

CMSC 132: Object-Oriented Programming II



Minimal Spanning Tree Algorithms

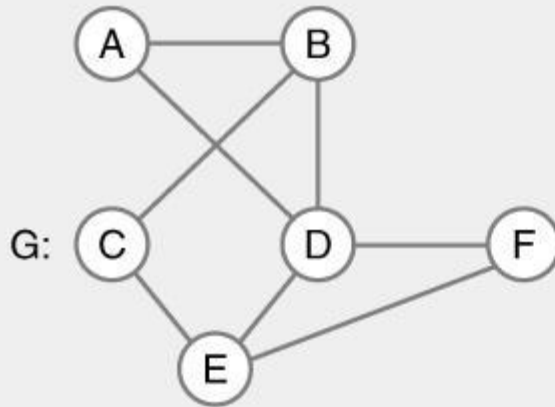
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Overview

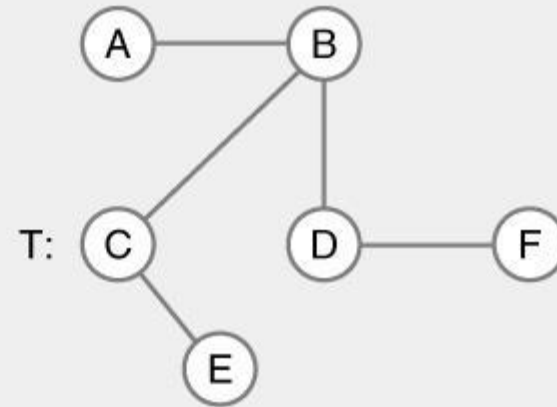
- **Spanning trees**
- **Minimum spanning tree (MST)**
 - **Prim's algorithm**
 - **Kruskal's algorithm**
- **Graph implementation**
 - **Adjacency list / matrix / set**

Spanning Tree

- Set of edges connecting all nodes in graph
 - need $N-1$ edges for N nodes
 - no cycles, can be thought of as a tree
- Can build tree during traversal



(a) Graph G



(b) Spanning tree T of graph G

Spanning Tree Construction

■ Recursive algorithm

Known = { start }

explore (start);

```
void explore (Node X) {  
    for each successor Y of X  
        if (Y is not in Known)  
            Parent[Y] = X  
            Add Y to Known  
            explore(Y)  
}
```

Spanning Tree Construction

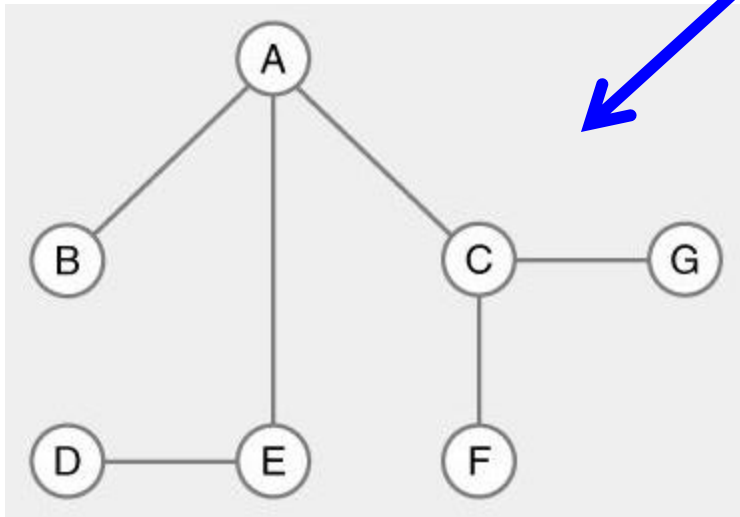
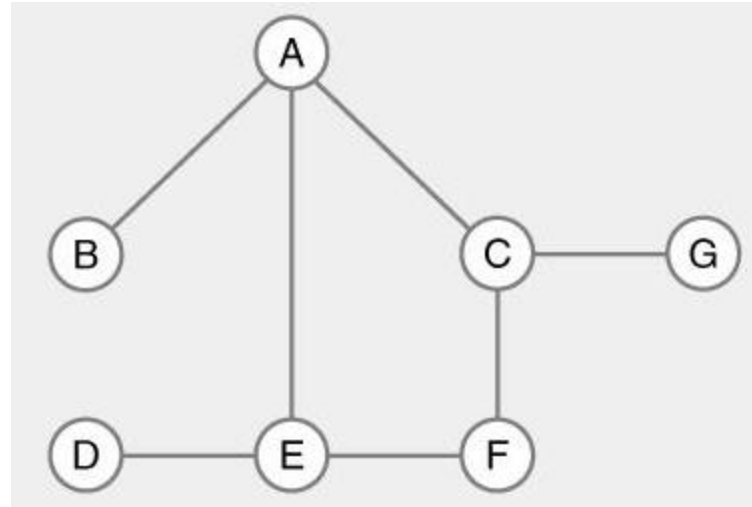
■ Iterative algorithm

