COMP2823

Graphs
[GT 13.1-4]

Joachim Gudmundsson
School of Computer Science

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THE UNIVERSITY OF SYDNEY

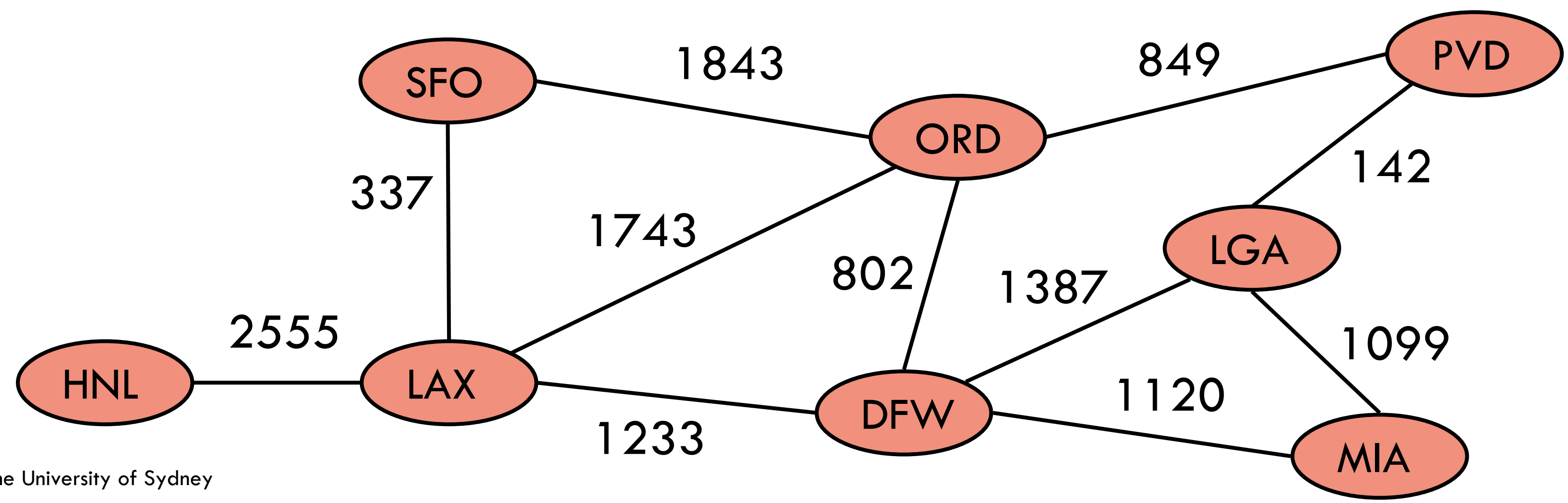
Graphs

A graph **G** is a pair (***V***, ***E***), where

- ***V*** is a set of nodes, called vertices
- ***E*** is a collection of pairs of vertices, called edges

Example:

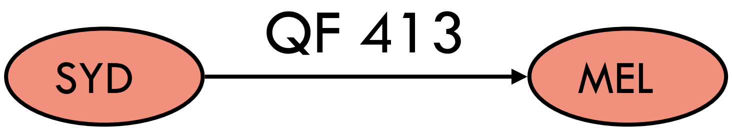
- A vertex represents an airport and stores the three-letter airport code
- An edge represents a flight route between two airports and stores the mileage of the route



Edge Types

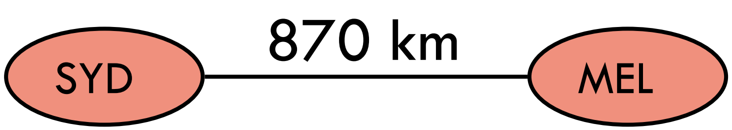
Directed edge

- ordered pair of vertices (u, v)
- u is the origin/tail
- v is the destination/head
- e.g., a flight



Undirected edge

- unordered pair of vertices (u, v)
- e.g., a two-way road



Applications

Electronic circuits

- Printed circuit board
- Integrated circuit

Transportation networks

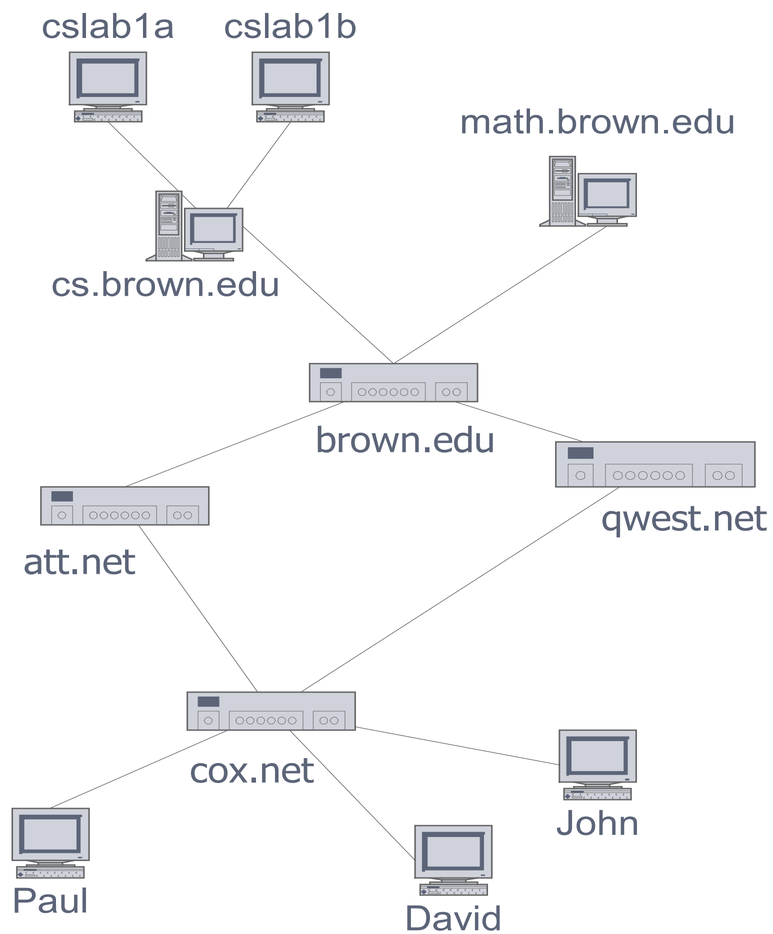
- Highway network
- Flight network

Computer networks

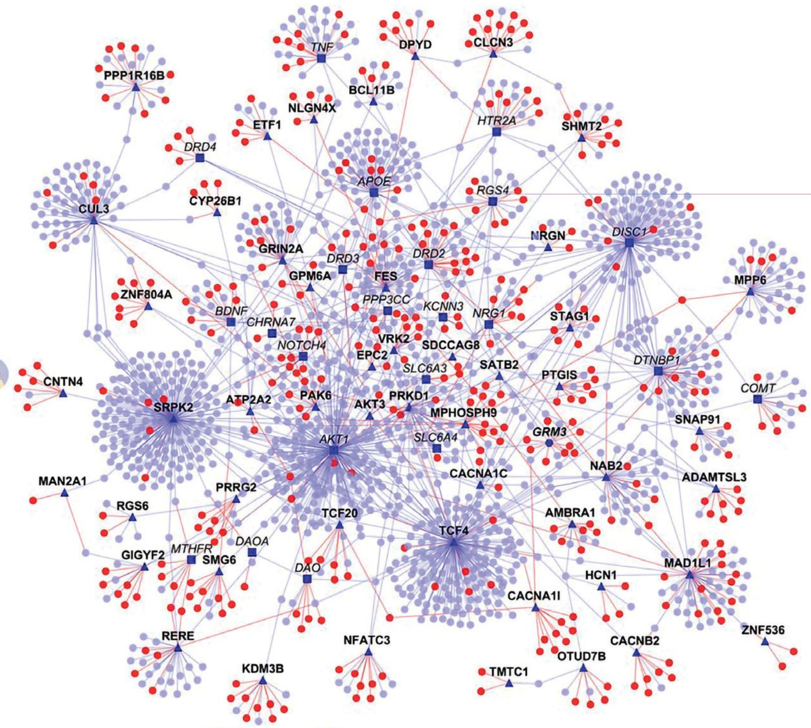
- Internet
- Web

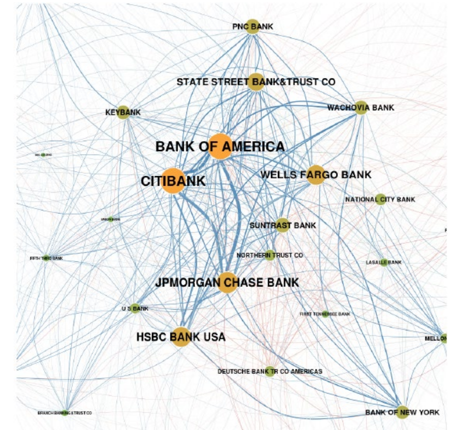
Modeling

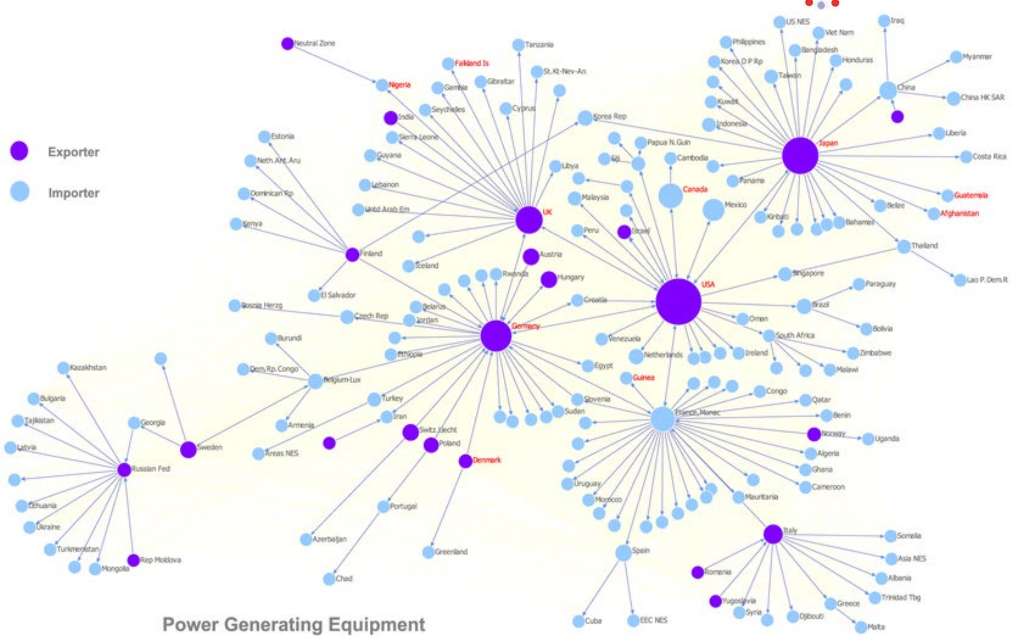
- Entity-relationship diagram
- Gantt precedence constraints

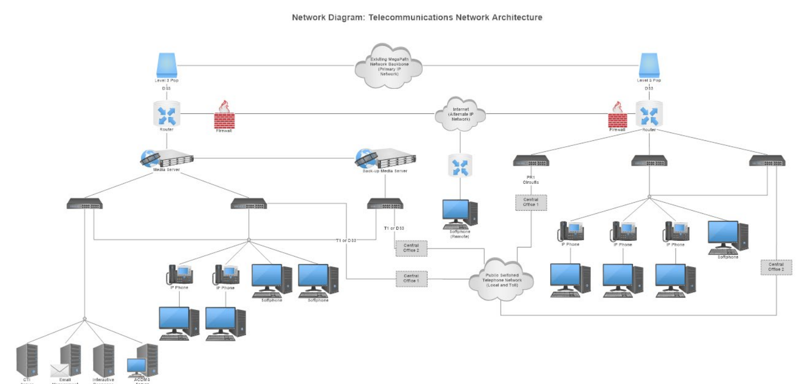


More examples

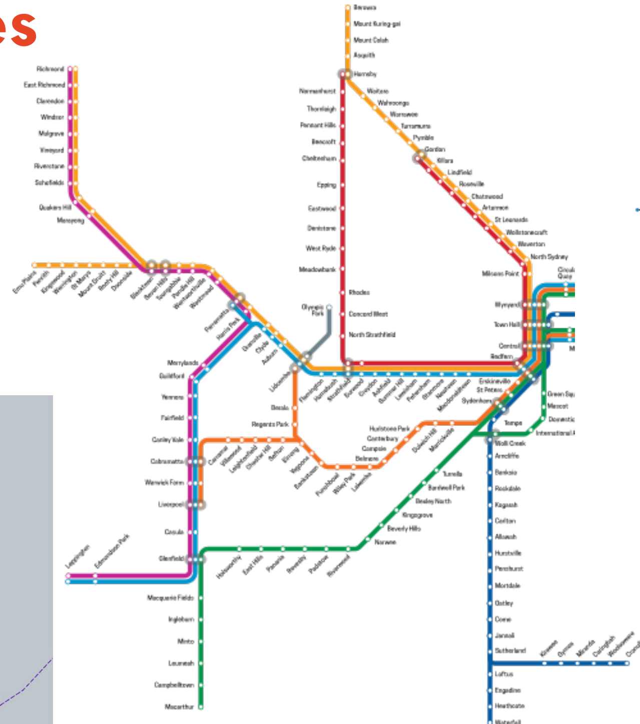




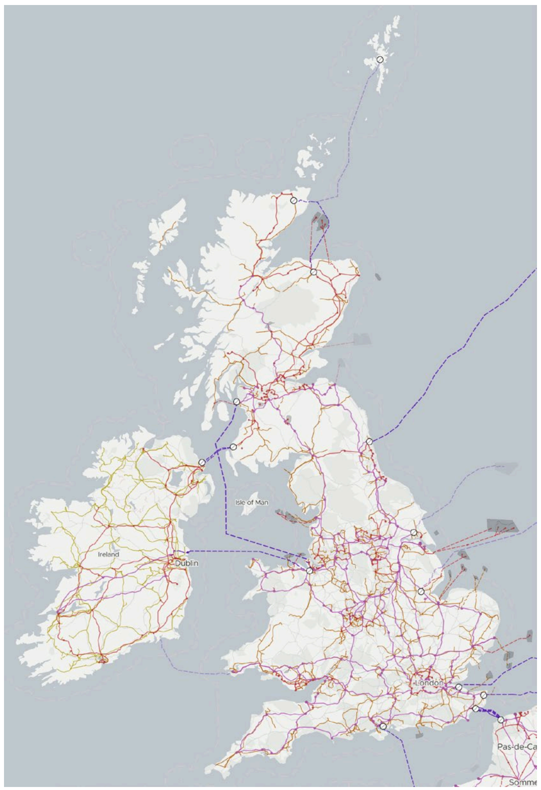


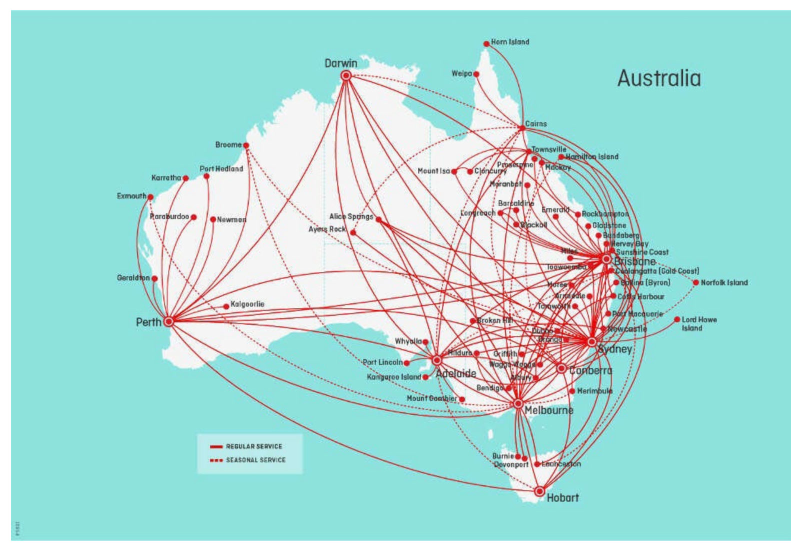


More examples



Cambridge
1521 nodes, 1856 edges





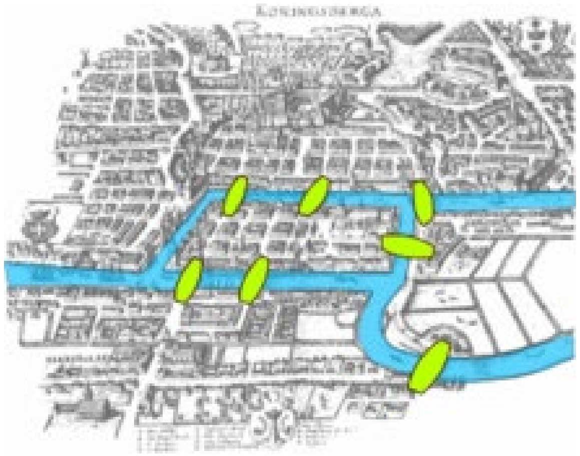
History: Graph theory

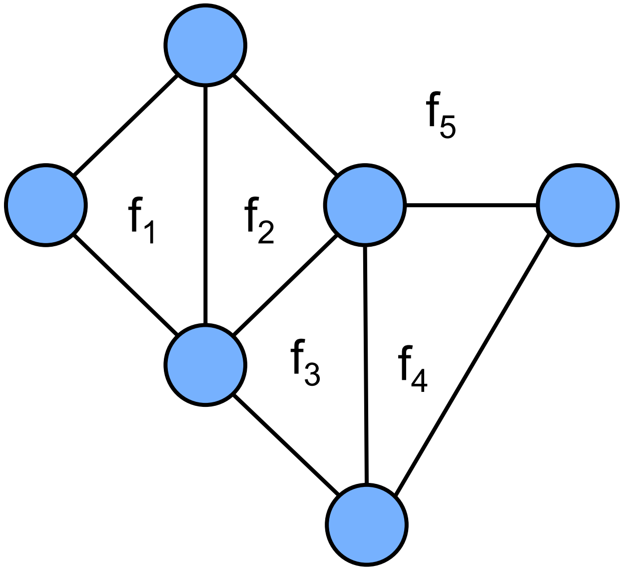
First paper on graph theory in 1736 by Leonhard Euler on the Seven Bridges of Königsberg.

An Eulerian walk exists in the graph if exactly zero or two vertices have odd degree.

In 1758 he showed Euler's characteristics. For planar graphs (non-intersecting edges):

#vertices - #edges + #faces =2





#vertices = 6
#edges = 9
#faces = 5

Graph Concept: Paths

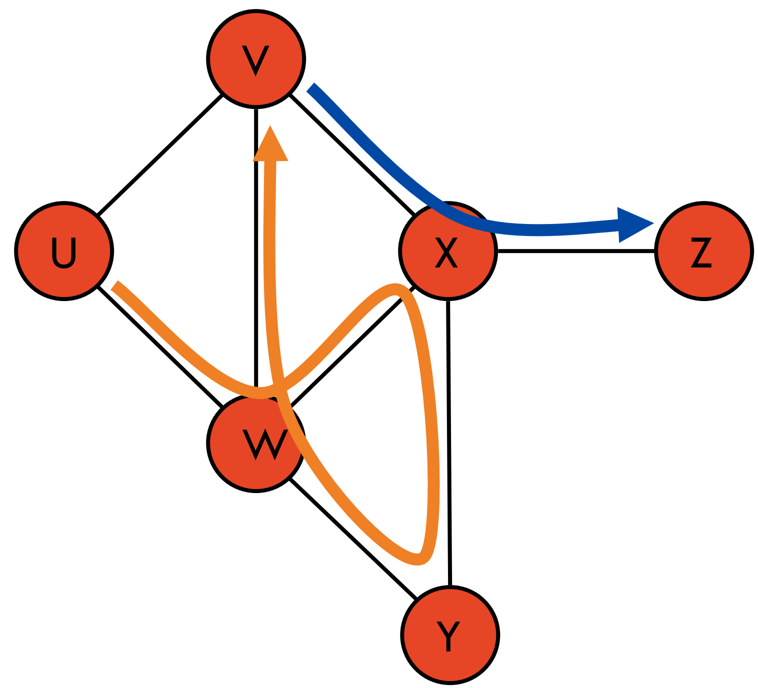
A path is a sequence of vertices such that every pair of consecutive vertices is connected by an edge.

A simple path is one where all vertices are distinct

Examples

- (V, X, Z) is a simple path
- (U, W, X, Y, W, V) is a path that is not simple

A (simple) path from s to t is also called an s-t path.



