https://algs4.cs.princeton.edu

4.3 MINIMUM SPANNING TREES

- *introduction*
- *cut property*
- *edge-weighted graph API*
- *Kruskal's algorithm*
- *Prim's algorithm*

https://algs4.cs.princeton.edu

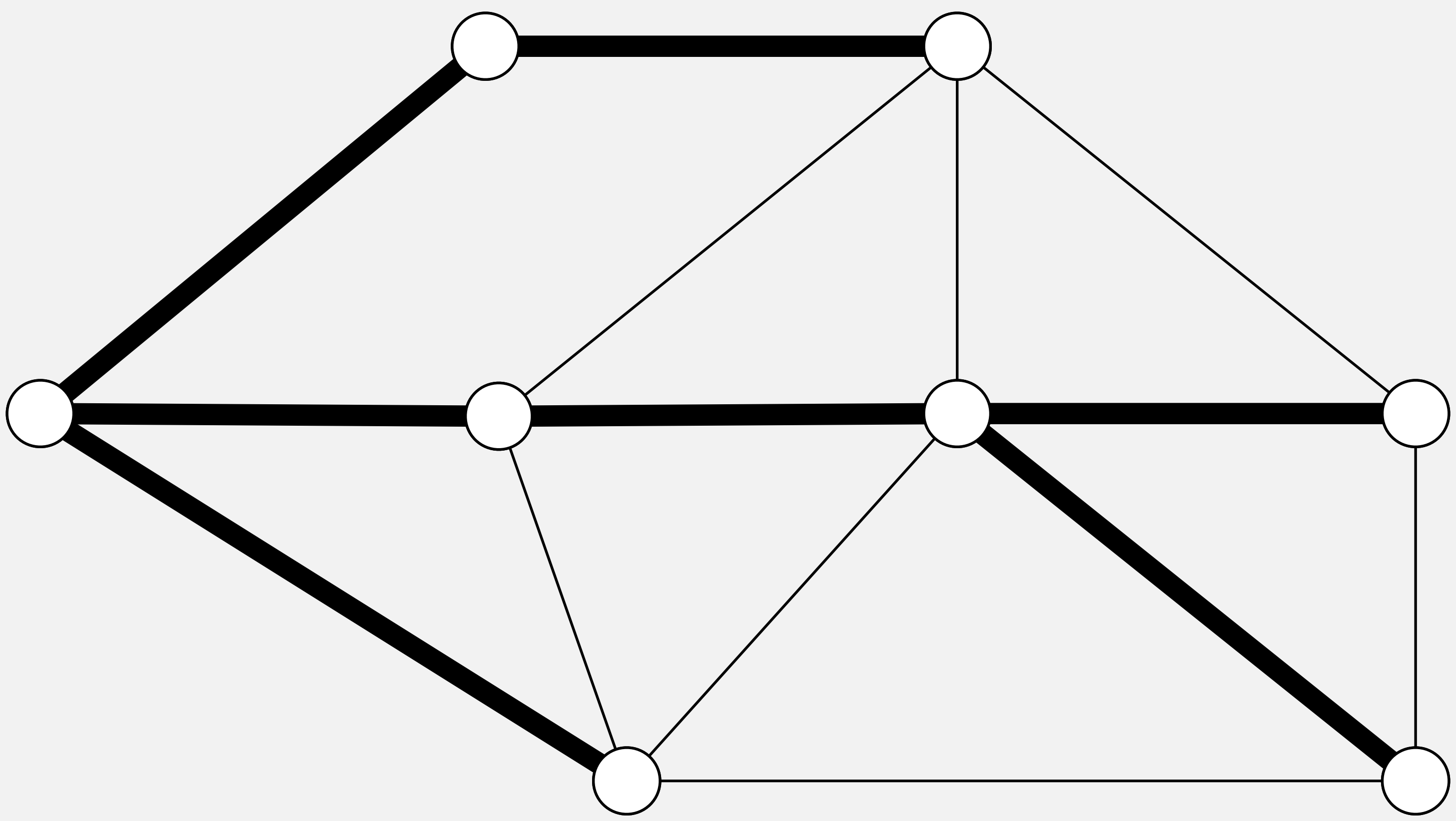
4.3 Minimum Spanning Trees

- *introduction*
- *cut property*
- *edge-weighted graph API*
- *Kruskal's algorithm*
- *Prim's algorithm*

Spanning tree

Def. A spanning tree of G is a subgraph T that is:

- A tree: connected and acyclic.
- Spanning: includes all of the vertices.

