CSE 332 Summer 2024
Lecture 16: Graphs

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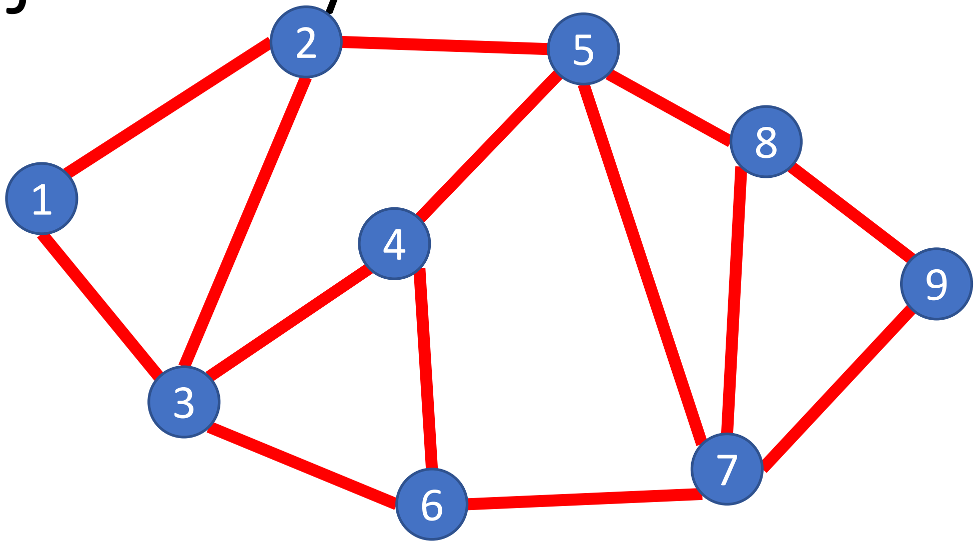
http://www.cs.uw.edu/332

Adjacency List



1	2	3		
2	1	3	5	
3	1	2	4	6
4	3	5	6	
5	2	4	7	8
6	3	4	7	
7	5	6	8	9
8	5	7	9	
9	7	8		

<u>Time/Space Tradeoffs</u>

Space to represent: $\Theta(n+m)$

Add Edge (v,w): $\Theta(\deg(v))$

Remove Edge (v,w): $\Theta(\deg(v))$

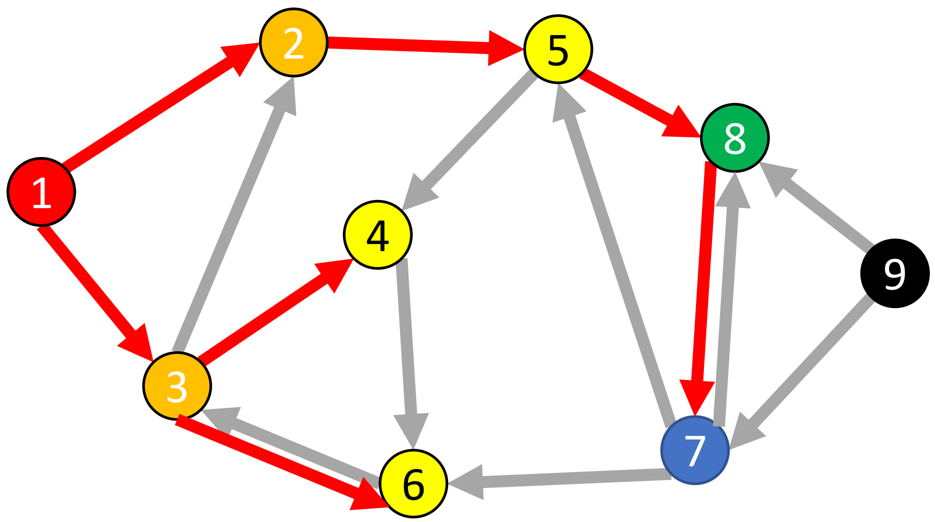
Check if Edge (v,w) Exists: $\Theta(\deg(v))$

Get Neighbors (incoming): $\Theta(n+m)$

Get Neighbors (outgoing): $\Theta(\deg(v))$

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

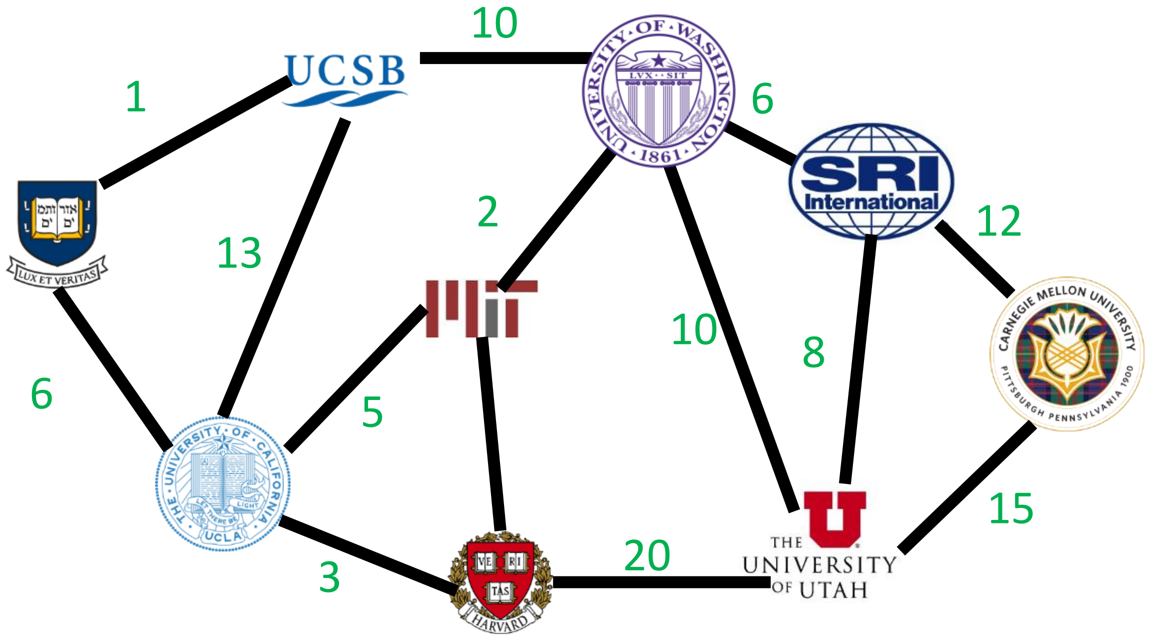
Shortest Path (unweighted)



Idea: when it's seen, remember its "layer" depth!

```
int shortestPath(graph, s, t){
        found = new Queue();
        layer = 0;
        found.enqueue(s);
        mark s as "visited";
        While (!found.isEmpty()){
                current = found.dequeue();
                layer = depth of current;
                for (v : neighbors(current)){
                        if (! v marked "visited"){
                                mark v as "visited";
                                depth of v = layer + 1;
                                found.enqueue(v);
                        }
                }
        }
        return depth of t;
}
```

Single-Source Shortest Path



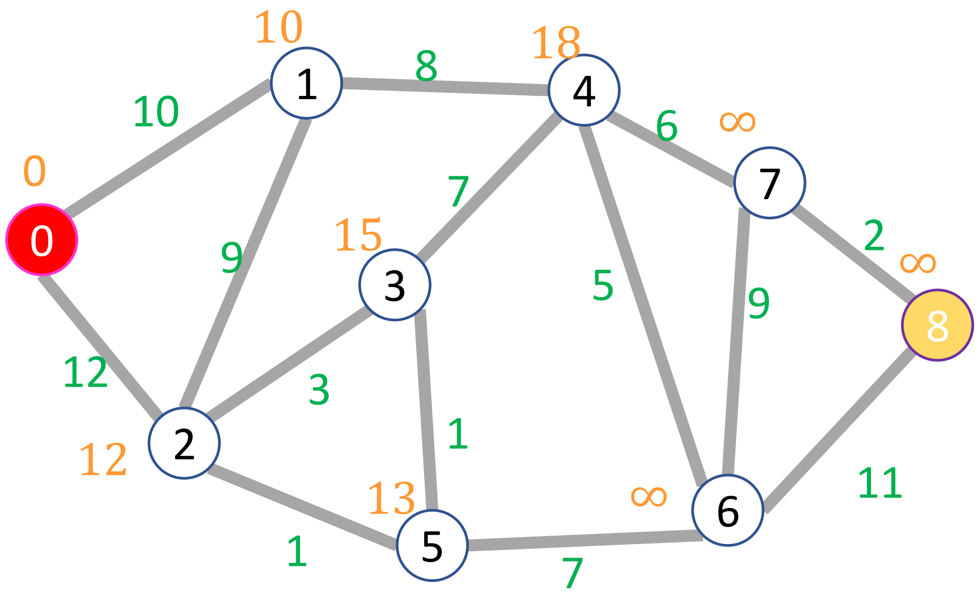
Find the quickest way to get from UW to each of these other places

Given a graph $G = (V, E)$ and a start node $s \in V$, for each $v \in V$ find the least-weight path from $s \to v$ (call this weight $\delta(s, v)$)

(assumption: all edge weights are positive)

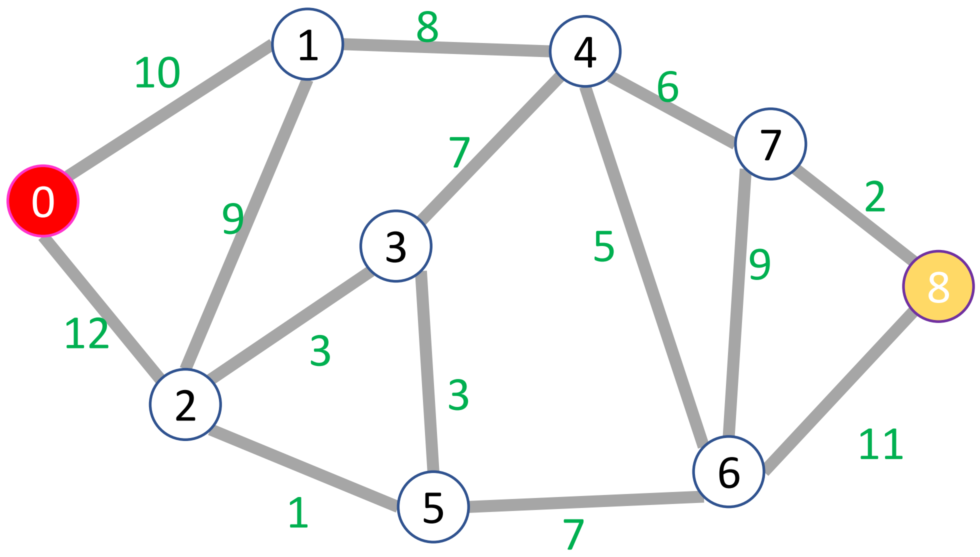
Dijkstra's Algorithm

- Input: graph with **no negative edge weights**, start node s, end node t
- Behavior: Start with node s, repeatedly go to the incomplete node "nearest" to s, stop when
- Output:
  - Distance from start to end
  - Distance from start to every node



Dijkstra's Algorithm

```
int dijkstras(graph, start, end){
        distances = [∞, ∞, ∞,…];  // one index per node
        done = [False,False,False,…];  // one index per node
        PQ = new minheap();
        PQ.insert(0, start);  // priority=0, value=start
        distances[start] = 0;
        while (!PQ.isEmpty){
                current = PQ.extract();
                done[current] = true;
                for (neighbor : current.neighbors){
                        if (!done[neighbor]){
                                new_dist = distances[current]+weight(current,neighbor);
                                if(distances[neighbor] == ∞){
                                        distances[neighbor] = new_dist;
                                        PQ.insert(new_dist, neighbor);
                                }
                                if (new_dist < distances[neighbor]){
                                        distances[neighbor] = new_dist;
                                        PQ.decreaseKey(new_dist,neighbor); }
                        }
                }
        }
        return distances[end]
}
```