Graph Concept: Cycle

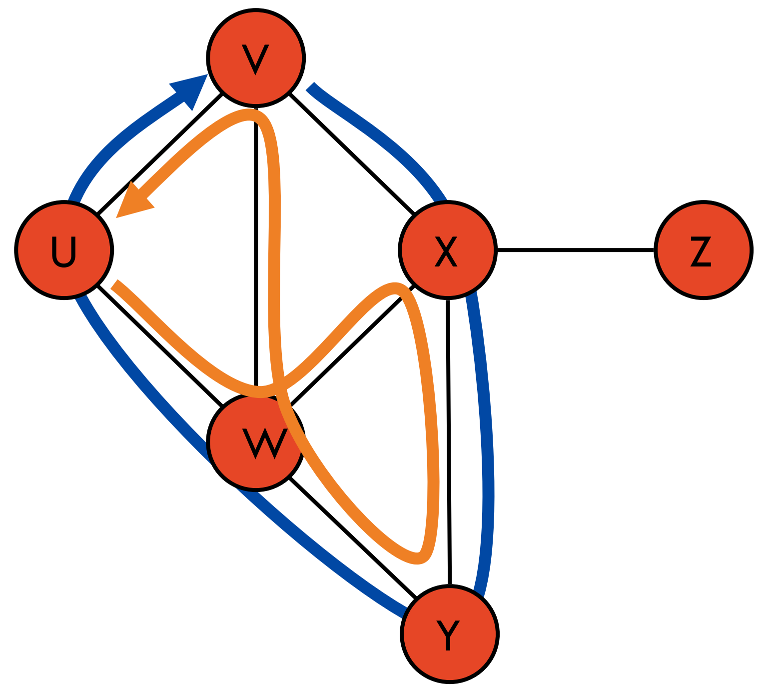
A cycle is defined by a path that starts and ends at the same vertex

A simple cycle is one where all vertices are distinct

Examples

- (V, X, Y, W, U, V) is a simple cycle
- (U, W, X, Y, W, V, U) is a cycle that is not simple

An acyclic graph has no cycles

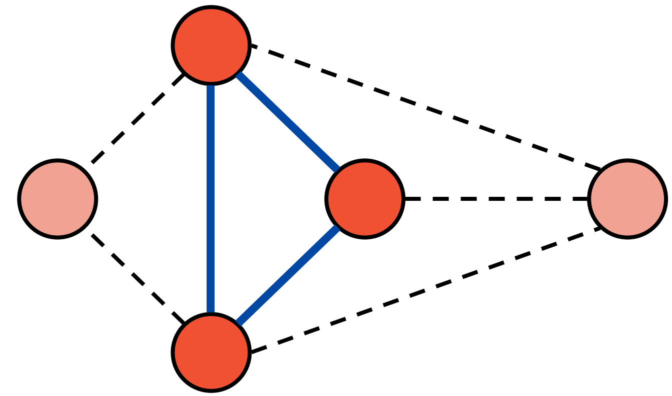


Graph Concept: Subgraphs

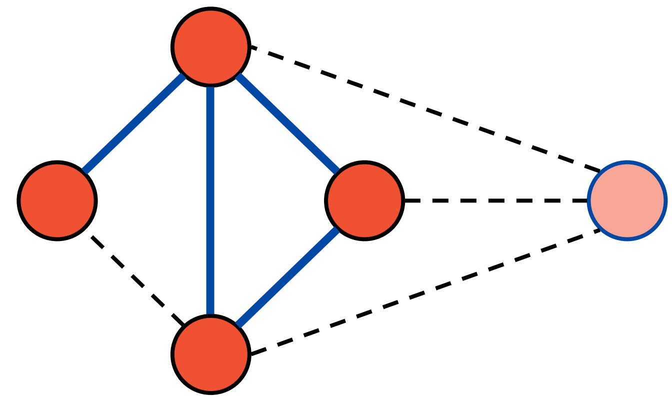
Let $G=(V, E)$ be a graph. We say $S=(U, F)$ is a subgraph of G if $U \subseteq V$ and $F \subseteq E$

A subset $U \subseteq V$ induces a graph $G[U] = (U, E[U])$ where $E[U]$ are the edges in E with both endpoints in U

A subset $F \subseteq E$ induces a graph $G[F] = (V[F], F)$ where $V[F]$ are the endpoints of edges in F



Subgraph induced by red vertices

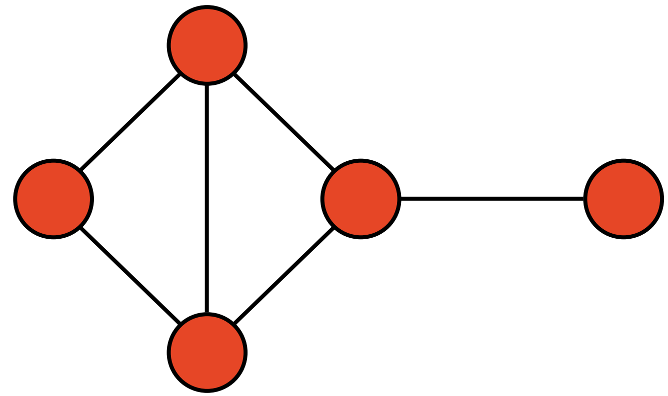


Subgraph induced by blue edges

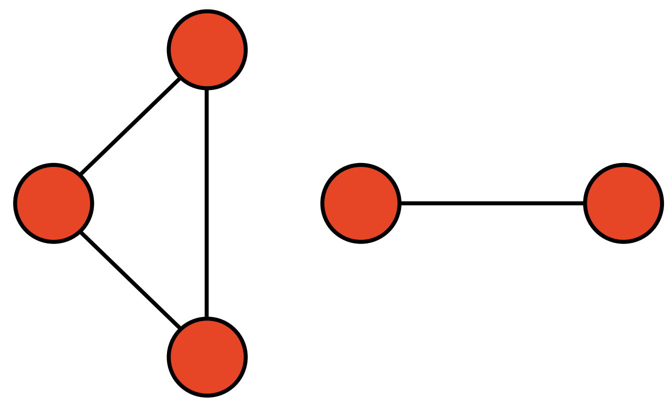
Graph Concept: Connectivity

A graph G=(V, E) is connected if there is a path between every pair of vertices in V

A connected component of a graph G is a maximal connected subgraph of G



Connected graph

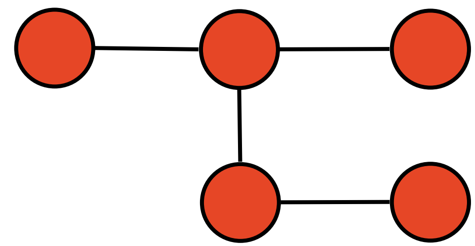


Graph with two connected components

Graph Concept: Trees and Forests

An unrooted tree T is a graph such that

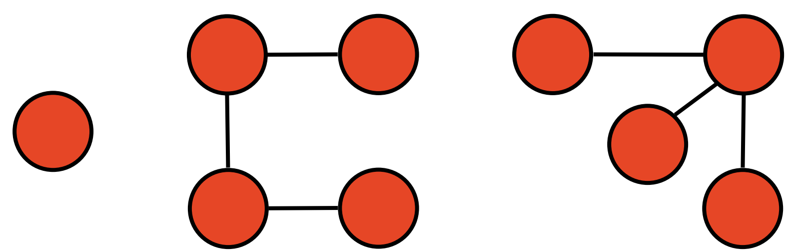
- T is connected
- T has no cycles



Tree

A forest is a graph without cycles. In other words, its connected components are trees

Fact: Every tree on n vertices has n-1 edges



Forest

Properties

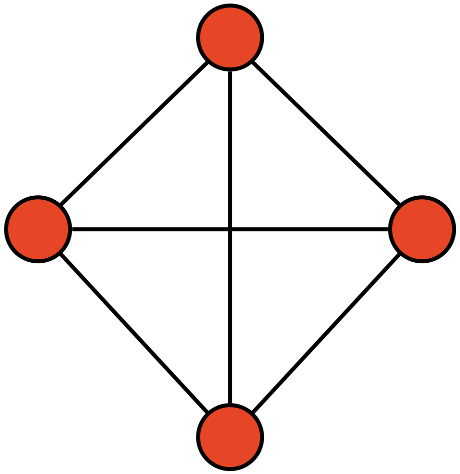
Fact: $\sum_{v \text{ in } V} \deg(v) = 2m$

Fact: In a simple directed graph $m \leq n\,(n - 1)$

Fact: In a simple undirected graph $m \leq n\,(n - 1)/2$

Notation

n	number of vertices
m	number of edges
Δ	maximum degree



Example: K_4

$n = 4$

$m = 6$

max deg $= 3$

Graph ADT

We model the abstraction as a combination of three data types: Vertex, Edge, and Graph.

A Vertex stores an associated object (e.g., an airport code) that is retrieved with a getElement() method.

An Edge stores an associated object (e.g., a flight number, travel distance) that is retrieved with a getElement() method.

Directed Graph ADT

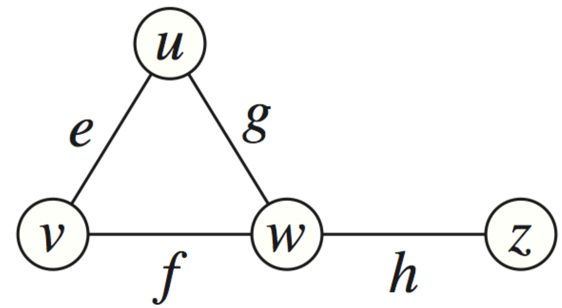
Undirected Graph alternatives

degree(v) ←

incidentEdges(v) ←

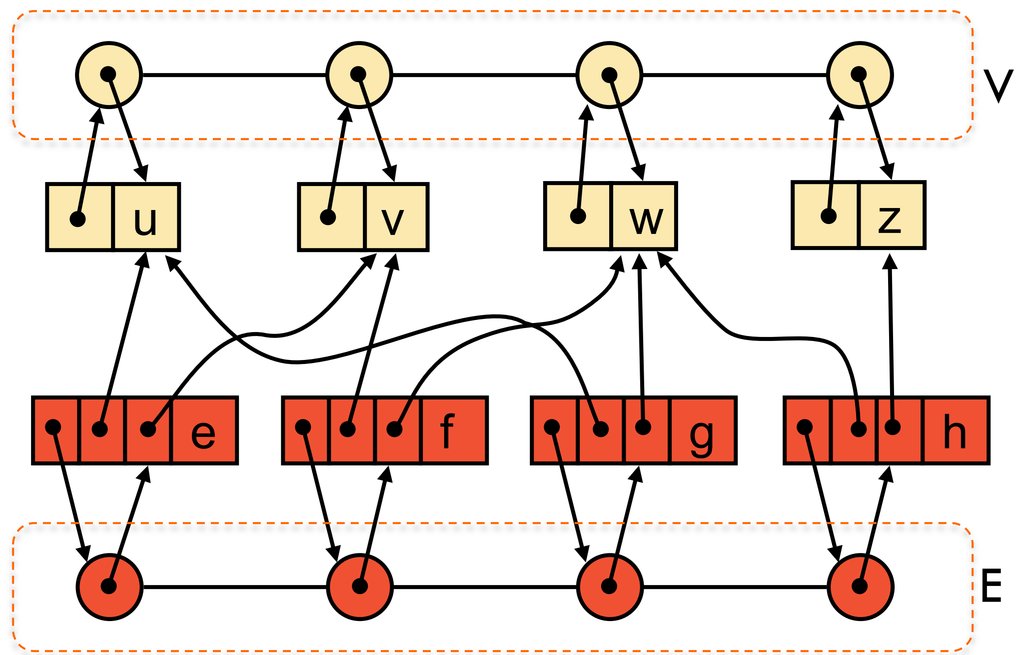
numVertices():	Returns the number of vertices of the graph.
vertices():	Returns an iteration of all the vertices of the graph.
numEdges():	Returns the number of edges of the graph.
edges():	Returns an iteration of all the edges of the graph.
getEdge(u, v):	Returns the edge from vertex u to vertex v, if one exists; otherwise return null. For an undirected graph, there is no difference between getEdge(u, v) and getEdge(v, u).
endVertices(e):	Returns an array containing the two endpoint vertices of edge e. If the graph is directed, the first vertex is the origin and the second is the destination.
opposite(v, e):	For edge e incident to vertex v, returns the other vertex of the edge; an error occurs if e is not incident to v.
outDegree(v):	Returns the number of outgoing edges from vertex v.
inDegree(v):	Returns the number of incoming edges to vertex v. For an undirected graph, this returns the same value as does outDegree(v).
outgoingEdges(v):	Returns an iteration of all outgoing edges from vertex v.
incomingEdges(v):	Returns an iteration of all incoming edges to vertex v. For an undirected graph, this returns the same collection as does outgoingEdges(v).
insertVertex(x):	Creates and returns a new Vertex storing element x.
insertEdge(u, v, x):	Creates and returns a new Edge from vertex u to vertex v, storing element x; an error occurs if there already exists an edge from u to v.
removeVertex(v):	Removes vertex v and all its incident edges from the graph.
removeEdge(e):	Removes edge e from the graph.

Edge List Structure



Vertex sequence holds

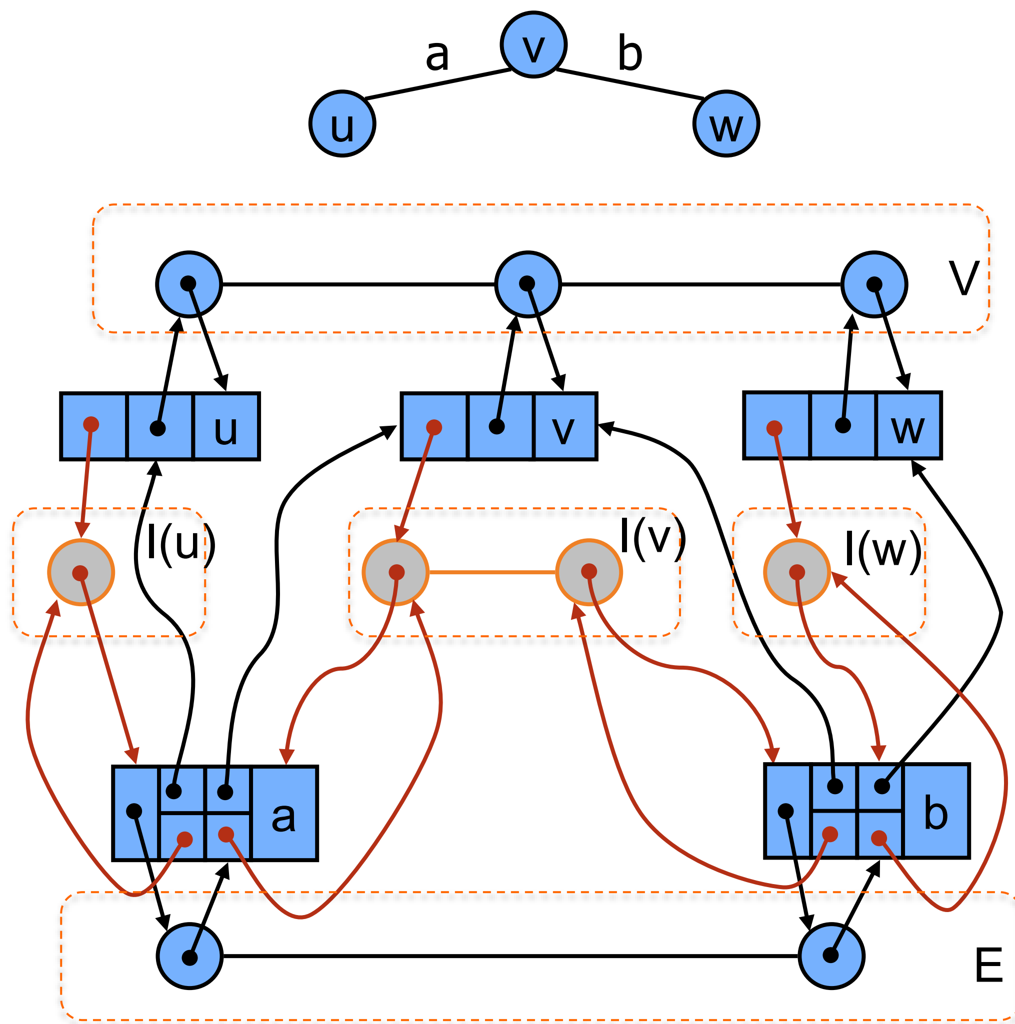
- sequence of vertices
- vertex objects keeps track of its position in the sequence



Edge sequence

- sequence edges
- edge object keeps track of its position in the sequence
- Edge object points to the two vertices it connects

Adjacency List



Additionally each vertex keeps a sequence of edges incident on it

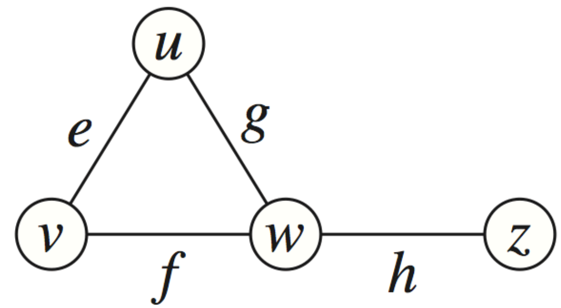
Edge objects keep reference to their position in the incidence sequence of its endpoints

Adjacency Matrix Structure

Vertex array induces an index from 0 to n-1 for each vertex

2D-array adjacency matrix

- Reference to edge object for adjacent vertices
- Null for nonadjacent vertices



		0	1	2	3
$u \rightarrow$	0		e	g	
$v \rightarrow$	1	e		f	
$w \rightarrow$	2	g	f		h
$z \rightarrow$	3			h	

Asymptotic performance

▪ *n* vertices, *m* edges ▪ no parallel edges ▪ no self-loops	Edge List	Adjacency List	Adjacency Matrix
Space	$O(n + m)$	$O(n + m)$	$O(n^2)$
incidentEdges(**v**)	$O(m)$	O(deg(**v**))	$O(n)$
getEdge(**u, v**)	$O(m)$	O(min(deg(**u**), deg(**v**)))	O(1)
insertVertex(**x**)	O(1)	O(1)	$O(n^2)$
insertEdge(**u, v, x**)	O(1)	O(1)	O(1)
removeVertex(**v**)	$O(m)$	O(deg(**v**))	$O(n^2)$
removeEdge(**e**)	O(1)	O(1)	O(1)

Graph traversals

A fundamental kind of algorithmic operation that we might wish to perform on a graph is traversing the edges and the vertices of that graph.

A traversal is a systematic procedure for exploring a graph by examining all its vertices and edges.

For example, a web crawler, which is the data collecting part of a search engine, must explore a graph of hypertext documents by examining its vertices, which are the documents, and its edges, which are the hyperlinks between documents.

A traversal is efficient if it visits all the vertices and edges in linear time: $O(n+m)$ where n=number of vertices, m=number of edges.

Graph traversal techniques

A systematic and structured way of visiting all the vertices and all the edges of a graph

Two main strategies:

– Depth first search
– Breadth first search

Given adjacency list representation of the graph with n vertices and m edges both traversals run in $O(n + m)$ time

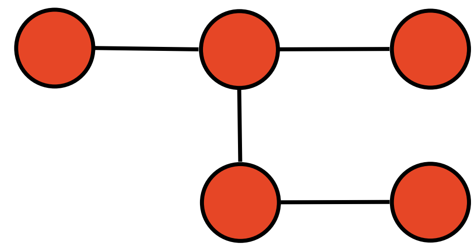
Reminder: Trees and Forests

An unrooted tree T is a graph such that

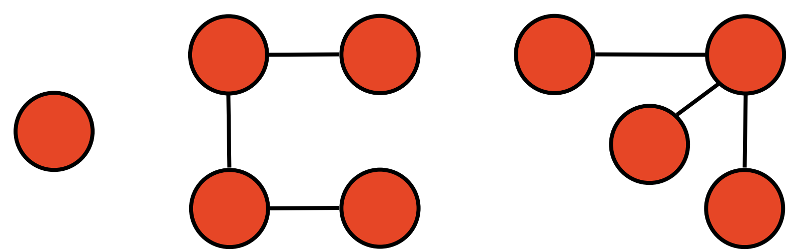
- T is connected
- T has no cycles

A forest is a graph without cycles. In other words, its connected components are trees

Fact: Every tree on n vertices has $n-1$ edges



Tree

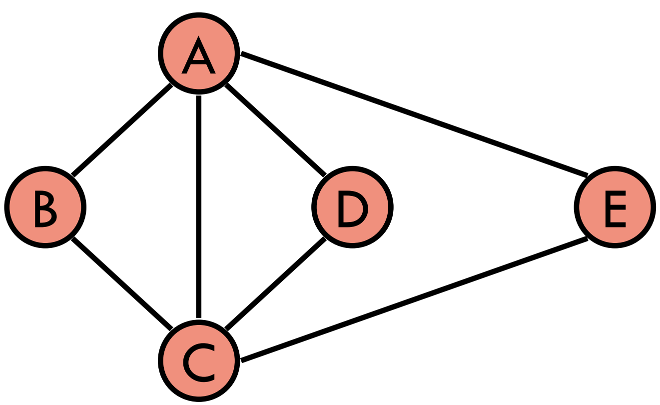


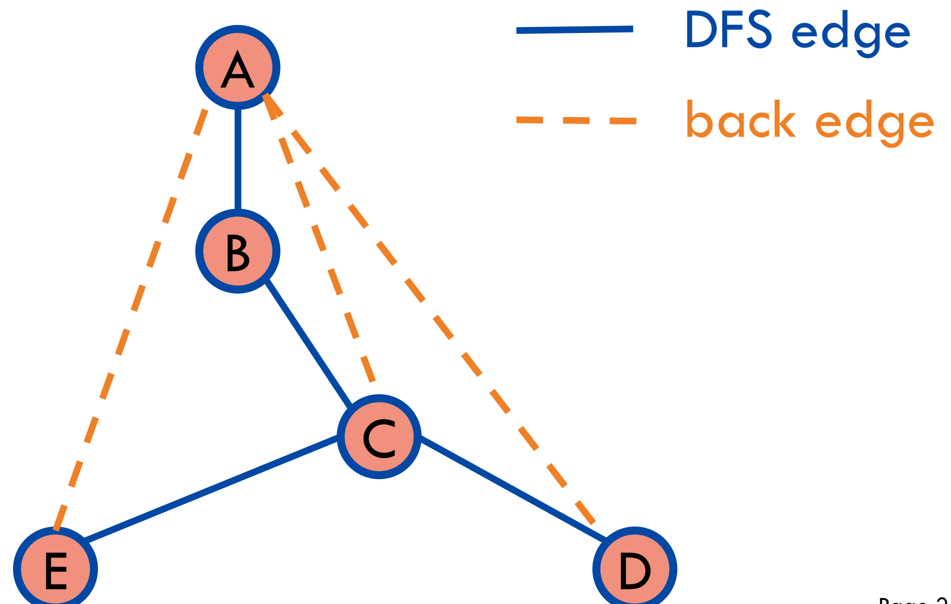
Forest

Depth-First Search (DFS) for undirected graphs

This strategy tries to follow outgoing edges leading to yet unvisited vertices whenever possible, and backtrack if "stuck"