Known = { start }

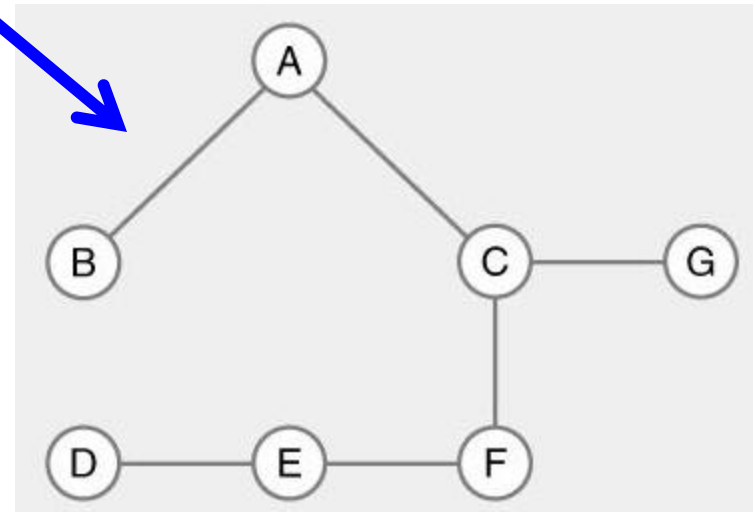
Discovered = { start }

```
while ( Discovered  $\neq \emptyset$  ) {  
    take node X out of Discovered  
    for each successor Y of X  
        if (Y is not in Known)  
            Parent[Y] = X  
            Add Y to Discovered  
            Add Y to Known  
}
```

