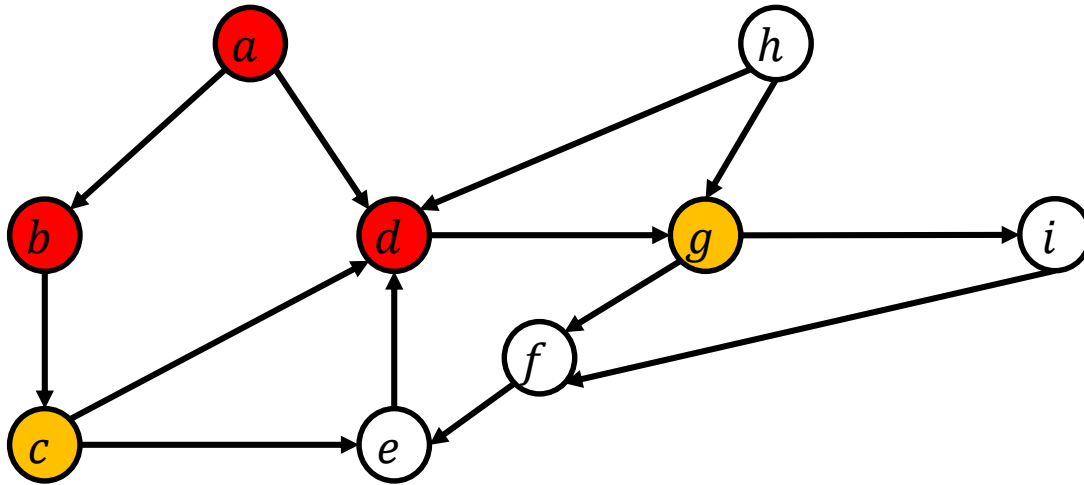
BFS tree



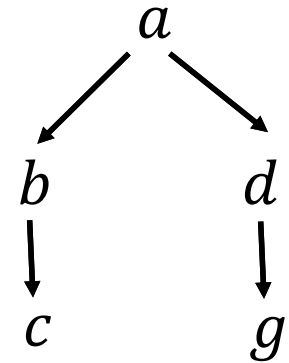
◆  $Q = (d, c)$

# Breadth First Search Example

◆ After dequeuing  $d$ :



BFS tree

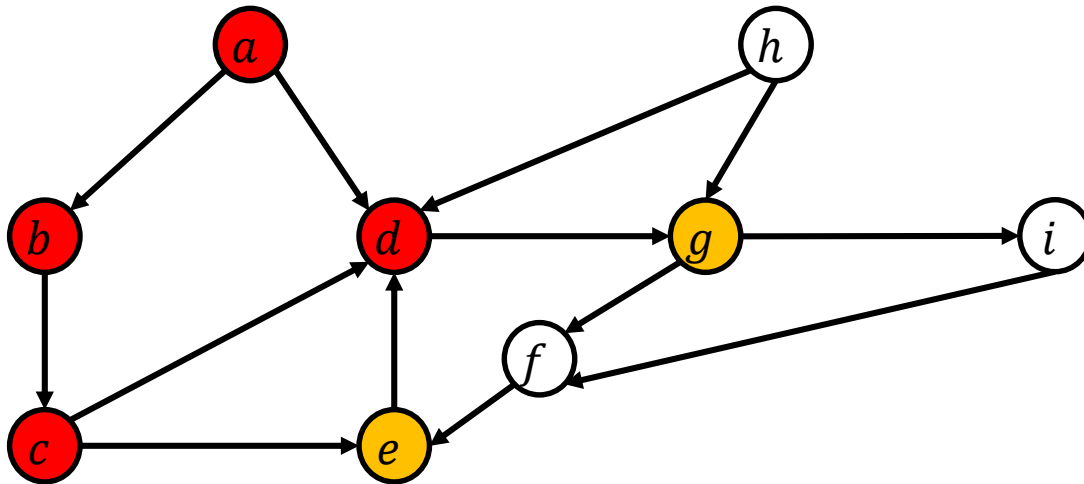


◆  $Q = (c, g)$

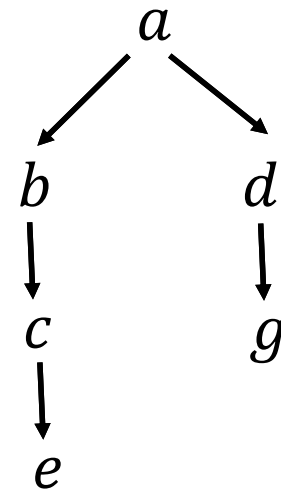


# Breadth First Search Example

- After dequeuing  $c$ :



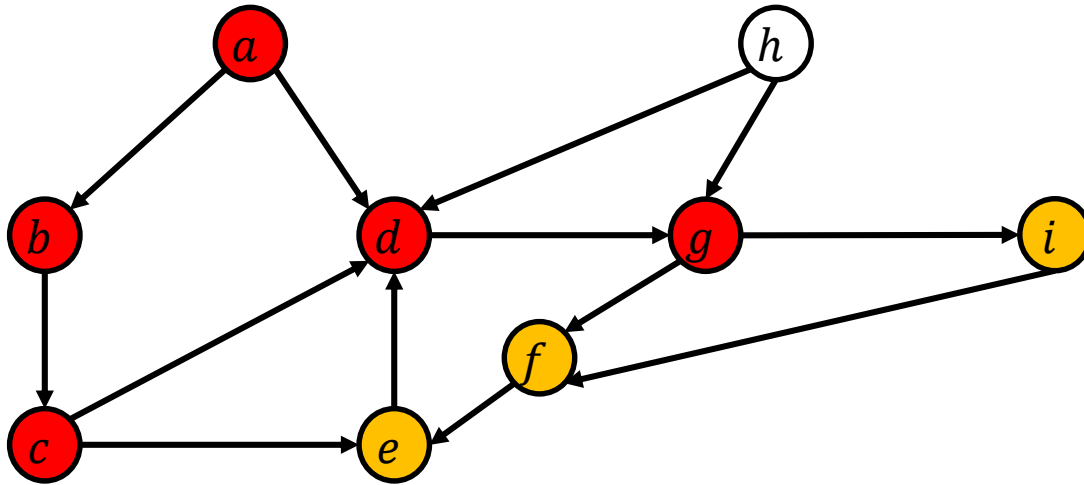
BFS tree



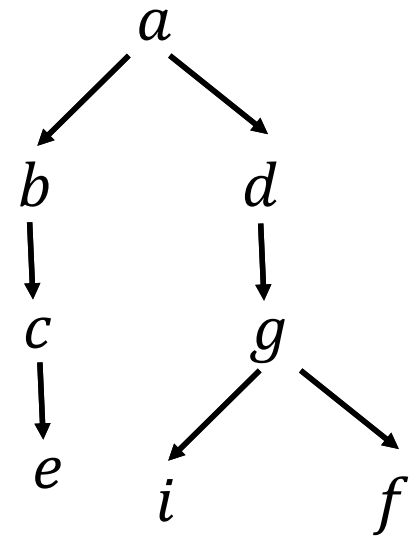
- $Q = (g, e)$
- $d$  is not enqueue again as it is red now

# Breadth First Search Example

◆ After dequeuing  $g$ :



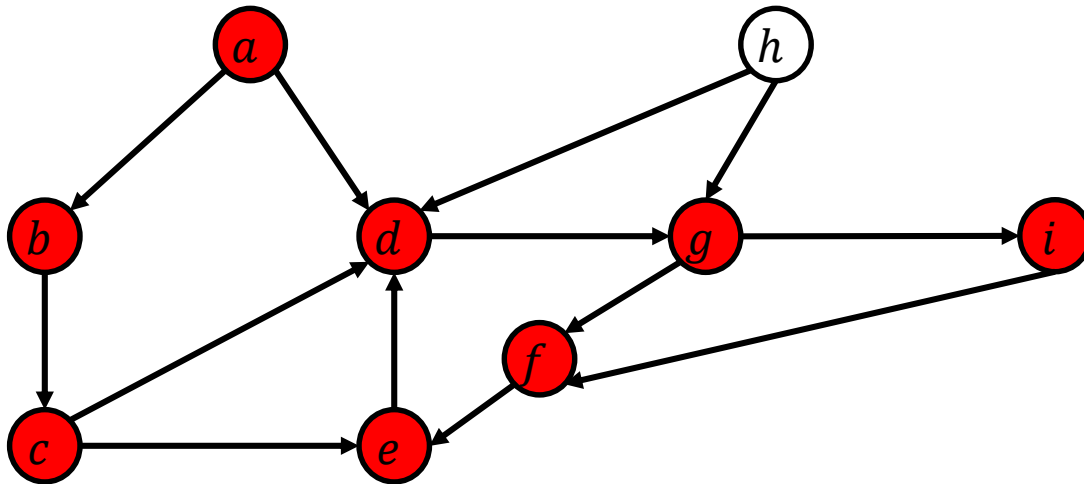
BFS tree



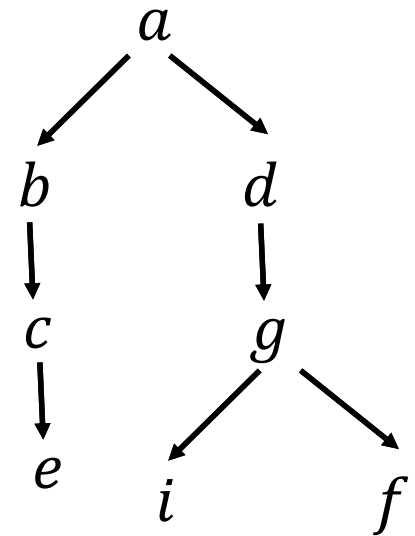
◆  $Q = (e, i, f)$

# Breadth First Search Example

- After dequeuing e, i, f



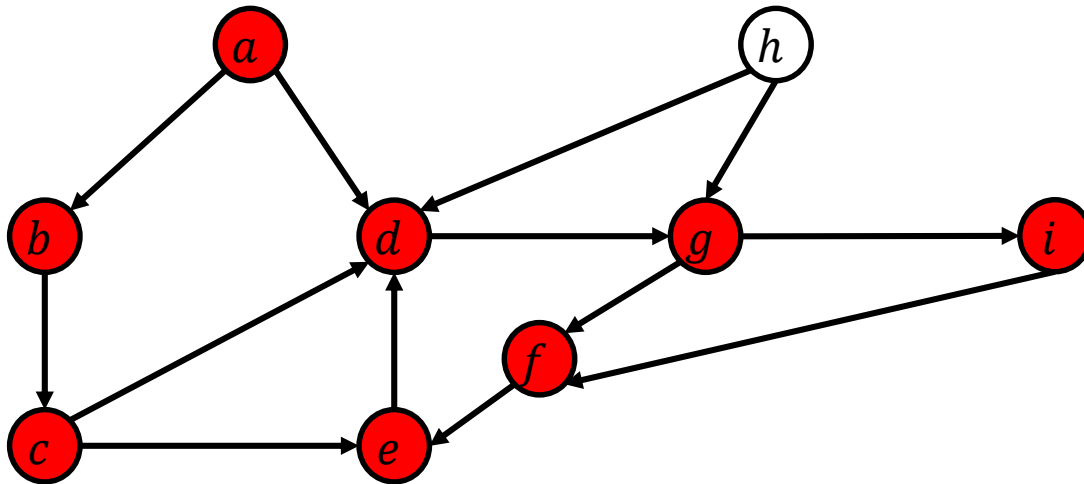
BFS tree



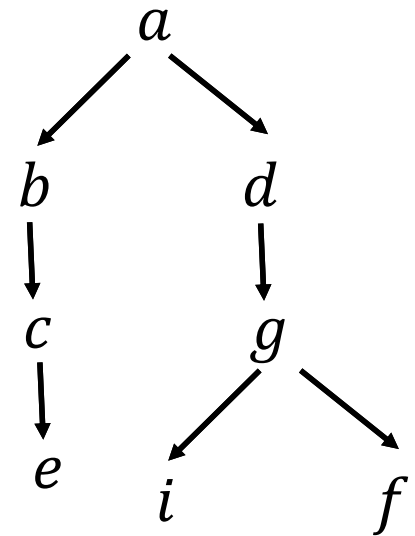
- $Q = ()$
- This is the end of BFS. Note that h remains white: we can conclude that it is not reachable from a.

# SSSP solution

- Where are the shortest paths?



BFS tree



- The shortest path from a to any vertex x is simply the path from a to node x in the BFS tree!.
  - Proof?

# Complexity Analysis

- ◆ When a vertex  $v$  is dequeued, we spend  $O(1+d^+(v))$  time processing it, where  $d^+(v)$  is the out-degree of  $v$ .
- ◆ Clearly, every vertex enters the queue at most once.
- ◆ The total running time of BFS is therefore:

$$O\left(\sum_{v \in V} (1 + d^+(v))\right) = O(|V| + |E|)$$

# Our Roadmap

- ◆ Graph Concepts

- ◆ Graph Traversal

- ◆ Breath First Search (SSSP)

- ◆ Depth First Search (DAG, topological sort)

- ◆ Shortest Path Algorithm (SP)

- ◆ Minimum Spanning Tree (MST)

- ◆ Strongly Connected Component (SCC)

forward edge.

backward edge

cross edge.

出发点和终点。

判断有没有环。

dfs 如何证环, 已知 end, 然后 dfs

发现 d 是 e 的  
爸, 则说明  
有环。

# Depth First Search

- ◆ We have already learnt breadth first search (BFS). Today, we will discuss its “sister version”: the depth first search (DFS) algorithm. Our discussion will once again focus on directed graphs, because the extension to undirected graphs is straight forward.
- ◆ DFS is surprisingly powerful algorithm, and solves several classic problem elegantly. In this lecture, we will see one such problem: detecting whether the input graph contains cycles.

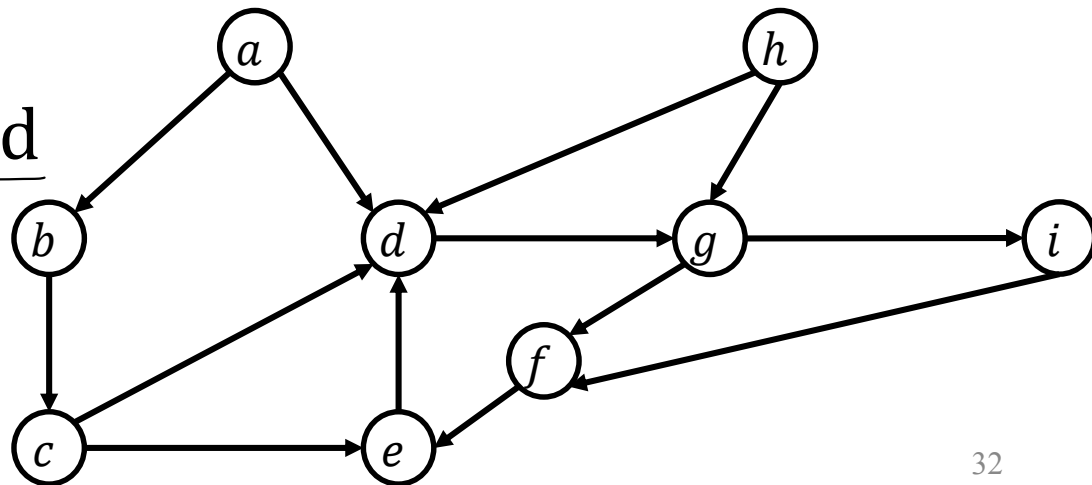
# Path and Cycles

- ◆ Recall: let  $G = (V, E)$  be a directed graph. A path in  $G$  is a sequence of nodes  $(v_1, v_2, \dots, v_k)$  such that
  - ◆ For every  $i \in [1, k]$ , there is an edge between  $v_i$  and  $v_{i+1}$ .
  - ◆ E.g.,  $(v_1, v_2), (v_2, v_3), \dots, (v_{k-1}, v_k)$
  - ◆ Sometimes, we also denote the path as  $v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_k$
- ◆ A cycle in  $G$  is a path  $(v_1, v_2, \dots, v_k)$  such that  $k \geq 4$  and  $v_1 = v_k$ .

