# CSE 421: Introduction to Algorithms

## Graph Traversal

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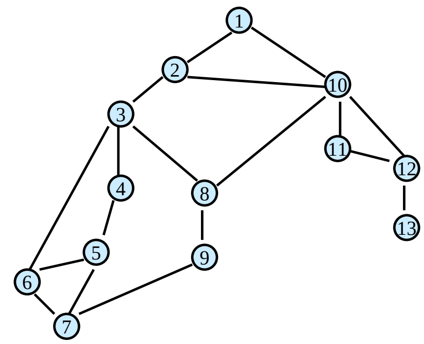
## Undirected Graph G = (V,E)

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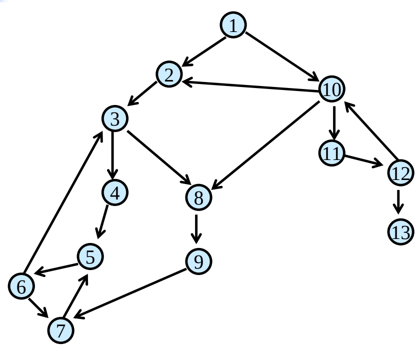
## Directed Graph G = (V,E)

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## Graph Traversal

- Learn the basic structure of a graph
- Walk from a fixed starting vertex s to find all vertices reachable from s
- Three states of vertices
  - **unvisited**
  - **visited/discovered**
  - **fully-explored**

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## Generic Graph Traversal Algorithm

Find: set **R** of vertices reachable from **s∈V**

Reachable(**s**):
  **R**← {**s**}
  While there is a (**u**,**v**)∈**E** where **u**∈**R** and **v**∉**R**
    Add **v** to **R**

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## Generic Traversal Always Works

- Claim: At termination **R** is the set of nodes reachable from **s**
- Proof
  - ⊆: For every node **v∈R** there is a path from s to v
  - ⊇: Suppose there is a node **w∉R** reachable from s via a path **P**
    - Take first node **v** on **P** such that **v∉R**
    - Predecessor **u** of **v** in **P** satisfies
      - **u ∈ R**
      - **(u,v)∈E**
    - But this contradicts the fact that the algorithm exited the while loop.

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## Breadth-First Search

- Completely explore the vertices in order of their distance from s
- Naturally implemented using a queue

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## BFS(s)

Global initialization: mark all vertices "unvisited"

BFS(**s**)
    mark **s** "visited"; R←{s}; layer $L_0$←{s}
    while $\mathbf{L_i}$ not empty
        $\mathbf{L_{i+1}} \leftarrow \varnothing$
        For each $\mathbf{u \in L_i}$
            for each edge {**u**,**v**}
                if (**v** is "unvisited")
                    mark **v** "visited"
                    Add **v** to set **R** and to layer $\mathbf{L_{i+1}}$
        mark **u** "fully-explored"

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## Properties of BFS(v)

- BFS(**s**) visits **x** if and only if there is a path in **G** from **s** to **x**.
- Edges followed to undiscovered vertices define a "breadth first spanning tree" of **G**
- Layer **i** in this tree, $\mathbf{L_i}$
  - those vertices **u** such that the shortest path in **G** from the root **s** is of length **i**.
- On undirected graphs
  - All non-tree edges join vertices on the same or adjacent layers

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## Properties of BFS

- On undirected graphs
  - All non-tree edges join vertices on the same or adjacent layers
  - Suppose not
    - Then there would be vertices **(x,y)** such that $\mathbf{x \in L_i}$ and $\mathbf{y \in L_j}$ and $\mathbf{j>i+1}$
    - Then, when vertices incident to **x** are considered in BFS **y** would be added to $\mathbf{L_{i+1}}$ and not to $\mathbf{L_j}$

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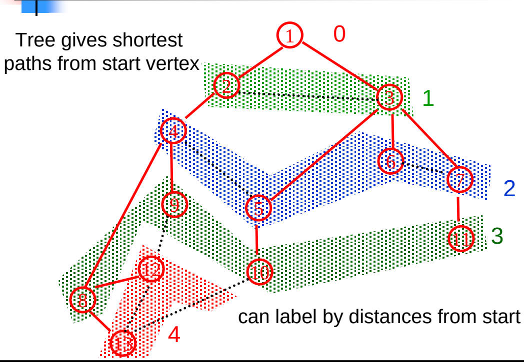
## BFS Application: Shortest Paths

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## Graph Search Application: Connected Components

- Want to answer questions of the form:
  - Given: vertices **u** and **v** in **G**
  - Is there a path from **u** to **v**?
- Idea: create array **A** such that
  **A[u]** = smallest numbered vertex that is connected to **u**
  - question reduces to whether **A[u]=A[v]**?