Breadth & Depth First Spanning Trees

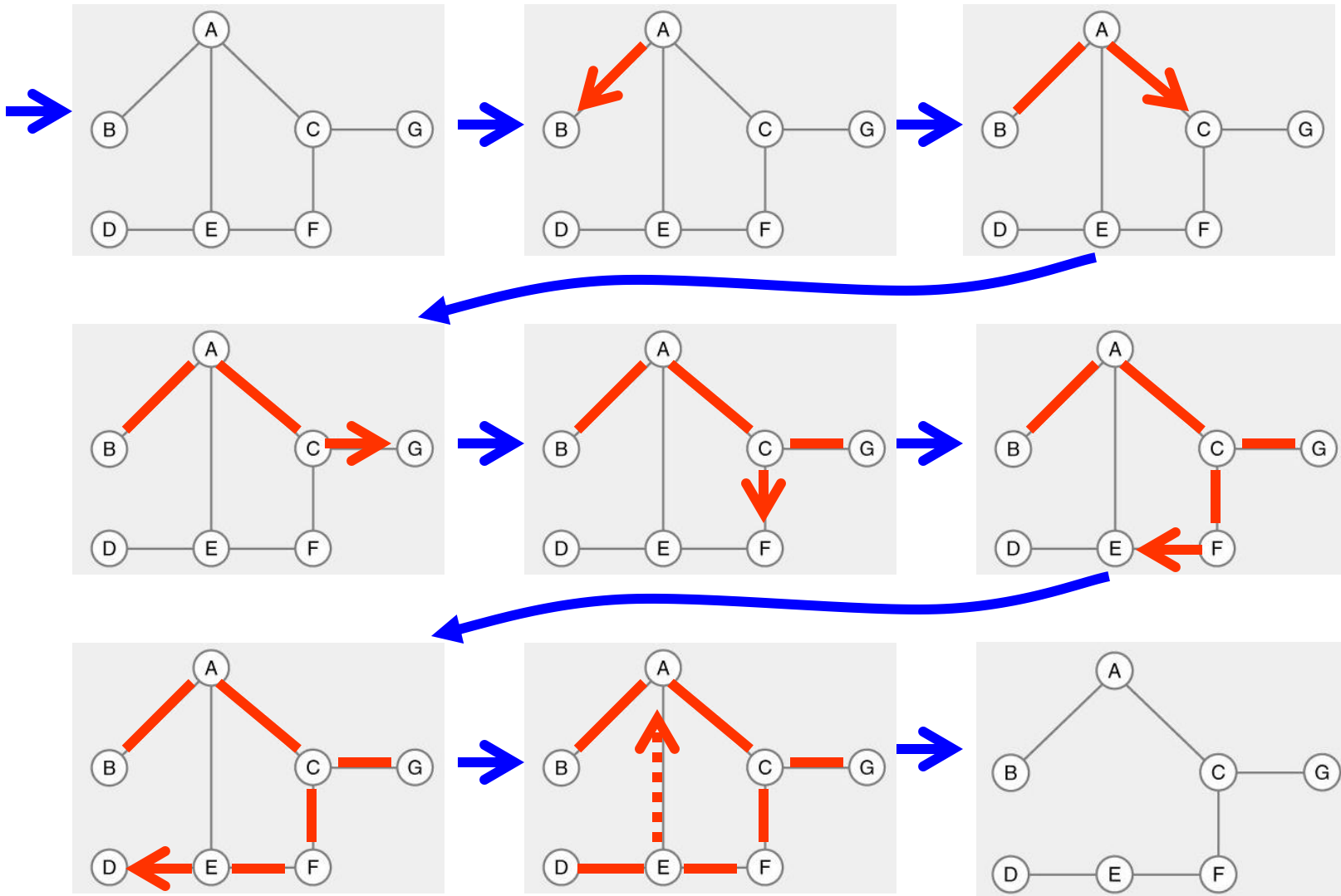


Breadth-first

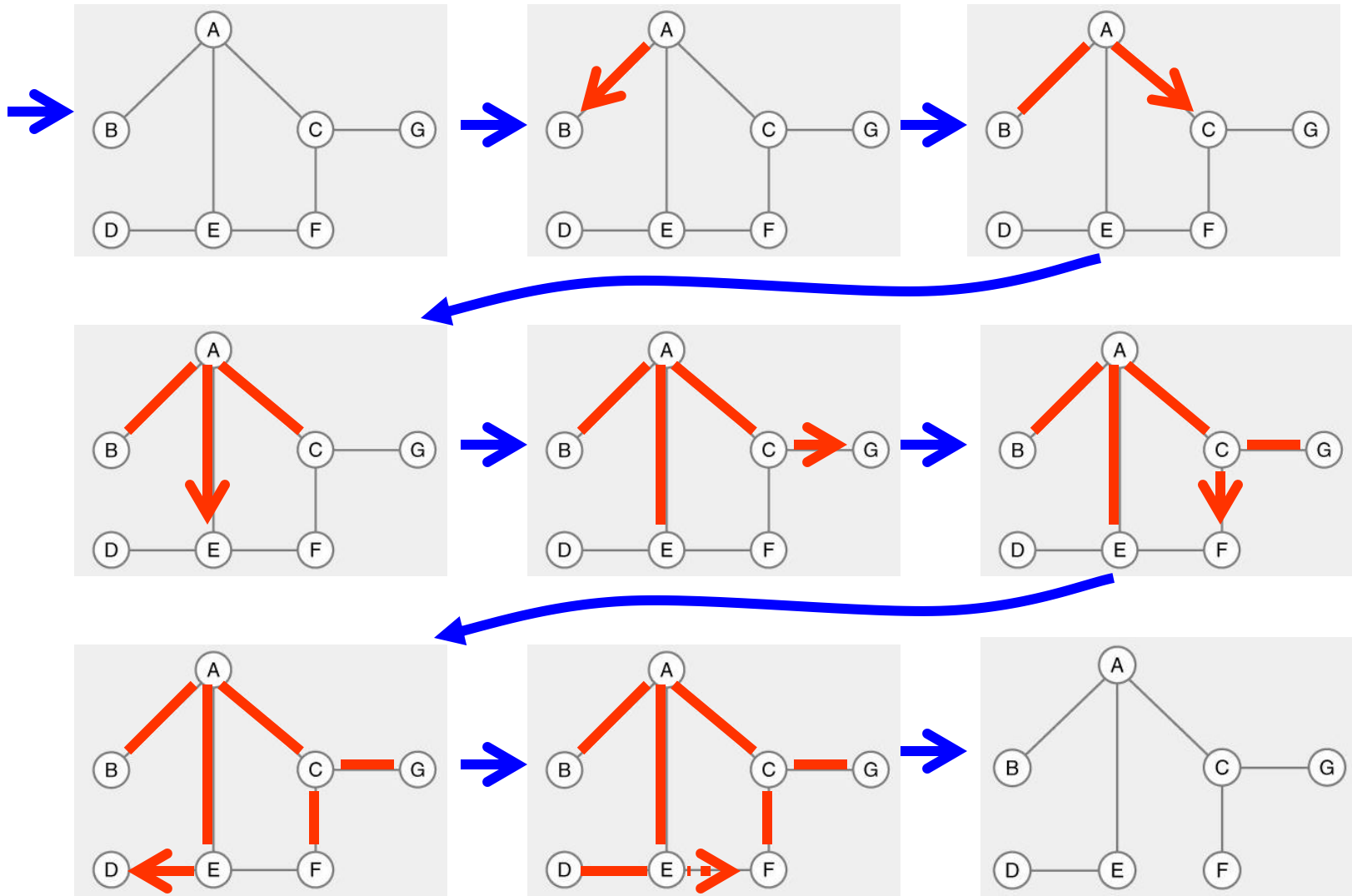


Depth-first

Depth-First Spanning Tree Example



Breadth-First Spanning Tree Example

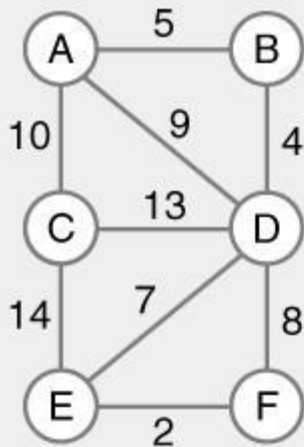


Spanning Tree Construction

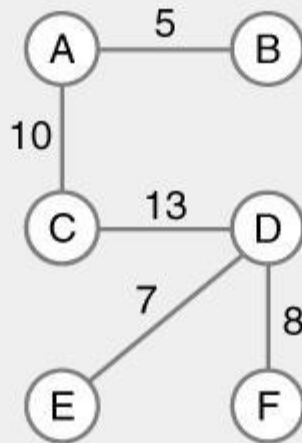
- **Many spanning trees possible**
 - **Different breadth-first traversals**
 - **Nodes same distance visited in different order**
 - **Different depth-first traversals**
 - **Neighbors of node visited in different order**
 - **Different traversals yield different spanning trees**

Minimum Spanning Tree (MST)

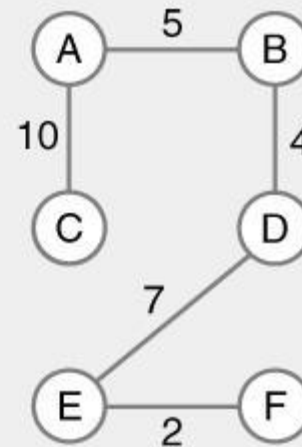
- **Spanning tree with minimum total edge weight**



(a) Graph G



(b) A spanning tree
of cost $C = 43$



(c) A minimum spanning
tree of cost $C = 28$

Minimum Spanning Tree (MST)

- Possible to have multiple MSTs
 - Different spanning trees with same weight
- Example applications
 - Minimize length of telephone lines for neighborhood
 - Minimize distance of airplane routes serving cities

Algorithms for Finding MST

■ Three well known algorithms

1. **Borůvka's algorithm** [1926]
 - For constructing efficient electricity network
 - Rediscovered by Sollin in 1960s
2. **Prim's algorithm** [1957]
 - First discovered by Vojtěch Jarník in 1930