◆ Example:

◆  $d \rightarrow g \rightarrow i \rightarrow f \rightarrow e \rightarrow d$

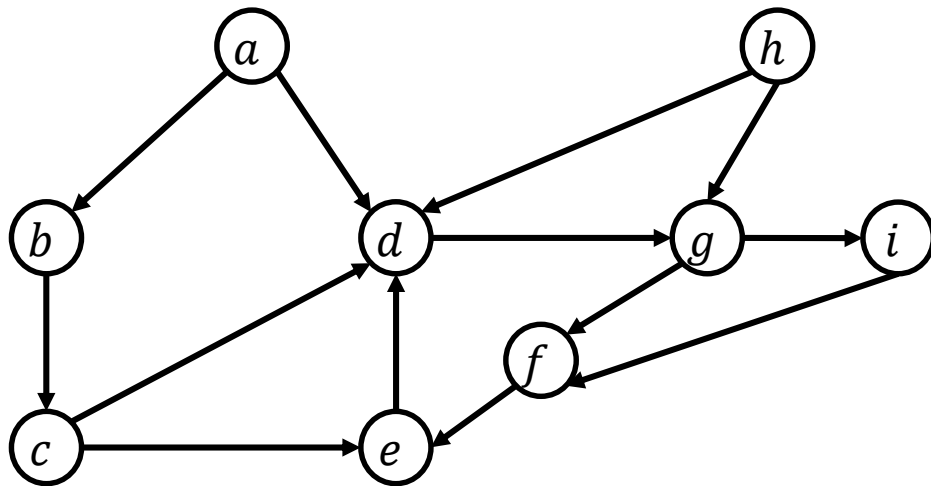
◆  $d \rightarrow g \rightarrow f \rightarrow e \rightarrow d$



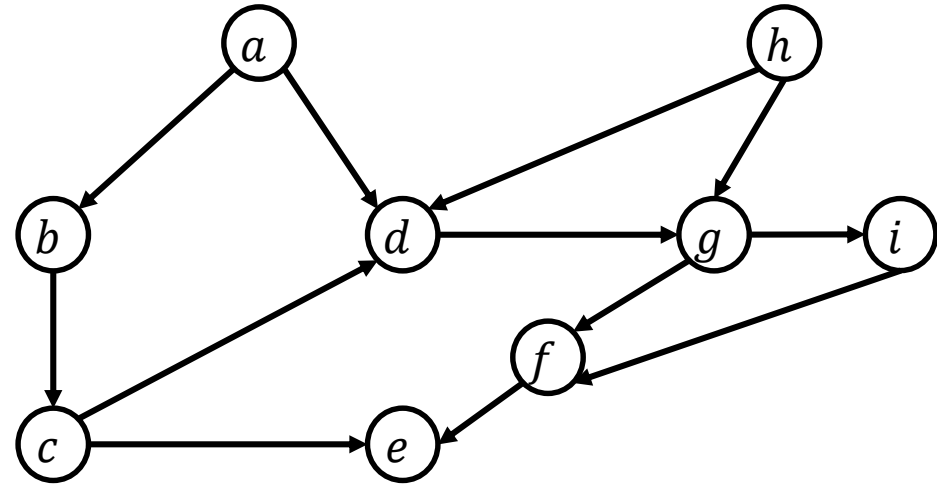


# Directed Acyclic/Cyclic Graph

- ◆ If a directed graph contains no cycles, we say that it is a directed acyclic graph (DAG). Otherwise, G is Cyclic.
- ◆ DAG is extremely important concept in Computer Science, e.g., spark, tensorflow
- ◆ Example



Cyclic



DAG

# The Cycle Detection Problem

- ◆ Let  $G=(V,E)$  be a directed graph. Determine whether it is a DAG.
- ◆ Next, we will describe the depth first search (DFS) algorithm to solve the problem in  $O(|V|+|E|)$  time, which is optimal (because any algorithm must at least see every vertex and edge once in the worst case).
- ◆ Just like BFS, the DFS algorithm also outputs a tree, called the DFS-tree. This tree contains vital information about the input graph that allows us to decide whether the input graph is a DAG.

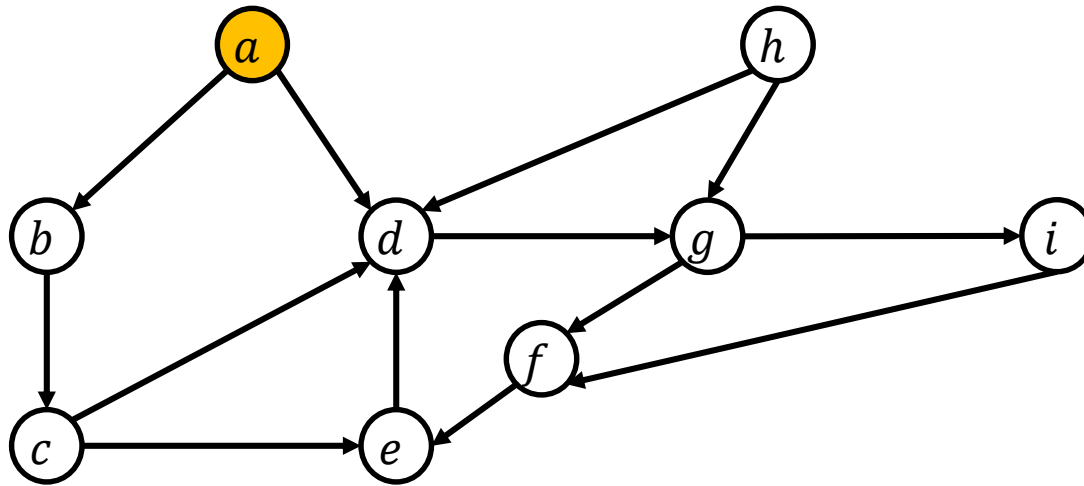
# Depth First Search

- ◆ At the beginning, color all vertices in the graph white, and create an empty DFS tree  $T$ .
- ◆ Create a stack  $S$ . Pick an arbitrary vertex  $v$ . Push  $v$  into  $S$ , and color it yellow (which means “in the stack”)
  - ◆ What is the difference between BFS and DFS underlying data structure?
  - ◆ BFS  $\rightarrow$  Queue, DFS  $\rightarrow$  Stack
- ◆ Make  $v$  the root of  $T$

# Depth First Search Example

- Suppose we start from a.

深搜



DFS tree

*a*

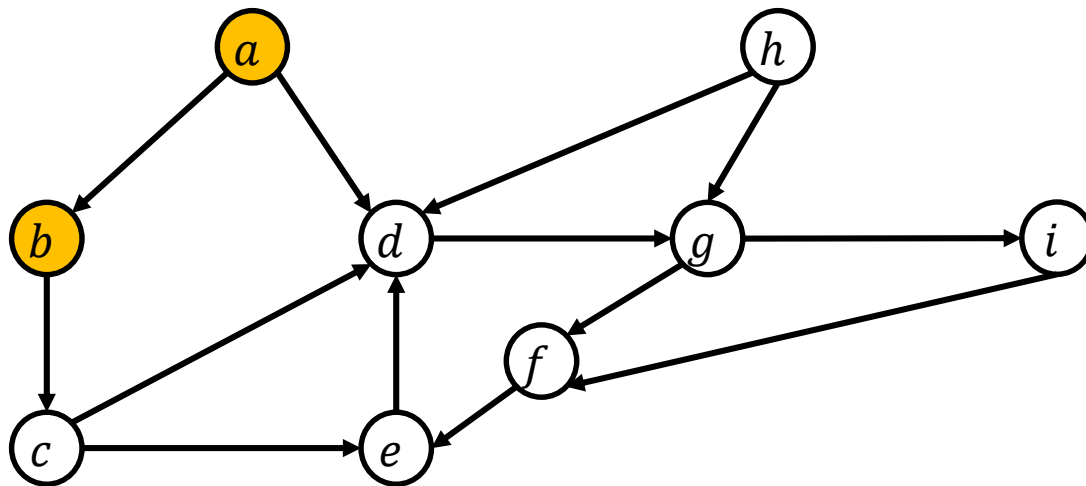
- $S = (a)$

# Depth First Search Example

- ◆ Repeat the following until  $S$  is empty
  - ◆ Let  $v$  be the vertex that currently tops the stack  $S$  (do not remove  $v$  from  $S$ )
  - ◆ Does  $v$  still have a white out-neighbor
    - ◆ 2.1 If yes: let it be  $u$ .
      - ◆ Push  $u$  into  $S$ , and color  $u$  yellow
      - ◆ Make  $u$  a child of  $v$  in the DFS-tree  $T$
    - ◆ 2.2 If no, pop  $v$  from  $S$ , and color  $v$  red (meaning  $v$  is visited)
  - ◆ If there are still white vertices, repeat the above by restarting from an arbitrary white vertex  $v'$ , creating a new DFS tree rooted at  $v'$ .

# Depth First Search Example

- ◆ Top of stack: a, which has white out-neighbors b, d. Suppose we access b first. Push b into S



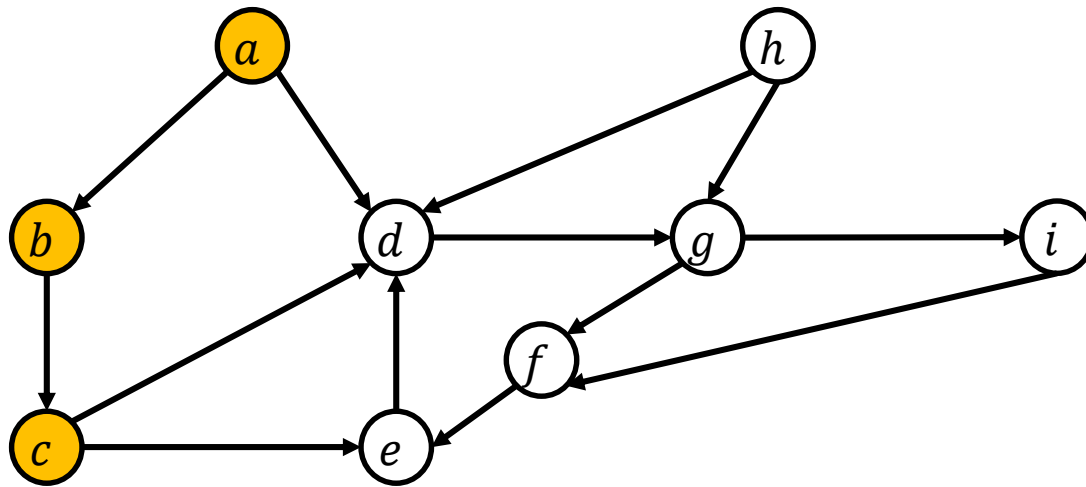
DFS tree

$a$   
↓  
 $b$

- ◆  $S = (a, b)$ .

# Depth First Search Example

- ◆ Top of stack: b, which has white out-neighbors c. Push c into S



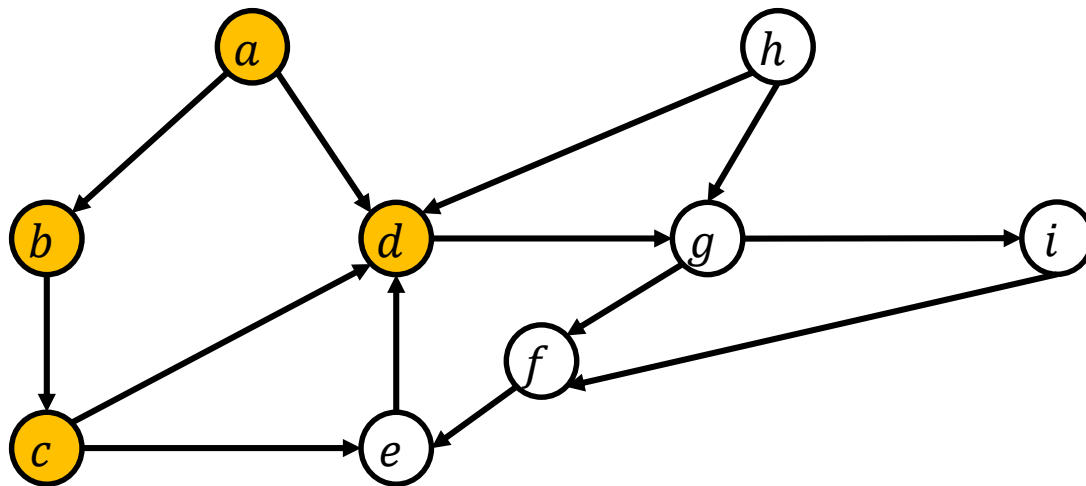
DFS tree

$a$   
 $\downarrow$   
 $b$   
 $\downarrow$   
 $c$

- ◆  $S = (a, b, c).$

# Depth First Search Example

- ◆ Top of stack: c, which has white out-neighbors d and e. Suppose we access d first. Push d into S



DFS tree

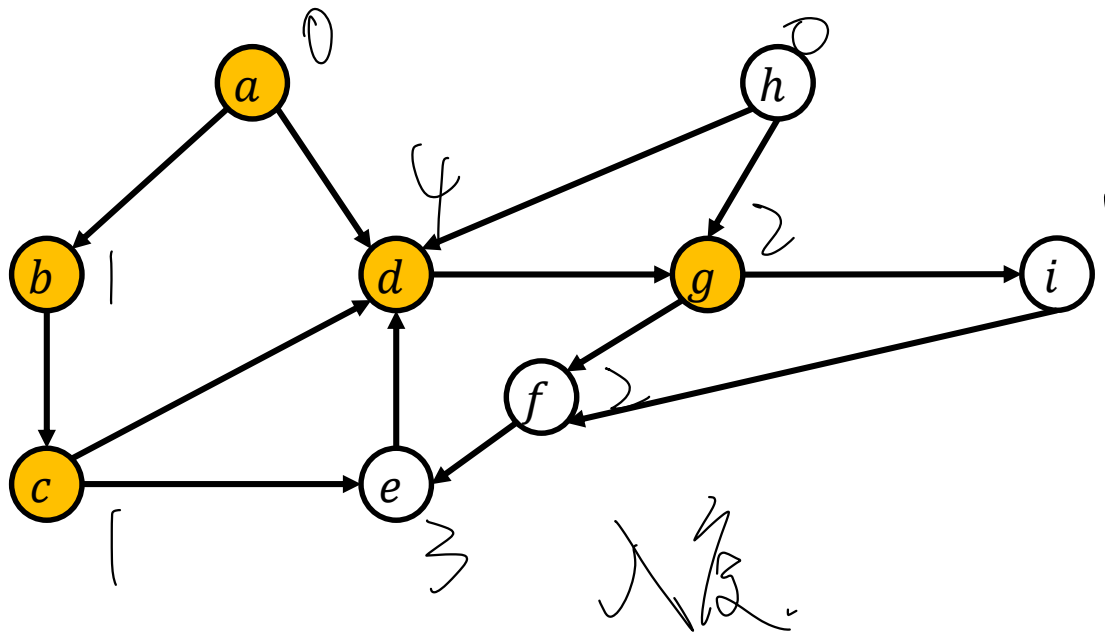
$a$   
 $\downarrow$   
 $b$   
 $\downarrow$   
 $c$   
 $\downarrow$   
 $d$

- ◆  $S = (a, b, c, d).$

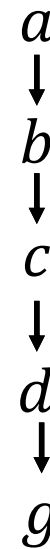


# Depth First Search Example

- Top of stack: d, which has white out-neighbors g. Push g into S



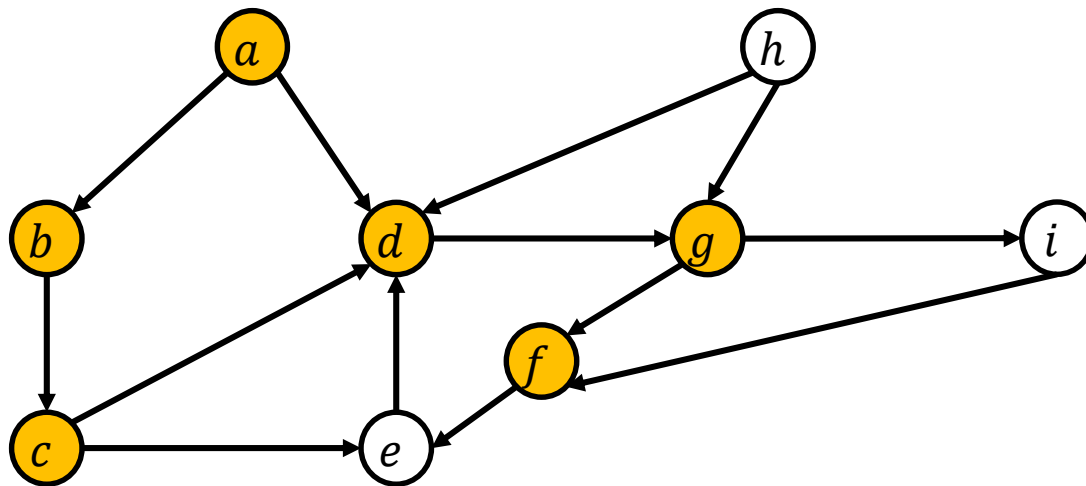
DFS tree



- $S = (a, b, c, d, g).$

# Depth First Search Example

- Top of stack: g, which has white out-neighbors f and i. Suppose we access f first. Push f into S



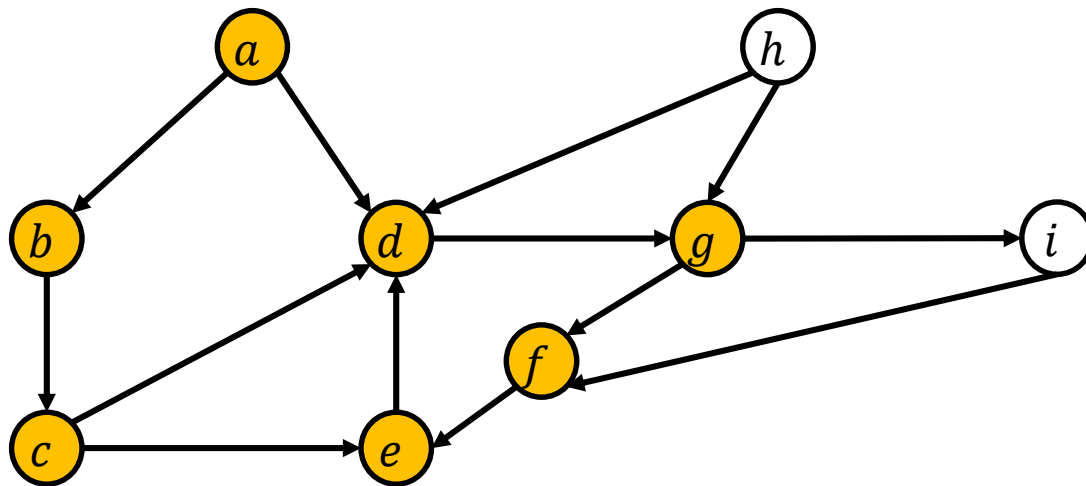
DFS tree



- $S = (a, b, c, d, g, f).$

# Depth First Search Example

- Top of stack: f, which has white out-neighbors e. Push e into S



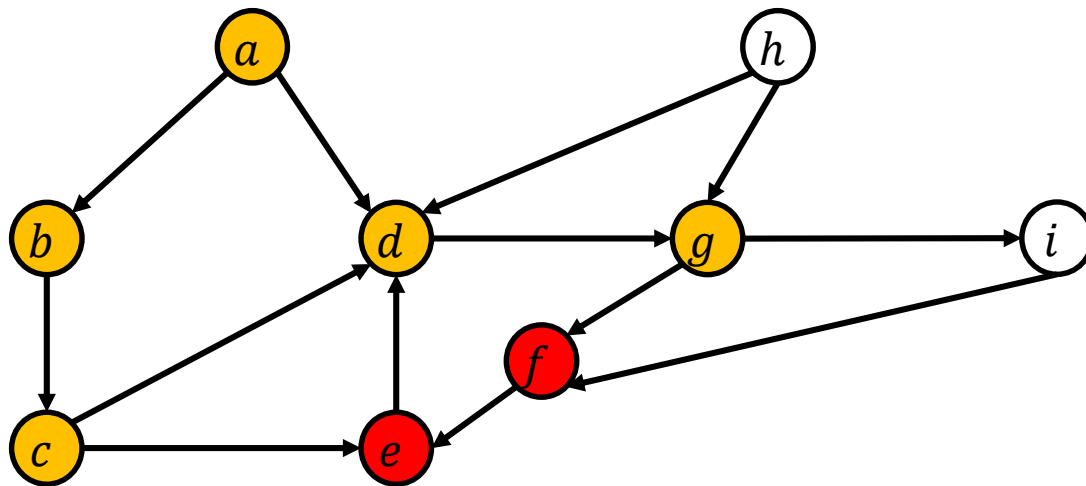
- $S = (a, b, c, d, g, f, e).$

DFS tree



# Depth First Search Example

- Top of stack:  $e$ ,  $e$  has no white out-neighbors. So pop it from  $S$ , and color it red. Similarly for  $s$ .



