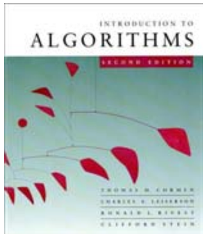
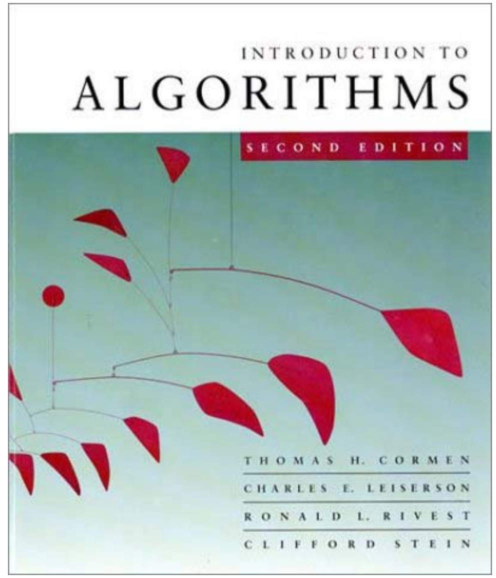


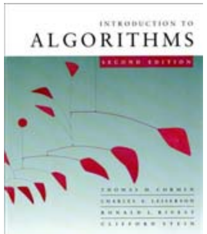
CS 5633 -- Spring 2008



Graphs

Carola Wenk

Slides courtesy of Charles Leiserson with changes and additions by Carola Wenk



Graphs (review)

Definition. A ***directed graph (digraph)*** $G = (V, E)$ is an ordered pair consisting of

- a set V of ***vertices*** (singular: ***vertex***),
- a set $E \subseteq V \times V$ of ***edges***.

In an ***undirected graph*** $G = (V, E)$, the edge set E consists of *unordered* pairs of vertices.

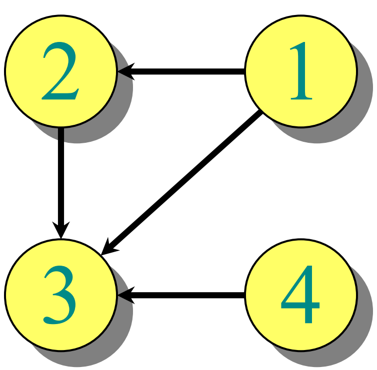
In either case, we have $|E| = O(|V|^2)$. Moreover, if G is connected, then $|E| \geq |V| - 1$.

(Review CLRS, Appendix B.4 and B.5.)

Adjacency-matrix representation

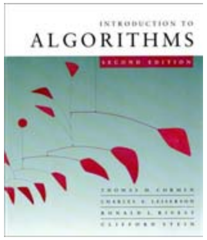
The ***adjacency matrix*** of a graph $G = (V, E)$, where $V = \{1, 2, \ldots, n\}$, is the matrix $A[1 \,.\,.\, n, 1 \,.\,.\, n]$ given by

$$A[i, j] = \begin{cases} 1 & \text{if } (i, j) \in E, \\ 0 & \text{if } (i, j) \notin E. \end{cases}$$



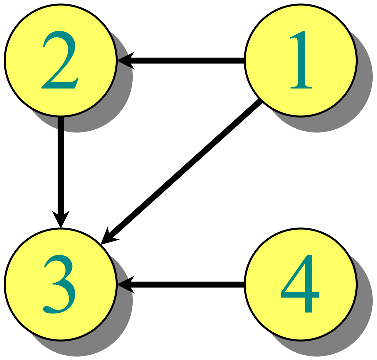
A	1	2	3	4
1	0	1	1	0
2	0	0	1	0
3	0	0	0	0
4	0	0	1	0

$\Theta(|V|^2)$ storage $\Rightarrow$ ***dense*** representation.



Adjacency-list representation

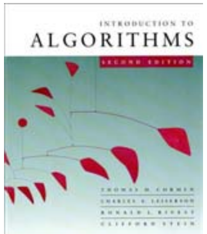
An ***adjacency list*** of a vertex $v \in V$ is the list $Adj[v]$ of vertices adjacent to v.



$Adj[1] = \{2, 3\}$
$Adj[2] = \{3\}$
$Adj[3] = \{\}$
$Adj[4] = \{3\}$

For undirected graphs, $|Adj[v]| = degree(v)$.

For digraphs, $|\,Adj[v]\,| = out\text{-}degree(v)$.



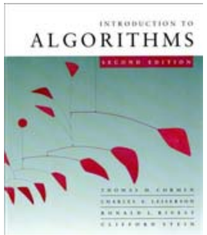
Adjacency-list representation

Handshaking Lemma:

Every edge is counted twice

- For undirected graphs:
  $\sum_{v \in V} \mathit{degree}(v) = 2|E|$
- For digraphs:
  $\sum_{v \in V} \mathit{in\text{-}degree}(v) + \sum_{v \in V} \mathit{out\text{-}degree}(v) = 2|E|$

$\Rightarrow$ adjacency lists use $\Theta(|V| + |E|)$ storage
$\Rightarrow$ a ***sparse*** representation



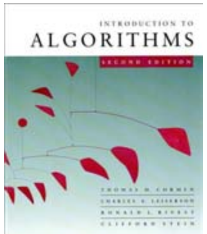
Graph Traversal

Let $G=(V,E)$ be a (directed or undirected) graph, given in adjacency list representation.

$|V| = n$, $|E| = m$

A graph traversal visits every vertex:

- Breadth-first search (BFS)
- Depth-first search (DFS)

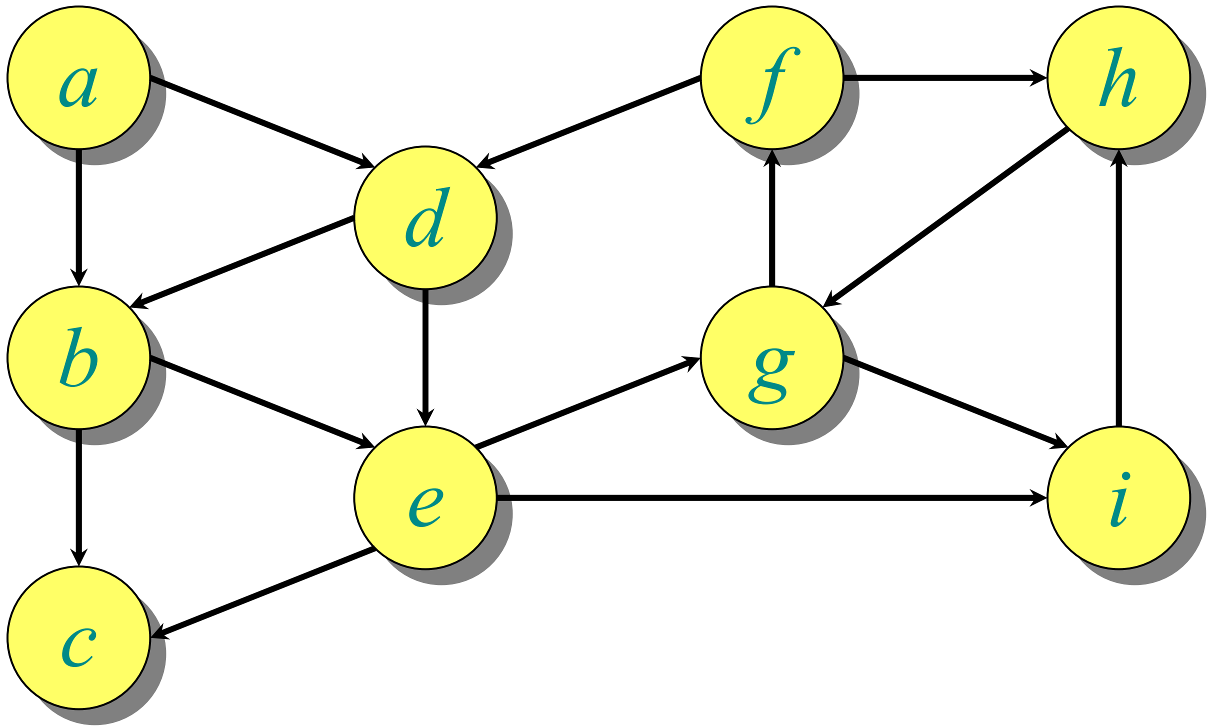


Breadth-First Search (BFS)

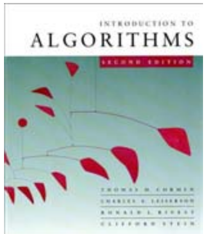
```
BFS(G=(V,E))
    Mark all vertices in G as "unvisited" // time=0
    Initialize empty queue Q
    for each vertex v ∈ V do
        if v is unvisited
            visit v // time++
            Q.enqueue(v)
            BFS_iter(G)
```

```
BFS_iter(G)
    while Q is non-empty do
        v = Q.dequeue()
        for each w adjacent to v do
            if w is unvisited
                visit w   // time++
                Add edge (v,w) to T
                Q.enqueue(w)
```

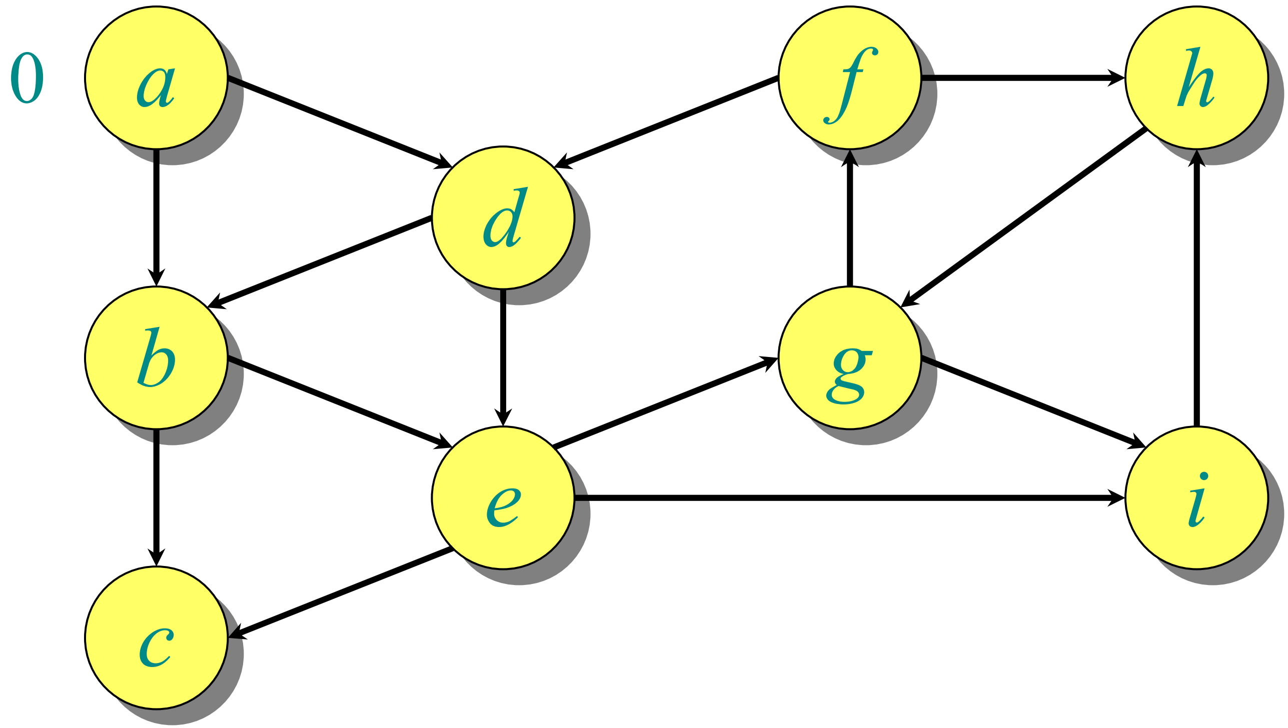
Example of breadth-first search



Q:

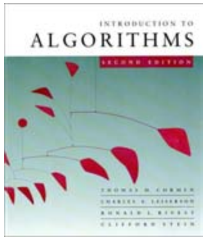


Example of breadth-first search

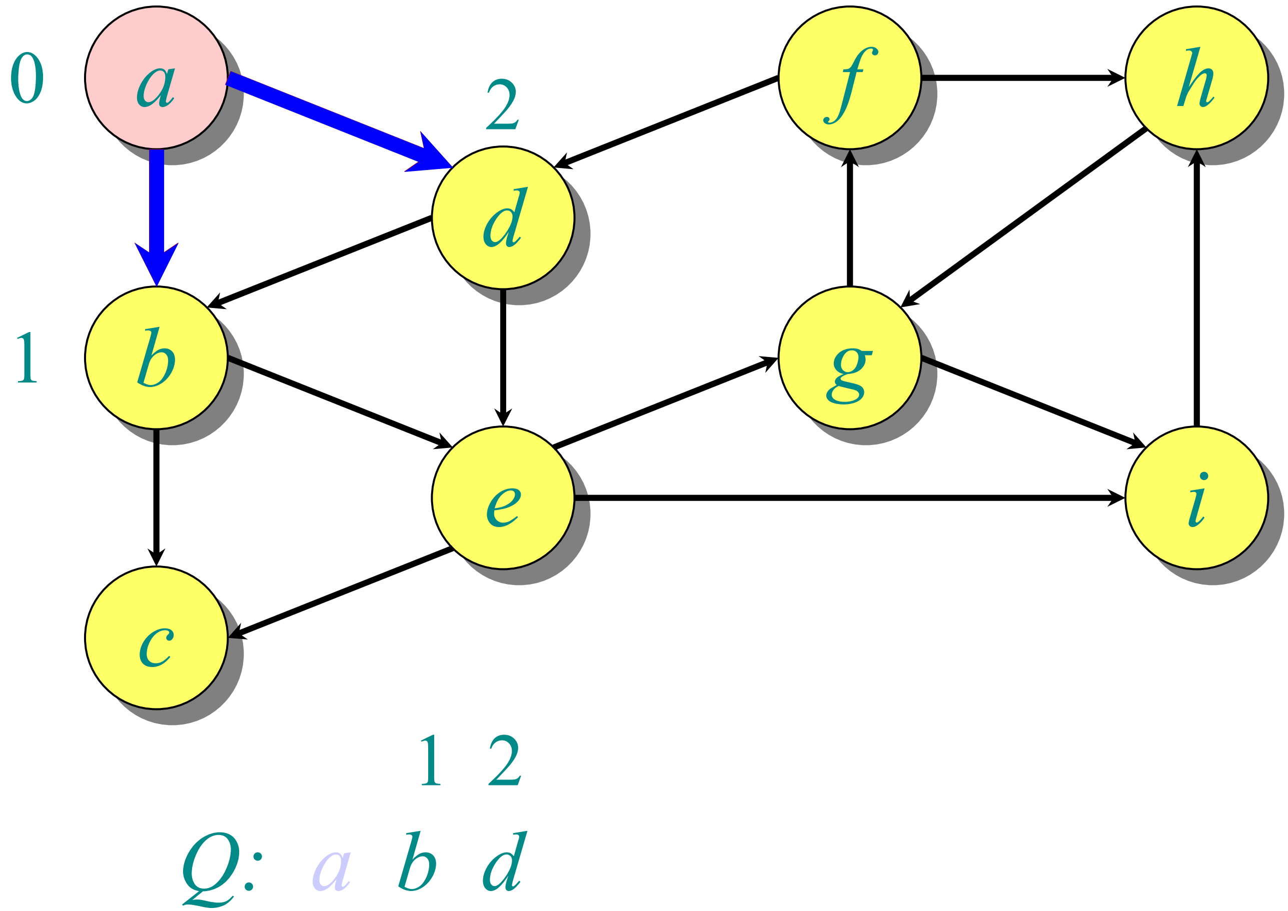


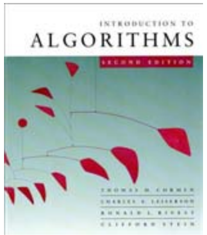
0

Q: *a*

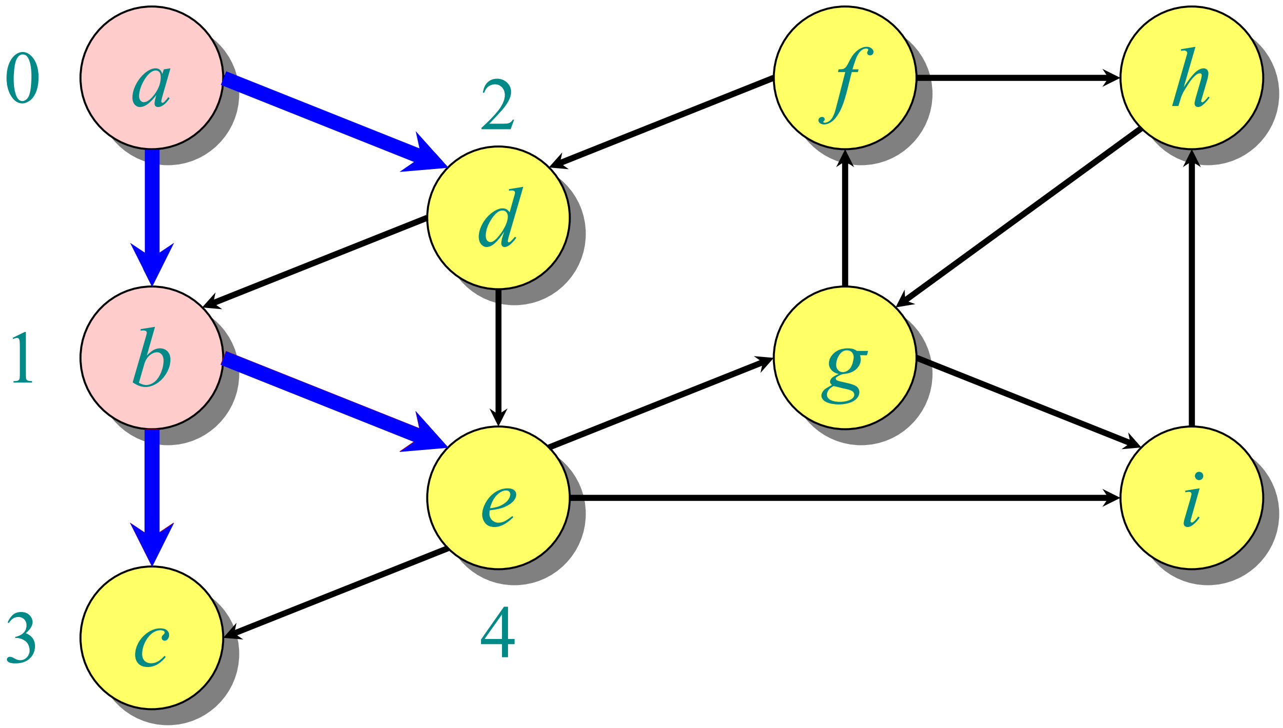


Example of breadth-first search



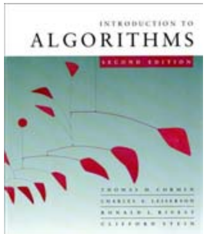


Example of breadth-first search

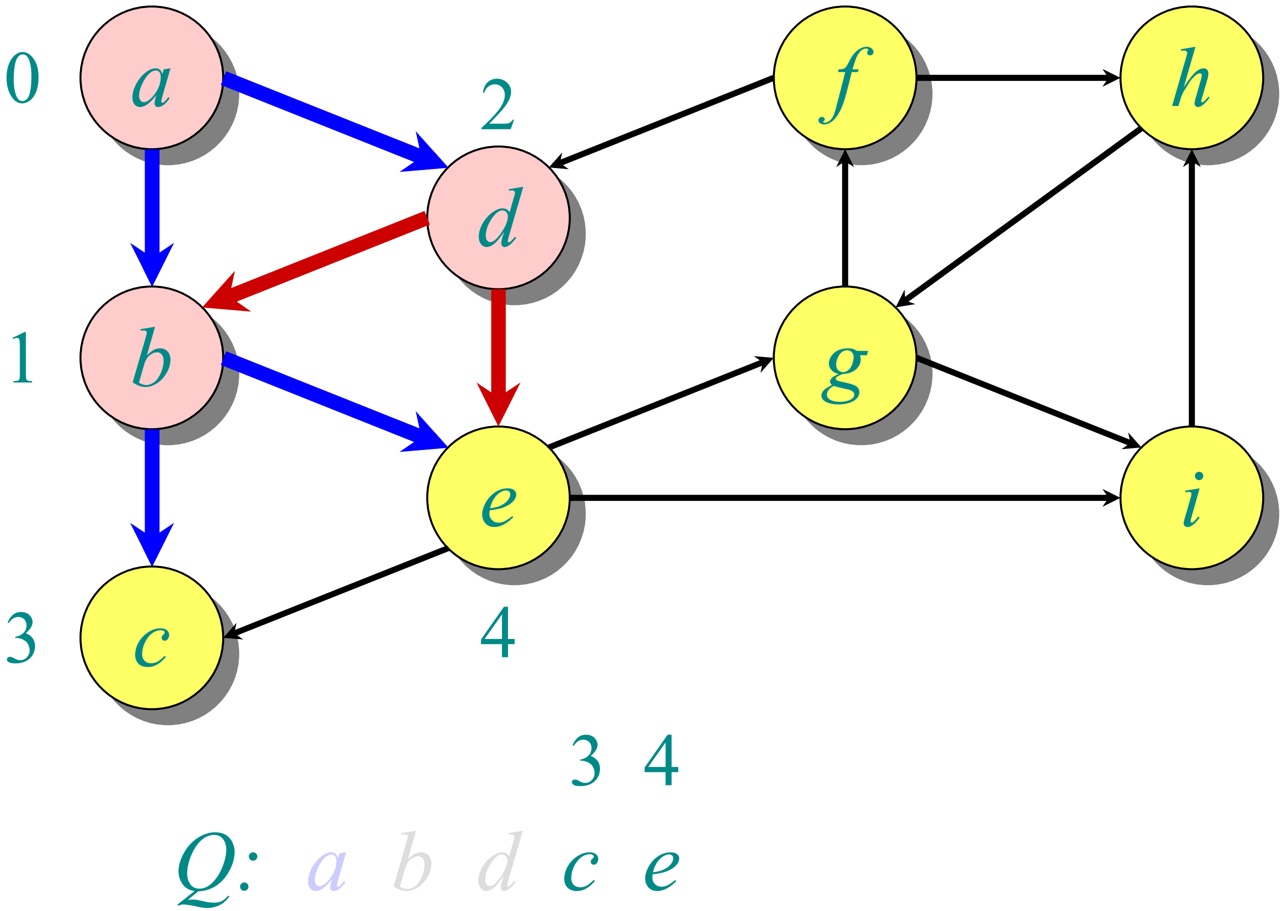


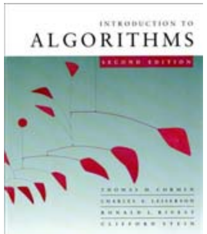
2 3 4

Q: a b d c e

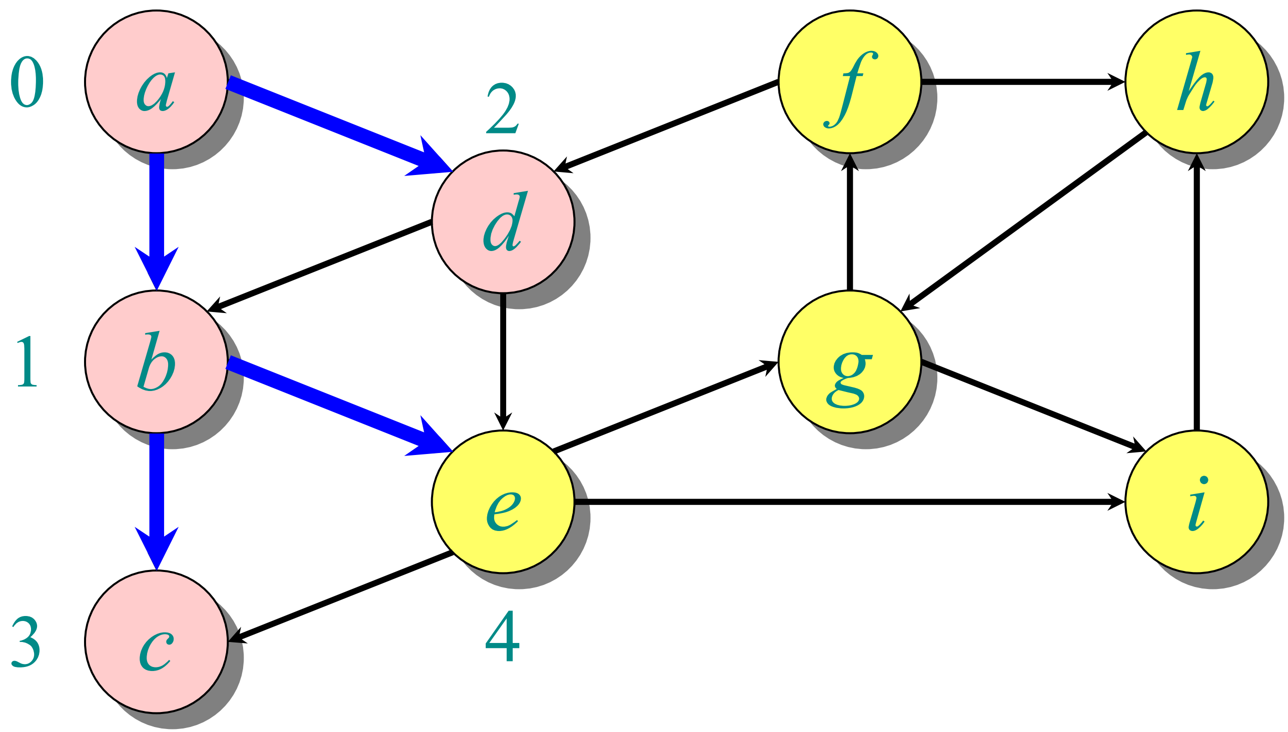


Example of breadth-first search



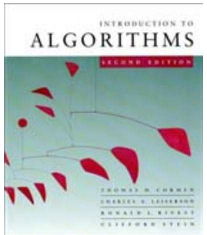


Example of breadth-first search

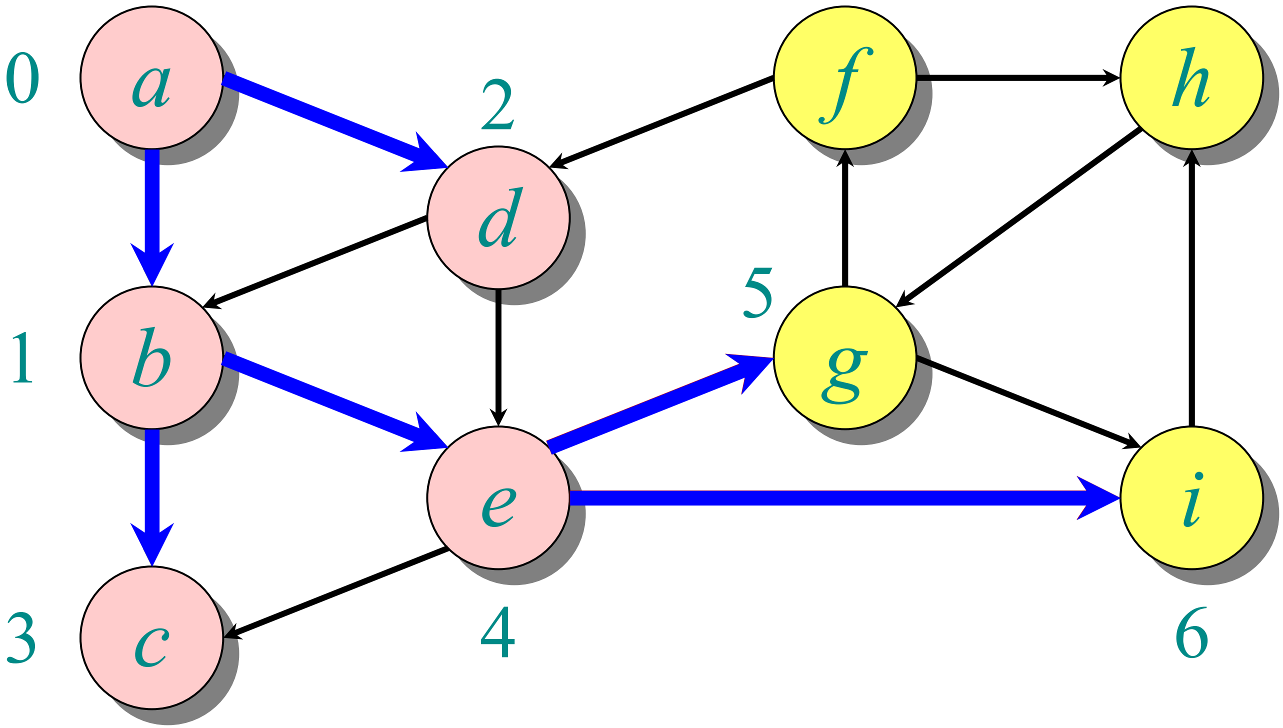


4

Q: *a* *b* *d* *c* *e*

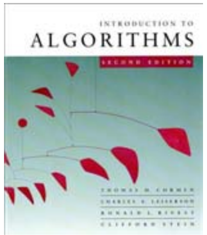


Example of breadth-first search

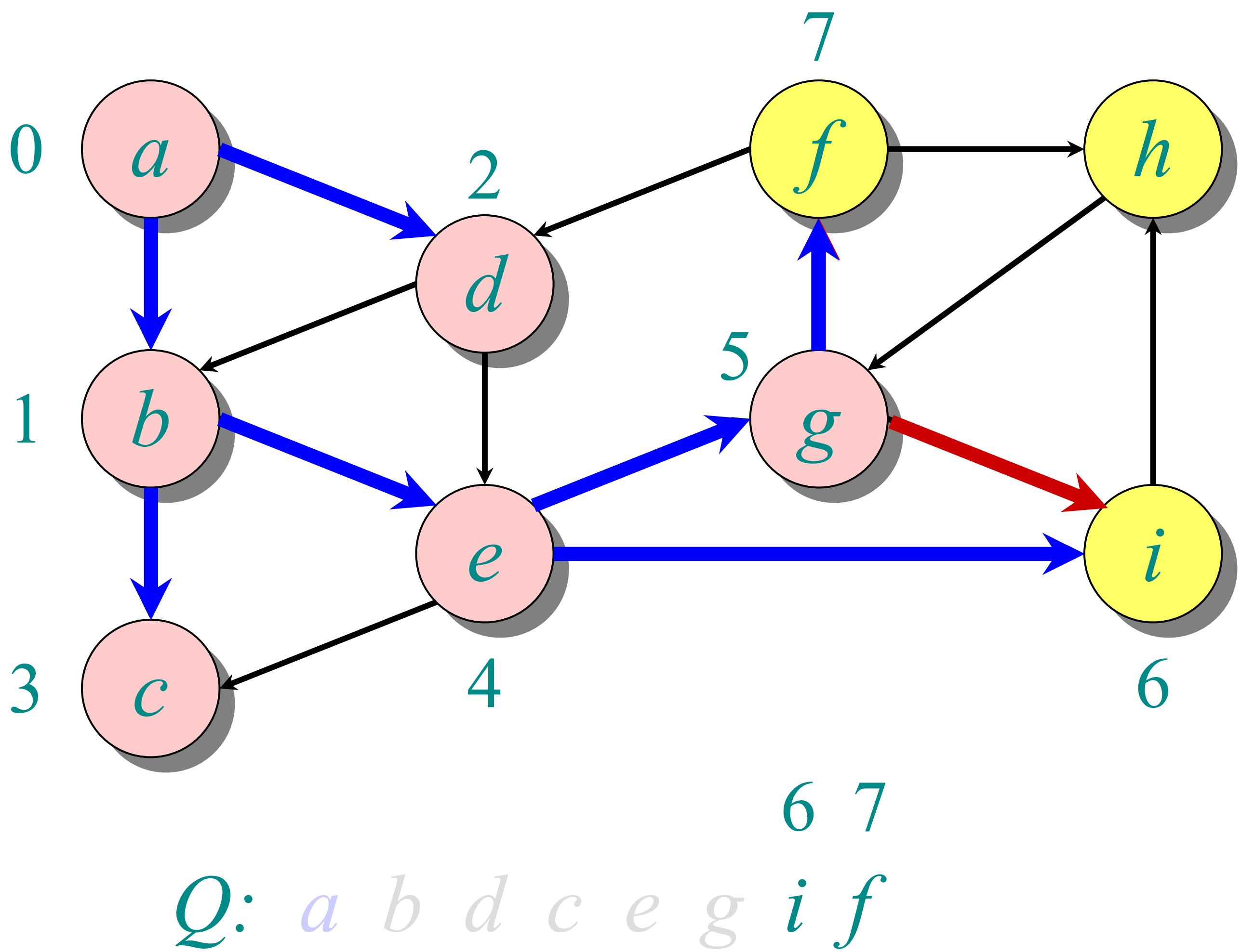


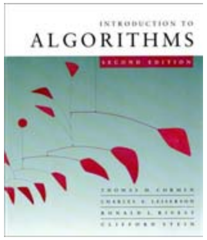
5 6

Q: *a b d c e g i*

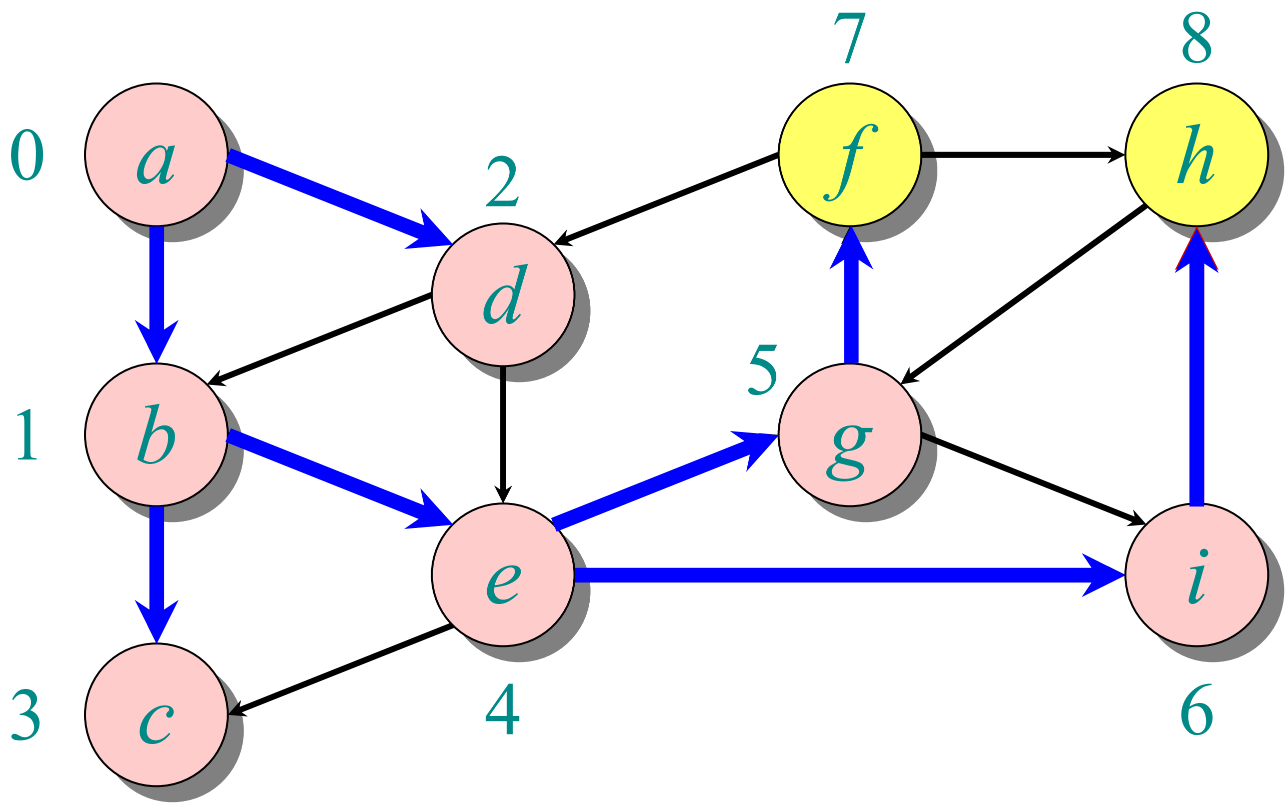


Example of breadth-first search



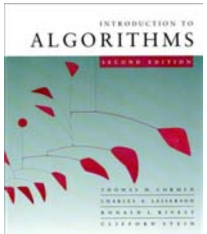


Example of breadth-first search

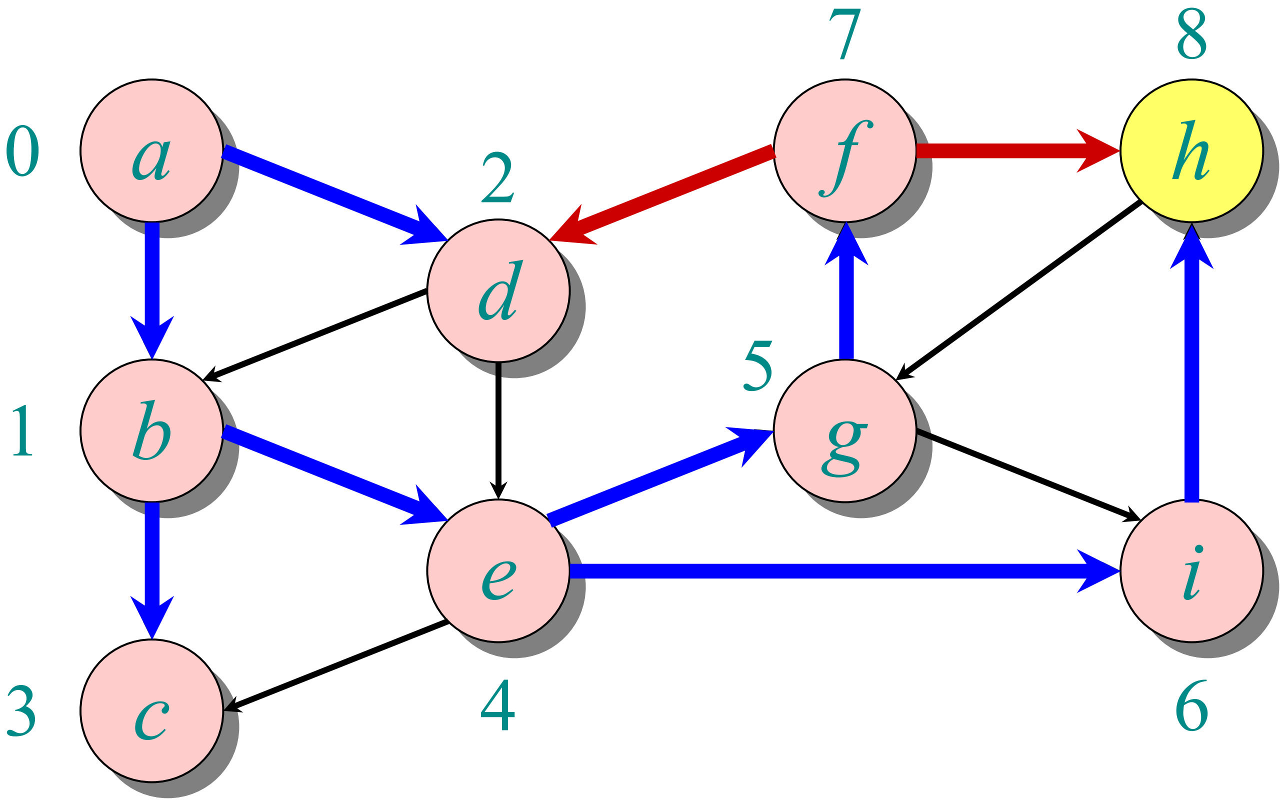