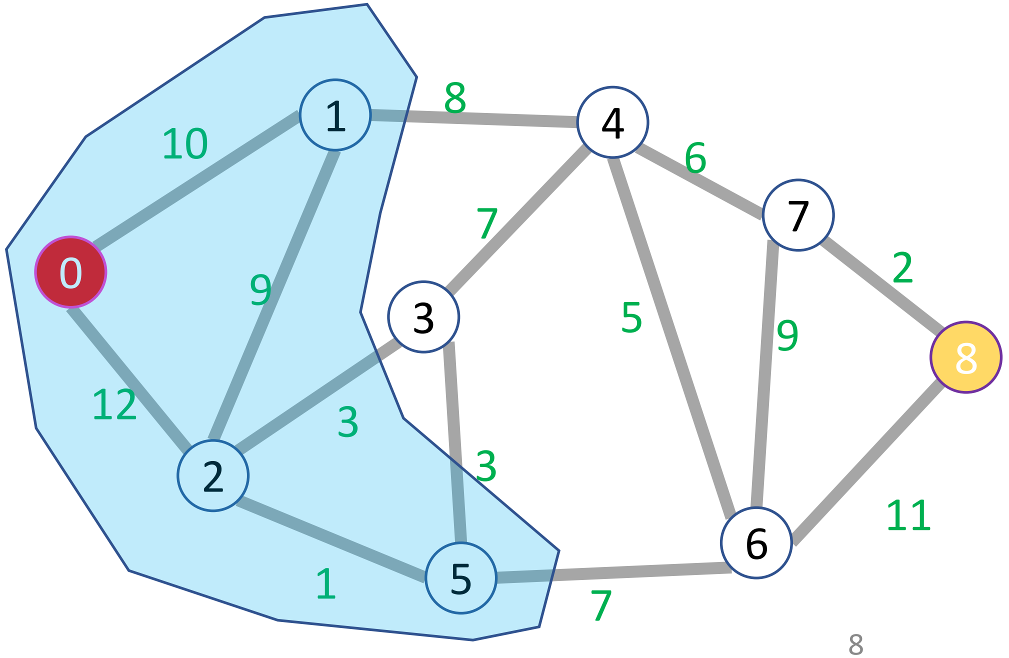


Dijkstra’s Algorithm: Running Time

- How many total priority queue operations are necessary?
  - How many times is each node added to the priority queue?
    - At most once
  - How many times might a node’s priority be changed?
    - Indegree of that node
- What’s the running time of each priority queue operation?
  - $\log |V|$
- Overall running time:
  - $|\mathrm{V}| \log |V| + |E| \log |V|$
  - $\Theta(|E| \log |V|)$

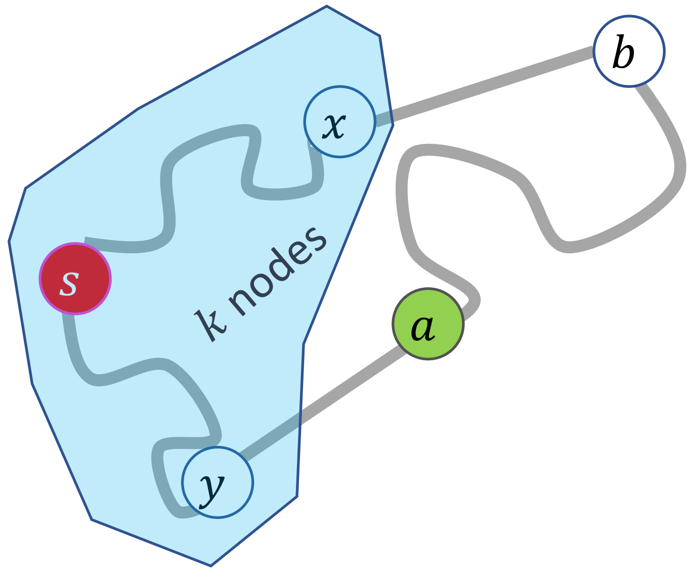
Dijkstra’s Algorithm: Correctness

- Claim: when a node is removed from the priority queue, we have found its shortest path
- Induction over number of completed nodes
- Base Case:
- Inductive Step:



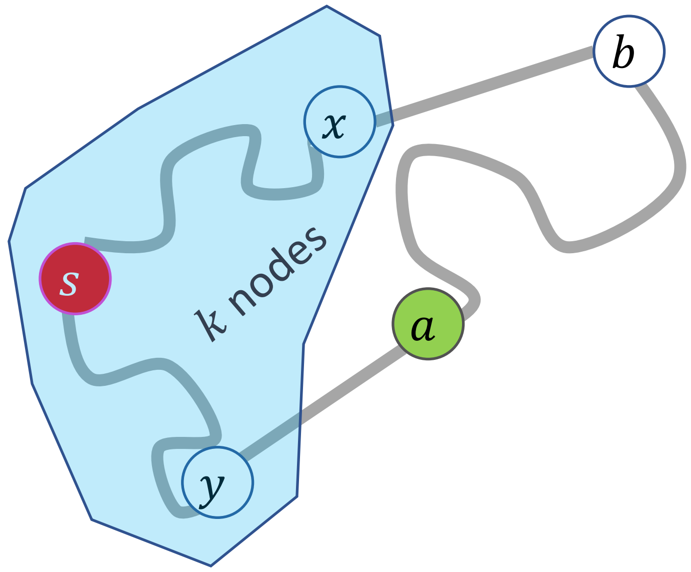
Dijkstra’s Algorithm: Correctness

- Claim: when a node is removed from the priority queue, its distance is that of the shortest path
- Induction over number of completed nodes
- Base Case: Only the start node removed
  - It is indeed 0 away from itself
- Inductive Step:
  - If we have correctly found shortest paths for the first k nodes, then when we remove node $k+1$ we have found its shortest path



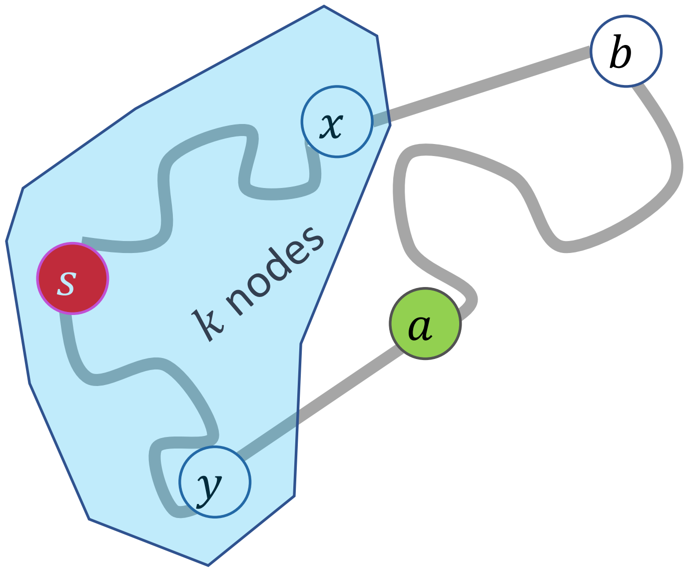
Dijkstra's Algorithm: Correctness

- Suppose a is the next node removed from the priority queue. What do we know bout a?



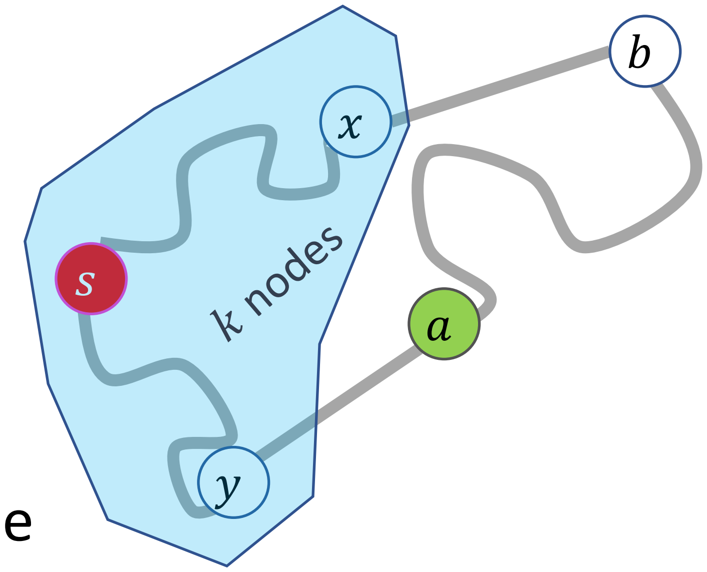
Dijkstra's Algorithm: Correctness

- Suppose a is the next node removed from the priority queue.
  - No other incomplete node has a shorter path discovered so far (e.g. b)
- Claim: no undiscovered path to a could be shorter
  - Consider any other incomplete node b that is 1 edge away from a complete node
  - a is the closest node that is one away from a complete node
  - Thus no path that includes b can be a shorter path to a
  - Therefore the shortest path to a must use only complete nodes, and therefore we have found it already!



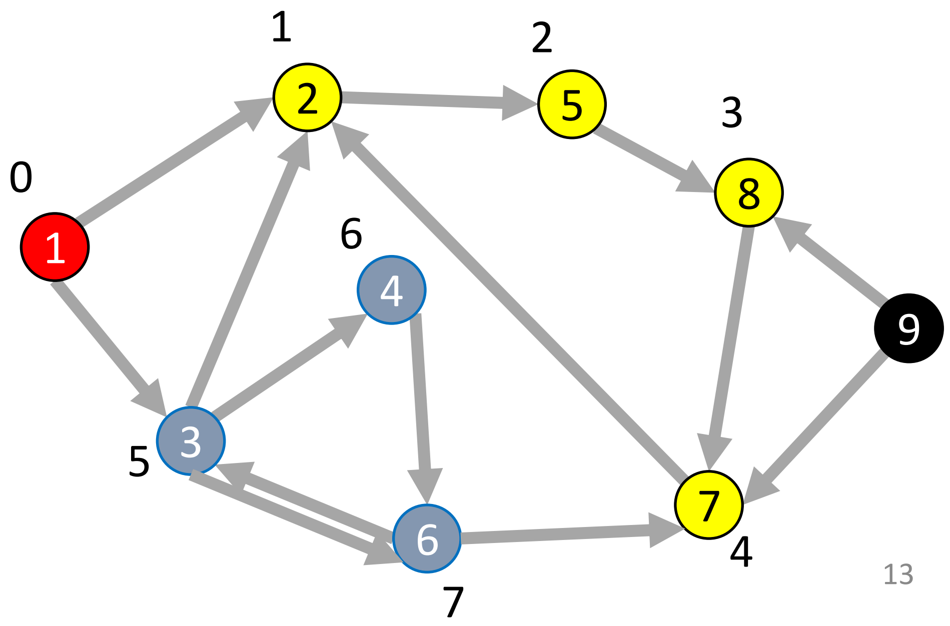
Dijkstra's Algorithm: Correctness

- Suppose a is the next node removed from the queue.
  - No other node incomplete node has a shorter path discovered so far
- Claim: no undiscovered path to a could be shorter
  - Consider any other incomplete node b that is 1 edge away from a complete node
  - a is the closest node that is one away from a complete node
  - Thus no path that includes b can be a shorter path to a
    - Only because no path from b to a can have negative weight!
  - Therefore the shortest path to a must use only complete nodes, and therefore we have found it already!