If an edge is used to discover a new vertex, we call it a DFS edge, otherwise we call it a back edge





DFS pseudocode

```
def DFS(G):

 # set things up for DFS
 for u in G.vertices() do
  visited[u] ← False
  parent[u] ← None

 # visit vertices
 for u in G.vertices() do
  if not visited[u] then
   DFS_visit(u)

 return parent
```

```
def DFS_visit(u):

 visited[u] ← True

 # visit neighbors of u
 for v in G.incident(u) do
  if not visited[v] then
   parent[v] ← u
   DFS_visit(v)
```

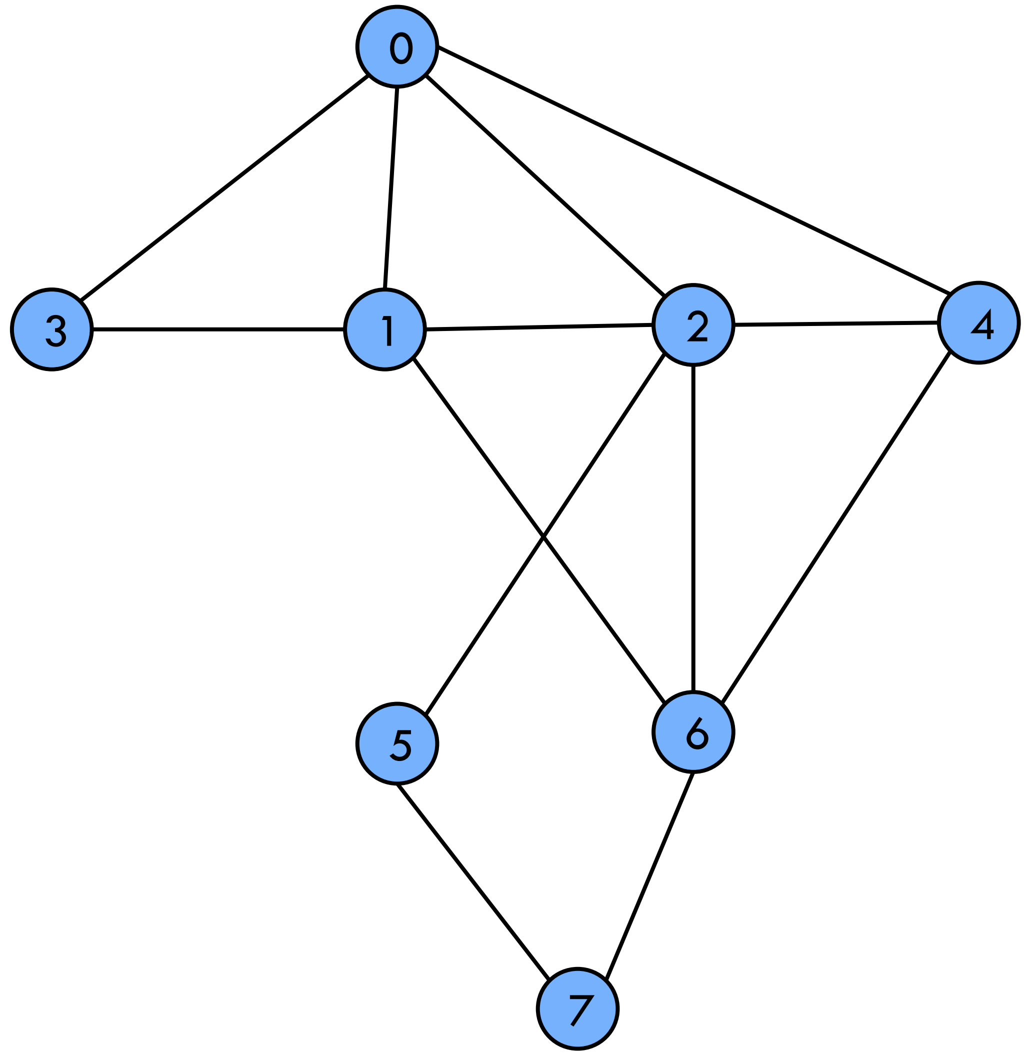
Example

parent

0	
1	
2	
3	
4	
5	
6	
7	

visited

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



Starting at 0
Ordering decided by values

Example

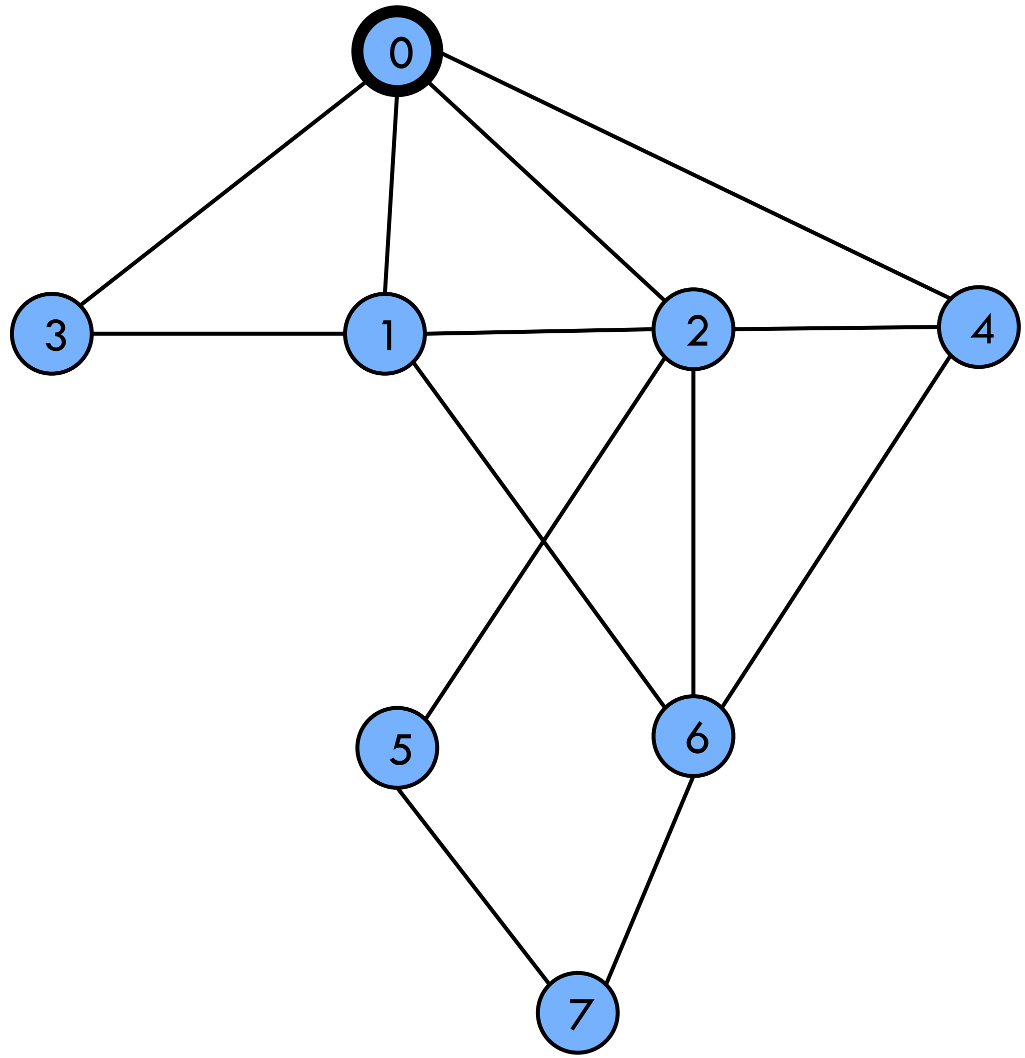
parent

0	
1	
2	
3	
4	
5	
6	
7	

visited

0	T
1	F
2	F
3	F
4	F
5	F
6	F
7	F

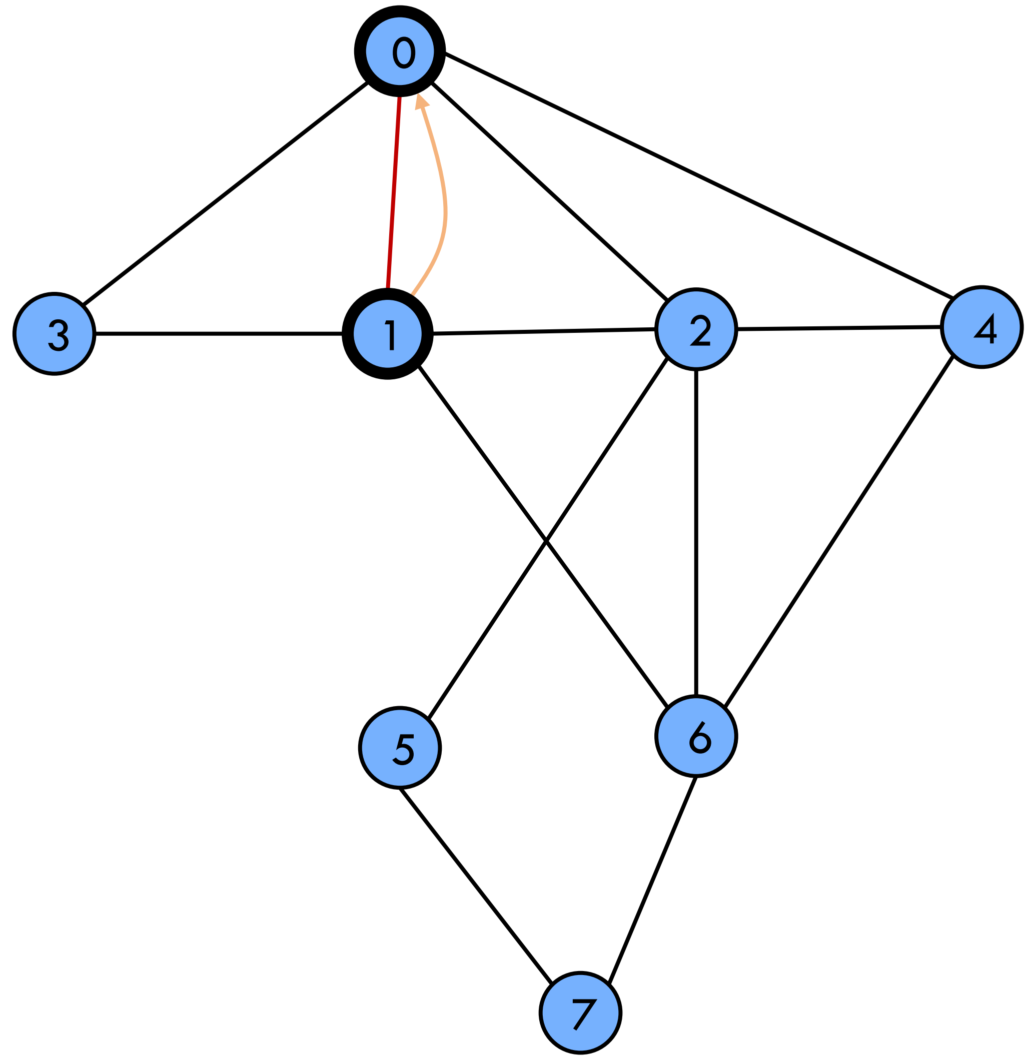
DFS(0)



Example

	parent	visited
0		T
1	0	T
2		F
3		F
4		F
5		F
6		F
7		F

DFS(0)
    DFS(1)



Example

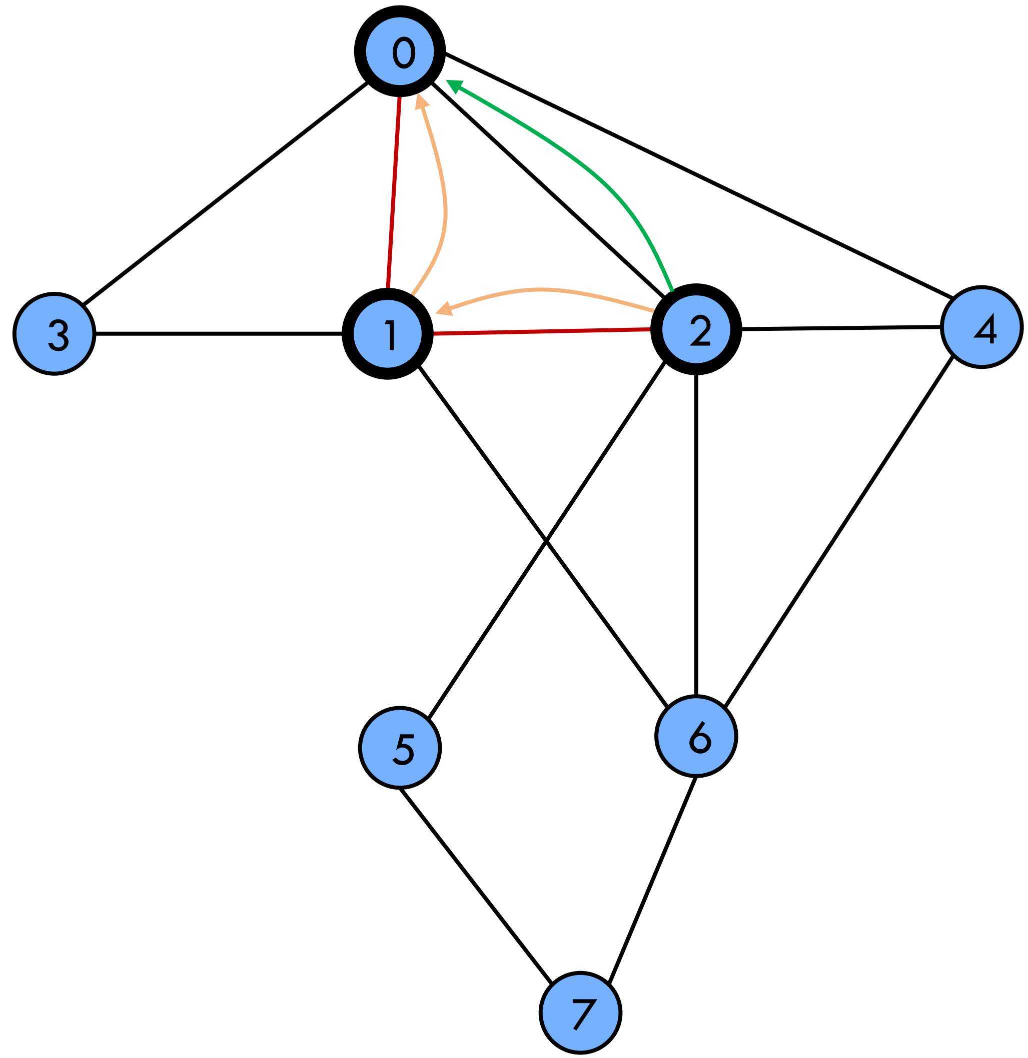
parent

0	
1	0
2	1
3	
4	
5	
6	
7	

visited

0	T
1	T
2	T
3	F
4	F
5	F
6	F
7	F

DFS(0)
  DFS(1)
    DFS(2)



Example

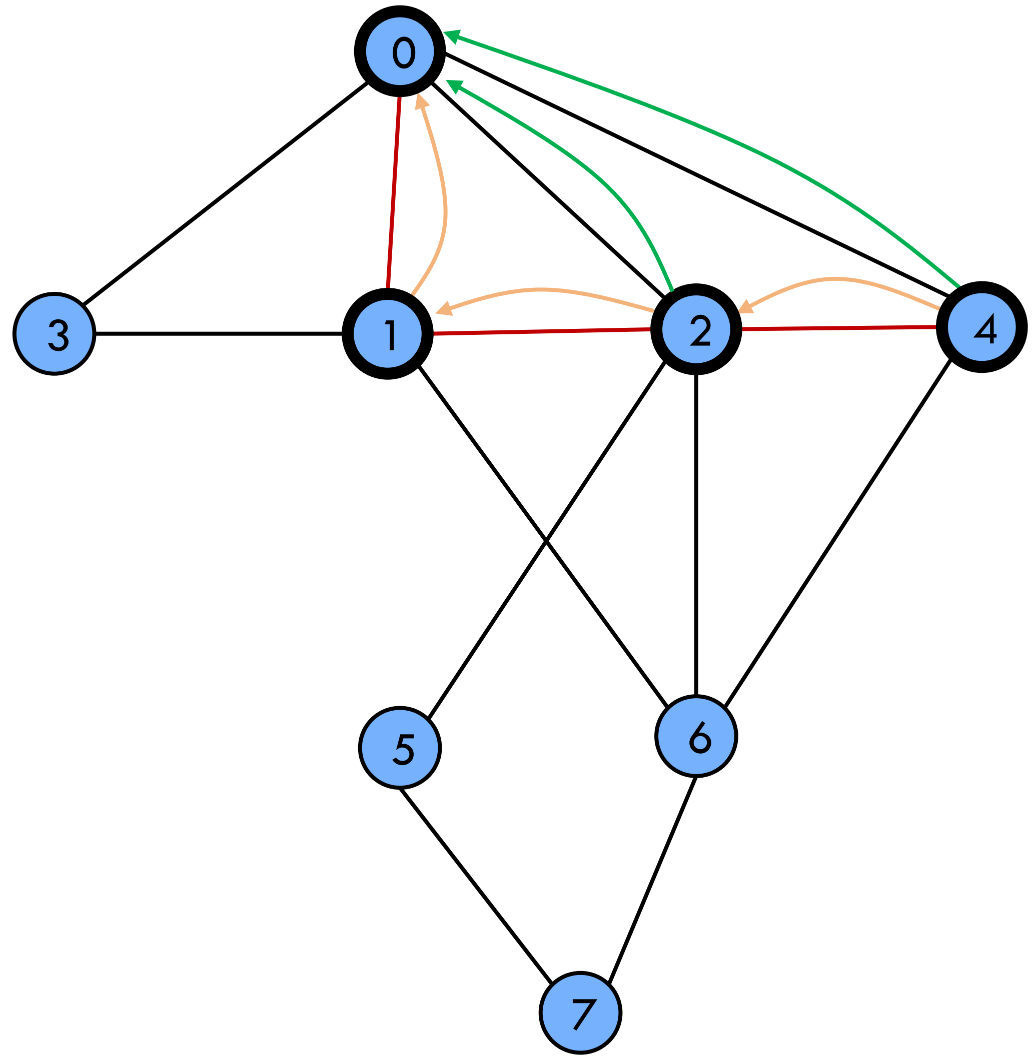
parent

0	
1	0
2	1
3	
4	2
5	
6	
7	

visited

0	T
1	T
2	T
3	F
4	T
5	F
6	F
7	F

DFS(0)
    DFS(1)
        DFS(2)
            DFS(4)



Example

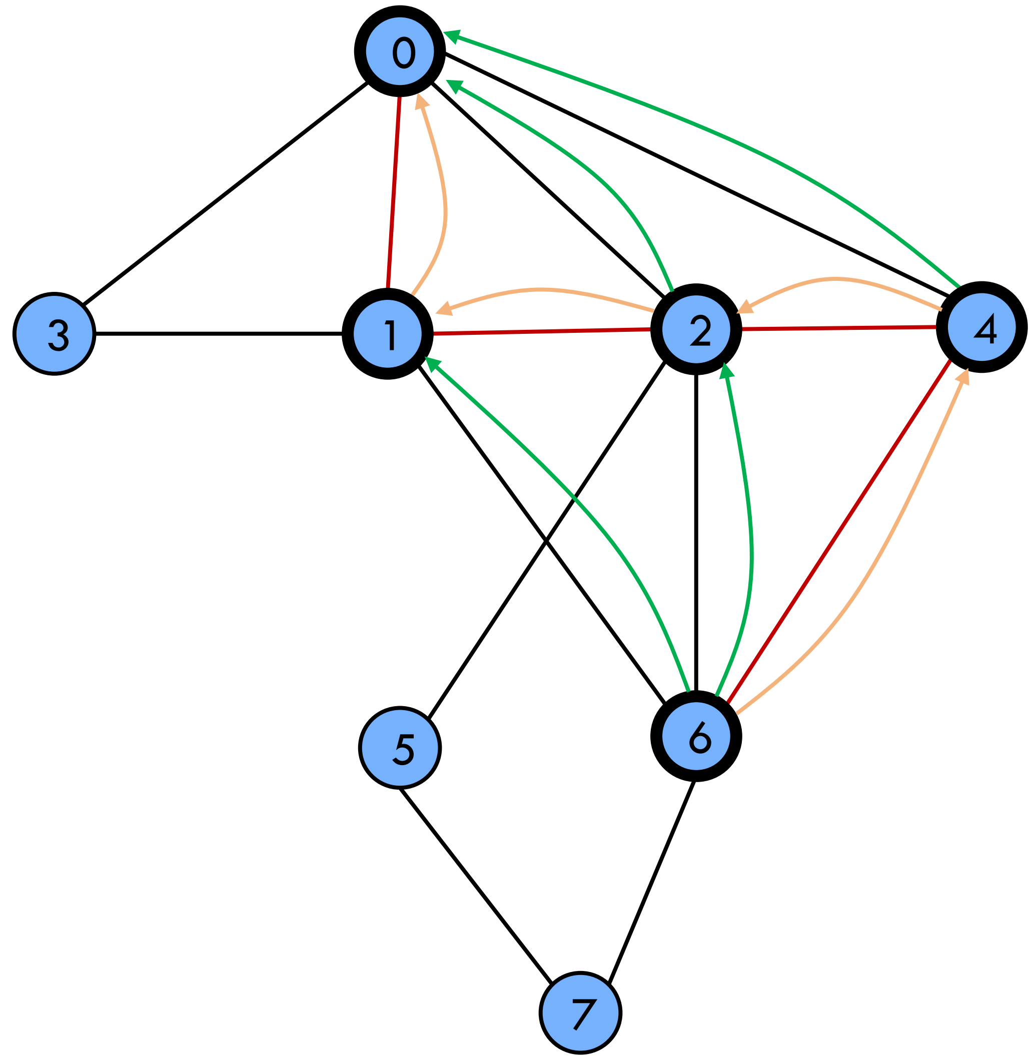
parent

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

visited

0	T
1	T
2	T
3	F
4	T
5	F
6	T
7	F

DFS(0)
- DFS(1)
  - DFS(2)
    - DFS(4)
      - DFS(6)