7 8

Q: *a b d c e g i f h*



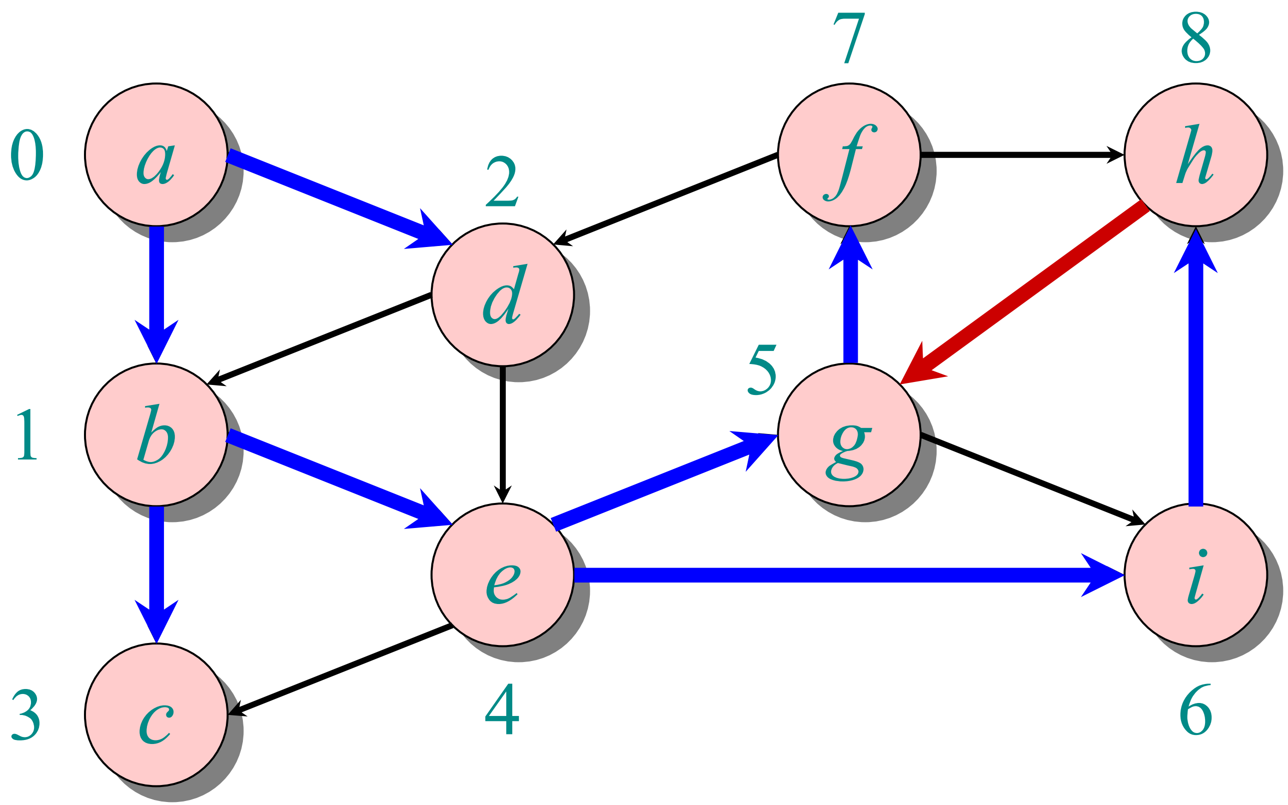
Example of breadth-first search



8

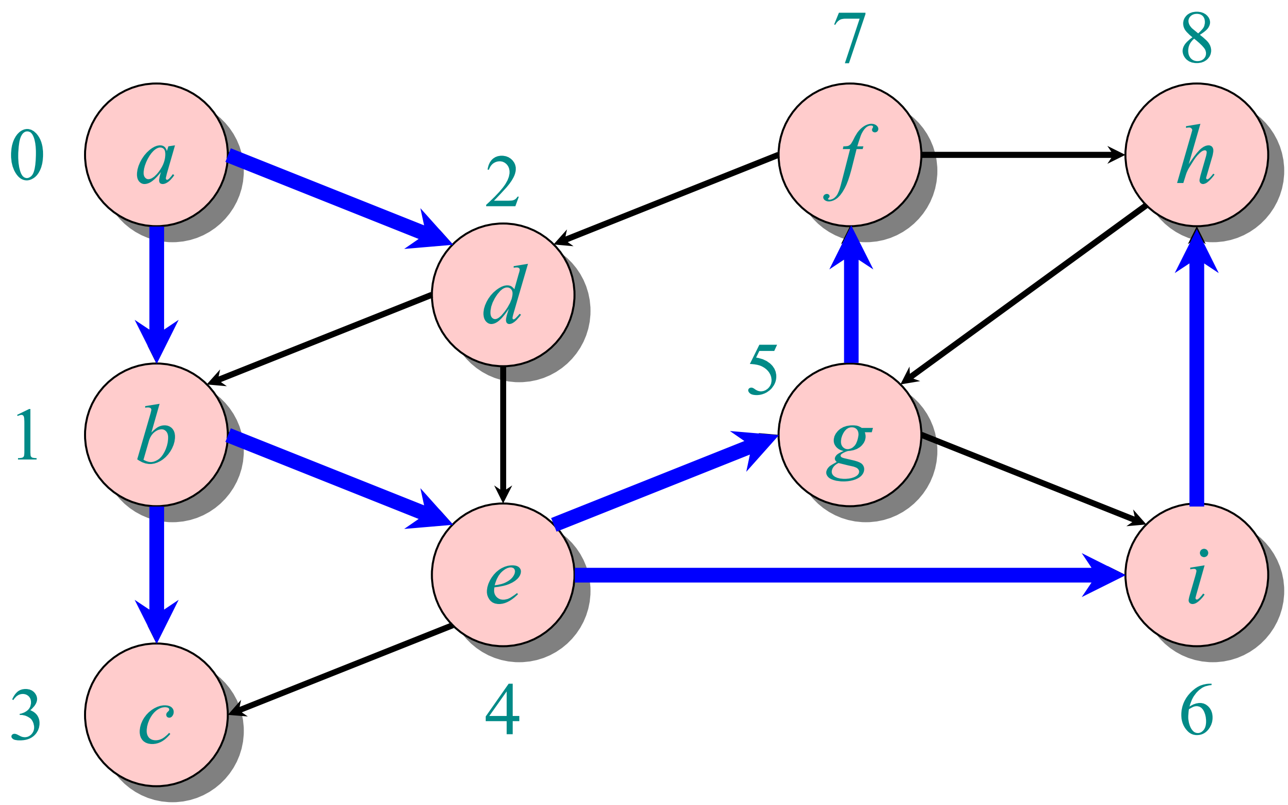
Q: *a b d c e g i f h*

Example of breadth-first search

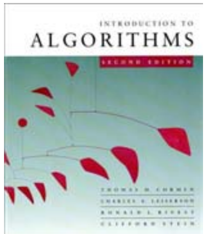


Q: *a b d c e g i f h*

Example of breadth-first search



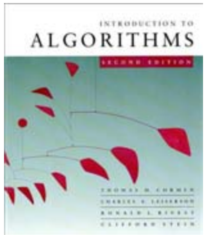
Q: *a b d c e g i f h*



Breadth-First Search (BFS)

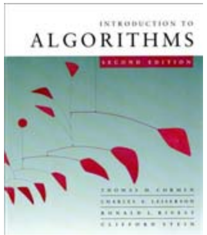
```
BFS(G=(V,E))
      Mark all vertices in G as "unvisited" // time=0          O(n)
      Initialize empty queue Q                                 O(1)
      for each vertex v ∈ V do
            if v is unvisited                                  O(n) without BFS_iter
                  visit v // time++
                  Q.enqueue(v)
                  BFS_iter(G)
```

```
BFS_iter(G)
      while Q is non-empty do                                  O(m)
            v = Q.dequeue()
            for each w adjacent to v do