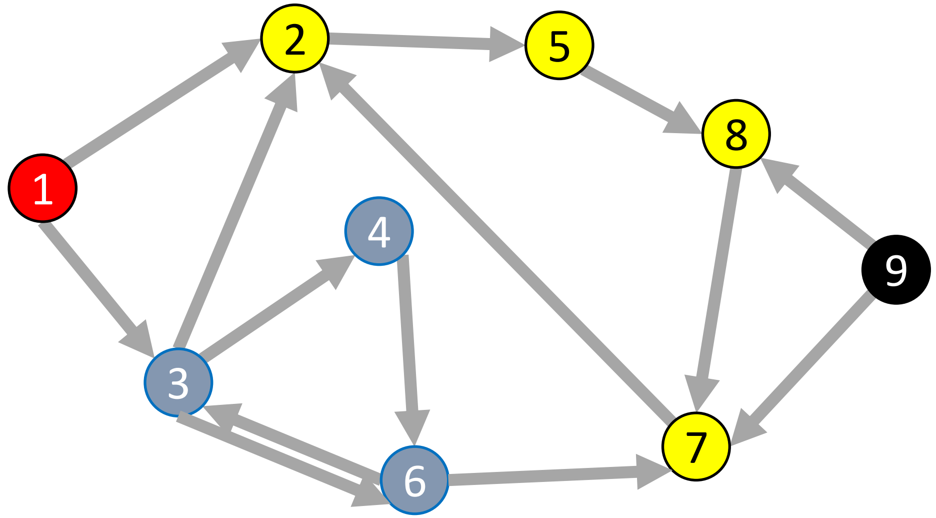
Depth-First Search

- Input: a node s
- Behavior: Start with node s, visit one neighbor of s, then all nodes reachable from that neighbor of s, then another neighbor of s,…
  - Before moving on to the second neighbor of s, visit everything reachable from the first neighbor of s
- Output:
  - Does the graph have a cycle?
  - A **topological sort** of the graph.



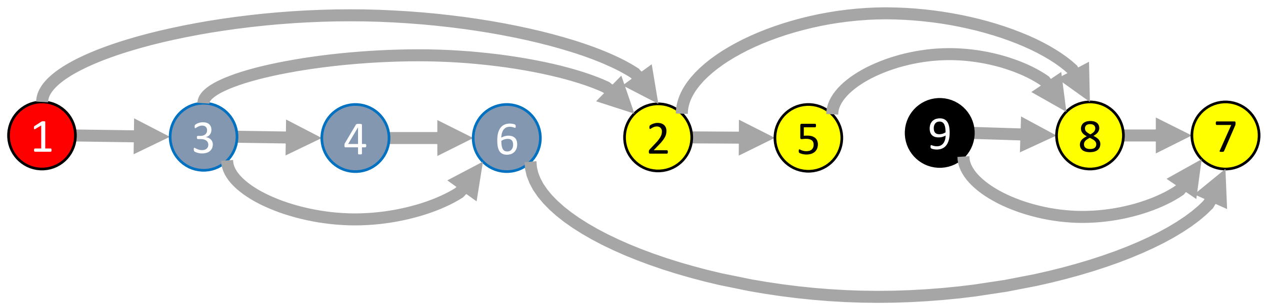
DFS Recursively (more common)

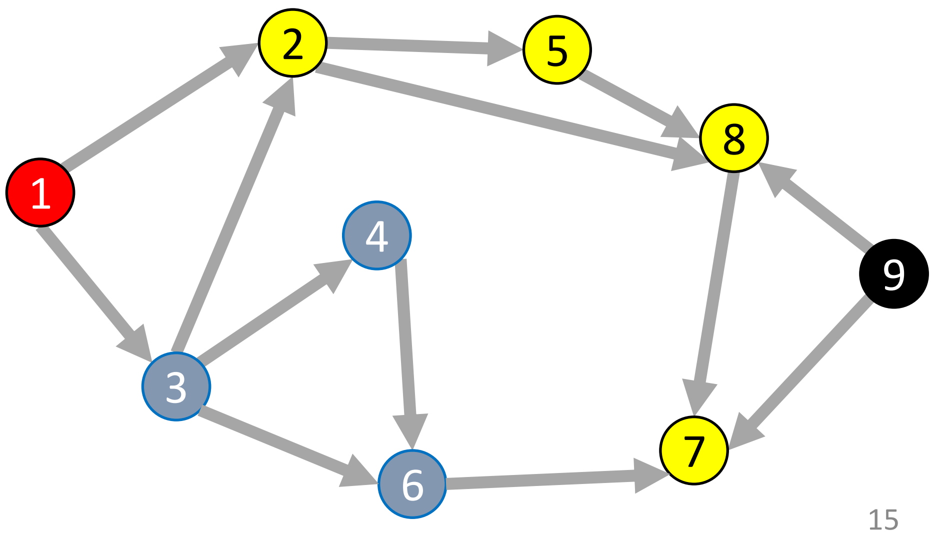
```
void dfs(graph, curr){
        mark curr as "visited";
        for (v : neighbors(current)){
                if (! v marked "visited"){
                        dfs(graph, v);
                }
        }
        mark curr as "done";
}
```



Topological Sort

- A Topological Sort of a **directed acyclic graph** $\boldsymbol{G = (V, E)}$ is a permutation of V such that if $(u, v) \in E$ then u is before v in the permutation

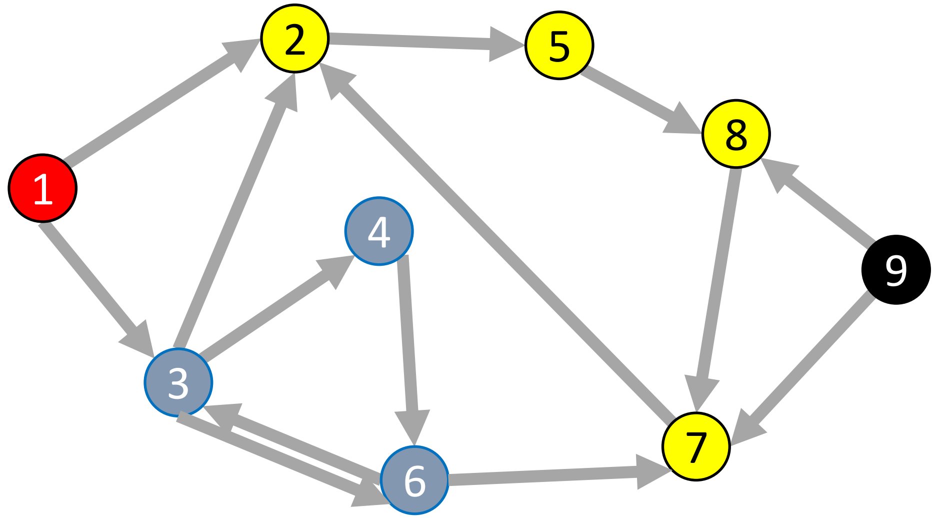




DFS Recursively

```
void dfs(graph, curr){
        mark curr as "visited";
        for (v : neighbors(current)){
                if (! v marked "visited"){
                        dfs(graph, v);
                }
        }
        mark curr as "done";
}
```

Idea: List in reverse order by "done" time



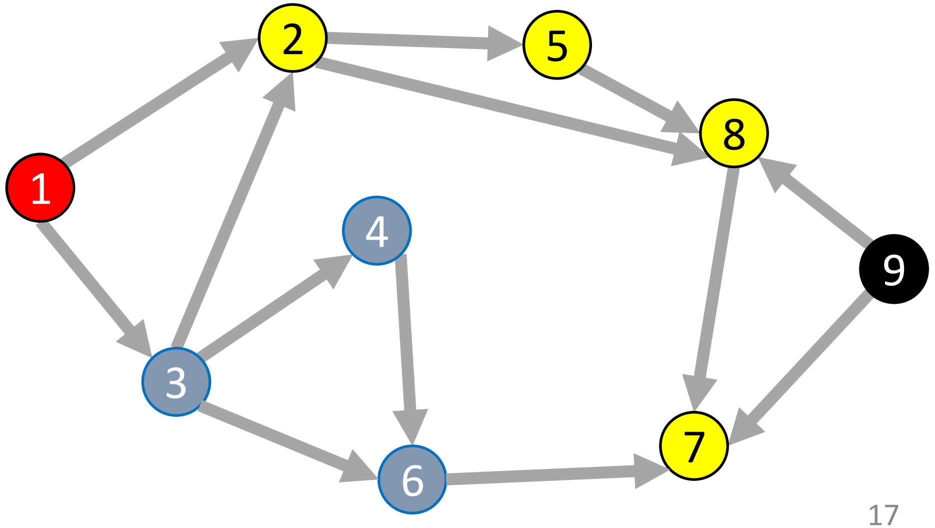
DFS: Topological sort

```
List topSort(graph){
        List<Nodes> done = new List<>();
        for (Node v : graph.vertices){
                if (!v.visited){
                        finishTime(graph, v, finished);
                }
        }
        done.reverse();
        return done;
}

void finishTime(graph, curr, finished){
        curr.visited = true;
        for (Node v : curr.neighbors){
                if (!v.visited){
                        finishTime(graph, v, finished);
                }
        }
        done.add(curr)
}
```

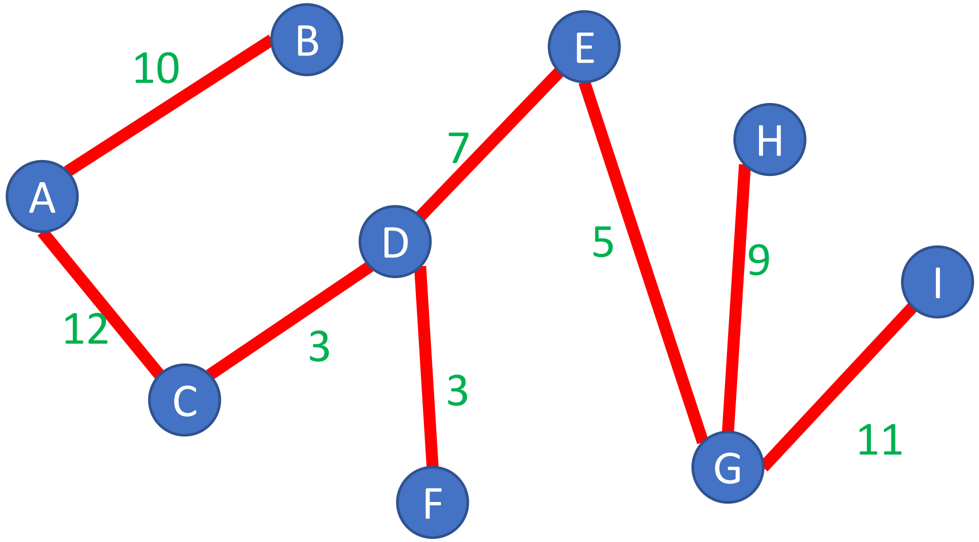
Idea: List in reverse order by "done" time

finished:



Definition: Tree

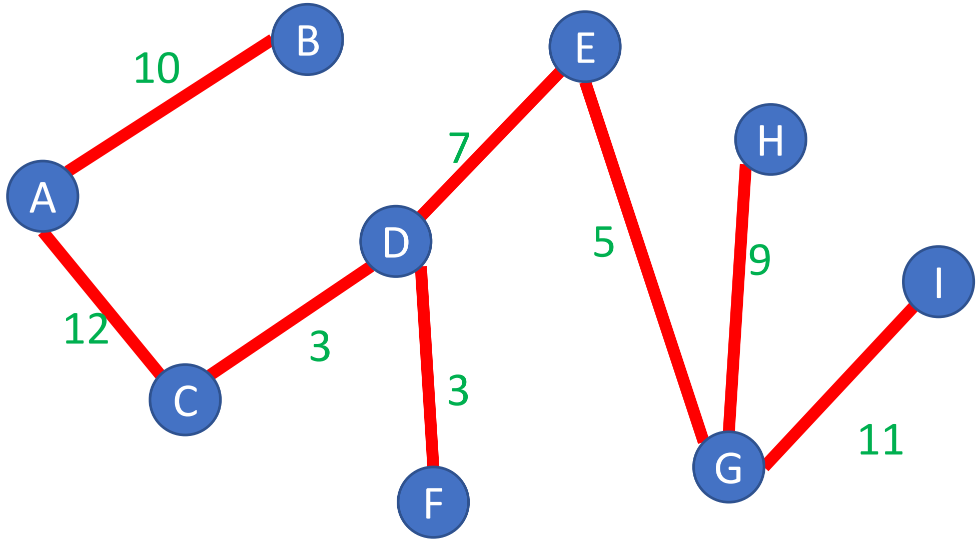
A connected graph with no cycles



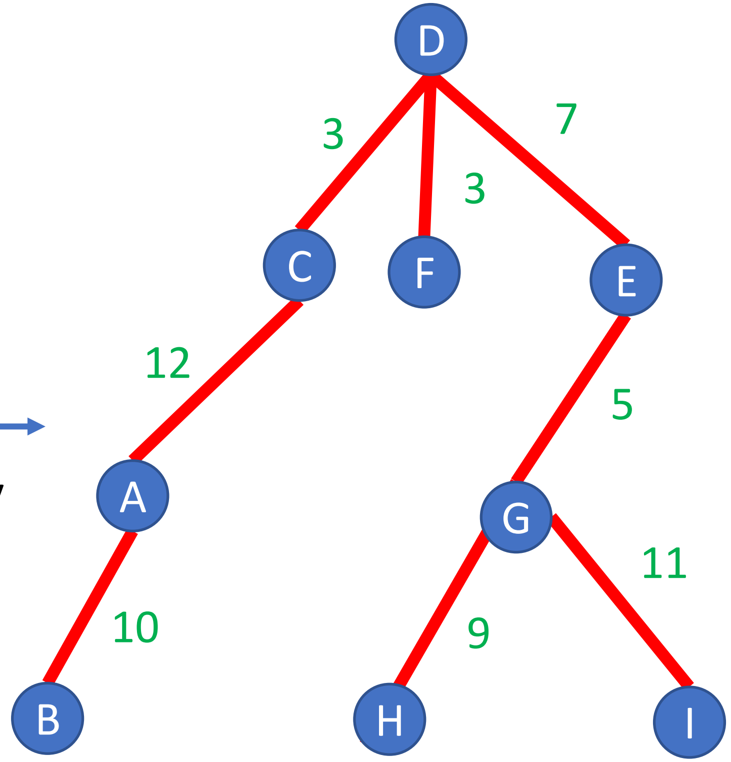
Note: A tree does not need a root, but they often do!

Definition: Tree

A connected graph with no cycles

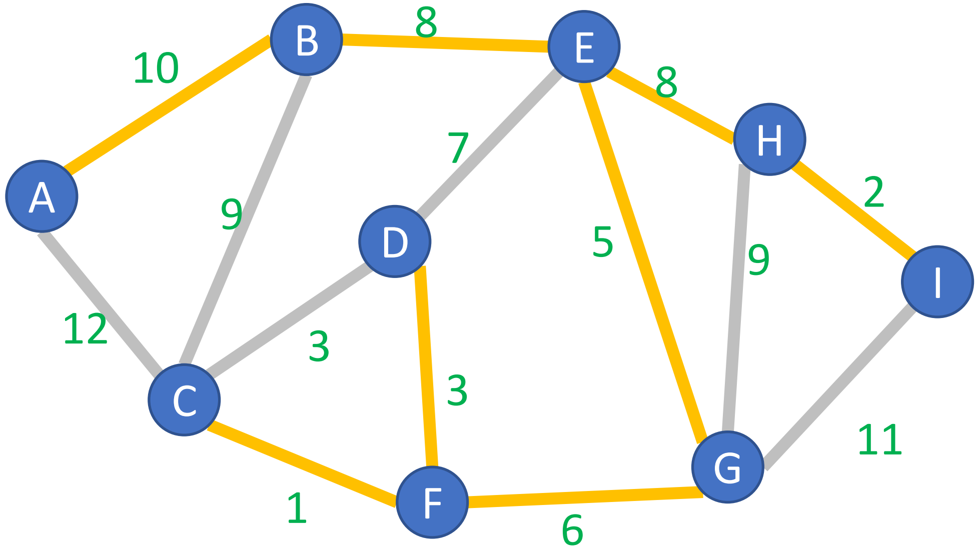


Pick some arbitrary root node and rearrange tree



Definition: Spanning Tree

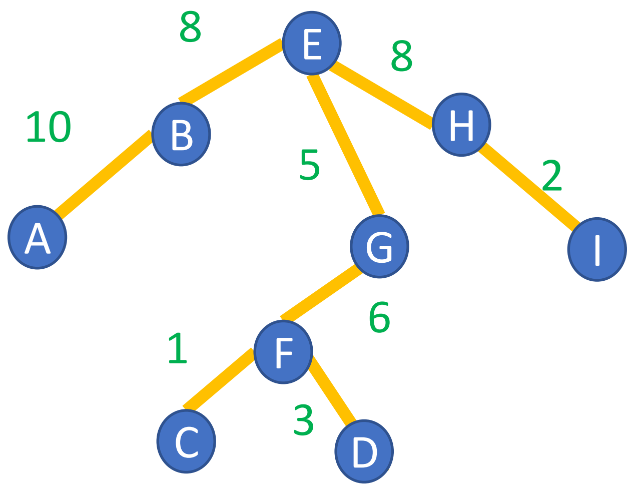
A Tree $\boldsymbol{T} = (V_T, E_T)$ which connects ("spans") all the nodes in a graph $G = (V, E)$



How many edges does T have?

$V - 1$

Pick some arbitrary root node and rearrange tree

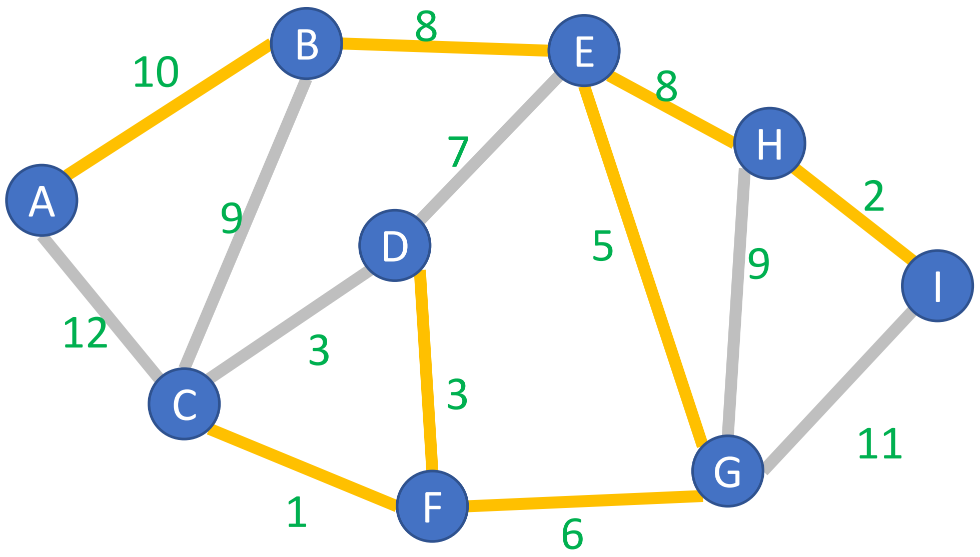


Any set of V-1 edges in the graph that doesn't have any cycles is guaranteed to be a spanning tree!

Any set of V-1 edges that connects all the nodes in the graph is guaranteed to be a spanning tree!

Definition: Minimum Spanning Tree

A Tree $\boldsymbol{T} = (V_T, E_T)$ which connects ("spans") all the nodes in a graph $G = (V, E)$, that has minimal cost

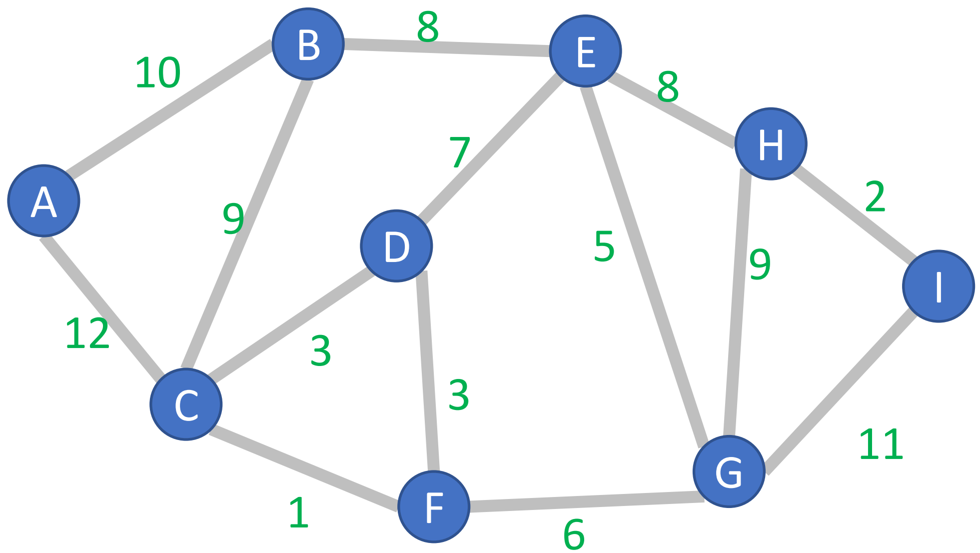


$$Cost(T) = \sum_{e \in E_T} w(e)$$

Kruskal's Algorithm

Start with an empty tree A

Add to A the lowest-weight edge that does not create a cycle



Kruskal's Algorithm

Start with an empty tree A

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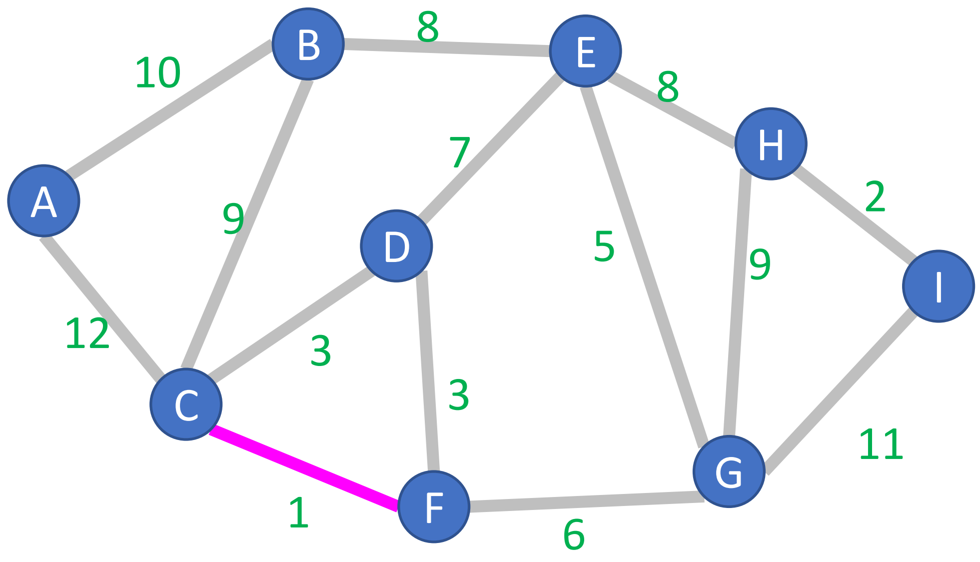

