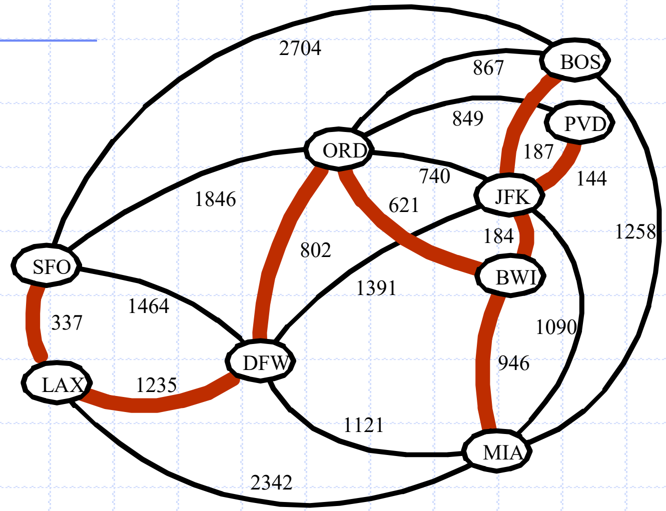
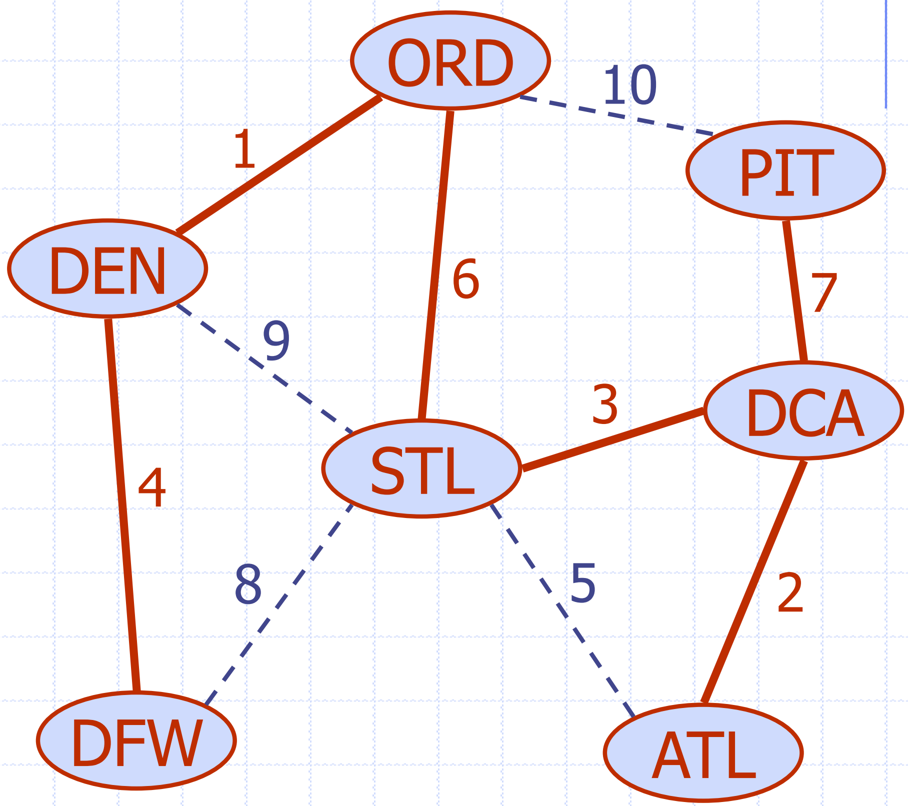
Minimum Spanning Trees



Minimum Spanning Trees

- Spanning subgraph
  - Subgraph of a graph ***G*** containing all the vertices of ***G***
- Spanning tree
  - Spanning subgraph that is itself a (free) tree
- Minimum spanning tree (MST)
  - Spanning tree of a weighted graph with minimum total edge weight
- Applications
  - Communications networks
  - Transportation networks



Spanning → Contain all nodes!

Cycle Property

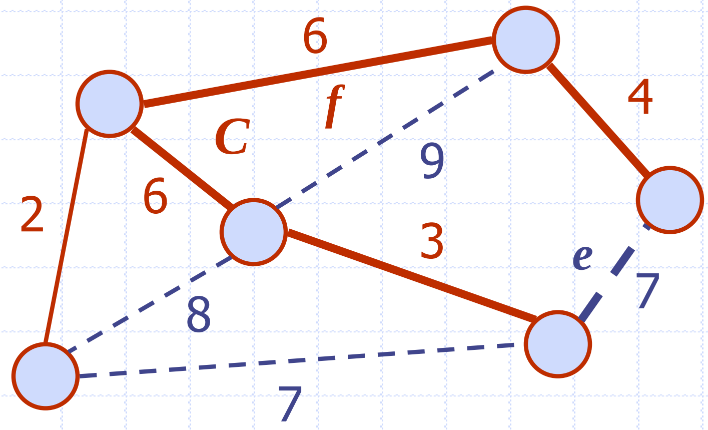
➔ Edge e must be in MST
if weight(e) is the smallest among all.

Cycle Property:

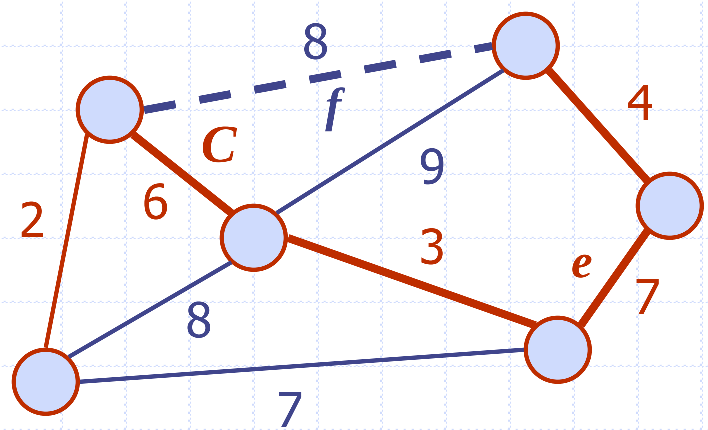
- Let T be a minimum spanning tree of a weighted graph G
- Let e be an edge of G that is not in T and let C be the cycle formed by e with T
- For every edge f of C, $weight(f) \le weight(e)$

Proof by contradiction:

- If $weight(f) > weight(e)$ we can get a spanning tree of smaller weight by replacing f with e ➔ Contradiction!



