算法设计与分析(2025年春季学期)

Graph Basics

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南京大学计算机学院

Outline

Examples of Graphs

Figure: Road Networks

Figure: Internet

Figure: Social Networks

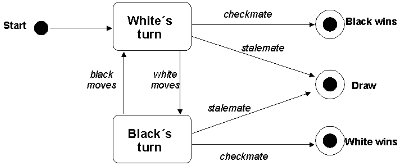
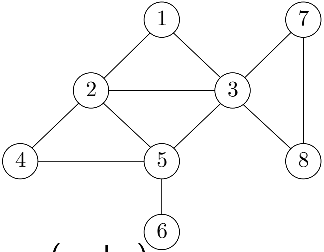


Figure: Transition Graphs

(Undirected) Graph $G = (V, E)$



- V: set of vertices (nodes);
- E: pairwise relationships among V;
  - (undirected) graphs: relationship is symmetric, E contains subsets of size 2

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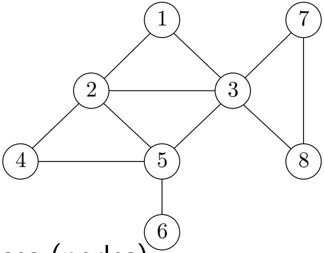
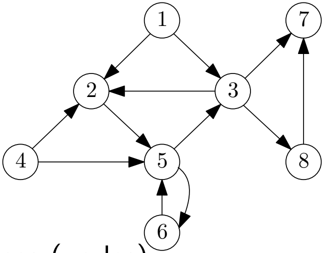


- V: set of vertices (nodes);
  - $V = \{1, 2, 3, 4, 5, 6, 7, 8\}$
- E: pairwise relationships among V;
  - (undirected) graphs: relationship is symmetric, E contains subsets of size 2
  - $E = \{\{1, 2\}, \{1, 3\}, \{2, 3\}, \{2, 4\}, \{2, 5\}, \{3, 5\}, \{3, 7\}, \{3, 8\}, \{4, 5\}, \{5, 6\}, \{7, 8\}\}$

Directed Graph $G = (V, E)$



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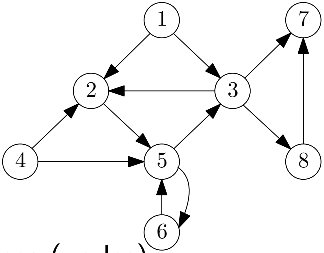

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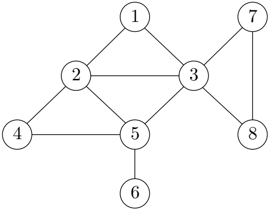
    $(4, 5), (5, 6), (6, 5), (8, 7)\}$

Abuse of Notations

- For (undirected) graphs, we often use (i, j) to denote the set $\{i, j\}$.
- We call (i, j) an unordered pair; in this case $(i, j) = (j, i)$.



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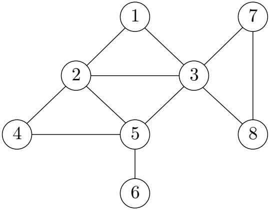
- Social Network : Undirected
- Transition Graph : Directed
- Road Network : Directed or Undirected
- Internet : Directed or Undirected

Representation of Graphs



	1	2	3	4	5	6	7	8
1	0	1	1	0	0	0	0	0
2	1	0	1	1	1	0	0	0
3	1	1	0	0	1	0	1	1
4	0	1	0	0	1	0	0	0
5	0	1	1	1	0	1	0	0
6	0	0	0	0	1	0	0	0
7	0	0	1	0	0	0	0	1
8	0	0	1	0	0	0	1	0

- Adjacency matrix
  - $n \times n$ matrix, $A[u, v] = 1$ if $(u, v) \in E$ and $A[u, v] = 0$ otherwise
  - A is symmetric if graph is undirected

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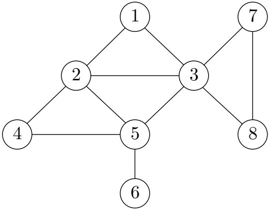

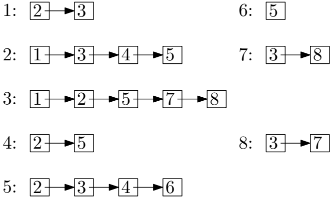

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  - For every vertex v, there is a linked list containing all neighbours of v.

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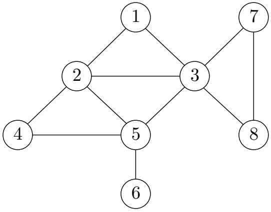

1: [2 | 3]

2: [1 | 3 | 4 | 5]

3: [1 | 2 | 5 | 7 | 8]

4: [2 | 5]

5: [2 | 3 | 4 | 6]

6: [5]

7: [3 | 8]

8: [3 | 7]

$d : (2, 4, 5, 2, 4, 1, 2, 2)$

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  - A is symmetric if graph is undirected
- Linked lists
  - For every vertex v, there is a linked list containing all neighbours of v.
- If graph is static: store neighbors of all vertices in a length-$2m$ array, where the neighbors of any vertex are consecutive.

Comparison of Two Representations

- Assuming we are dealing with undirected graphs
- n: number of vertices
- m: number of edges, assuming $n - 1 \leq m \leq n(n-1)/2$
- d_v: number of neighbors of v

	Matrix	Linked Lists
memory usage		
time to check $(u, v) \in E$		
time to list all neighbours of v		

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memory usage	$O(n^2)$	$O(m)$
time to check $(u,v) \in E$	$O(1)$	
time to list all neighbours of v		

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time to list all neighbours of v	$O(n)$	

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time to list all neighbours of v	$O(n)$	$O(d_v)$

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Connectivity Problem

Input: graph $G = (V, E)$, (using linked lists)
two vertices $s, t \in V$

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  - Breadth-First Search (BFS)
  - Depth-First Search (DFS)

Breadth-First Search (BFS)

- Build layers $L_0, L_1, L_2, L_3, \cdots$
- $L_0 = \{s\}$
- L_{j+1} contains all nodes that are not in $L_0 \cup L_1 \cup \cdots \cup L_j$ and have an edge to a vertex in L_j

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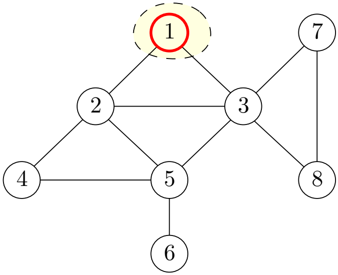

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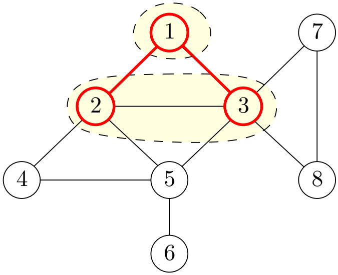

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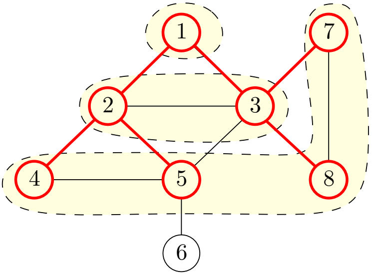

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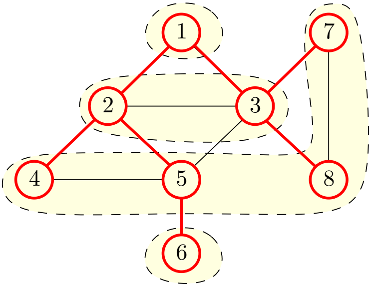


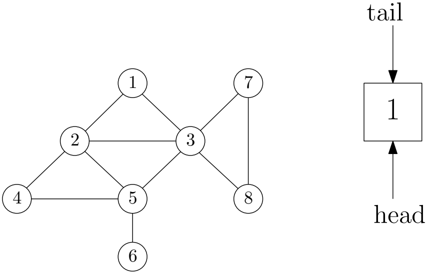
Implementing BFS using a Queue

BFS(s)

```
head ← 1, tail ← 1, queue[1] ← s
mark s as "visited" and all other vertices as "unvisited"
while head ≤ tail do
    v ← queue[head], head ← head + 1
    for all neighbours u of v do
        if u is "unvisited" then
            tail ← tail + 1, queue[tail] = u
            mark u as "visited"
```

- Running time: $O(n+m)$.

Example of BFS via Queue



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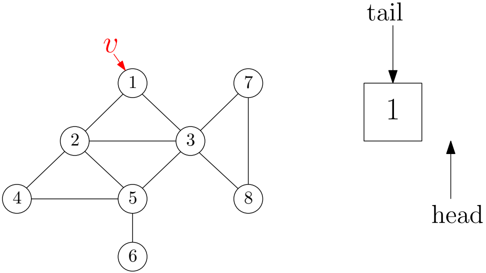

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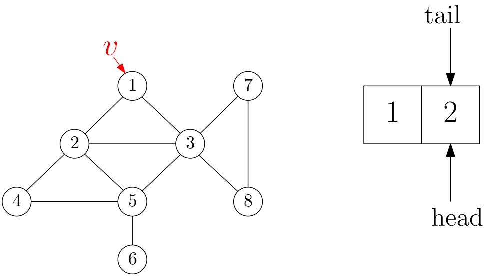

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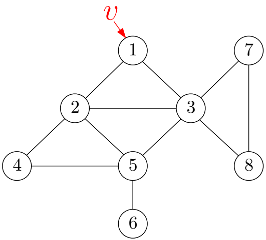

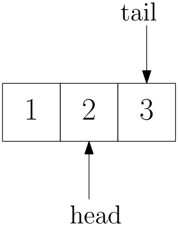

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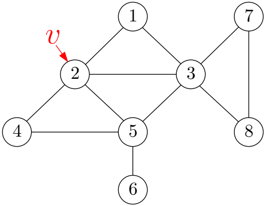

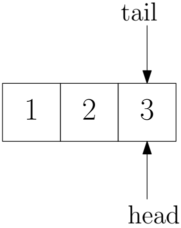

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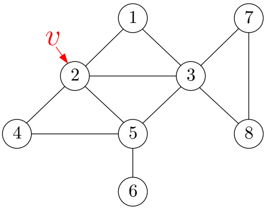

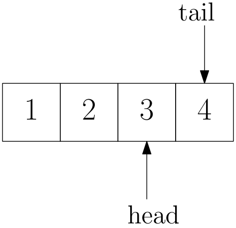

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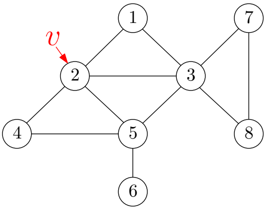

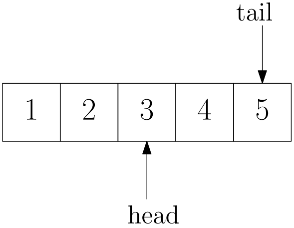

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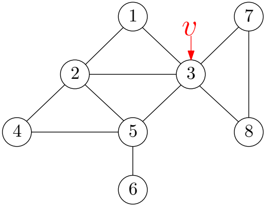

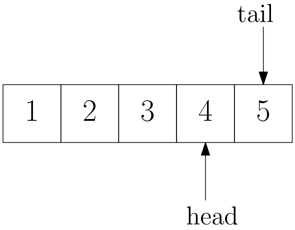

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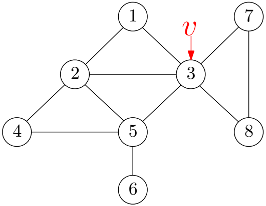

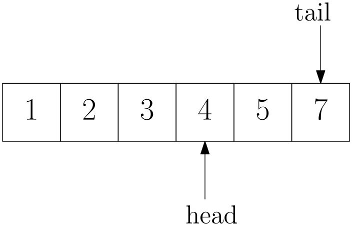

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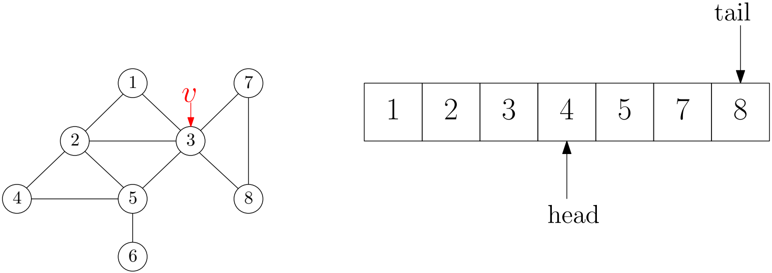

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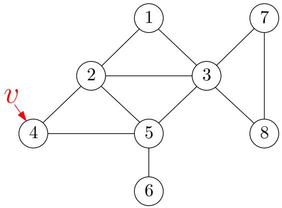

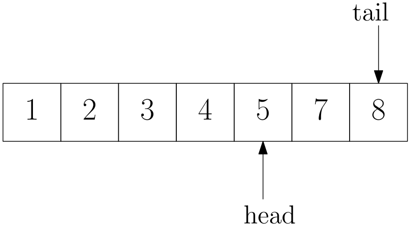

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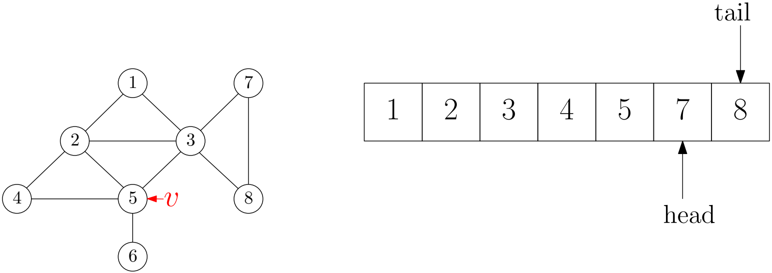

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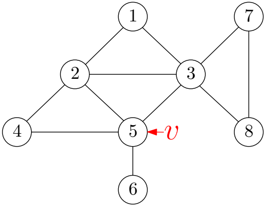

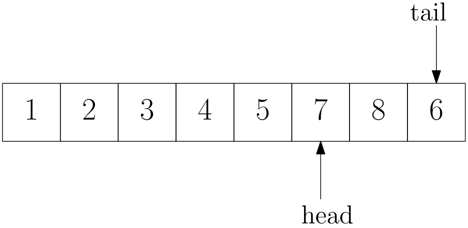

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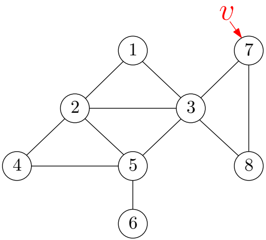

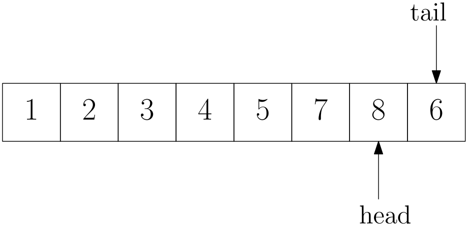

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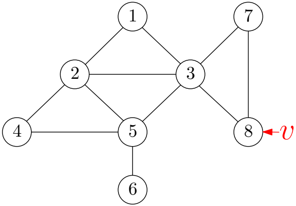