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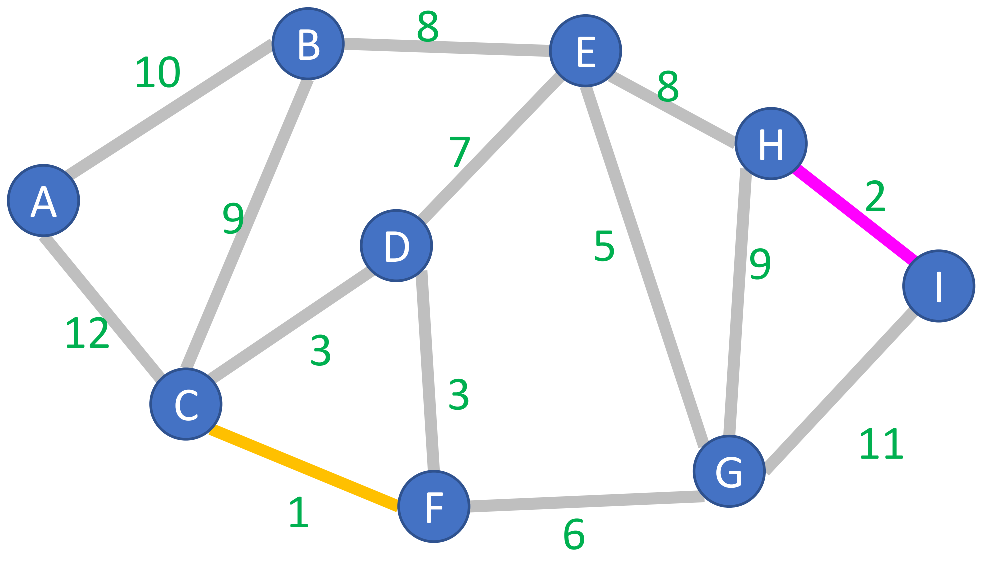

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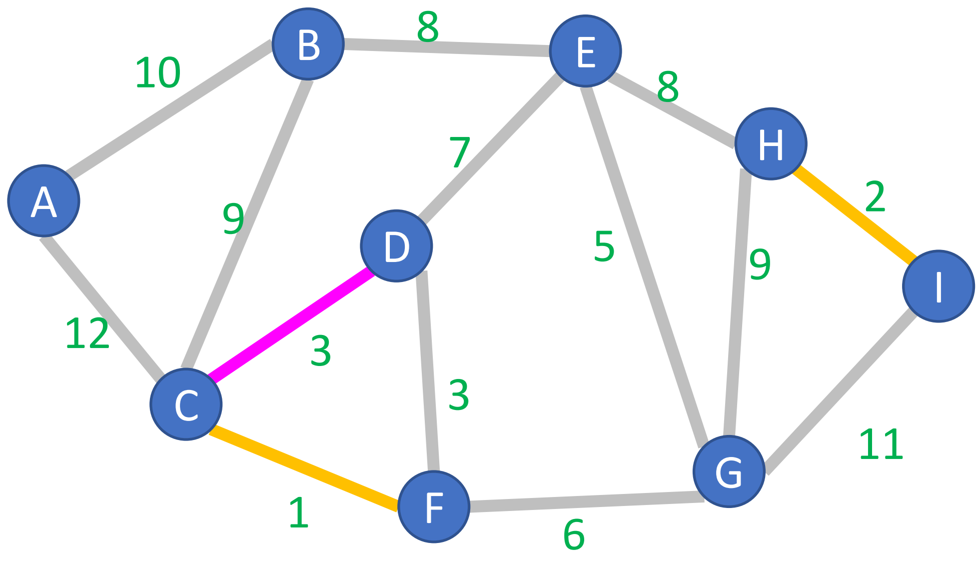

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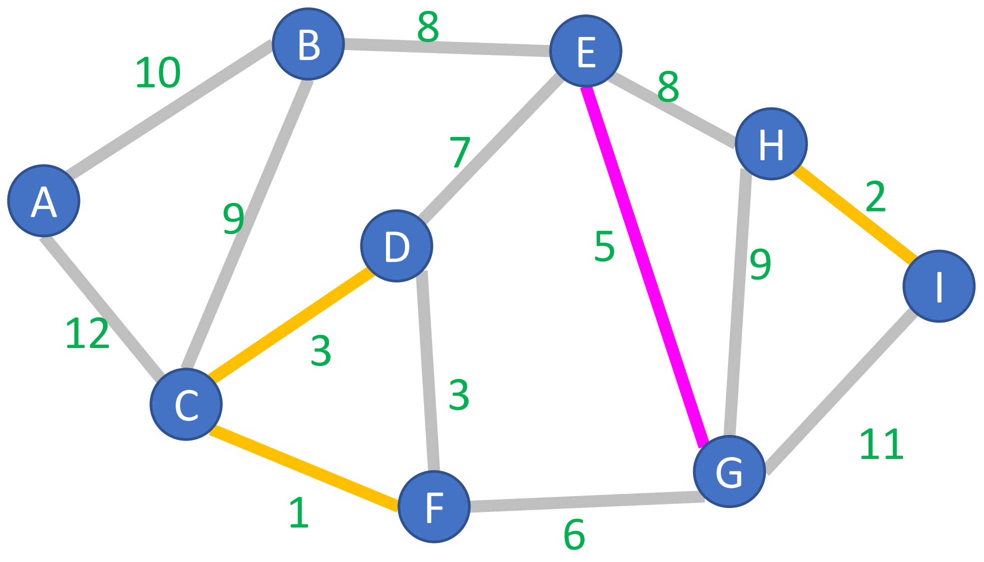

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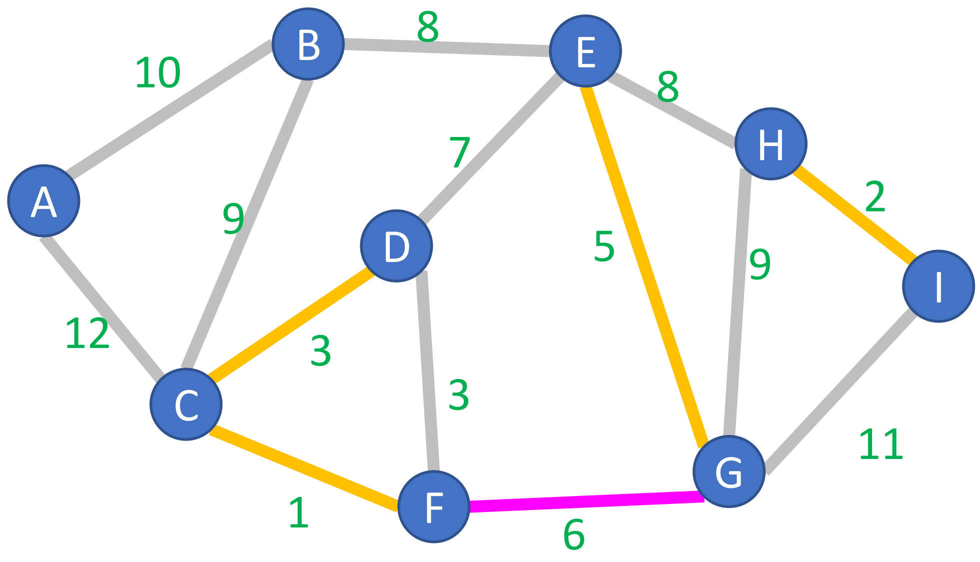
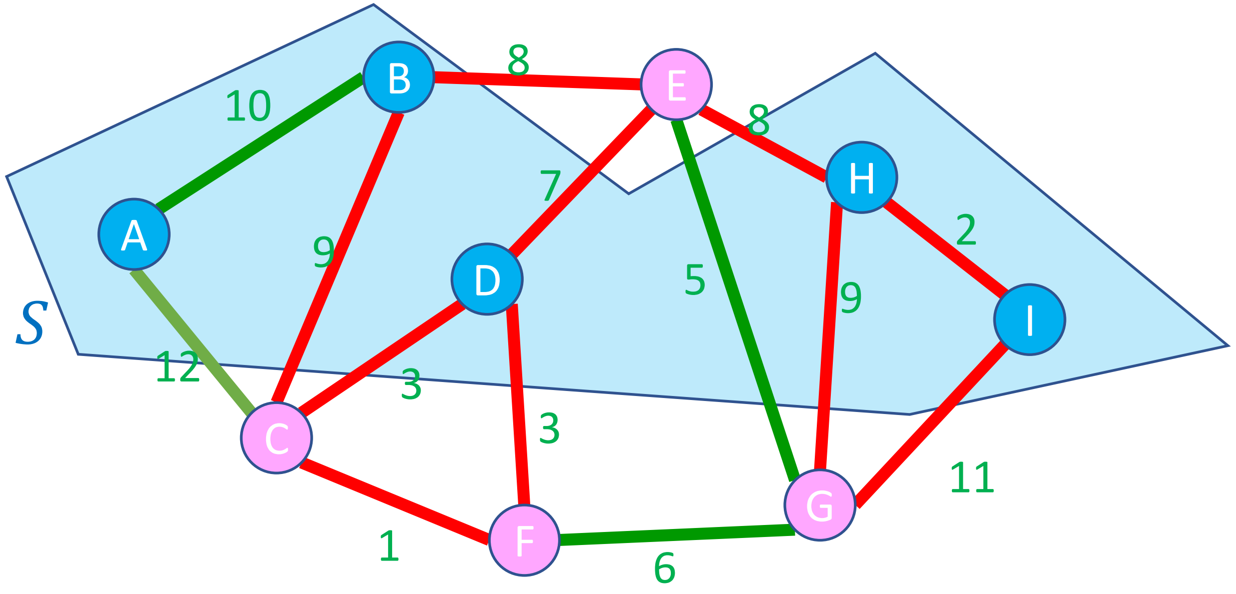


Definition: Cut

A Cut of graph $G = (V, E)$ is a partition of the nodes into two sets, S and $V - S$



Edge $(v_1, v_2) \in E$ crosses a cut if $v_1 \in S$ and $v_2 \in V - S$ (or opposite), e.g. (A, C)

A set of edges R Respects a cut if no edges cross the cut e.g. $R = \{(A, B), (E, G), (F, G)\}$

Cut Theorem

If a set of edges A is a subset of a minimum spanning tree T, let $(S, V - S)$ be any cut which A respects. Let e be the least-weight edge which crosses $(S, V - S)$. $A \cup \{e\}$ is also a subset of a minimum spanning tree.

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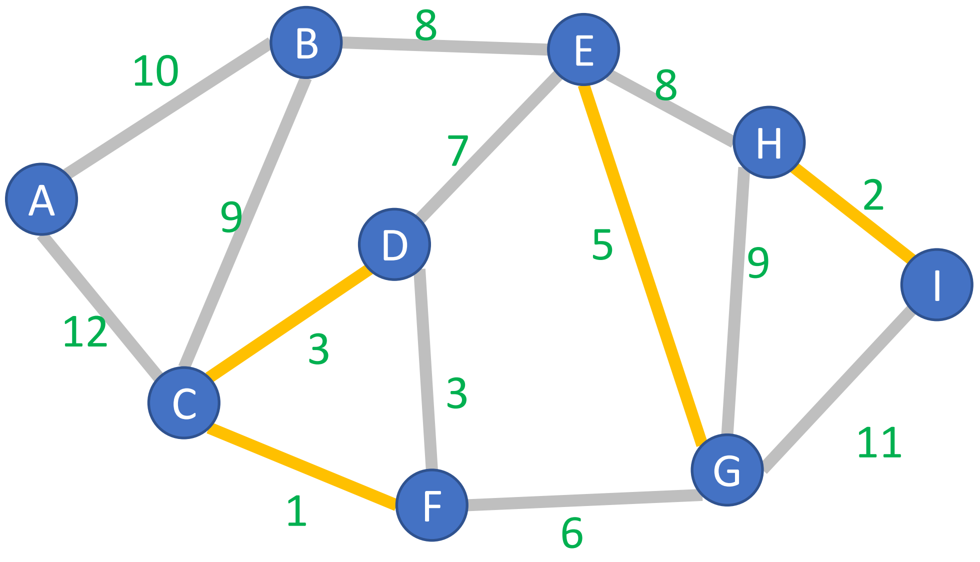