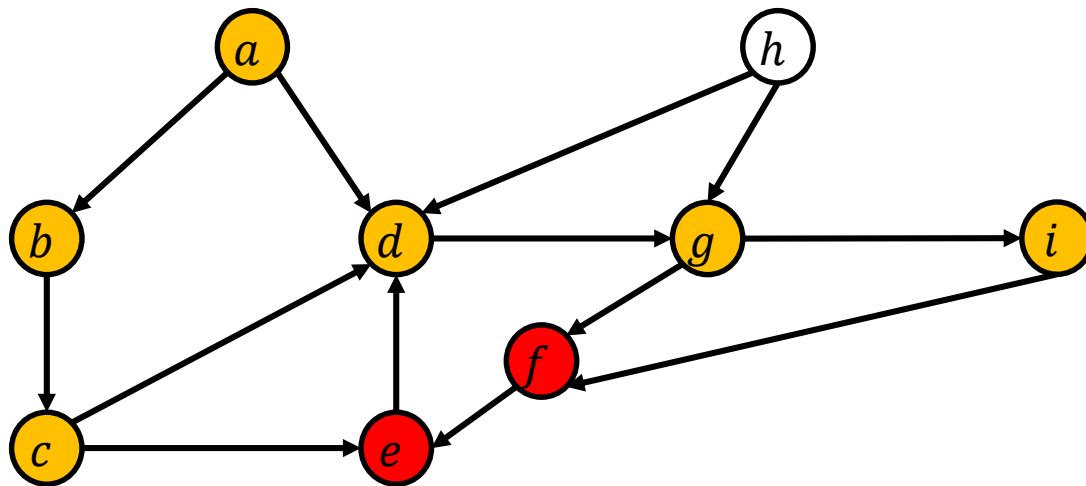
DFS tree

$a$   
 $\downarrow$   
 $b$   
 $\downarrow$   
 $c$   
 $\downarrow$   
 $d$   
 $\downarrow$   
 $g$   
 $\downarrow$   
 $f$   
 $\downarrow$   
 $e$

- $S = (a, b, c, d, g)$ .

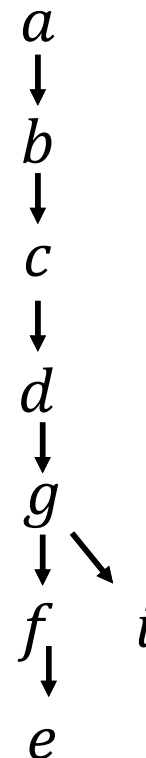
# Depth First Search Example

- Top of stack: g, which still has white out-neighbors i. Push i into S



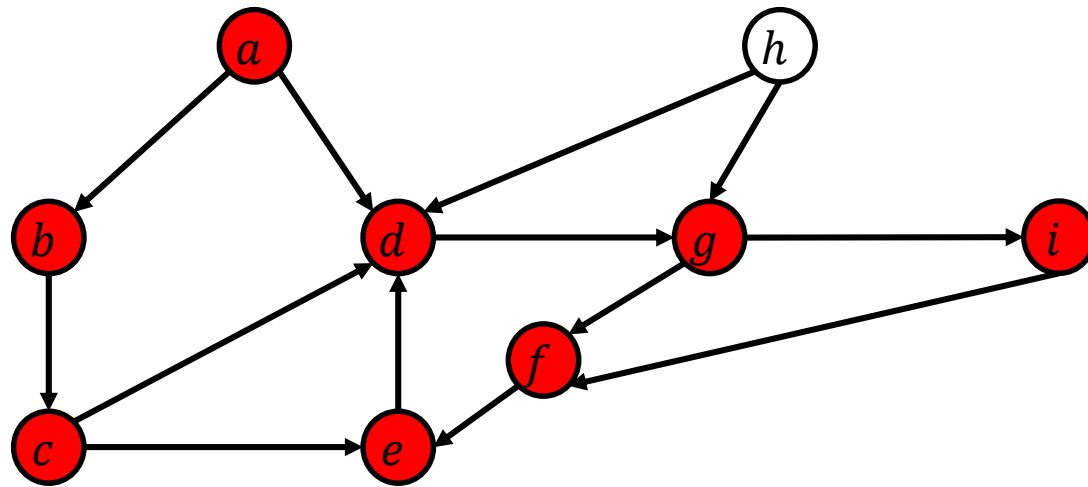
- $S = (a, b, c, d, g, i).$

DFS tree



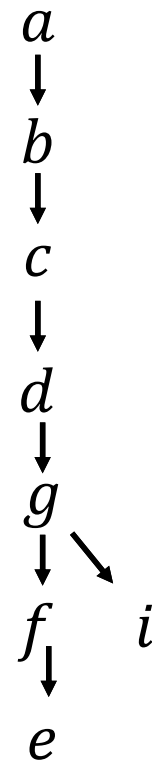
# Depth First Search Example

- After popping i, g, d, c, b, a



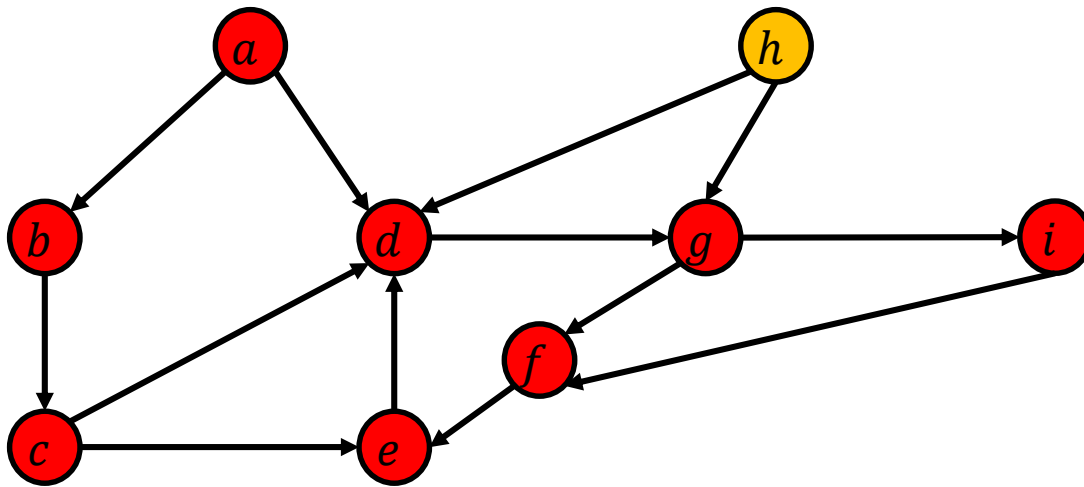
- $S = ()$ .

DFS tree



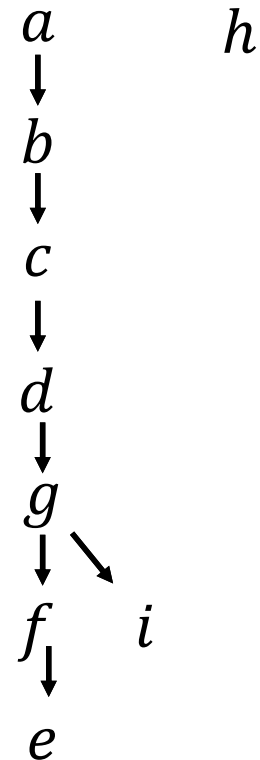
# Depth First Search Example

- Now there is still a white vertex  $h$ . So we perform another DFS starting from  $h$



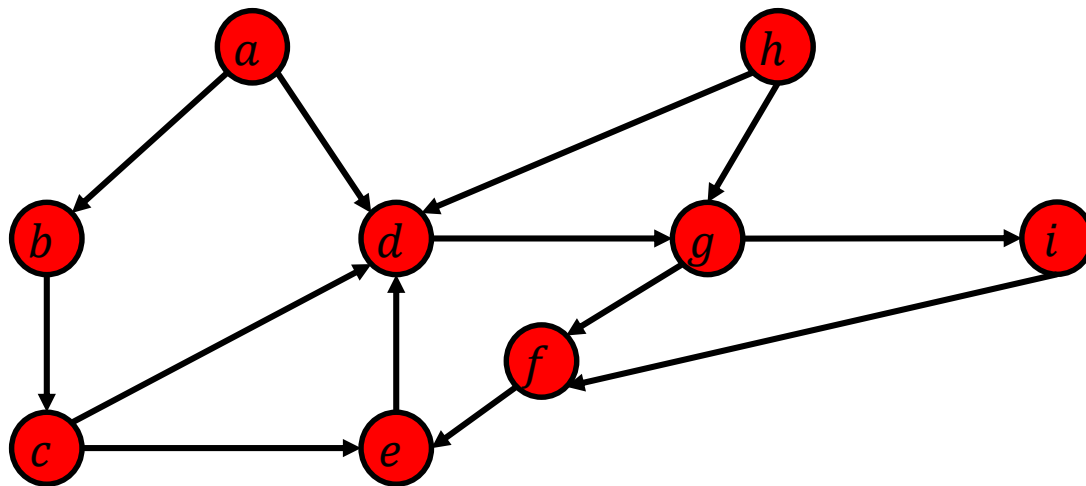
- $S = (h)$ .

DFS forest



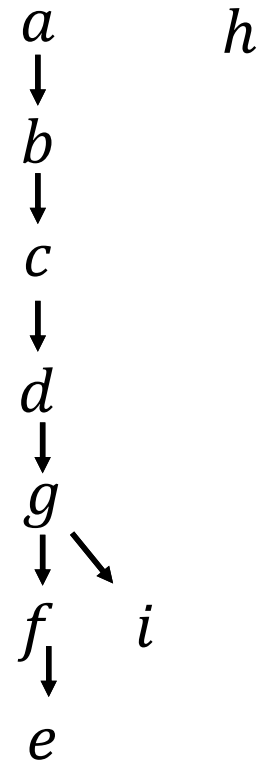
# Depth First Search Example

- ◆ Pop h. The end.



- ◆  $S = ( )$ .
- ◆ Note that we have created a DFS-forest, Which consists of 2 DFS-trees.

DFS forest





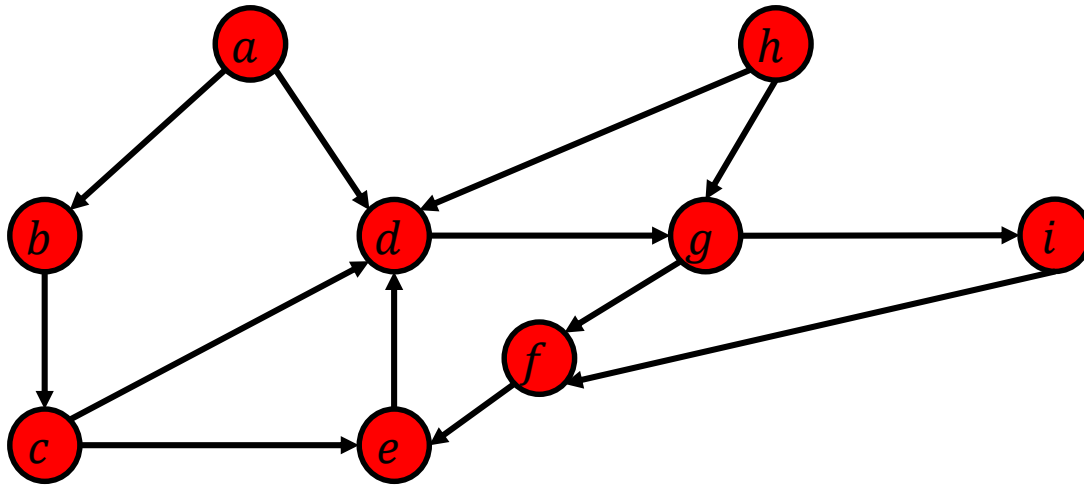
# DFS Complexity Analysis

- ◆ DFS can be implemented efficiently as follows.
  - ◆ Store  $G$  in the adjacency list format
  - ◆ For every vertex  $v$ , remember the out-neighbor to explore next
  - ◆  $O(|V|+|E|)$  stack operations
  - ◆ Use an array to remember the colors of all vertices
- ◆ Hence, the total running time is  $O(|V|+|E|)$ .

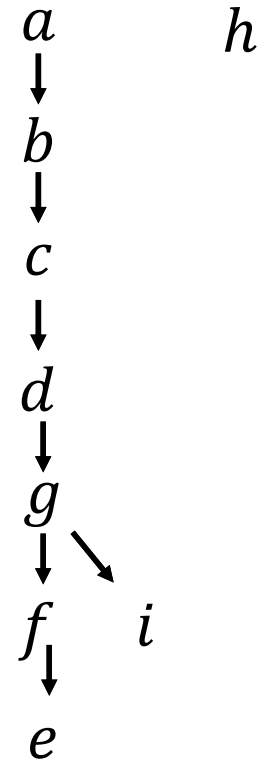
# DFS Tree (Forest)

- ◆ Recall that we said earlier that the DFS-tree (well, perhaps a DFS forest) encodes information about the input graph. Next, we will make this point specific, and solve the edge detection problem.
- ◆ Edge Classification
  - ◆ Suppose we have already built a DFS-forest  $T$ .
  - ◆ Let  $(u,v)$  be an edge in  $G$  (remember that the edge is directed from  $u$  to  $v$ ). It can be classified into:
    - ◆ Forward edge:  $u$  is a proper ancestor of  $v$  in a DFS-tree of  $T$ .
    - ◆ Backward edge:  $u$  is a descendant of  $v$  in a DFS-tree of  $T$ .
    - ◆ Cross edge: if neither of the above applies.

# Edge Classification Example



DFS Forest

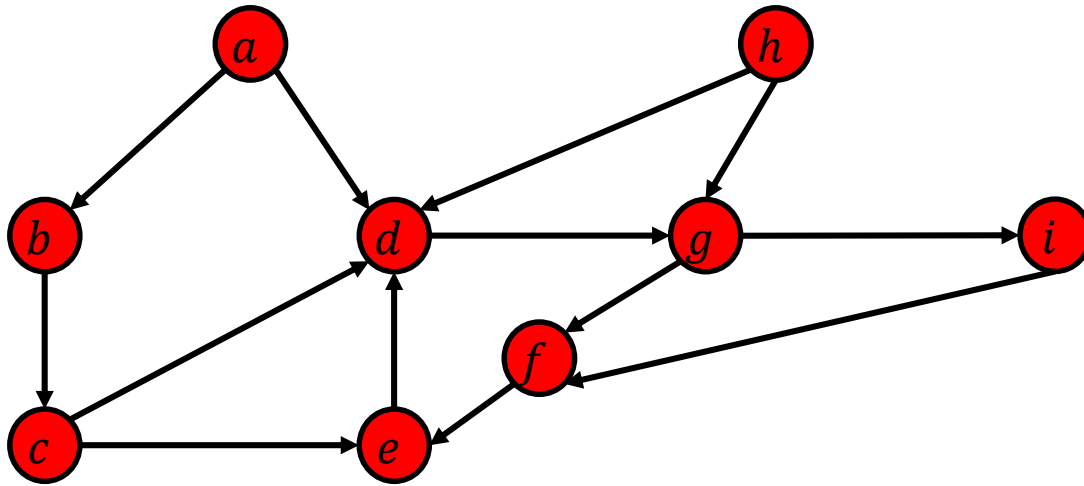


- ◆ Forward edge:
  - ◆  $(a,b), (a,d), (b,c), (c,d), (c,e), (d,g), (g,f), (g,i), (f,e)$
- ◆ Backward edge:  $(e,d)$
- ◆ Cross edge:  $(i,f), (h,d), (h,g)$

# Edge Classification Example

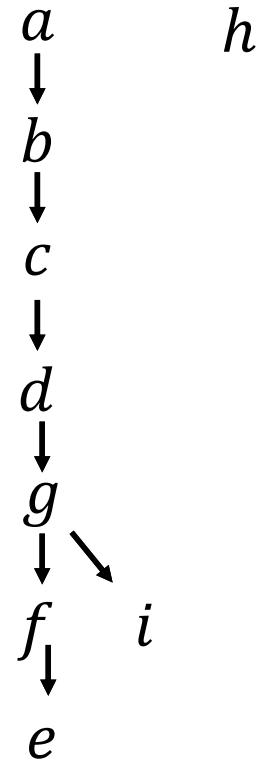
- ◆ How to determine type of each edge  $(u,v)$  by  $O(1)$  cost?
  - ◆ Augmenting DFS slightly!
- ◆ Maintain a counter  $c$ , which is initially 0. Every time a push or pop is performed on the stack, we increment  $c$  by 1.
- ◆ For every vertex  $v$ , define:
  - ◆ Its discovery time  $d\text{-tm}(v)$  to be the value of  $c$  right after  $v$  is pushed into the stack
  - ◆ Its finish time  $f\text{-tm}(v)$  to be the value of  $c$  right after  $v$  is popped from the stack
  - ◆ Define  $I(v) = [d\text{-time}(v), f\text{-tm}(v)]$
- ◆ It is straight forward to obtain  $I(v)$  for all  $v \in V$  by paying  $O(|V|)$  extra time on top of DFS's running time.