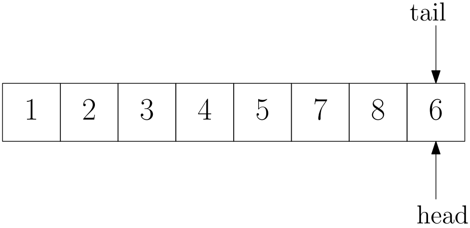

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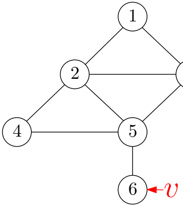

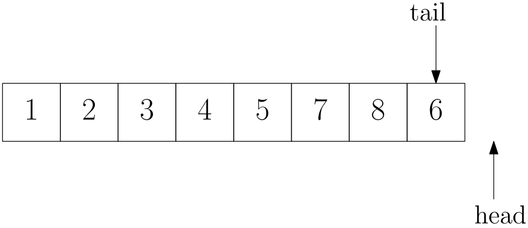

Depth-First Search (DFS)

- Starting from s
- Travel through the first edge leading out of the current vertex
- When reach an already-visited vertex ("dead-end"), go back
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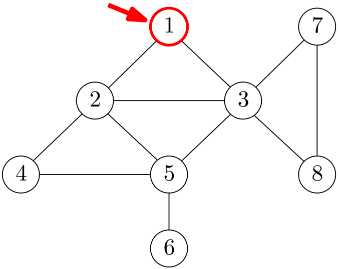

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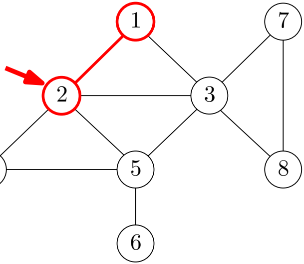

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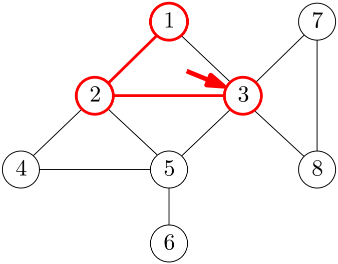

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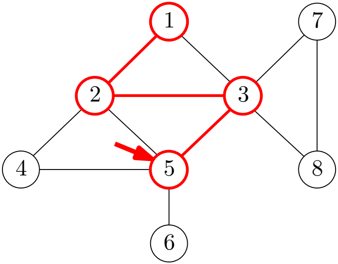

Depth-First Search (DFS)

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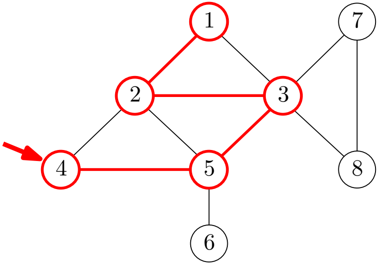

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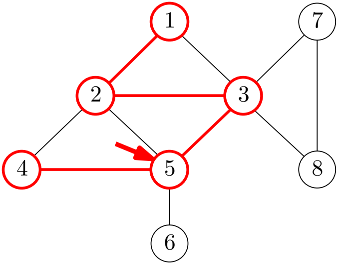

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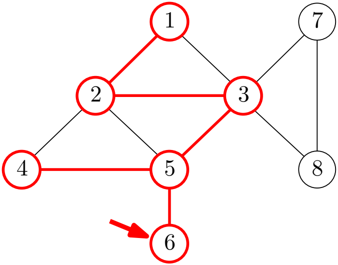

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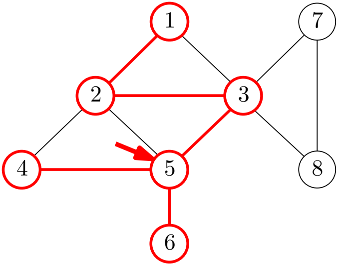

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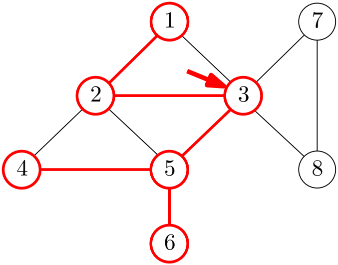

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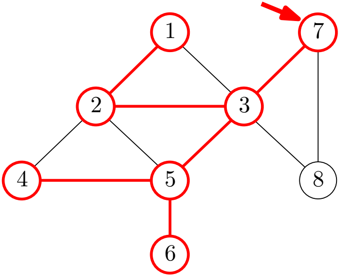

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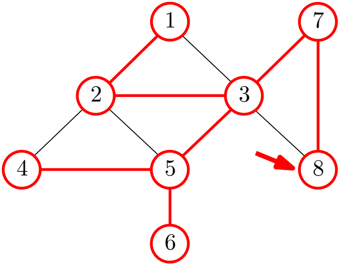


Implementing DFS using Recurrsion

DFS(s)

```
mark all vertices as "unvisited"
recursive-DFS(s)
```

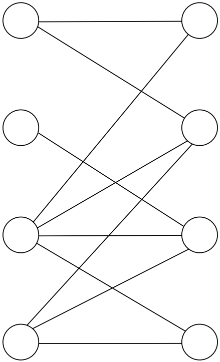
recursive-DFS(v)

```
mark v as "visited"
for all neighbours u of v do
    if u is unvisited then recursive-DFS(u)
```

Outline

Testing Bipartiteness: Applications of BFS

Def. A graph $G = (V, E)$ is a bipartite graph if there is a partition of V into two sets L and R such that for every edge $(u, v) \in E$, we have either $u \in L, v \in R$ or $v \in L, u \in R$.



Testing Bipartiteness

- Taking an arbitrary vertex $s \in V$

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- Assuming $s \in L$ w.l.o.g

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- $\cdots$
- Report “not a bipartite graph” if contradiction was found

Testing Bipartiteness

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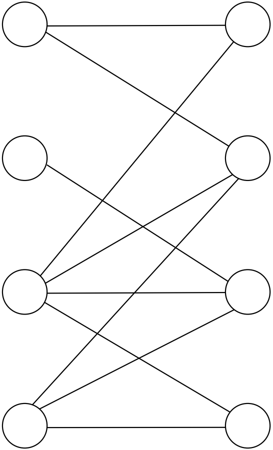
- Assuming $s \in L$ w.l.o.g
- Neighbors of s must be in R
- Neighbors of neighbors of s must be in L
- $\cdots$
- Report "not a bipartite graph" if contradiction was found
- If G contains multiple connected components, repeat above algorithm for each component

Test Bipartiteness



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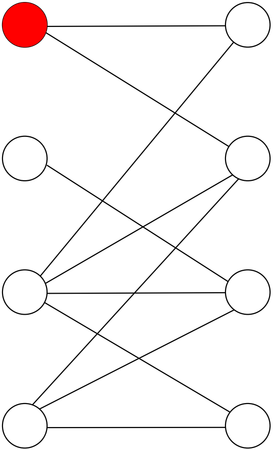

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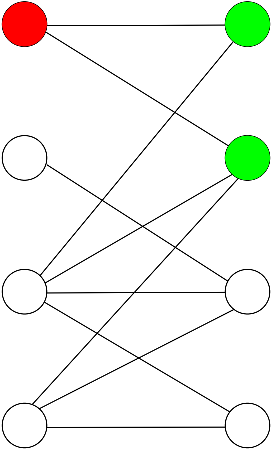

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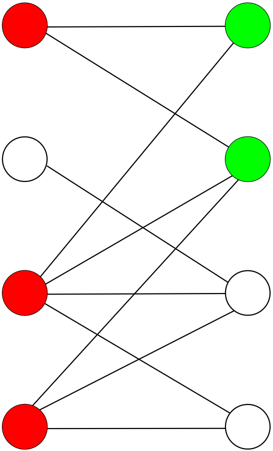

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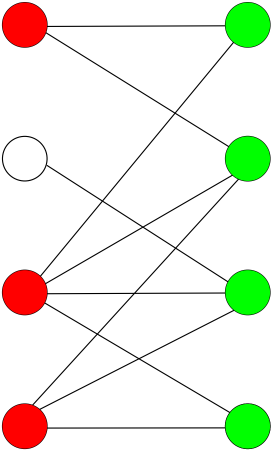

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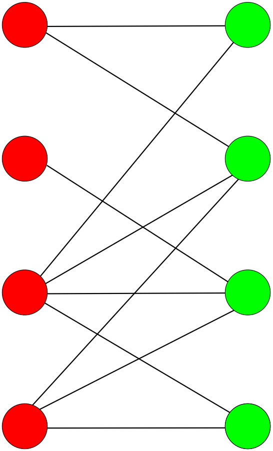

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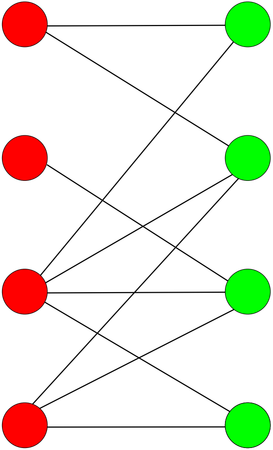

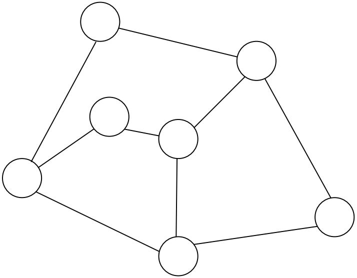

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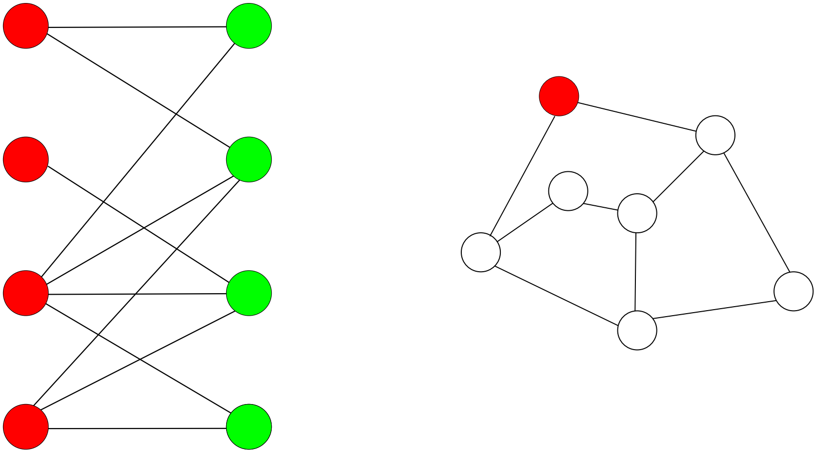

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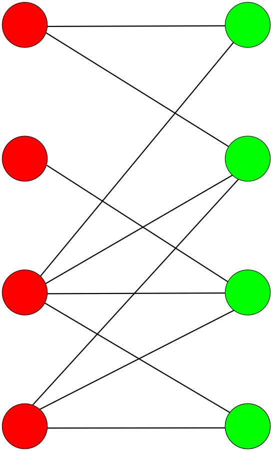

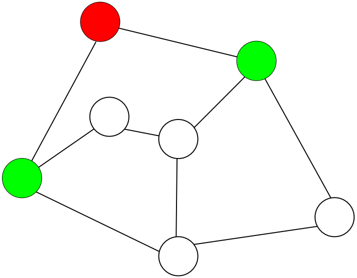

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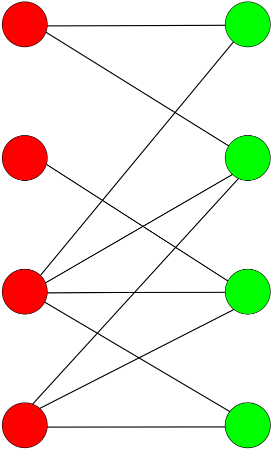

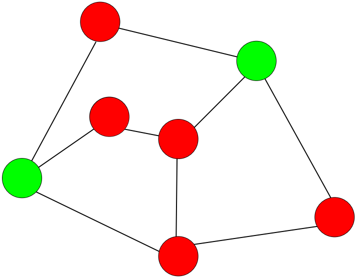

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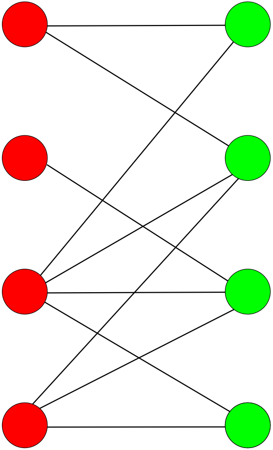
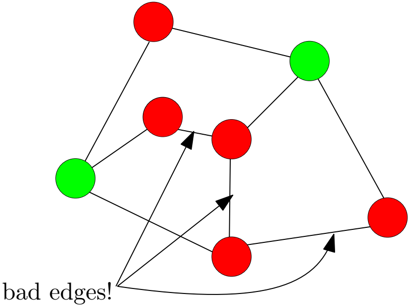




Testing Bipartiteness using BFS

BFS(s)

$head \leftarrow 1, tail \leftarrow 1, queue[1] \leftarrow s$
mark s as "visited" and all other vertices as "unvisited"
while $head \leq tail$ **do**
    $v \leftarrow queue[head], head \leftarrow head + 1$
    for all neighbours u of v **do**
        if u is "unvisited" **then**
            $tail \leftarrow tail + 1, queue[tail] = u$
            mark u as "visited"

Testing Bipartiteness using BFS

test-bipartiteness(s)

$head \leftarrow 1, tail \leftarrow 1, queue[1] \leftarrow s$
mark s as "visited" and all other vertices as "unvisited"
$color[s] \leftarrow 0$
while $head \leq tail$ **do**
    $v \leftarrow queue[head], head \leftarrow head + 1$
    for all neighbours u of v **do**
        if u is "unvisited" **then**
            $tail \leftarrow tail + 1, queue[tail] = u$
            mark u as "visited"
            $color[u] \leftarrow 1 - color[v]$
        else if $color[u] = color[v]$ **then**
            print("G is not bipartite") and exit

Testing Bipartiteness using BFS

mark all vertices as "unvisited"
for each vertex $v \in V$ **do**
    if v is "unvisited" **then**
        test-bipartiteness(v)
print("G is bipartite")

Testing Bipartiteness using BFS

```
mark all vertices as "unvisited"
for each vertex v ∈ V do
    if v is "unvisited" then
        test-bipartiteness(v)
print("G is bipartite")
```