                  if w is unvisited                            O(deg(v))
                        visit w   // time++
                        Add edge (v,w) to T
                        Q.enqueue(w)
```



BFS runtime

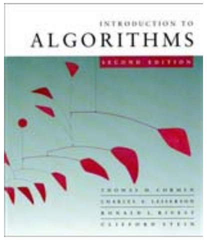
- Each vertex is marked as unvisited in the beginning ⇒ O(n) time
- Each vertex is marked at most once, enqueued at most once, and therefore dequeued at most once
- The time to process a vertex is proportional to the size of its adjacency list (its degree), since the graph is given in adjacency list representation
 ⇒ O(m) time
- Total runtime is O(n+m) = O(|V| + |E|)



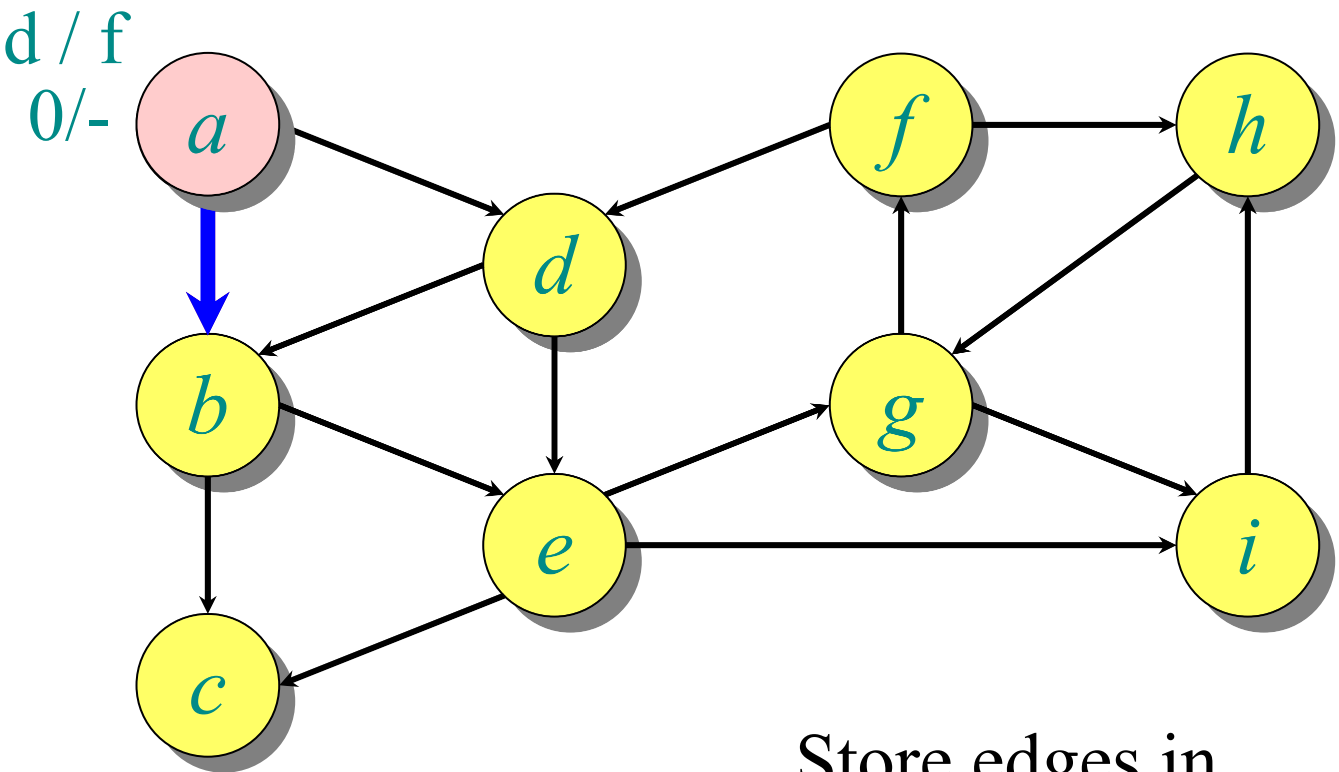
Depth-First Search (DFS)

```
DFS(G=(V,E))
    Mark all vertices in G as "unvisited"  // time=0
    for each vertex v ∈ V do
        if v is unvisited
            DFS_rec(G,v)
```

```
DFS_rec(G, v)
    visit v  // d[v]=++time
    for each w adjacent to v do
        if w is unvisited
            Add edge (v,w) to tree T
            DFS_rec(G,w)
    // f[v]=++time
```