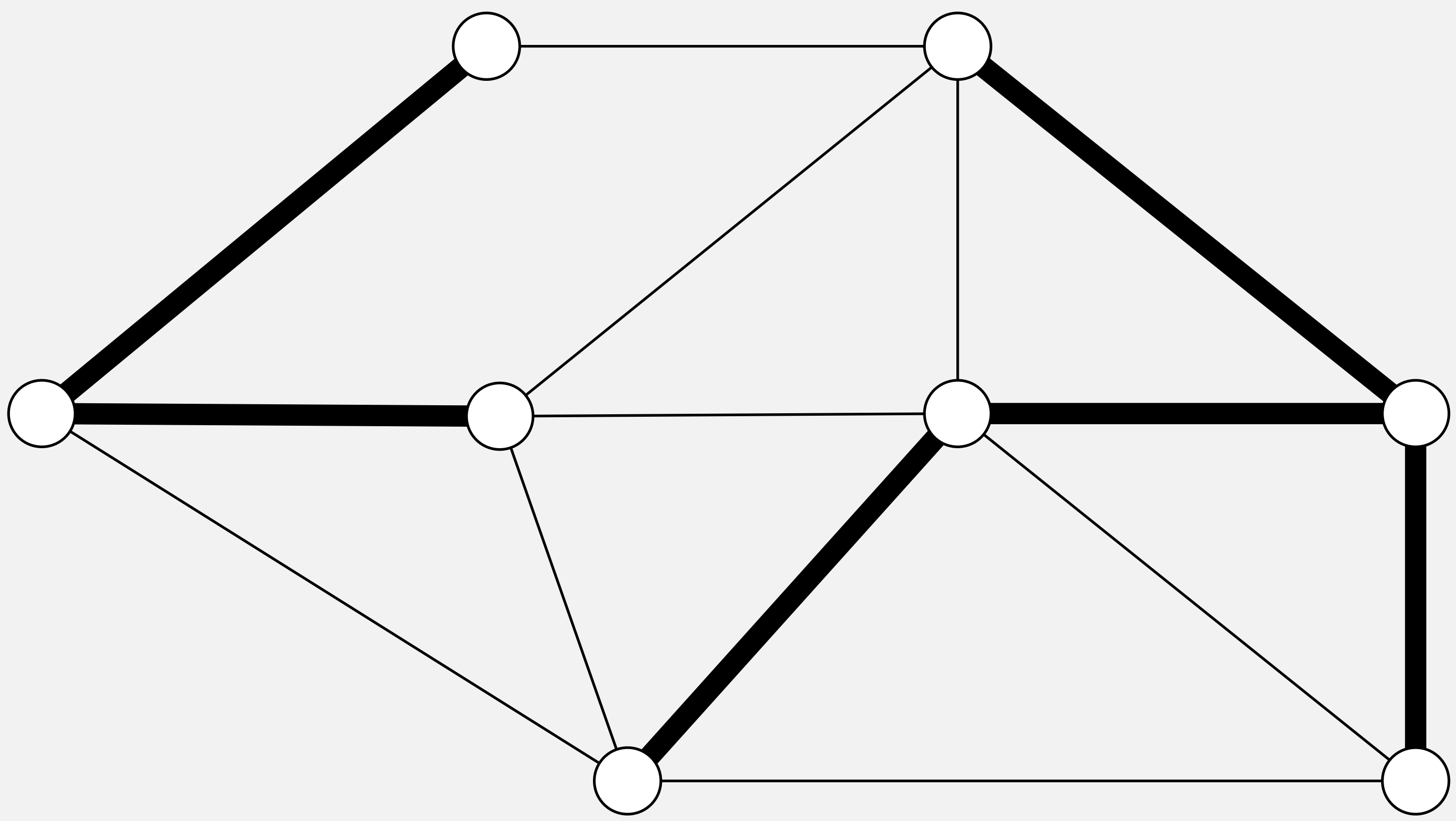


graph G
spanning tree T

Spanning tree

Def. A spanning tree of G is a subgraph T that is:

- A tree: connected and acyclic.
- Spanning: includes all of the vertices.

