Graphs: Representation and Elementary Algorithms

Antonio Carzaniga

Faculty of Informatics
Università della Svizzera italiana

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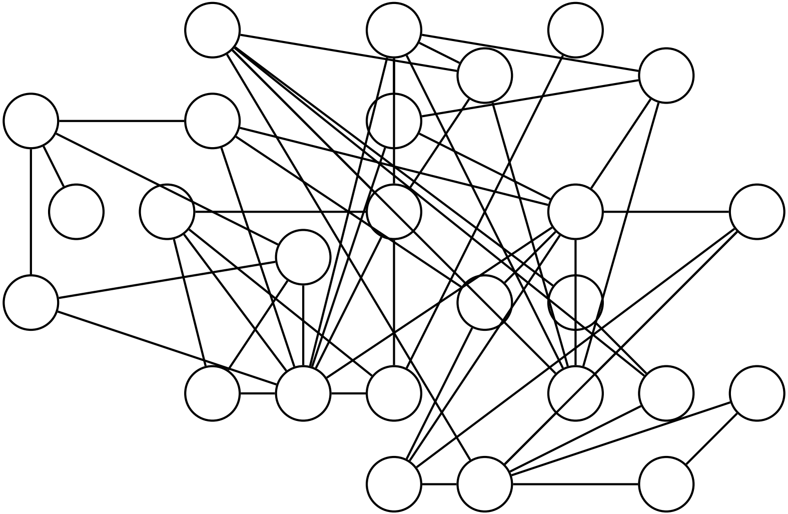
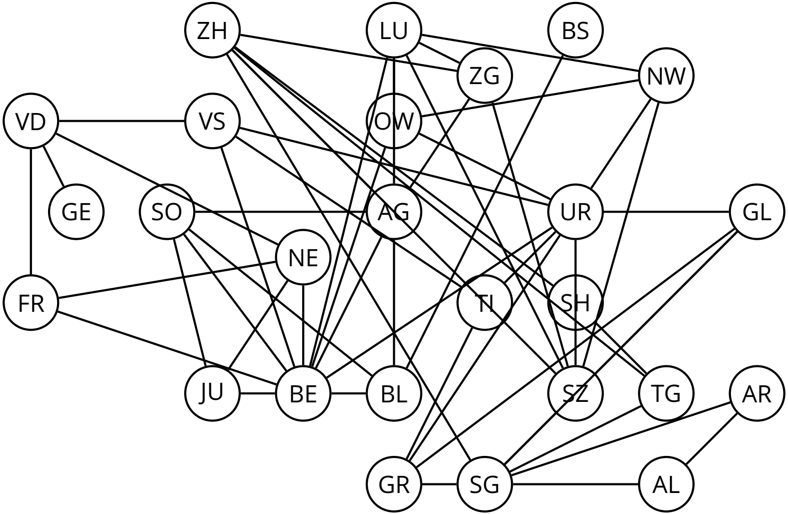
Outline

- Graphs: definitions
- Representations
- Breadth-first search
- Depth-first search

Example



Example



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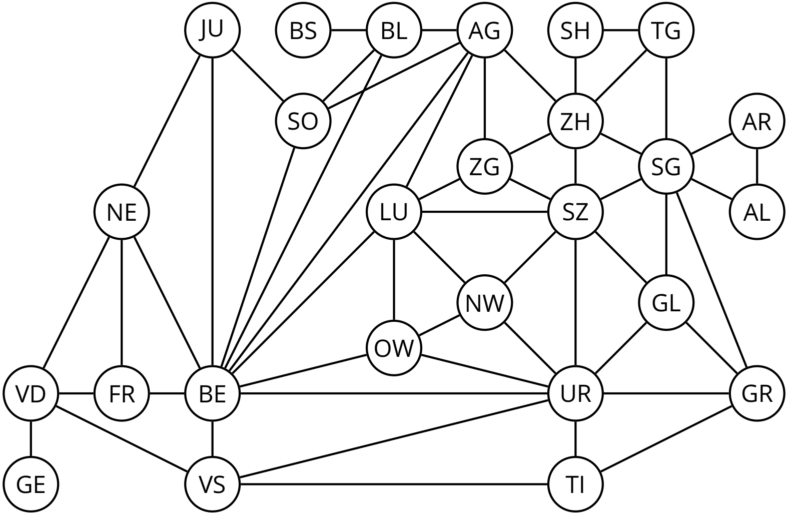
Same Example (Better Layout)

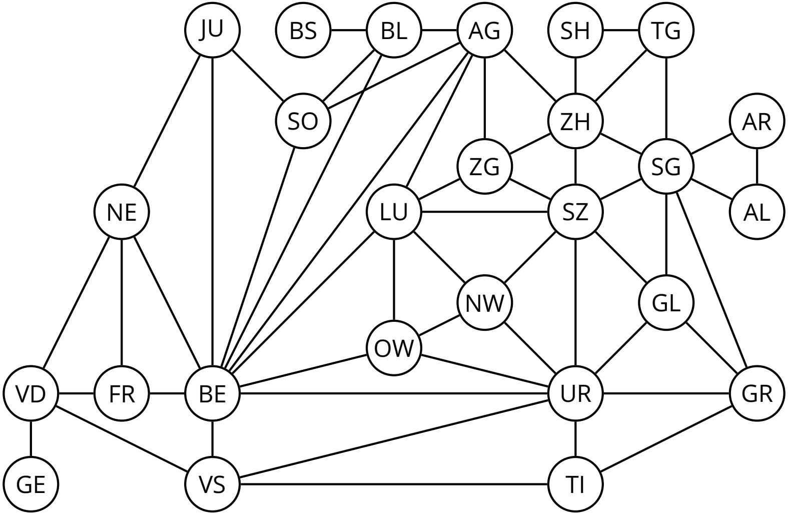


Many Models and Applications

- Social networks: *who knows who*
- The Web graph: *which page links to which*
- The Internet graph: *which router links to which*
- Citation graphs: *who references whose papers*
- Planar graphs: *which country is next to which*
- Well-shaped meshes: *pretty pictures with triangles*
- Geometric graphs: *who is near who*
- Random graphs: *whichever…*

Examples and descriptions taken from Daniel A. Spielman's course "Graphs and Networks."

Example (1)



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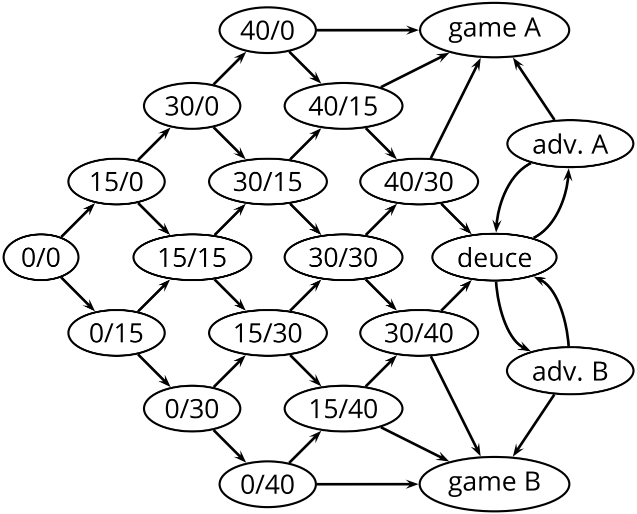
Example (2)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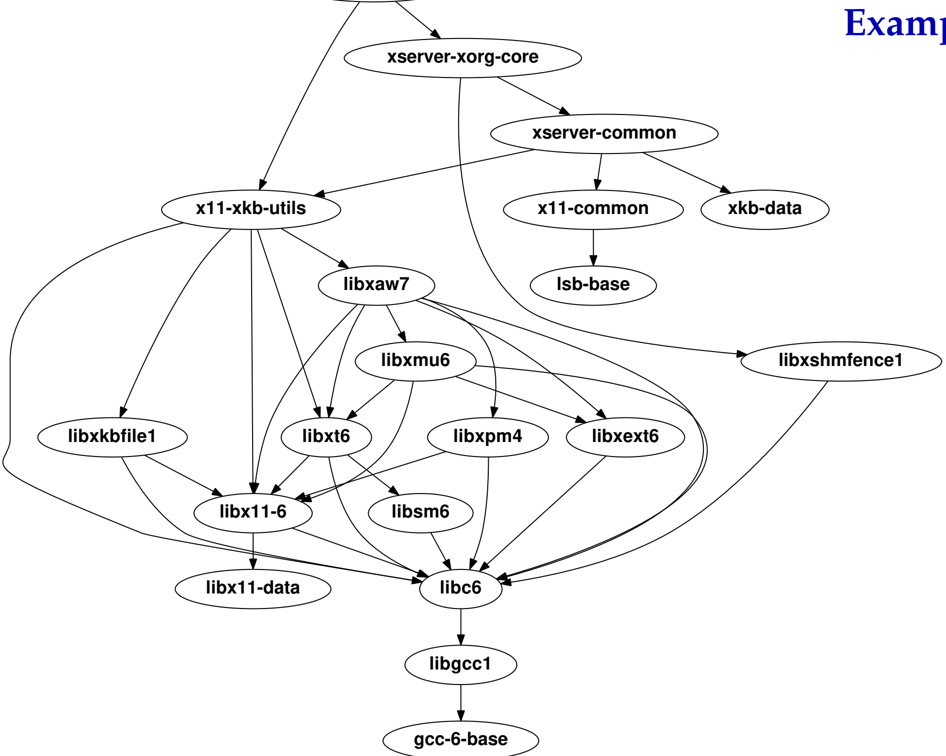
Example (3)