# Augment DFS algorithm



- ◆  $I(a)=[1,16], I(b)=[2,15], I(c)=[3,14]$
- ◆  $I(d)=[4,13], I(g)=[5,12], I(f)=[6,9]$
- ◆  $I(e)=[7,8], I(i)=[10,11], I(h)=[17,18]$

DFS Forest



# Theorems

- ◆ **Parenthesis Theorem:** all the following are true:
  - ◆ If  $u$  is a proper ancestor of  $v$  in DFS-tree of  $T$ , then  $I(u)$  contains  $I(v)$ .
  - ◆ If  $u$  is a proper descendant of  $v$  in DFS-tree of  $T$ , then  $I(u)$  is contained in  $I(v)$ .
  - ◆ Otherwise,  $I(u)$  and  $I(v)$  are disjoint.
- ◆ **Proof:** Follows directly from the first-in-last-out property of the stack.
- ◆ **Cycle Theorem:** let  $T$  be an arbitrary DFS-forest.  $G$  contains a cycle if and only if there is a backward edge with respect to  $T$ .
- ◆ **Proof:** will left as exercise.

# Cycle Detection

- ◆ Equipped with the cycle theorem, we know that we can detect whether  $G$  has a cycle easily after having obtained a DFS-forest  $T$ :
  - ◆ For every edge  $(u,v)$ , determine whether it is a backward edge in  $O(1)$  time.
- ◆ If no backward edges are found, decide  $G$  to be a DAG; otherwise,  $G$  has at least a cycle.
- ◆ Only  $O(|E|)$  extra time is needed
- ◆ We now conclude that the cycle detection problem can be solved in  $O(|V|+|E|)$  time.

# Hint of Cycle Theorem Proof

- ◆ “if” direction,  $(e,d)$  is backward edge.
- ◆ “only-if” direction:
  - ◆ White Path Theorem: let  $u$  be a vertex in  $G$ . Consider the moment when  $u$  is pushed into the stack in the DFS algorithm. Then a vertex  $v$  becomes a proper descendant of  $u$  in the DFS-forest if and only if the following is true:
    - ◆ We can go from  $u$  to  $v$  by travelling only on white vertices
- ◆ We will now prove that if  $G$  has a cycle, then there must be a backward edge in the DFS-forest.
  - ◆ Suppose the cycle is  $v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_k \rightarrow v_1$ , let  $v_i$  is the first to enter the stack. Then, by white path theorem, all the other vertices in the cycle must be proper descendants of  $v_i$  in the DFS-forest. This means the edge pointing to  $v_i$  in the cycle is a backward edge.



# Our Roadmap

- ◆ Graph Concepts
- ◆ Graph Traversal
  - ◆ Breath First Search (SSSP)
  - ◆ Depth First Search (DAG, topological sort)
- ◆ Shortest Path Algorithm (SP)
- ◆ Minimum Spanning Tree (MST)
- ◆ Strongly Connected Component (SCC)

# Topological Sort on a DAG

- ◆ As mentioned earlier, depth first search (DFS) algorithm is surprisingly powerful. Indeed, we have already used it to detect efficiently whether a directed graph contains any cycle.
- ◆ We will use it to settle another classic problem: topological sort, in linear time.
- ◆ This algorithm is very elegant, and simple enough.

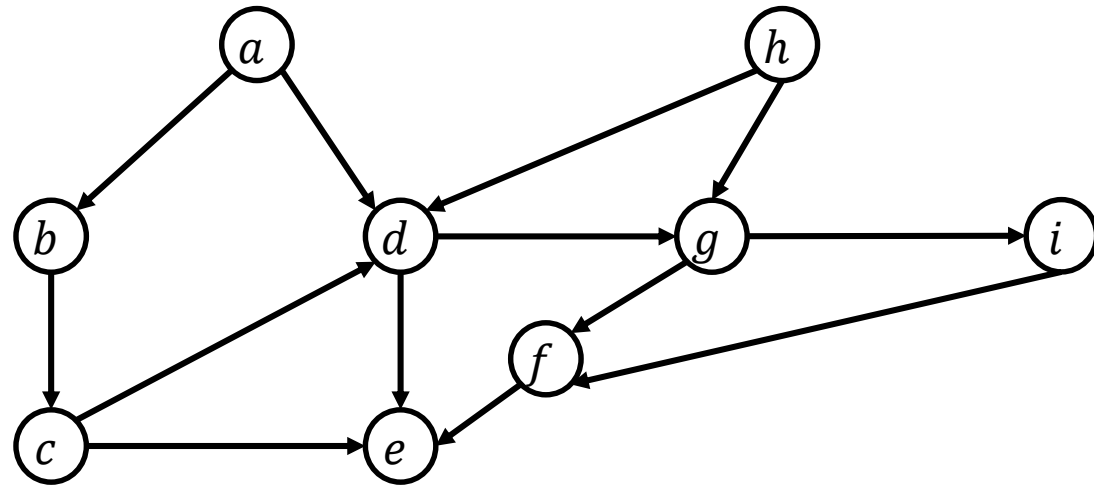
# Topological Order

- Let  $G=(V,E)$  be a directed acyclic graph (DAG).
- A topological order of  $G$  is an ordering of the vertices in  $V$  such that, for any edge  $(u,v)$ , it must hold that  $u$  precedes  $v$  in the ordering.
- Example: two possible topological orders:

- h, a, b, c, d, g, i, f, e

- a, h, b, c, d, g, i, f, e

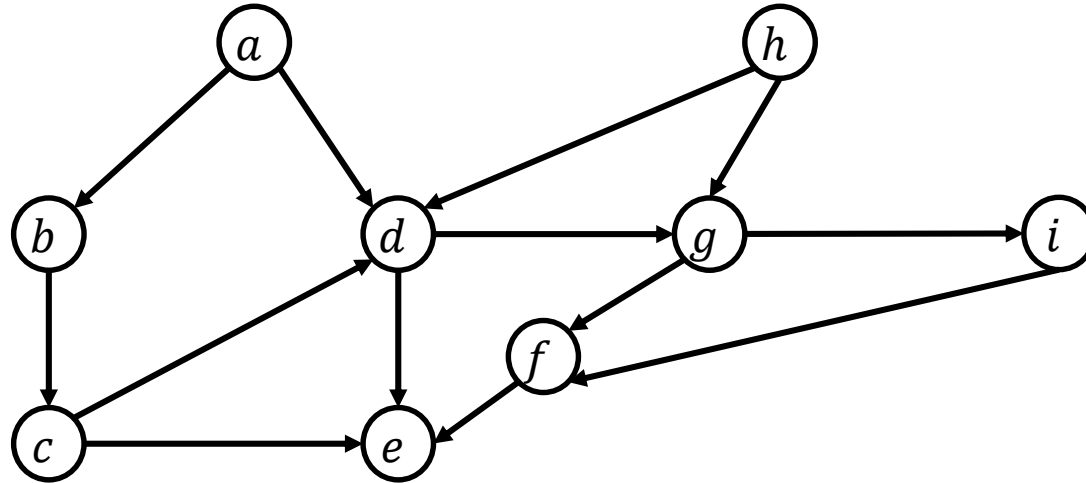
- a, h, d, b, c, g, i, f, e  
is not topological order,  
because of edge (c,d).



# The Topological Sort Problem

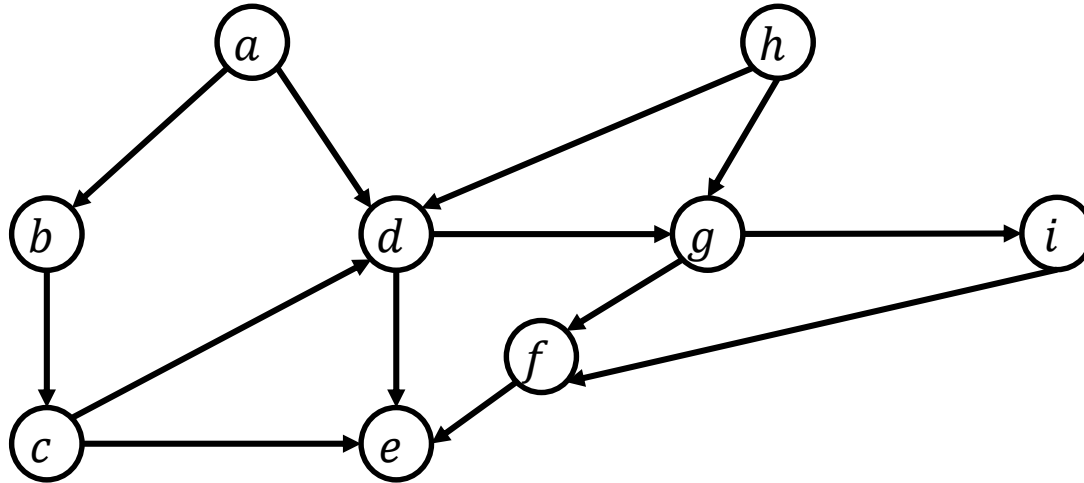
- ◆ Let  $G=(V,E)$  be a directed acyclic graph (DAG). The goal of topological sort is to produce a topological order of  $G$ .
- ◆ Topological Sort Algorithm
  - ◆ Create an empty list  $L$  → 跑一遍前序
  - ◆ Run DFS on  $G$ , whenever a vertex  $v$  turns red (i.e., it is popped from the stack), append it to  $L$ .
  - ◆ Output the reverse order of  $L$
- ◆ The total running time is clearly  $O(|V|+|E|)$

# The Topological Sort Example



- ◆ Suppose we run DFS starting from a. The following is one possible order by which the vertices turn red:
  - ◆ e, f, i, g, d, c, b, a, h
- ◆ Therefore, we output h, a, b, c, d, g, i, f, e as a topological order.

# The Topological Sort Example



- Suppose we run DFS starting from d, then restarting from h, then from a. The following is one possible order by which the vertices turn red:
  - e, f, i, g, d, h, c, b, a
- Therefore, we output a, b, c, h, d, g, i, f, e as a topological order.

# Hint: Correctness Analysis

- ◆ We now prove that the algorithm is correct.
- ◆ Proof. Take any edge  $(u,v)$ . We will show that  $u$  turns red after  $v$ , which will complete the proof.
  - ◆ Consider the moment when  $u$  enters the stack, We argue that that currently  $v$  cannot be in the stack. Suppose that  $v$  was in the stack. As there must be a path chaining up all the vertices in the stack bottom up, we know that there is a path from  $v$  to  $u$ . Then, adding the edge  $(u,v)$  forms a cycle, contradicting the fact that  $G$  is a DAG.
  - ◆  $v$  is red at this moment then obviously  $u$  will turn red after  $v$ .
  - ◆  $v$  is white: then by the white path theorem of DFS, we know that  $v$  will become a proper descendant of  $u$  in the DFS-forest. Therefore,  $u$  will turn red after  $v$ .
- ◆ Every DAG has a topological order!

# Our Roadmap

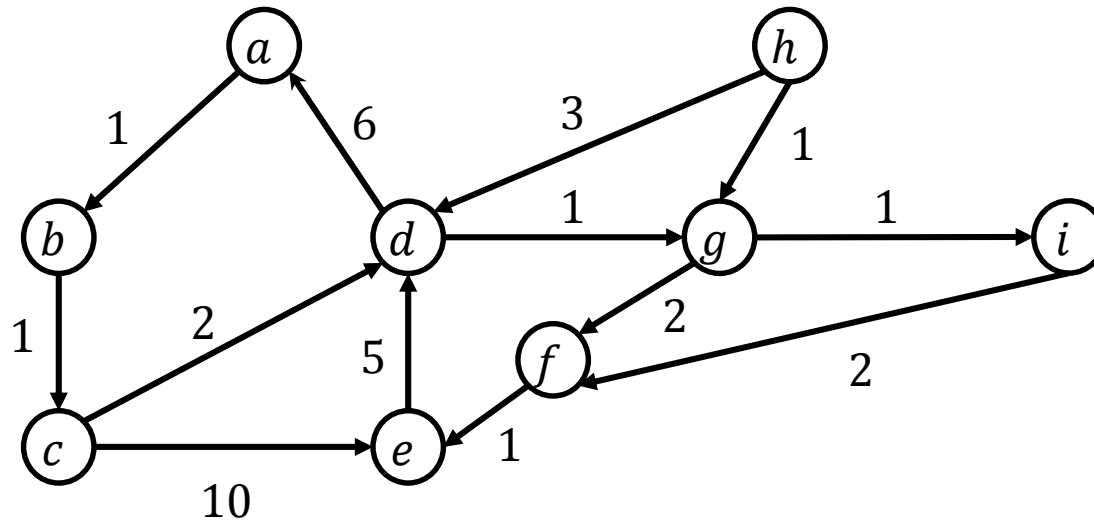
- ◆ Graph Concepts
- ◆ Graph Traversal
  - ◆ Breath First Search (SSSP)
  - ◆ Depth First Search (DAG, topological sort)
- ◆ Shortest Path Algorithms (SP) 最短路, 最短重路
- ◆ Minimum Spanning Tree (MST)
- ◆ Strongly Connected Component (SCC)



# Shortest Path

- ◆ Single source shortest path (SSSP)
  - ◆ BFS algorithm
  - ◆ All the edges have the same weight
- ◆ SSSP with arbitrary positive path (SP)
- ◆ Weight graph
  - ◆ Let  $G=(V,E)$  be a directed graph. Let  $w$  be a function that maps each edge in  $E$  to a positive integer value. Specifically, for each  $e \in E$ ,  $w(e)$  is a positive integer value, which we call the weight of  $e$ .
  - ◆ A directed weighted graph is defined as the pair  $(G,w)$ .

# Weighted Graph



- ◆ The integer on each edge indicates its weight. For example,  $w(d,g)=1$ ,  $w(g,f)=2$ , and  $w(c,e)=10$

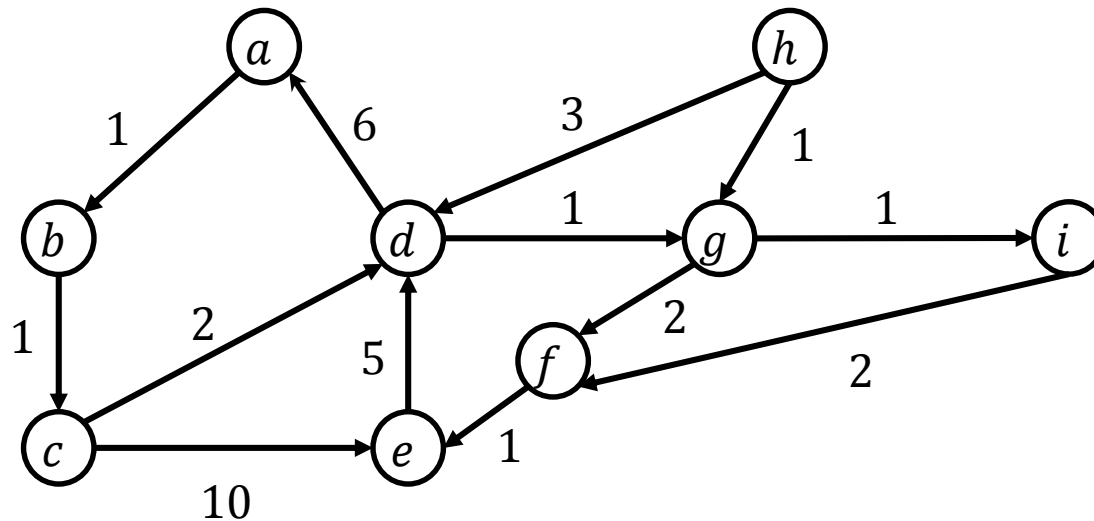
# Shortest Path

- ◆ Consider a directed weighted graph defined by a directed graph  $G=(V,E)$  and function  $w$ .
- ◆ Consider a path in  $G$ :  $(v_1, v_2), (v_2, v_3), \dots, (v_l, v_{l+1})$ , for some integer  $l \geq 1$ . We define the length of the path as:  $\sum_{i=1}^l w(v_i, v_{i+1})$ .
- ◆ Recall that we may also denote the path as:  $v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_{l+1}$ .
- ◆ Give two vertices  $u, v \in V$ , a shortest path from  $u$  to  $v$  is a path from  $u$  to  $v$  that has the minimum length among all the paths from  $u$  to  $v$ .
- ◆ If  $v$  is unreachable from  $u$ , then the shortest path distance from  $u$  to  $v$  is  $\infty$ .

# SSSP with Positive Weights

- ◆ Let  $(G, w)$  with  $G=(V, E)$  be a directed weighted graph, where  $w$  maps every edge of  $E$  to a positive value.
- ◆ Give a vertex  $s$  in  $V$ , the goal of the SSSP problem is to find, for every other vertex  $t \in V \setminus \{s\}$ , a shortest path from  $s$  to  $t$ , unless  $t$  is unreachable from  $s$ .
- ◆ A subsequence property
  - ◆ Lemma: if  $v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_{l+1}$  is a shortest path from  $v_1$  to  $v_{l+1}$ , then for every  $i, j$  satisfying  $1 \leq i \leq j \leq l + 1$ ,  $v_i \rightarrow v_{i+1} \rightarrow \dots \rightarrow v_j$  is shortest path from  $v_i$  to  $v_j$ .
  - ◆ Proof: suppose that this is not true, then we can find a shorter path from  $v_i$  to  $v_j$ . Using that path to replace the original path from  $v_1$  to  $v_{l+1}$ , which contradicts the fact that  $v_1 \rightarrow v_2 \rightarrow \dots \rightarrow v_{l+1}$  is a shortest path.