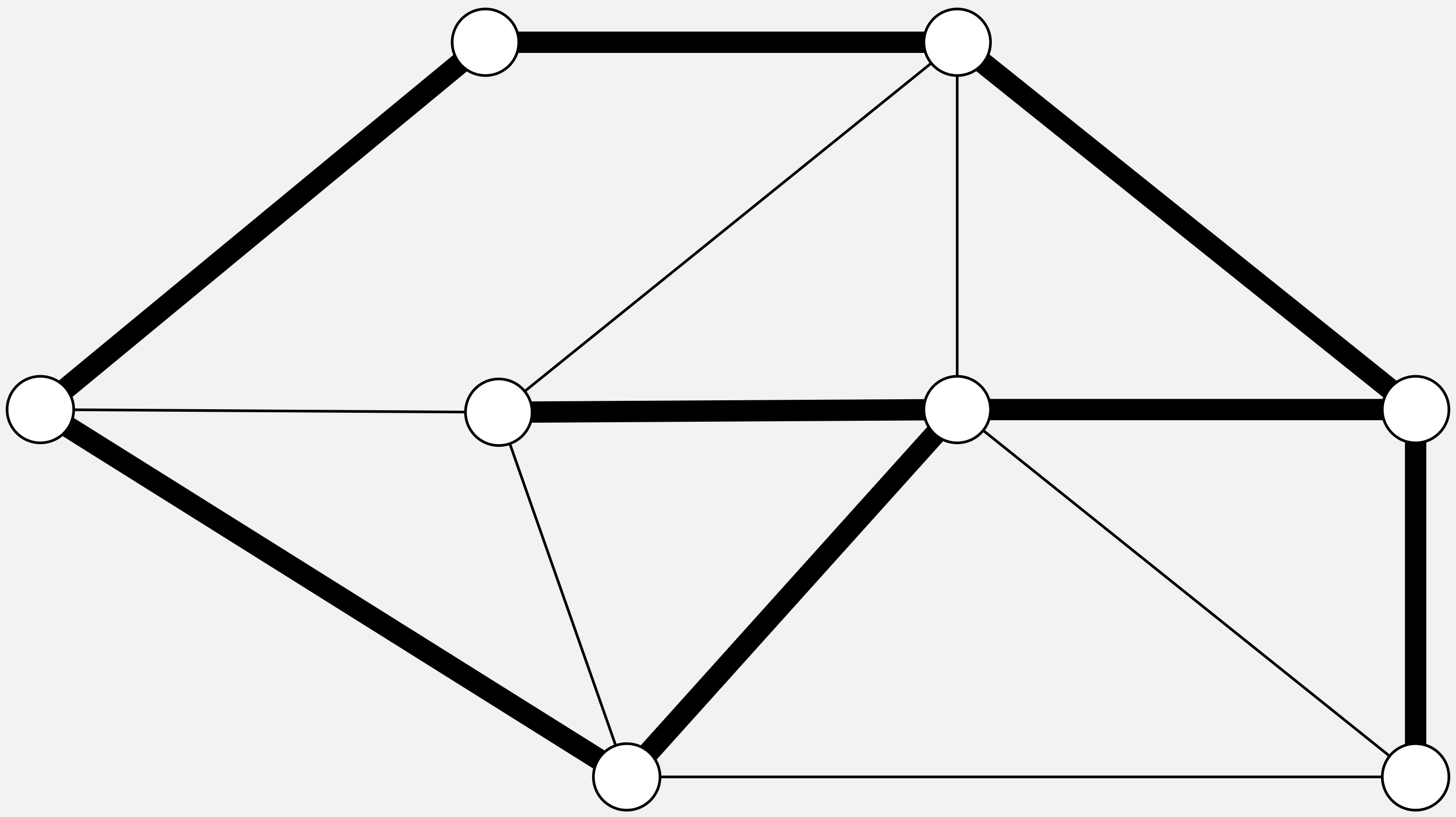


not connected

Spanning tree

Def. A spanning tree of G is a subgraph T that is:

- A tree: connected and acyclic.
- Spanning: includes all of the vertices.