xserver-xorg-core
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libxkbfile1
libxt6
libxpm4
libxext6
libx11-6
libsm6
libx11-data
libc6
libgcc1
gcc-6-base

- A ***graph***

$$G = (V, E)$$

- V is the set of ***vertices*** (also called ***nodes***)
- E is the set of ***edges***

- A ***graph***

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- E is the set of ***edges***
  - $E \subseteq V \times V$, i.e., E is a ***relation between vertices***
  - an edge $e = (u, v) \in V$ is a pair of vertices $u \in V$ and $v \in V$

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- An *undirected* graph is characterized by a *symmetric* relation between vertices
  - an edge is a set $e = \{u, v\}$ of two vertices

- How do we represent a graph $G = (E, V)$ in a computer?

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- *Adjacency-list representation*
- $V = \{1, 2, \ldots |V|\}$
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- A vertex $u \in V$ is represented by an element in the array Adj

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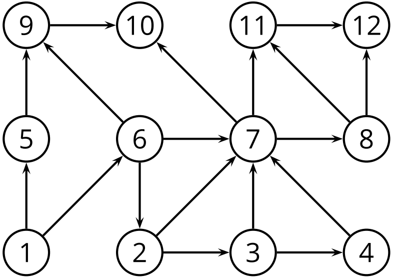
- *Adjacency-list representation*
- $V = \{1, 2, \ldots |V|\}$
- G consists of an array Adj
- A vertex $u \in V$ is represented by an element in the array Adj
- $Adj[u]$ is the ***adjacency list*** of vertex u
  - the list of the vertices that are adjacent to u
  - i.e., the list of all v such that $(u, v) \in E$

Example



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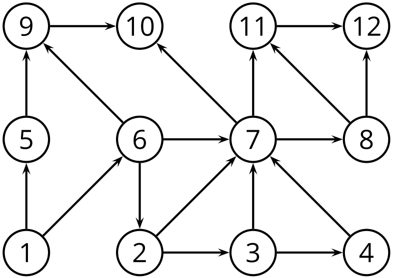
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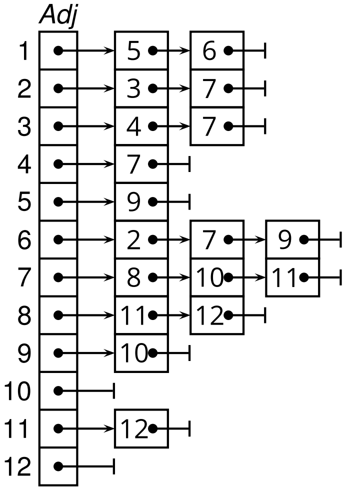
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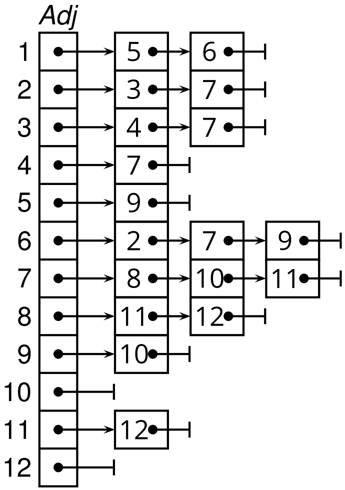
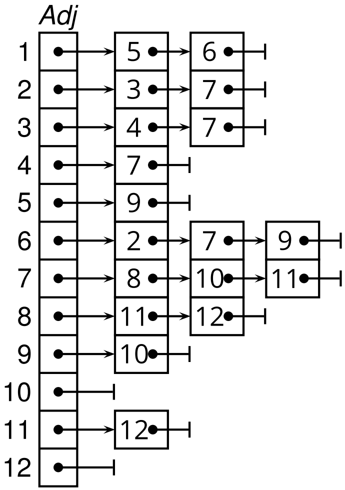
Using the Adjacency List

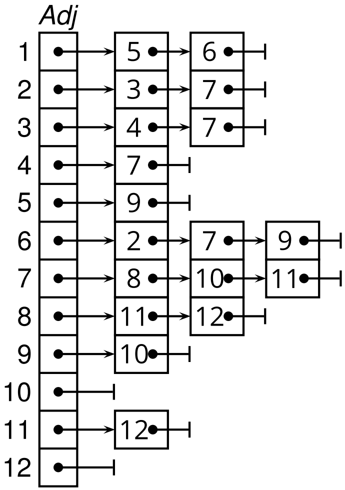


- Accessing a vertex u?



Using the Adjacency List

- Accessing a vertex *u*? $O(1)$
  - optimal



Using the Adjacency List

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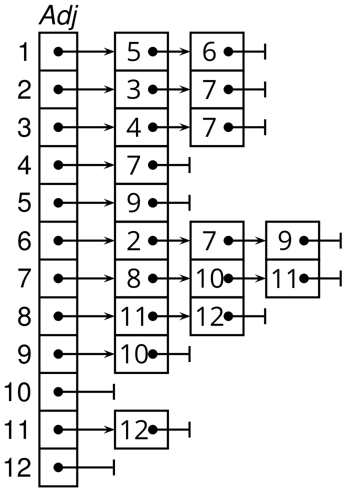
- Iteration through V?



Using the Adjacency List

- Accessing a vertex u? $O(1)$
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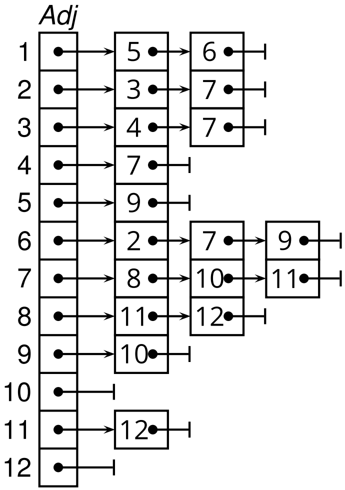
- Iteration through V? $\Theta(|V|)$
  - optimal



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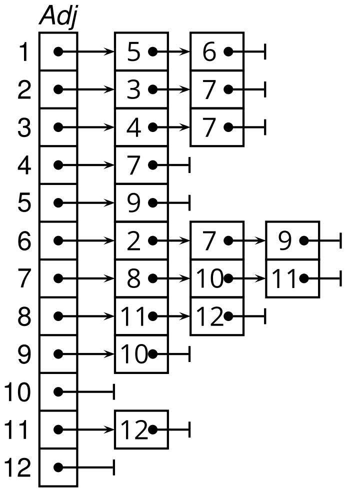