Obs. Running time of algorithm $= O(n + m)$

Outline

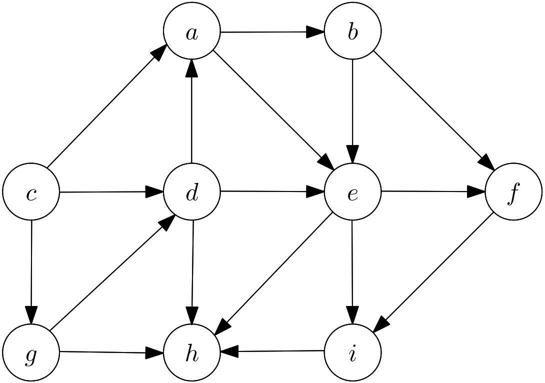
1. Graphs
2. Connectivity and Graph Traversal
   - Testing Bipartiteness
3. Topological Ordering
4. Bridges and 2-Edge-Connected Components
   - $O(n+m)$-Time Algorithm to Find Bridges
   - Related Concept: Cut Vertices
5. Strong Connectivity in Directed Graphs
   - Tarjan's $O(n+m)$-Time Algorithm for Finding SCCes

Topological Ordering Problem

Input: a directed acyclic graph (DAG) $G = (V, E)$

Output: 1-to-1 function $\pi : V \to \{1, 2, 3 \cdots, n\}$, so that

- if $(u, v) \in E$ then $\pi(u) < \pi(v)$



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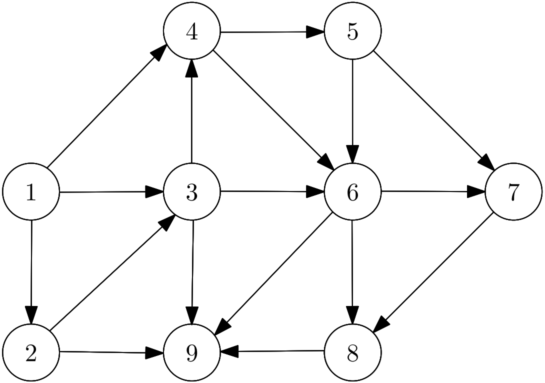
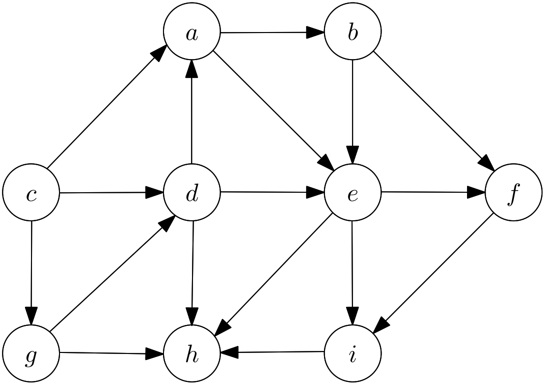


Topological Ordering

- Algorithm: each time take a vertex without incoming edges, then remove the vertex and all its outgoing edges.



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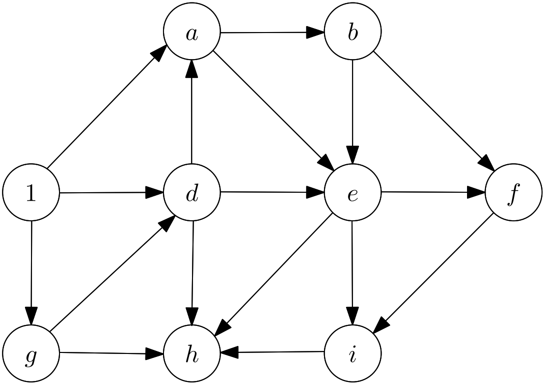

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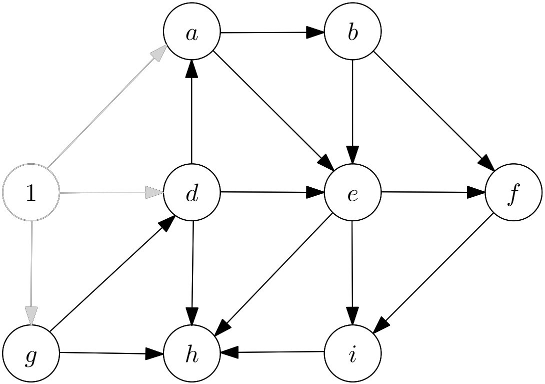

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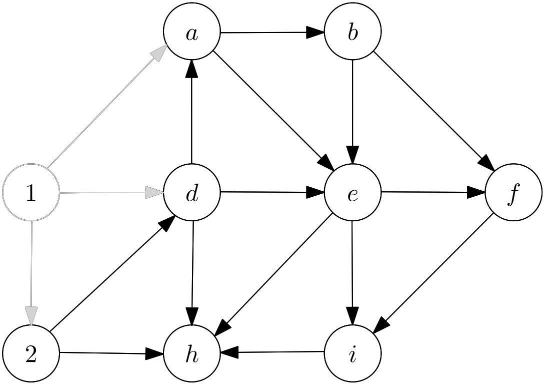

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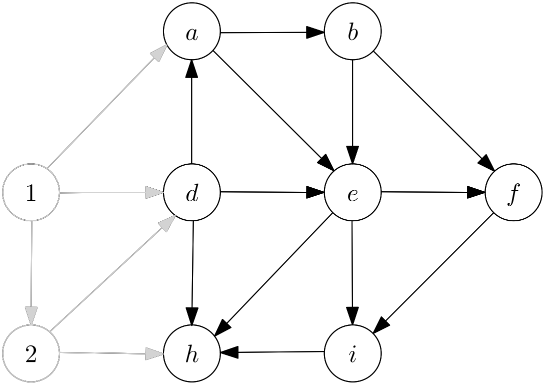

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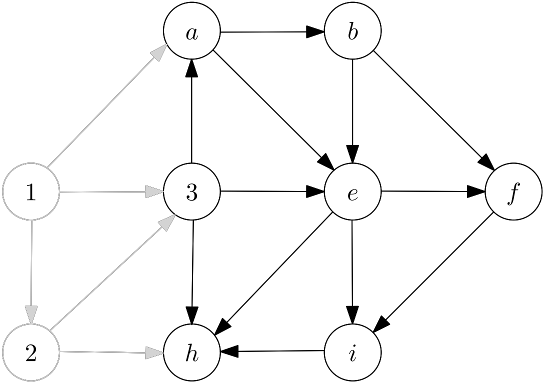

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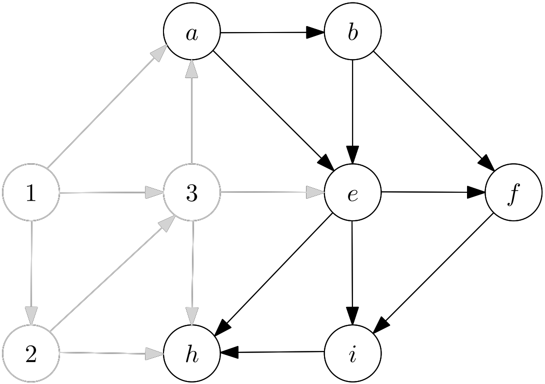

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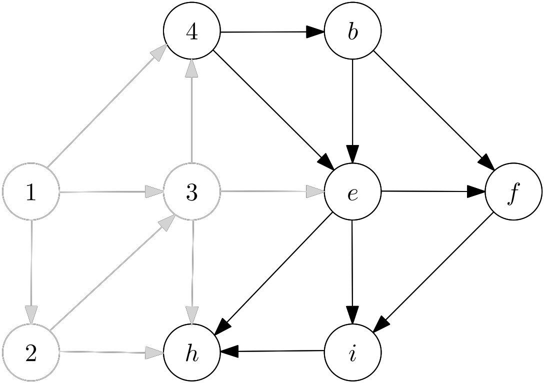

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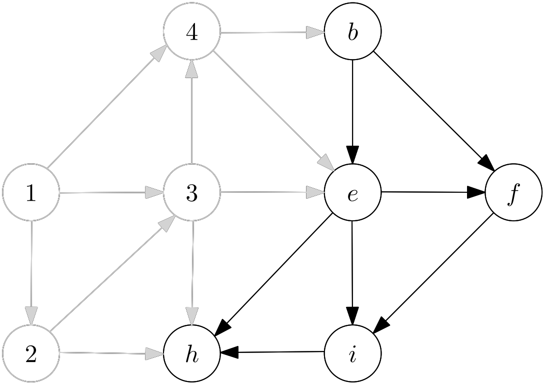

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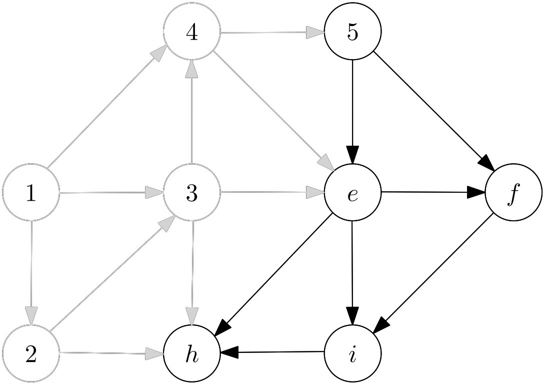

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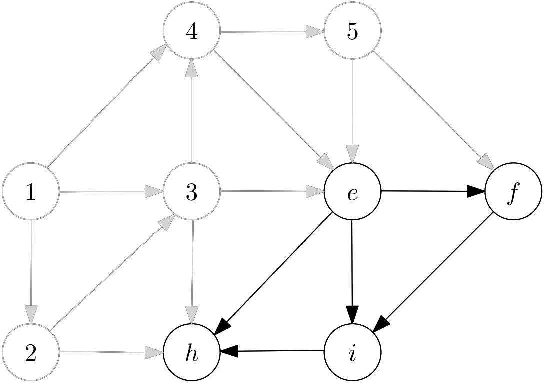

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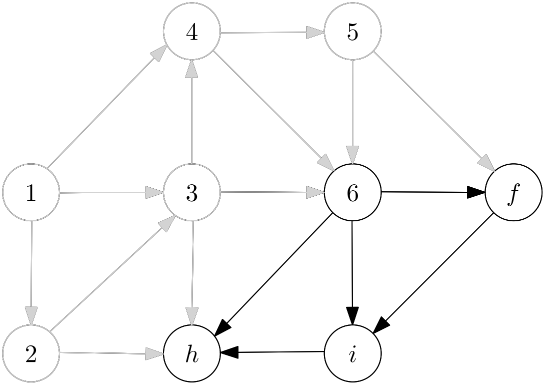

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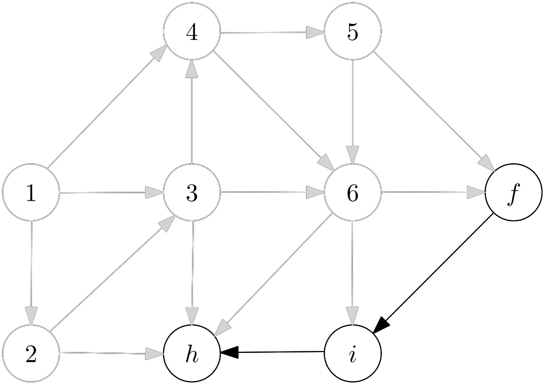

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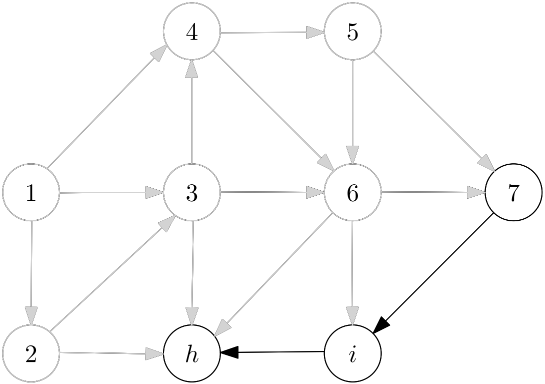

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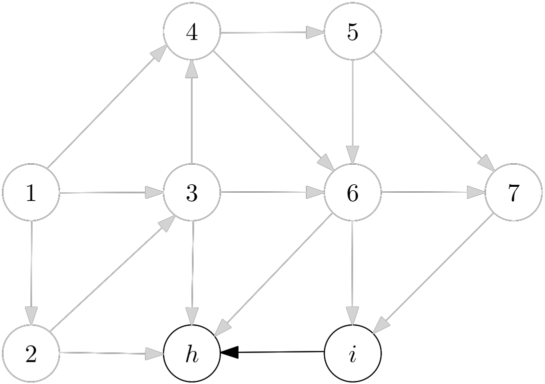

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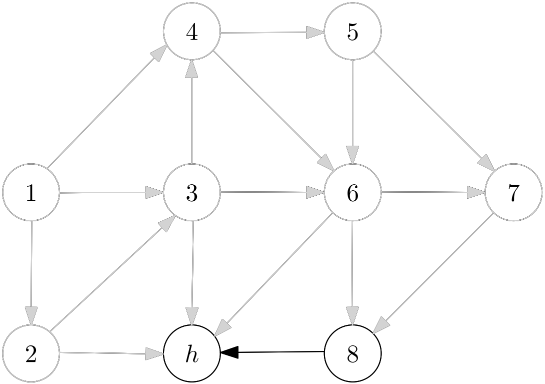

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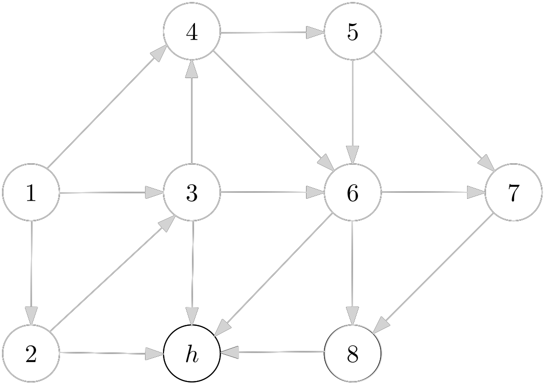

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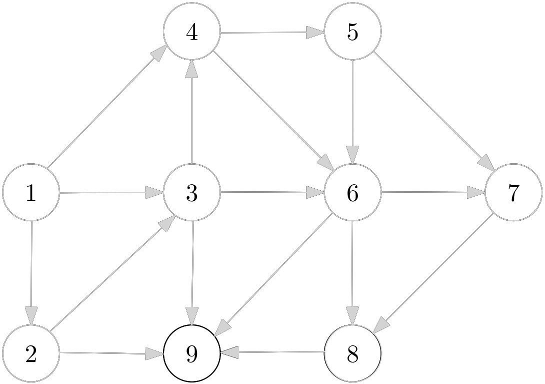

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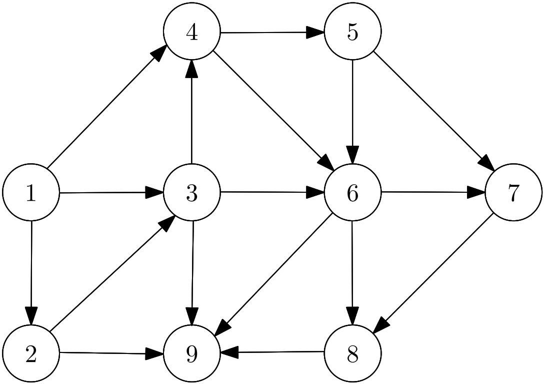

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Q: How to make the algorithm as efficient as possible?