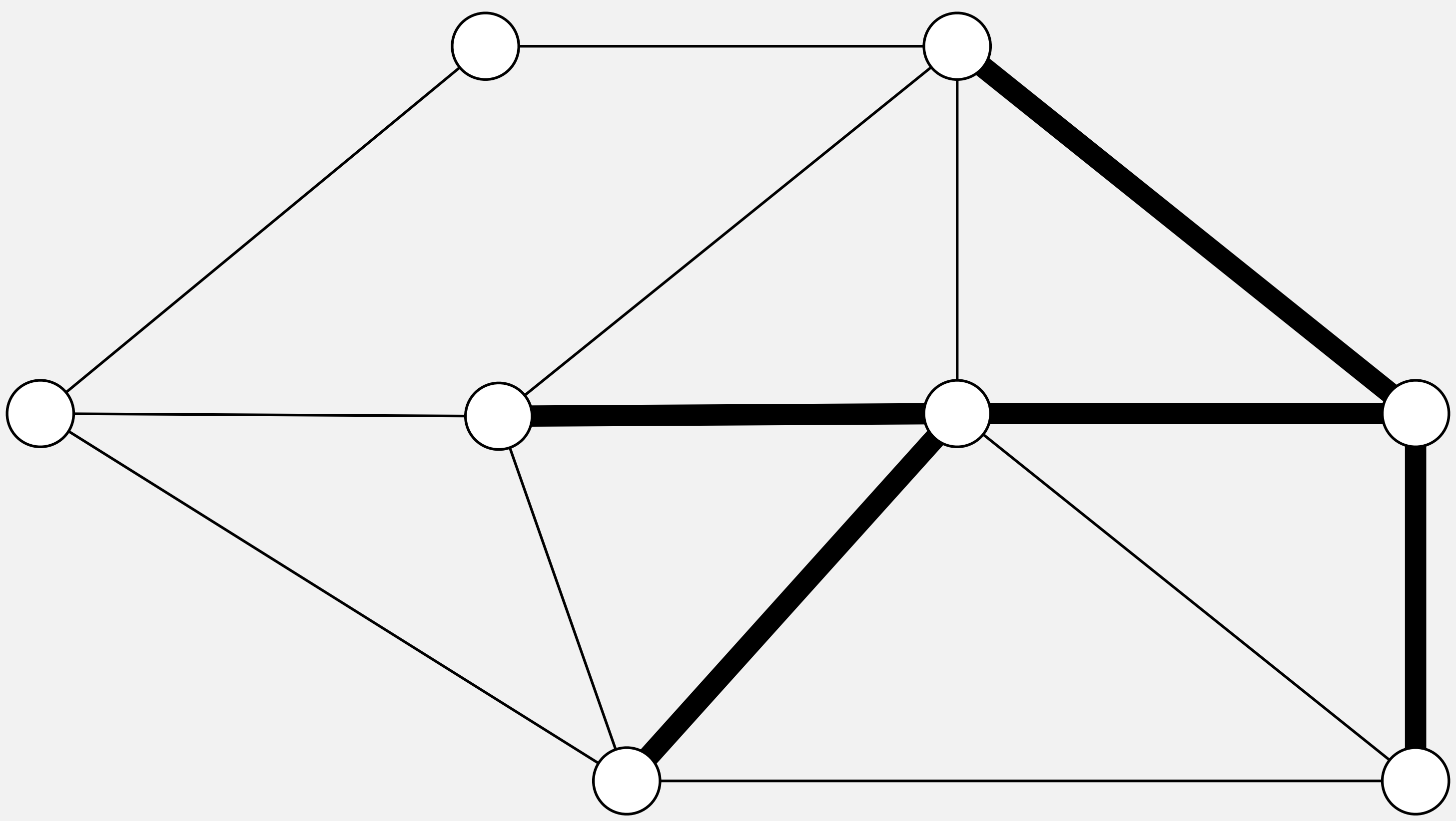


not acyclic

Spanning tree

Def. A spanning tree of G is a subgraph T that is:

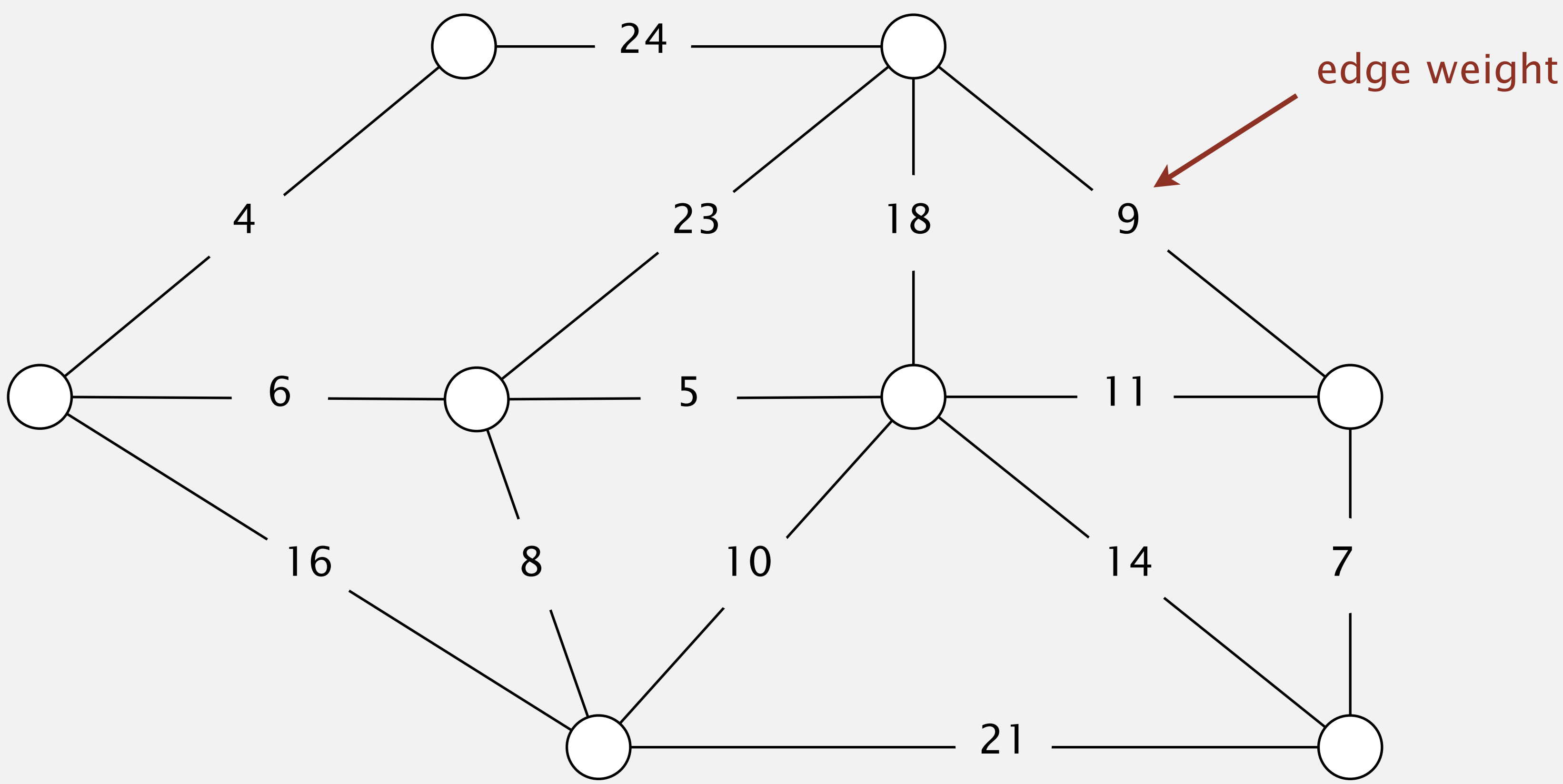
- A tree: connected and acyclic.
- Spanning: includes all of the vertices.



not spanning

Minimum spanning tree problem

Input. Connected, undirected graph G with positive edge weights.