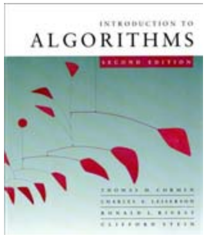


Example of depth-first search

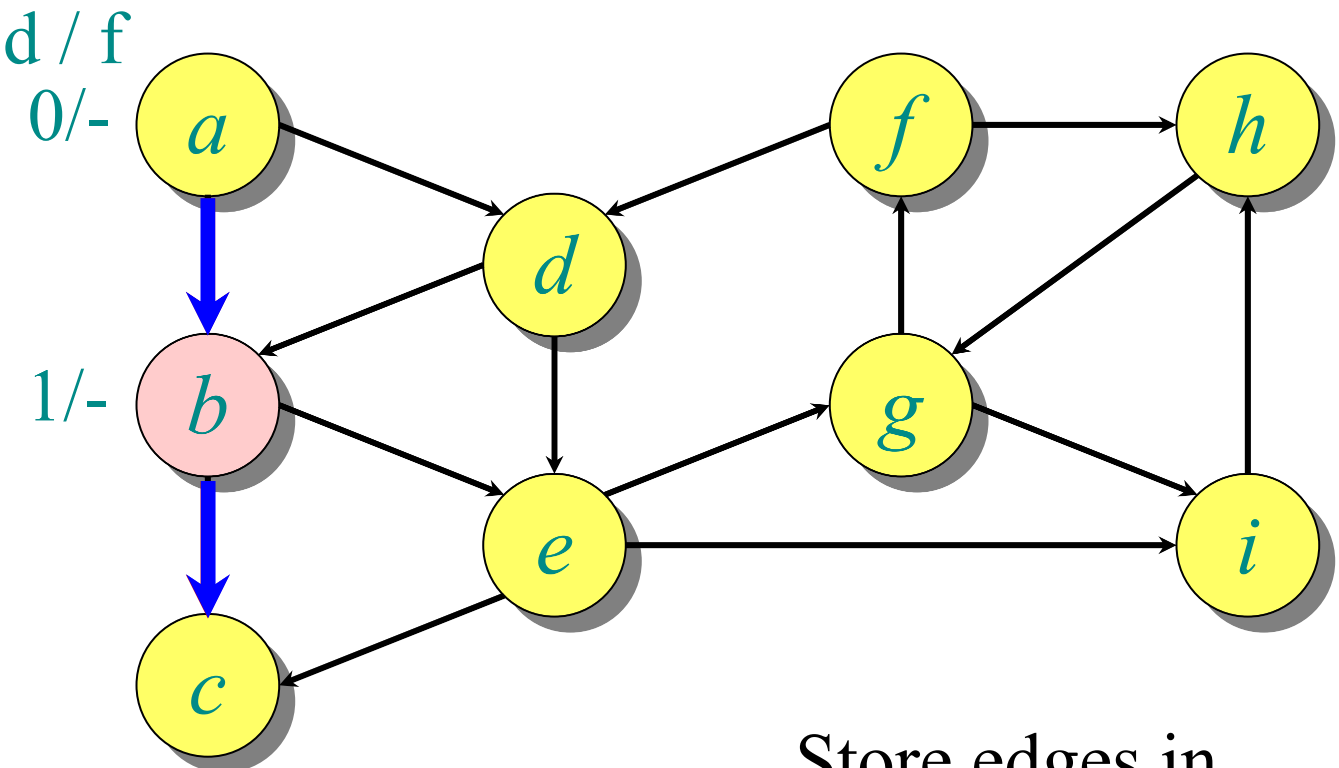


Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a							

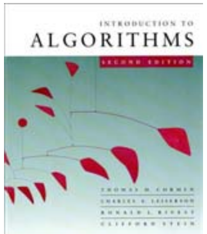


Example of depth-first search



Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b						



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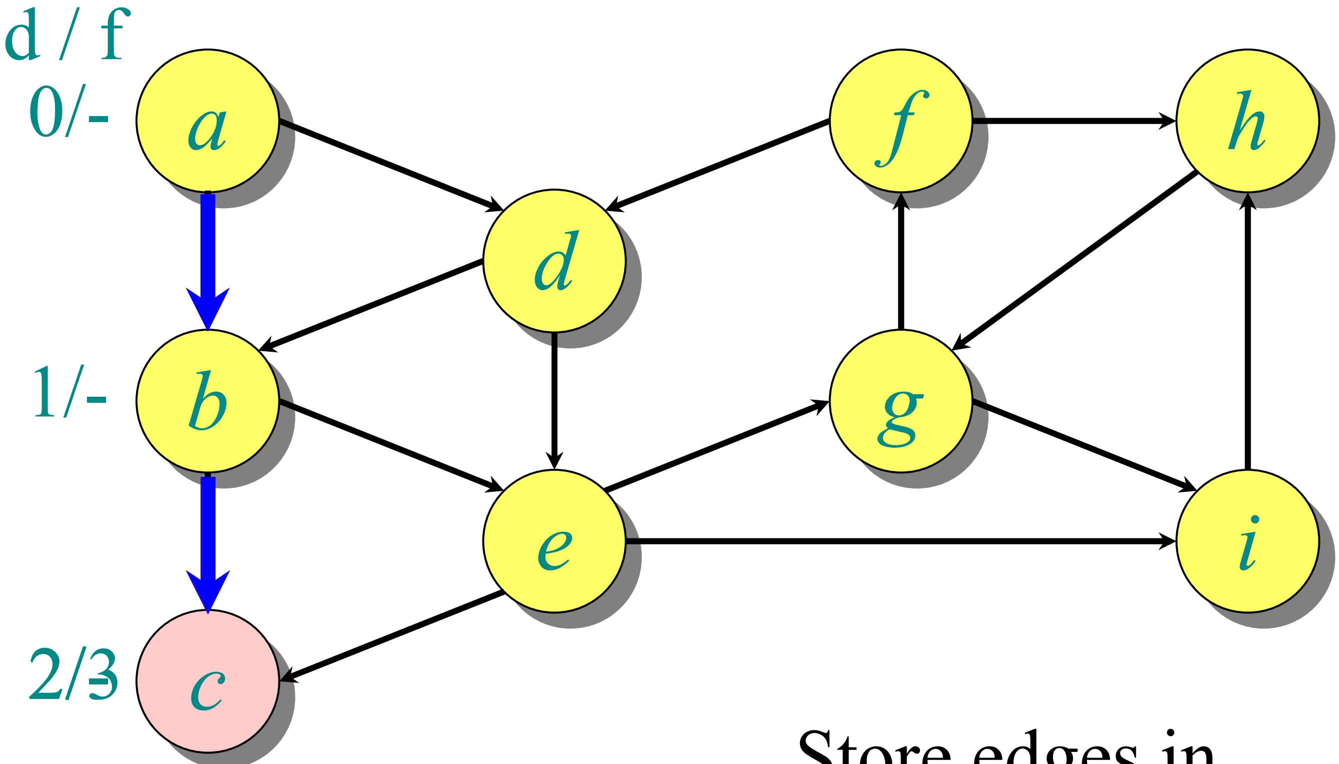
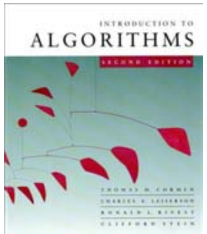
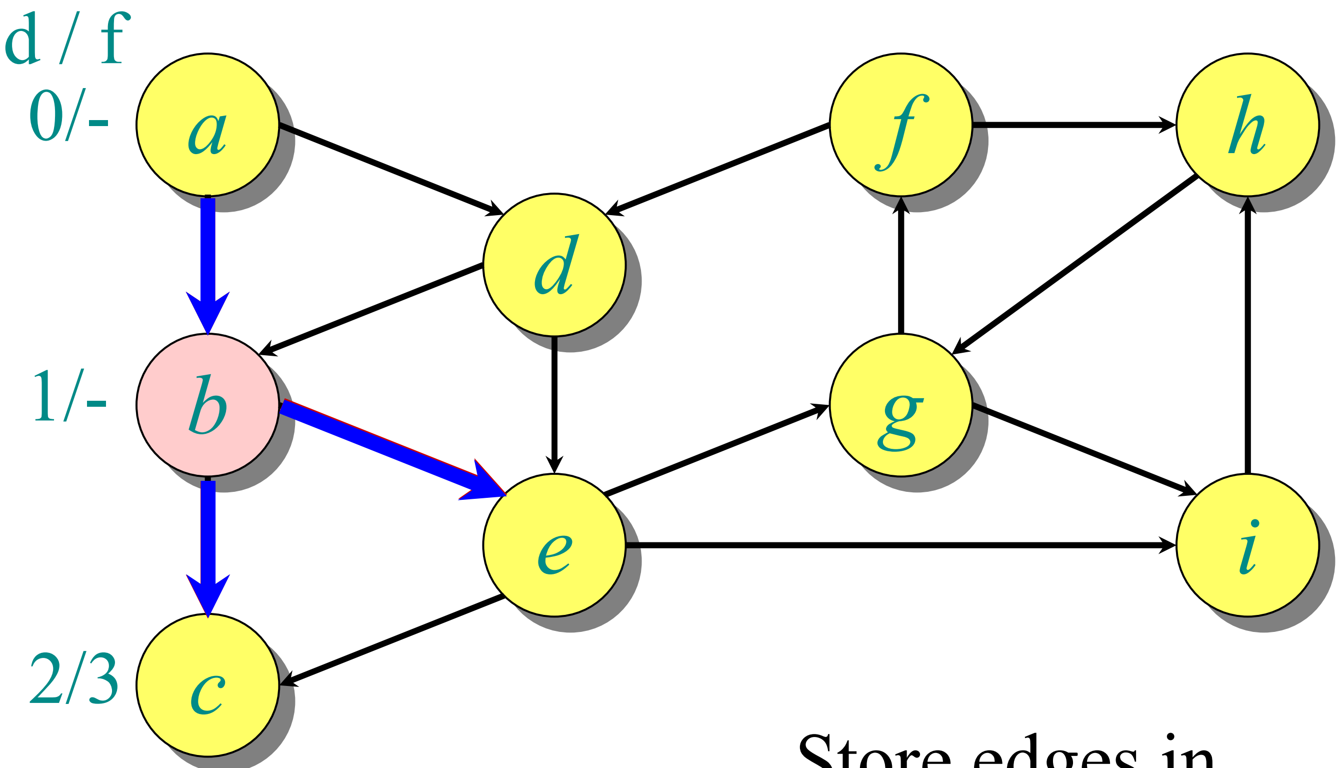