 - Similar to Djikstra's algorithm
3. **Kruskal's algorithm** [1956]
 - By Prof. Clyde Kruskal's uncle

Algorithms for Finding MST

1. Borůvka's algorithm

- Add vertices to MST in parallel

2. Prim's algorithm

- Add vertices to MST
 - One at a time
 - Closest vertex first

3. Kruskal's algorithm

- Add edges to MST
 - One at a time
 - Lightest edge first

Shortest Path – Dijkstra's Algorithm

$S = \emptyset$

$P[] = \text{none}$ for all nodes

$C[\text{start}] = 0$, $C[] = \infty$ for all other nodes

while (not all nodes in S)

 find node K not in S with smallest $C[K]$

 add K to S

 for each node J not in S adjacent to K

 if ($C[K] + \text{cost of } (K,J) < C[J]$)

$C[J] = C[K] + \text{cost of } (K,J)$

$P[J] = K$

Optimal solution computed with **greedy** algorithm

MST – Prim's Algorithm

$S = \emptyset$

$P[] = \text{none}$ for all nodes

$C[\text{start}] = 0$, $C[] = \infty$ for all other nodes

while (not all nodes in S)

 find node K not in S with smallest $C[K]$

 add K to S

 for each node J not in S adjacent to K

 if ($/* C[K] + */ \text{cost of } (K,J) < C[J]$)

$C[J] = /* C[K] + */ \text{cost of } (K,J)$

$P[J] = K$

Keeps track of vertex w/ minimal distance to current tree

Optimal solution computed with **greedy** algorithm

MST – Kruskal's Algorithm

sort edges by weight (from least to most)