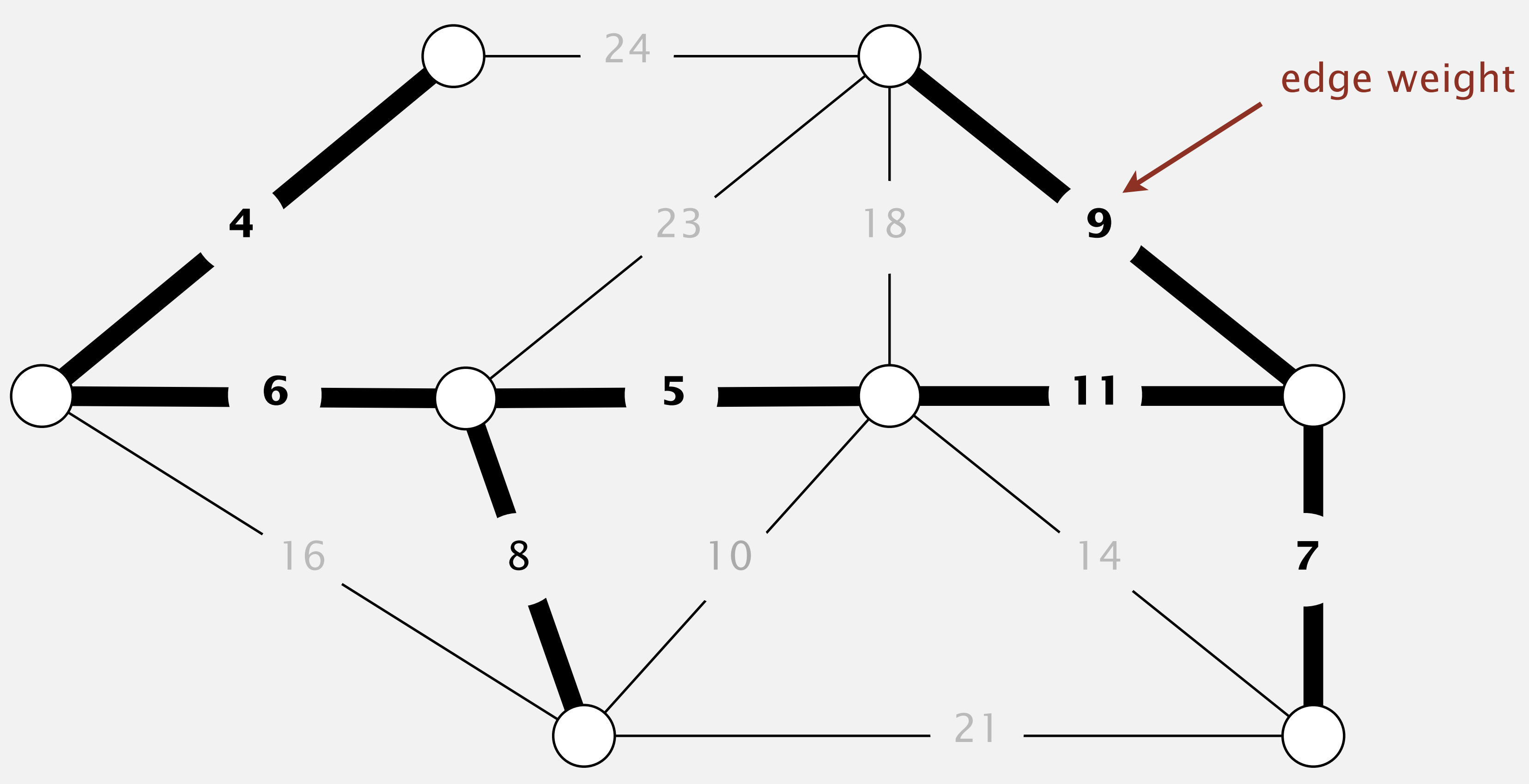


edge-weighted graph G

Minimum spanning tree problem

Input. Connected, undirected graph G with positive edge weights.