Topological Ordering

- Algorithm: each time take a vertex without incoming edges, then remove the vertex and all its outgoing edges.

Q: How to make the algorithm as efficient as possible?

A:

- Use linked-lists of outgoing edges
- Maintain the in-degree d_v of vertices
- Maintain a queue (or stack) of vertices v with $d_v = 0$

topological-sort(G)

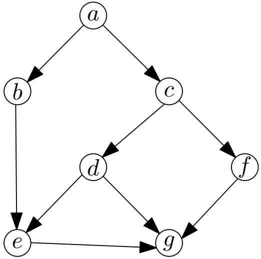
let $d_v \leftarrow 0$ for every $v \in V$
for every $v \in V$ **do**
    for every u such that $(v, u) \in E$ **do**
        $d_u \leftarrow d_u + 1$
$S \leftarrow \{v : d_v = 0\}, i \leftarrow 0$
while $S \neq \emptyset$ **do**
    $v \leftarrow$ arbitrary vertex in S, $S \leftarrow S \setminus \{v\}$
    $i \leftarrow i + 1$, $\pi(v) \leftarrow i$
    for every u such that $(v, u) \in E$ **do**
        $d_u \leftarrow d_u - 1$
        if $d_u = 0$ **then** add u to S
if $i < n$ then output "not a DAG"

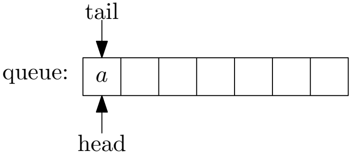
- S can be represented using a queue or a stack
- Running time $= O(n + m)$

S as a Queue or a Stack

DS	Queue	Stack
Initialization	$head \leftarrow 1$, $tail \leftarrow 0$	$top \leftarrow 0$
Non-Empty?	$head \leq tail$	$top > 0$
Add(v)	$tail \leftarrow tail + 1$ $S[tail] \leftarrow v$	$top \leftarrow top + 1$ $S[top] \leftarrow v$
Retrieve v	$v \leftarrow S[head]$ $head \leftarrow head + 1$	$v \leftarrow S[top]$ $top \leftarrow top - 1$

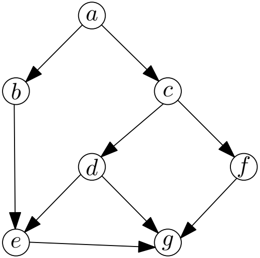
Example

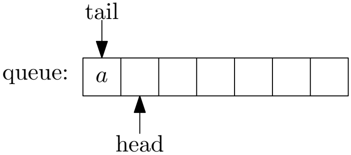




	a	b	c	d	e	f	g
degree	0	1	1	1	2	1	3

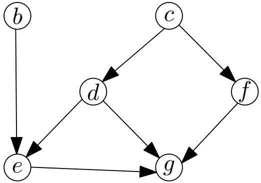
Example

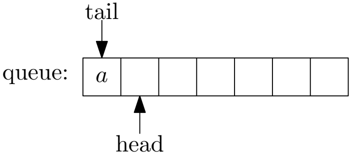




	a	b	c	d	e	f	g
degree	0	1	1	1	2	1	3

Example





	a	b	c	d	e	f	g
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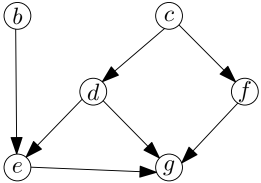
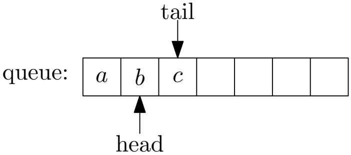
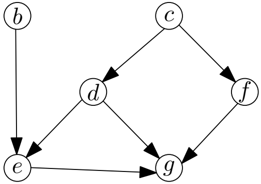
Example

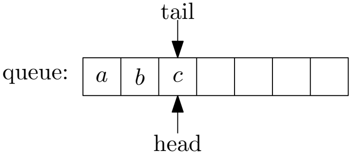




	a	b	c	d	e	f	g
degree	0	0	0	1	2	1	3

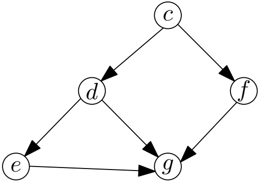
Example

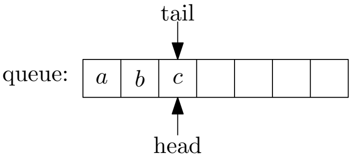




	a	b	c	d	e	f	g
degree	0	0	0	1	2	1	3

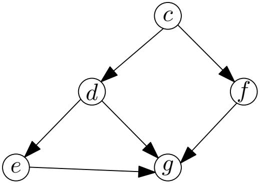
Example

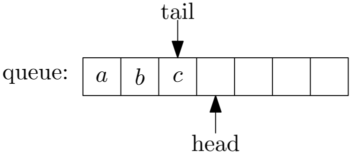




	a	b	c	d	e	f	g
degree	0	0	0	1	1	1	3

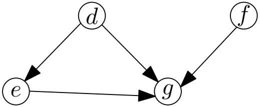
Example





	a	b	c	d	e	f	g
degree	0	0	0	1	1	1	3

Example



tail

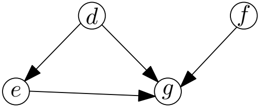
queue:

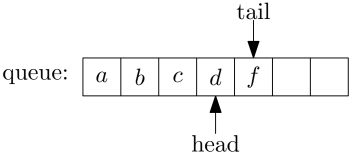
a	b	c				

head

	a	b	c	d	e	f	g
degree	0	0	0	0	1	0	3

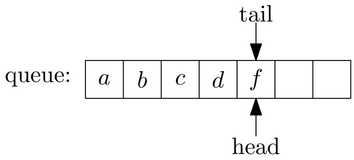
Example

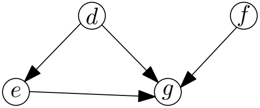




	a	b	c	d	e	f	g
degree	0	0	0	0	1	0	3

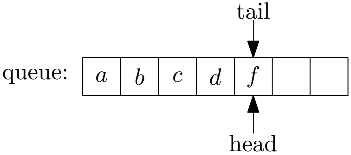
Example



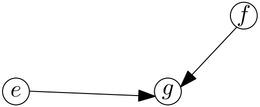


	a	b	c	d	e	f	g
degree	0	0	0	0	1	0	3

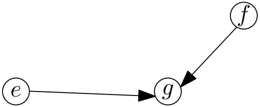
Example

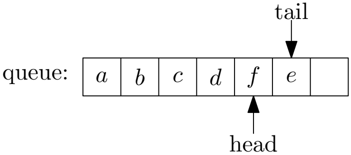


	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	2



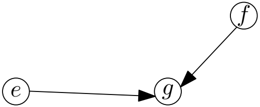
Example

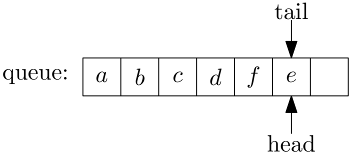




	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	2

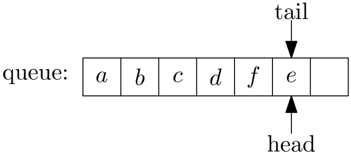
Example





	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	2

Example



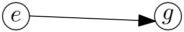
	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	1

Example

tail

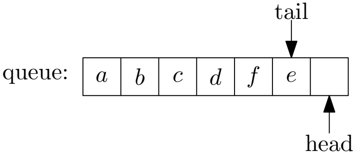
queue:	a	b	c	d	f	e	

head



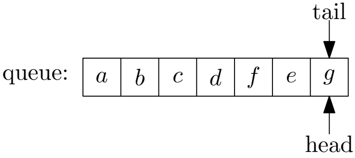
	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	1

Example



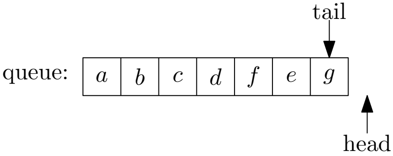
	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	0

Example



	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	0

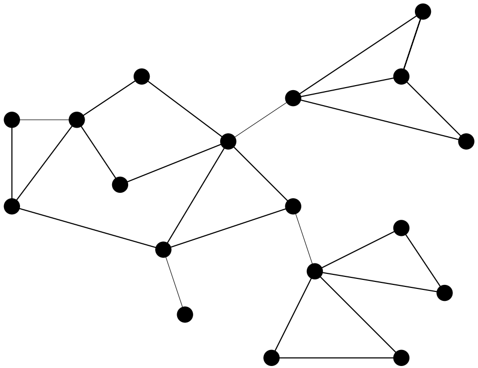
Example



	a	b	c	d	e	f	g
degree	0	0	0	0	0	0	0

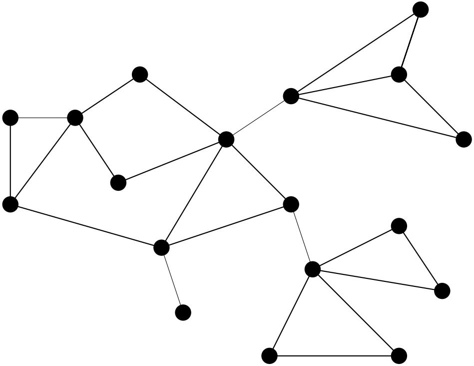
Outline

Def. Given $G = (V, E)$, $e \in E$ is called a bridge if the removal of e from G will increase its number of connected components.



Def. Given $G = (V, E)$, $e \in E$ is called a bridge if the removal of e from G will increase its number of connected components.

- When G is connected, $e \in E$ is a bridge iff its removal will disconnect G.



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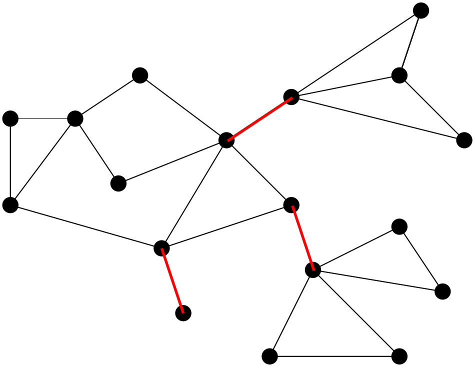

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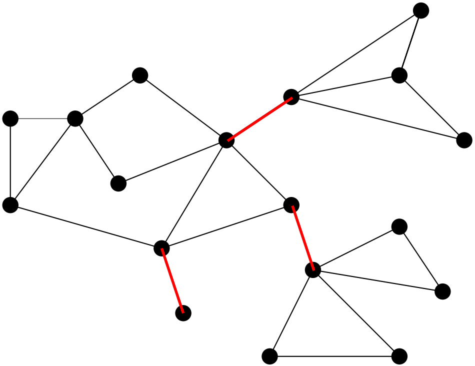

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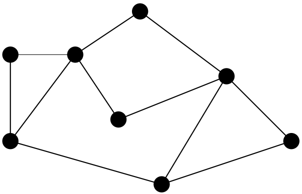

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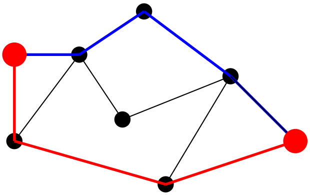

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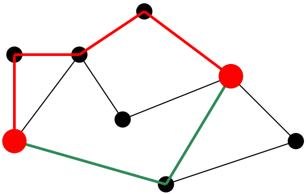

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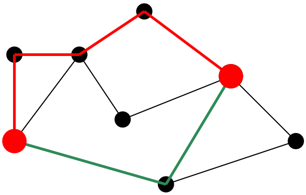

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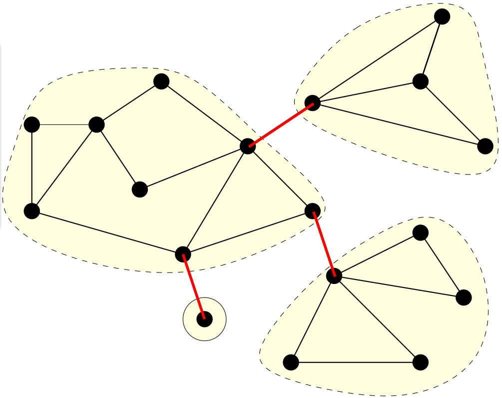

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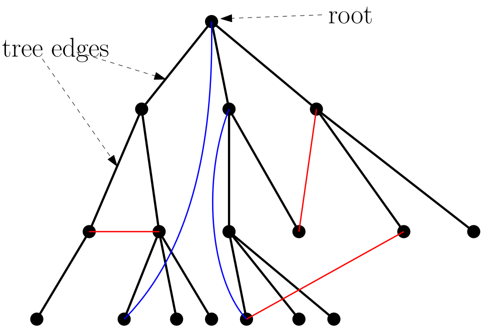
Outline

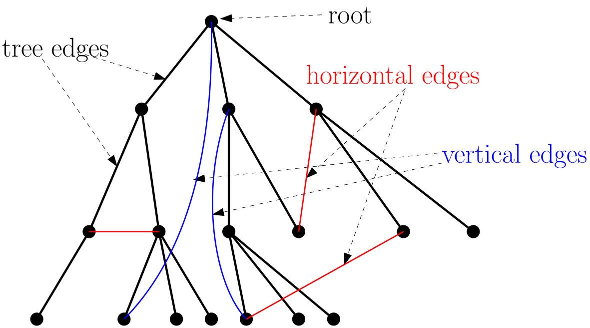
Vertical and Horizontal Edges

- $G = (V, E)$: connected graph
- $T = (V, E_T)$: rooted spanning tree of G

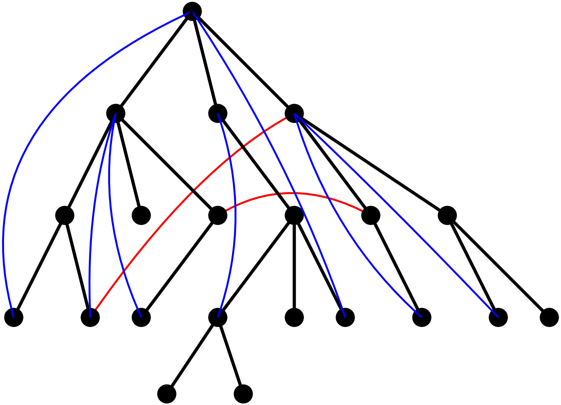


Vertical and Horizontal Edges

- $G = (V, E)$: connected graph
- $T = (V, E_T)$: rooted spanning tree of G
- $(u, v) \in E \setminus E_T$ is
  - vertical if one of u and v is an ancestor of the other in T,
  - horizontal otherwise.