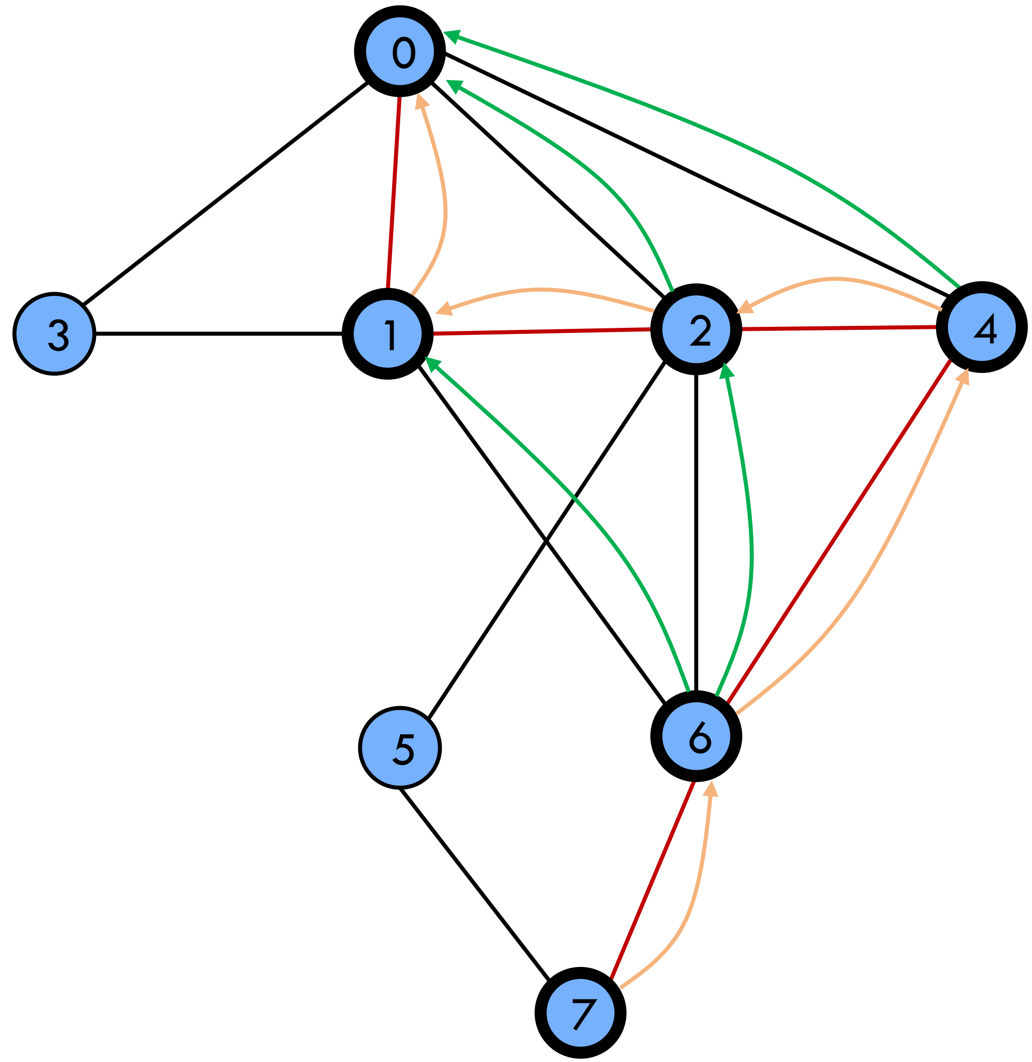


Example

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

	visited
0	T
1	T
2	T
3	F
4	T
5	F
6	T
7	T

DFS(0)
    DFS(1)
        DFS(2)
            DFS(4)
                DFS(6)
                    DFS(7)



Example

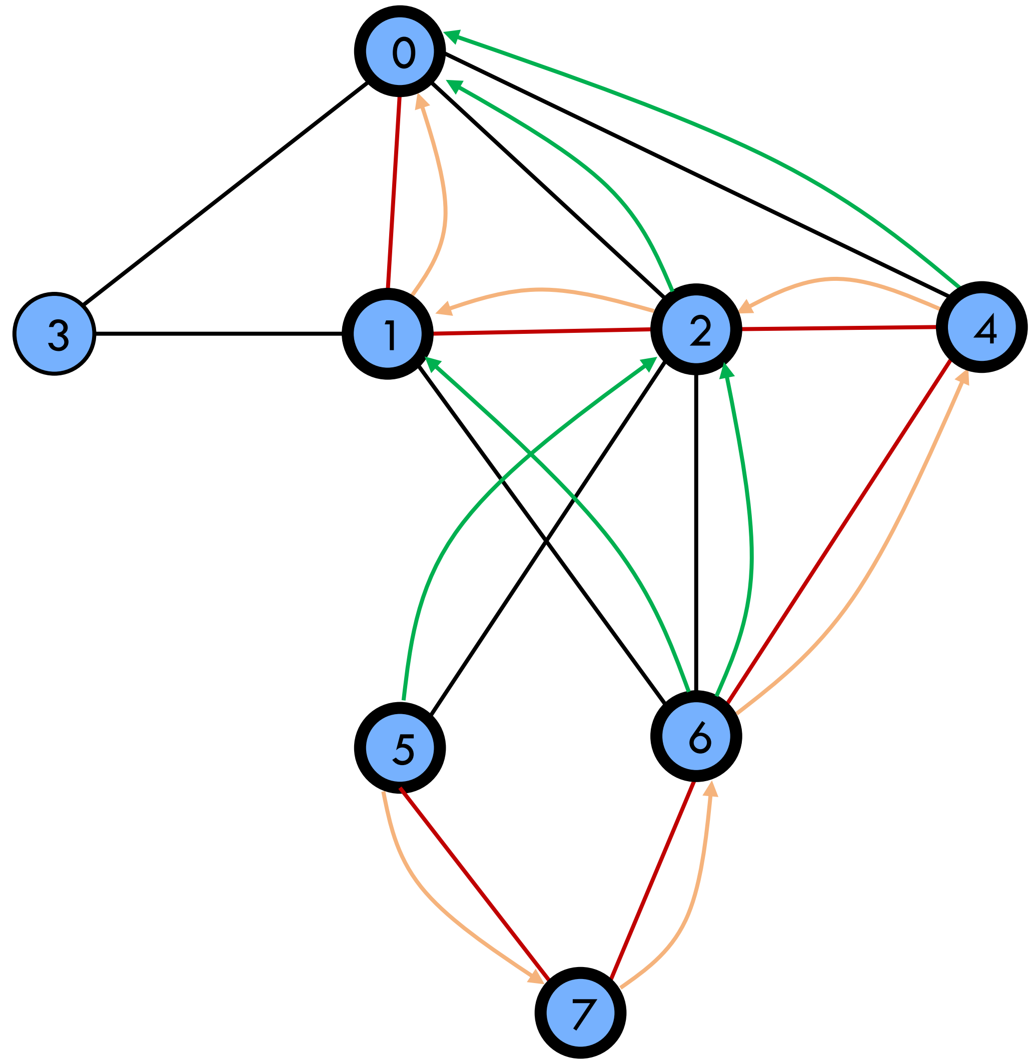
parent

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

visited

0	T
1	T
2	T
3	F
4	T
5	F
6	T
7	T

DFS(0)
  DFS(1)
    DFS(2)
      DFS(4)
        DFS(6)
          DFS(7)
            DFS(5)



Example

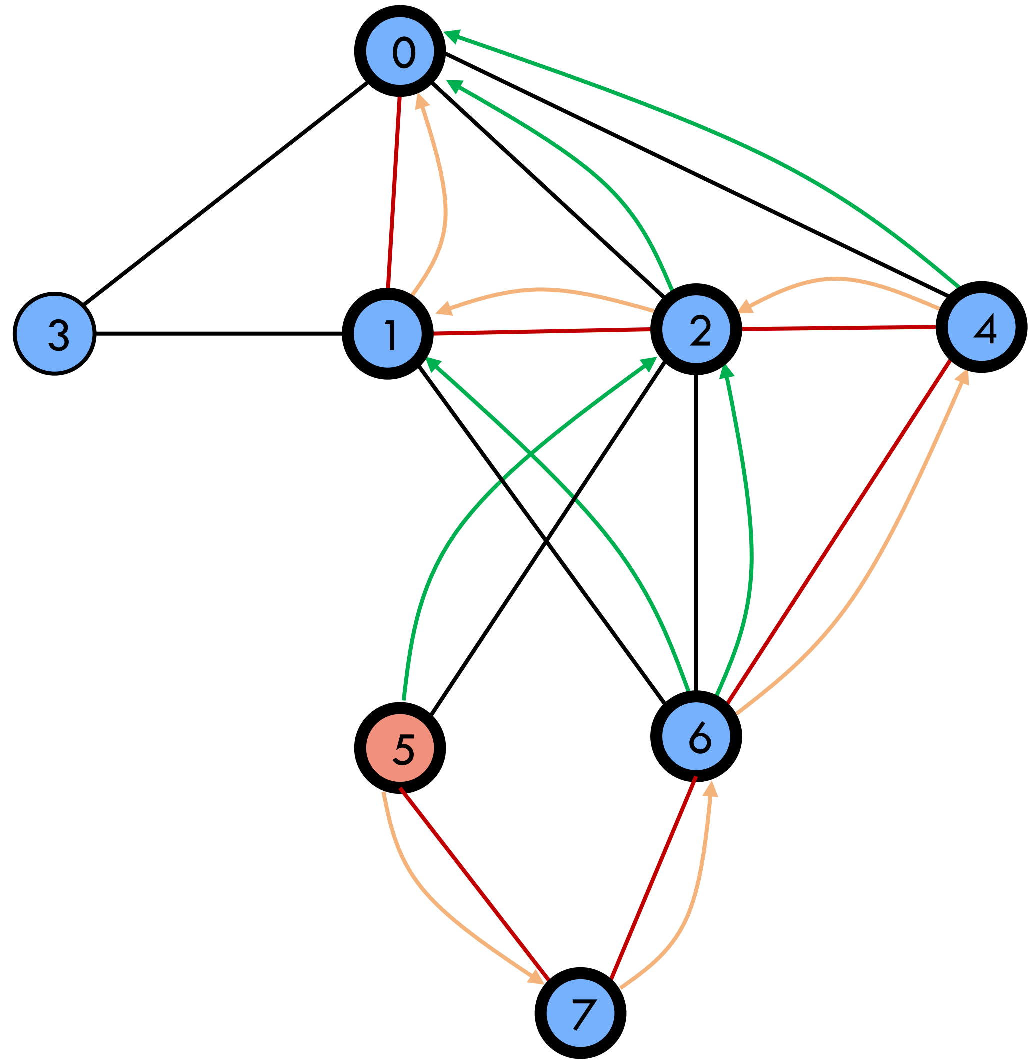
parent

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

visited

0	T
1	T
2	T
3	F
4	T
5	T
6	T
7	T

DFS(0)
  DFS(1)
    DFS(2)
      DFS(4)
        DFS(6)
          DFS(7)



Example

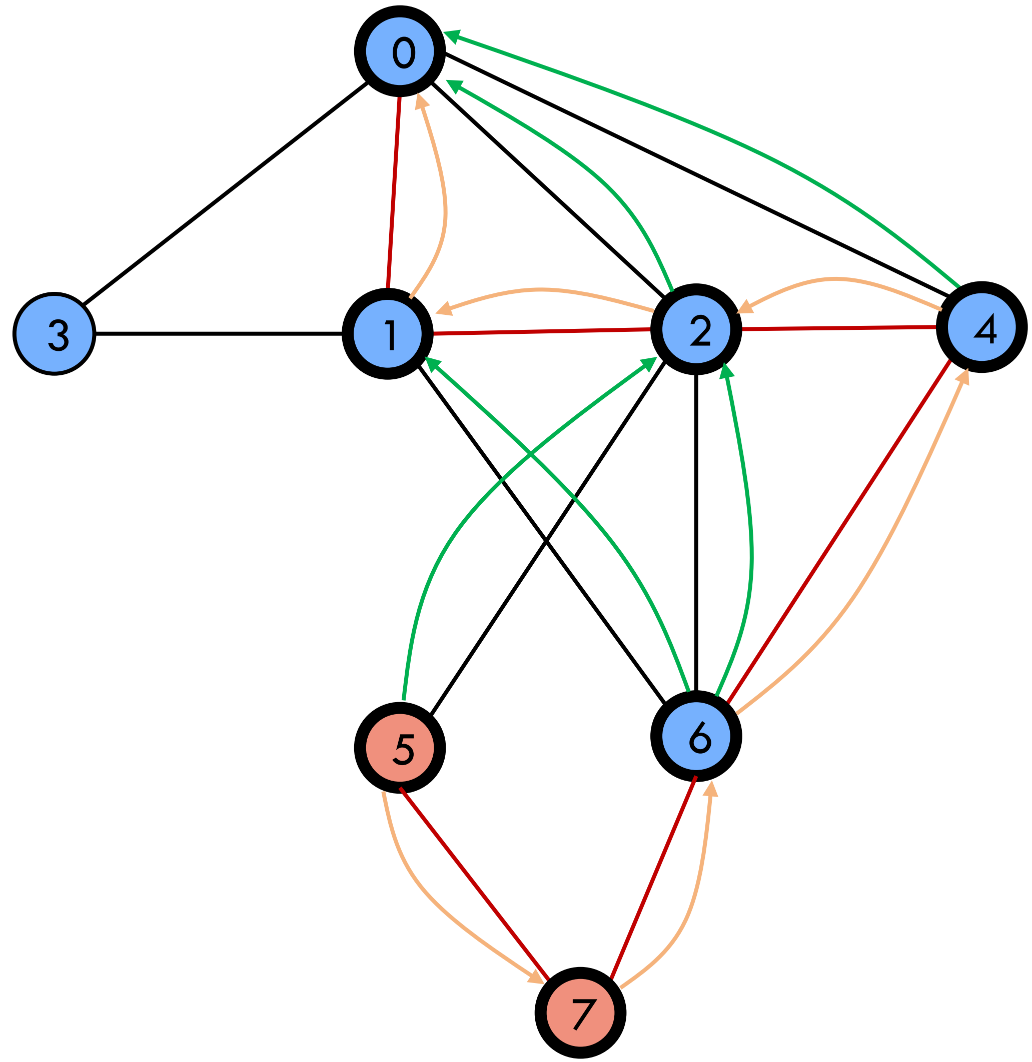
parent

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

visited

0	T
1	T
2	T
3	F
4	T
5	T
6	T
7	T

DFS(0)
  DFS(1)
    DFS(2)
      DFS(4)
        DFS(6)

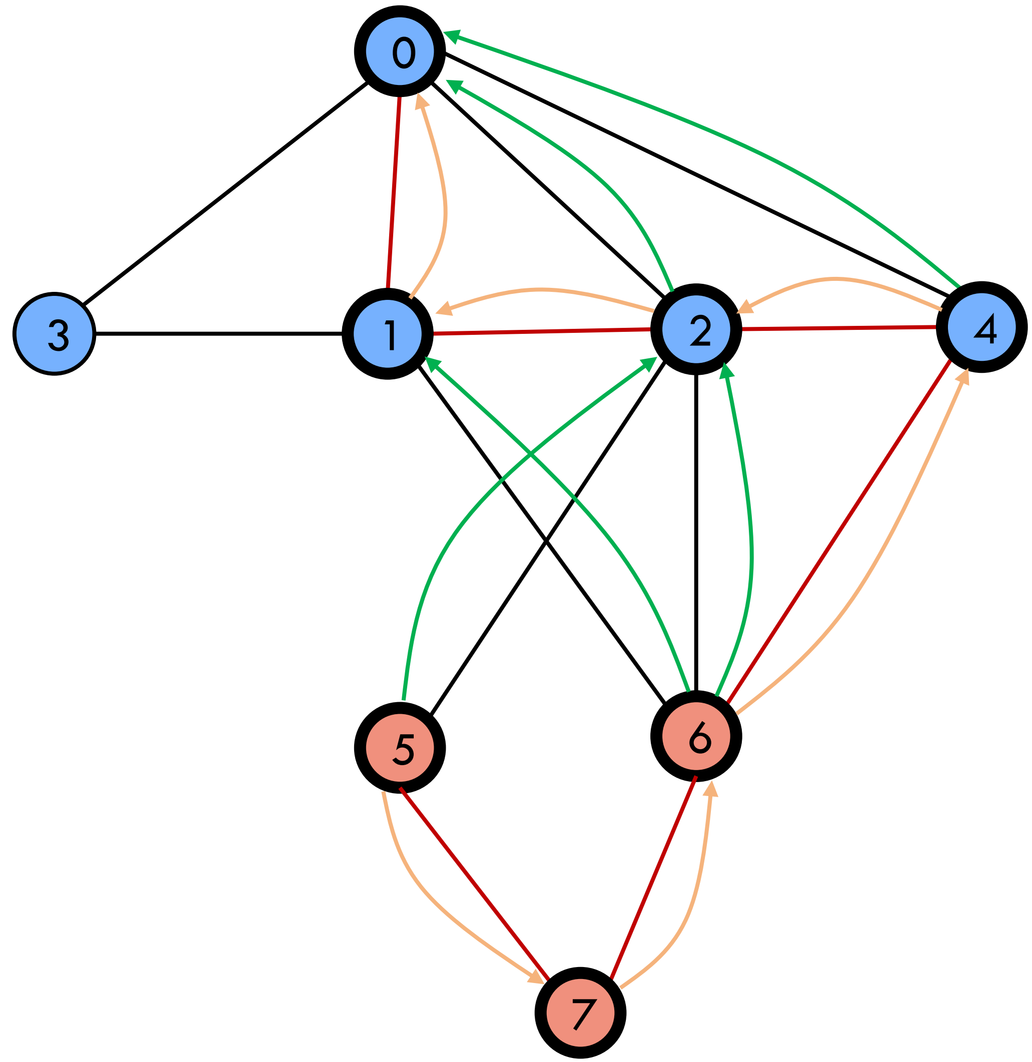


Example

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

	visited
0	T
1	T
2	T
3	F
4	T
5	T
6	T
7	T

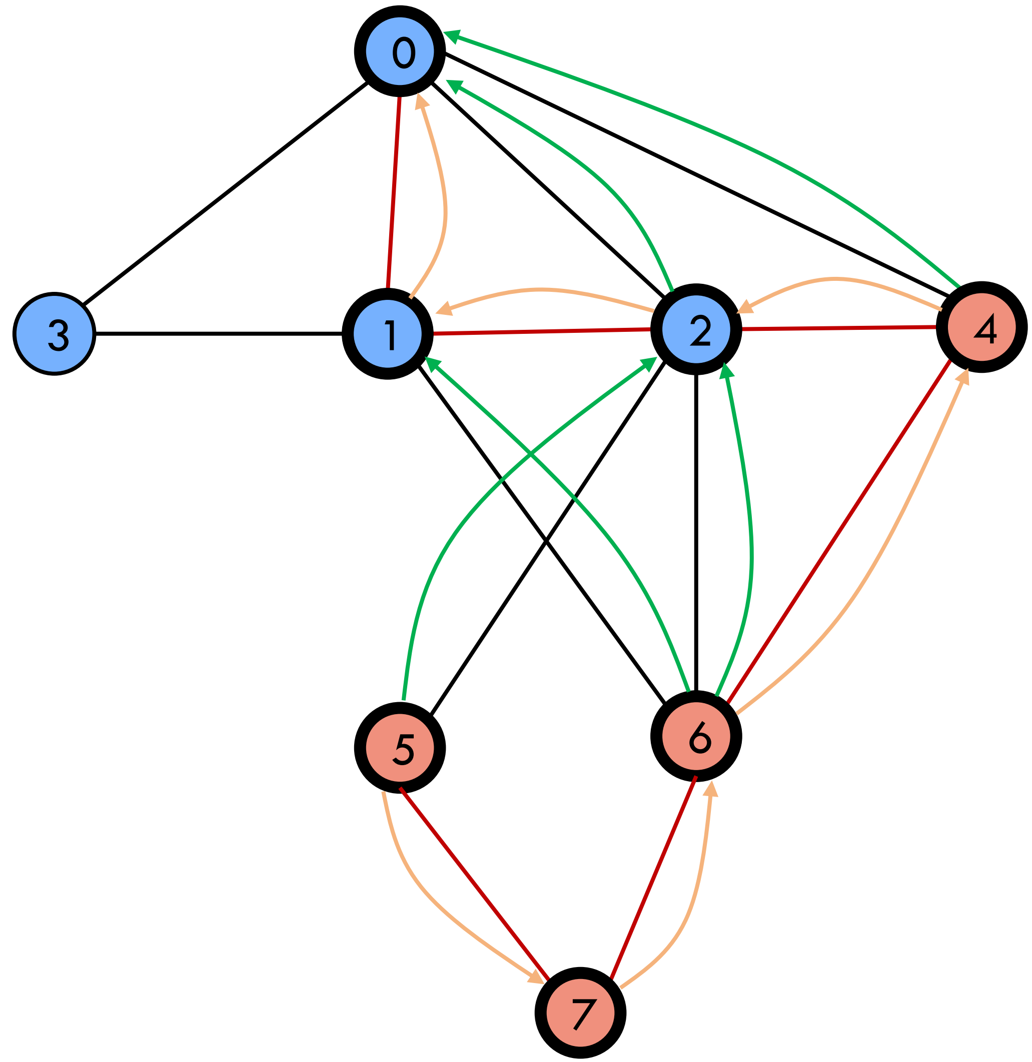
DFS(0)
DFS(1)
DFS(2)
DFS(4)