Replacing f with e yields a better spanning tree



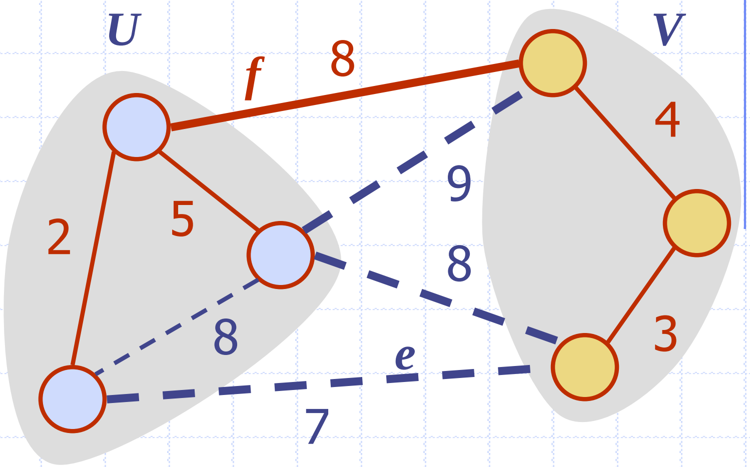
Partition Property

Partition Property:

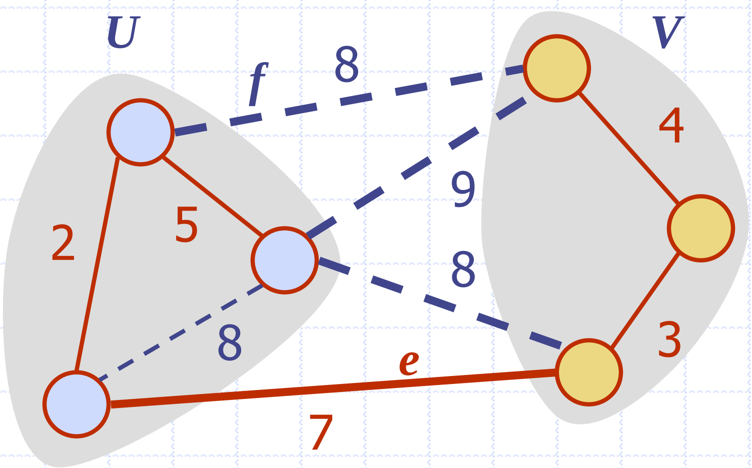
- Consider a partition of the vertices of G into subsets U and V
- Let e be an edge of minimum weight across the partition
- There is a minimum spanning tree of G containing edge e

Proof by contradiction:

- Let T be an MST of G
- If T does not contain e, consider the cycle C formed by e with T and let f be an edge of C across the partition.
- Since $weight(f) > weight(e)$, T is not a MST ➔ Contradiction!



Replacing f with e yields another MST



Kruskal's Algorithm

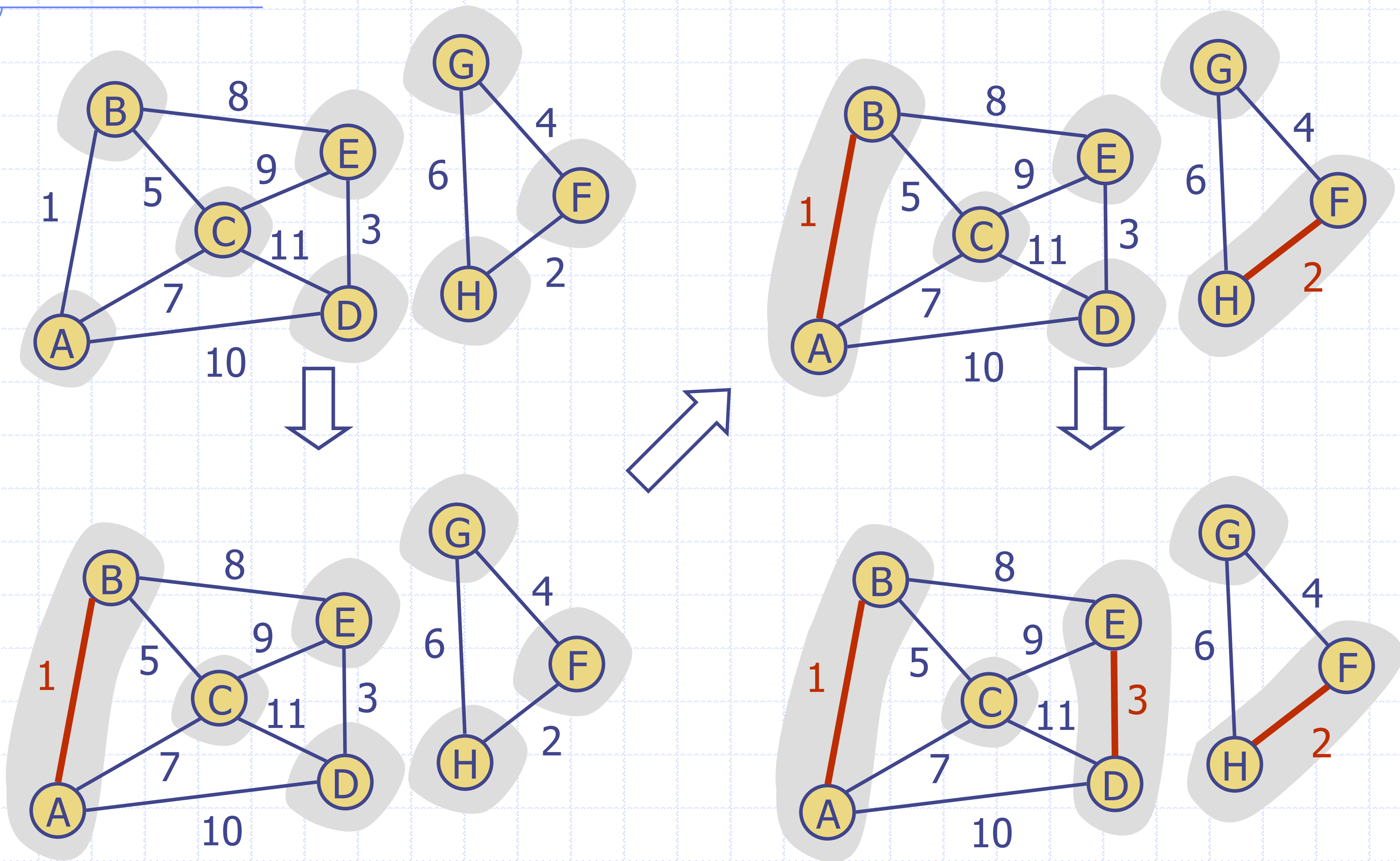
Based on the concept that
edge e must be in MST
if weight(e) is the smallest among all.