Using the Adjacency List

- Accessing a vertex u? $O(1)$
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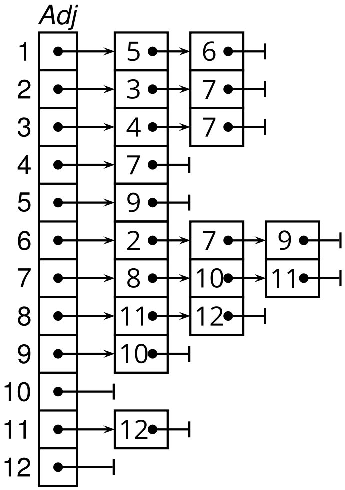
- Iteration through E? $\Theta(|V| + |E|)$
  - okay (not optimal)



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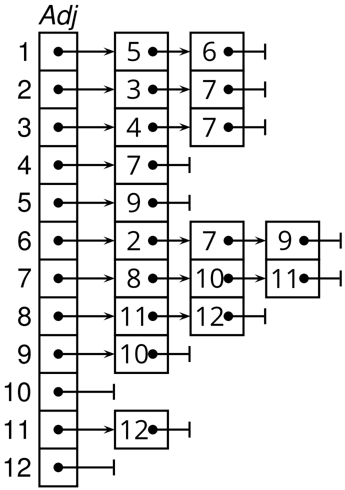

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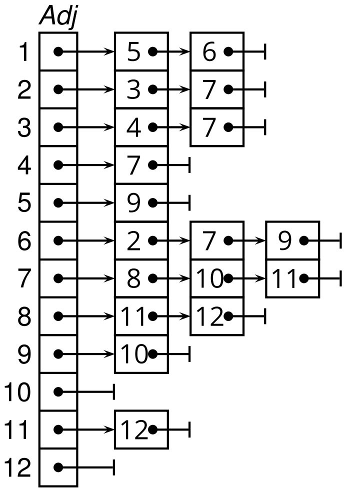

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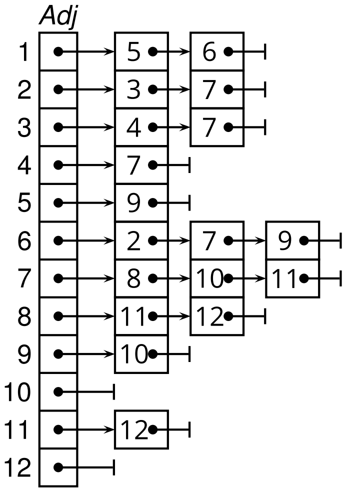
  - optimal
- Iteration through E? $\Theta(|V| + |E|)$
  - okay (not optimal)
- Checking $(u, v) \in E$? $O(|V|)$
  - bad

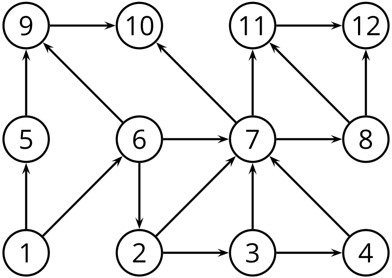


Graph Representation (2)

- *Adjacency-matrix representation*
- $V = \{1, 2, \ldots |V|\}$
- G consists of a $|V| \times |V|$ matrix A
- $A = (a_{ij})$ such that

$$a_{ij} = \begin{cases} 1 & \text{if } (i, j) \in E \\ 0 & \text{otherwise} \end{cases}$$

Example



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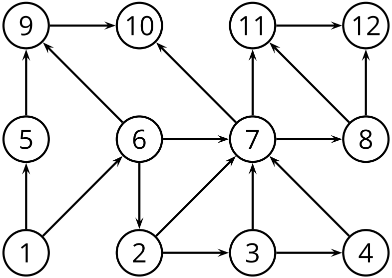

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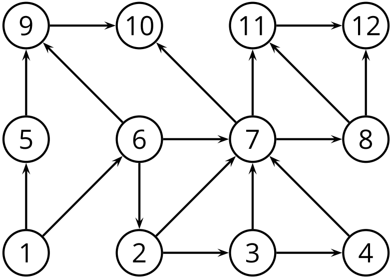
Example



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Using the Adjacency Matrix

	1	2	3	4	5	6	7	8	9	10	11	12
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Using the Adjacency Matrix

- Accessing a vertex *u*?

	1	2	3	4	5	6	7	8	9	10	11	12
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Using the Adjacency Matrix

- Accessing a vertex u? $O(1)$
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	1	2	3	4	5	6	7	8	9	10	11	12
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Using the Adjacency Matrix

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- Iteration through *V*?

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Using the Adjacency Matrix

- Accessing a vertex u? $O(1)$
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- Iteration through V? $\Theta(|V|)$
  - optimal

	1	2	3	4	5	6	7	8	9	10	11	12
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- Iteration through E?

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Using the Adjacency Matrix

- Accessing a vertex u? $O(1)$
  - optimal
- Iteration through V? $\Theta(|V|)$
  - optimal
- Iteration through E? $\Theta(|V|^2)$
  - possibly very bad

	1	2	3	4	5	6	7	8	9	10	11	12
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Space Complexity

- Adjacency-list representation

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$$\boxed{\Theta(|V| + |E|)}$$

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Space Complexity

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- Adjacency-matrix representation

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  optimal

- Adjacency-matrix representation

$$\boxed{\Theta(|V|^2)}$$

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- When is the adjacency-matrix “very bad”?

Choosing a Graph Representation

- Adjacency-list representation
  - generally good, especially for its optimal space complexity
  - bad for ***dense*** graphs and algorithms that require random access to edges
  - preferable for ***sparse*** graphs or graphs with ***low degree***

Choosing a Graph Representation

- Adjacency-list representation
  - generally good, especially for its optimal space complexity
  - bad for ***dense*** graphs and algorithms that require random access to edges
  - preferable for ***sparse*** graphs or graphs with ***low degree***
- Adjacency-matrix representation
  - suffers from a bad space complexity
  - good for algorithms that require random access to edges
  - preferable for ***dense*** graphs

- One of the simplest but also a fundamental algorithm

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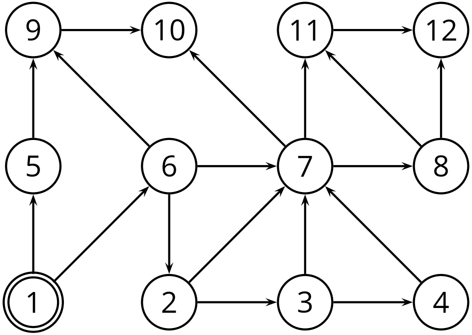
- *Input:* $G = (V, E)$ and a vertex $s \in V$
  - explores the graph, touching all vertices that are reachable from s
  - iterates through the vertices at increasing distance (edge distance)
  - computes the distance of each vertex from s
  - produces a ***breadth-first tree*** rooted at s
  - works on both *directed* and *undirected* graphs

Example



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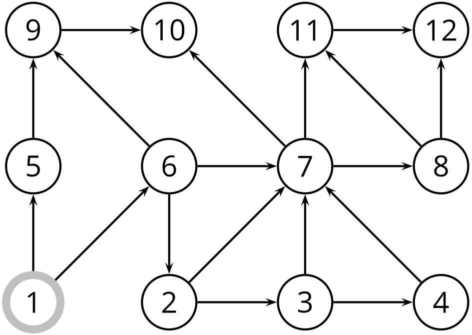

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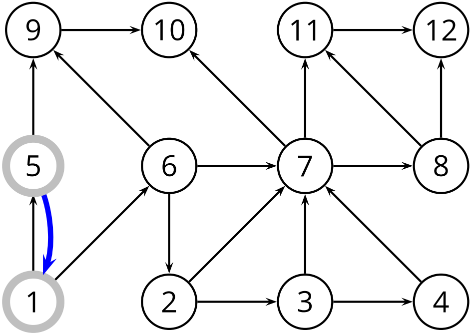