Example

	parent	visited
0		T
1	0	T
2	1	T
3		F
4	2	T
5	7	T
6	4	T
7	6	T

DFS(0)
    DFS(1)
        DFS(2)

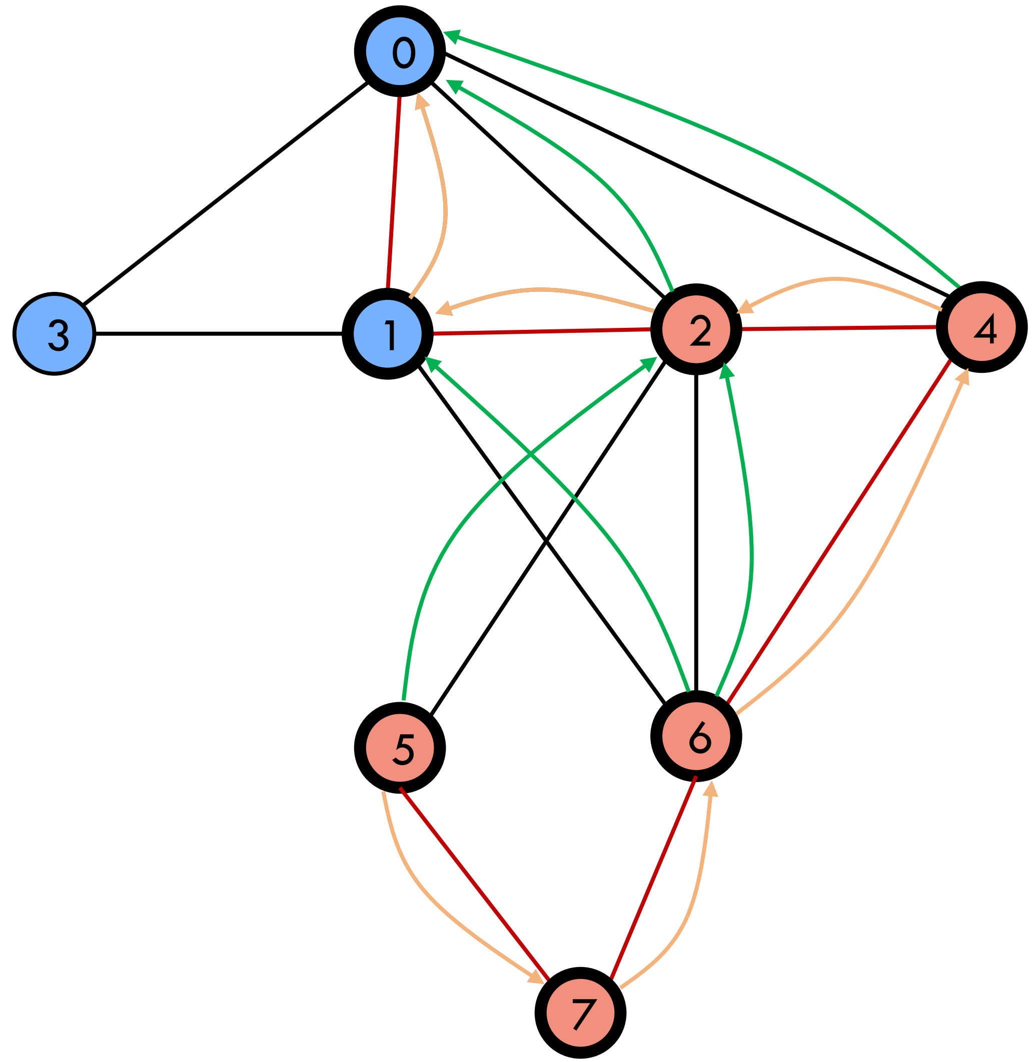


Example

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

	visited
0	T
1	T
2	T
3	F
4	T
5	T
6	T
7	T

DFS(0)
    DFS(1)



Example

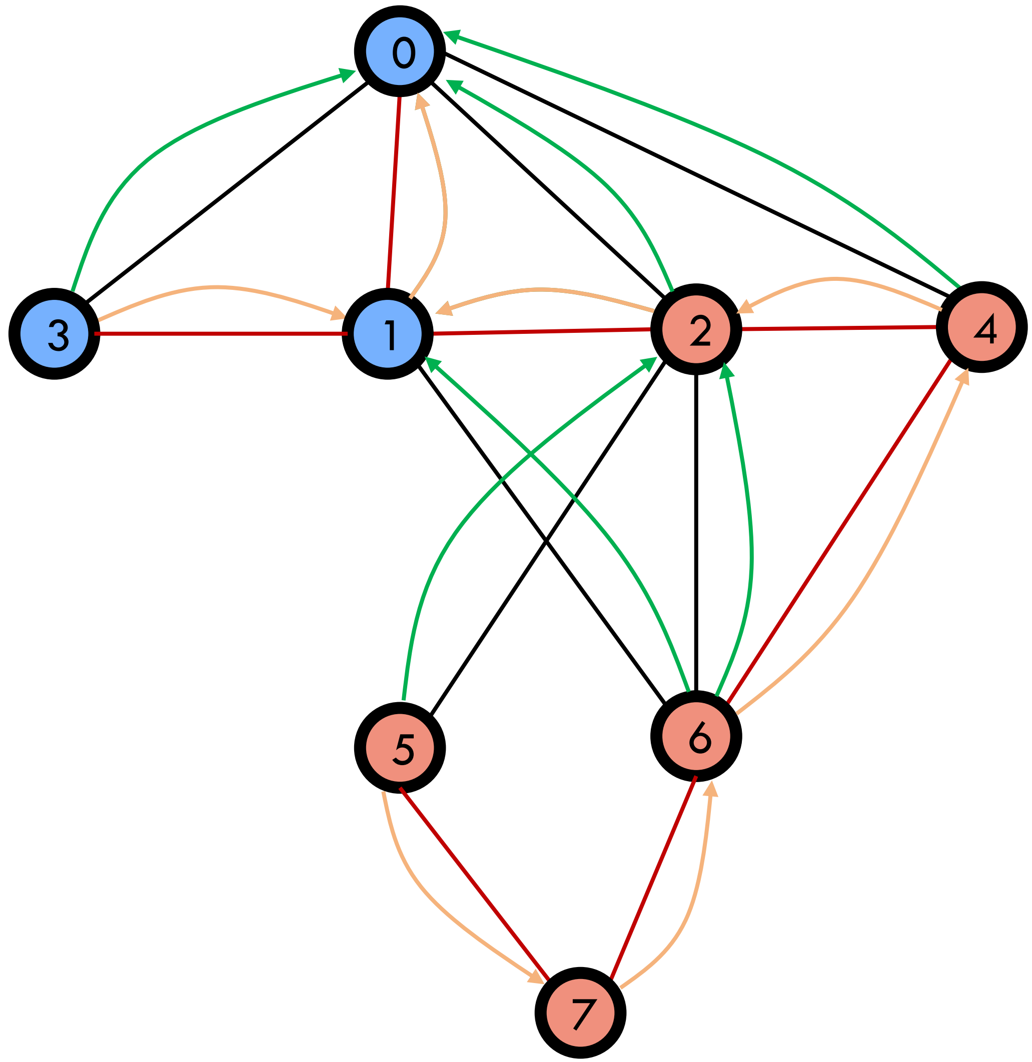
parent

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

visited

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

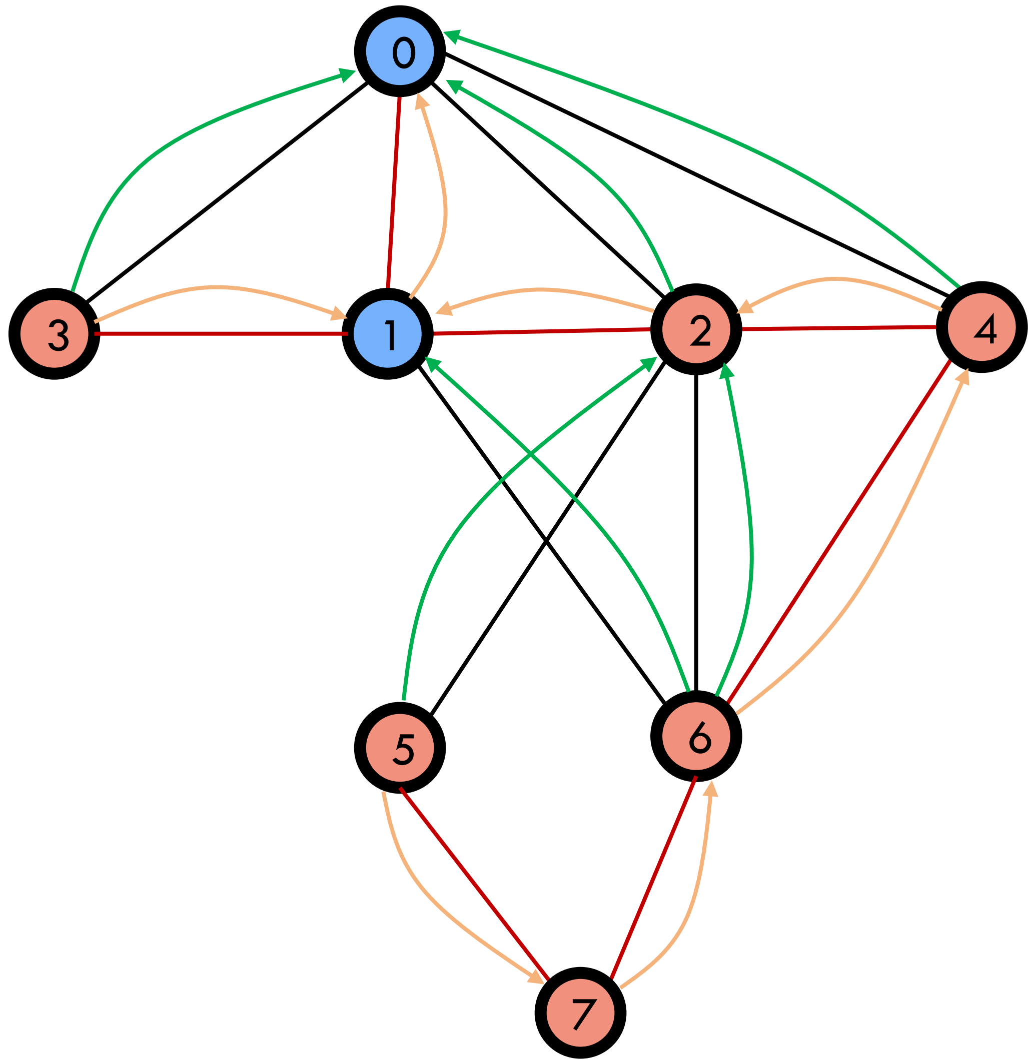
DFS(0)
    DFS(1)
        DFS(3)



Example

	parent	visited
0		T
1	0	T
2	1	T
3	1	T
4	2	T
5	7	T
6	4	T
7	6	T

DFS(0)
    DFS(1)

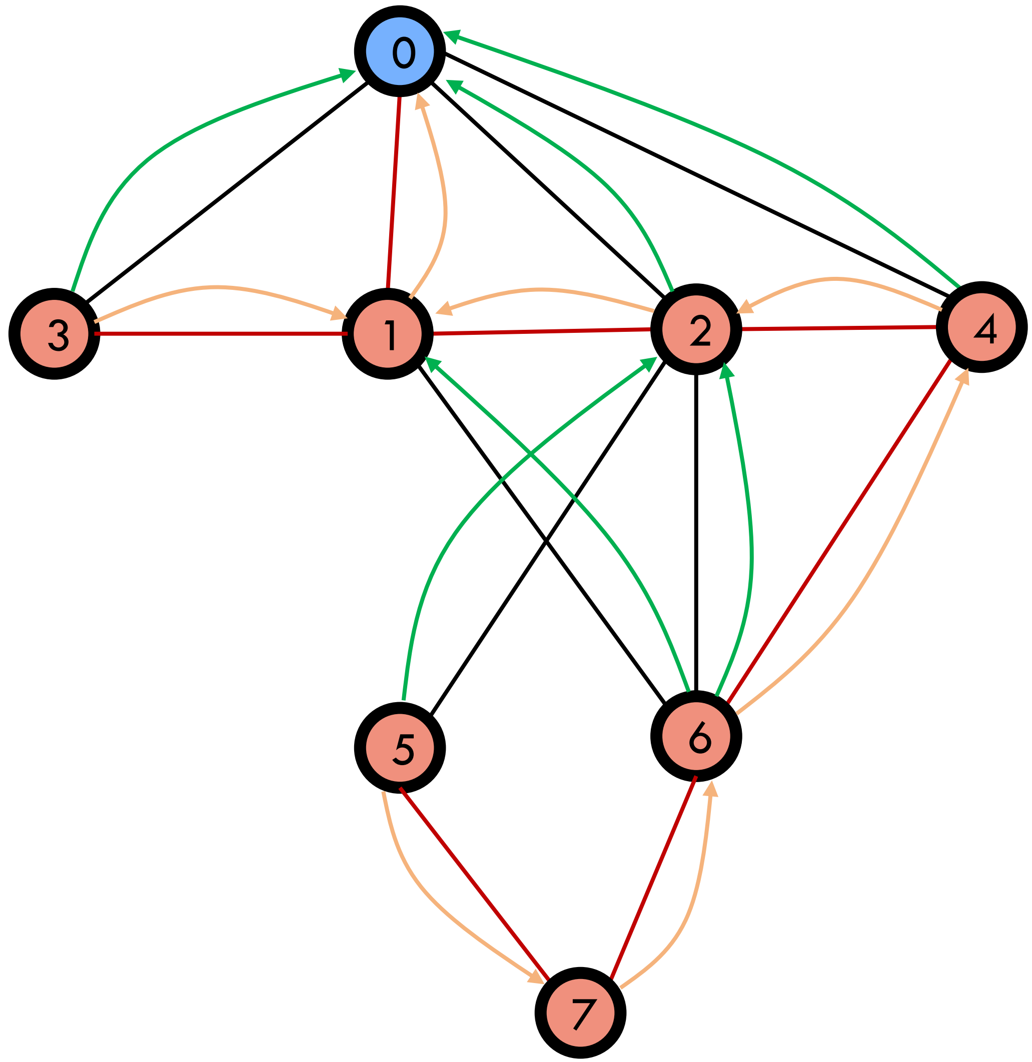


Example

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

visited	
0	T
1	T
2	T
3	T
4	T
5	T
6	T
7	T

DFS(0)