tree = $\emptyset$

for each edge (X,Y) in order

if it does not create a cycle

add (X,Y) to tree

stop when tree has N-1 edges

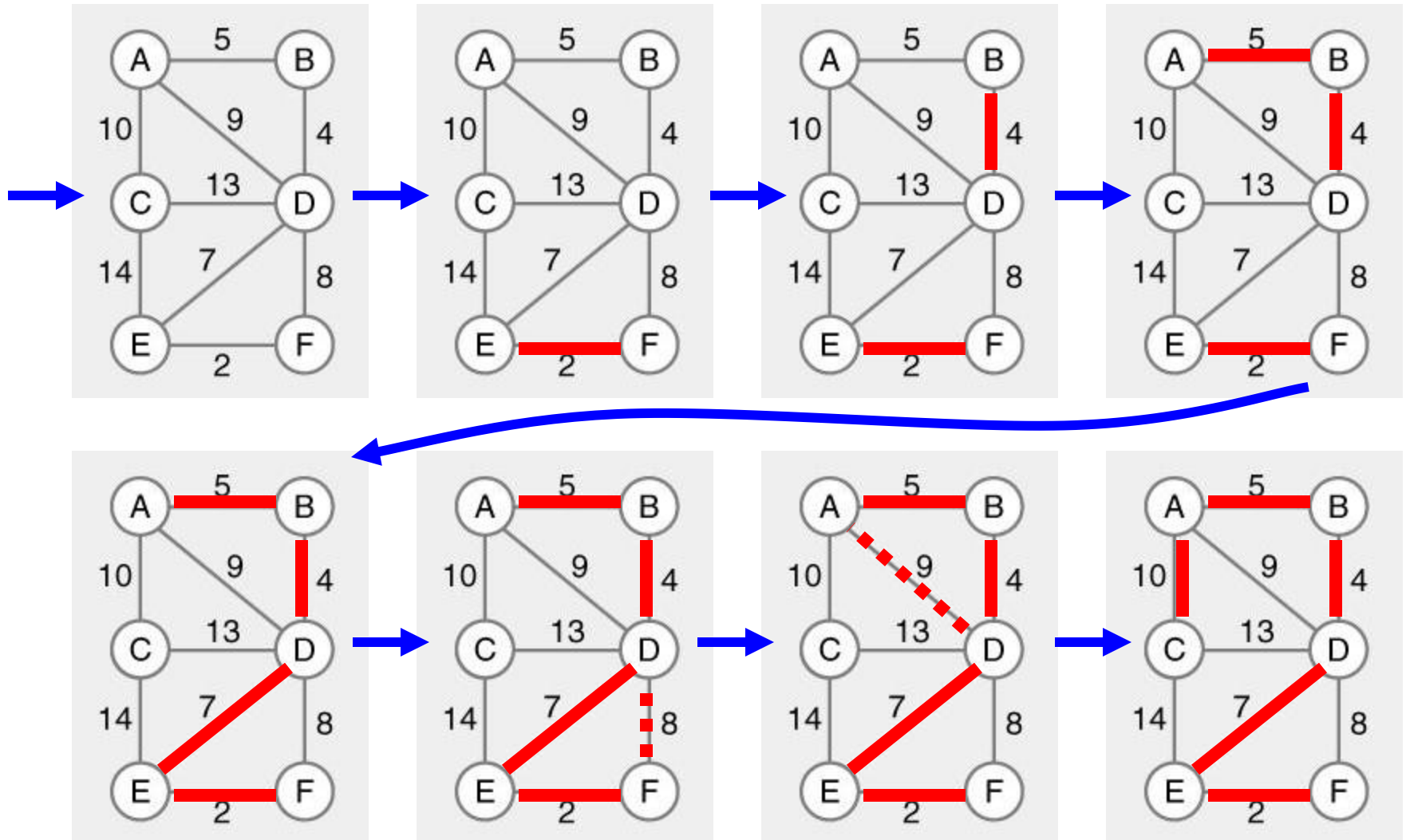
Keeps track of

- lightest edge remaining

- whether adding edge to MST creates cycle

Optimal solution computed with **greedy** algorithm

MST – Kruskal's Algorithm Example



MST – Kruskal's Algorithm

- When does adding (X,Y) to tree create cycle?
- Two approaches to finding cycles
 1. Traversal
 2. Connected subgraph

MST – Kruskal's Algorithm

■ Traversal approach

- Traverse tree starting at X
- If we can reach Y, adding (X,Y) would create cycle

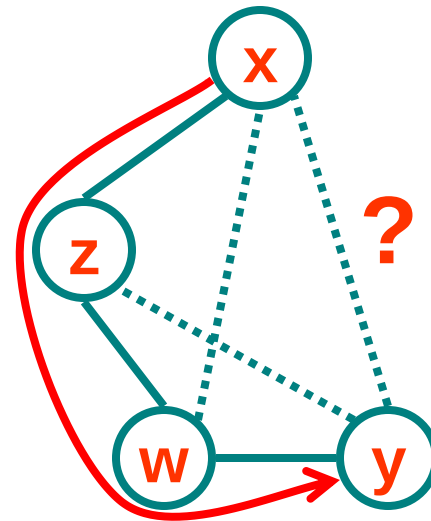
■ Example

■ Question

- Add (X,Y) to MST?