# Shortest Path Example



- ◆ The path  $c \rightarrow e$  has length 10
- ◆ The path  $c \rightarrow d \rightarrow g \rightarrow f \rightarrow e$  has length 6
- ◆ The second path is the shortest path from  $c$  to  $e$
- ◆ We know that any subsequence of this path is also a shortest path. For example,  $c \rightarrow d \rightarrow g \rightarrow f$  must be a shortest path from  $c$  to  $f$ .

# 最短的下限 → Dijkstra's Algorithm

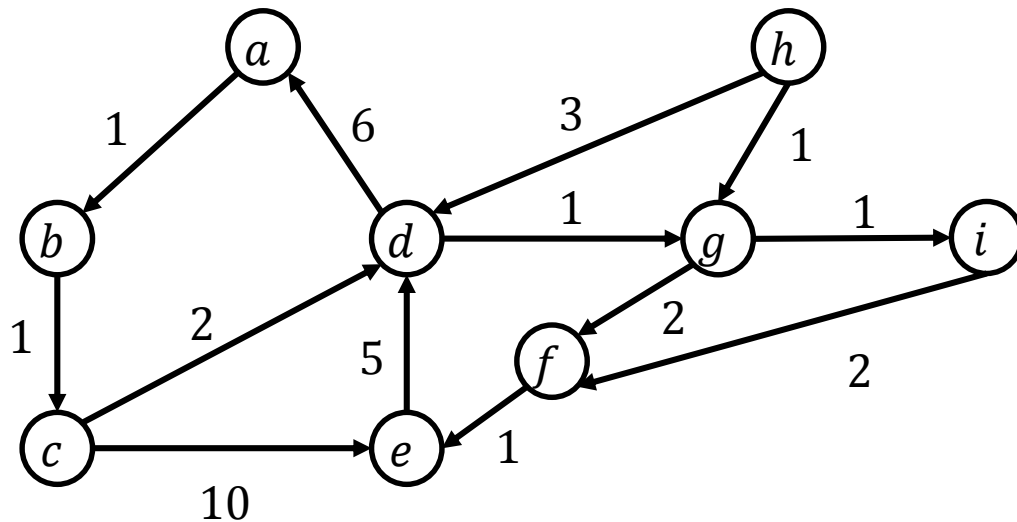
- ◆ We will first introduce the Dijkstra's algorithm for solving the SSSP with positive weights problem
- ◆ Utilizing the subsequence property, our algorithm will return a shortest path tree that encodes all the shortest paths from the source vertex  $s$ .
- ◆ The edge relaxation idea
  - ◆ For every vertex  $v \in V$ , we will maintain a value  $\text{dist}(v)$  that represents the length of the shortest path from  $s$  to  $v$  found so far.
  - ◆ At the end of the algorithm, we will ensure that every  $\text{dist}(v)$  equals to the precise shortest path from  $s$  to  $v$
  - ◆ A core operation in our algorithm is called edge relaxation. Given an edge  $(u,v)$ , we relax it as follows:
    - ◆ If  $\text{dist}(v) < \text{dist}(u) + w(u,v)$ , do nothing
    - ◆ Otherwise, reduce  $\text{dist}(v)$  to  $\text{dist}(u) + w(u,v)$

# Dijkstra's Algorithm

- ◆ Set parent(v) = nil for all vertices  $v \in V$
- ◆ Set dist(s) = 0 and  $\text{dist}(v) = \infty$  for all other vertices  $v \in V$
- ◆ Set  $S = V$
- ◆ Repeat the following until  $S$  is empty
  - ◆ Remove from  $S$  the vertex  $u$  with the smallest  $\text{dist}(u)$ .  
/\* next we relax all the outgoing edges of  $u$  \*/
  - ◆ For every outgoing edge  $(u,v)$  of  $u$ 
    - ◆ If  $\text{dist}(v) > \text{dist}(u) + w(u,v)$  then
      - ◆ Set  $\text{dist}(v) = \text{dist}(u) + w(u,v)$ , and parent(v) = u

# Dijkstra's Algorithm Example

- Suppose that the source is c.



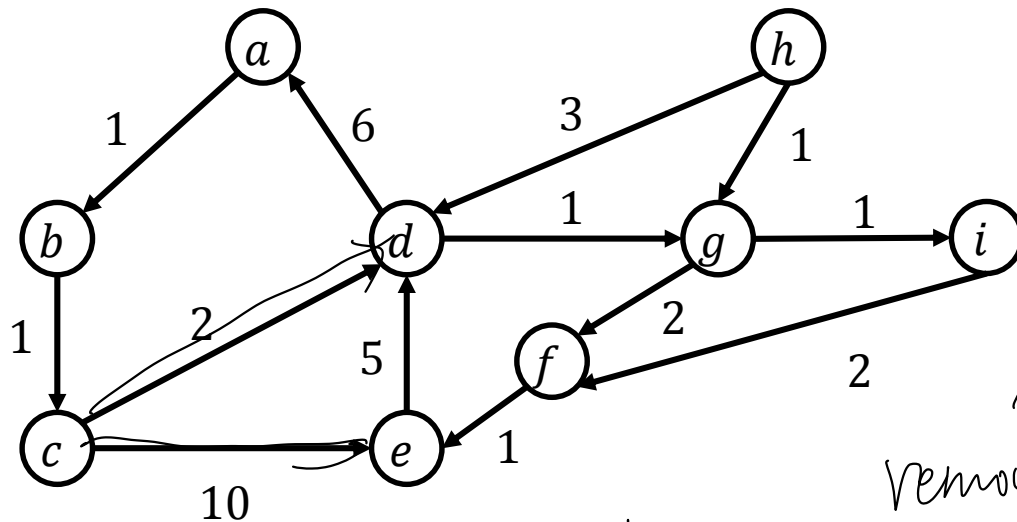
- $S = \{a, b, c, d, e, f, g, h, i\}$

Vertex v	dist(v)	parent(v)
a	$\infty$	nil
b	$\infty$	nil
c	0	nil
d	$\infty$	nil
e	$\infty$	nil
f	$\infty$	nil
g	$\infty$	nil
h	$\infty$	nil
i	$\infty$	nil



# Dijkstra's Algorithm Example

- Relax the out-going edge of c (why is c?)



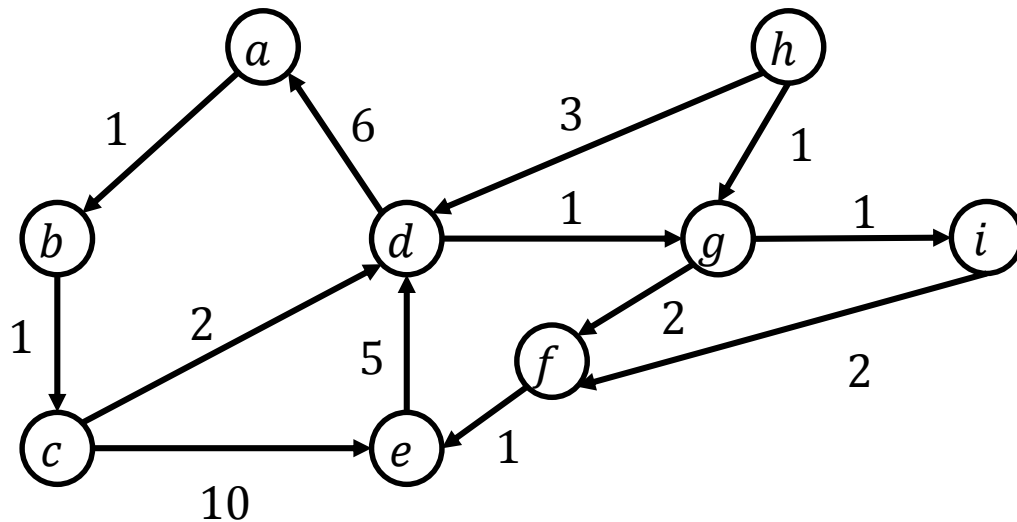
Vertex v	dist(v)	parent(v)
a	$\infty$	nil
b	$\infty$	nil
c	0	nil
d	<u>2</u>	<u>c</u>
e	<u>10</u>	<u>c</u>
f	$\infty$	nil
g	$\infty$	nil
h	$\infty$	nil
i	$\infty$	nil

- $S = \{a, b, d, e, f, g, h, i\}$

- Note that c has been removed!

# Dijkstra's Algorithm Example

- Relax the out-going edge of d

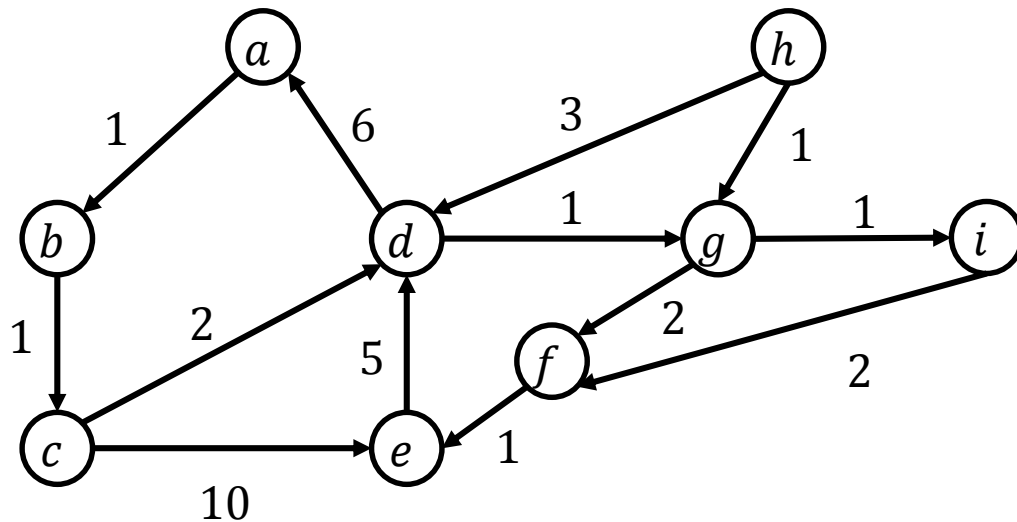


Vertex v	dist(v)	parent(v)
a	8	d
b	$\infty$	nil
c	0	nil
d	2	c
e	10	c
f	$\infty$	nil
g	3	d
h	$\infty$	nil
i	$\infty$	nil

- $S = \{a, b, e, f, g, h, i\}$
- Note that d has been removed!

# Dijkstra's Algorithm Example

- ◆ Relax the out-going edge of g

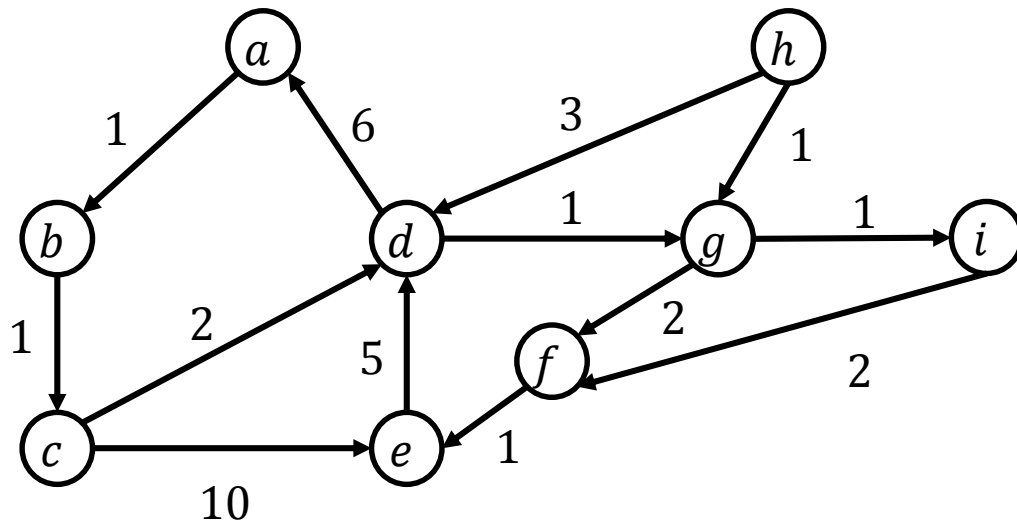


Vertex v	dist(v)	parent(v)
a	8	d
b	$\infty$	nil
c	0	nil
d	2	c
e	10	c
f	5	g
g	3	d
h	$\infty$	nil
i	4	g

- ◆  $S = \{a, b, e, f, h, i\}$
- ◆ Note that g has been removed!

# Dijkstra's Algorithm Example

- ◆ Relax the out-going edge of i

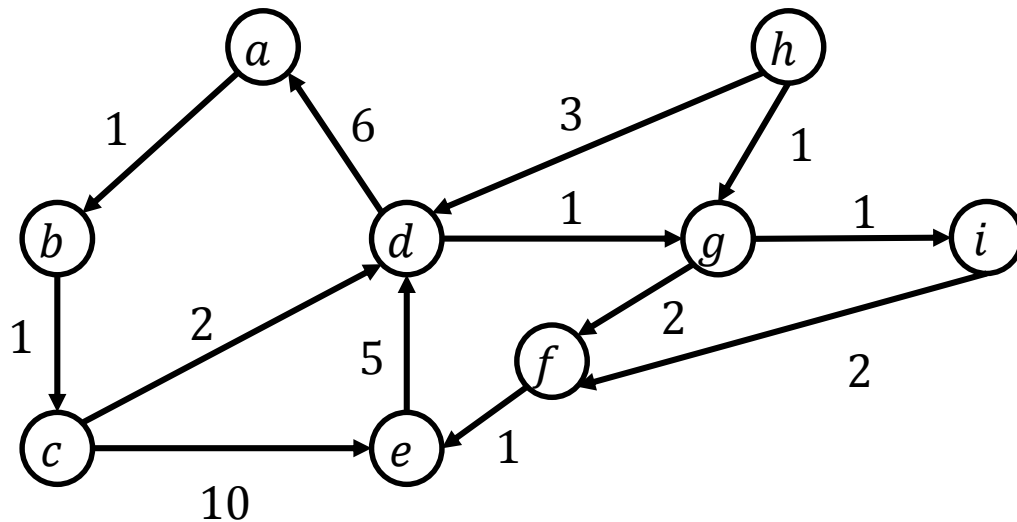


Vertex v	dist(v)	parent(v)
a	8	d
b	$\infty$	nil
c	0	nil
d	2	c
e	10	c
f	5	g
g	3	d
h	$\infty$	nil
i	4	g

- ◆  $S = \{a, b, e, f, h\}$
- ◆ Note that i has been removed!

# Dijkstra's Algorithm Example

- Relax the out-going edge of f

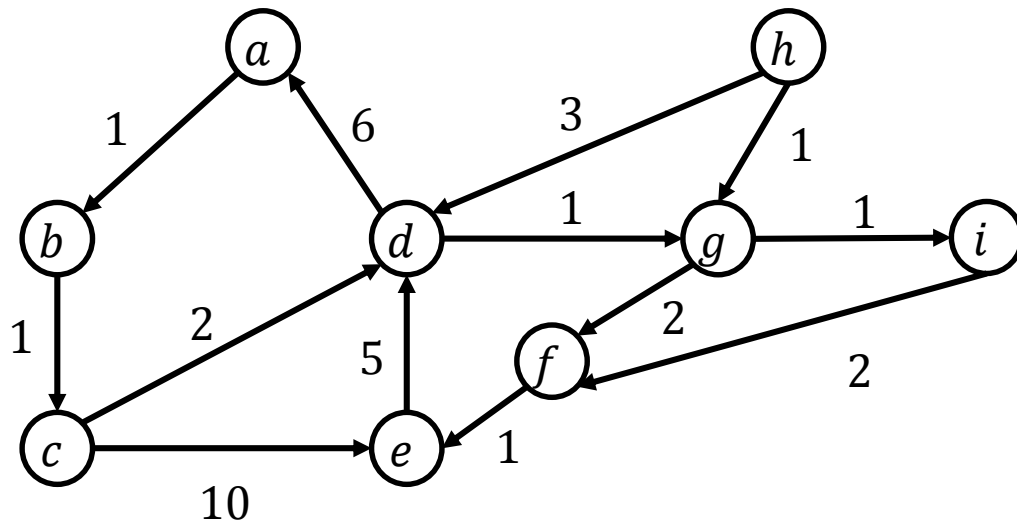


Vertex v	dist(v)	parent(v)
a	8	d
b	$\infty$	nil
c	0	nil
d	2	c
e	6	f
f	5	g
g	3	d
h	$\infty$	nil
i	4	g

- $S = \{a, b, e, h\}$
- Note that f has been removed!

# Dijkstra's Algorithm Example

- Relax the out-going edge of e

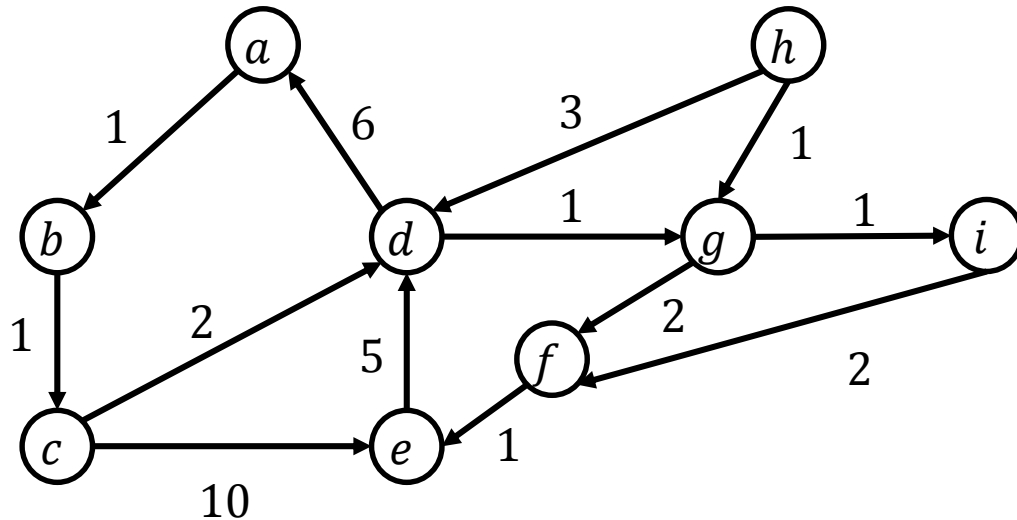


Vertex v	dist(v)	parent(v)
a	8	d
b	$\infty$	nil
c	0	nil
d	2	c
e	6	f
f	5	g
g	3	d
h	$\infty$	nil
i	4	g

- $S = \{a, b, h\}$
- Note that e has been removed!