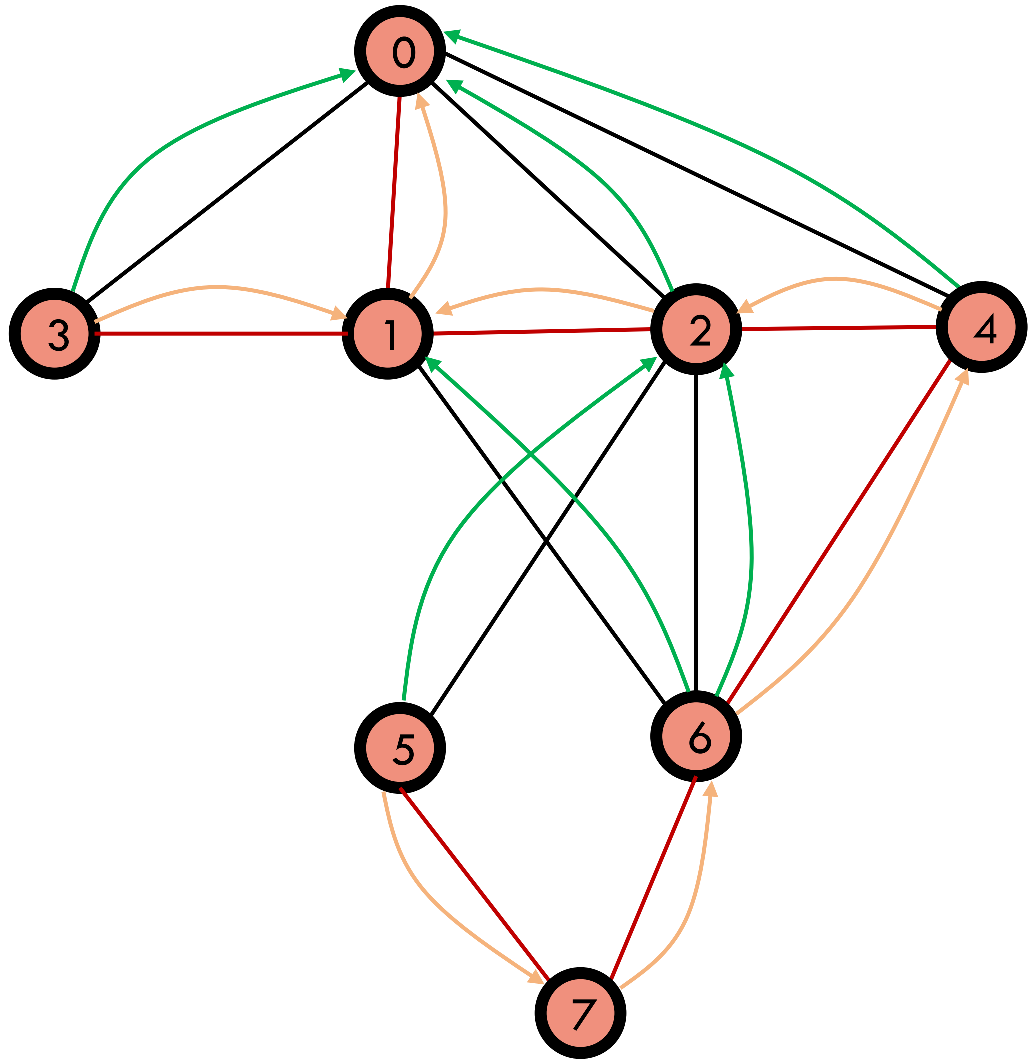
Example

parent

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

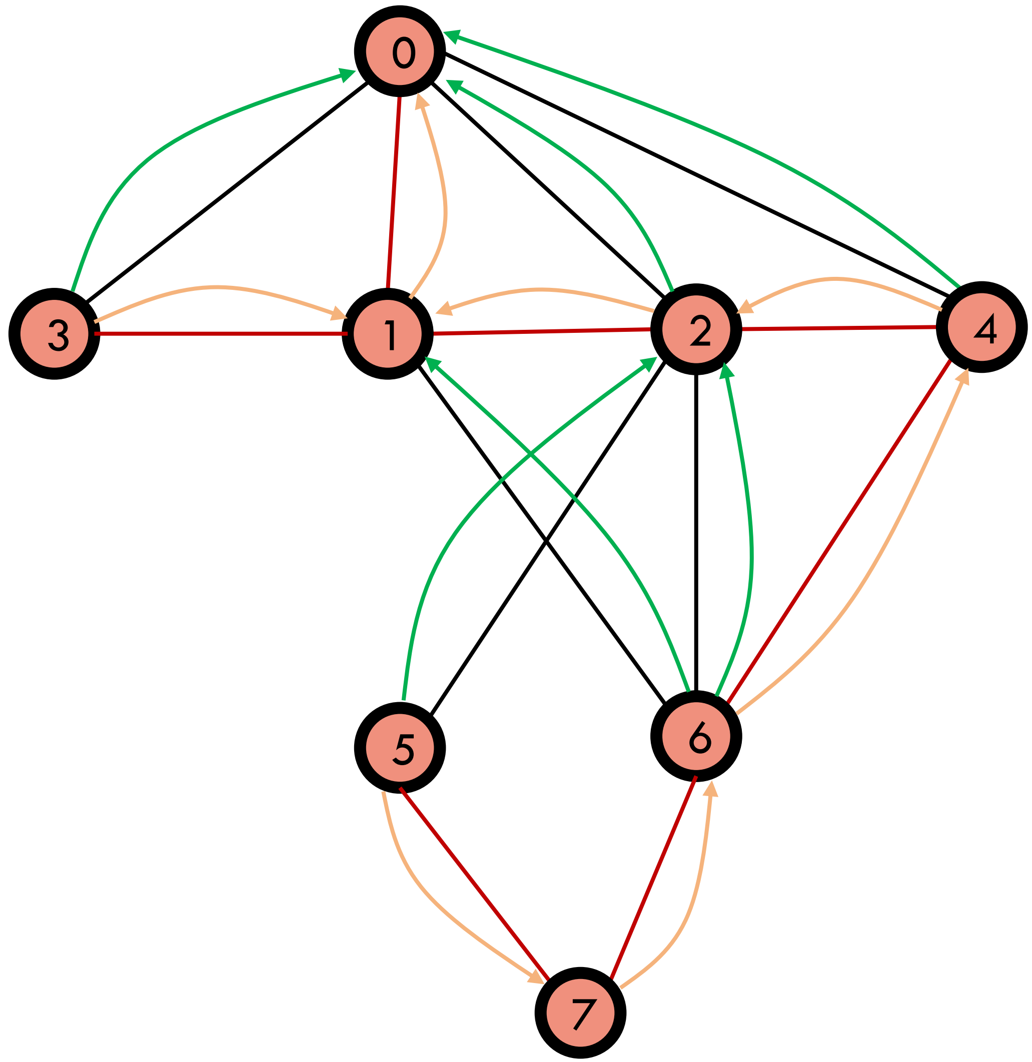
visited

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



Example

	parent		visited
0		0	T
1	0	1	T
2	1	2	T
3	1	3	T
4	2	4	T
5	7	5	T
6	4	6	T
7	6	7	T

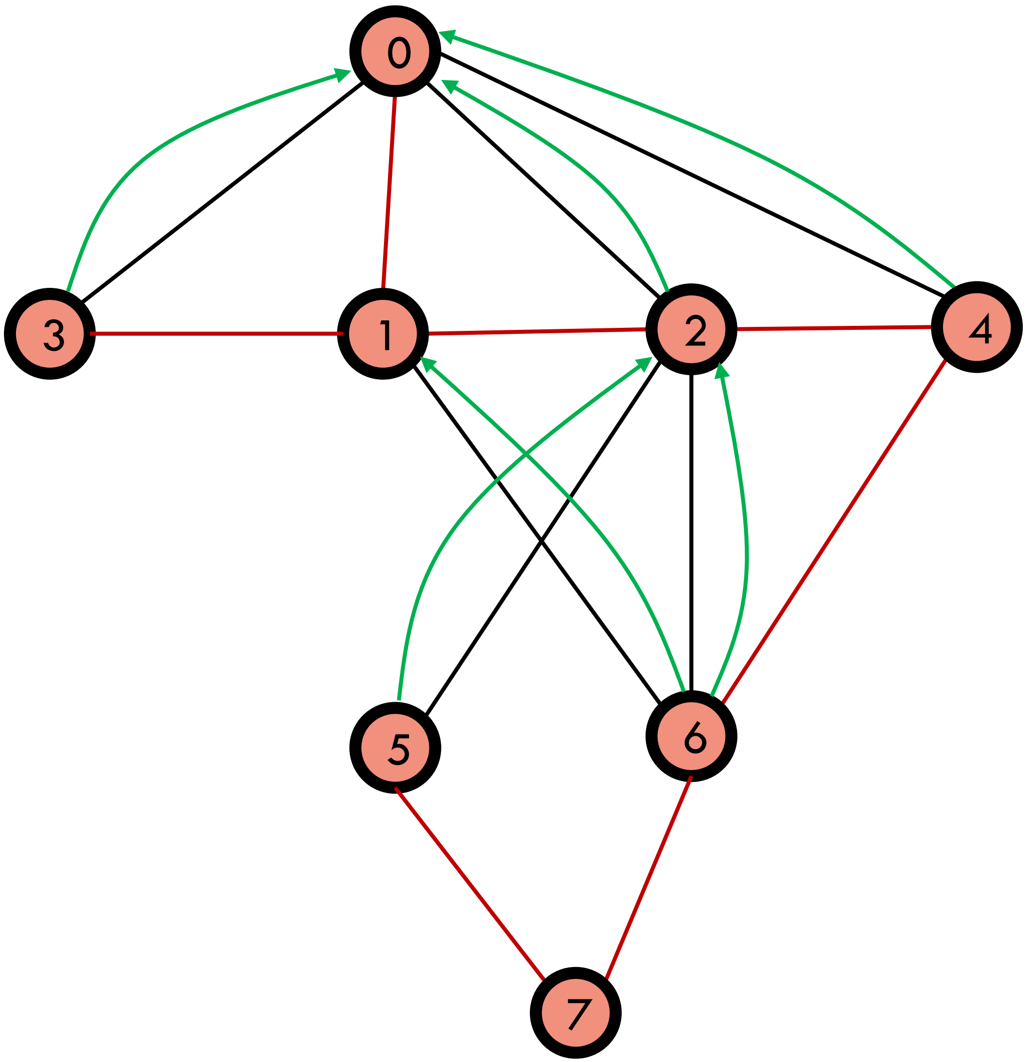


Running time?

Example

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

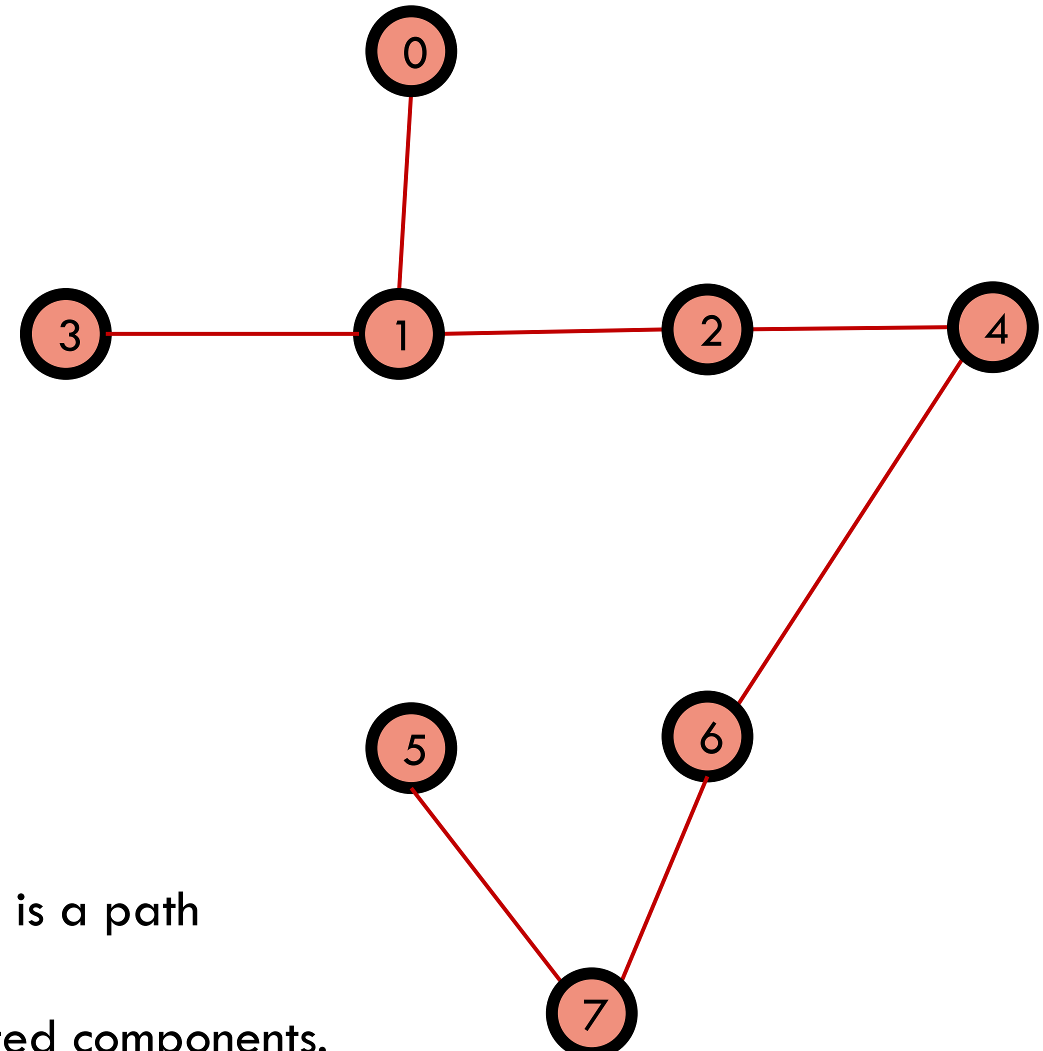
visited	
0	T
1	T
2	T
3	T
4	T
5	T
6	T
7	T



Example

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

	visited
0	T
1	T
2	T
3	T
4	T
5	T
6	T
7	T



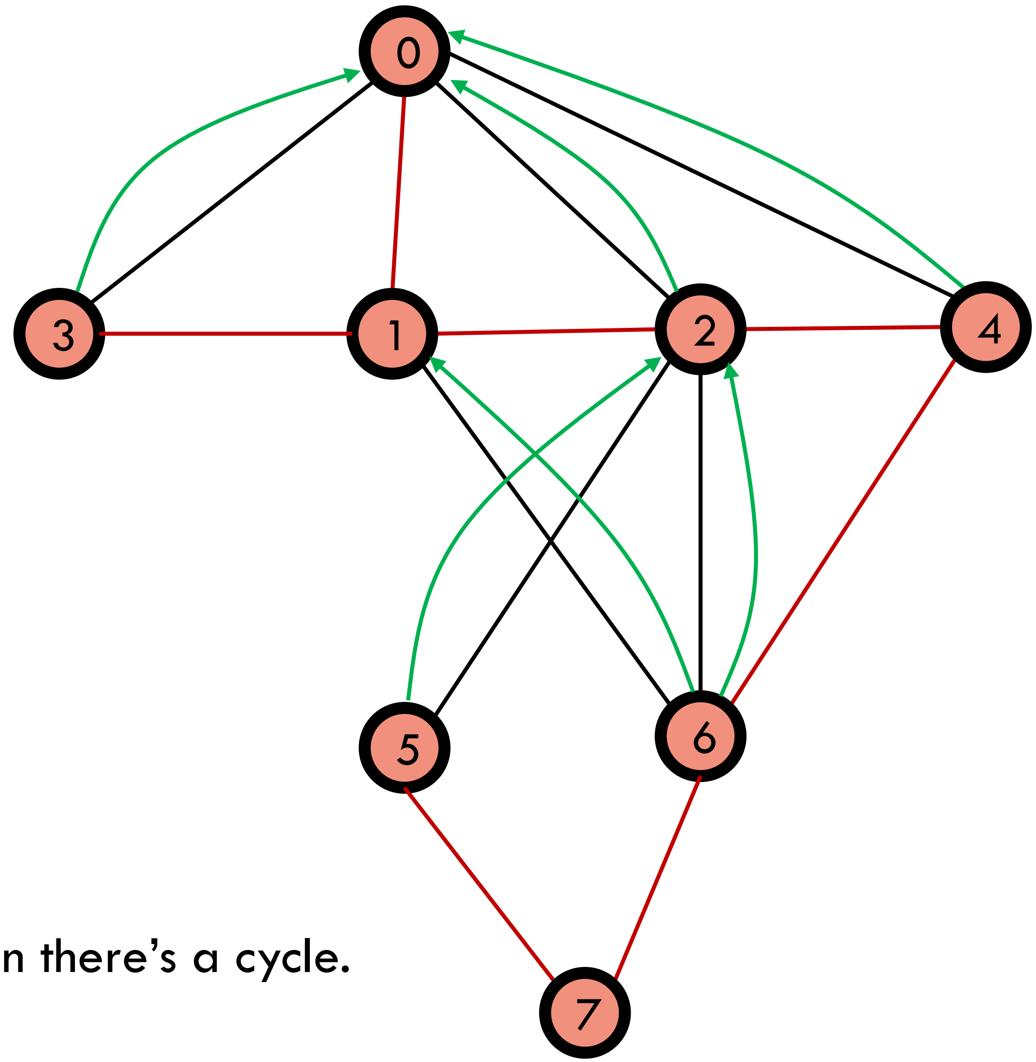
Observation:

Red edges form a spanning tree.

- Can be used to check if there is a path between two edges.
- Can be used to check connected components.

Example

	parent	visited
0		T
1	0	T
2	1	T
3	1	T
4	2	T
5	7	T
6	4	T
7	6	T



Observation:

If there's a back edge (green) then there's a cycle.

DFS main function performance

```
def DFS(G):

  # set things up for DFS
  for u in G.vertices() do
    visited[u] ← False
    parent[u] ← None

  # visit vertices
  for u in G.vertices() do
    if not visited[u] then
      DFS_visit(u)

  return parent
```

Assuming adjacency list representation

O(n) time

O(n) time not counting work done in DFS_visit

DFS_visit performance

Assuming adjacency list representation

O(deg(u)) time not counting work done in recursive calls to DFS_visit

Thus, overall time is

$$O(\textstyle\sum_u \deg(u)) = O(m)$$

```
def DFS_visit(u):

 visited[u] ← True

 # visit neighbors of u
 for v in G.incident(u) do
  if not visited[v] then
   parent[v] ← u
   DFS_visit(v)
```

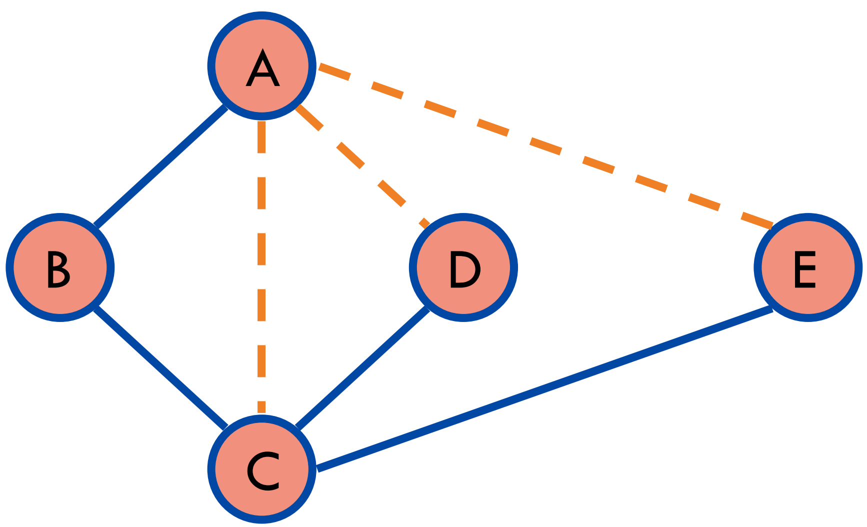
Properties of DFS

Let C_v be the connected component of v in our graph G

Fact: DFS_visit(v) visits all vertices in C_v

Fact: Edges { (u, parent[u]): u in C_v } form a spanning tree of C_v

Fact: Edges { (u, parent[u]): u in V } form a spanning forest of G



DFS Applications

DFS can be used to solve other graph problems in $O(n + m)$ time:

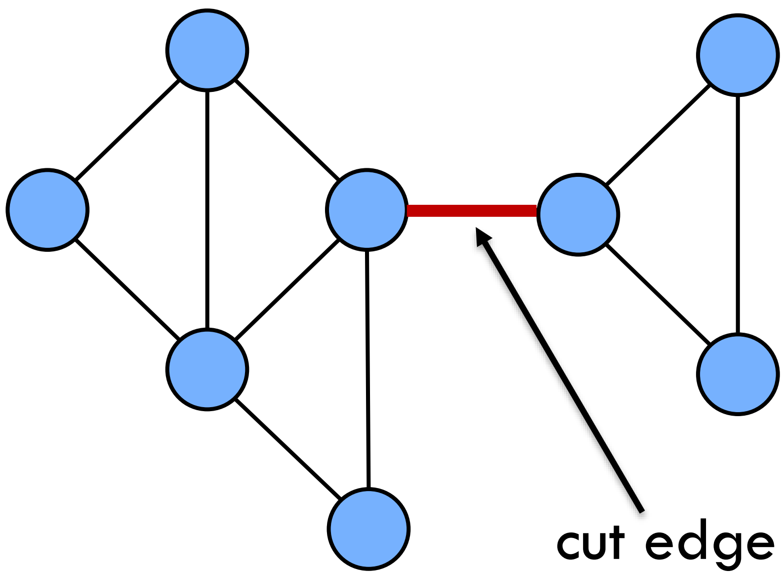
- Find a path between two given vertices, if any
- Find a cycle in the graph
- Test whether a graph is connected
- Compute connected components of a graph
- Compute spanning tree of a graph (if connected)

And is the building block of more sophisticated algorithms:

- testing bi-connectivity
- finding cut edges
- finding cut vertices

Identifying cut edges

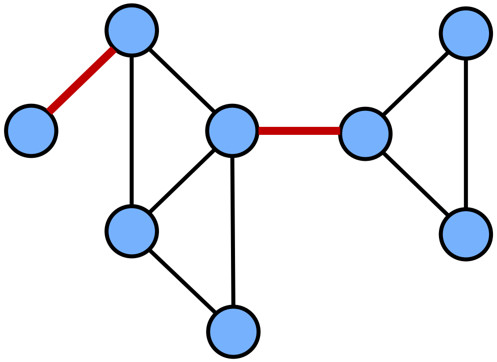
In a connected graph $G=(V, E)$, we say that an edge (u, v) in E is a cut edge if $(V, E \setminus \{(u, v)\})$ is not connected



Identifying cut edges

In a connected graph $G=(V, E)$, we say that an edge (u, v) in E is a cut edge if $(V, E \setminus \{(u, v)\})$ is not connected

The cut edge problem is to identify all cut edges



Trivial $O(m^2)$ time algorithm: For each edge (u,v) in E, remove (u,v) and check using DFS if G is still connected, put back (u,v)

Identifying cut edges

In a connected graph $G=(V, E)$, we say that an edge (u, v) in E is a cut edge if $(V, E \setminus \{(u, v)\})$ is not connected

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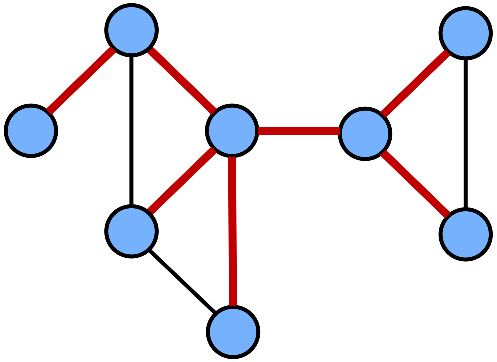


Trivial $O(m^2)$ time algorithm: For each edge (u,v) in E, remove (u,v) and check using DFS if G is still connected, put back (u,v)

Better $O(nm)$ time algorithm: Only test edges in a DFS tree of G

Identifying cut edges in O(n+m) time

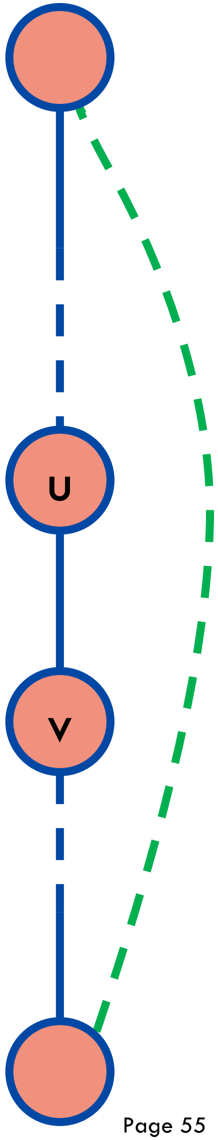
Compute a DFS tree of the input graph G=(V, E)

For every u in V, compute level[u], its level in the DFS tree

For every vertex v compute the highest level that we can reach by taking DFS edges down the tree and then one back edge up. Call this down_and_up[v]

Fact: A DFS edge (u, v) where u = parent[v] is a cut edge if and only if down_and_up[v] > level[u]