- Maintain a partition of the vertices into clusters
  - Initially, single-vertex clusters
  - Keep an MST for each cluster
  - Merge "closest" clusters and their MSTs
- A priority queue stores the edges outside clusters
  - Key: weight
  - Element: edge
- At the end of the algorithm
  - One cluster and one MST

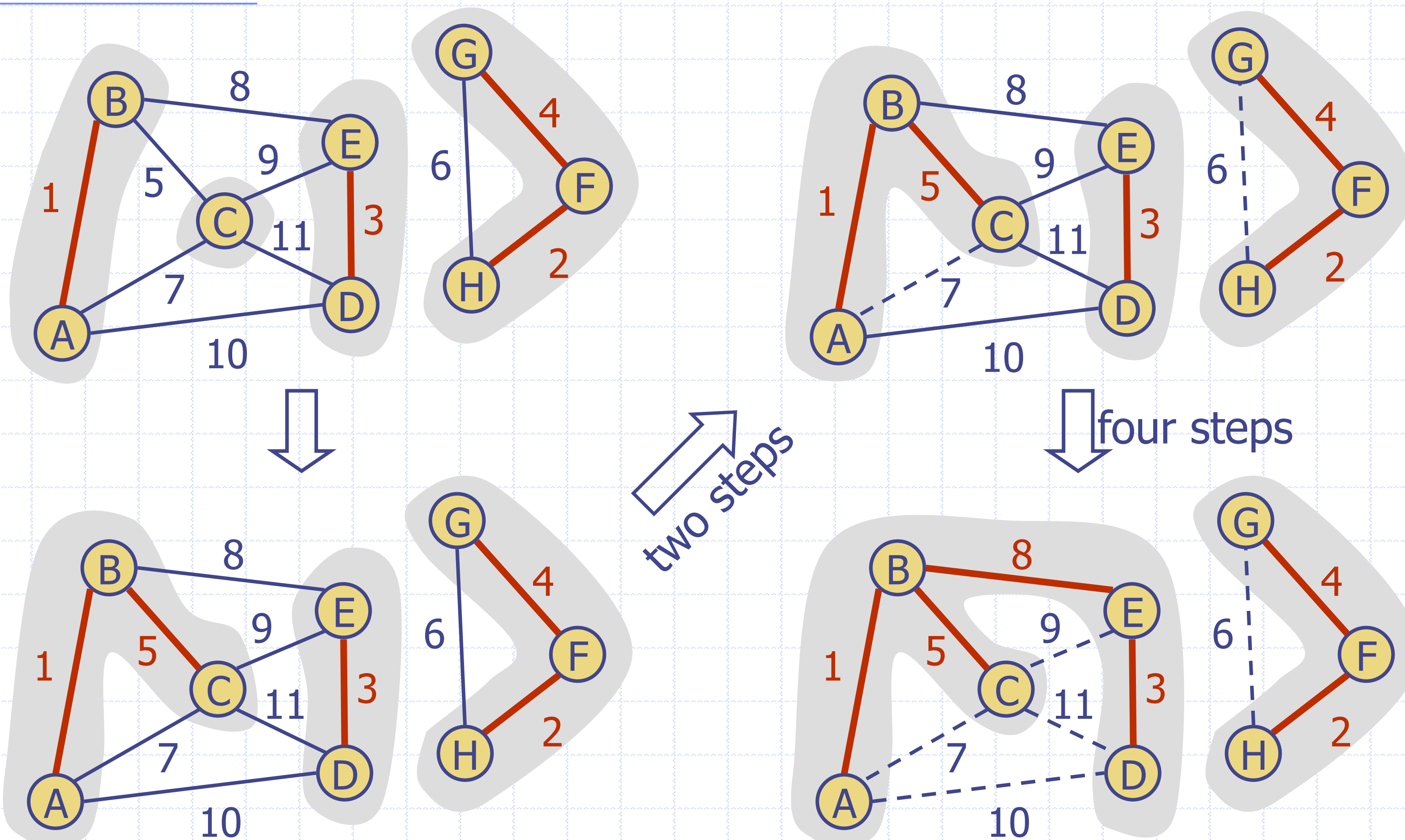
Algorithm ***KruskalMST*(*G*)**
  for each vertex *v* in *G* **do**
    Create a cluster consisting of *v*
  let *Q* be a priority queue.
  Insert all edges into *Q*
  $T \leftarrow \varnothing$
  {*T* is the union of the MSTs of the clusters}
  while *T* has fewer than $n - 1$ edges **do**
  e ← *Q.removeMin*().*getValue*()
    [*u*, *v*] ← *G.endVertices*(*e*)
    A ← *getCluster*(*u*)
    B ← *getCluster*(*v*)
    if $A \neq B$ **then**
      Add edge *e* to *T*
      mergeClusters(*A*, *B*)
  return *T*

Example

Quiz!