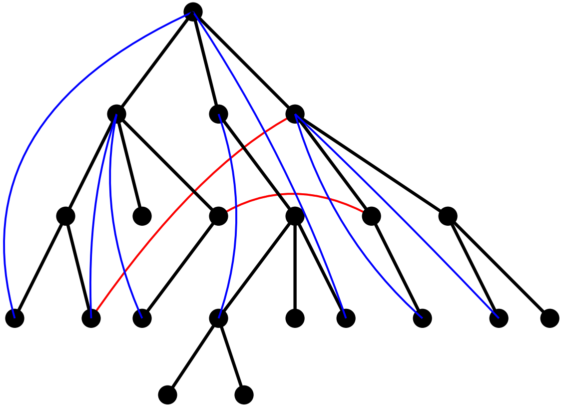


- $G = (V, E)$: connected graph T: a DFS tree for G



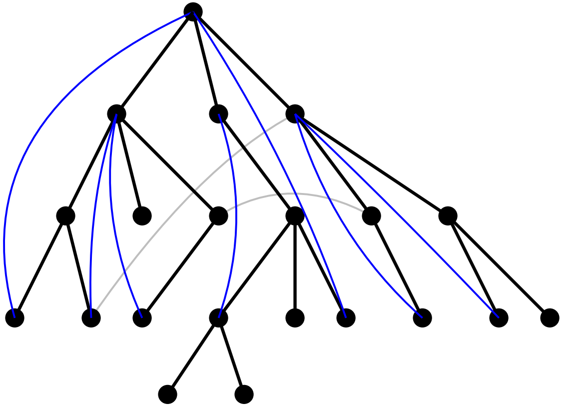
- $G = (V, E)$: connected graph

T: a DFS tree for G



Q: Can there be a horizontal edges (u, v) w.r.t T?

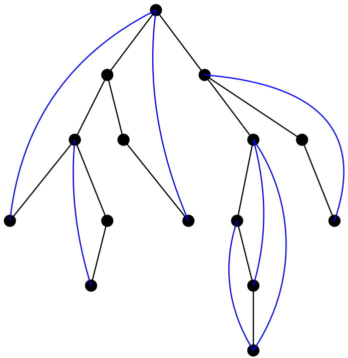
- $G = (V, E)$: connected graph T: a DFS tree for G



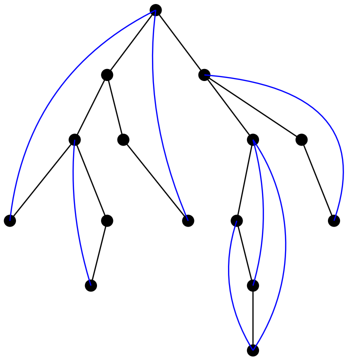
Q: Can there be a horizontal edges (u, v) w.r.t T?

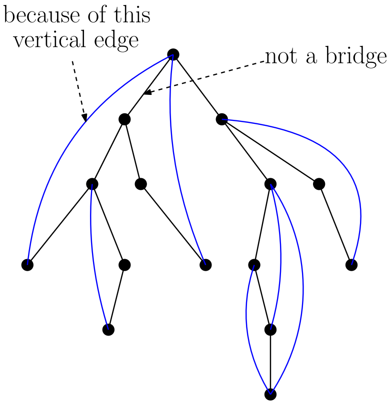
A: No!

- $G = (V, E)$: connected graph
- T: a DFS tree for G
- G contains only tree and vertical edges



- $G = (V, E)$: connected graph
- T: a DFS tree for G
- G contains only tree and vertical edges
- vertical edges: not bridges





- $G = (V, E)$: connected graph
- T: a DFS tree for G
- G contains only tree and vertical edges
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Lemma

- $(u, v) \in T$, u is parent
- (u, v) is not a bridge $\iff \exists$ vertical edge connecting an (inclusive) descendant of v and an (inclusive) ancestor of u

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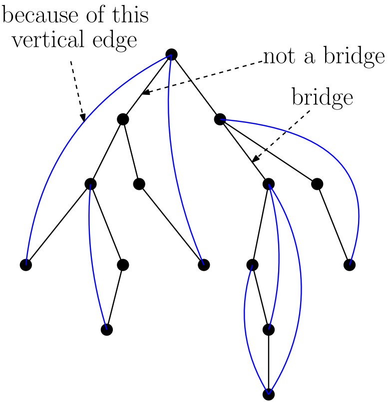

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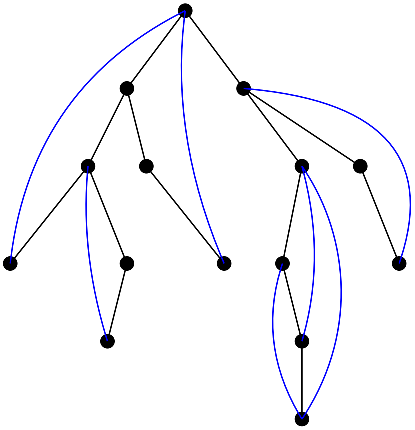
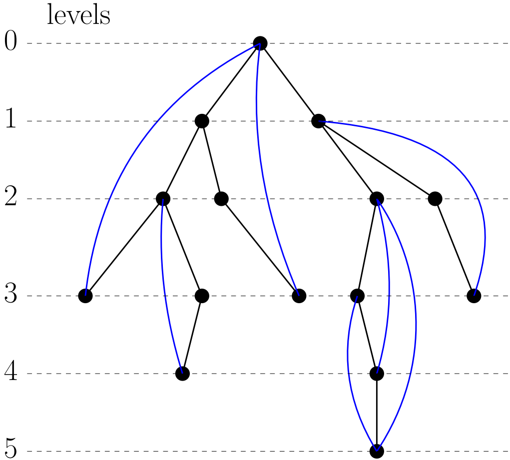
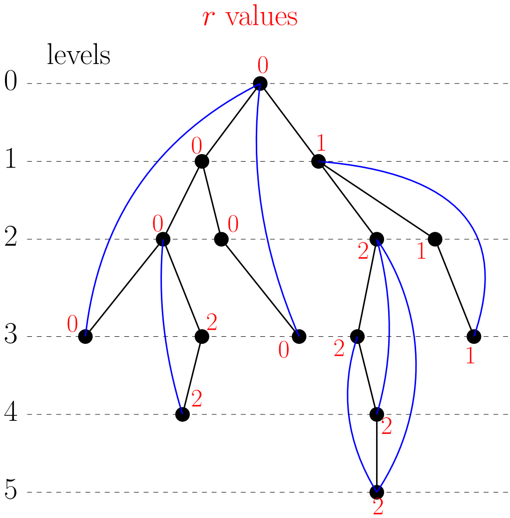


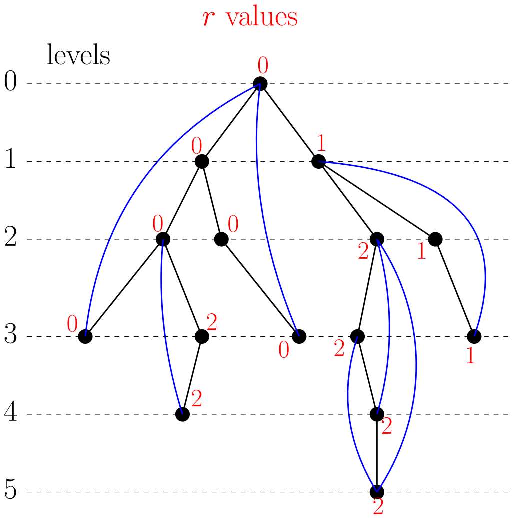
- $v.l$: the level of vertex v in DFS tree



- $v.l$: the level of vertex v in DFS tree
- T_v: subtree rooted at v
- $v.r$: the smallest level that can be reached by a vertical edge from T_v



- $v.l$: the level of vertex v in DFS tree
- T_v: subtree rooted at v
- $v.r$: the smallest level that can be reached by a vertical edge from T_v
- $(parent(u), u)$ is a bridge if and only if $u.r \geq u.l$.



recursive-DFS(v)

mark v as "visited"
$v.r \leftarrow \infty$
for all neighbours u of v **do**
    if u is unvisited **then** ▷ u is a child of v
        $u.l \leftarrow v.l + 1$
        recursive-DFS(u)
        if $u.r \geq u.l$ **then** claim (v, u) is a bridge
        if $u.r < v.r$ **then** $v.r \leftarrow u.r$
    else if $u.l < v.l - 1$ **then** ▷ u is ancestor but not parent
        if $u.l < v.r$ **then** $v.r \leftarrow u.l$

finding-bridges

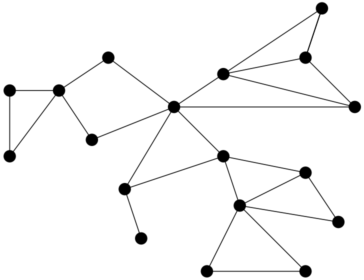
```
mark all vertices as "unvisited"
for every v ∈ V do
    if v is unvisited then
        v.l ← 0
        recursive-DFS(v)
```

- Running time: $O(n+m)$

Outline

Cut vertices

Def. A vertex is a cut vertex of $G = (V, E)$ if its removal will increase the number of connected components of G.



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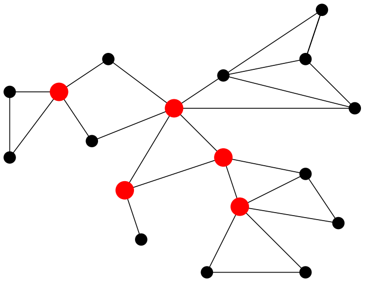

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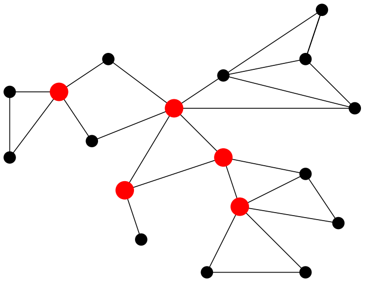
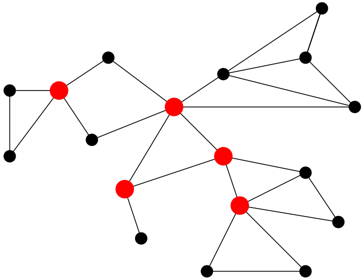
Def. A graph $G = (V, E)$ is 2-(vertex-)connected (or biconnected) if for every $u, v \in V$, there are 2 internally-disjoint paths between u and v.

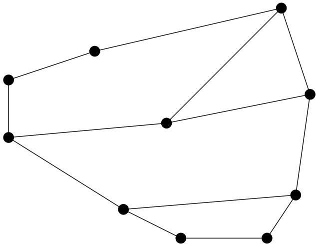


Cut vertices

Def. A vertex is a cut vertex of $G = (V, E)$ if its removal will increase the number of connected components of G.

Def. A graph $G = (V, E)$ is 2-(vertex-)connected (or biconnected) if for every $u, v \in V$, there are 2 internally-disjoint paths between u and v.





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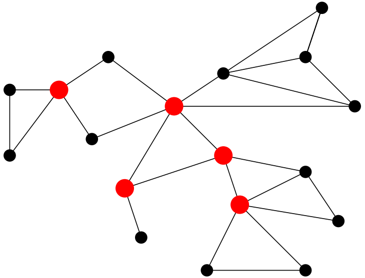

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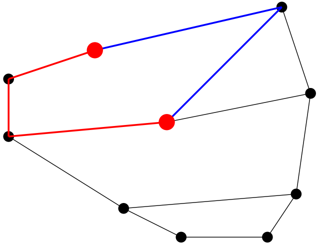

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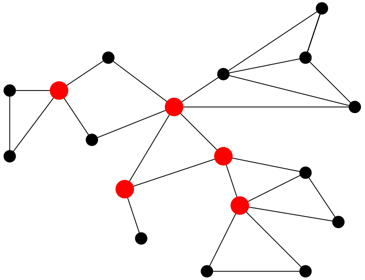

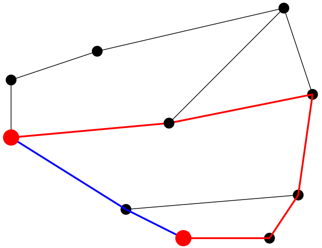

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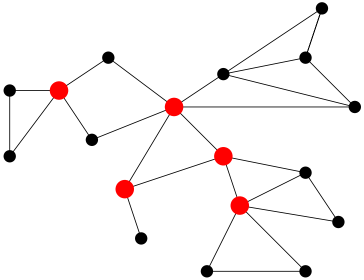
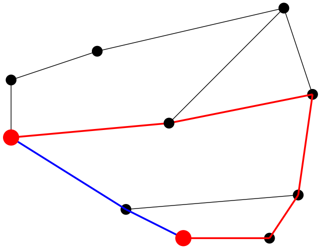
Lemma A graph $G = (V, E)$ with $|V| \geq 3$ does not contain a cut vertex, if and only if it is biconnected.





Q: How can we find the cut vertices?

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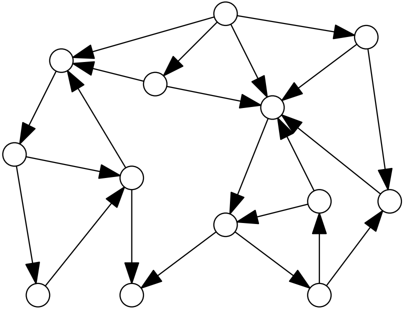
A: With a small modification to the algorithm for finding bridges.

Outline

- directed graph $G = (V, E)$.



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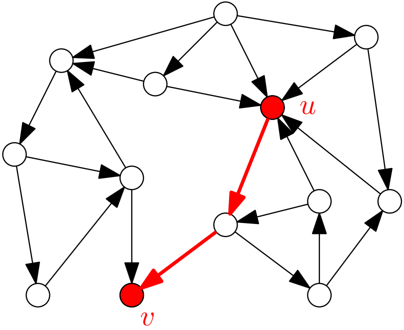

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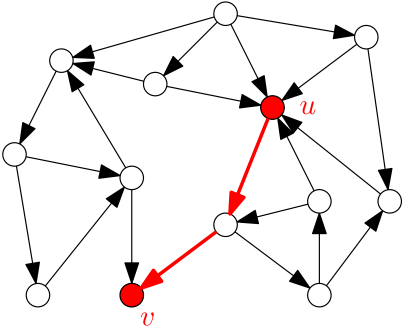

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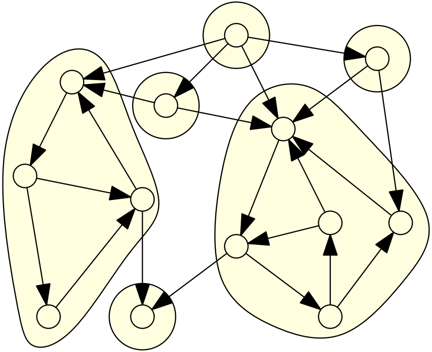
Def. A strongly connected component (SCC) of a directed graph G is a maximal strongly connected subgraph of G.