Basis of an O(n+m) time algorithm for finding cut edges



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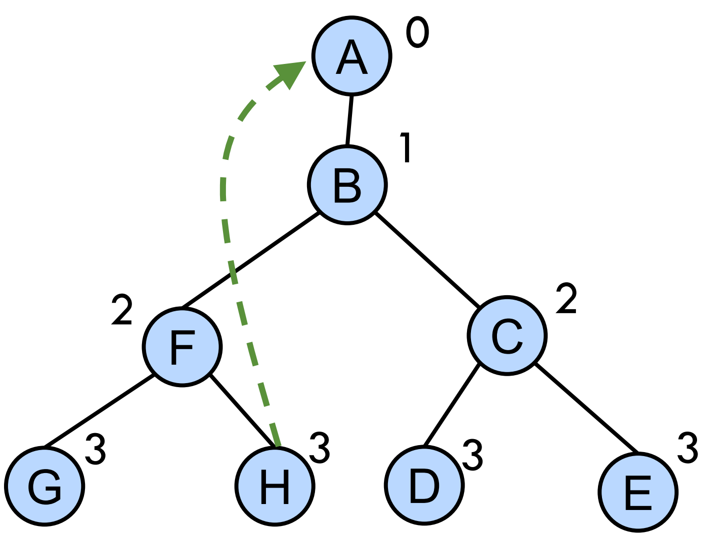

	level	d&u
A		
B		
C		
D		
E		
F		
G		
H		

Identifying cut edges in O(n+m) time

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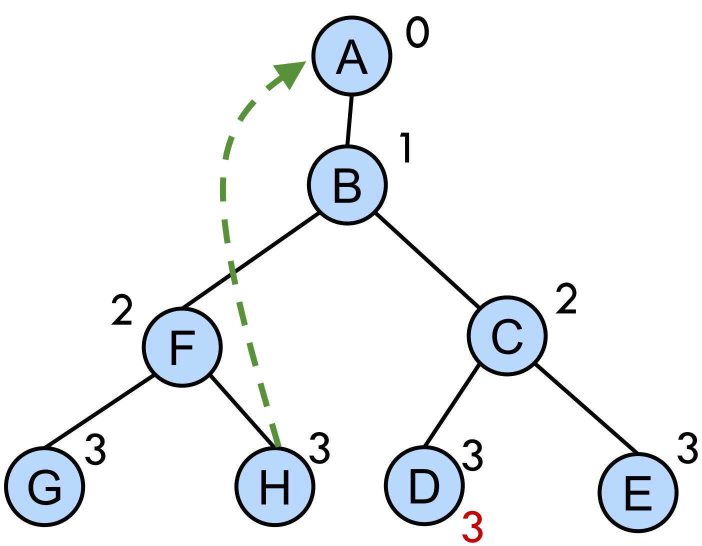

	level	d&u
A	0	
B	1	
C	2	
D	3	
E	3	
F	2	
G	3	
H	3	

Identifying cut edges in O(n+m) time

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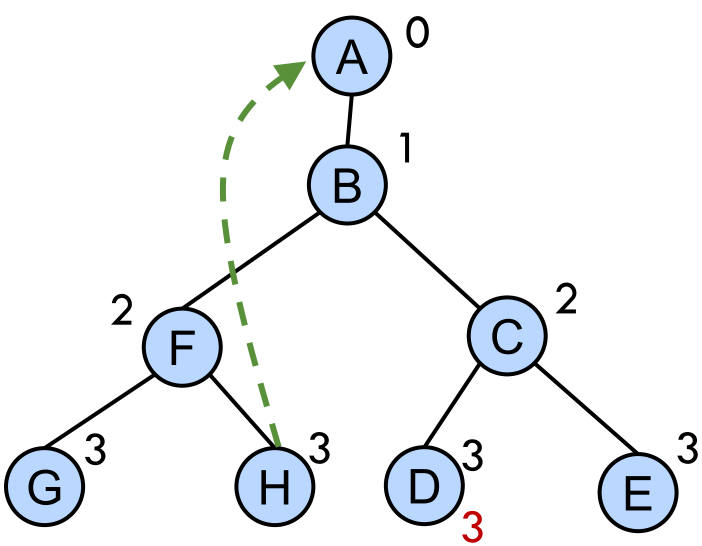

	level	d&u
A	0	
B	1	
C	2	
D	3	3
E	3	
F	2	
G	3	
H	3	

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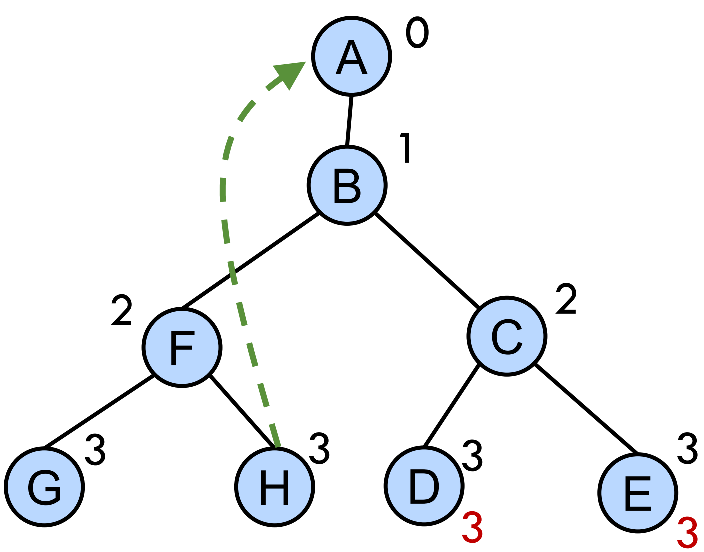

	level	d&u
A	0	
B	1	
C	2	
D	3	3
E	3	3
F	2	
G	3	
H	3	

Identifying cut edges in O(n+m) time

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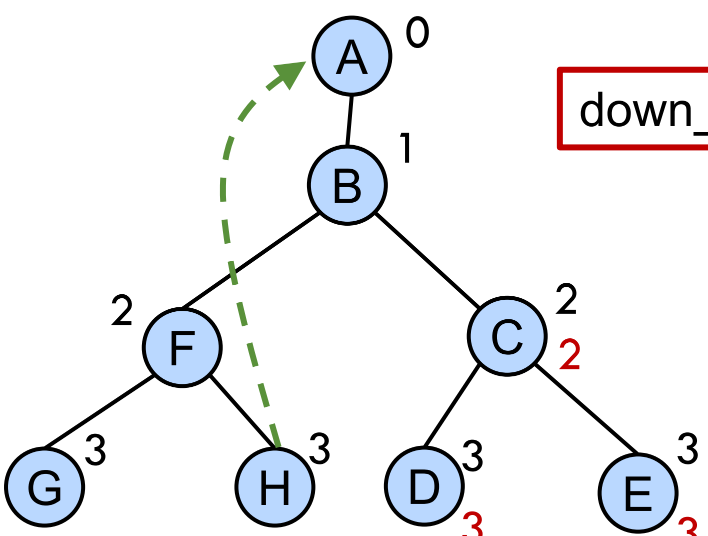
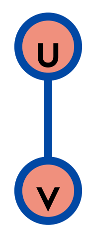


down_and_up[v] > level[u]



	level	d&u
A	0	
B	1	
C	2	2
D	3	3
E	3	3
F	2	
G	3	
H	3	

Identifying cut edges in O(n+m) time

Compute a DFS tree of the input graph G=(V, E)

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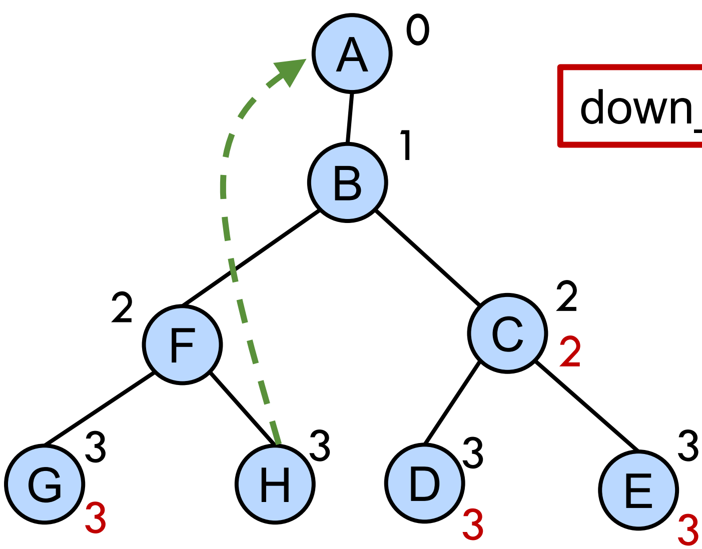
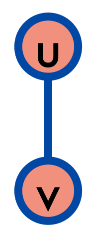


down_and_up[v] > level[u]



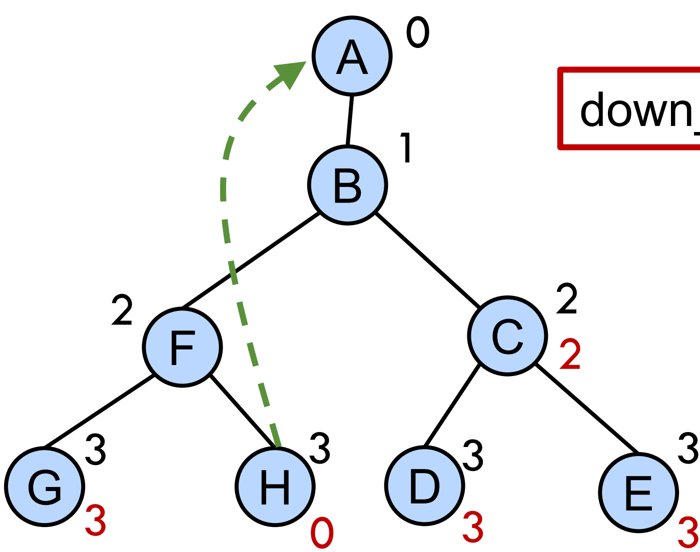
	level	d&u
A	0	
B	1	
C	2	2
D	3	3
E	3	3
F	2	
G	3	3
H	3	

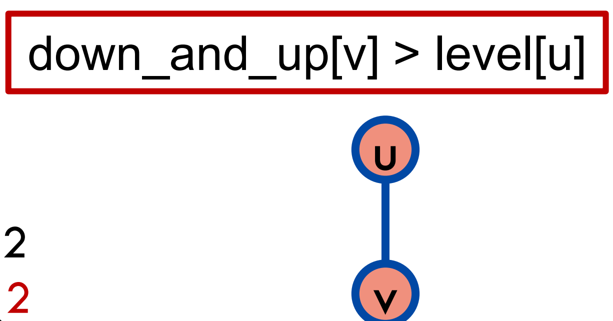
Identifying cut edges in O(n+m) time

Compute a DFS tree of the input graph G=(V, E)

For every u in V, compute level[u], its level in the DFS tree

For every vertex v compute the highest level that we can reach by taking DFS edges down the tree and then one back edge up. Call this down_and_up[v]





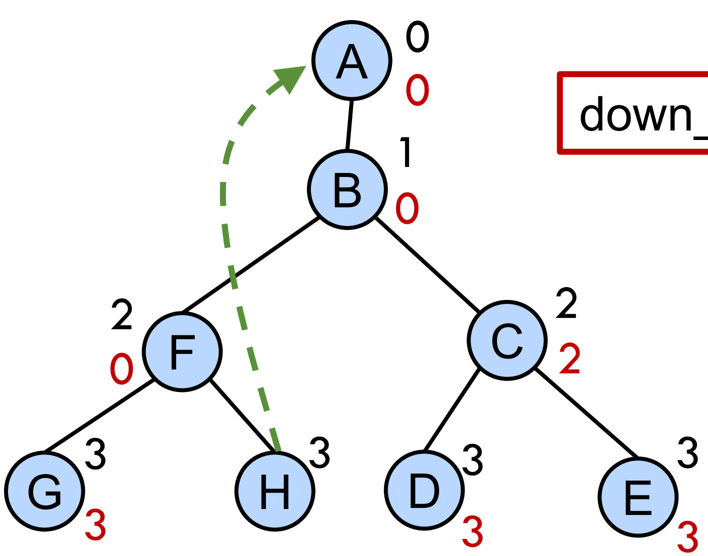
	level	d&u
A	0	
B	1	
C	2	2
D	3	3
E	3	3
F	2	
G	3	3
H	3	0

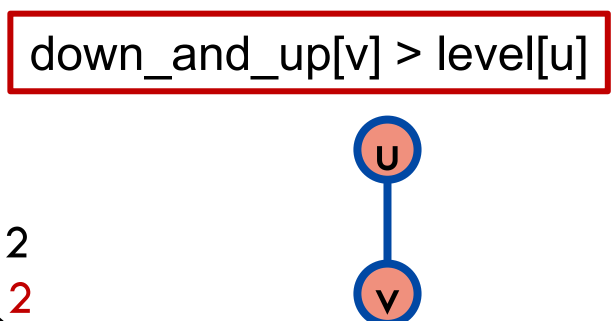
Identifying cut edges in O(n+m) time

Compute a DFS tree of the input graph G=(V, E)

For every u in V, compute level[u], its level in the DFS tree

For every vertex v compute the highest level that we can reach by taking DFS edges down the tree and then one back edge up. Call this down_and_up[v]





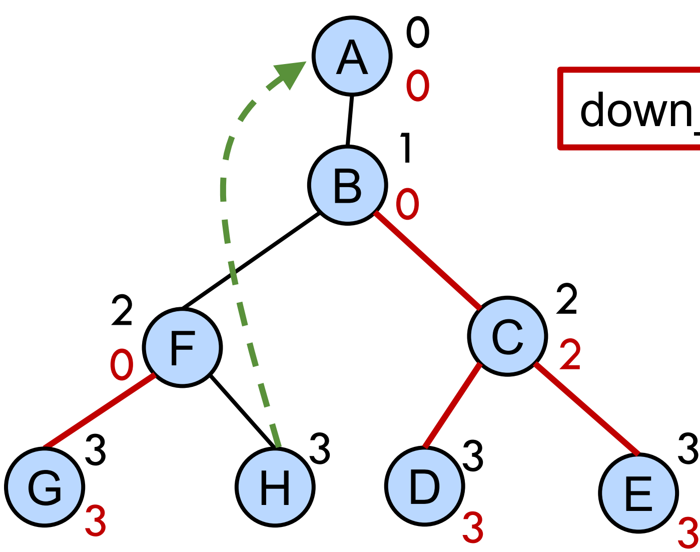
	level	d&u
A	0	0
B	1	0
C	2	2
D	3	3
E	3	3
F	2	0
G	3	3
H	3	0

Identifying cut edges in O(n+m) time

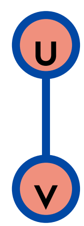
Compute a DFS tree of the input graph G=(V, E)

For every u in V, compute level[u], its level in the DFS tree

For every vertex v compute the highest level that we can reach by taking DFS edges down the tree and then one back edge up. Call this down_and_up[v]



down_and_up[v] > level[u]



	level	d&u
A	0	0
B	1	0
C	2	2
D	3	3
E	3	3
F	2	0
G	3	3
H	3	0

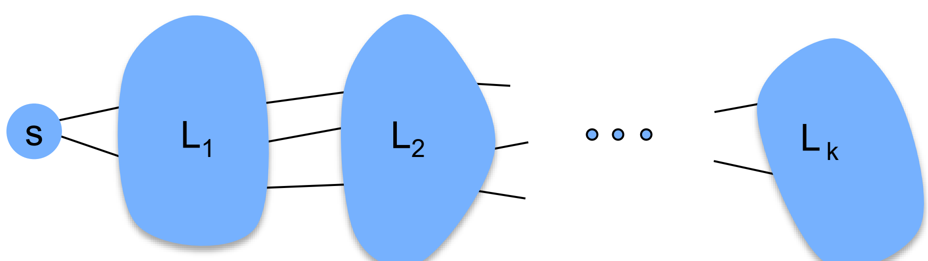
Breadth-First Search (BFS)

This strategy tries to visit all vertices at distance k from a start vertex s before visiting vertices at distance $k + 1$:

- $L_0 = \{s\}$
- L_1 = vertices one hop away from s
- L_2 = vertices two hops away from s but no closer

⋮

- L_k = vertices k hops away from s but no closer



BFS

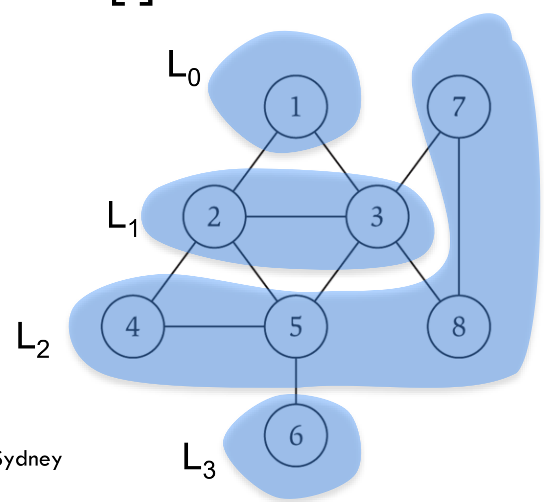
```
def BFS(G,s):

  # set things up for BFS
  for u in G.vertices() do
    seen[u] ← False
    parent[u] ← None

  seen[s] ← True
  layers ← []
  current ← [s]
  next ← []

  # process current layer
  while not current.is_empty() do
    layers.append(current)
    # iterate over current layer
    for u in current do
      for v in G.incident(u) do
        if not seen[v] then
          next.append(v)
          seen[v] ← True
          parent[v] ← u
    # update current & next layers
    current ← next
    next ← []

  return layers, parent
```



BFS

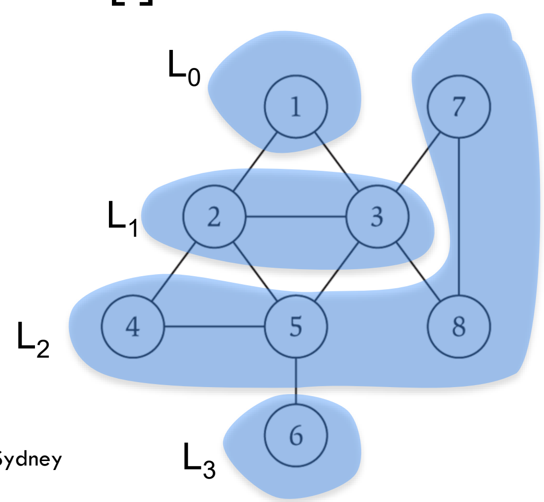
```
def BFS(G,s):

  # set things up for BFS
  for u in G.vertices() do
    seen[u] ← False
    parent[u] ← None

  seen[s] ← True
  layers ← []
  current ← [s]
  next ← []

  # process current layer
  while not current.is_empty() do
    layers.append(current)
    # iterate over current layer
    for u in current do
      for v in G.incident(u) do
        if not seen[v] then
          next.append(v)
          seen[v] ← True
          parent[v] ← u
    # update current & next layers
    current ← next
    next ← []

  return layers, parent
```



Properties

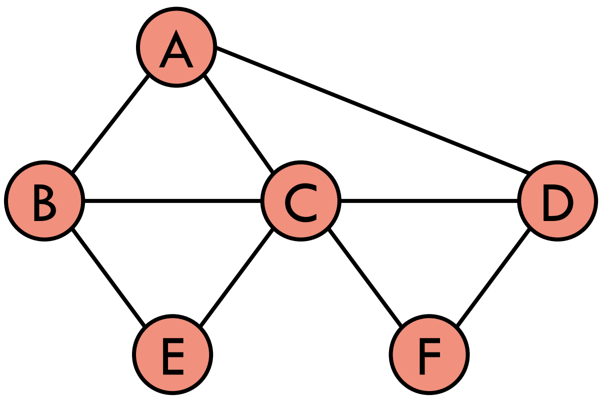
Let C_s be the connected component of s in our graph G

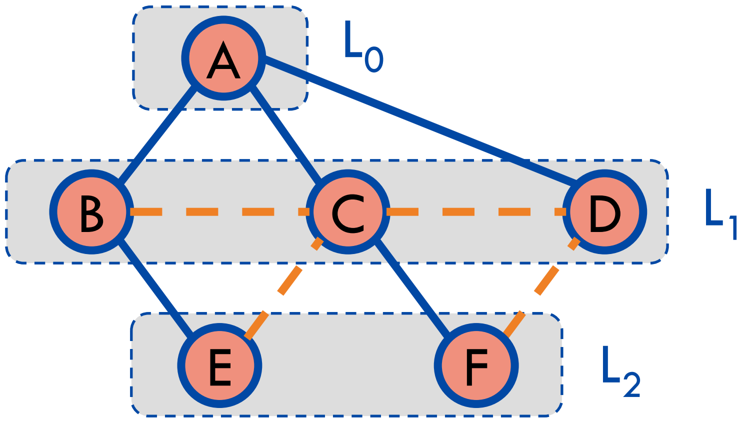
Fact: BFS(G, s) visits all vertices in C_s

Fact: Edges $\{ (u, parent[u]): u \text{ in } C_s \}$ form a spanning tree T_s of C_s

Fact: For each v in L_i there is a path in T_s from s to v with i edges

Fact: For each v in L_i any path in G from s to v has at least i edges





BFS performance

```
def BFS(G,s):

  # set things up for BFS
  for u in G.vertices() do
    seen[u] ← False
    parent[u] ← None

  seen[s] ← True
  layers ← []
  current ← [s]
  next ← []

  # process current layer
  while not current.is_empty() do
    layers.append(current)
    # iterate over current layer
    for u in current do
      for v in G.incident(u) do
        if not seen[v] then
          next.append(v)
          seen[v] ← True
          parent[v] ← u
    # update curr and next layers
    current ← next
    next ← []

  return layers
```

O(n) time

$\boxed{O(\sum_u \deg(u)) = O(m) \text{ time}}$

BFS performance

Fact: Assuming adjacency list representation we can perform a BFS traversal of a graph with n vertices and m edges in $O(n+m)$ time

Fact: Assuming adjacency matrix representation we can perform a BFS traversal of a graph with n vertices and m edges in $O(n^2)$ time

The additional attributes about the vertices (seen and parent) can be associated directly via Vertex class or we can use an external map data structure

BFS Applications

BFS can be used to solve other graph problems in $O(n + m)$ time:

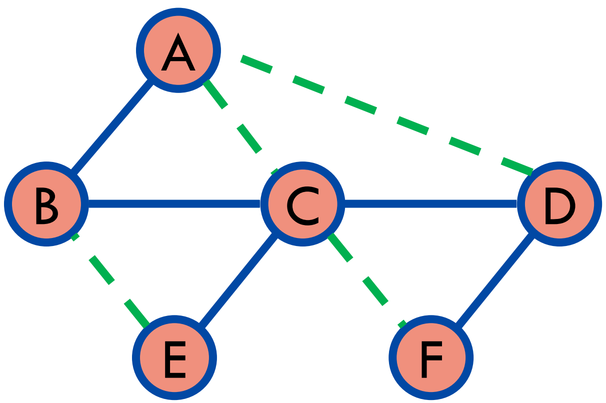
- Find a shortest path between two given vertices
- Find a cycle in the graph
- Test whether a graph is connected
- Compute a spanning tree of a graph (if connected)

And is the building block of more sophisticated algorithms:

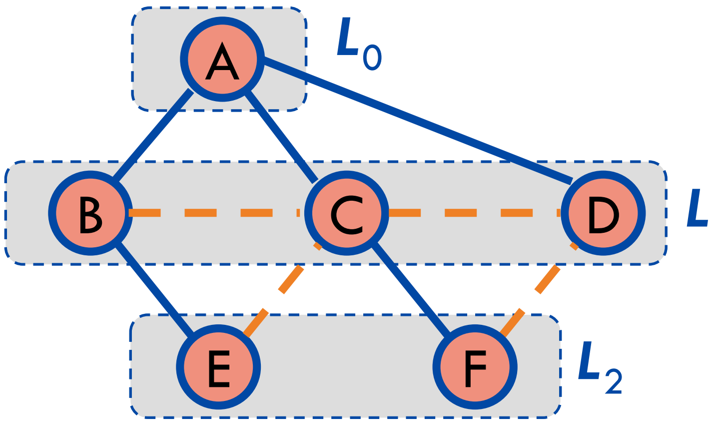
- Testing if graph is bipartite

DFS vs. BFS

Applications	DFS	BFS
Spanning forest, connected components, paths, cycles	√	√
Shortest paths		√
Cut edges	√	



DFS



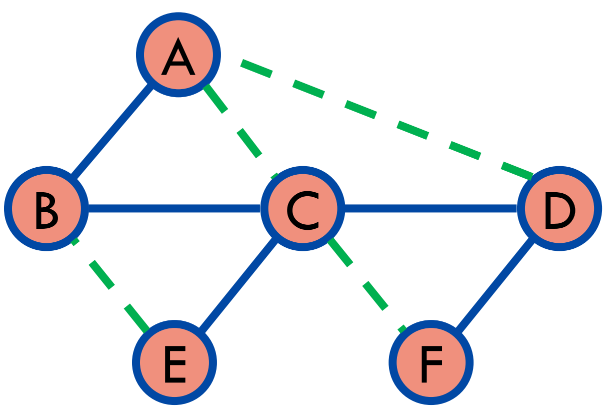
BFS

DFS vs. BFS (cont.)