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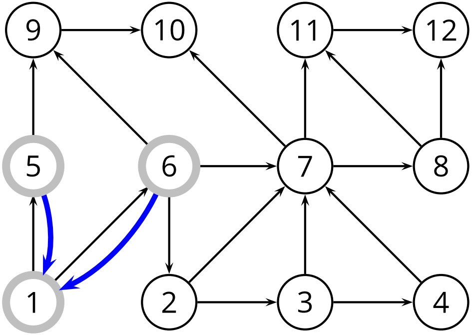

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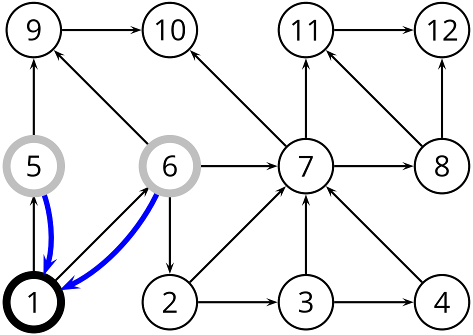

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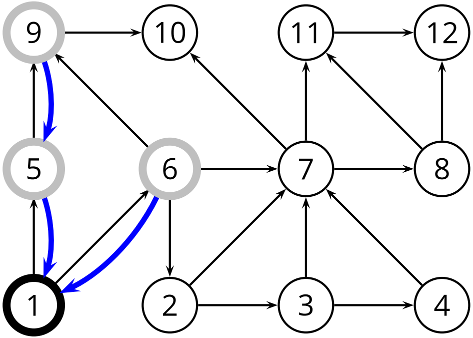

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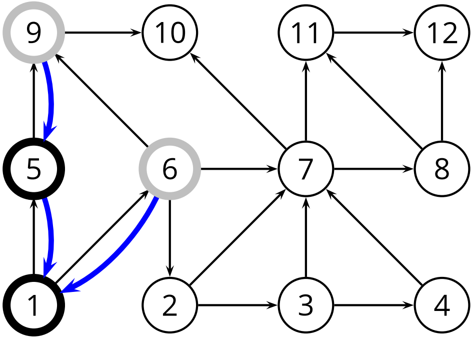

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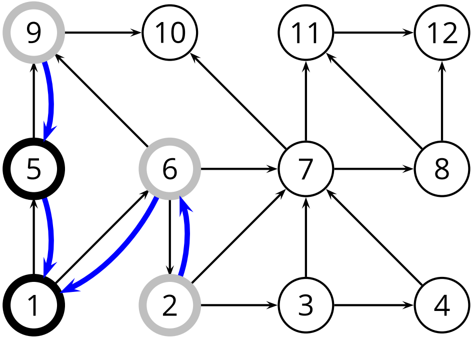

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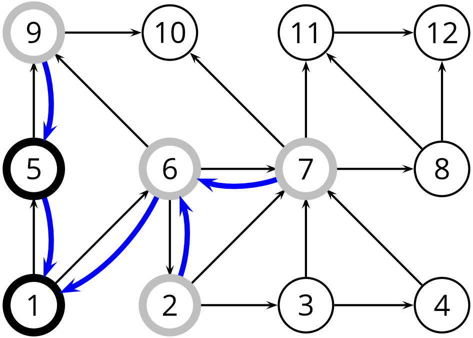

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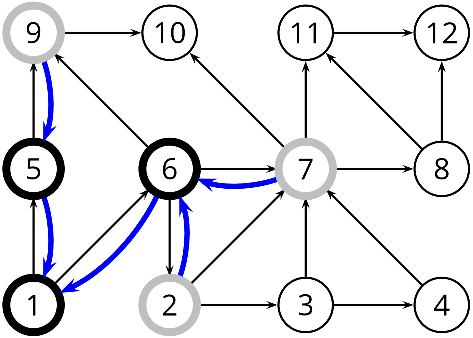

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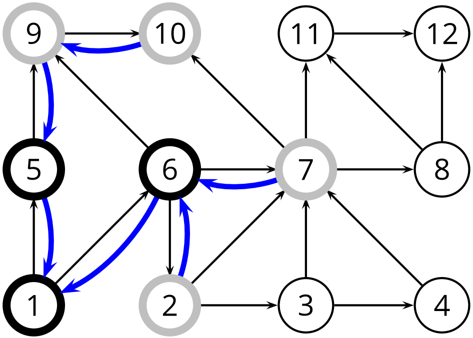

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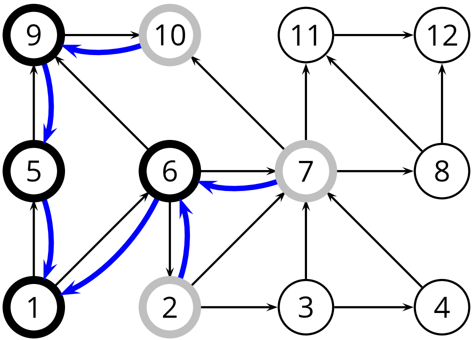
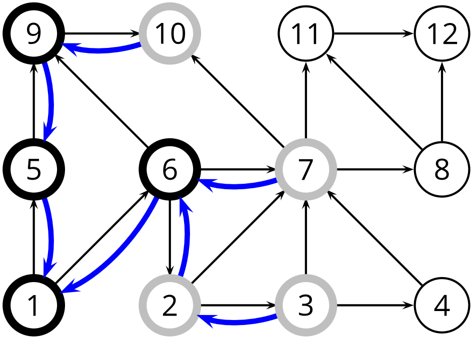
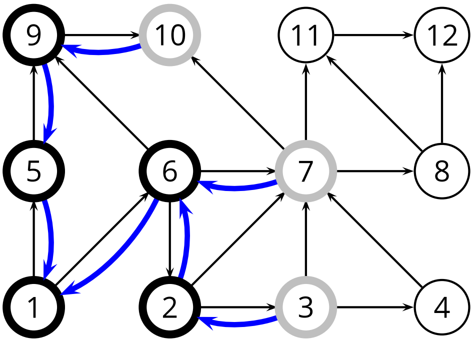