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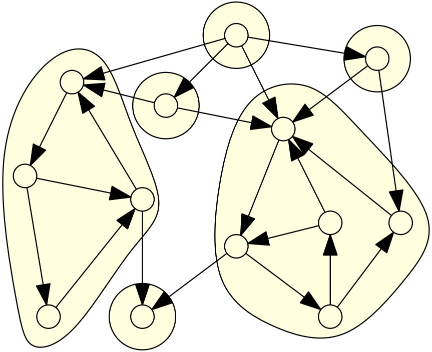

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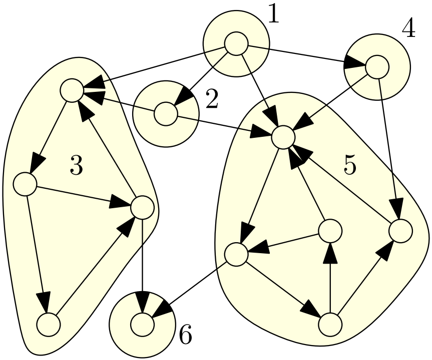

- Define equivalence relation: u and v are related if they are reachable from each other
- equivalence class $\equiv$ SCC
- After contracting each SCC, G becomes a directed-acyclic (multi-)graph (DAG).

Q: How can we check if a directed graph $G = (V, E)$ is strongly-connected?

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A:

- Run a traversal algorithm (either BFS or DFS) from s twice, one on G, one on G with all directions of edges reversed
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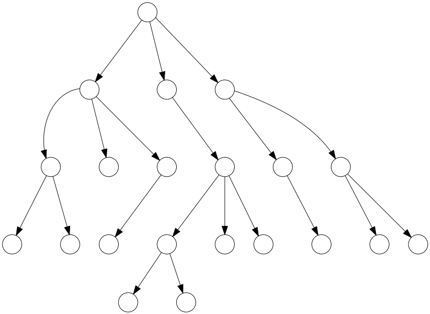
Q: How can we find all strongly-connected components (SCCes) of a directed graph G?

A: A much harder problem. Tarjan's $O(n + m)$-time algorithm.

Outline

Type of Edges w.r.t a Directed DFS Tree

- directed graph, $G = (V, E)$, a DFS-tree T,
- assuming every vertex is reachable from the root of T



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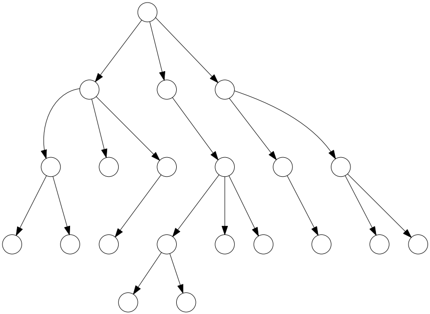

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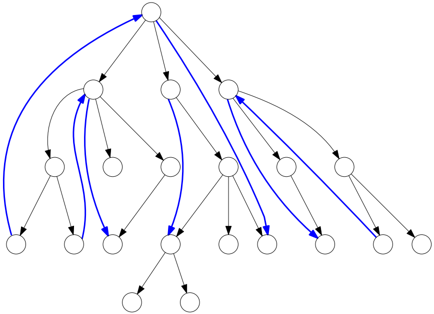

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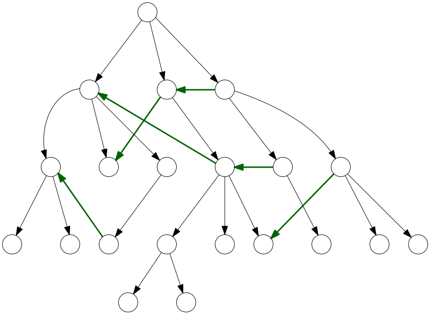

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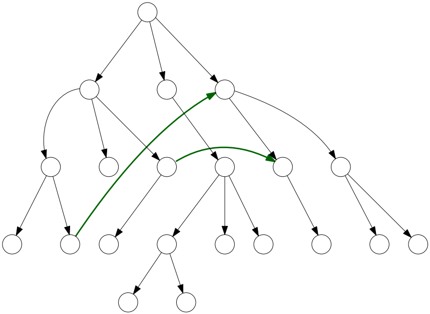

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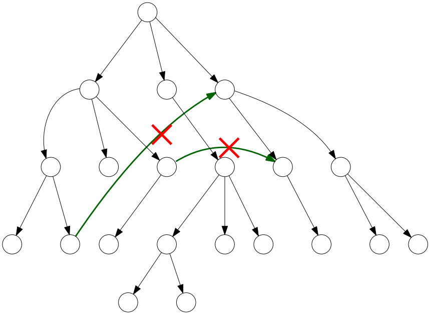

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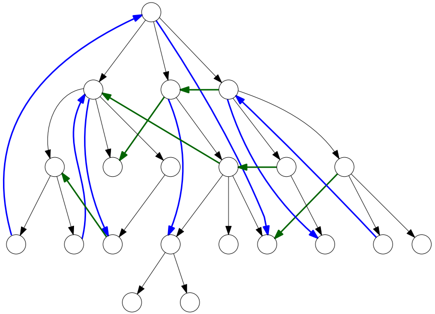

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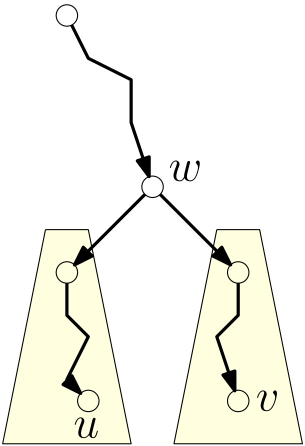
A: No!

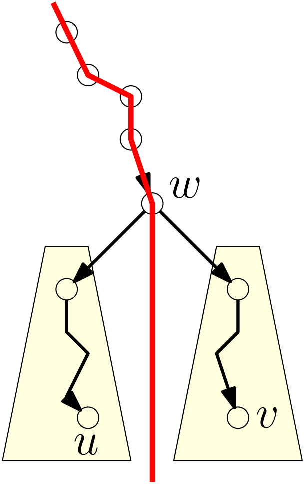
Lemma Suppose u and v are in the same SCC, and w is the lowest common ancestor (LCA) of u and v in T. Then w is the same SCC as u and v.



Lemma Suppose u and v are in the same SCC, and w is the lowest common ancestor (LCA) of u and v in T. Then w is the same SCC as u and v.

Proof.

- Idea: using leftward, upwards and tree edges, u can not reach v without touching w or its ancestors. □



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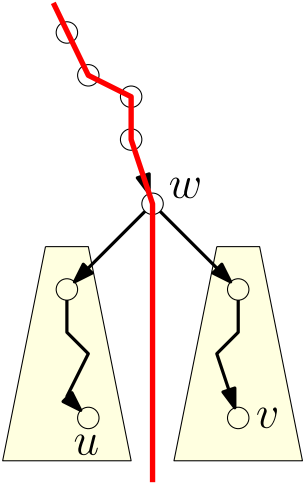

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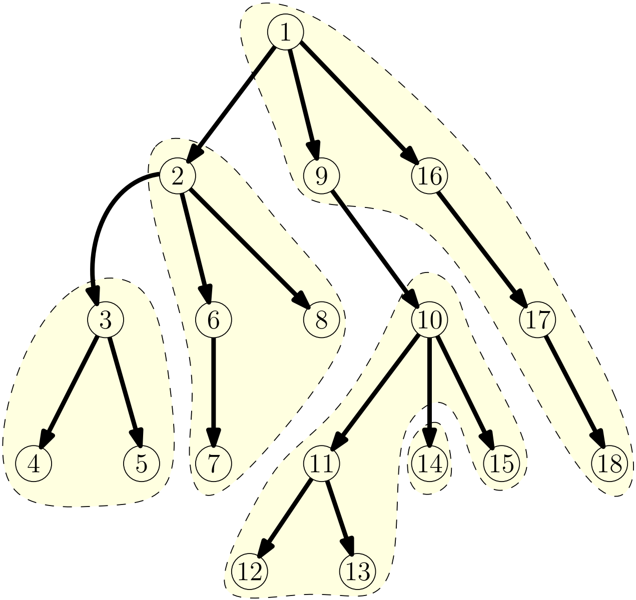
Lemma The vertices in every SCC of G induce a sub-tree in T.


1
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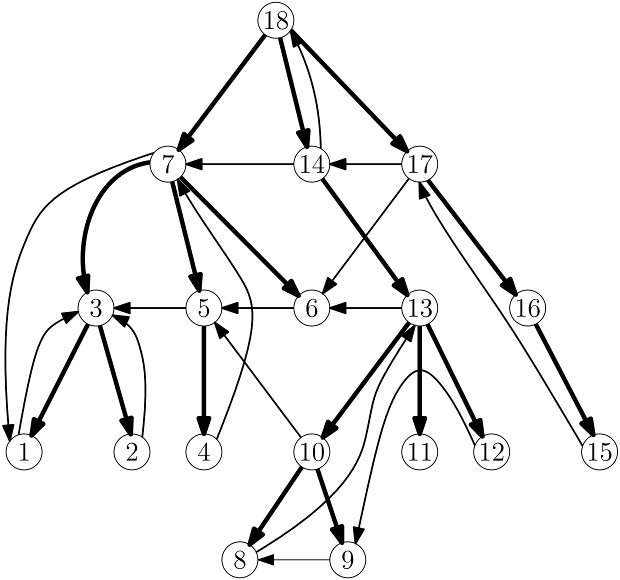
13

An Intermediate Algorithm to Keep in Mind

1: build the DFS tree T
2: **while** T is not empty **do**
3: find the first vertex v in the posterior-order-traversal of T satisfying the following property: there are no edges from T_v to outside T_v
4: claim vertices in T_v as a SCC, remove them from T and all edges incident to them from T and G

Illustration of Intermediate Algorithm



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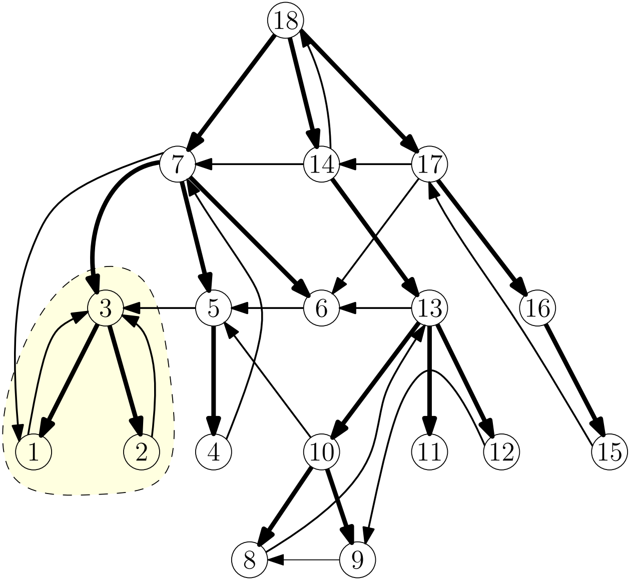

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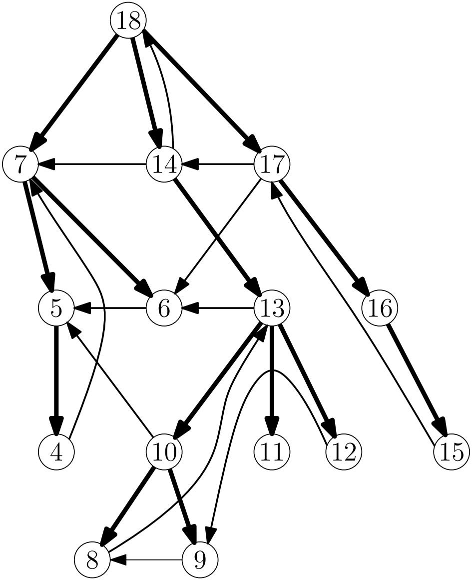

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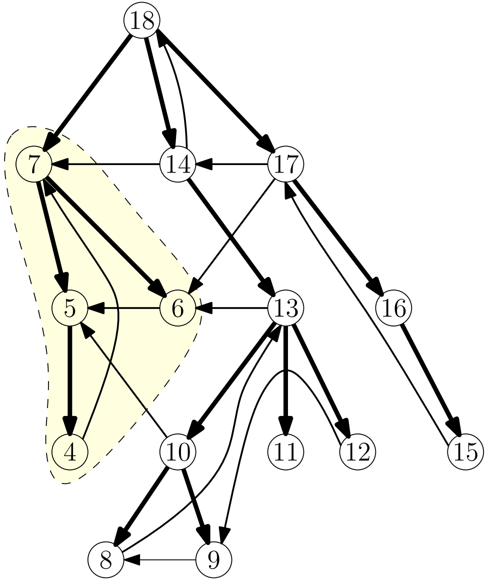

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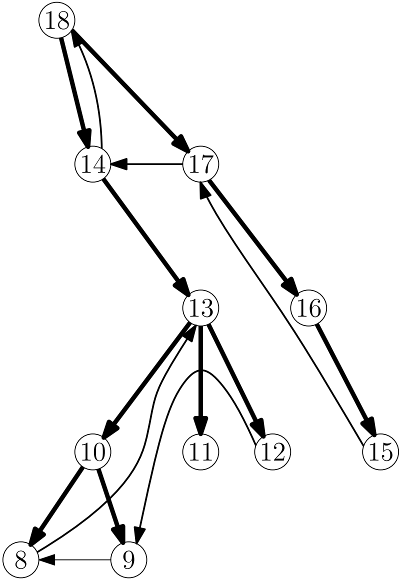

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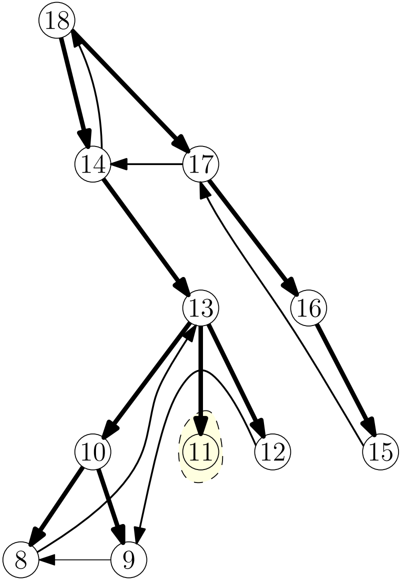

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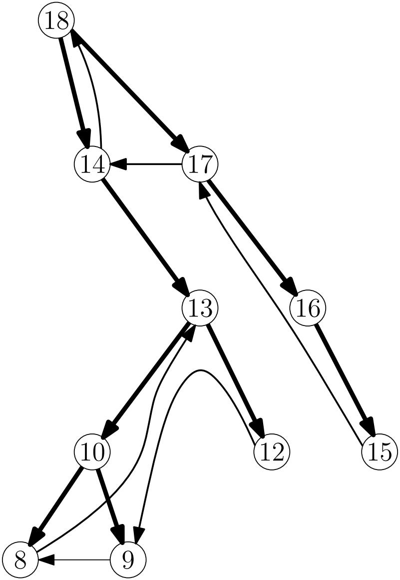