Q: Why not create an array **Path[u,v]**?

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## Graph Search Application: Connected Components

- initial state: all **v** unvisited
  for **s**←**1** to **n** do
  if state(**s**) ≠ "fully-explored" then
  BFS(**s**): setting **A**[**u**] ←**s** for each **u** found
  (and marking **u** visited/fully-explored)
  endif
  endfor
- Total cost: **O(n+m)**
  - each vertex is touched once in this outer procedure and the edges examined in the different BFS runs are disjoint
  - works also with Depth First Search

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## DFS(u) – Recursive version

Global Initialization: mark all vertices "unvisited"
DFS(**u**)
mark **u** "visited" and add **u** to **R**
for each edge {**u**,**v**}
if (**v** is "unvisited")
DFS(**v**)
end for
mark **u** "fully-explored"

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## Properties of DFS(s)

- Like BFS(**s**):
  - DFS(**s**) visits **x** if and only if there is a path in **G** from **s** to **x**
  - Edges into undiscovered vertices define a "depth first spanning tree" of **G**
- Unlike the BFS tree:
  - the DFS spanning tree isn't minimum depth
  - its levels don't reflect min distance from the root
  - non-tree edges never join vertices on the same or adjacent levels
- BUT…

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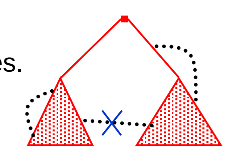
## Non-tree edges

- All non-tree edges join a vertex and one of its descendents/ancestors in the DFS tree
- No cross edges.



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## No cross edges in DFS on undirected graphs

- Claim: During **DFS(x)** every vertex marked visited is a descendant of **x** in the DFS tree **T**
- Claim: For every **x,y** in the DFS tree **T**, if **(x,y)** is an edge not in **T** then one of **x** or **y** is an ancestor of the other in **T**
- Proof:
  - One of **x** or **y** is visited first, suppose WLOG that **x** is visited first and therefore **DFS(x)** was called before **DFS(y)**
    - During **DFS(x)**, the edge **(x,y)** is examined
  - Since **(x,y)** is a not an edge of **T**, **y** was visited when the edge **(x,y)** was examined during **DFS(x)**
  - Therefore **y** was visited during the call to **DFS(x)** so **y** is a descendant of **x**.

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## Applications of Graph Traversal: Bipartiteness Testing

- Easy: A graph G is not bipartite if it contains an odd length cycle
- WLOG: G is connected
  - Otherwise run on each component
- Simple idea: start coloring nodes starting at a given node s
  - Color s red
  - Color all neighbors of s blue
  - Color all their neighbors red
  - If you ever hit a node that was already colored
    - the same color as you want to color it, ignore it
    - the opposite color, output error

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## BFS gives Bipartiteness

- Run BFS assigning all vertices from layer $L_i$ the color i mod 2
  - i.e. red if they are in an even layer, blue if in an odd layer
- If there is an edge joining two vertices from the same layer then output “Not Bipartite”

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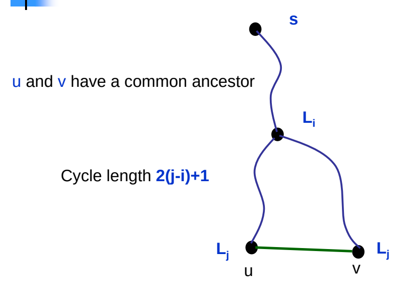
## Why does it work?

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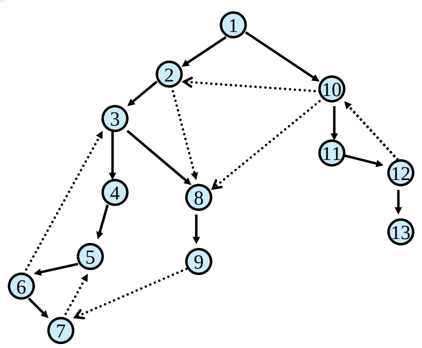
## DFS(v) for a directed graph

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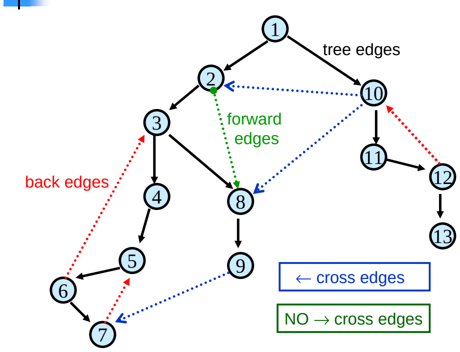
## DFS(v)

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## Properties of Directed DFS

- Before DFS(s) returns, it visits all previously unvisited vertices reachable via directed paths from s
- Every cycle contains a back edge in the DFS tree