■ Answer

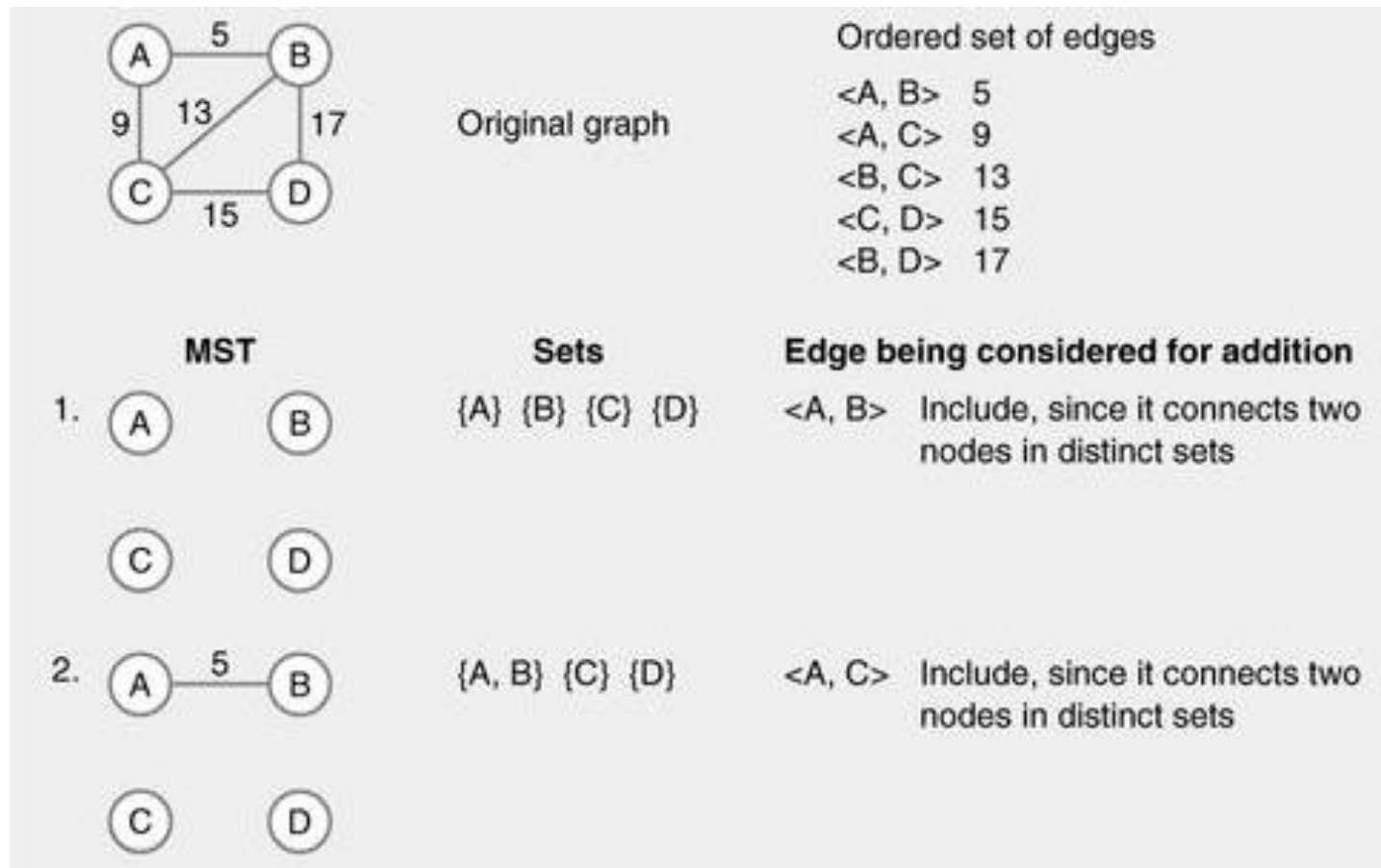
- No, since can already reach Y from X by traversing MST