π:	a	b	c	d	e	f	g	h	i
	-	a	b						

Store edges in
predecessor array



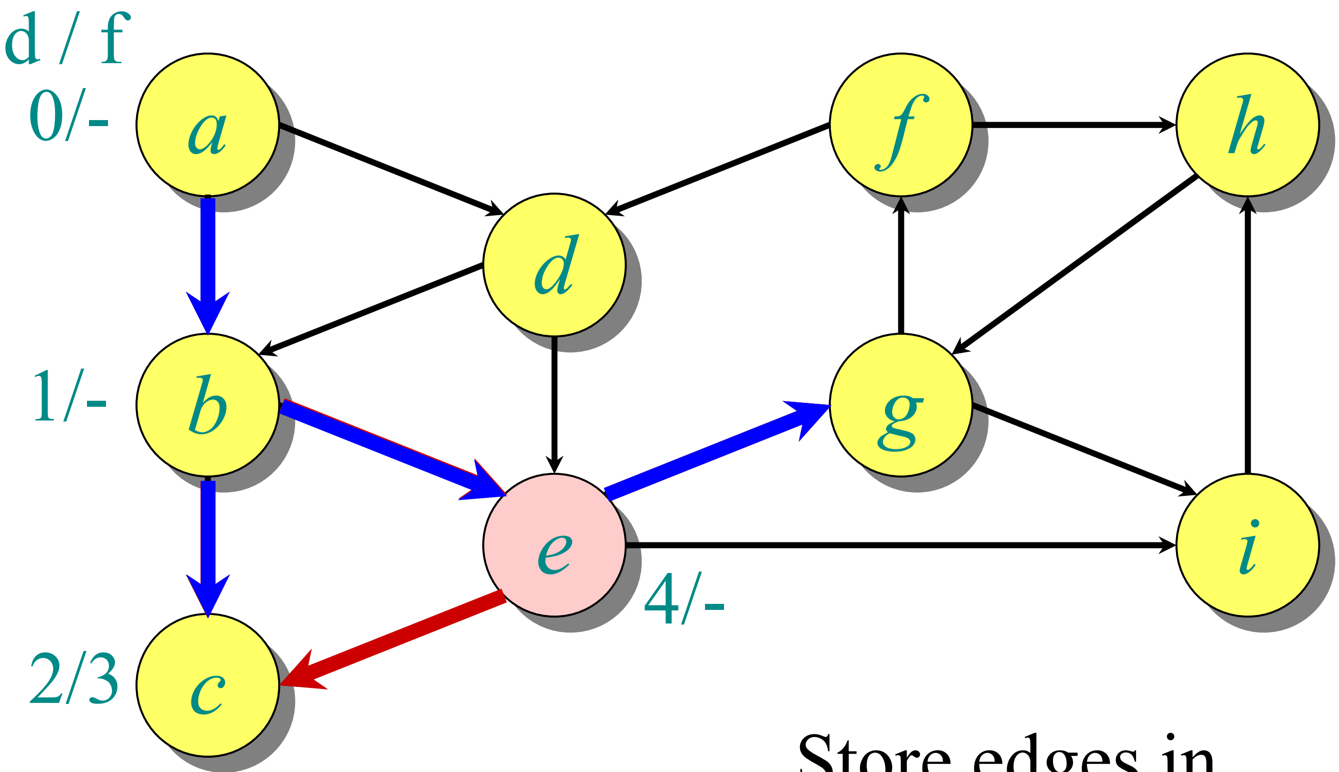
Example of depth-first search



Store edges in predecessor array

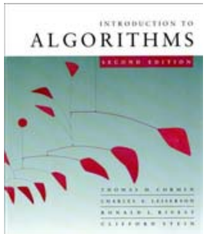
π:	a	b	c	d	e	f	g	h	i
	-	a	b		b				

Example of depth-first search

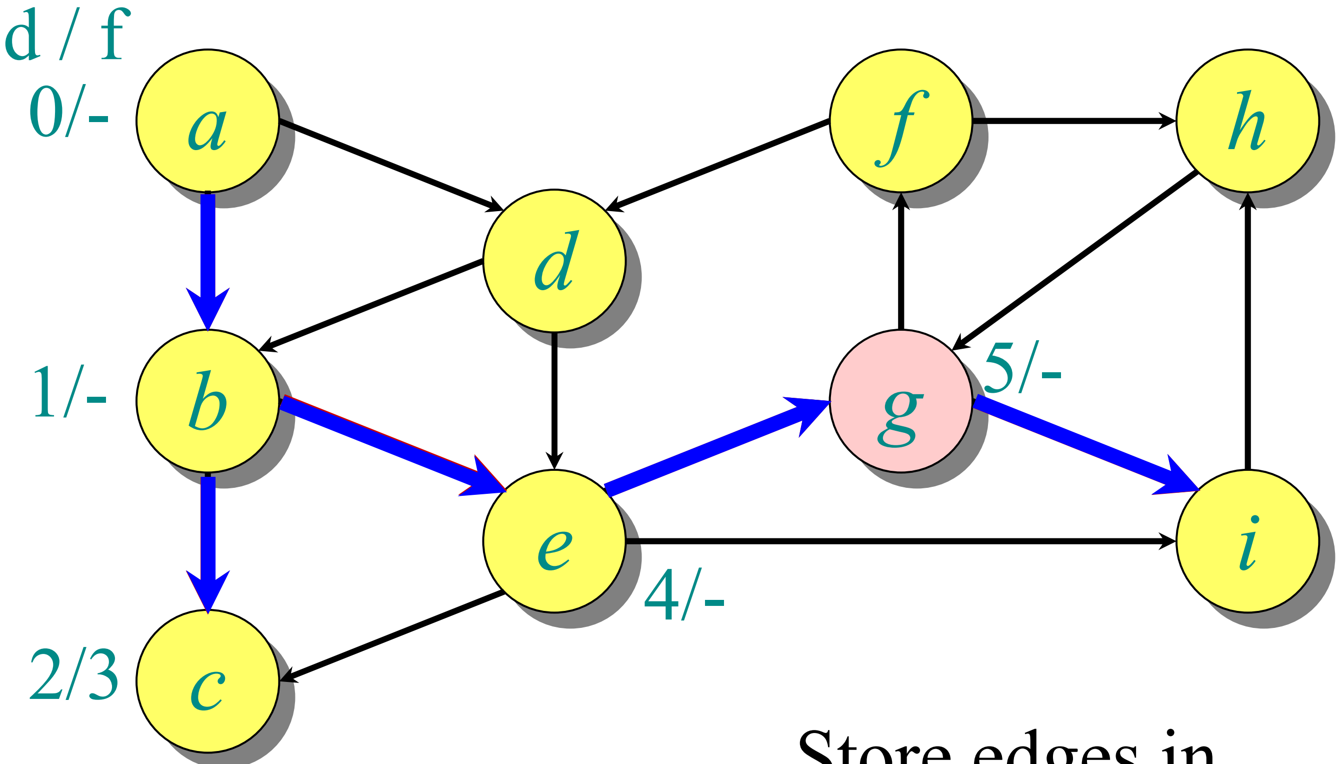


π:	a	b	c	d	e	f	g	h	i
	-	a	b		b		e		

Store edges in predecessor array



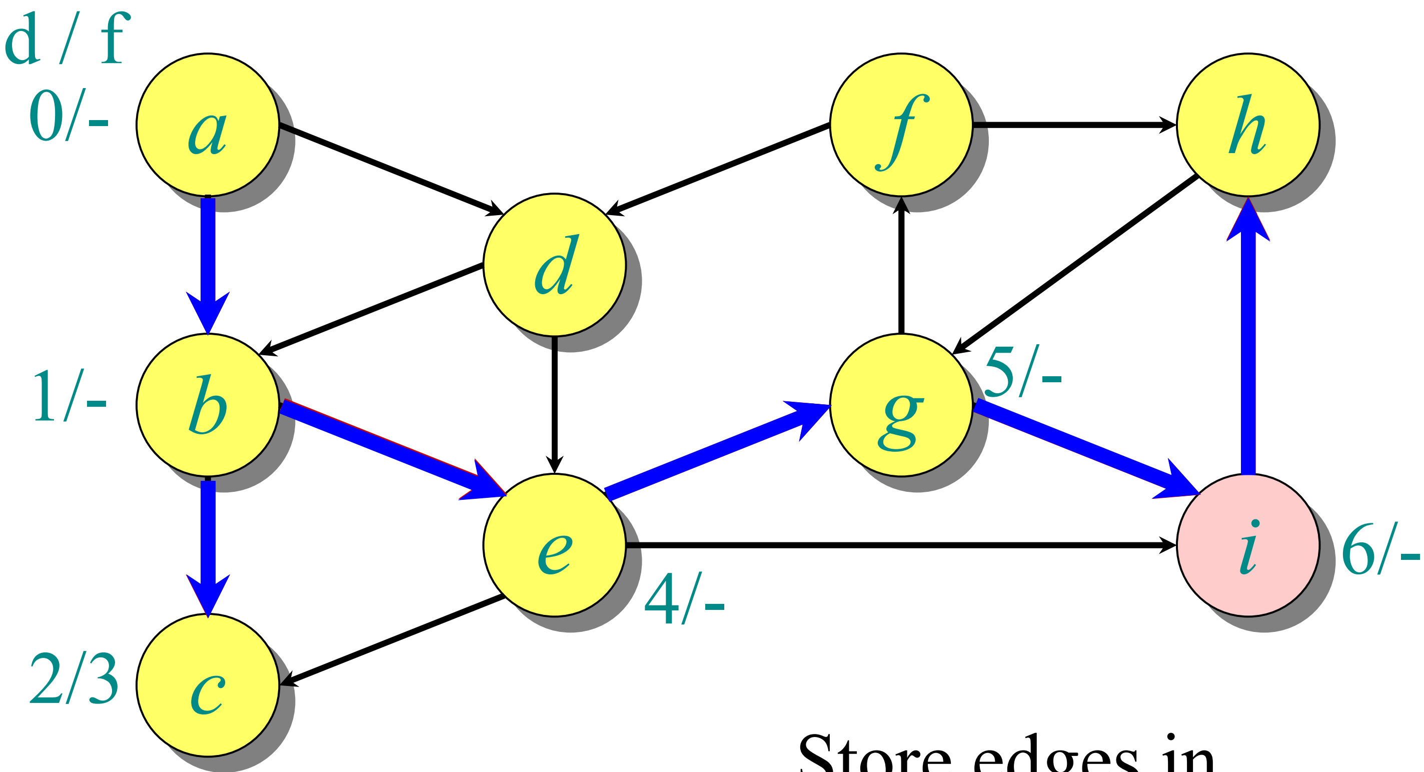
Example of depth-first search



Store edges in predecessor array

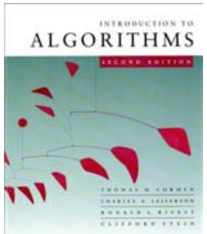
π:	a	b	c	d	e	f	g	h	i
	-	a	b		b		e		g

Example of depth-first search

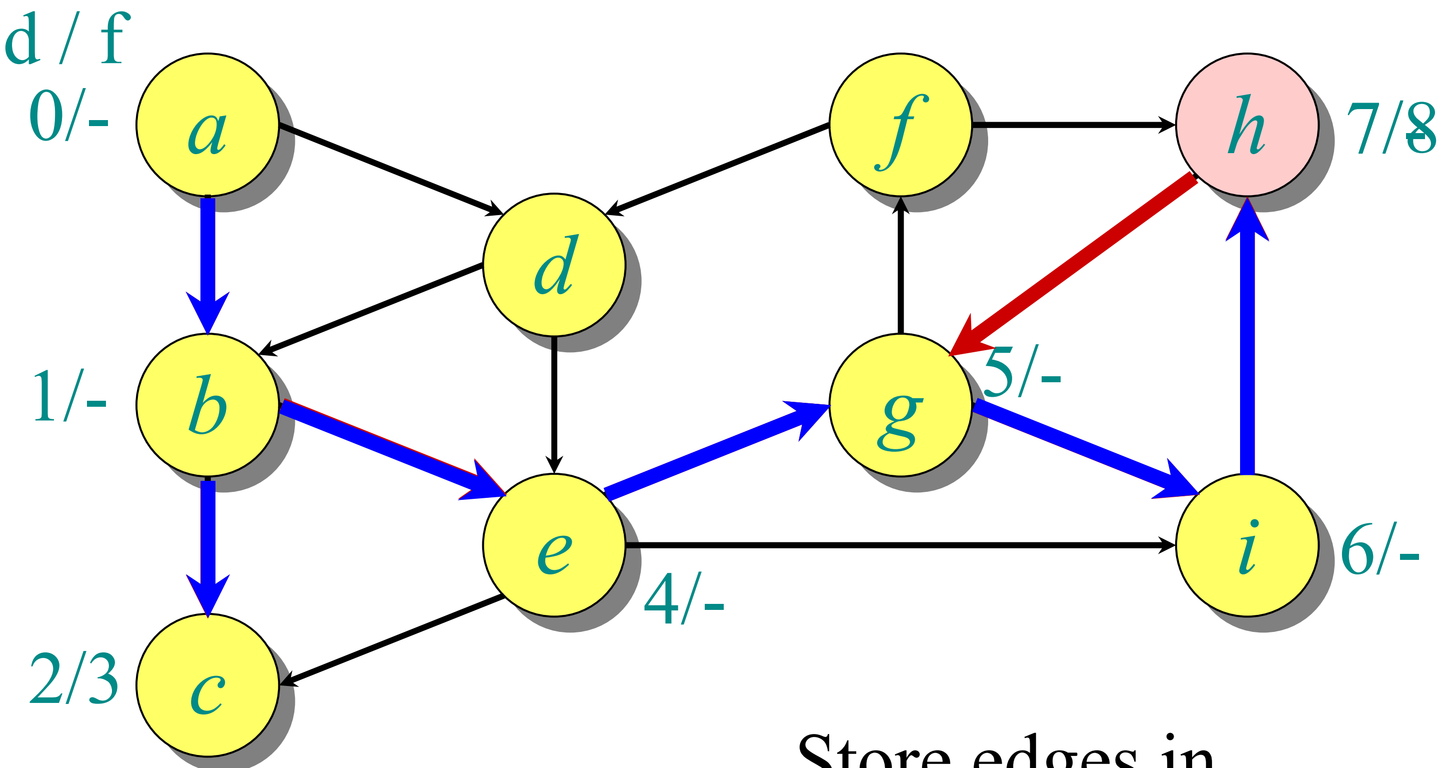


Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b		b		e	i	g

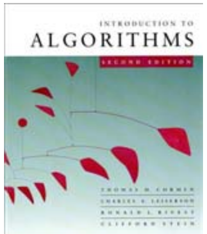


Example of depth-first search

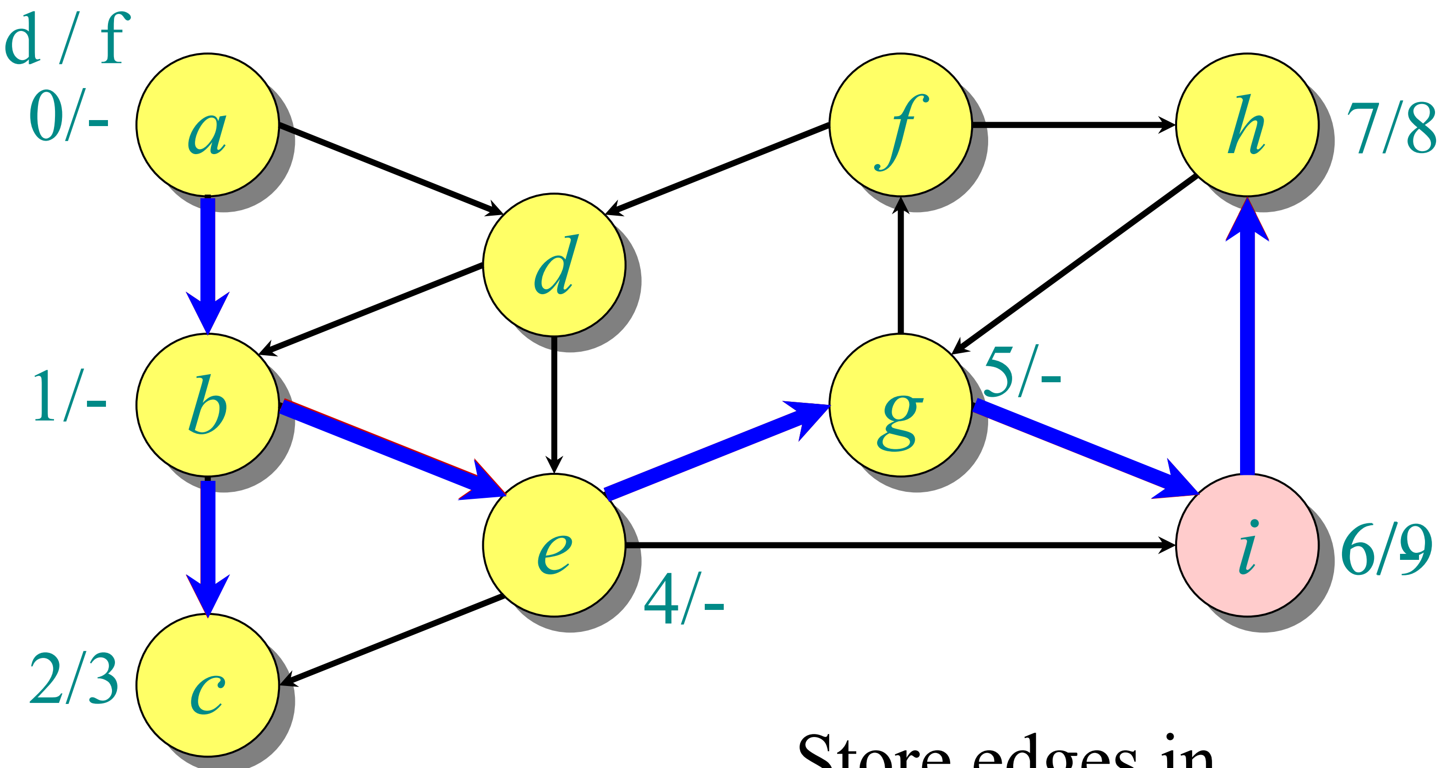


Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b		b		e	i	g

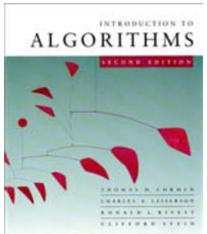


Example of depth-first search

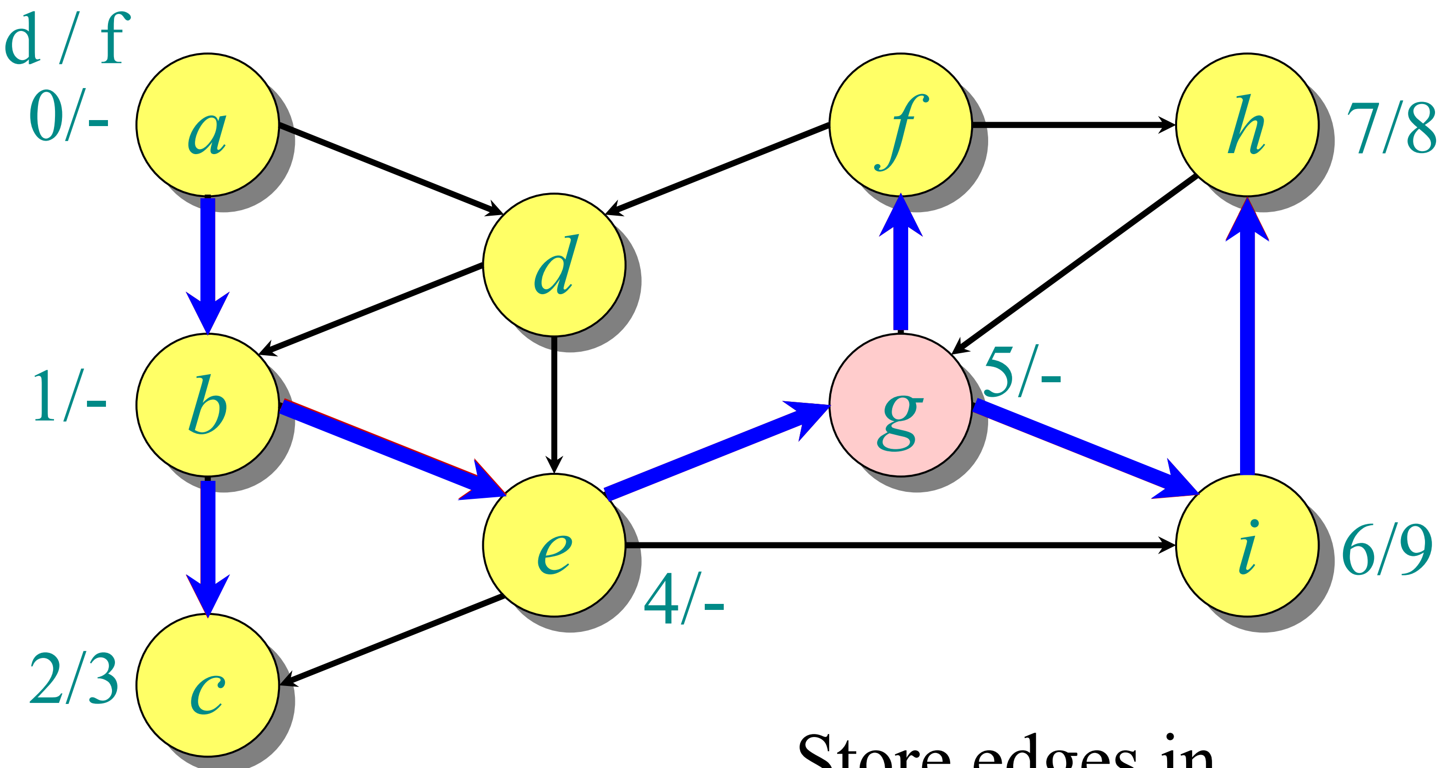


Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b		b		e	i	g



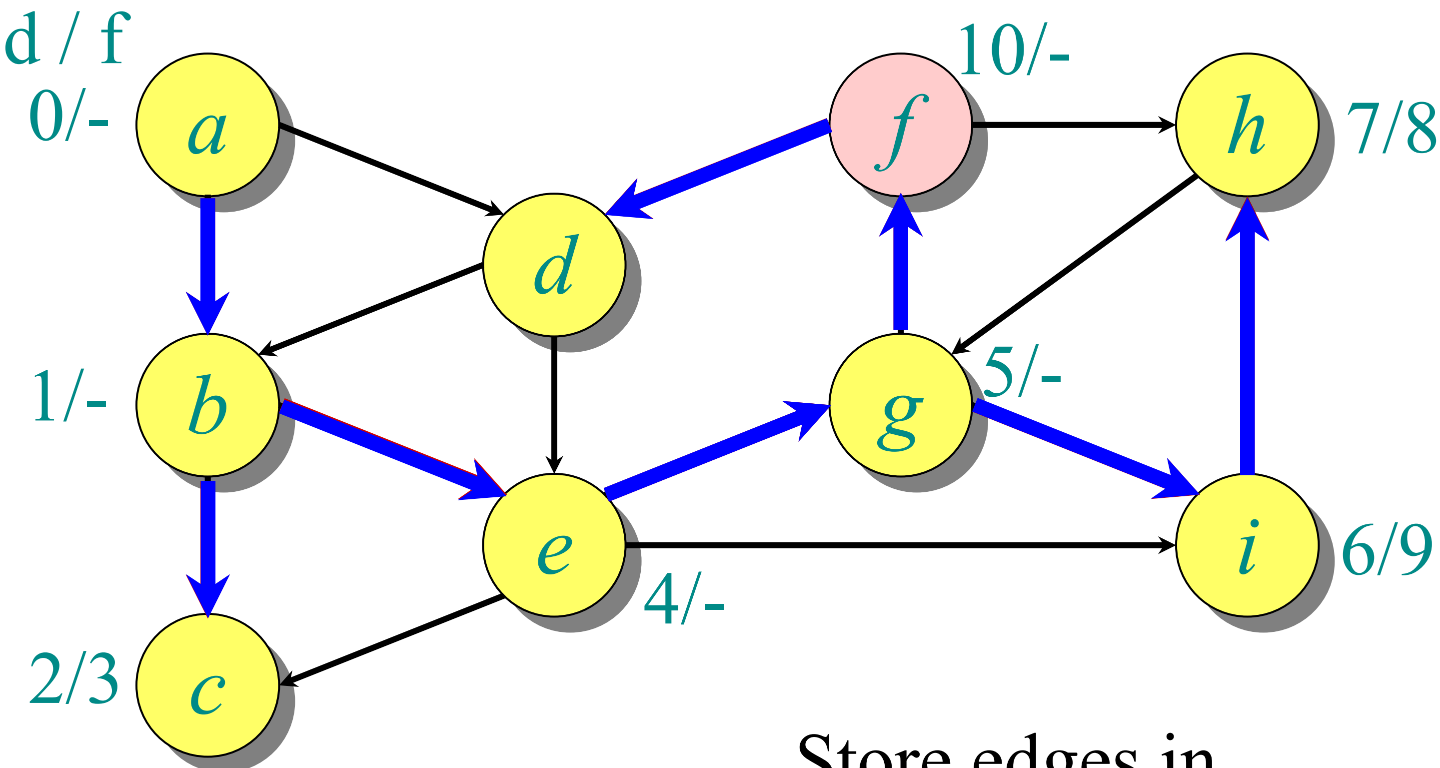
Example of depth-first search



π:	a	b	c	d	e	f	g	h	i
	-	a	b		b	g	e	i	g

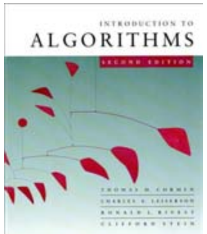
Store edges in predecessor array

Example of depth-first search

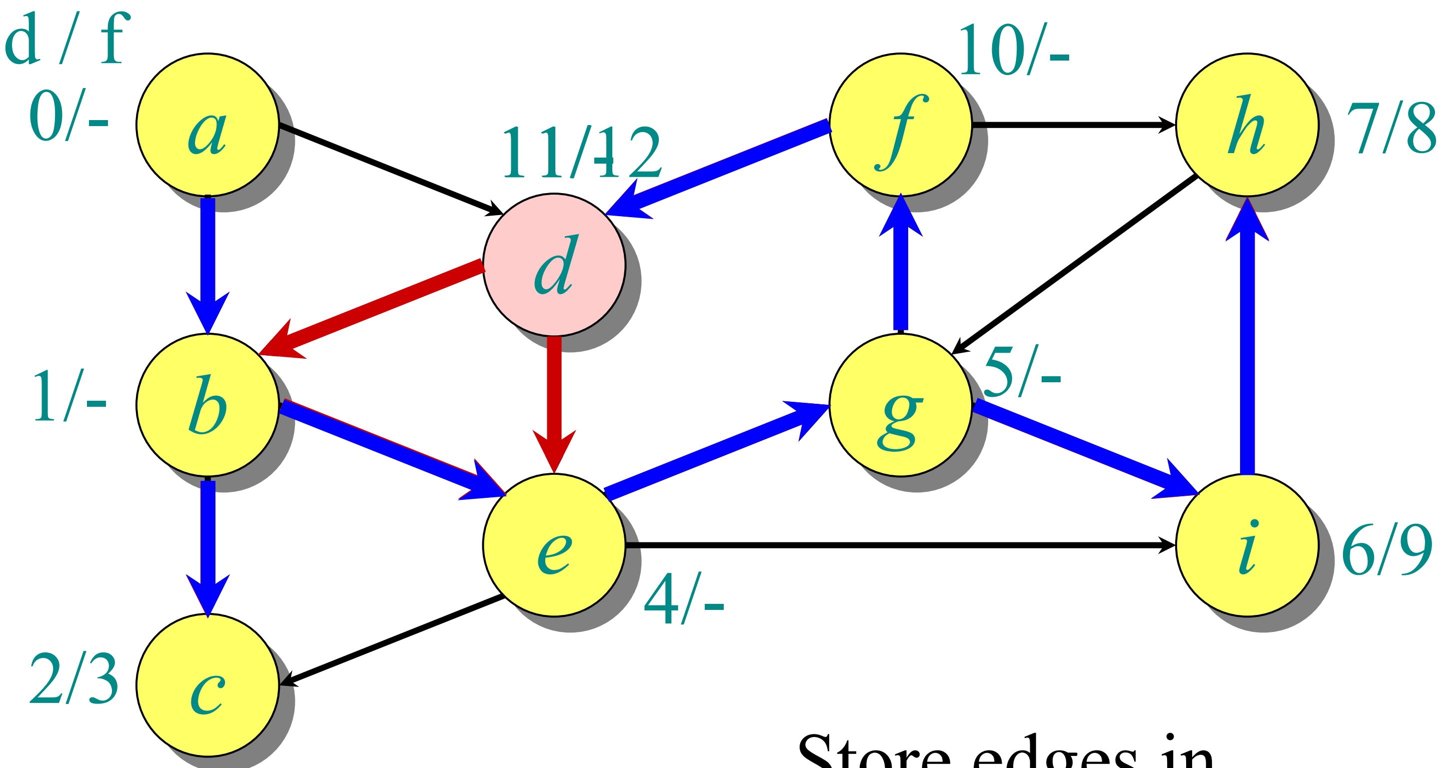


π:	a	b	c	d	e	f	g	h	i
	-	a	b	f	b	g	e	i	g

Store edges in predecessor array

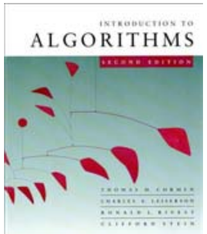


Example of depth-first search



Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b	f	b	g	e	i	g



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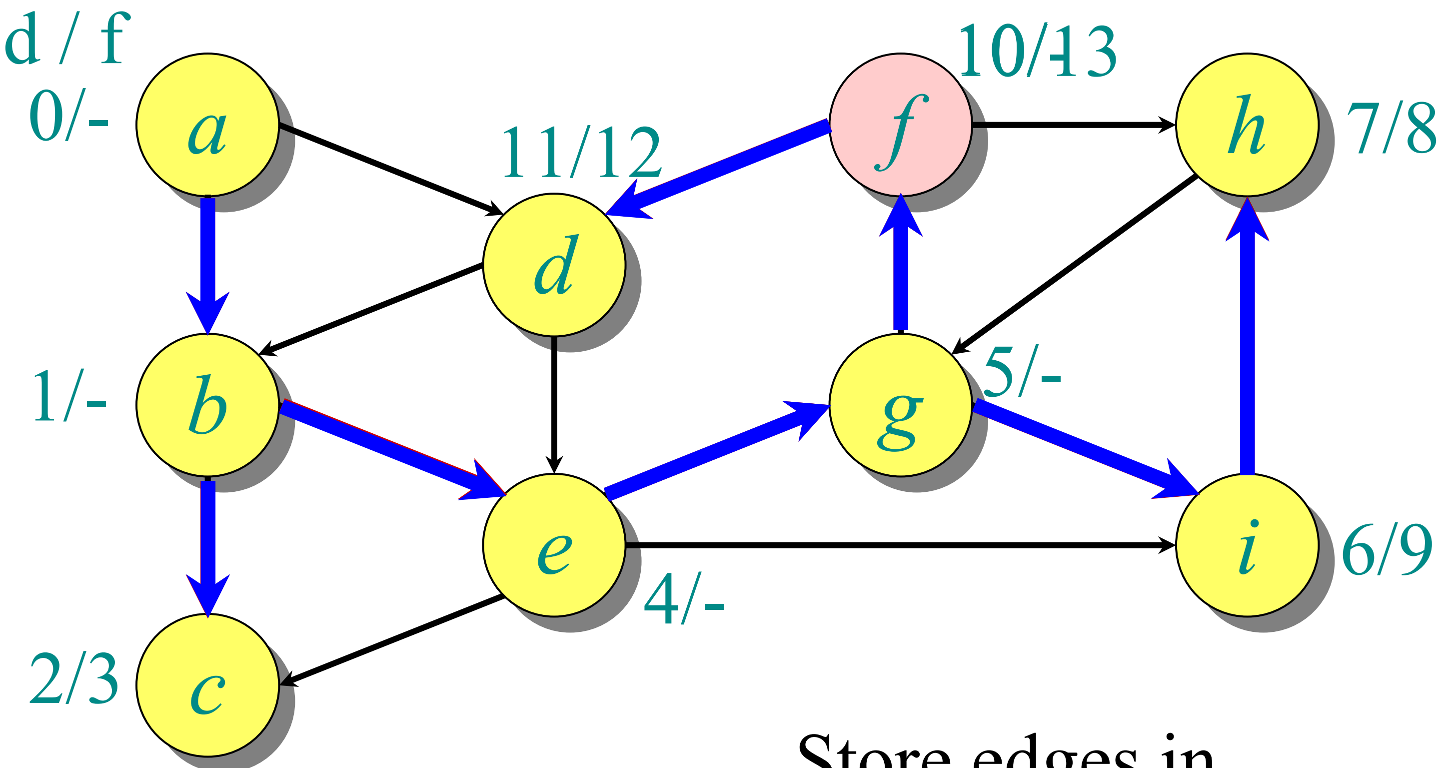
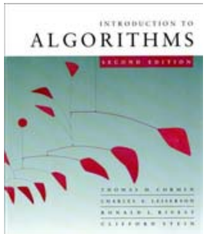
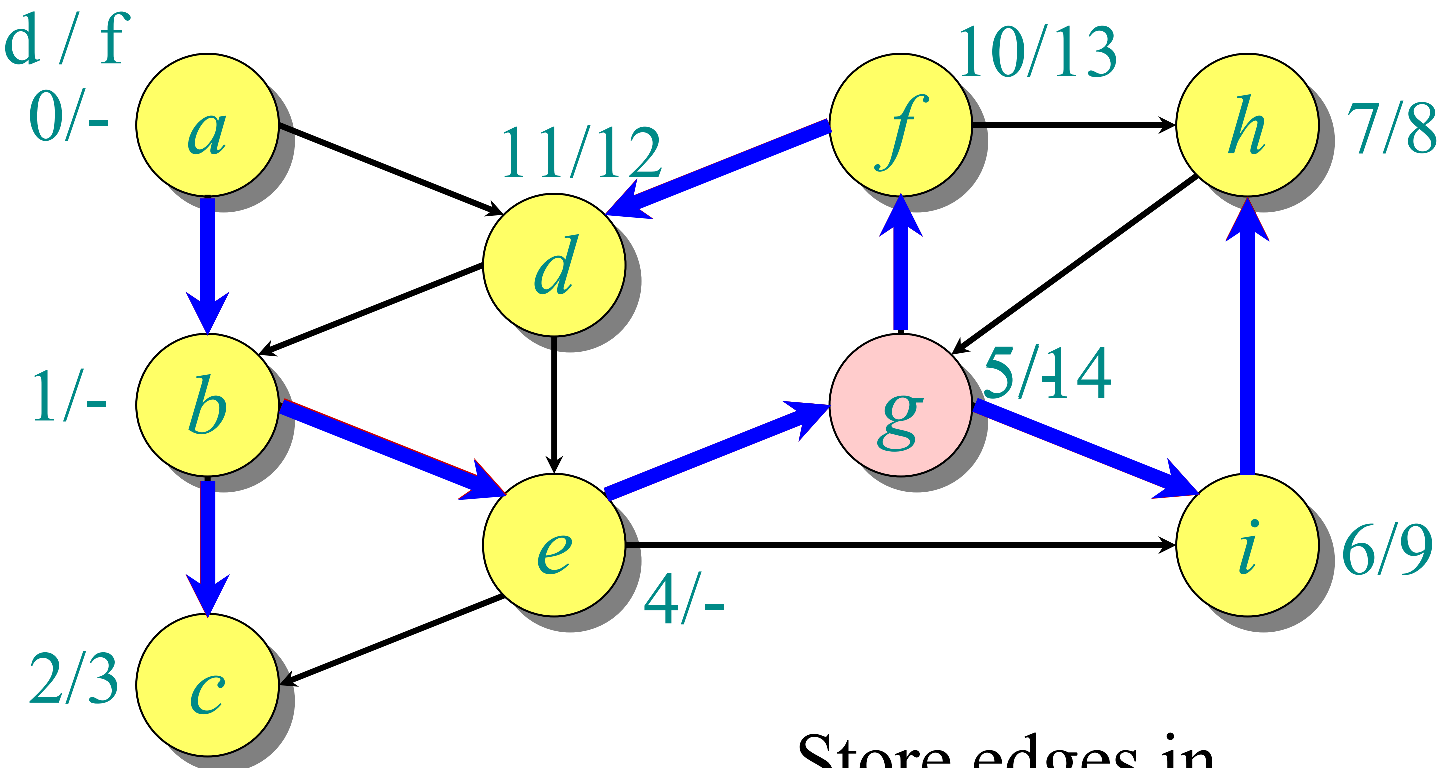