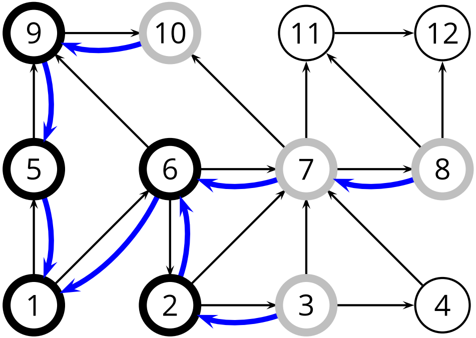
Example



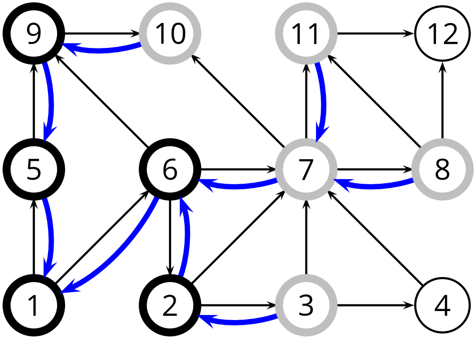
Example



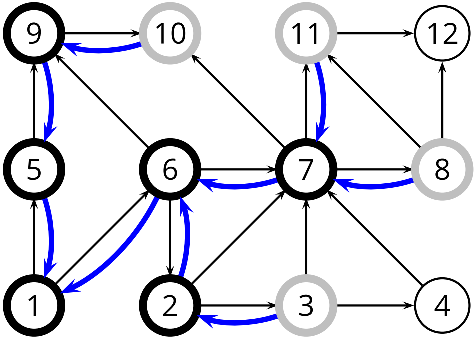
Example



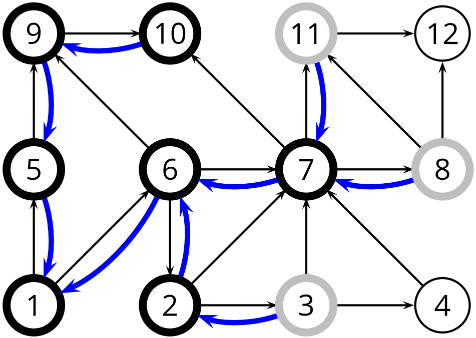
Example



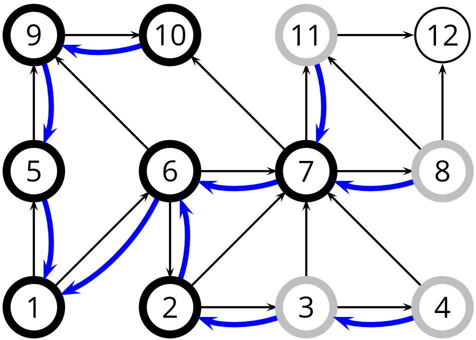
Example



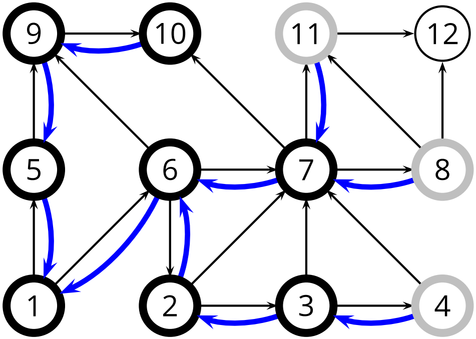
Example



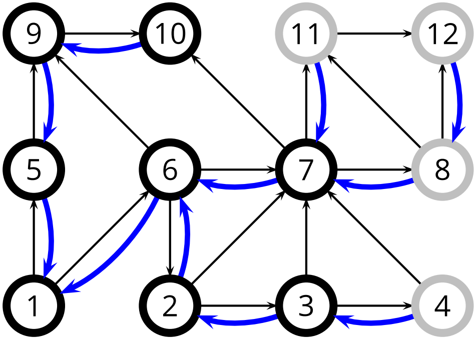
Example



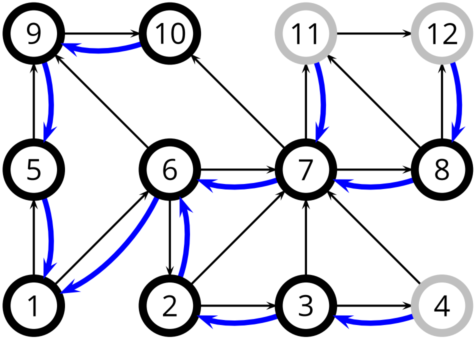
Example



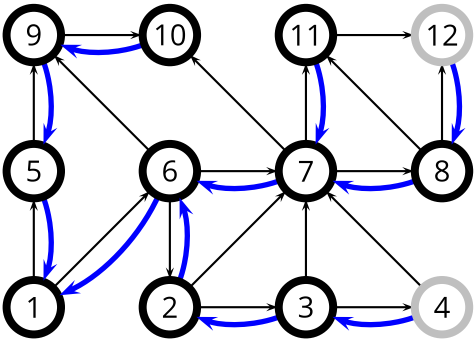
Example



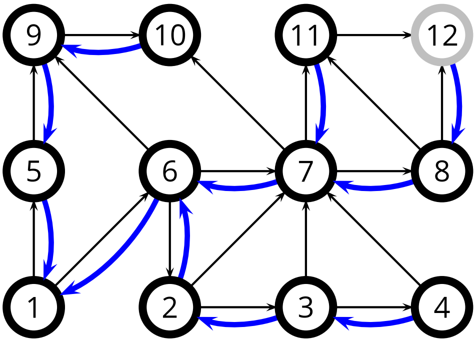
Example



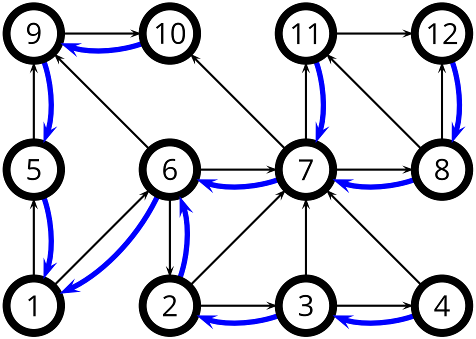
Example



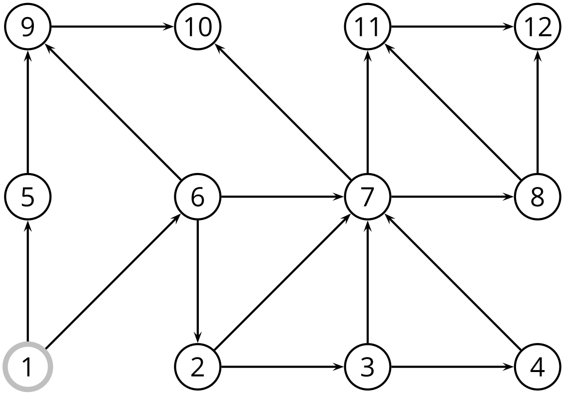
Example



Example

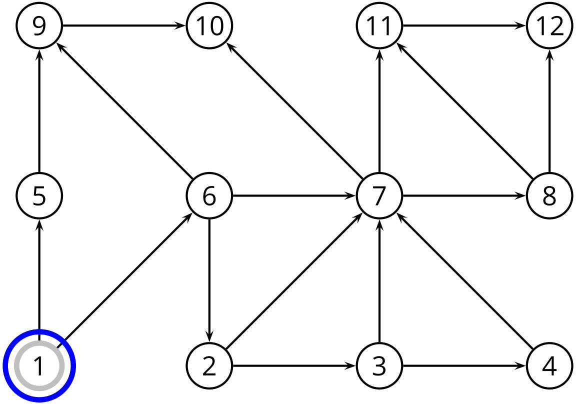


```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```



BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

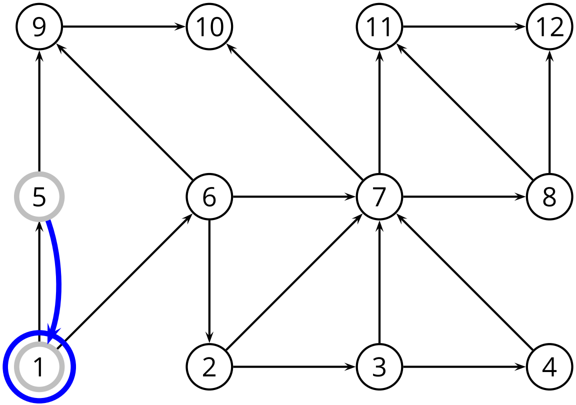


$u = 1$

$Q = \emptyset$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
        color[u] = white
        d[u] = ∞
        π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
        u = Dequeue(Q)
        for each v ∈ Adj[u]
                if color[v] == white
                        color[v] = gray
                        d[v] = d[u] + 1
                        π[v] = u
                        Enqueue(Q, v)
        color[u] = black
```

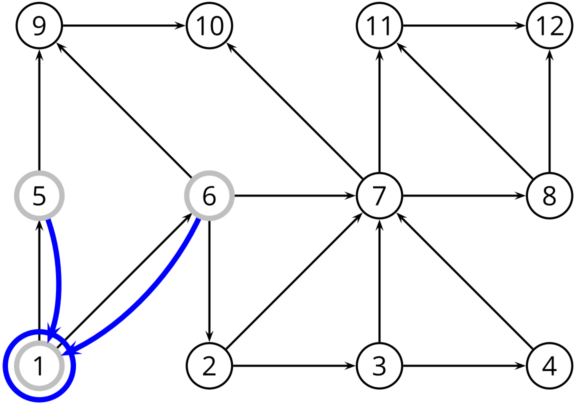


$u = 1$

$Q = \{5\}$

BFS Algorithm

```
BFS(G, s)
    for each vertex u ∈ V(G) \ {s}
        color[u] = white
        d[u] = ∞
        π[u] = nil
    color[s] = gray
    d[s] = 0
    π[s] = nil
    Q = ∅
    Enqueue(Q, s)
    while Q ≠ ∅
        u = Dequeue(Q)
        for each v ∈ Adj[u]
            if color[v] == white
                color[v] = gray
                d[v] = d[u] + 1
                π[v] = u
                Enqueue(Q, v)
        color[u] = black
```