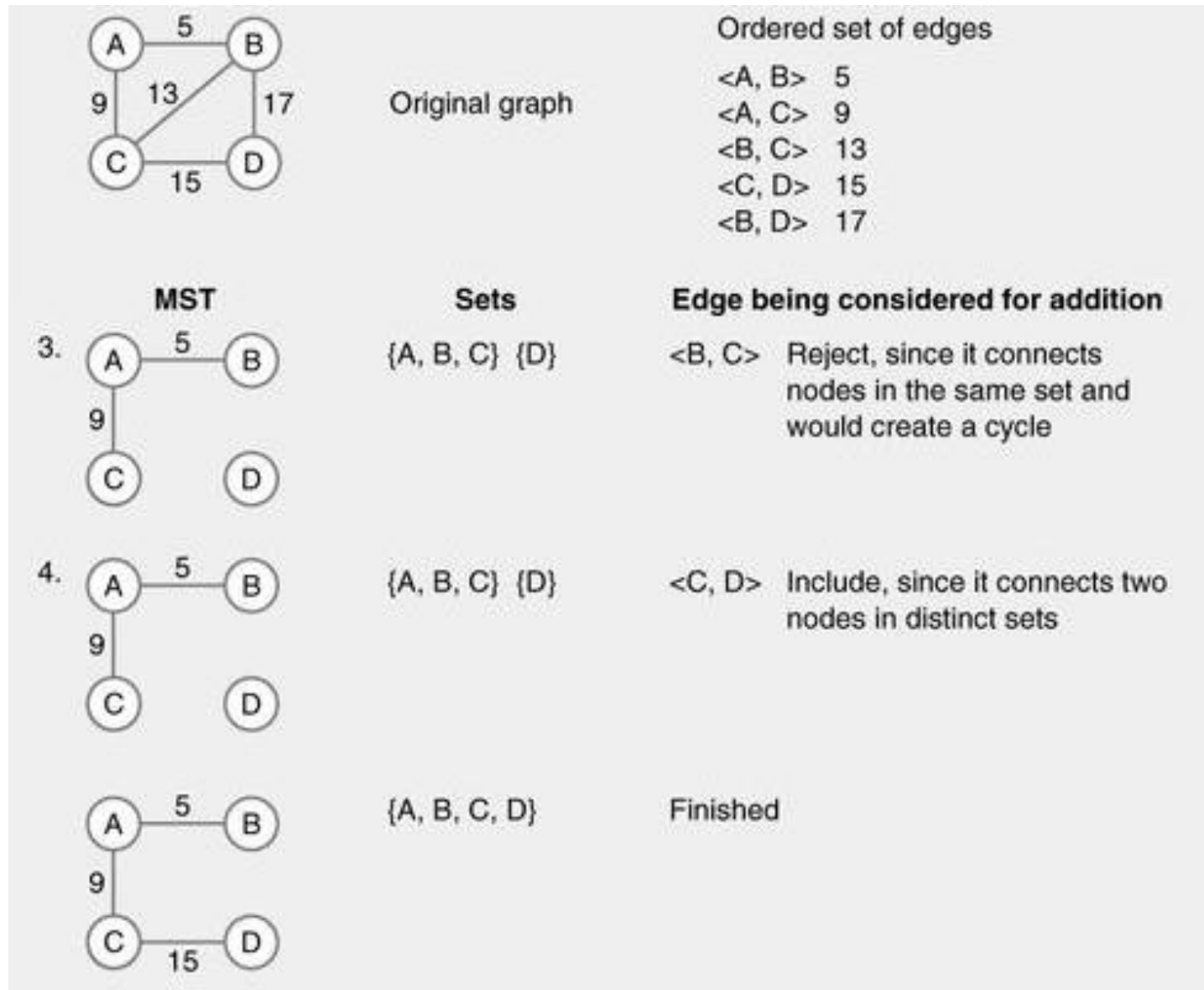
MST – Kruskal's Algorithm

- **Connected subgraph approach**
 - Maintain set of nodes for each connected subgraph
 - Initialize one connected subgraph for each node
 - If X, Y in same set, adding (X, Y) would create cycle
 - Otherwise
 1. Add edge (X, Y) to spanning tree
 2. Merge sets containing X, Y
- **To test set membership**
 - Use Union-Find algorithm

MST – Connected Subgraph Example



MST – Connected Subgraph Example



Union-Find Algorithm

■ Union-Find

- Algorithm & data structure
- Very efficient for testing membership in disjoint sets

■ Problem description

- Start with n nodes, each in different subgraph
- Support two operations
 - Find – are nodes x & y in same subgraph?
 - Union – merge subgraphs containing x & y