# Dijkstra's Algorithm Example

- Relax the out-going edge of a

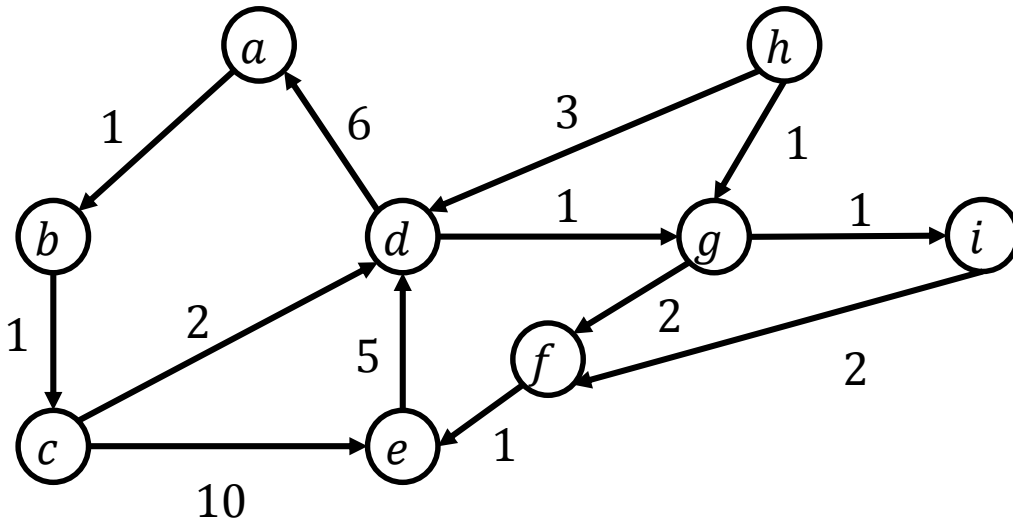


Vertex v	dist(v)	parent(v)
a	8	d
b	9	a
c	0	nil
d	2	c
e	6	f
f	5	g
g	3	d
h	$\infty$	nil
i	4	g

- $S = \{b, h\}$
- Note that a has been removed!

# Dijkstra's Algorithm Example

- Relax the out-going edge of b



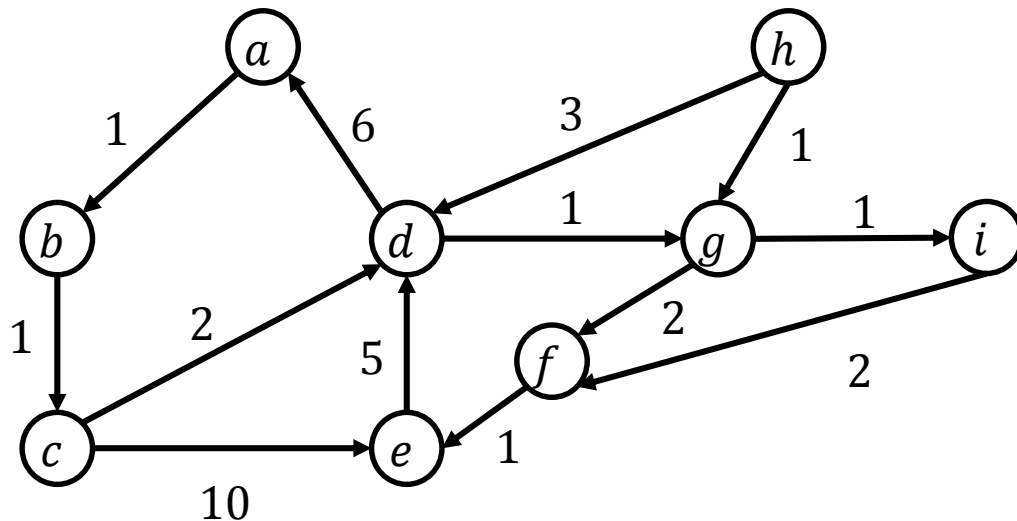
Vertex v	dist(v)	parent(v)
a	8	d
b	9	a
c	0	nil
d	2	c
e	6	f
f	5	g
g	3	d
h	$\infty$	nil
i	4	g

- $S = \{h\}$
- Note that b has been removed!



# Dijkstra's Algorithm Example

- Relax the out-going edge of h

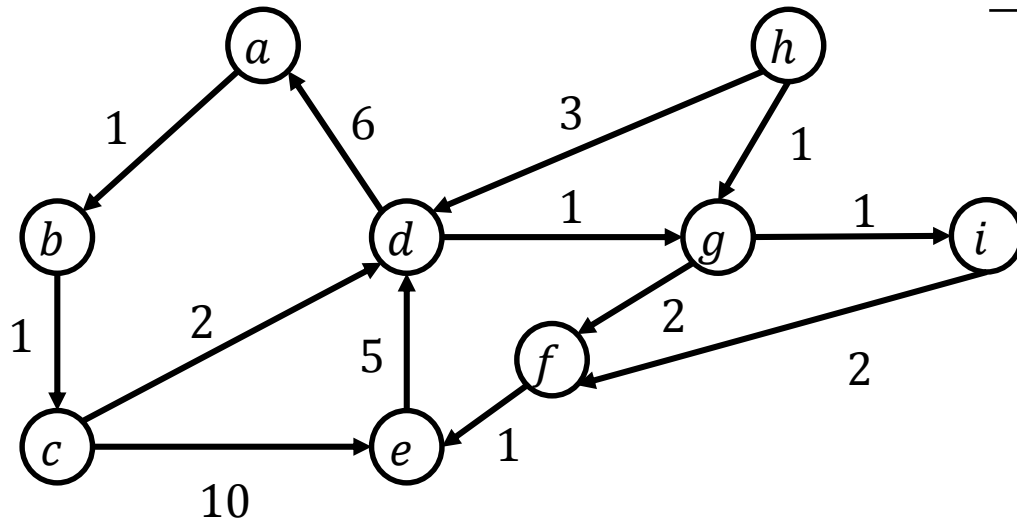


Vertex v	dist(v)	parent(v)
a	8	d
b	9	a
c	0	nil
d	2	c
e	6	f
f	5	g
g	3	d
h	$\infty$	nil
i	4	g

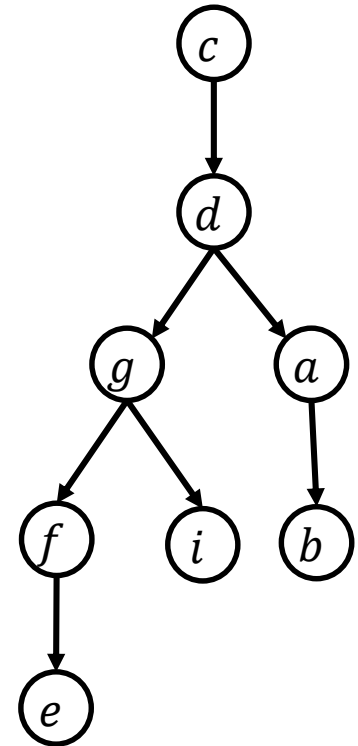
- $S = \{ \}$
- Note that h has been removed!
- All the shortest path distance are now final.

# Constructing the SP Tree

- For every vertex  $v$ , if  $u = \text{parent}(v)$  is not nil, then make  $v$  a child of  $u$ .



Vertex $v$	$\text{parent}(v)$
a	d
b	a
c	nil
d	c
e	f
f	g
g	d
h	nil
i	g



# Correctness and Running Time

- ◆ It will be left as an exercise for you to prove that Dijkstra's algorithm is correct
- ◆ Just as equally instructive is an exercise for you to implement Dijkstra's algorithm in  $O((|V|+|E|)\log|V|)$  time. Why?
- ◆ You have already learned all the data structure for this purpose. Now it is time to practice using them.

# Our Roadmap

- ◆ Graph Concepts
- ◆ Graph Traversal
  - ◆ Breath First Search (SSSP)
  - ◆ Depth First Search (DAG, topological sort)
- ◆ Shortest Path Algorithms (SP)
- ◆ Minimum Spanning Tree (MST)
- ◆ Strongly Connected Component (SCC)

# Minimum Spanning Tree

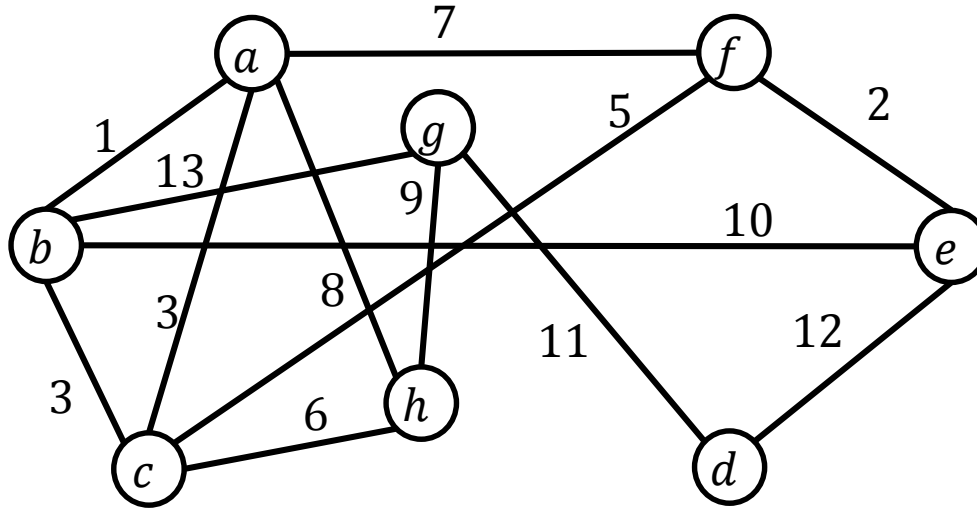
- ◆ We will study another classic problem: finding a minimum spanning tree of an undirected weighted graph.
- ◆ Interestingly, even though the problem appears rather different from SSSP (single source shortest path), it can be solved by an algorithm that is reminiscent of Dijkstra's algorithm

# Undirected Weighted Graphs

- ◆ Let  $G=(V, E)$  be an undirected graph. Let  $w$  be a function that maps each edge of  $G$  to a positive integer value. Specifically, for each edge  $e$ ,  $w(e)$  is a positive integer value, which we call the weight of  $e$ .
- ◆ An undirected weighted graph is defined as the pair  $(G,w)$
- ◆ We will denote an edge between vertices  $u$  and  $v$  in  $G$  as  $\{u,v\}$ , instead of  $(u,v)$ , to emphasize that the ordering of  $u, v$  does not matter
- ◆ We consider that  $G$  is connected, namely, there is a path between any two vertices in  $V$ .

# Undirected Weighted Graphs

## ◆ Example



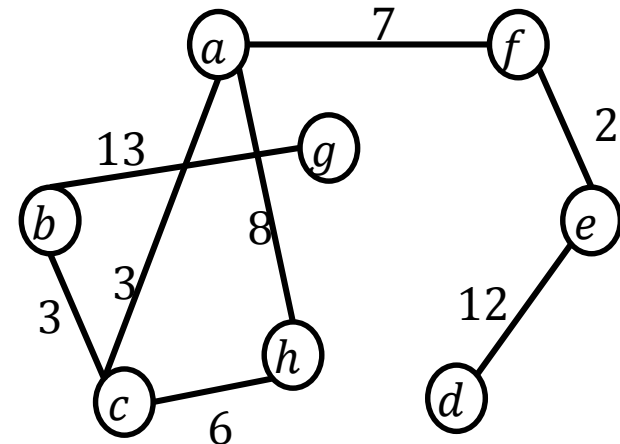
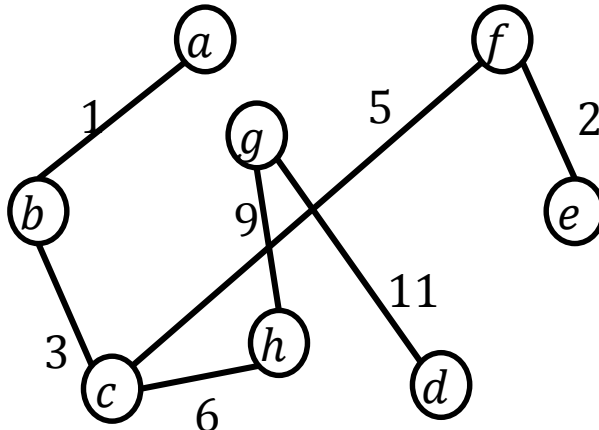
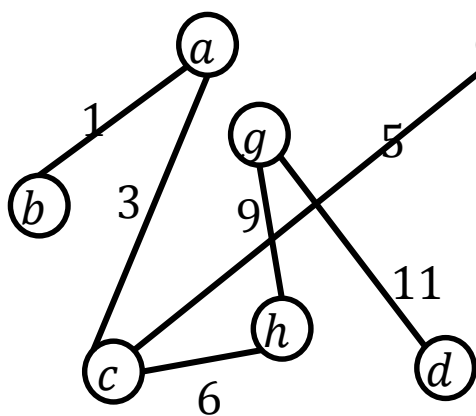
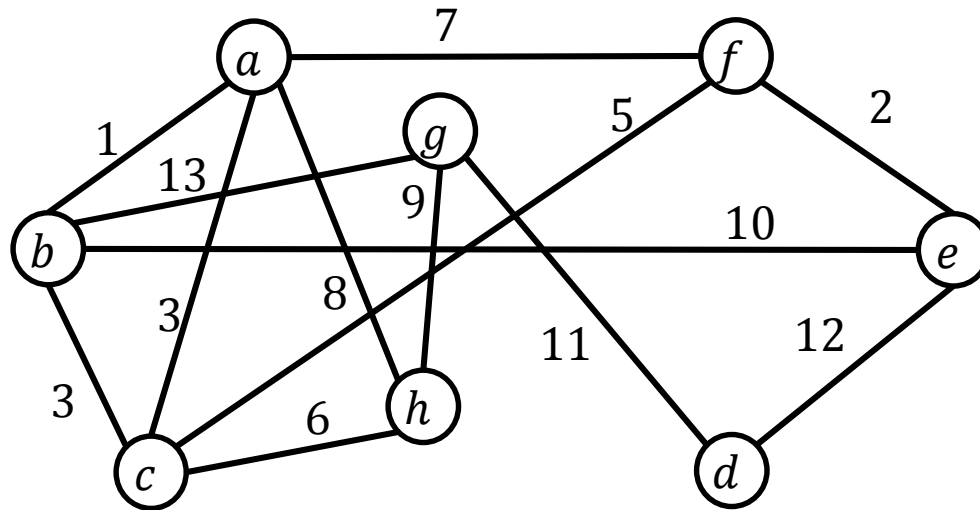
- ◆ The integer on each edge indicates its weight.
- ◆ For example, the weight of  $\{g,h\}=9$ ,
- ◆ and that of  $\{d,h\}$  is 11

# Spanning Trees

- ◆ Remember that a tree is defined as a connected undirected graph with no cycles.
- ◆ Given a connected undirected weighted graph  $(G, w)$  with  $G=(V, E)$ , a spanning tree  $T$  is a tree satisfying the following conditions:
  - ◆ The vertex set of  $T$  is  $V$ .
  - ◆ Every edge of  $T$  is an edge of  $G$ .
- ◆ The cost of  $T$  is defined as the sum of the weights of all the edges in  $T$  (note that  $T$  must have  $|V|-1$  edges)



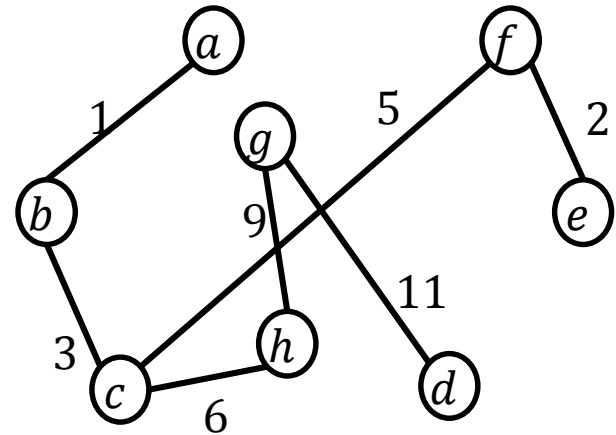
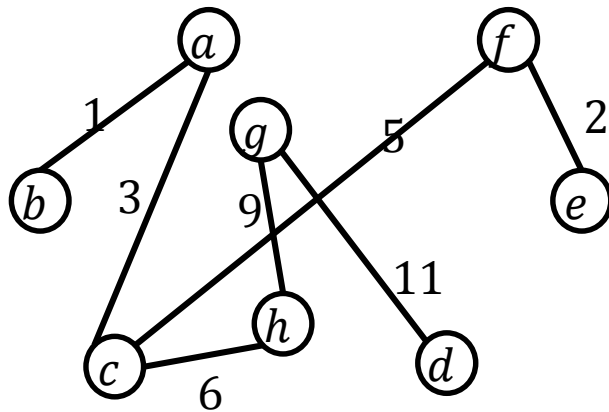
# Spanning Trees Examples



- ◆ The second row shows three spanning trees. What are the costs?

# Minimum Spanning Tree

- ◆ The minimum spanning tree problem
- ◆ Given a connected undirected weighted graph  $(G, w)$  with  $G=(V, E)$ , the goal of the minimum spanning tree (MST) problem is to find a spanning tree of the smallest cost.
- ◆ Such a tree is called an MST of  $(G, w)$



- ◆ Both trees are MSTs. This means that MSTs may not be unique.