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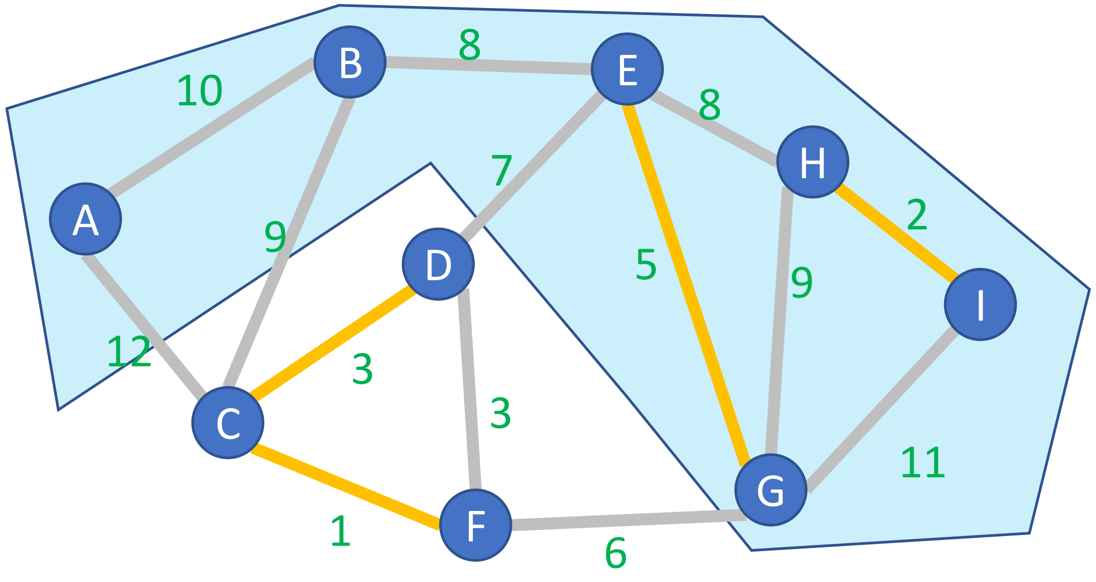

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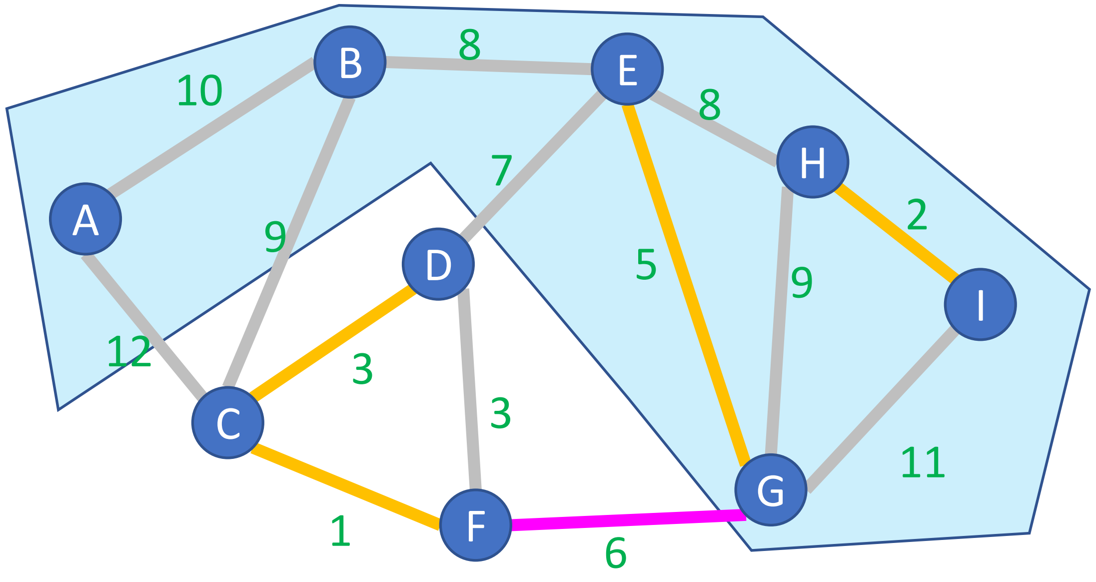

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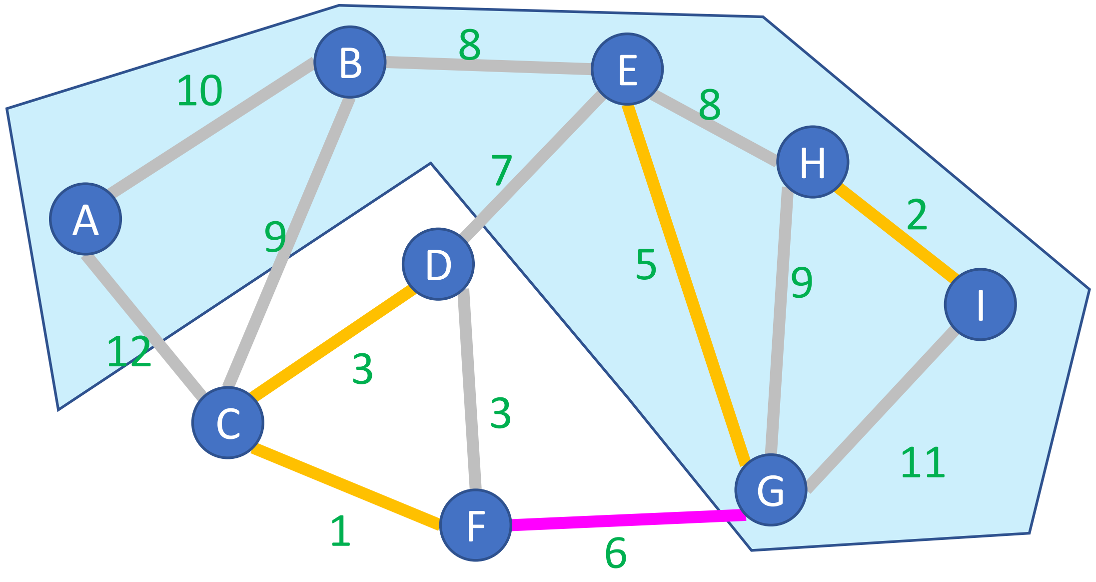
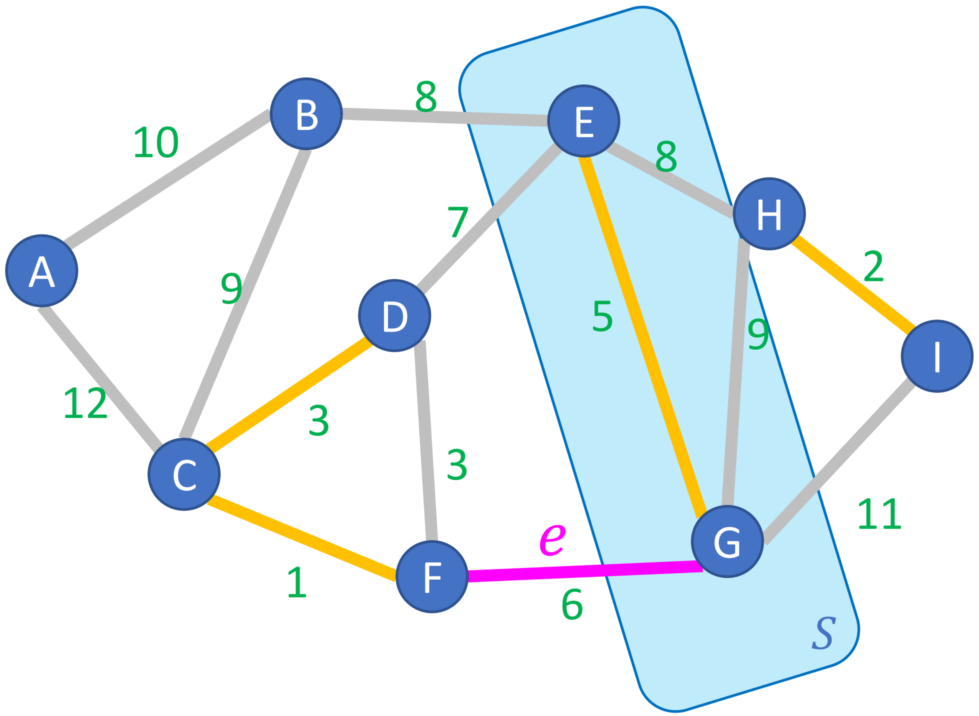


Proof of Kruskal's Algorithm

Start with an empty tree A

Repeat $V - 1$ times:

  Add the min-weight edge that doesn't cause a cycle



Proof: Suppose we have some arbitrary set of edges A that Kruskal's has already selected to include in the MST. $e = (F, G)$ is the edge Kruskal's selects to add next

We know that there cannot exist a path from F to G using only edges in A because e does not cause a cycle

We can cut the graph therefore into 2 disjoint sets:

- nodes reachable from G using edges in A
- All other nodes

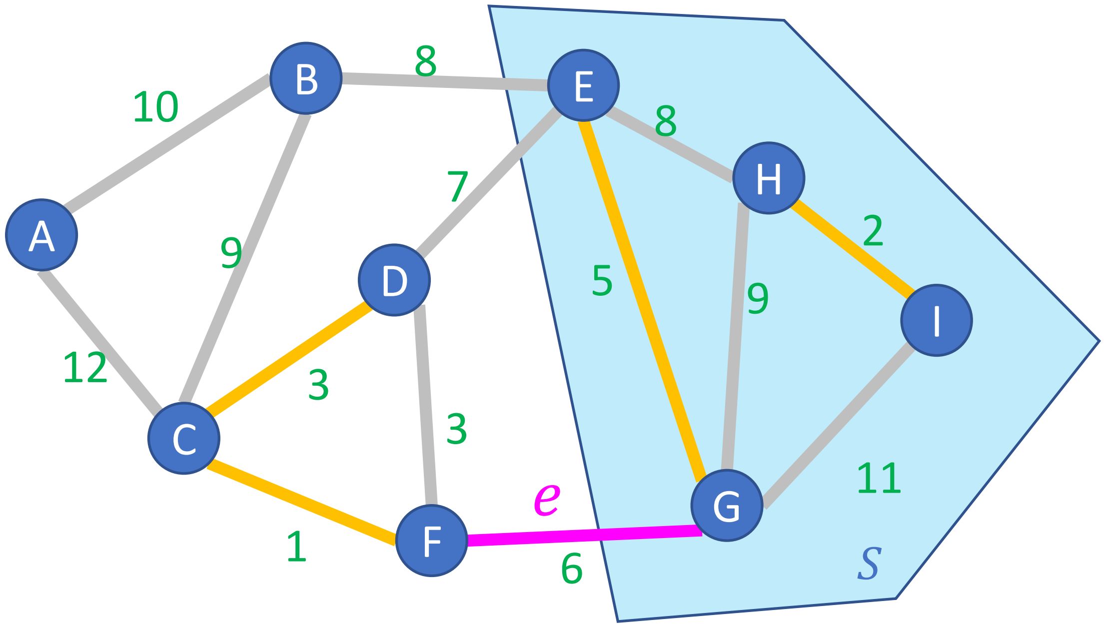
e is the minimum cost edge that crosses this cut, so by the Cut Theorem, Kruskal's is optimal!