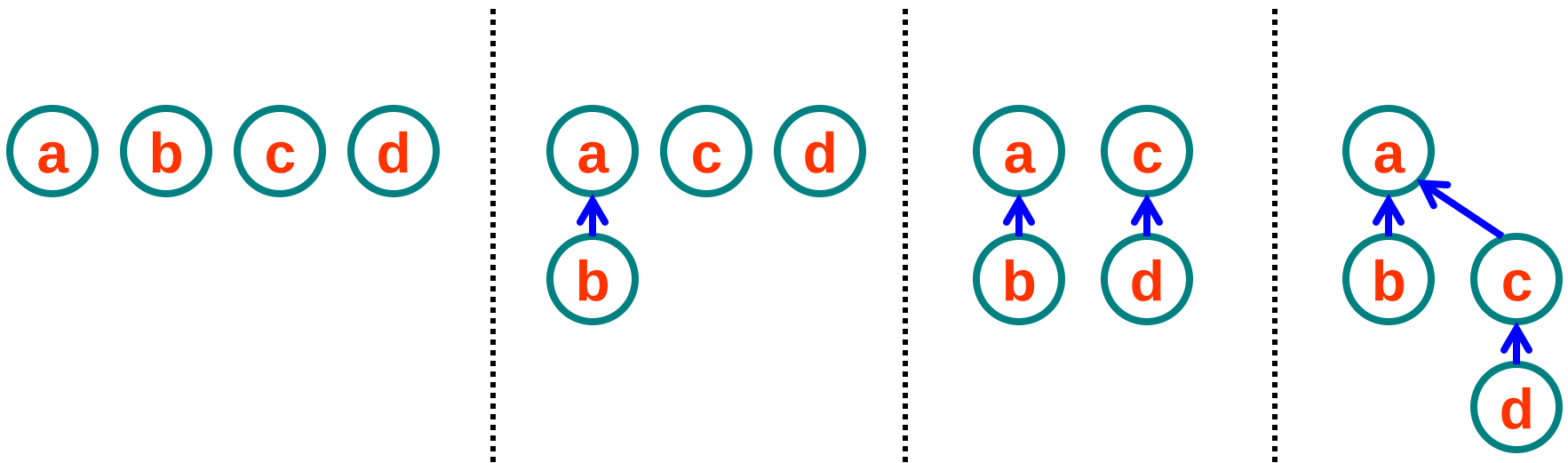
Union-Find Algorithm

■ Basic approach

- Each node has a parent pointer
- Find – follow parent pointer(s) to root of tree
- Union – point root of 1st tree to root of 2nd tree

■ Example

- Union(a, b) ; union(c , d); union(b, d)



Union-Find Algorithm

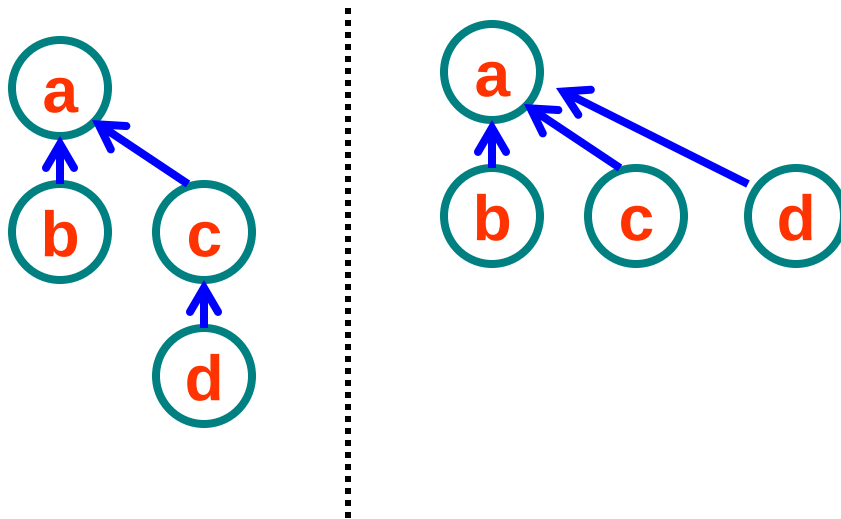
■ Path compression

■ Speeds up future Find() operations

1. Follow parent pointer(s) to root of tree
2. Update all nodes along path to point to root

■ Example

■ Find(d)



So how fast is
Union-Find?

Ackermann's Function

■ Function

```
int A(x,y) {  
    if (x == 0)  
        return y+1;  
    if (y == 0)  
        return A(x - 1, 1);  
    return A(x - 1, A(x, y - 1));  
}
```

■ A() grows fast

■ $A(2,2) = 7$

■ $A(3,3) = 61$

■ $A(4,2) = 2^{65536} - 3$

■ $A(4,3) = 2^{2^{65536}} - 3$

■ $A(4,4) = 2^{2^{2^{65536}}} - 3$

Inverse Ackermann's Function

■ Definition

- $\alpha(n)$ is the inverse Ackermann's function
- $\alpha(n)$ = the smallest k such that $A(k,k) \geq n$

■ Fun fact

- $\alpha(\text{number of atoms in universe}) = 4$

■ Union-find

- A sequence of n operations requires $O(n \alpha(n))$ time
- Practically speaking, indistinguishable from $O(n)$

Graph Summary

- **Graph data structure**
 - Very useful in practice
 - Different representations
- **Many graph algorithms**
 - Traversal
 - Shortest path
 - Minimum spanning tree