# Prim's Algorithm

- ◆ Next, we will discuss an algorithm, called Prim's algorithm, for solving the MST problem.
- ◆ We assume that  $G$  is stored in the adjacency list format. Recall that an edge  $\{u,v\}$  is represented twice: once by placing  $u$  in the adjacency list of  $v$ , and another time by placing  $v$  in the adjacency of  $u$ . The weight of  $\{u,v\}$  is stored in both places.

# Prim's Algorithm

- ◆ The algorithm grows a tree  $T_{\text{mst}}$  by including one vertex at a time, at any moment, it divides the vertex set  $V$  into two parts:
  - ◆ The set  $S$  of vertices that are already in  $T_{\text{mst}}$
  - ◆ The set of other vertices:  $V \setminus S$
- ◆ at the end of the algorithm,  $S = V$
- ◆ If an edge connects a vertex in  $S$  and a vertex in  $V \setminus S$ , we call it an extension edge.
- ◆ At all times, the algorithm enforces the following lightest extension principle:
  - ◆ For every vertex  $v \in V \setminus S$ , it remembers which extension edge of  $v$  has the smallest weight, referred to as the lightest extension edge of  $v$ , and denoted as *best-ext*( $v$ ).

# Prim's Algorithm

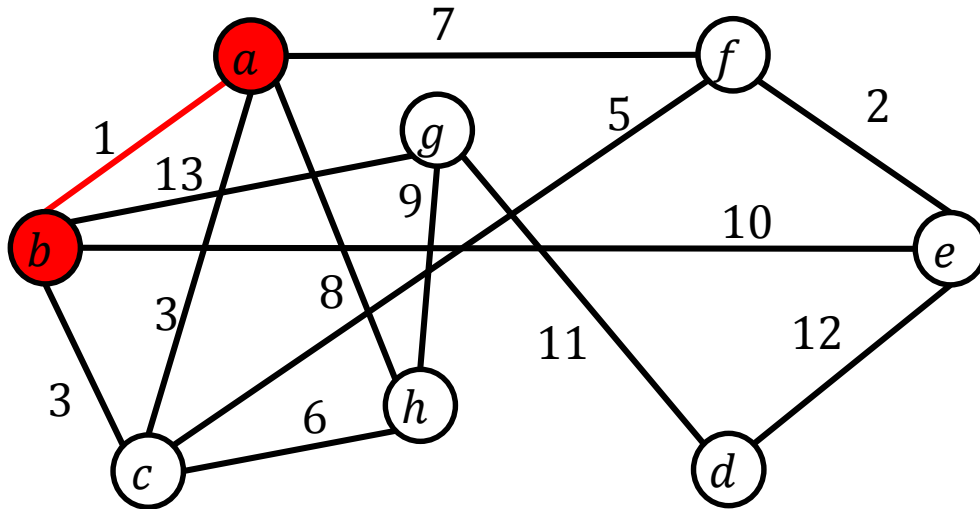
- ◆ 1. Let  $\{u,v\}$  be an edge with the smallest weight among all edges
- ◆ 2. Set  $S=\{u,v\}$ . Initialize a tree  $T_{\text{mst}}$  with only one edge  $\{u,v\}$ .
- ◆ 3. Enforce the lightest extension principle:
  - ◆ For every vertex  $z$  of  $V \setminus S$ 
    - ◆ If  $z$  is a neighbor of  $u$ , but not of  $v$ 
      - ◇  $\text{best-ext}(z) = \text{edge } \{z, u\}$
    - ◆ If  $z$  is a neighbor of  $v$ , but not of  $u$ 
      - ◇  $\text{best-ext}(z) = \text{edge } \{z, v\}$
    - ◆ If  $z$  is a neighbor of both  $u$  and  $v$ 
      - ◇  $\text{best-ext}(z) = \text{the lighter edge between } \{z, u\} \text{ and } \{z, v\}$

# Prim's Algorithm

- ◆ 4. Repeat the following until  $S = V$ :
  - ◆ 5. Get an extension edge of  $\{u, v\}$  with the smallest weight  
/\* Without loss of generality, suppose  $u \in S$ , and \*/
  - ◆ 6. Add  $v$  to  $S$ , and add edge  $\{u, v\}$  into  $T_{\text{mst}}$   
/\* Next, we restore the lightest extension principle. \*/
  - ◆ For every edge  $\{v, z\}$  of  $v$ :
    - ◆ If  $z \notin S$  then
      - ◇ If  $\text{best-ext}(z)$  is heavier than edge  $\{v, z\}$  then
        - ◆ Set  $\text{best-ext}(z) = \text{edge } \{v, z\}$

# Prim's Algorithm Example

- Edge  $\{a,b\}$  is the lightest of all. So, at the beginning  $S = \{a, b\}$ . The MST we are growing now has one edge  $\{a,b\}$

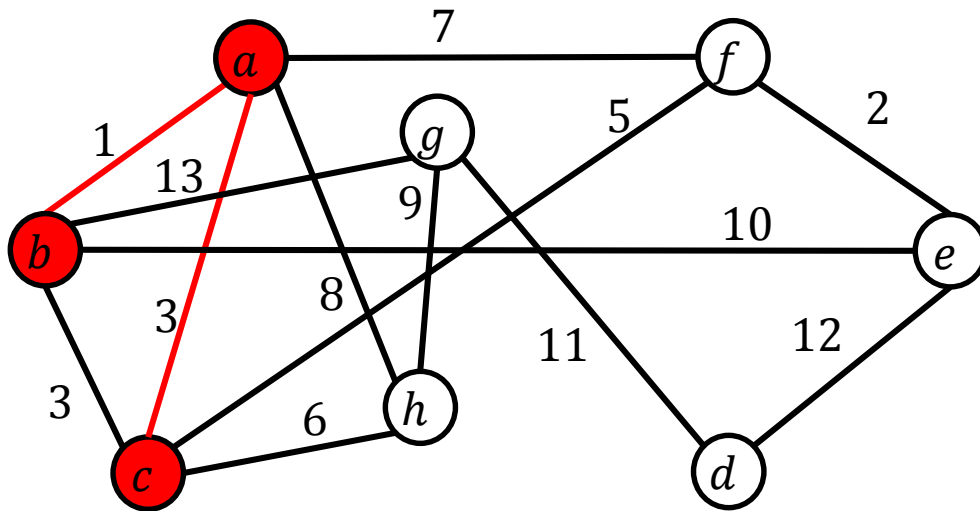


- Note: edge  $\{c,a\}$  and  $\{c,b\}$  have the same weight. Either of them can be  $\text{best-ext}(c)$ .

Vertex $v$	$\text{best-ext}(v)$ and weight
a	n/a
b	n/a
c	$\{c,a\}, 3$
d	nil, $\infty$
e	$\{e,b\}, 10$
f	$\{a,f\}, 7$
g	$\{g,b\}, 13$
h	$\{a,h\}, 8$

# Prim's Algorithm Example

- Edge  $\{c,a\}$  is the lightest extension edge. So, we add  $c$  to  $S$ , which now  $S = \{a,b,c\}$ , add edge  $\{c,a\}$  into MST

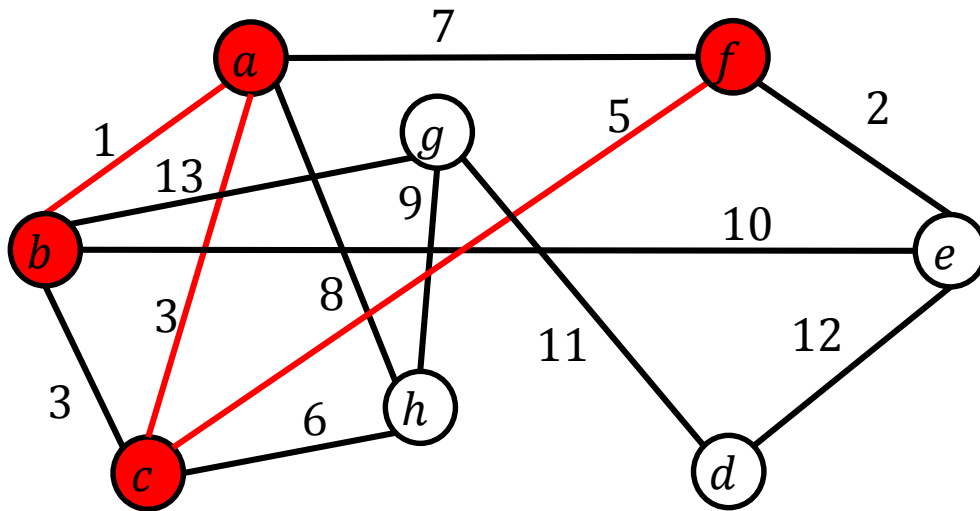


Vertex $v$	best-ext( $v$ ) and weight
a	n/a
b	n/a
c	n/a
d	nil, $\infty$
e	$\{e,b\}, 10$
f	$\{c,f\}, 5$
g	$\{g,b\}, 13$
h	$\{c,h\}, 6$



# Prim's Algorithm Example

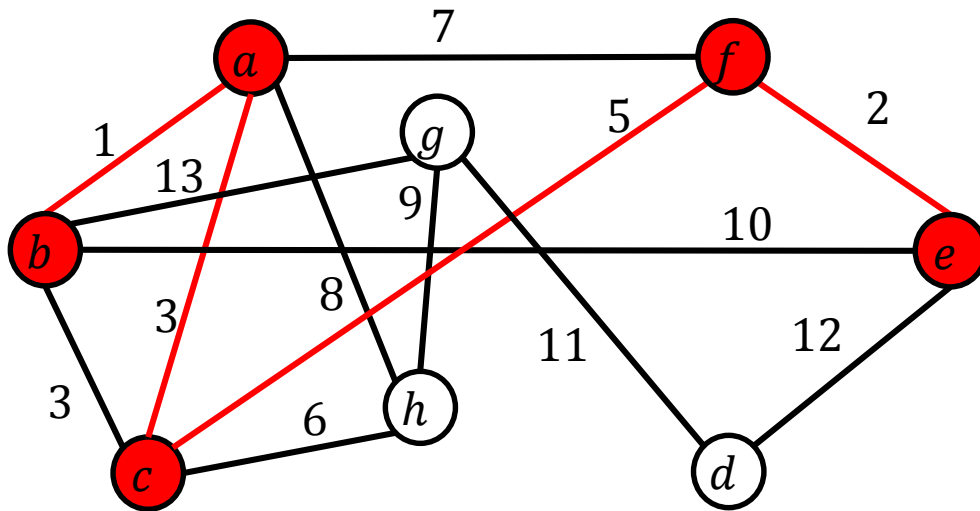
- Edge  $\{c,f\}$  is the lightest extension edge. So, we add  $f$  to  $S$ , which now  $S = \{a,b,c,f\}$ , add edge  $\{c,f\}$  into MST



Vertex v	best-ext(v) and weight
a	n/a
b	n/a
c	n/a
d	nil, $\infty$
e	<b><math>\{e,f\}, 2</math></b>
f	n/a
g	$\{g,b\}, 13$
h	$\{c,h\}, 6$

# Prim's Algorithm Example

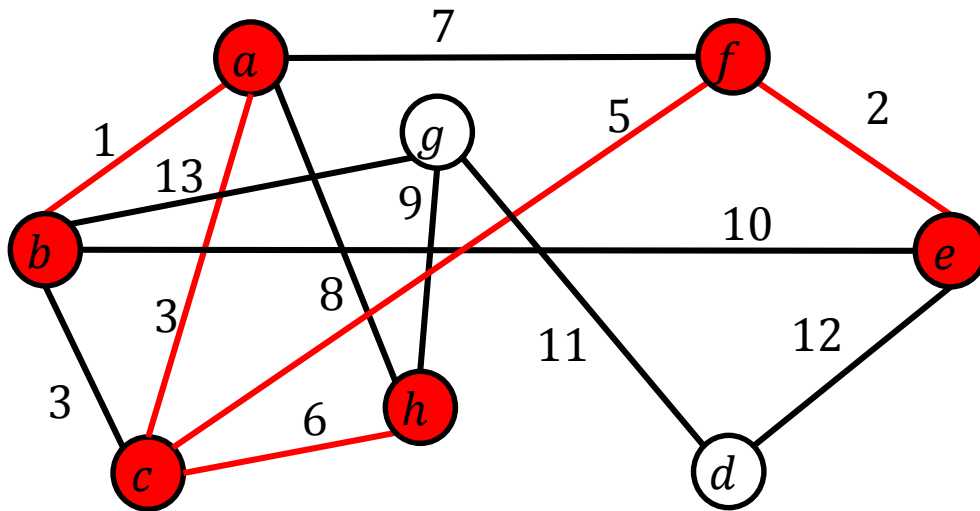
- Edge  $\{e,f\}$  is the lightest extension edge. So, we add  $e$  to  $S$ , which now  $S = \{a,b,c,f,e\}$ , add edge  $\{e,f\}$  into MST



Vertex $v$	best-ext( $v$ ) and weight
a	n/a
b	n/a
c	n/a
d	(e,d), 12
e	n/a
f	n/a
g	{g,b}, 13
h	{c,h}, 6

# Prim's Algorithm Example

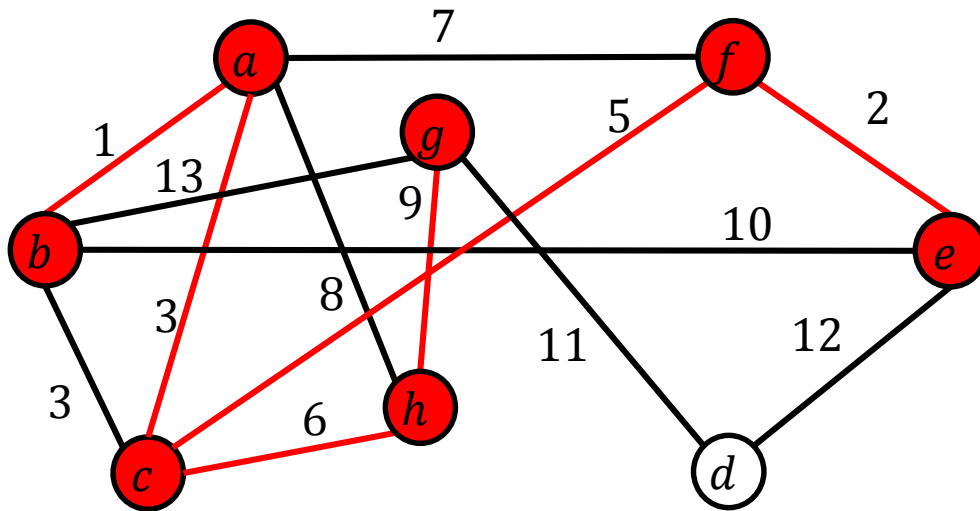
- Edge  $\{c,h\}$  is the lightest extension edge. So, we add  $h$  to  $S$ , which now  $S = \{a,b,c,f,e,h\}$ , add edge  $\{c,h\}$  into MST



Vertex $v$	best-ext( $v$ ) and weight
a	n/a
b	n/a
c	n/a
d	(e,d), 12
e	n/a
f	n/a
g	<b><math>\{g,h\}, 9</math></b>
h	n/a

# Prim's Algorithm Example

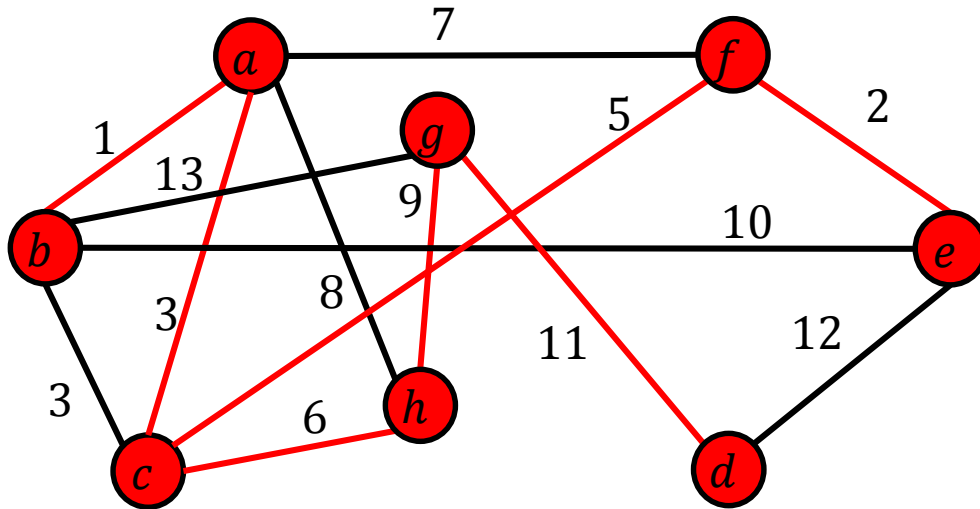
- Edge  $\{g,h\}$  is the lightest extension edge. So, we add  $h$  to  $S$ , which now  $S = \{a,b,c,f,e,h,g\}$ , add edge  $\{g,h\}$  into MST



Vertex $v$	best-ext( $v$ ) and weight
a	n/a
b	n/a
c	n/a
d	(g,d), 11
e	n/a
f	n/a
g	n/a
h	n/a

# Prim's Algorithm Example

- Finally, edge  $\{d,g\}$  is the lightest extension edge. So, we add  $d$  to  $S$ , which now  $S = \{a,b,c,f,e,h,g,d\}$ , add edge  $\{d,g\}$  into MST



Vertex v	best-ext(v) and weight
a	n/a
b	n/a
c	n/a
d	n/a
e	n/a
f	n/a
g	n/a
h	n/a

- We have obtained our final MST.