Example (contd.)

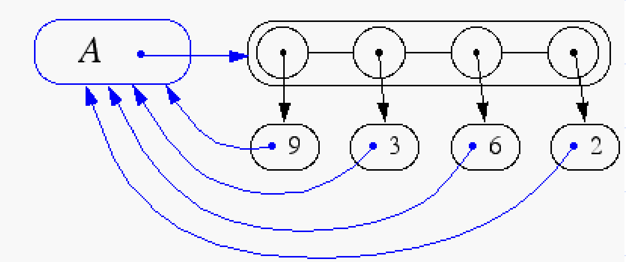


m=n-1

Data Structure for Kruskal's Algorithm

- The algorithm maintains a forest of trees
- A priority queue extracts the edges by increasing weight
- An edge is accepted it if connects distinct trees
- We need a data structure that maintains a partition, i.e., a collection of disjoint sets, with operations:
  - makeSet(u): create a set consisting of u
  - find(u): return the set storing u
  - union(A, B): replace sets A and B with their union

Recall of List-based Partition



- Each set is stored in a sequence
- Each element has a reference back to the set
  - operation find(u) takes O(1) time, and returns the set of which u is a member.
  - in operation union(A,B), we move the elements of the smaller set to the sequence of the larger set and update their references
  - the time for operation union(A,B) is min(|A|, |B|)
- Whenever an element is processed, it goes into a set of size at least double, hence each element is processed at most log n times

Partition-Based Implementation

- Partition-based version of Kruskal's Algorithm
  - Cluster merges as unions
  - Cluster locations as finds
- Running time $O((n + m) \log n)$
  - PQ operations $O(m \log n)$
  - UF operations $O(n \log n)$

Algorithm *KruskalMST*(*G*)
  Initialize a partition *P*
  for each vertex *v* in *G* **do**
    P.makeSet(*v*)
  let *Q* be a priority queue.
  Insert all edges into *Q*
  $T \leftarrow \emptyset$
  {*T* is the union of the MSTs of the clusters}
  while *T* has fewer than $n - 1$ edges **do**
  $e \leftarrow$ *Q.removeMin*().*getValue*()
    $[u, v] \leftarrow$ *G.endVertices*(*e*)
    $A \leftarrow$ *P.find*(*u*)
    $B \leftarrow$ *P.find*(*v*)
    if $A \neq B$ **then**
      Add edge *e* to *T*
      P.union(*A*, *B*)
  return *T*

Prim's Algorithm

Based on partition property

- Similar to Dijkstra's algorithm
- We pick an arbitrary vertex s and we grow the MST as a cloud of vertices, starting from s
- We store with each vertex v label $d(v)$ representing the smallest weight of an edge connecting v to a vertex in the cloud
- At each step:
  - We add to the cloud the vertex u outside the cloud with the smallest distance label
  - We update the labels of the vertices adjacent to u

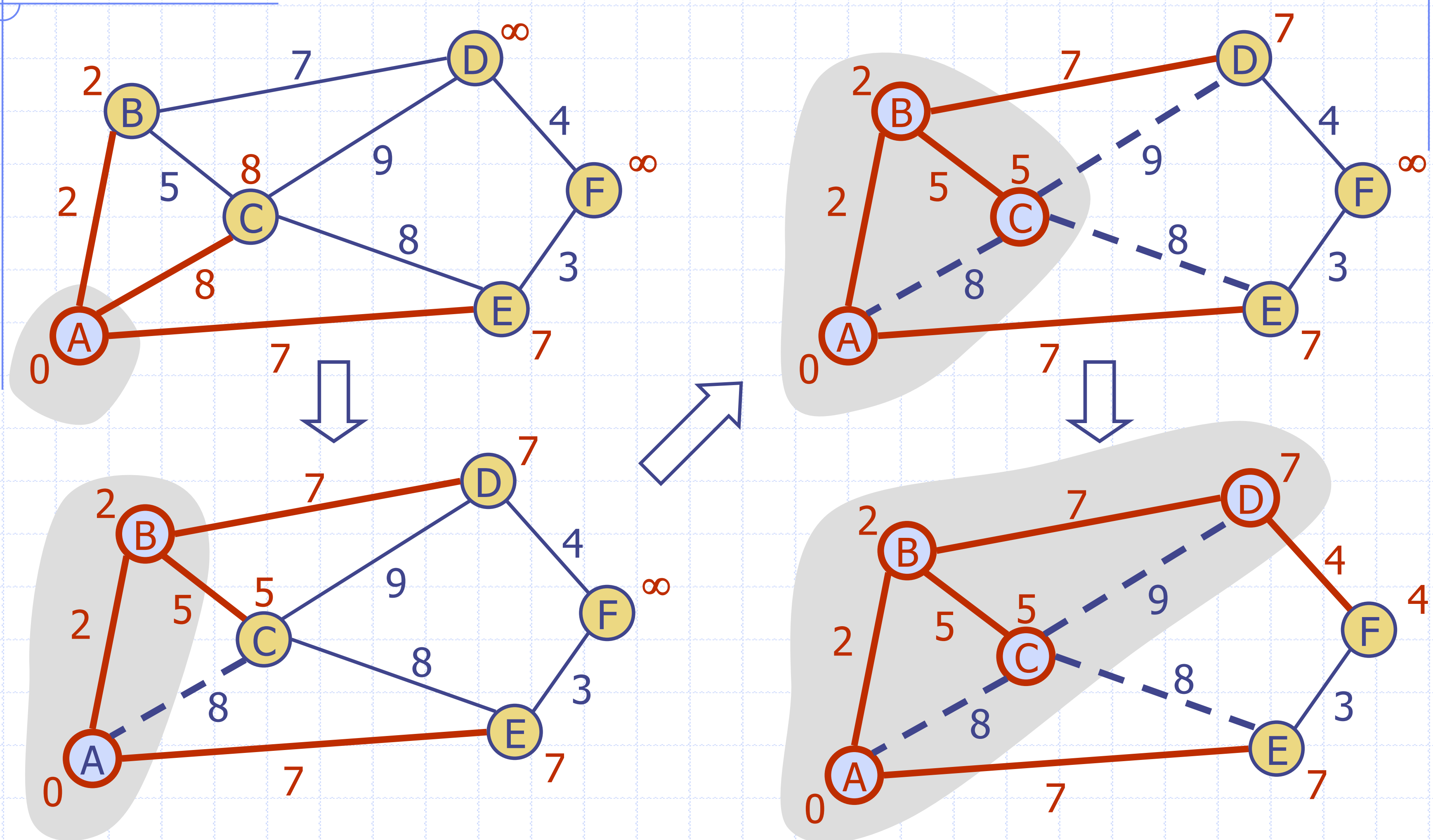
Prim's Algorithm (cont.)