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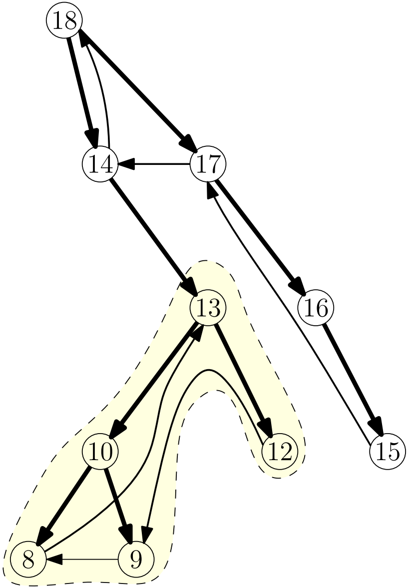

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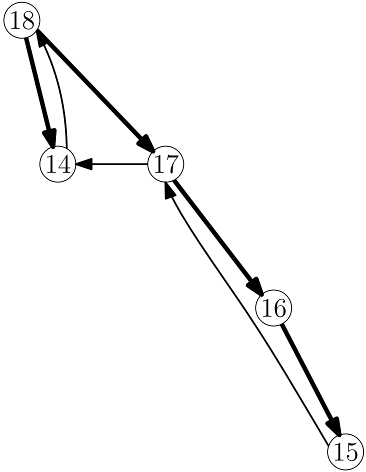

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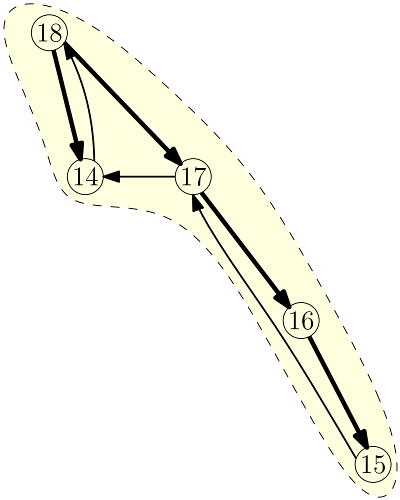

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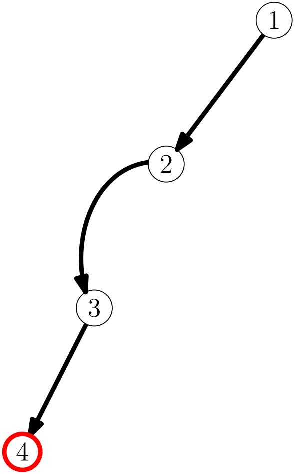

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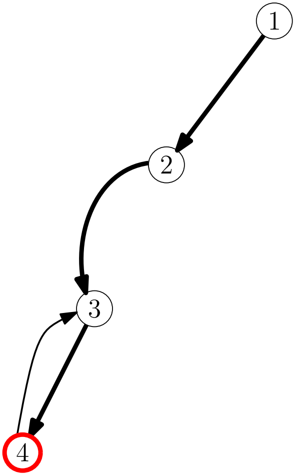

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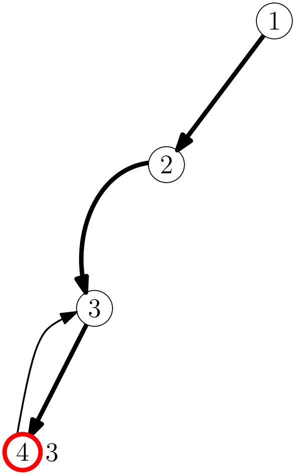

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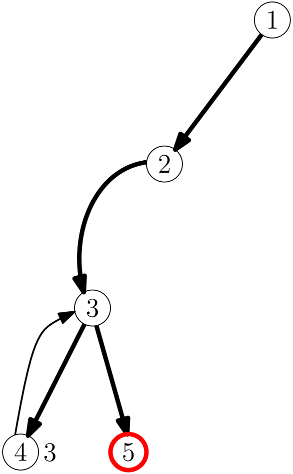

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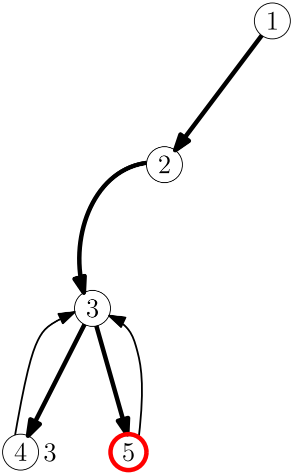

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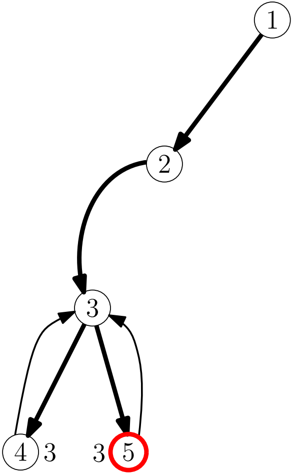

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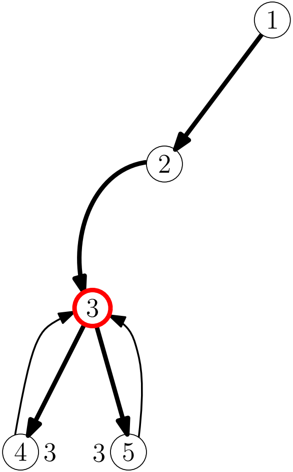

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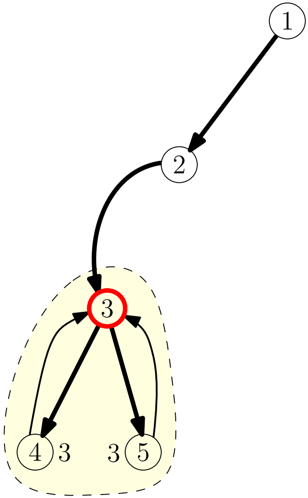

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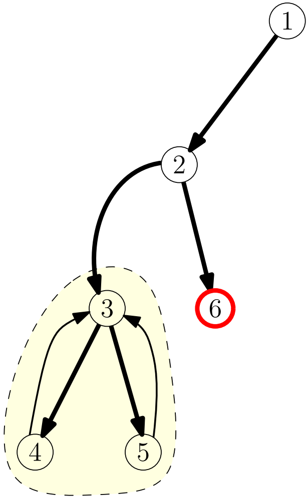

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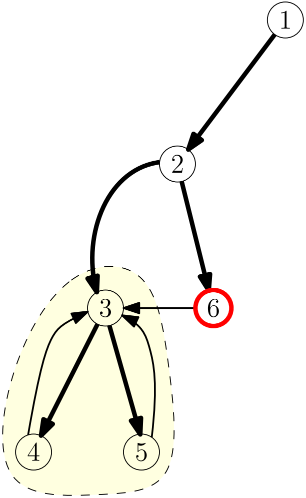

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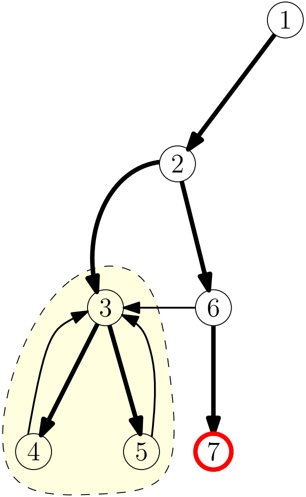

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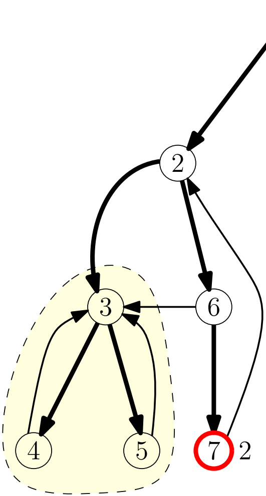

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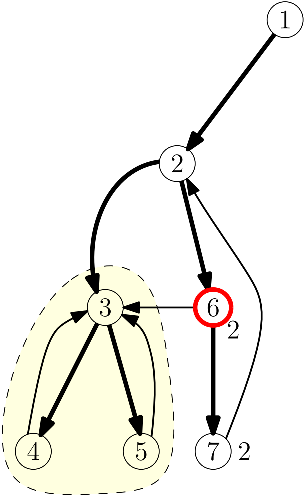

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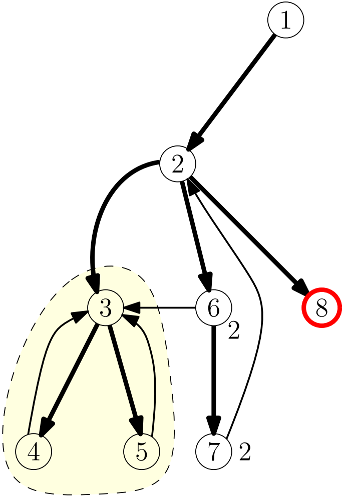

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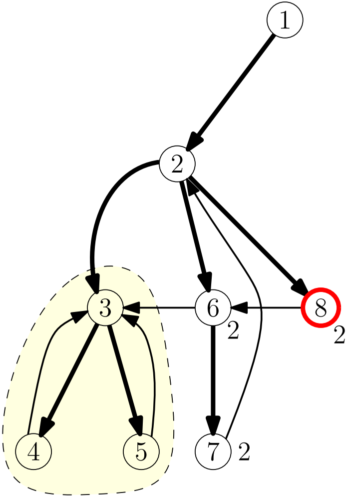

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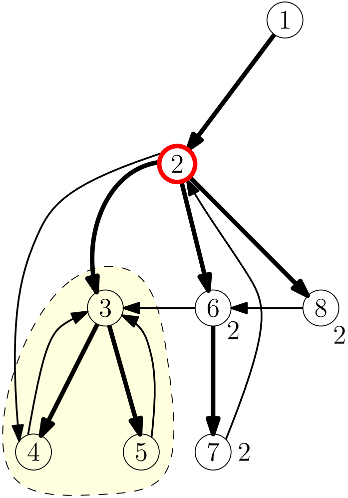

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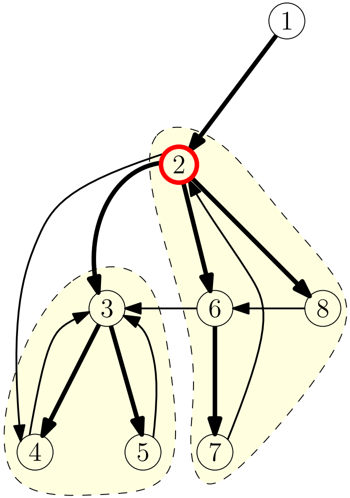

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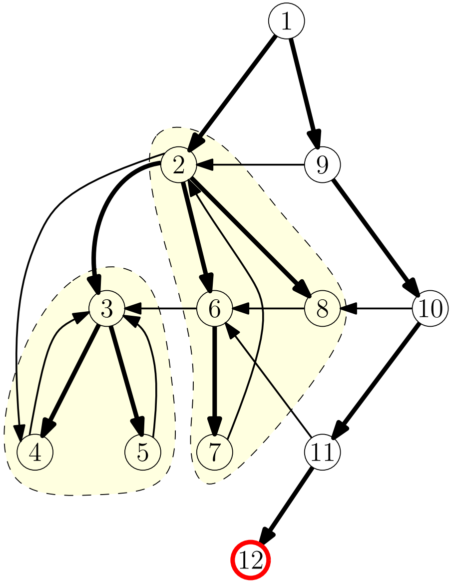

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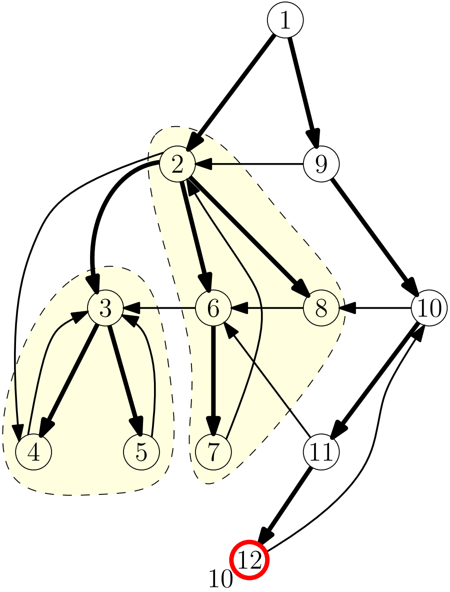

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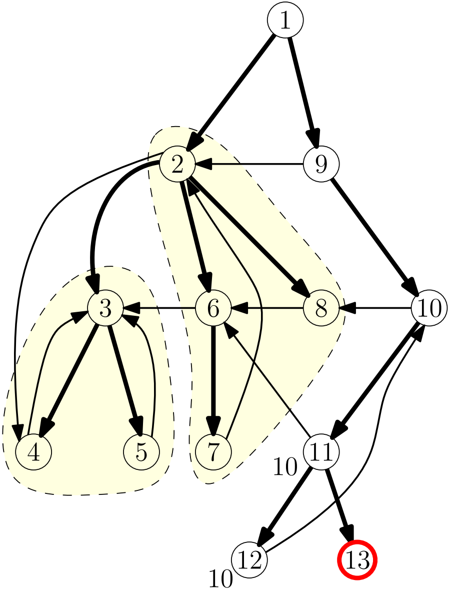

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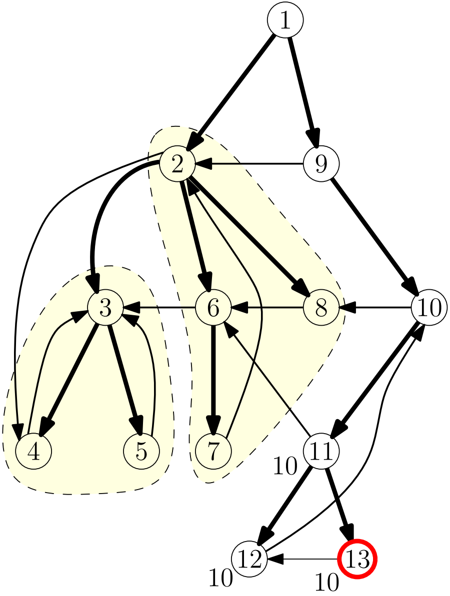

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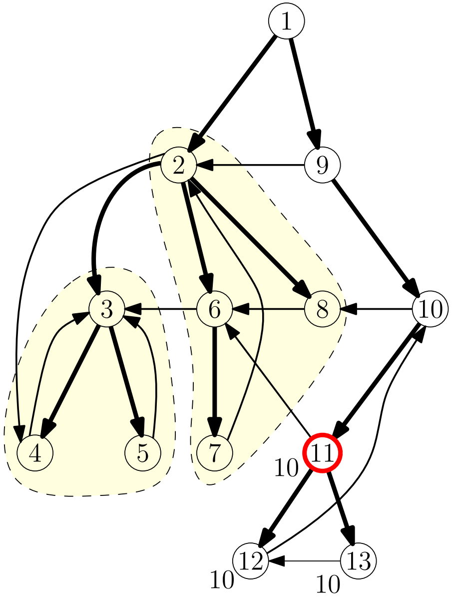