# Time Complexity Analysis

- ◆ A priority queue  $Q$  (min-heap) was employed in Prim's algorithm, what is the key of node in  $Q$ ?
- ◆ Line 1 & 2:  $O(1)$
- ◆ Line 3:  $O(|E|)$
- ◆ Line 4:  $O(|V|)$
- ◆ Line 5:  $O(|V| \log |V|)$
- ◆ Line 6:  $O(|V|)$
- ◆ Line 7:  $O(|E| \log |V|)$ , Total:  $O((|V|+|E|) \log |V|)$
- ◆ Remark: Using the Fibonacci Heap, will not cover in this course, we can improve the running time to  $O(|V| \log |V| + |E|)$

# Hint: Correctness Proof

- ◆ **Claim:** For any  $i \in [1, |V|-1]$ , there must be an MST containing all the first  $i$  edges chosen by the algorithm
- ◆ Then the algorithm's correctness follows from the above claim at  $i = |V|-1$
- ◆ We prove it by induction the sequence of the edges added to the tree
- ◆ Base case:  $i=1$ , let  $\{u,v\}$  be the edge with the smallest weight in the graph, the edge must exist in some MST
- ◆ Inductive case: the claim holds for  $i \leq k-1$
- ◆ We prove it also hold for  $i=k$

# Our Roadmap

- ◆ Graph Concepts
- ◆ Graph Traversal
  - ◆ Breath First Search (SSSP)
  - ◆ Depth First Search (DAG, topological sort)
- ◆ Shortest Path Algorithm (SP)
- ◆ Minimum Spanning Tree (MST)
- ◆ Strongly Connected Component (SCC)

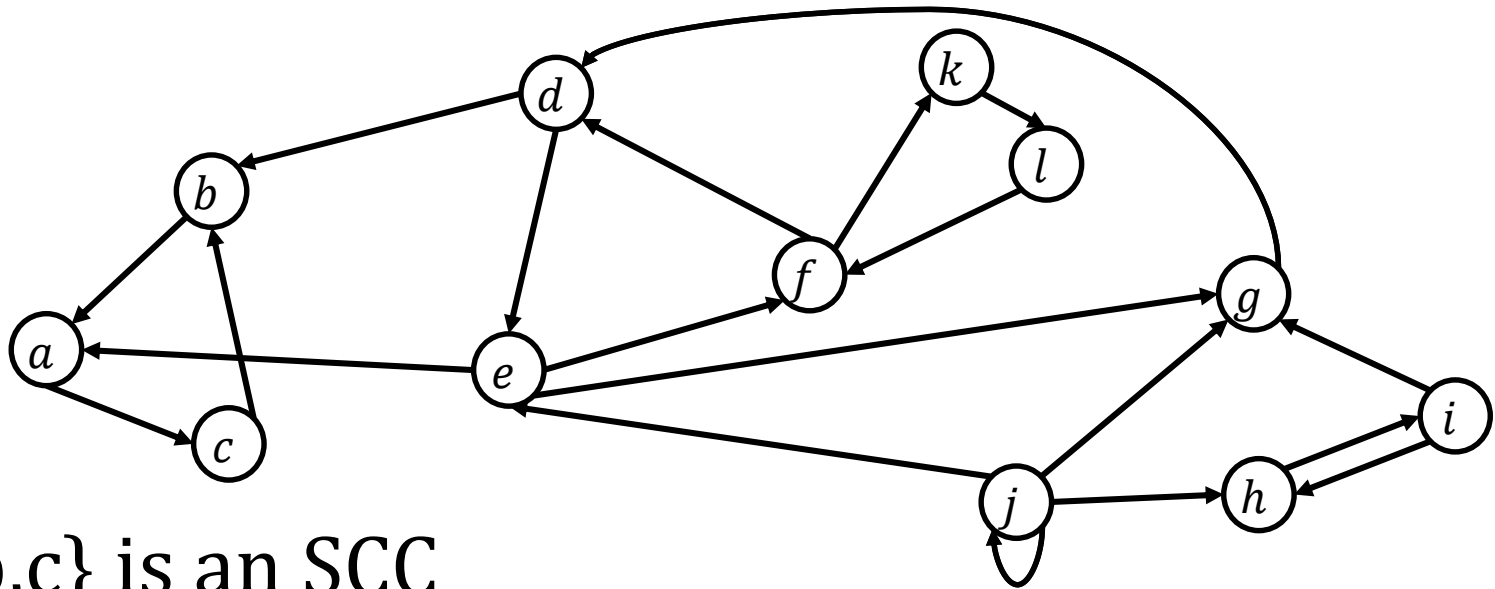


# Strongly Connected Components

- ◆ Let  $G=(V,E)$  be a directed graph.
- ◆ A strongly connected component (SCC) of  $G$  is a subset  $S$  of  $V$  such that:
  - ◆ For any two vertices  $u, v \in S$ , it must hold that:
    - ◆ There is a path from  $u$  to  $v$
    - ◆ There is a path from  $v$  to  $u$
  - ◆  $S$  is maximal in the sense that we cannot put any more vertex into  $S$  without violating the above property
- ◆ It seems to be rather difficult at first glance, the algorithm is once again very simple, run DFS only twice.

# SCC Example

- Consider the following graph:



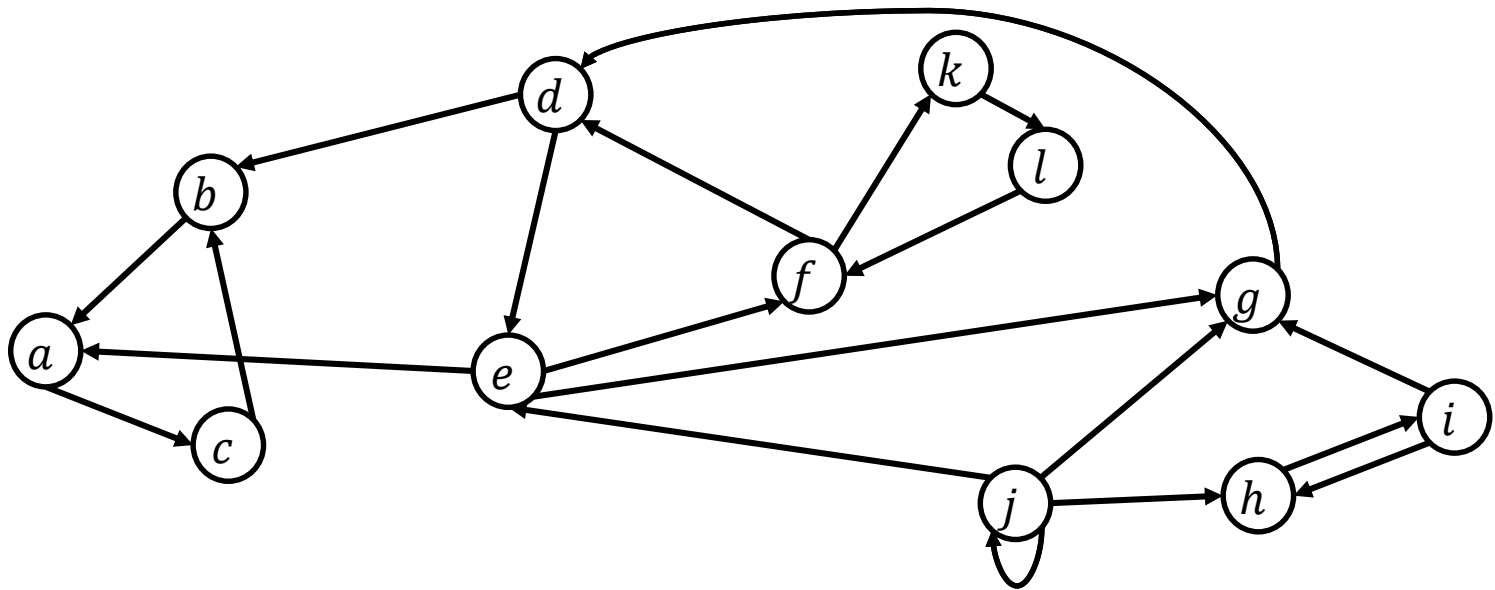
- $\{a, b, c\}$  is an SCC
- $\{a, b, c, d\}$  is not an SCC
- $\{d, e, f, k, l\}$  is not an SCC (why?)
- $\{e, d, f, k, l, g\}$  is an SCC

# SCCs are Disjoint

- ◆ Theorem: Suppose that  $S_1$  and  $S_2$  are both SCCs of  $G$ , Then  $S_1 \cap S_2 = \emptyset$
- ◆ Proof: Assume that there is a vertex  $v$  in both  $S_1$  and  $S_2$ . Then, for any vertex  $u_1 \in S_1$  and any vertex  $u_2 \in S_2$ :
  - ◆ There is a path from  $u_1$  to  $u_2$  : we can first go from  $u_1$  to  $v$  within  $S_1$ , and then from  $v$  to  $u_2$  within  $S_2$ .
  - ◆ Likewise, there is also a path from  $u_2$  to  $u_1$ .Hence, neither  $S_1$  and  $S_2$  is maximal, contradicting the fact that they are SCCs.

# Finding SCCs

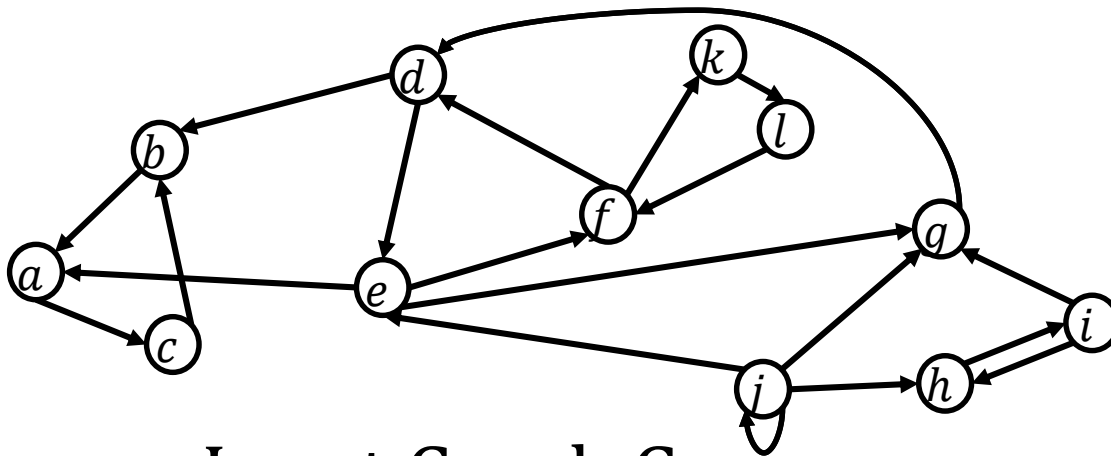
- Given a directed graph  $G = (V, E)$ , the goal of the finding strongly connected components problem is to divide  $V$  into disjoint subsets, each of which is an SCC.



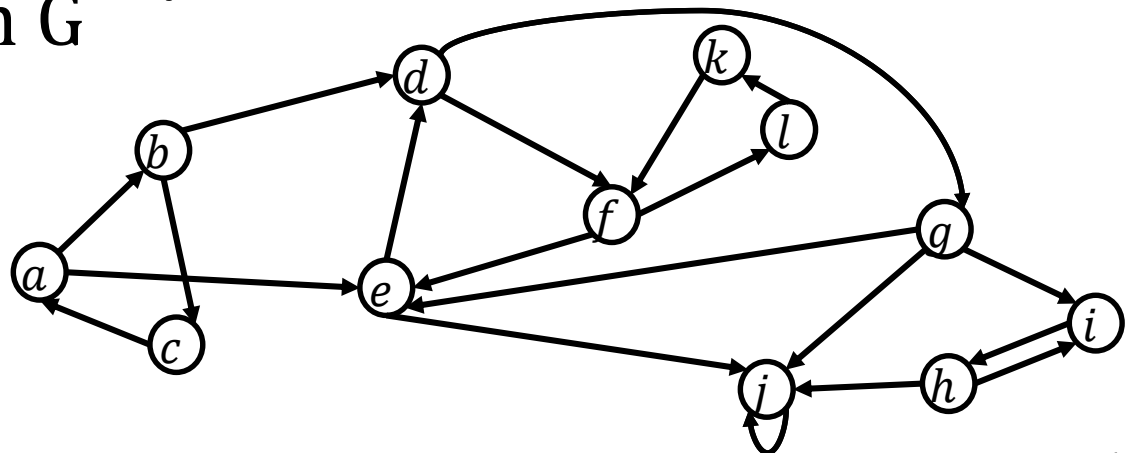
- The goal is to output the following 4 SCCs:  $\{a, b, c\}$ ,  $\{d, e, f, g, k, l\}$ ,  $\{h, i\}$ , and  $\{j\}$

# Finding SCCs Algorithm

- ◆ Step 1: obtain the reverse graph  $G^R$  by reversing the directions of all the edges in  $G$ .



Input Graph  $G$



Reverse Graph  $G^R$

# Finding SCCs Algorithm

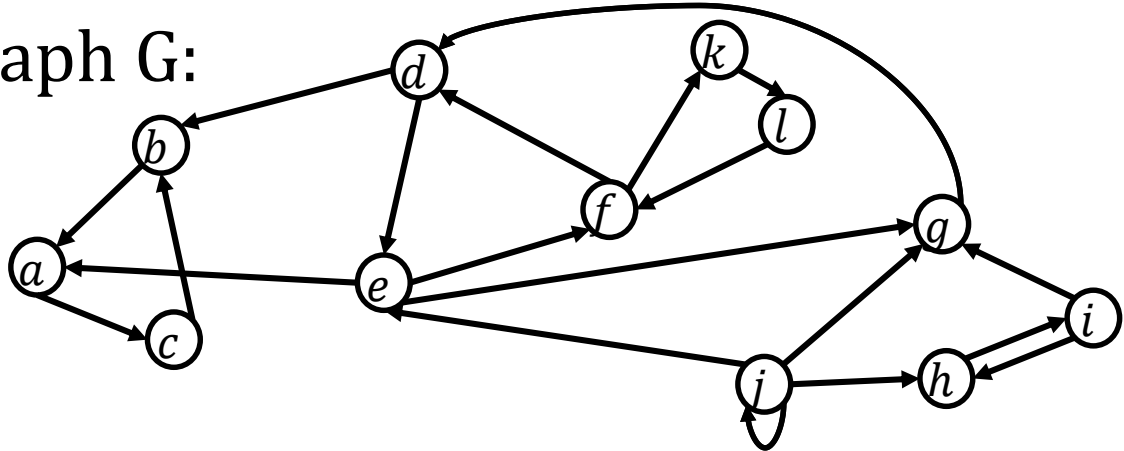
- ◆ Step 2: Perform DFS on  $G^R$ , and obtain the sequence  $L^R$  that the vertices in  $G^R$  turn red (i.e., whenever a vertex is popped out of the stack, append it to  $L^R$ )
- ◆ Obtain  $L$  as the reverse order of  $L^R$
- ◆ We may perform DFS starting from any vertex. The following is a possible order that the vertices are discovered: f,l,k,e,j,d,g,i,h,a,b,c
- ◆ The corresponding turn-red sequence is
- ◆  $L^R = \{k,l,j,h,i,g,d,e,f,c,b,a\}$
- ◆ Hence  $L = \{a,b,c,f,e,d,g,i,h,j,l,k\}$

# Finding SCCs Algorithm

- ◆ Step 3: Perform DFS on the original graph  $G$  by obeying the following rules:
  - ◆ Rule 1: start the DFS at the first vertex of  $L$
  - ◆ Rule 2: whenever a restart is needed, start from the first vertex of  $L$  that is still white.
- ◆ Output the vertices in each DFS-tree as an SCC

# Finding SCCs Algorithm

- From the last step, we have  $L = \{a, b, c, f, e, d, g, i, h, j, l, k\}$
- The original graph  $G$ :



- Starting DFS from a, which discovered  $\{a, b, c\}$
- Restart from f, which discovered  $\{f, k, l, d, e, g\}$
- Restart from i, which discovered  $\{i, h\}$
- Restart from j, which discovered  $\{j\}$
- The DFS returns 4 DFS-tree, whose vertex sets are as above, Each vertex set constitutes an SCC.



# Running Time Analysis

- ◆ Steps 1 and 2 obviously require only  $O(|V|+|E|)$  time.
- ◆ Regarding Step 3, the DFS itself takes  $O(|V|+|E|)$ , but how about the cost of implement Rule 2.
- ◆ Namely, whenever, DFS needs a restart, how do we find the first white vertex in  $L$  efficiently?
- ◆ It can be done in  $O(|V|)$  total time.
- ◆ Hence, the overall execution time is  $O(|V|+|E|)$

# Hint: Correctness Proof

- ◆ Let  $G$  be the input directed graph, with SCCs  $S_1, S_2, \dots, S_t$  for some  $t \geq 1$
- ◆ Let us define a SCC graph  $G^{\text{SCC}}$  as follows:
  - ◆ Each vertex in  $G^{\text{SCC}}$  is a distinct SCC in  $G$ .
  - ◆ Consider two vertices  $S_i$  and  $S_j$ ,  $G^{\text{SCC}}$  has an edge from  $S_i$  to  $S_j$  if and only if:
    - ◆  $i \neq j$
    - ◆ There is a path in  $G$  from a vertex in  $S_i$  to a vertex in  $S_j$
- ◆  $G^{\text{SCC}}$  is a DAG, define an SCC as a sink SCC if it has no outgoing edge in  $G^{\text{SCC}}$
- ◆ Lemma: There must be at least one sink SCC in  $G^{\text{SCC}}$

# Hint: Correctness Proof

- ◆ Let  $S$  be a sink SCC in  $G^{\text{SCC}}$ . Suppose that we perform a DFS starting from any vertex in  $S$ . Then the first DFS-tree output must include all and only the vertex in  $S$ .
- ◆ Finding SCC: The strategy
  - ◆ 1. Performing DFS from any vertex in a sink SCC  $S$
  - ◆ 2. Delete all vertices of  $S$  from  $G$ , as well as their edges
  - ◆ 3. Accordingly, delete  $S$  from  $G^{\text{SCC}}$ , as well as its edges.
  - ◆ 4. Repeat from Step 1, until  $G$  is empty.
- ◆ Lemma: Let  $S_1, S_2$  be SCCs such that there is a path from  $S_1$  to  $S_2$  in  $G^{\text{SCC}}$ . In the ordering of  $L$ , the earliest vertex in  $S_2$  must come before the earliest vertex in  $S_1$

Thank You!