- A heap-based adaptable priority queue with location-aware entries stores the vertices outside the cloud
  - Key: distance
  - Value: vertex
  - Recall that method ***replaceKey***(***l***,***k***) changes the key of entry ***l***
- We store three labels with each vertex:
  - Distance
  - Parent edge in MST
  - Entry in priority queue

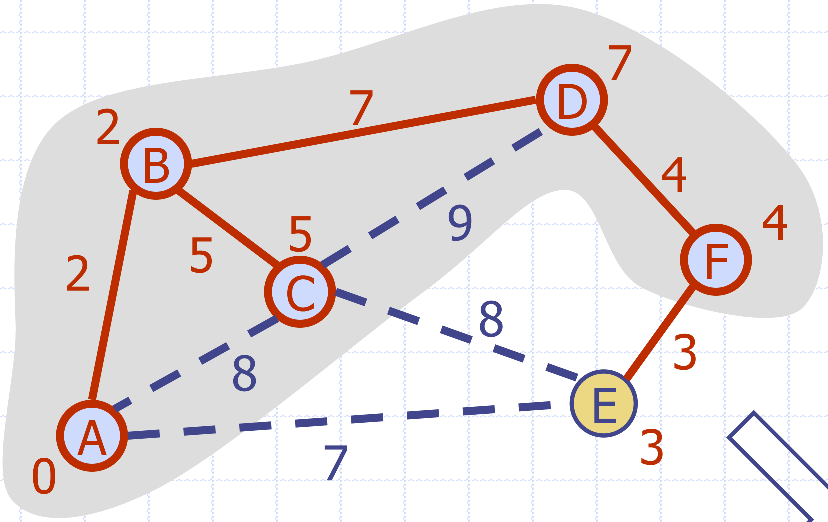
```
Algorithm PrimJarnikMST(G)
    Q ← new heap-based priority queue
    s ← a vertex of G
    for all v ∈ G.vertices()
        if v = s
            v.setDistance(0)
        else
            v.setDistance(∞)
        v.setParent(∅)
        l ← Q.insert(v.getDistance(), v)
        v.setLocator(l)
    while ¬Q.empty()
        l ← Q.removeMin()
        u ← l.getValue()
        for all e ∈ u.incidentEdges()
            z ← e.opposite(u)
            r ← e.weight()
            if r < z.getDistance()
                z.setDistance(r)
                z.setParent(e)
                Q.replaceKey(z.getEntry(), r)
```

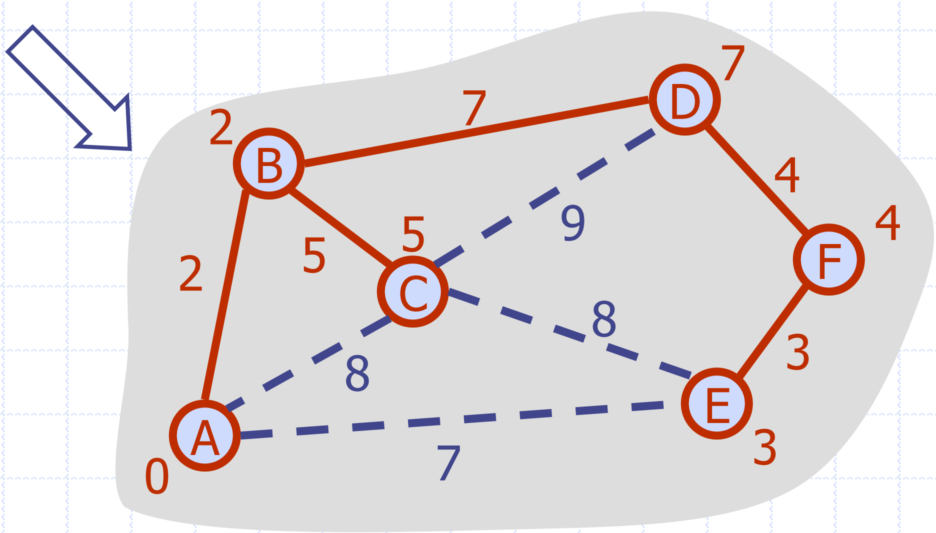
Example

Quiz!



Example (contd.)





Analysis

- Graph operations
  - Method incidentEdges is called once for each vertex
- Label operations
  - We set/get the distance, parent and locator labels of vertex z $O(\deg(z))$ times
  - Setting/getting a label takes $O(1)$ time
- Priority queue operations
  - Each vertex is inserted once into and removed once from the priority queue, where each insertion or removal takes $O(\log n)$ time
  - The key of a vertex w in the priority queue is modified at most $\deg(w)$ times, where each key change takes $O(\log n)$ time
- Prim's algorithm runs in $O((n + m) \log n)$ time provided the graph is represented by the adjacency list structure
  - Recall that $\Sigma_v \deg(v) = 2m$
- The running time is $O(m \log n)$ since the graph is connected