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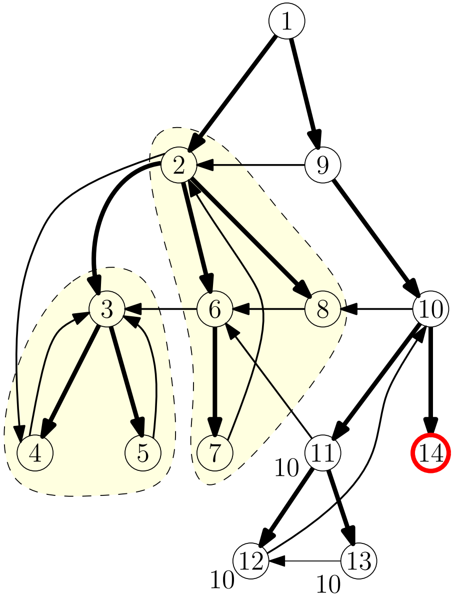

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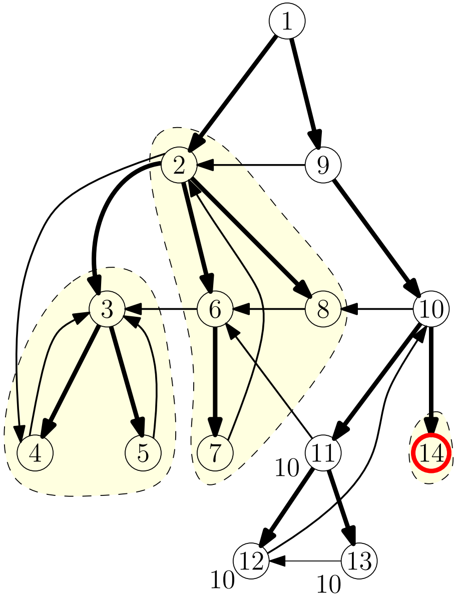

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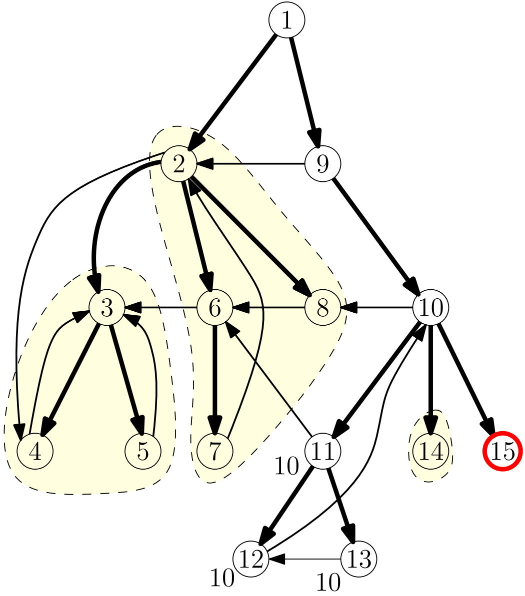

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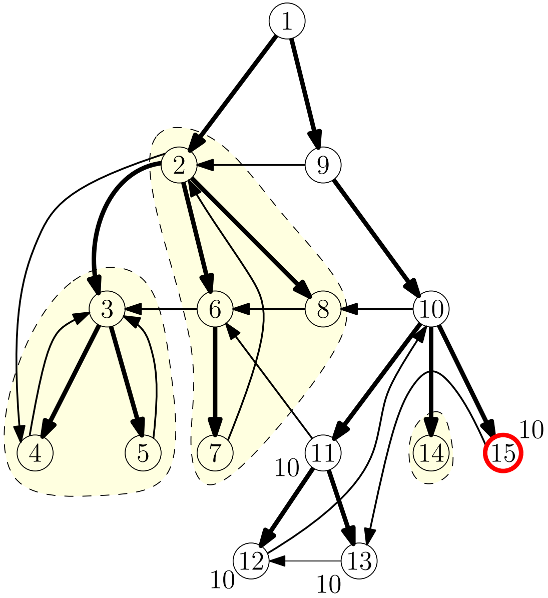

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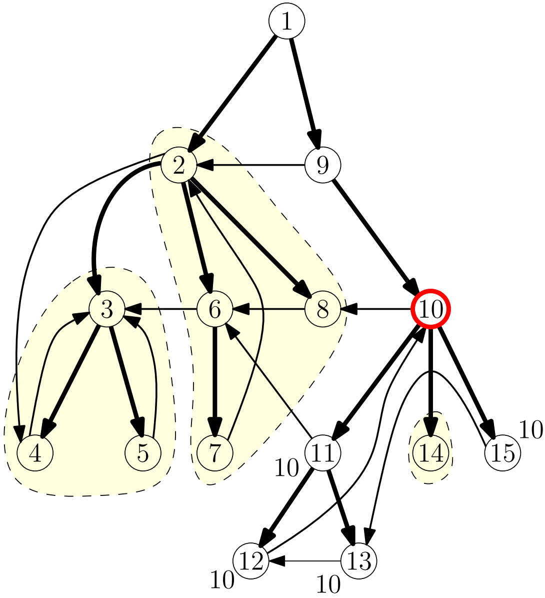

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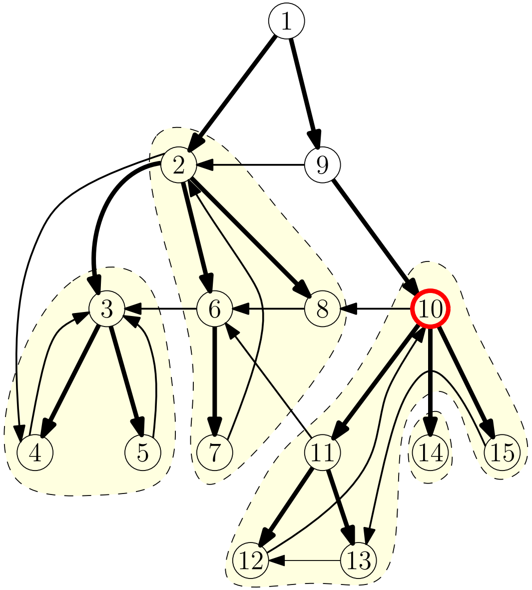

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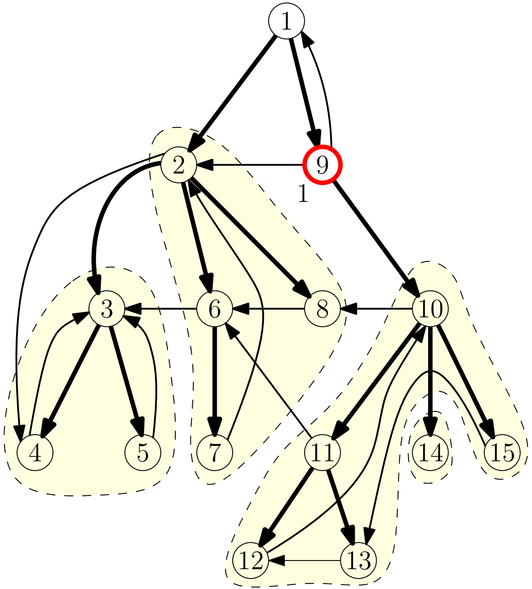

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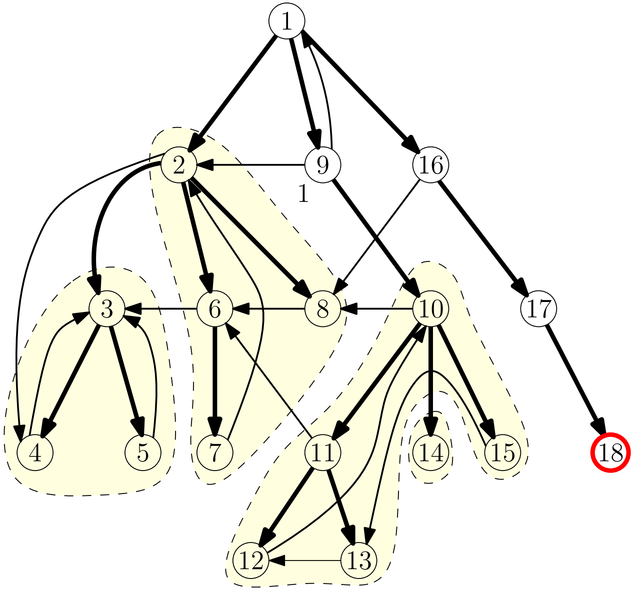

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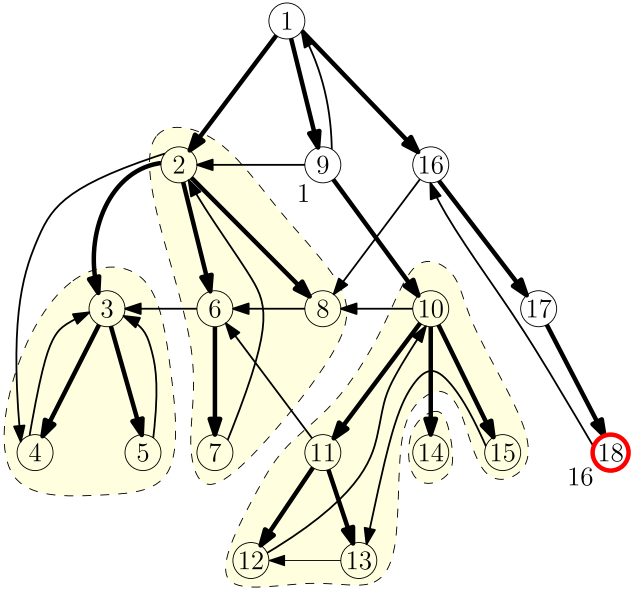

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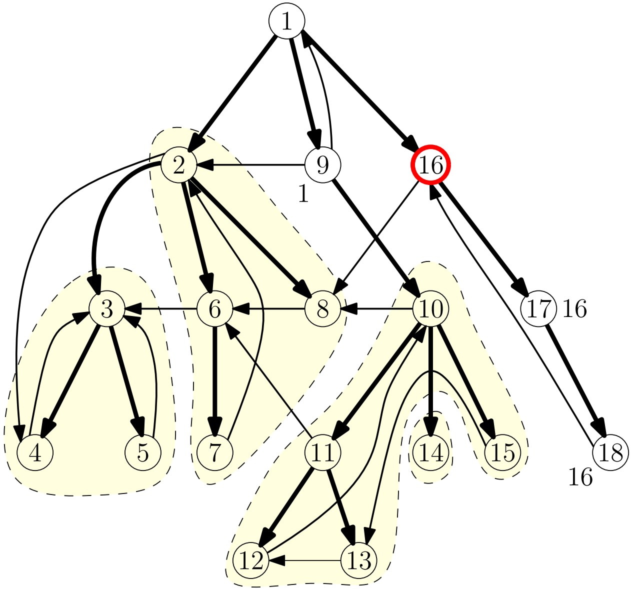

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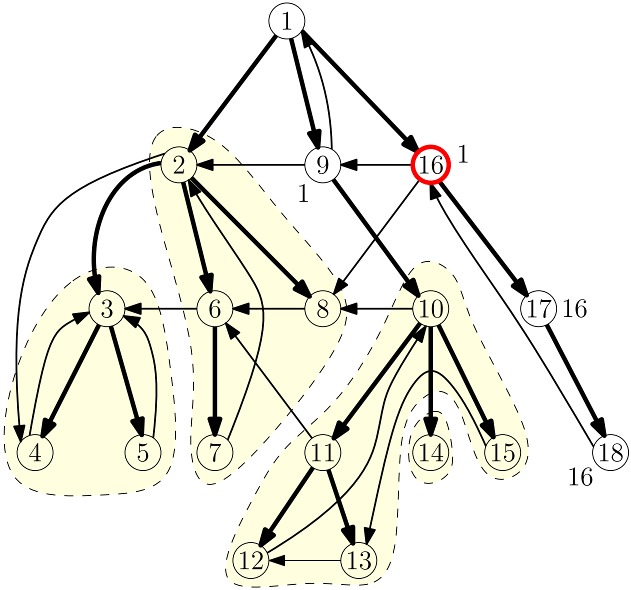

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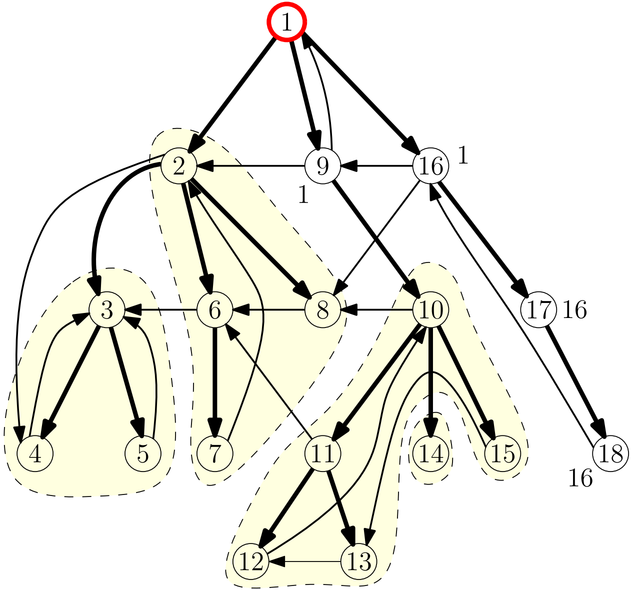

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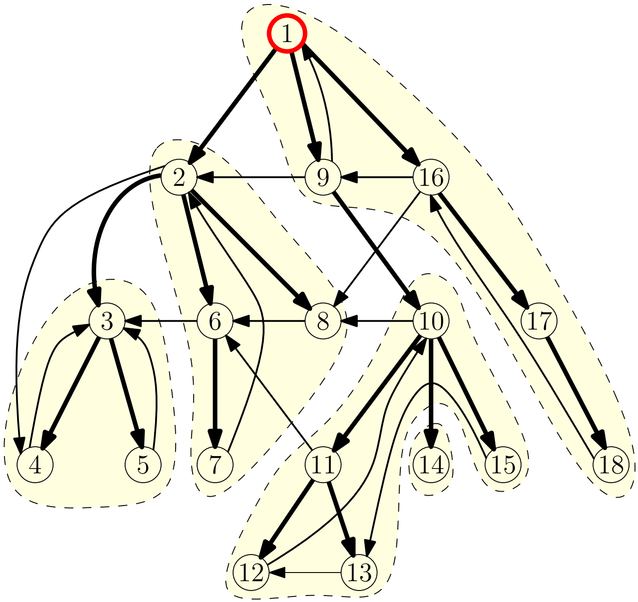

finding strongly connected components

```
statck ← empty stack, i ← 0
for every v ∈ V do: v.i ← ⊥, onstack[i] ← false
for every v ∈ V do
    if v.i = ⊥ then recursive-DFS(v)
```

recursive-DFS(v)

```
i ← i + 1, v.i ← i, v.r ← i
stack.push(v), onstack[v] ← true
for every outgoing edge (v, u) of v do
    if u.i = ⊥ then recursive-DFS(u)
    if onstack[u] and u.r < v.r then v.r ← u.r
if v.r = v.i then
    pop all vertices in stack after v, including v itself
    set onstack of these vertices to be false
    declare that these vertices form an SCC
```

Running time of the algorithm is $O(n + m)$.