Kruskal’s Algorithm Runtime

Start with an empty tree A

Repeat $V-1$ times:

Add the min-weight edge that doesn’t cause a cycle



Keep edges in a Disjoint-set data structure (very fancy)

$O(E \log V)$

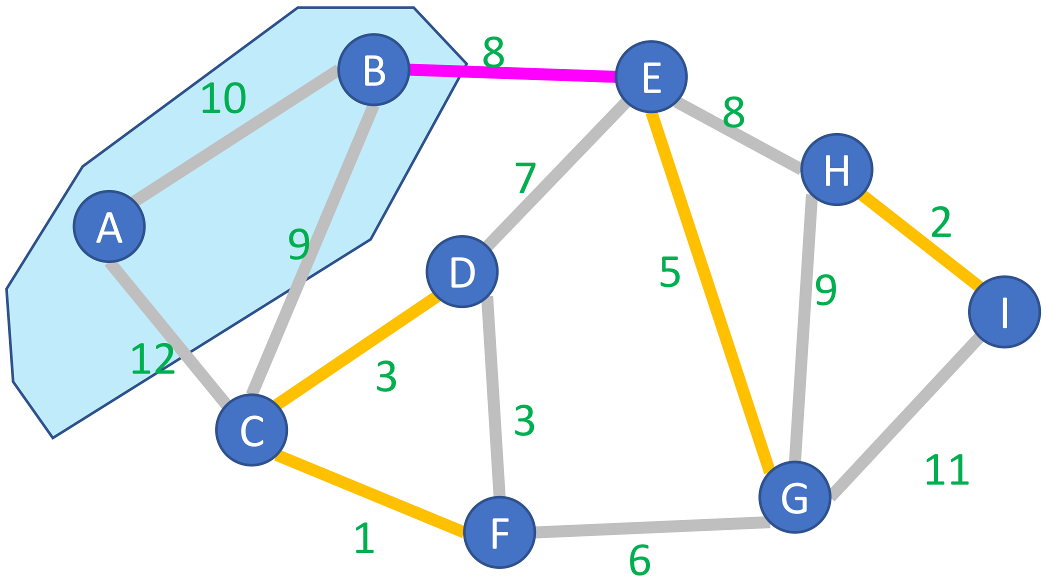
General MST Algorithm

Start with an empty tree A

Repeat $V - 1$ times:

Pick a cut $(S, V - S)$ which A respects (typically implicitly)

Add the min-weight edge which crosses $(S, V - S)$



Prim's Algorithm

Start with an empty tree A

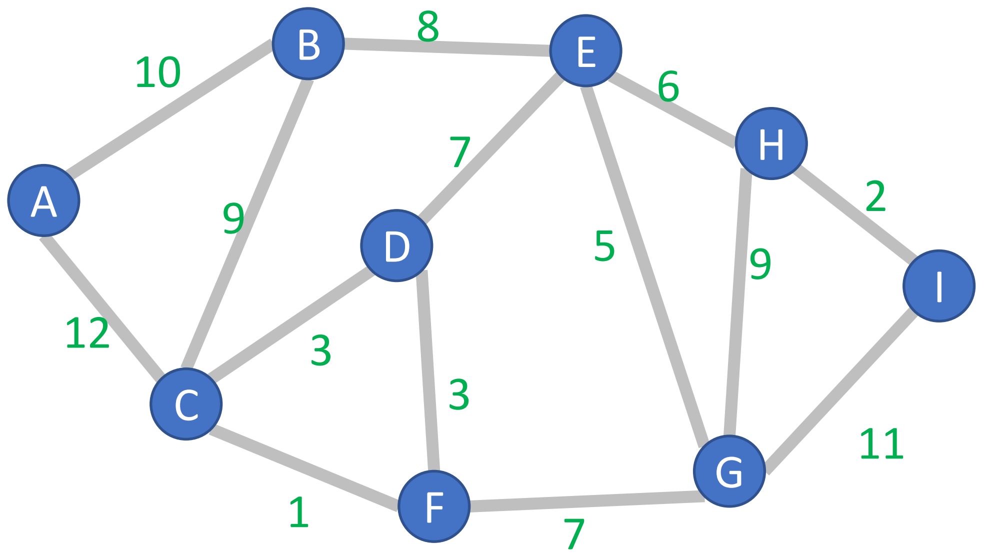
Repeat $V - 1$ times:

Pick a cut $(S, V - S)$ which A respects

Add the min-weight edge which crosses $(S, V - S)$

S is all endpoint of edges in A

e is the min-weight edge that grows the tree



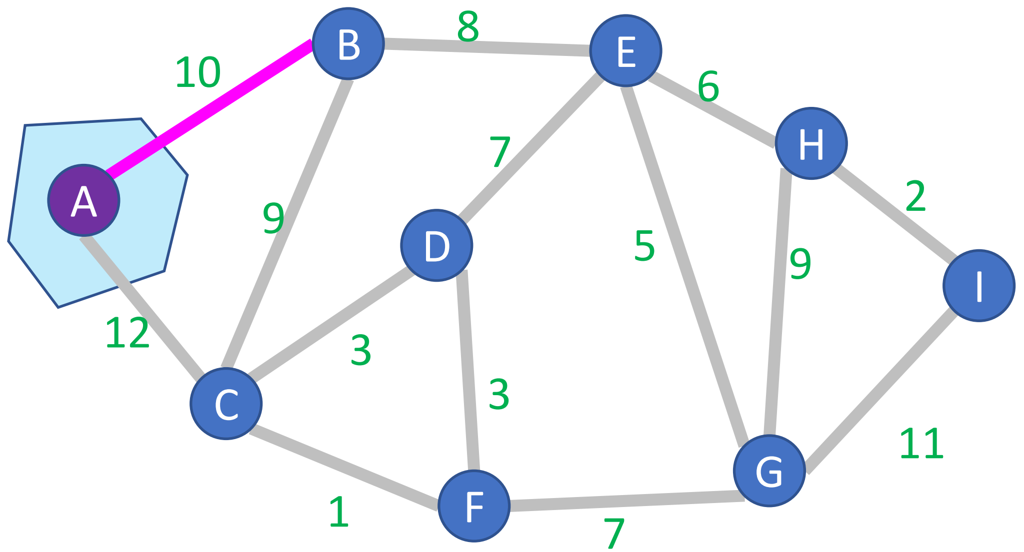
Prim's Algorithm

Start with an empty tree A

Pick a start node

Repeat $V - 1$ times:

Add the min-weight edge which connects to node in A with a node not in A



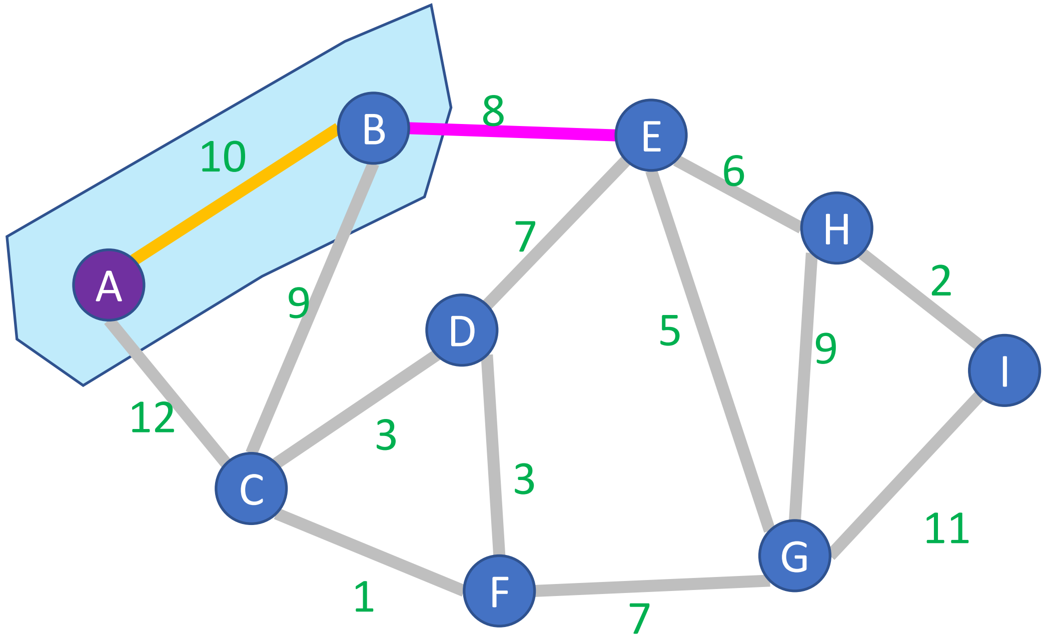
Prim's Algorithm

Start with an empty tree A

Pick a start node

Repeat $V - 1$ times:

Add the min-weight edge which connects to node in A with a node not in A



Prim’s Algorithm

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Repeat $V - 1$ times:

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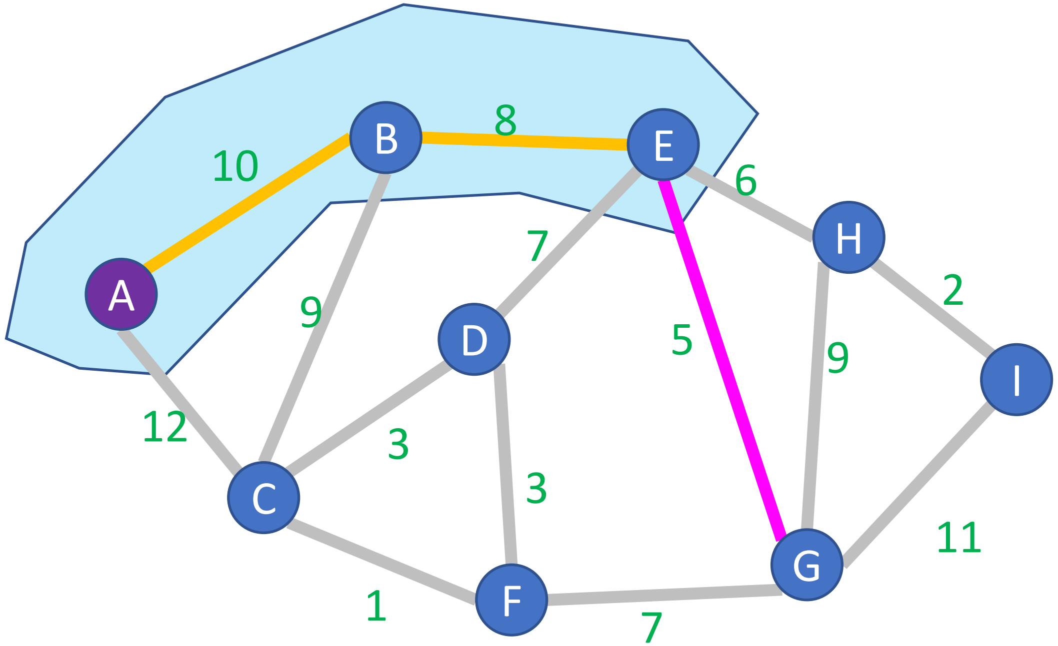


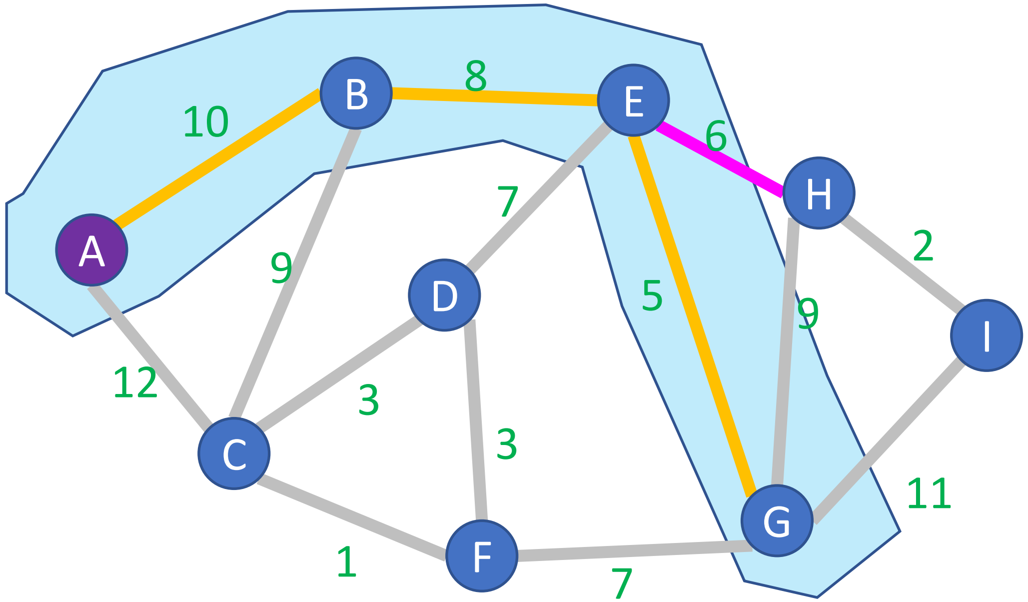
Prim's Algorithm

Start with an empty tree A

Pick a start node

Repeat $V - 1$ times:

Add the min-weight edge which connects to node in A with a node not in A



Prim's Algorithm

Start with an empty tree A

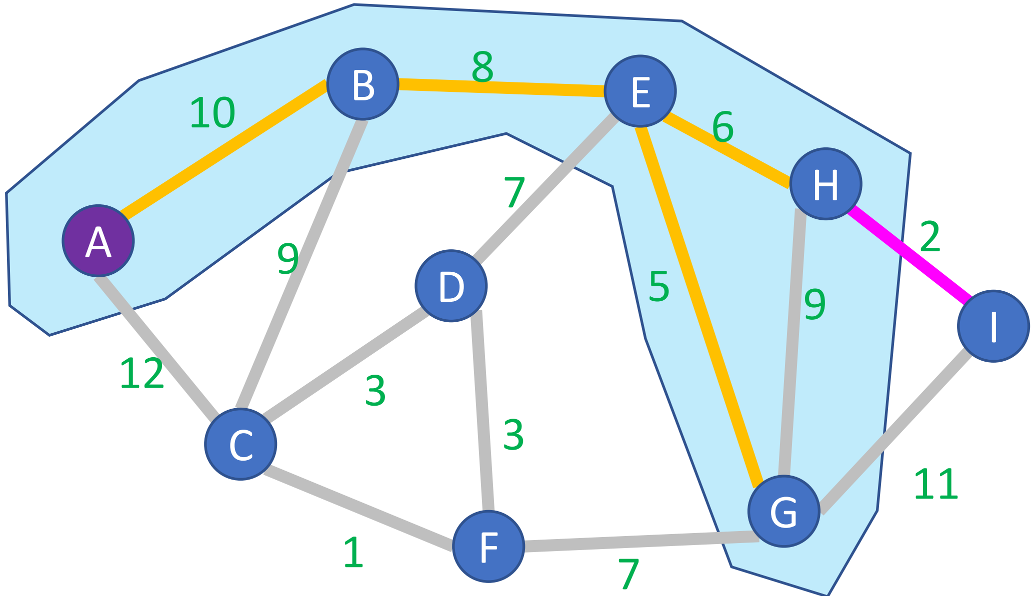
Pick a start node

Repeat $V - 1$ times:

Add the min-weight edge which connects to node in A with a node not in A

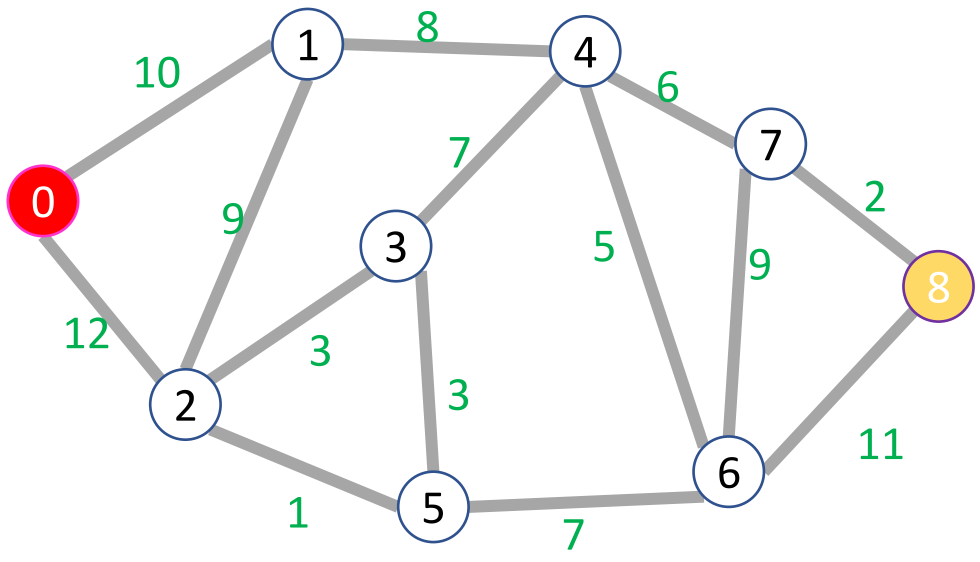
Keep edges in a Heap

$O(E \log V)$



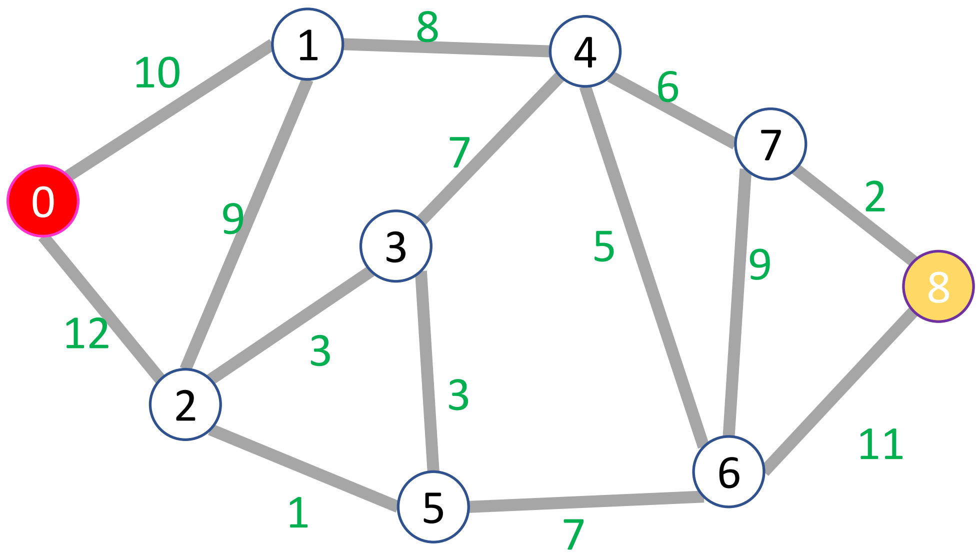
Dijkstra’s Algorithm

```
int dijkstras(graph, start, end){
        distances = [∞, ∞, ∞,…];  // one index per node
        done = [False,False,False,…];  // one index per node
        PQ = new minheap();
        PQ.insert(0, start);  // priority=0, value=start
        distances[start] = 0;
        while (!PQ.isEmpty){
                current = PQ.deleteMin();
                done[current] = true;
                for (neighbor : current.neighbors){
                        if (!done[neighbor]){
                                new_dist = distances[current]+weight(current,neighbor);
                                if(distances[neighbor] == ∞){
                                        distances[neighbor] = new_dist;
                                        PQ.insert(new_dist, neighbor);
                                }
                                if (new_dist < distances[neighbor]){
                                        distances[neighbor] = new_dist;
                                        PQ.decreaseKey(new_dist,neighbor); }
                        }
                }
        }
        return distances[end]
}
```



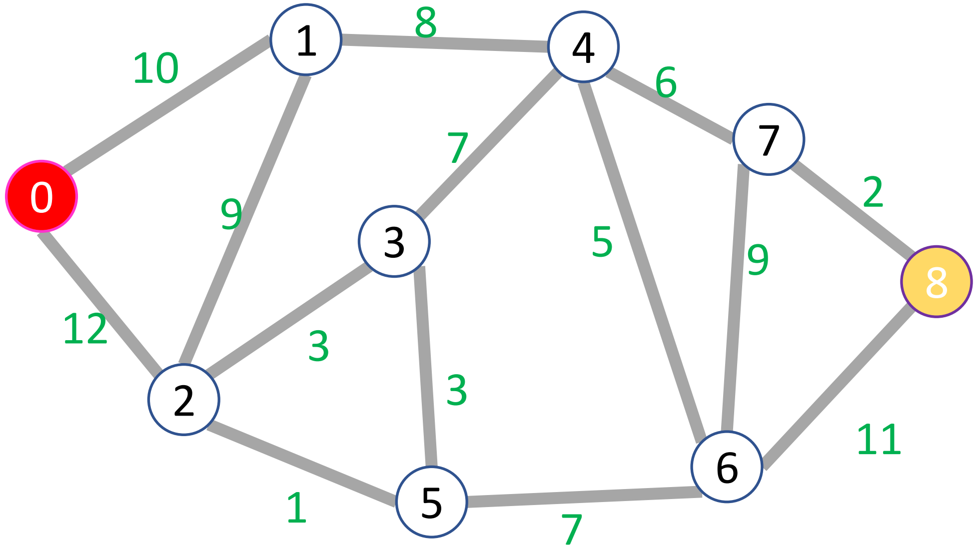
Prims's Algorithm

```
int primss(graph, start, end){
        distances = [∞, ∞, ∞,…];  // one index per node
        done = [False,False,False,…];  // one index per node
        PQ = new minheap();
        PQ.insert(0, start);  // priority=0, value=start
        distances[start] = 0;
        while (!PQ.isEmpty){
                current = PQ.deleteMin();
                done[current] = true;
                for (neighbor : current.neighbors){
                        if (!done[neighbor]){
                                new_dist = weight(current,neighbor);
                                if(distances[neighbor] == ∞){
                                        distances[neighbor] = new_dist;
                                        PQ.insert(new_dist, neighbor);
                                }
                                if (new_dist < distances[neighbor]){
                                        distances[neighbor] = new_dist;
                                        PQ.decreaseKey(new_dist,neighbor); }
                        }
                }
        }
        return distances[end]
}
```



Dijkstra’s Algorithm

```
int dijkstras(graph, start, end){
        distances = [∞, ∞, ∞,…];  // one index per node
        done = [False,False,False,…];  // one index per node
        PQ = new minheap();
        PQ.insert(0, start);  // priority=0, value=start
        distances[start] = 0;
        while (!PQ.isEmpty){
                current = PQ.deleteMin();
                done[current] = true;
                for (neighbor : current.neighbors){
                        if (!done[neighbor]){
                                new_dist = distances[current]+weight(current,neighbor);
                                if(distances[neighbor] == ∞){
                                        distances[neighbor] = new_dist;
                                        PQ.insert(new_dist, neighbor);
                                }
                                if (new_dist < distances[neighbor]){
                                        distances[neighbor] = new_dist;
                                        PQ.decreaseKey(new_dist,neighbor); }
                        }
                }
        }
        return distances[end]
}
```



Prims's Algorithm

```
int primss(graph, start, end){
        distances = [∞, ∞, ∞,…];  // one index per node
        done = [False,False,False,…];  // one index per node
        PQ = new minheap();
        PQ.insert(0, start);  // priority=0, value=start
        distances[start] = 0;
        while (!PQ.isEmpty){
                current = PQ.deleteMin();
                done[current] = true;
                for (neighbor : current.neighbors){
                        if (!done[neighbor]){
                                new_dist = weight(current,neighbor);
                                if(distances[neighbor] == ∞){
                                        distances[neighbor] = new_dist;
                                        PQ.insert(new_dist, neighbor);
                                }
                                if (new_dist < distances[neighbor]){
                                        distances[neighbor] = new_dist;
                                        PQ.decreaseKey(new_dist,neighbor); }
                        }
                }
        }
        return distances[end]
}
```