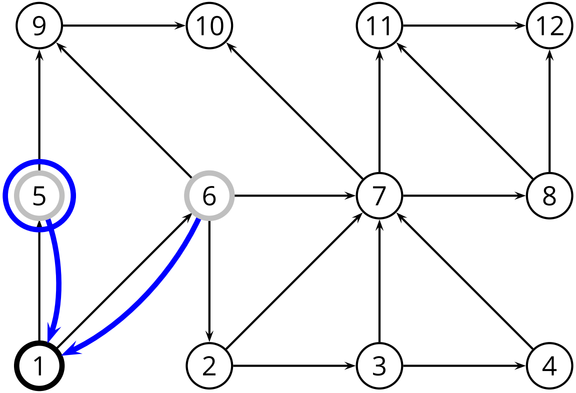


$u = 1$

$Q = \{5, 6\}$

BFS Algorithm

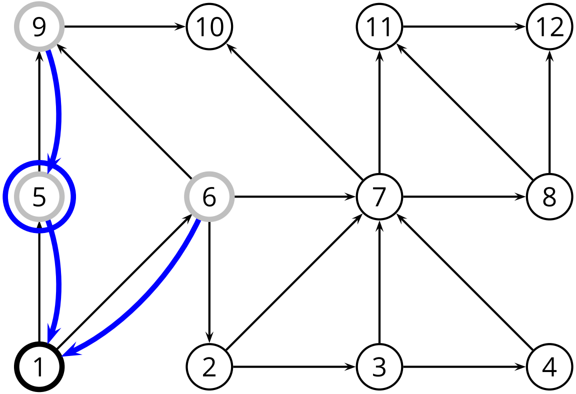
```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```



$u = 5$

$Q = \{6\}$

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
        color[u] = white
        d[u] = ∞
        π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
        u = Dequeue(Q)
        for each v ∈ Adj[u]
                if color[v] == white
                        color[v] = gray
                        d[v] = d[u] + 1
                        π[v] = u
                        Enqueue(Q, v)
        color[u] = black
```

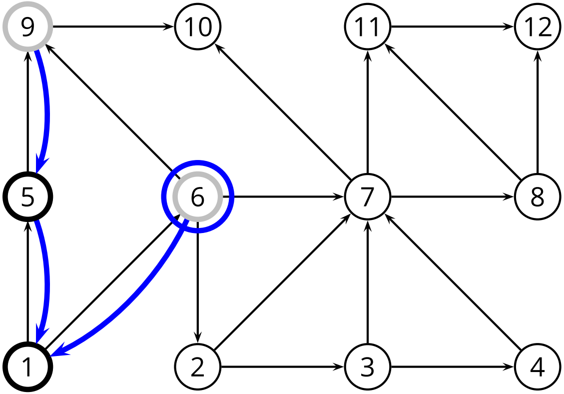


$u = 5$

$Q = \{6, 9\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

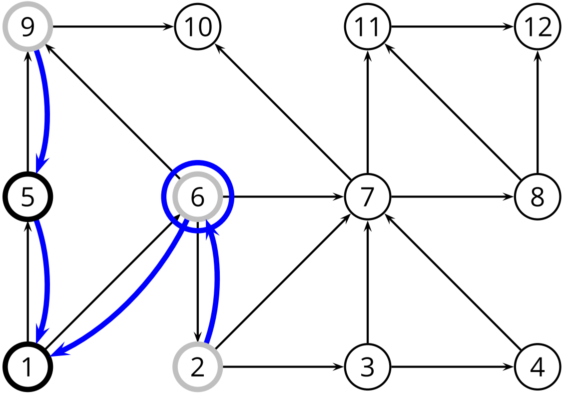


$u = 6$

$Q = \{9\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

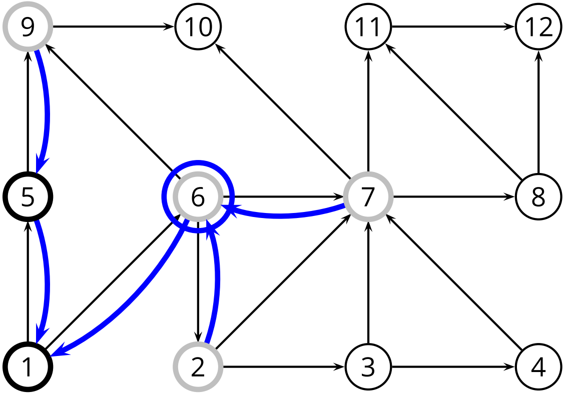


$u = 6$

$Q = \{9, 2, 7\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

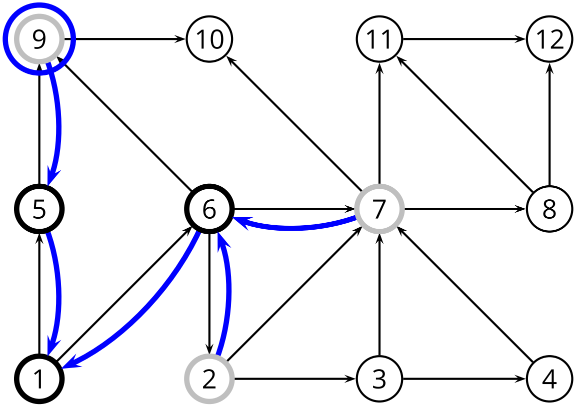


$u = 6$

$Q = \{9, 2, 7\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

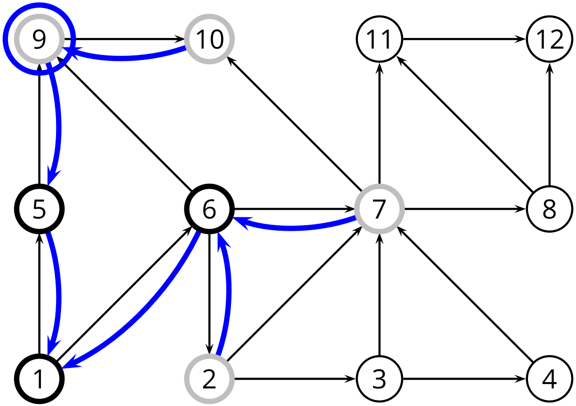


$u = 9$

$Q = \{2, 7\}$

BFS Algorithm

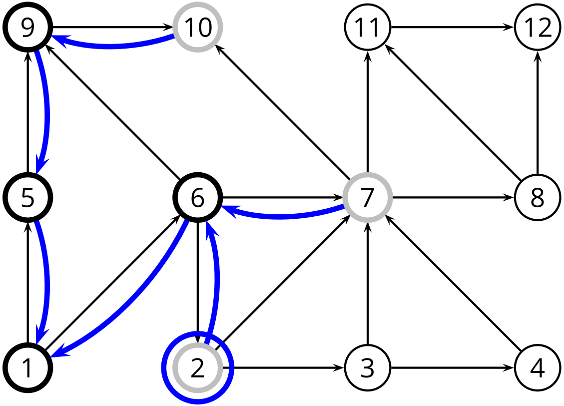
```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```



$u = 9$

$Q = \{2, 7, 10\}$