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## Directed Acyclic Graphs

- A directed graph G=(V,E) is acyclic if it has no directed cycles
- Terminology: A directed acyclic graph is also called a DAG

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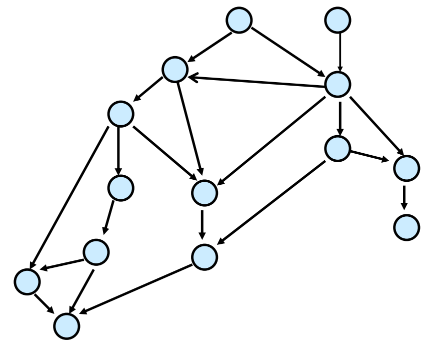
## Topological Sort

- **Given:** a directed acyclic graph (DAG) **G=(V,E)**
- **Output:** numbering of the vertices of **G** with distinct numbers from **1** to **n** so edges only go from lower number to higher numbered vertices

- Applications
  - nodes represent tasks
  - edges represent precedence between tasks
  - topological sort gives a sequential schedule for solving them



## Directed Acyclic Graph





## In-degree 0 vertices

- Every DAG has a vertex of in-degree 0
- Proof: By contradiction
  - Suppose every vertex has some incoming edge
  - Consider following procedure:

    while (true) do

    **v**←some predecessor of **v**

  - After **n+1** steps where **n**=|**V**| there will be a repeated vertex
    - This yields a cycle, contradicting that it is a DAG



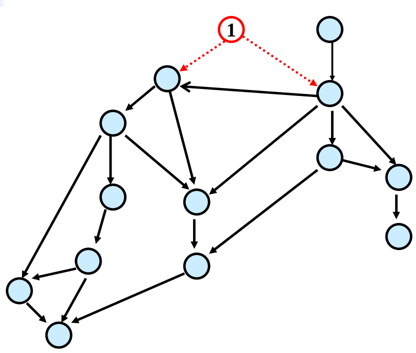
## Topological Sort

- Can do using DFS

- Alternative simpler idea:
  - Any vertex of in-degree 0 can be given number 1 to start
  - Remove it from the graph and then give a vertex of in-degree 0 number 2, etc.



## Topological Sort



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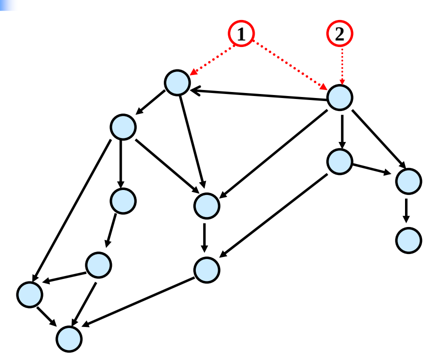

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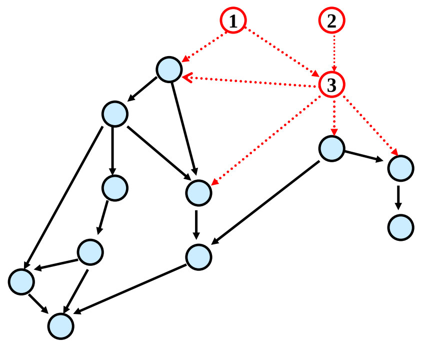




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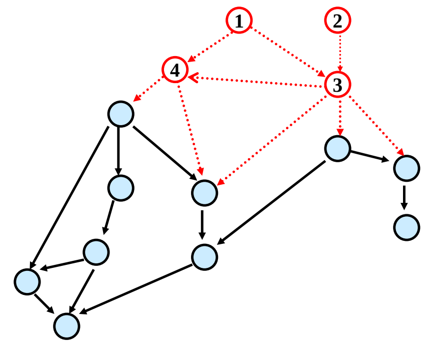




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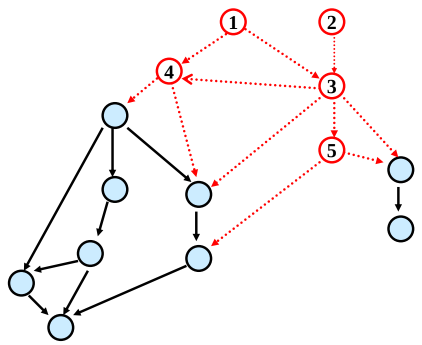




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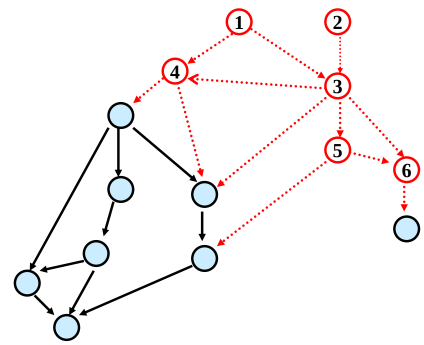