Non-tree DFS edge (v, w)

w is an ancestor of v in the DFS tree

Called back edges

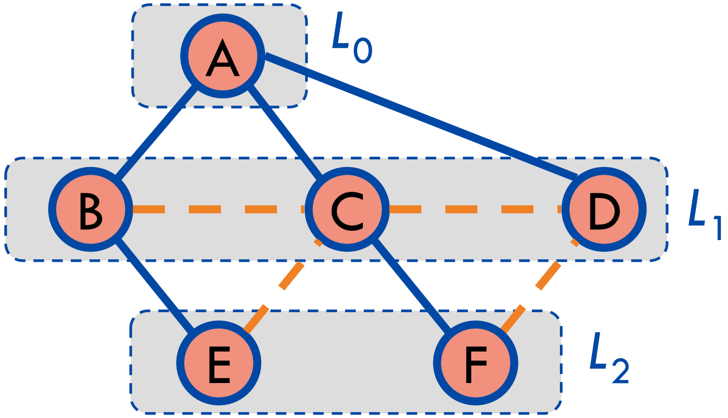


DFS

Non-tree BFS edge (v, w)

w is in the same level as v or in the next level

Called cross edges



BFS

Directed Graphs

Both DFS and BFS can be adapted to run in directed graphs:
When visiting vertex u, iterate over edges out of u

Both algorithm run in $O(n + m)$ time.

However, there are differences on the type of non-tree edges we can have.

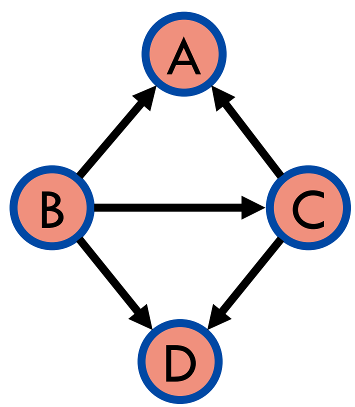
Topological Sort

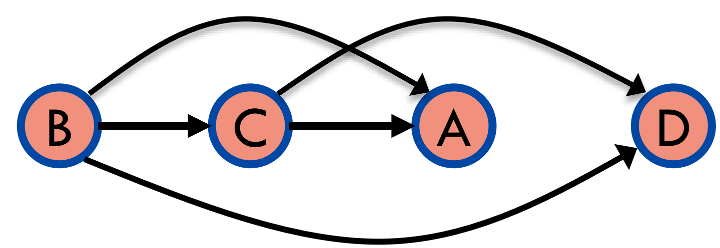
Directed Acyclic Graphs (DAG) have no directed cycles

Every DAG can be topologically sorted: Vertices can be laid out from left to right such that all edges go left to right as well.

For example, consider the graph on the right.
It admits two topological sorts:

- [B, C, A, D]
- [B, C, D, A]





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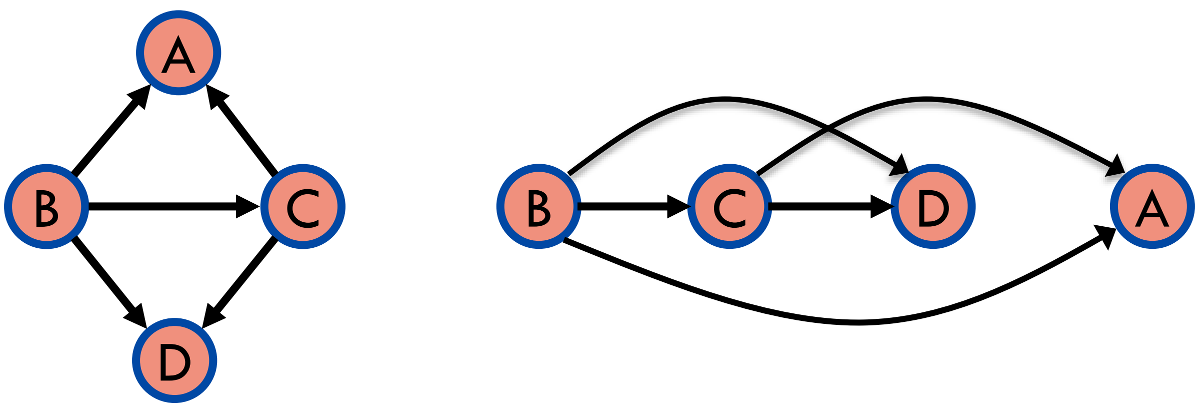


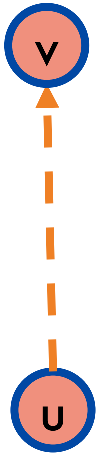
DFS based topological sort

```
def topo(G):

  run DFS on G
  for (u, v) in G.edges() do
    if (u, v) is a back edge then
      return “G is not acyclic”

  ans ← [ u for u in G.vertices()]
  sort ans in reverse order of DFS-visit call finish

  return ans
```



Correctness:

- Suppose (u, v) in E and u occurs after v in ans (i.e., v’s DFS call ends after u’s DFS call).
- This implies that (u, v) is a back edge, contradicting that G is a DAG.

DFS based topological sort running time

```
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```

To implement the algorithm efficiently, we can augment DFS-visit to perform the back edge check and build ans on the fly without increasing the time complexity of $O(n + m)$

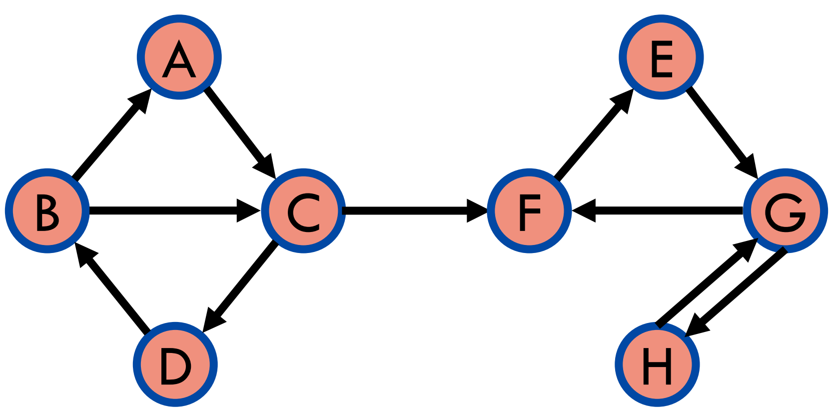
Strongly connected components

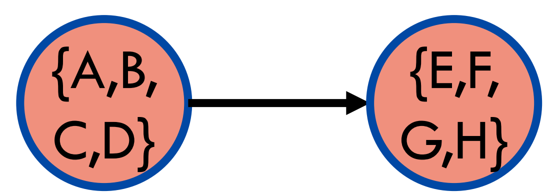
Let $G=(V, E)$ be a <u>directed</u> graph. A strongly connected component (SCC) of G is a subset C of vertices such that

- For any $u,v \in C$, there is a u-v path in G
- No superset of C has the above property

The SCC graph of G is $G^{SSC} = (V^{SCC}, E^{SCC})$ where

- $V^{SCC} = \{ C : C \text{ is a SCC of } G \}$
- $E^{SCC} = \{ (C, C') : \text{there is } u \in C \text{ and } v \in C' \text{ such that } (u,v) \in E \}$





The SCC problem

Given a directed graph G, compute G^{SCC}.

Notice that we only need to compute V^{SCC}

What is the trivial algorithm for this problem?

– Find one SCC
– Remove
– Iterate

The running time of the trivial algorithm is $O(n (m + n))$, where $O(m + n)$ is the time it takes to compute a single SCC

DFS-based algorithm for SCC

Time complexity:

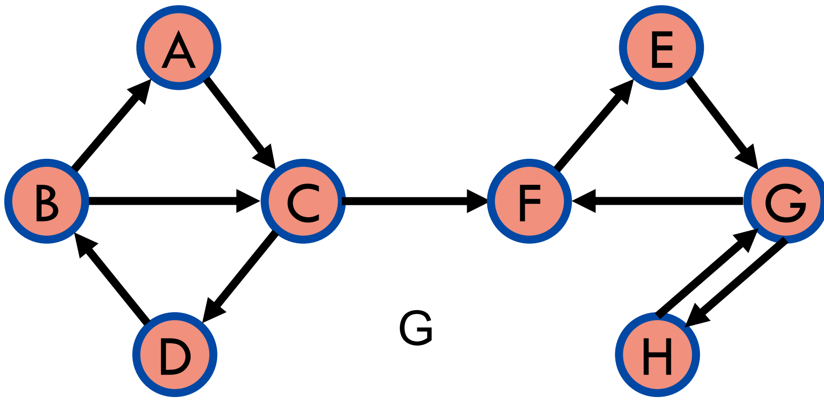
– DFS takes in O(n+m) time
– Building F takes O(n+m) time
– "Reading" components from DFS forest takes O(n) time

```
def SCC(G):

  DFS(G)
  F ← copy of G with reversed edges
  run DFS on F but process vertices in
    reverse order of DFS-visit call finish
  components ← []
  for tree T in DFS(F) forest:
     components.append(vertices in T)

  return components
```

DFS-based algorithm for SCC

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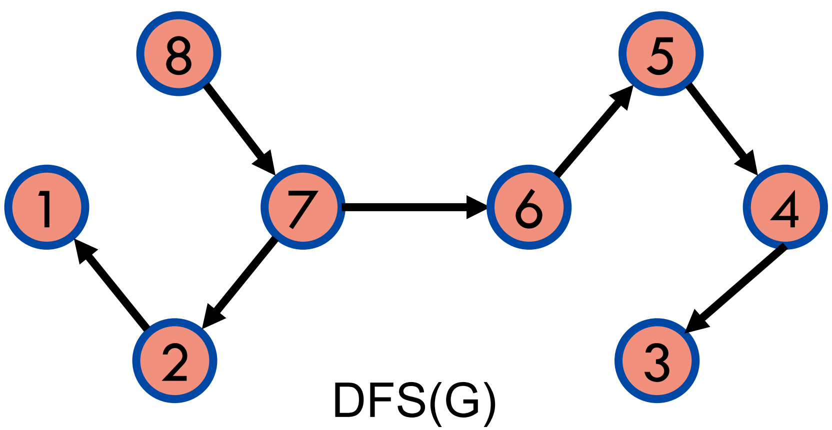
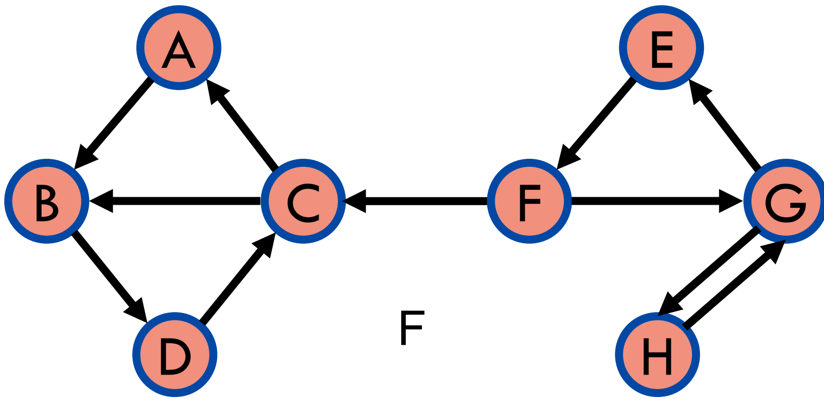


DFS-based algorithm for SCC: Run DFS(F)

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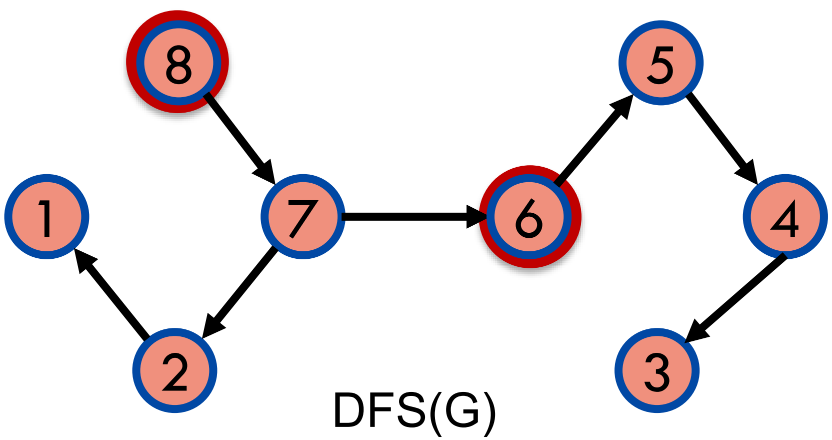

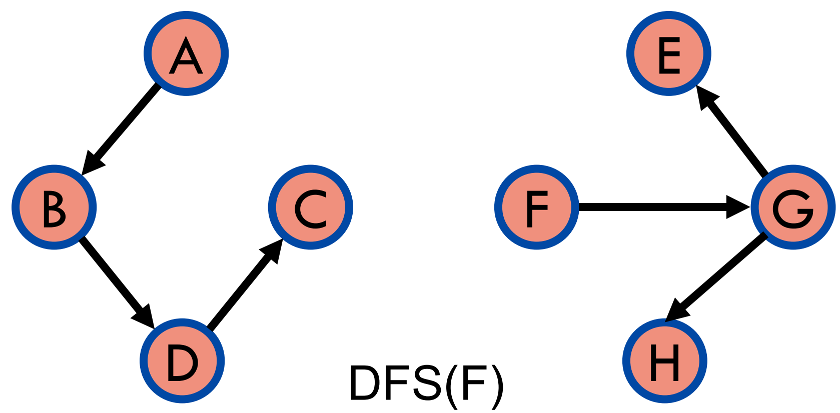

DFS-based algorithm for SCC

Correctness (sketch):

– Let T_r be a tree in DFS(F) forest rooted at r and let C_r be the SCC that r belongs to. We aim to show that $T_r = C_r$

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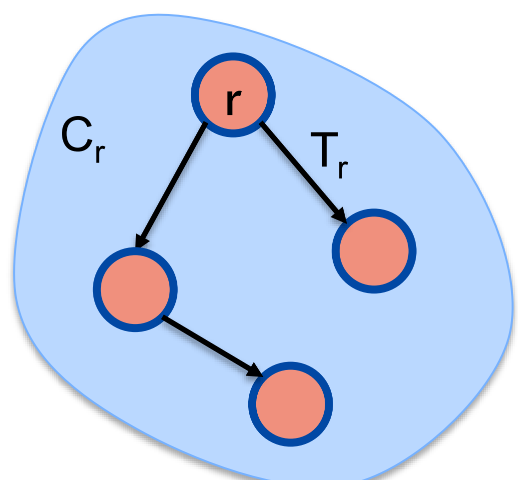

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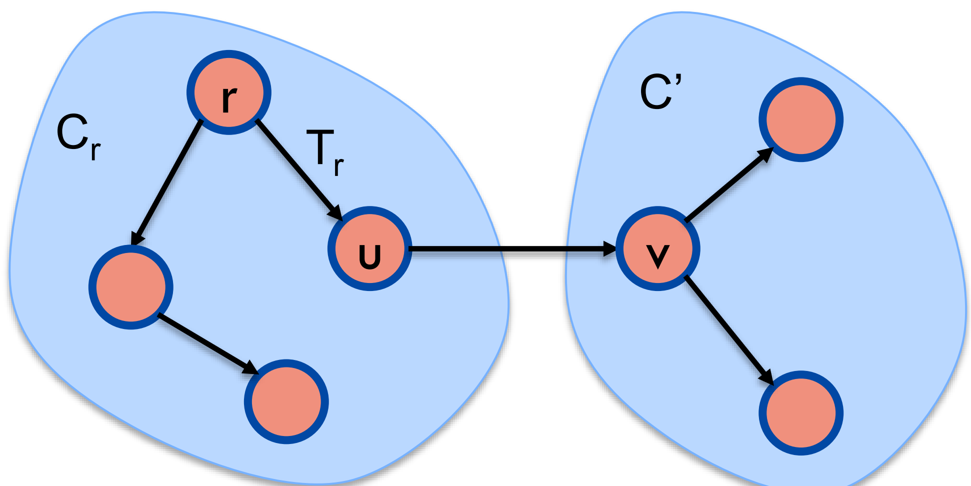

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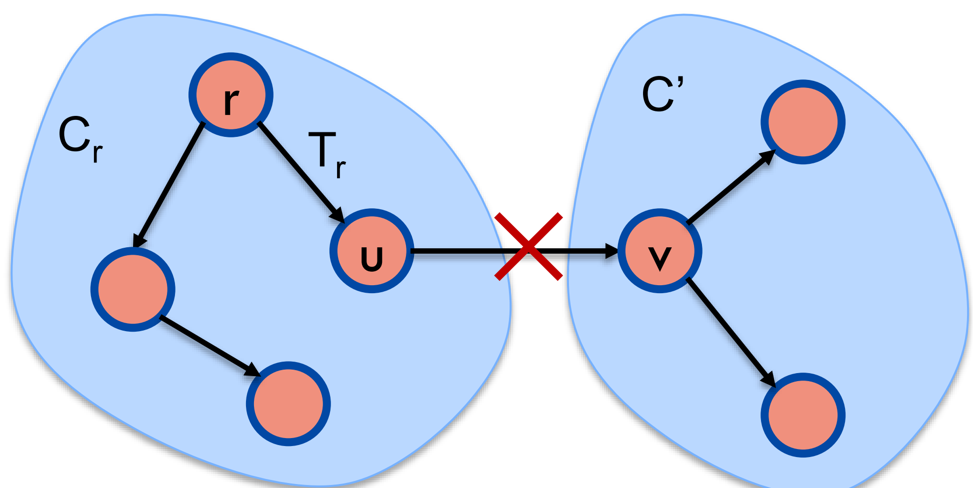
– Suppose there is an edge (u, v) in G connecting two SCCs C_r and C' such that u in C_r and v in C'. Then finish[C_r] > finish[C'].

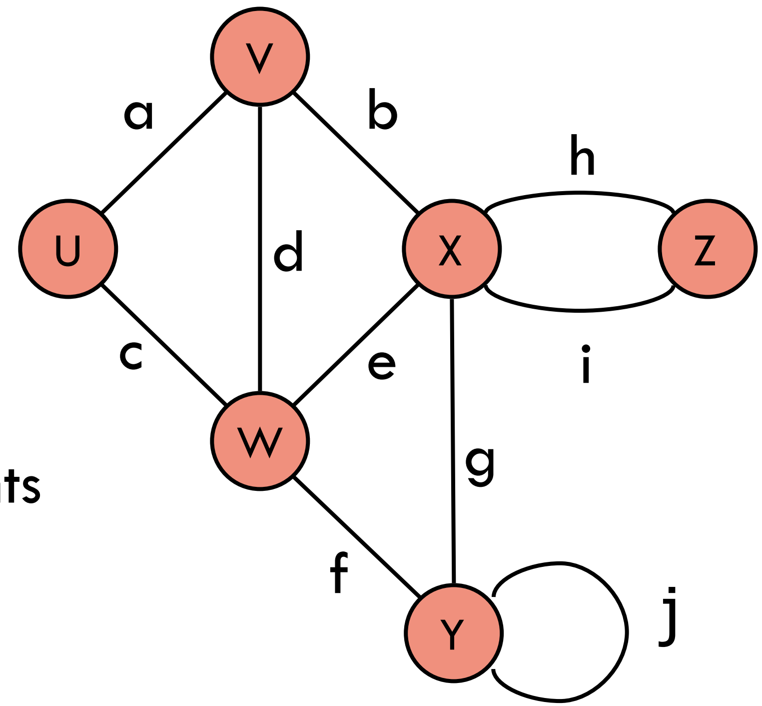
– Since we started from r with the highest finish time, there can be no edges from C_r to another SCC

– It follows that C_r is the only SCC in T_r



Terminology (Undirected graphs)

- Edges connect endpoints
  e.g., W and Y for edge f
- Edges are incident on endpoints
  e.g., a, d, and b are incident on V
- Adjacent vertices are connected
  e.g., U and V are adjacent
- Degree is # of edges on a vertex
  e.g., X has degree 5
- Parallel edges share same endpoints
  e.g., h and i are parallel
- Self-loop have only one endpoint
  e.g., j is a self-loop
- Simple graphs have no parallel or self-loops



Terminology (Directed graphs)

- Edges go from tail to head
  e.g., W is the tail of c and U its head
- Out-degree is # of edges out of a vertex
  e.g., W has out-degree 2
- In-degree is # of edges into a vertex
  e.g., W has in-degree 1
- Parallel edges share tail and head
  e.g., no parallel edge on the right
- Self-loop have same head and tail
  e.g., X has a self-loop
- Simple directed graphs have no parallel or self-loops, but are allowed to have anti-parallel loops like f and a