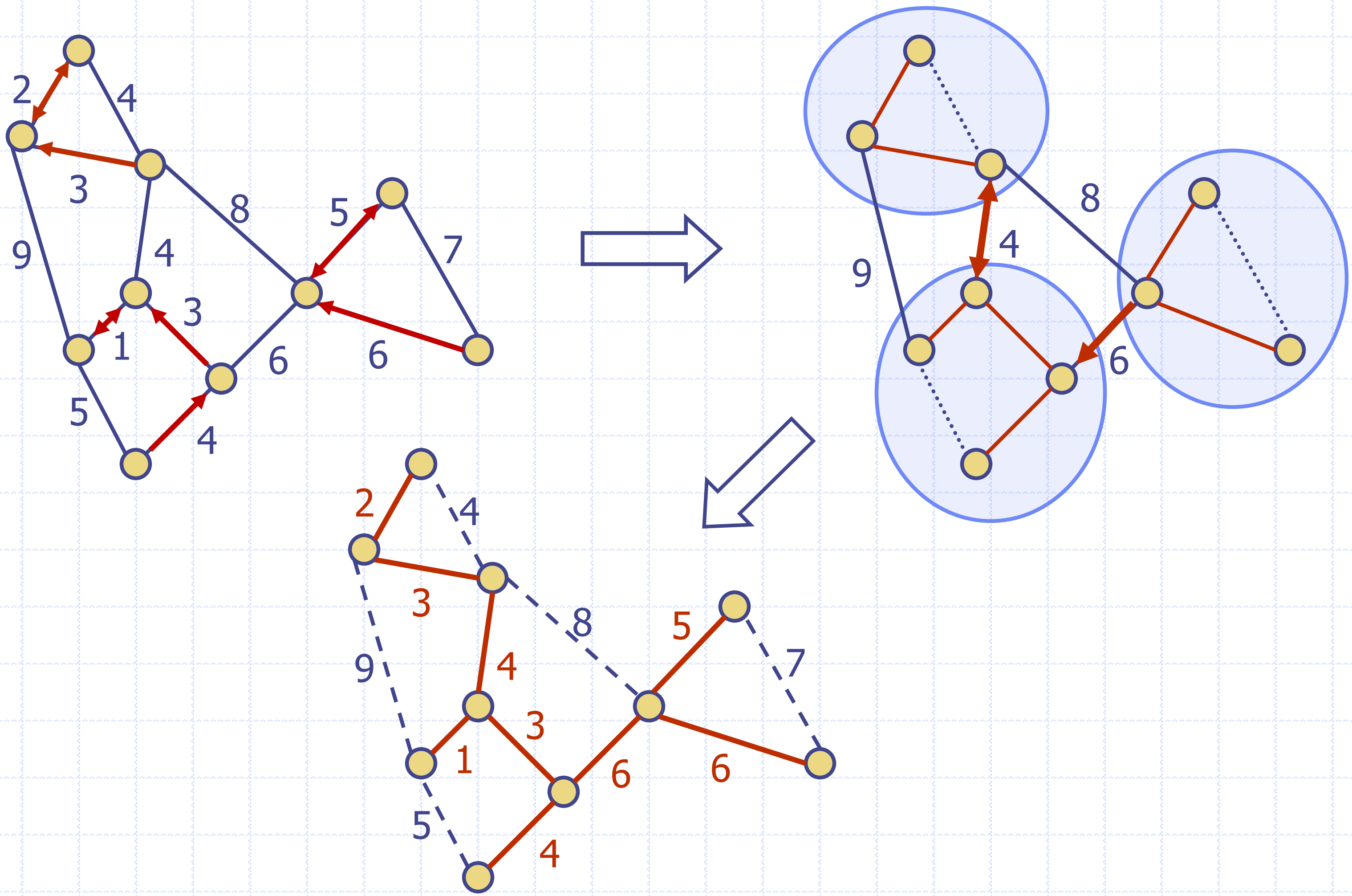
Baruvka's Algorithm (Exercise)

- Like Kruskal's Algorithm, Baruvka's algorithm grows many clusters at once and maintains a forest T
- Each iteration of the while loop halves the number of connected components in forest T
- The running time is $O(m \log n)$

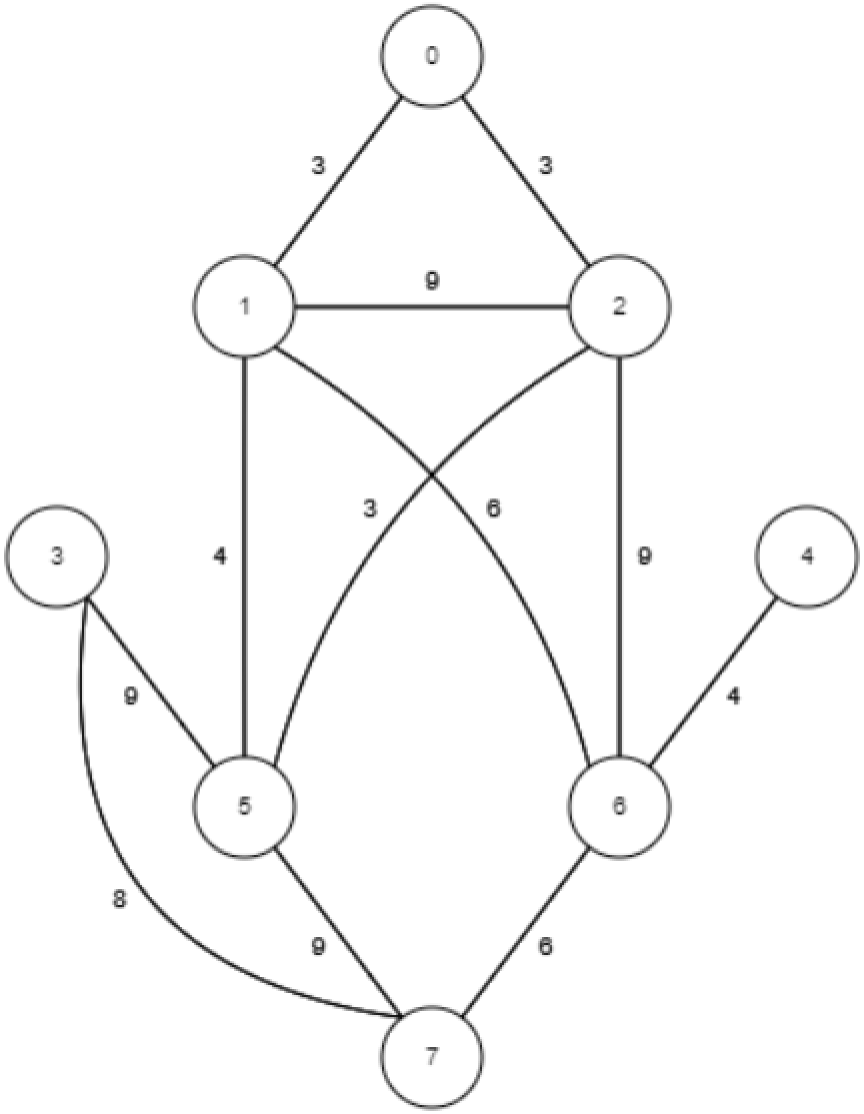
Algorithm *BaruvkaMST*(G)
    $T \leftarrow V$ {just the vertices of G}
  while T has fewer than $n - 1$ edges **do**
    for each connected component C in T **do**
      Let edge e be the smallest-weight edge from C to another component in T
      if e is not already in T **then**
        Add edge e to T
  return T