π:	a	b	c	d	e	f	g	h	i
	-	a	b	f	b	g	e	i	g

Store edges in predecessor array

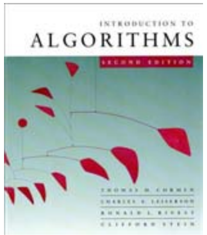


Example of depth-first search

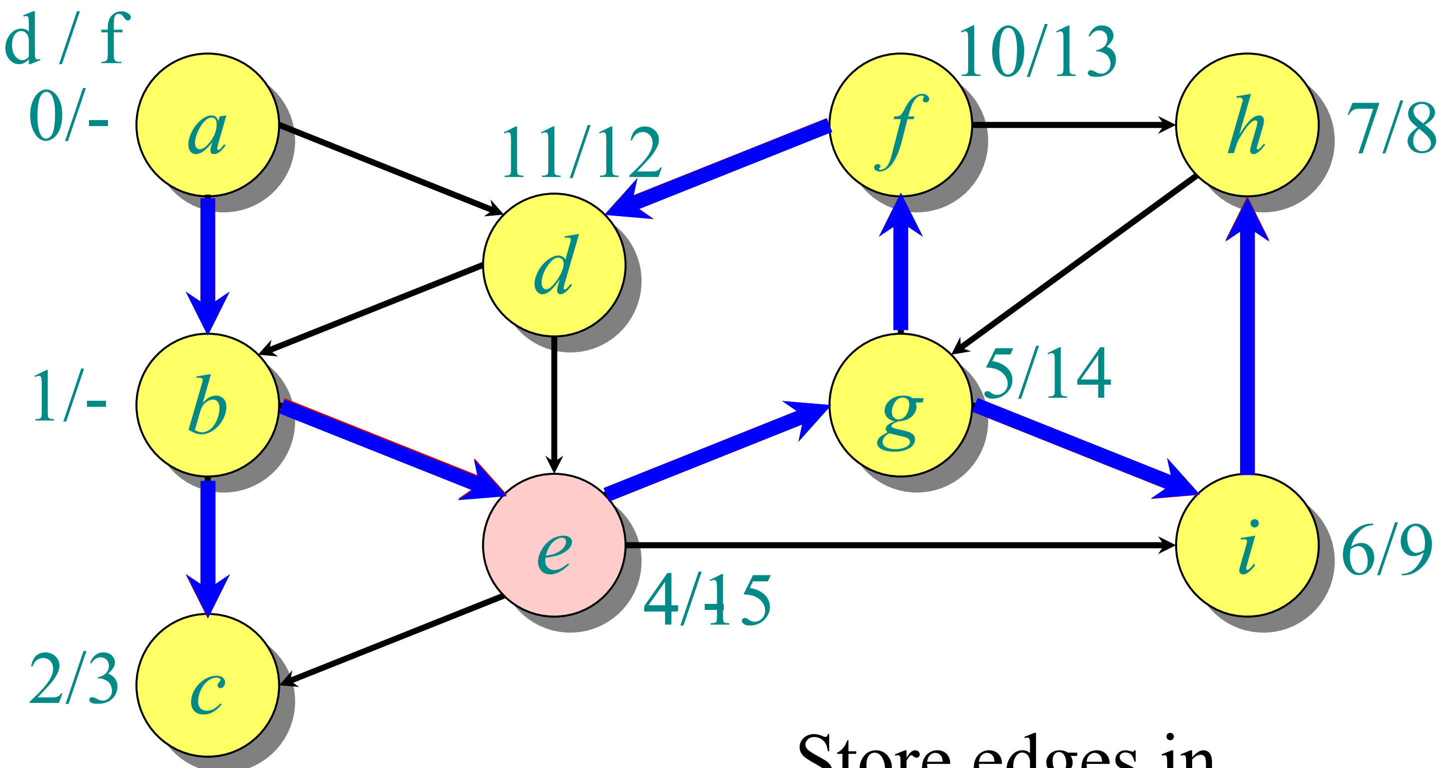


Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b	f	b	g	e	i	g



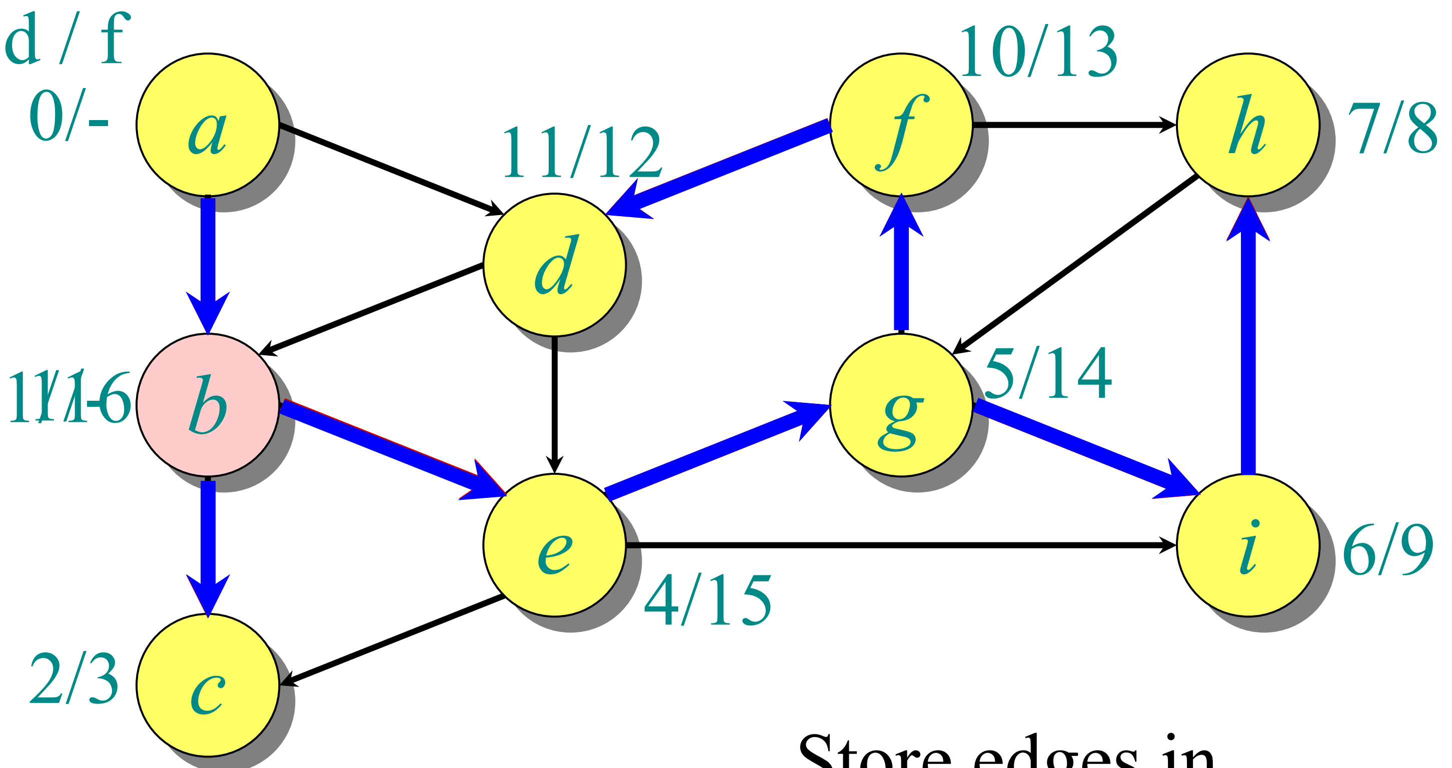
Example of depth-first search



Store edges in
predecessor array

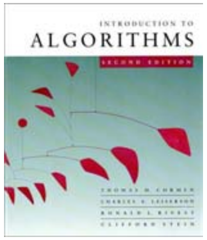
π:	a	b	c	d	e	f	g	h	i
	-	a	b	f	b	g	e	i	g

Example of depth-first search

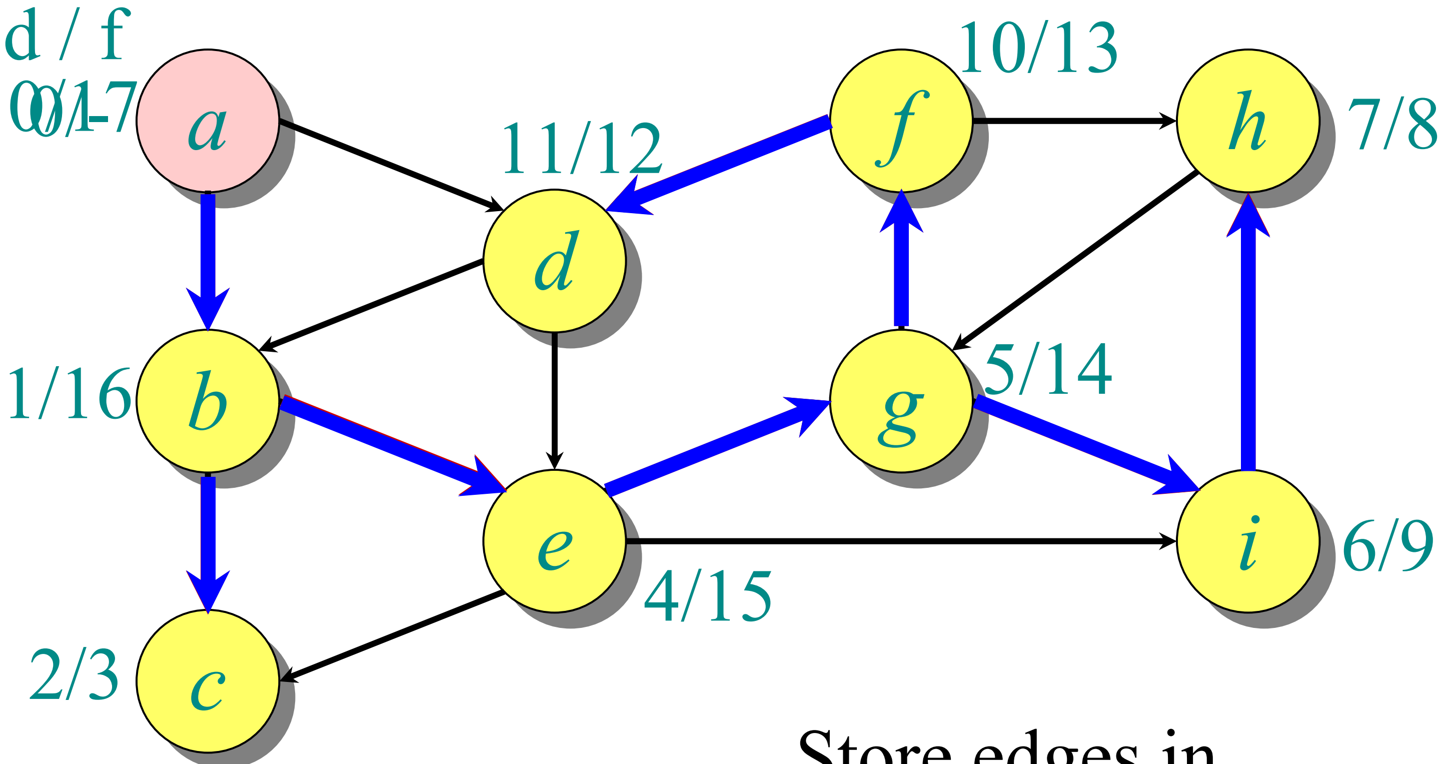


Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b	f	b	g	e	i	g

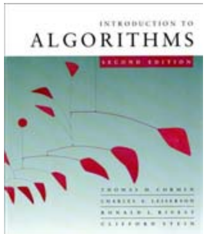


Example of depth-first search



Store edges in
predecessor array

π:	a	b	c	d	e	f	g	h	i
	-	a	b	f	b	g	e	i	g

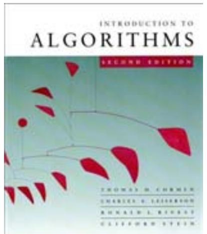


Depth-First Search (DFS)

```
DFS(G=(V,E))
    Mark all vertices in G as "unvisited"  // time=0        O(n)
    for each vertex v ∈ V do                                 O(n)
        if v is unvisited                                    without
            DFS_rec(G,v)                                     DFS_rec
```

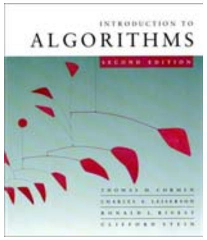
```
DFS_rec(G, v)
    visit v  // d[v]=++time                                  O(1)
    for each w adjacent to v do
        if w is unvisited                                    O(deg(v))
            Add edge (v,w) to tree T                         without
            DFS_rec(G,w)                                     recursive call
    // f[v]=++time
```

$\Rightarrow$ With Handshaking Lemma, all recursive calls are $O(m)$, for a total of $O(n + m)$ runtime

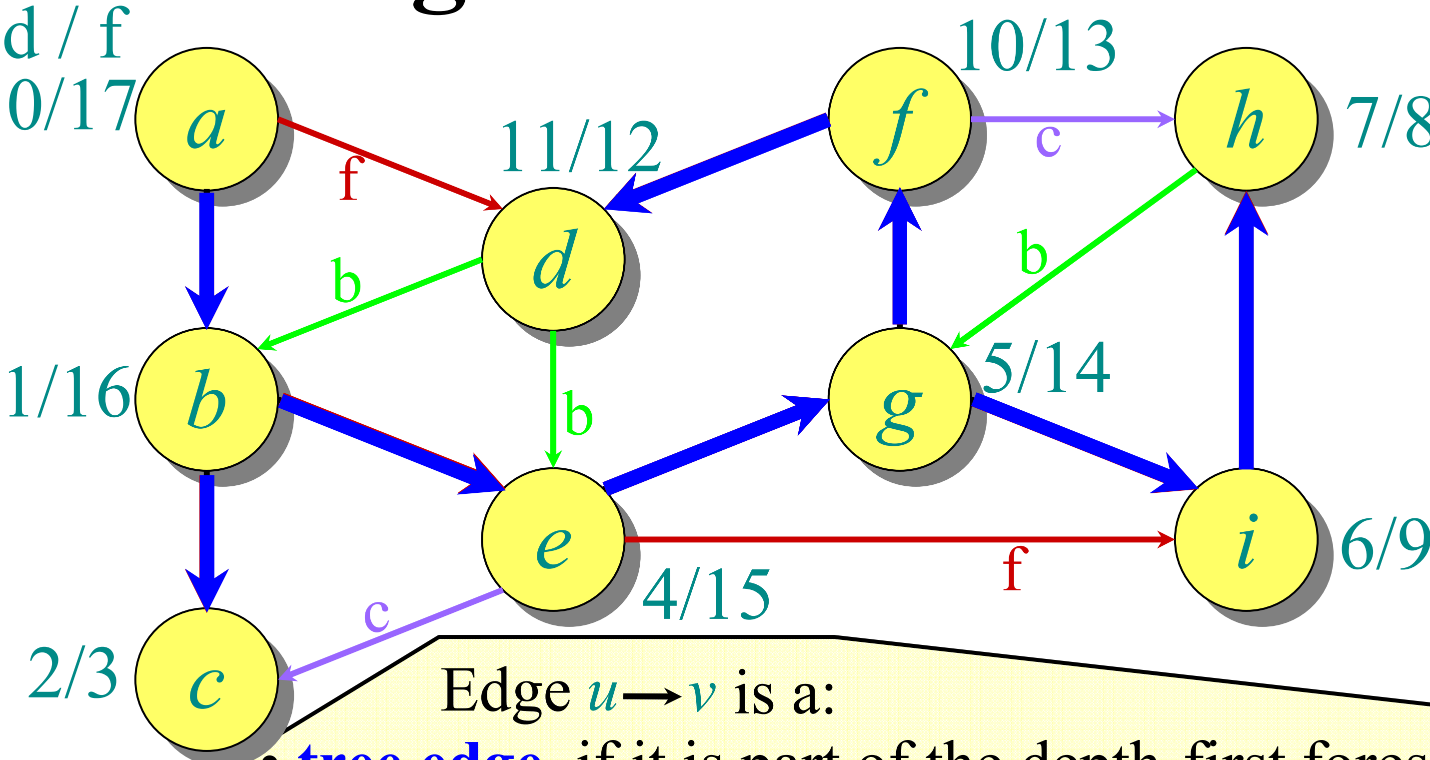


DFS runtime

- Each vertex is visited at most once ⇒ $O(n)$ time
- The body of the **for** loops (except the recursive call) take constant time per graph edge
- All **for** loops take $O(m)$ time
- Total runtime is $O(n+m) = O(|V| + |E|)$



DFS edge classification



Edge $u \to v$ is a:

- **tree edge**, if it is part of the depth-first forest.
- back edge, if u connects to an ancestor v in a depth-first tree. It holds $d(u)>d(v)$ and $f(u)<f(v)$.
- forward edge, if it connects u to a descendant v in a depth-first tree. It holds $d(u)<d(v)$.
- cross edge, if it is any other edge. It holds $d(u)>d(v)$ and $f(u)>f(v)$.