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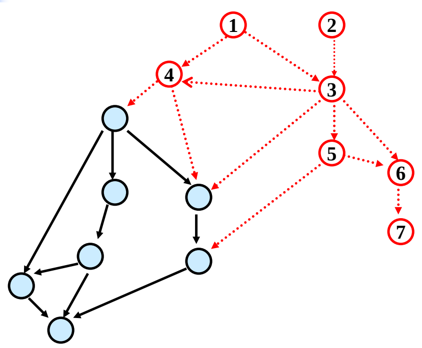




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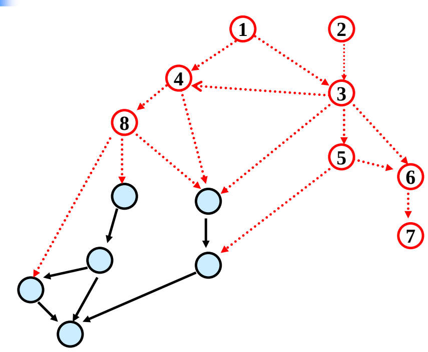

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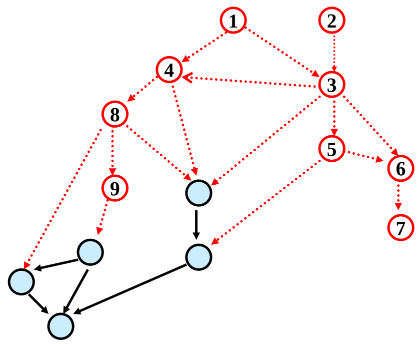


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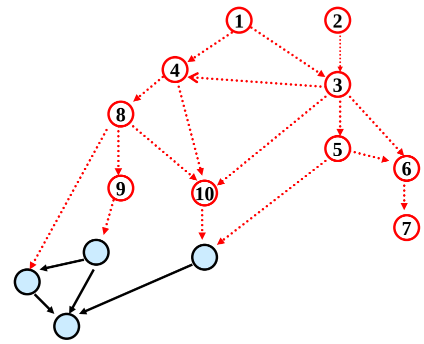


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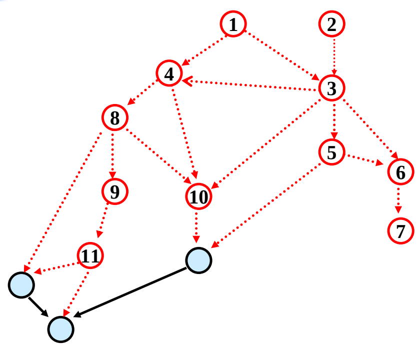


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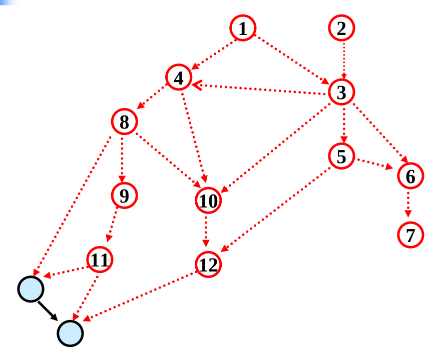


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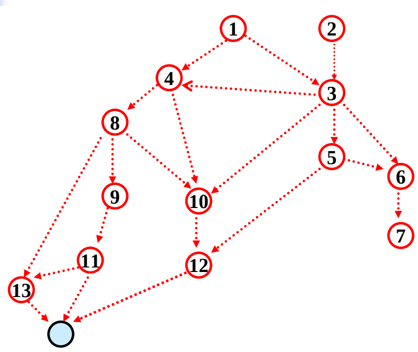


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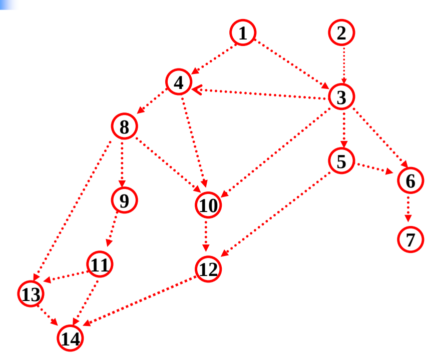


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## Implementing Topological Sort

- Go through all edges, computing in-degree for each vertex **O(m+n)**
- Maintain a queue (or stack) of vertices of in-degree **0**
- Remove any vertex in queue and number it
- When a vertex is removed, decrease in-degree of each of its neighbors by **1** and add them to the queue if their degree drops to **0**
- Total cost **O(m+n)**

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