```
BFS(G, s)
  for each vertex u ∈ V(G) \ {s}
      color[u] = white
      d[u] = ∞
      π[u] = nil
  color[s] = gray
  d[s] = 0
  π[s] = nil
  Q = ∅
  Enqueue(Q, s)
  while Q ≠ ∅
      u = Dequeue(Q)
      for each v ∈ Adj[u]
          if color[v] == white
              color[v] = gray
              d[v] = d[u] + 1
              π[v] = u
              Enqueue(Q, v)
      color[u] = black
```

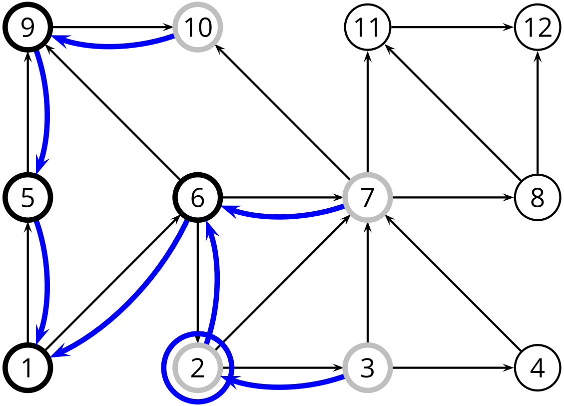


$u = 2$

$Q = \{7, 10\}$

BFS Algorithm

```
BFS(G, s)
    for each vertex u ∈ V(G) \ {s}
        color[u] = white
        d[u] = ∞
        π[u] = nil
    color[s] = gray
    d[s] = 0
    π[s] = nil
    Q = ∅
    Enqueue(Q, s)
    while Q ≠ ∅
        u = Dequeue(Q)
        for each v ∈ Adj[u]
            if color[v] == white
                color[v] = gray
                d[v] = d[u] + 1
                π[v] = u
                Enqueue(Q, v)
        color[u] = black
```

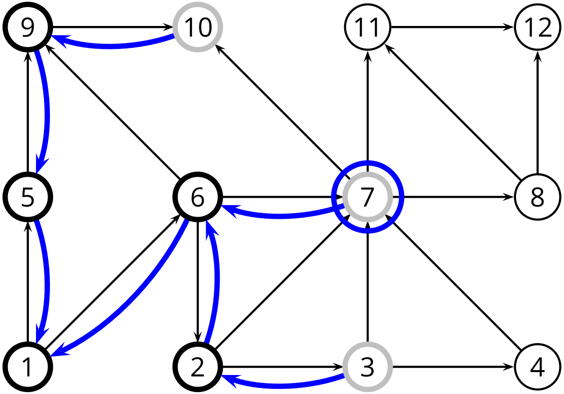


$u = 2$

$Q = \{7, 10, 3\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

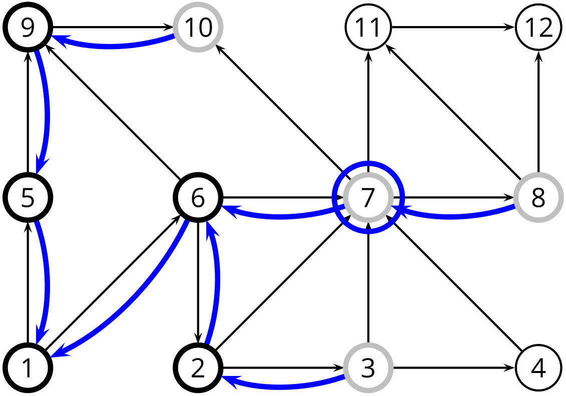


$u = 7$

$Q = \{10, 3\}$

BFS Algorithm

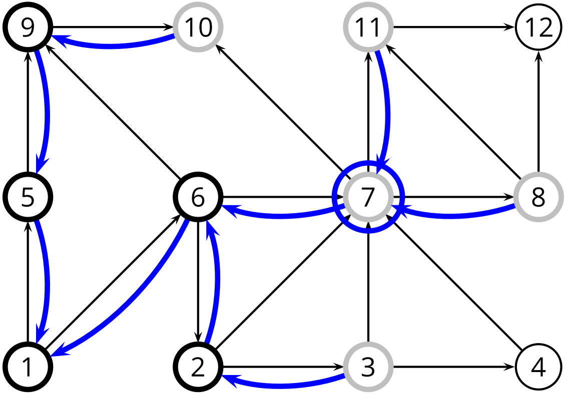
```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
        color[u] = white
        d[u] = ∞
        π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
        u = Dequeue(Q)
        for each v ∈ Adj[u]
                if color[v] == white
                        color[v] = gray
                        d[v] = d[u] + 1
                        π[v] = u
                        Enqueue(Q, v)
        color[u] = black
```



$u = 7$

$Q = \{10, 3, 8\}$

```
BFS(G, s)
    for each vertex u ∈ V(G) \ {s}
        color[u] = white
        d[u] = ∞
        π[u] = nil
    color[s] = gray
    d[s] = 0
    π[s] = nil
    Q = ∅
    Enqueue(Q, s)
    while Q ≠ ∅
        u = Dequeue(Q)
        for each v ∈ Adj[u]
            if color[v] == white
                color[v] = gray
                d[v] = d[u] + 1
                π[v] = u
                Enqueue(Q, v)
        color[u] = black
```

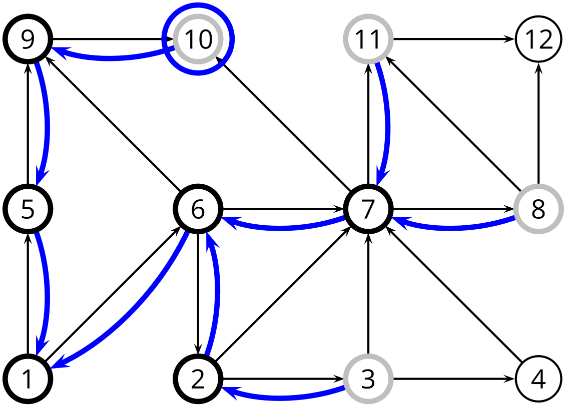


$u = 7$

$Q = \{10, 3, 8, 11\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

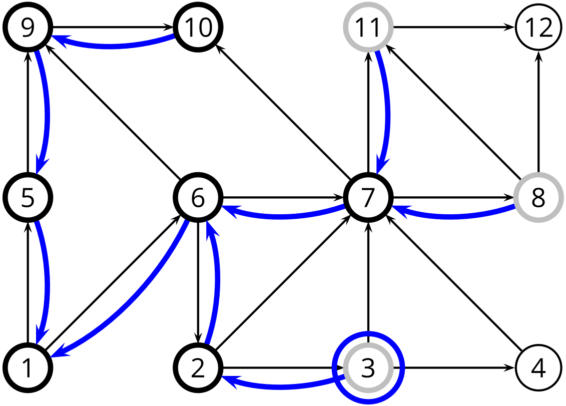


$u = 10$

$Q = \{3, 8, 11\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

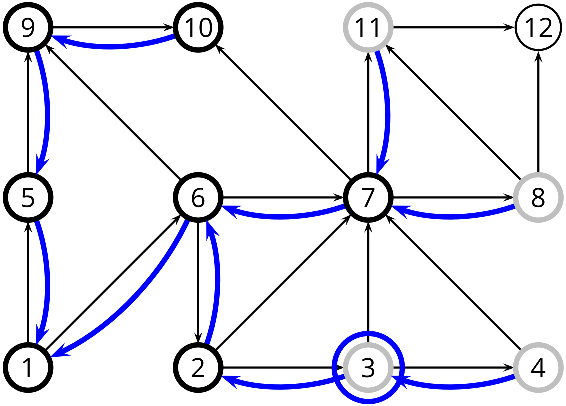


$u = 3$

$Q = \{8, 11\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```

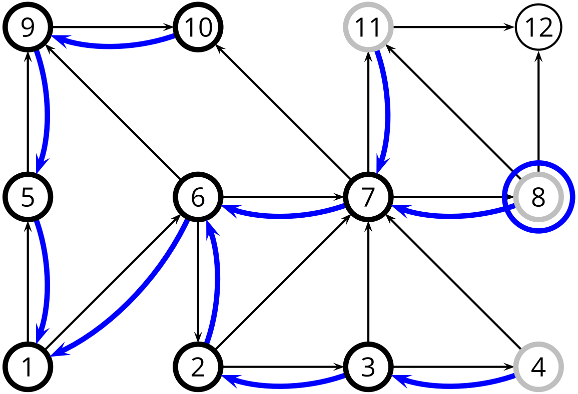


$u = 3$

$Q = \{8, 11, 4\}$

BFS Algorithm

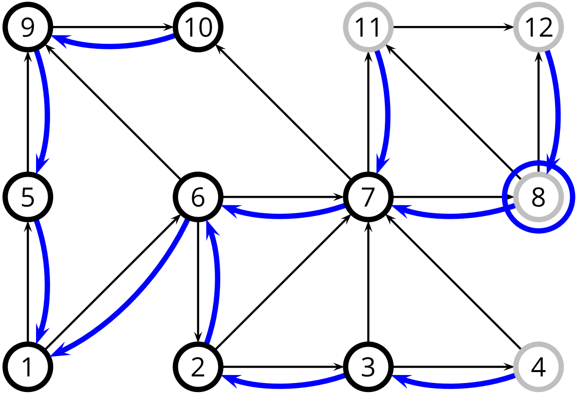
```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```