Example of Baruvka's Algorithm (animated)

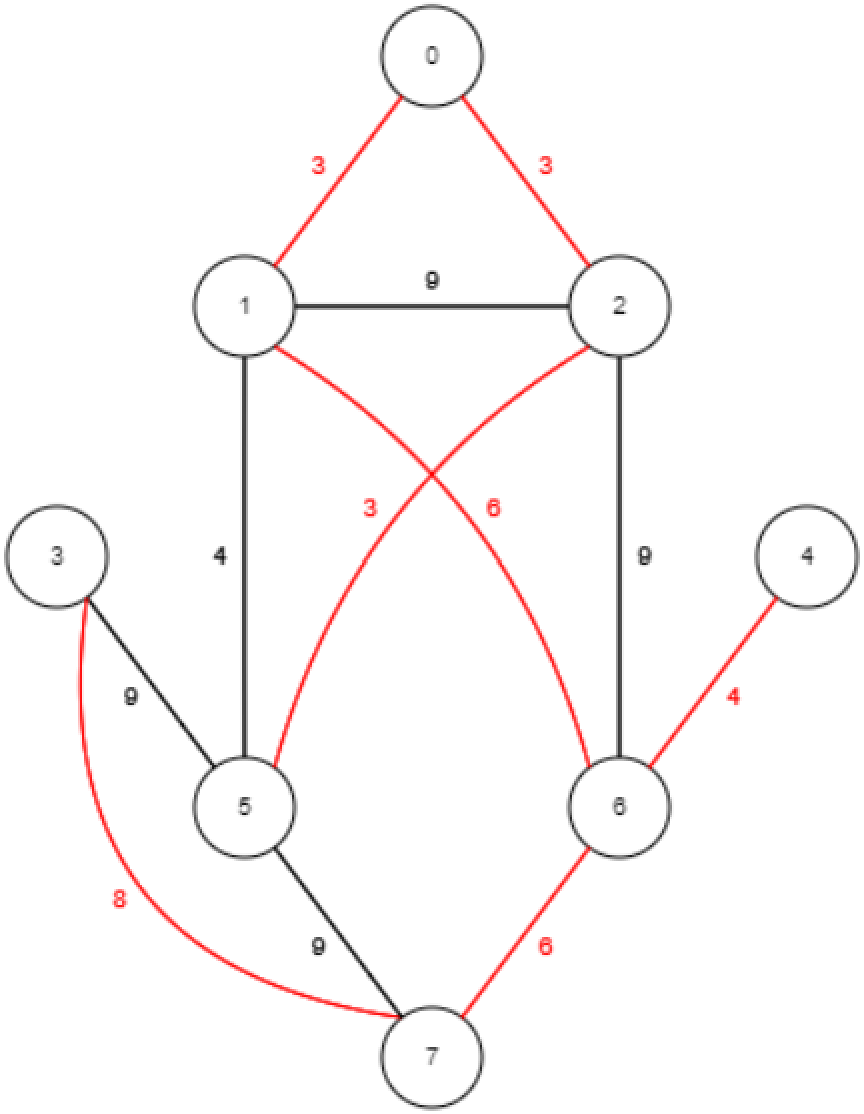
Slide by Matt Stallmann included with permission.



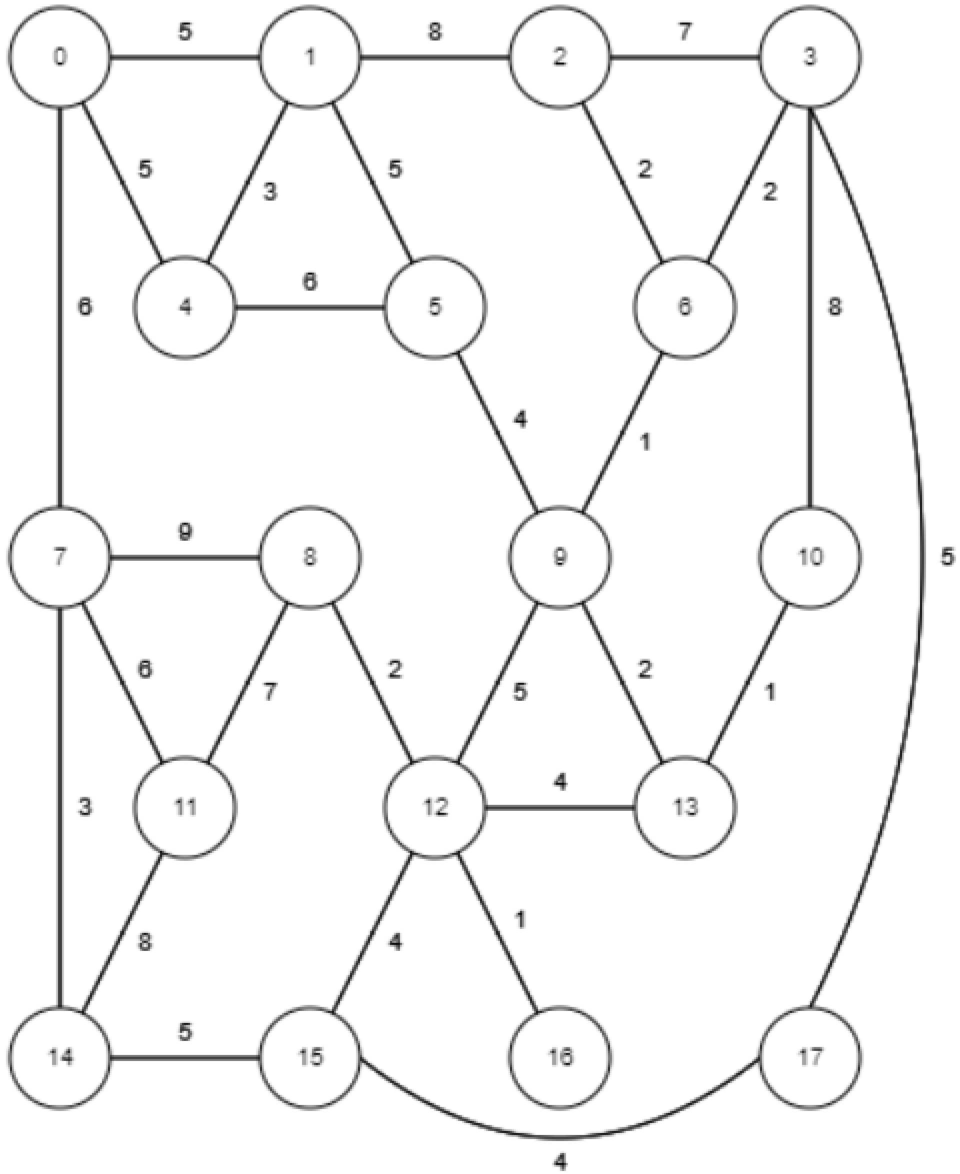
Exercise 1



Solution 1



Exercise 2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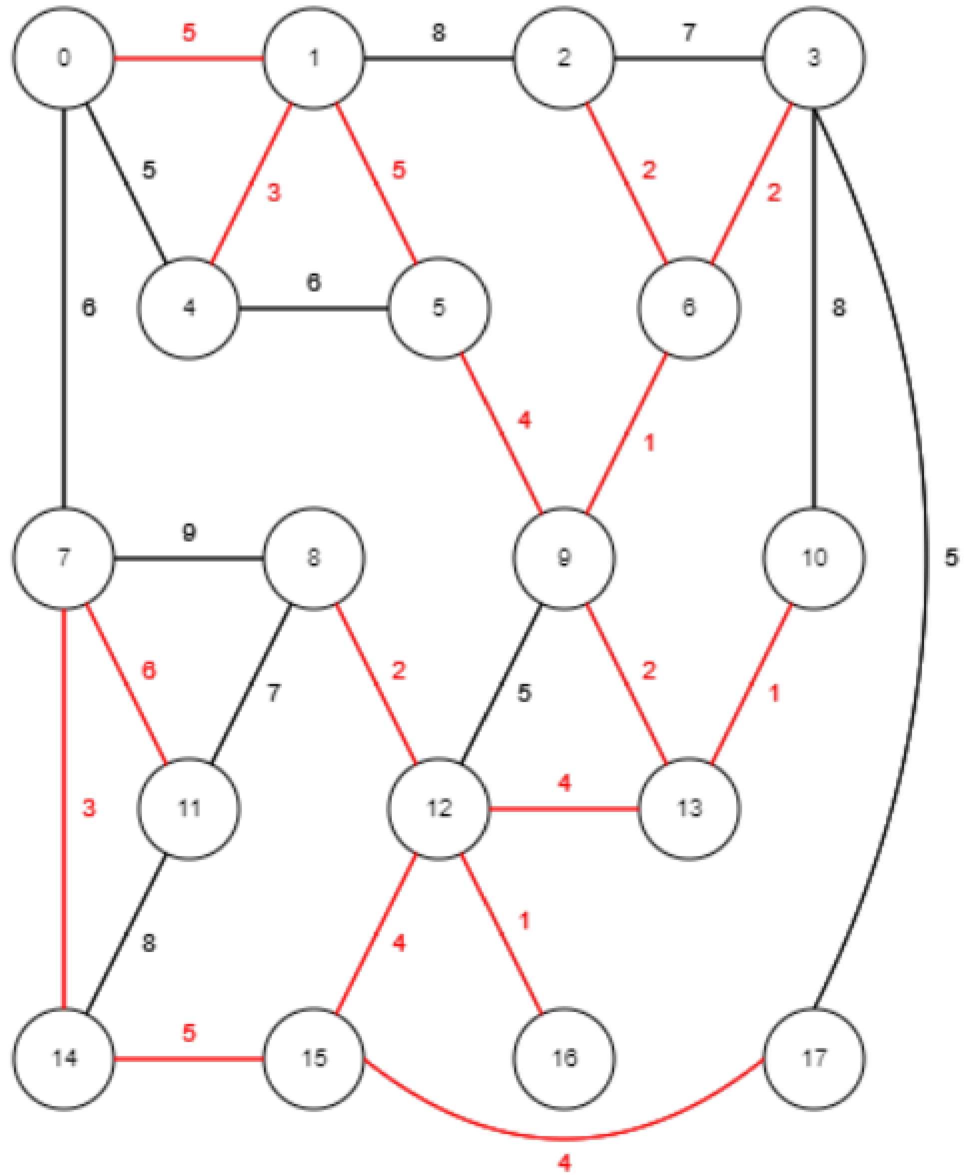
Solution 2



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Resources

- MST animation
  - Prim's algorithm
  - Kruskal's algorithm