$u = 8$

$Q = \{11, 4\}$

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
π[s] = nil
Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
        if color[v] == white
            color[v] = gray
            d[v] = d[u] + 1
            π[v] = u
            Enqueue(Q, v)
    color[u] = black
```



$u = 8$

$Q = \{11, 4, 12\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
    d[u] = ∞
    π[u] = nil
color[s] = gray
d[s] = 0
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Q = ∅
Enqueue(Q, s)
while Q ≠ ∅
    u = Dequeue(Q)
    for each v ∈ Adj[u]
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            d[v] = d[u] + 1
            π[v] = u
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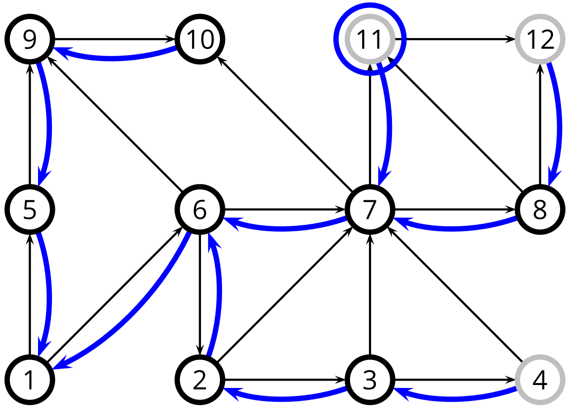
```



$u = 11$

$Q = \{4, 12\}$

BFS Algorithm

```
BFS(G, s)
for each vertex u ∈ V(G) \ {s}
    color[u] = white
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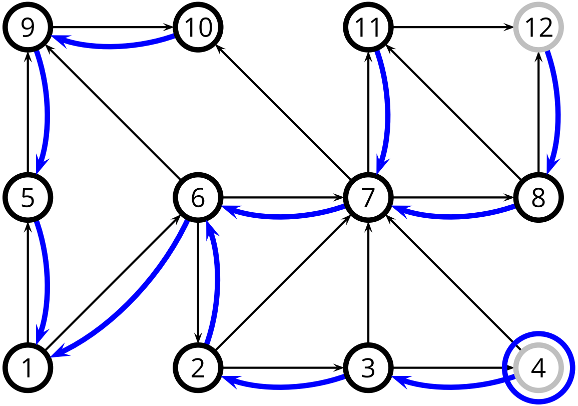

$u = 4$

$Q = \{12\}$

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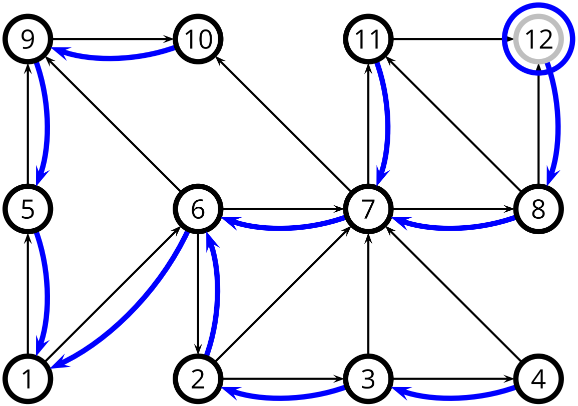

$u = 12$

$Q = \emptyset$

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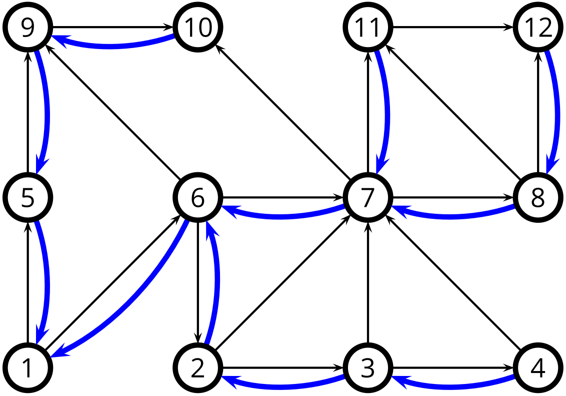

Complexity of BFS

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- For each vertex u, the inner loop executes $\Theta(|E_u|)$, for a total of $O(|E|)$ steps
- So, $O(|V| + |E|)$

Depth-First Search

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  - explores the graph, touching *all vertices*
  - produces a ***depth-first forest***, consisting of all the ***depth-first trees*** defined by the DFS exploration
  - associates ***two time-stamps*** to each vertex
    - $d[u]$ records when u is first discovered
    - $f[u]$ records when DFS finishes examining u's edges, and therefore backtracks from u

DFS Algorithm

```
DFS(G)
for each vertex u ∈ V(G)
    color[u] = white
    π[u] = nil
time = 0 // "global" variable
for each vertex u ∈ V(G)
    if color[u] == white
        DFS-Visit(u)
```

```
DFS-Visit(u)
color[u] = grey
time = time + 1
d[u] = time
for each v ∈ Adj[u]
    if color[v] == white
        π[v] = u
        DFS-Visit(v)
color[u] = black
time = time + 1
f[u] = time
```

Complexity of DFS

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- So, the overall complexity is $\Theta(|V| + |E|)$

Applications of DFS: Topological Sort

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- **Problem:** (topological sort)

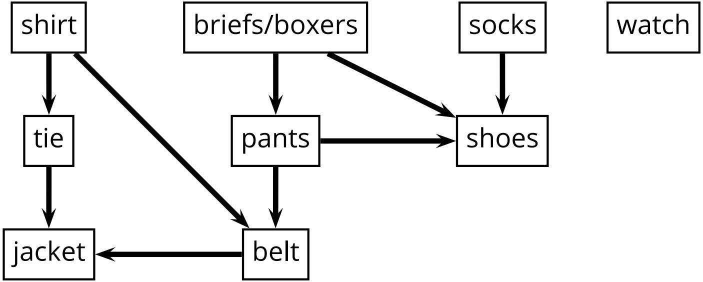
  Given a *directed acyclic graph* (DAG)

  - find an ordering of vertices such that you only end up with *forward links*

- **Example:** dependencies in software packages
  - find an installation order for a set of software packages
  - such that every package is installed only after all the packages it depends on

Topological Sort Algorithm

Topological Sort Algorithm



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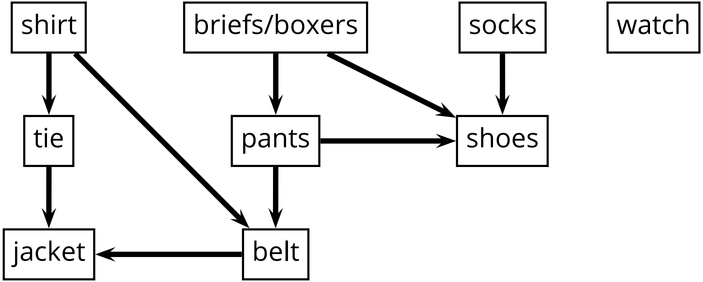

Topological-Sort(G)

1 **DFS**(G)
2 output V sorted in reverse order of $f[\cdot]$