Output. A spanning tree of minimum weight.



minimum spanning tree T

(weight = 50 = 4 + 6 + 5 + 8 + 9 + 11 + 7)

Brute force. Try all spanning trees?

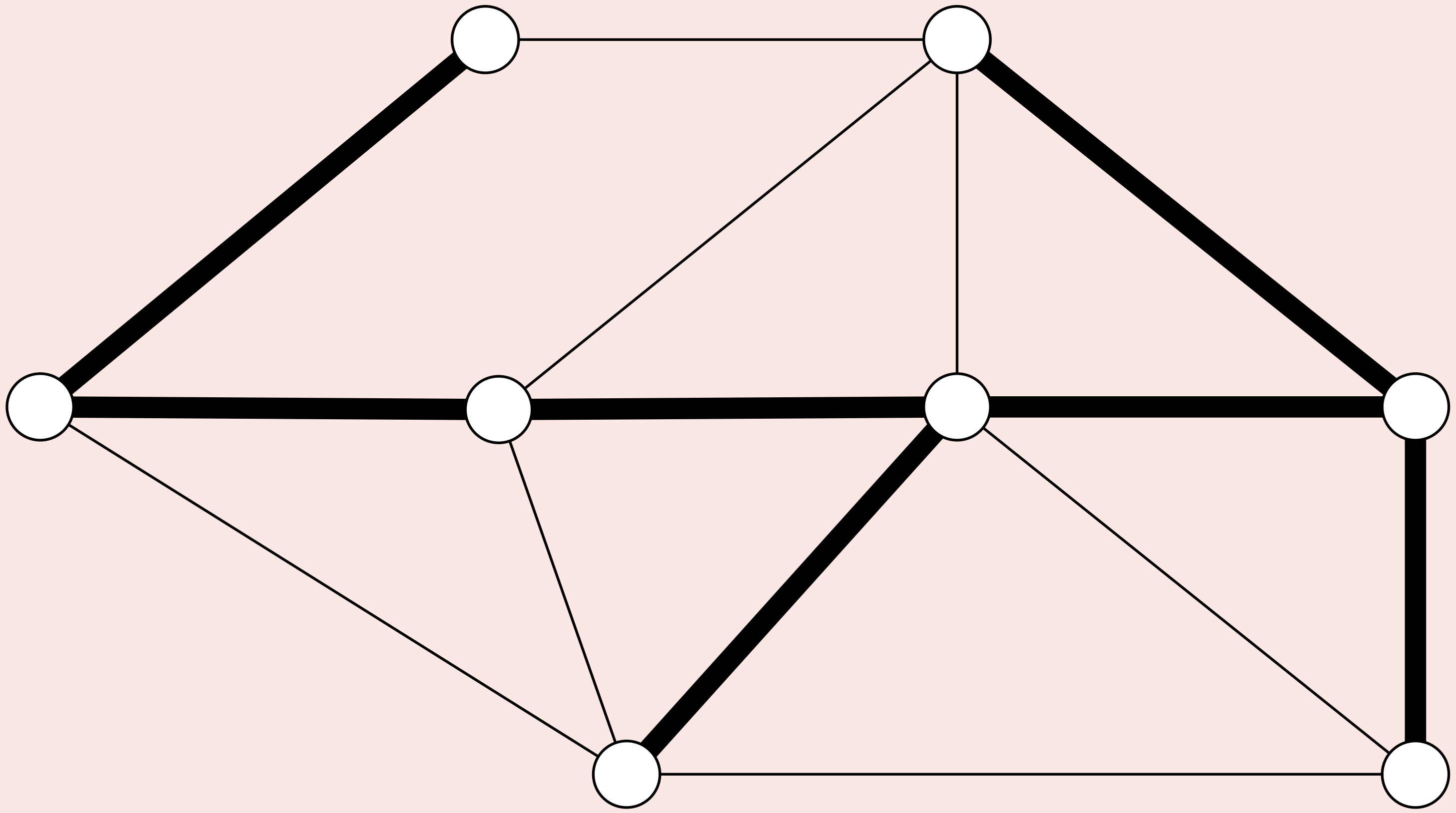
Let T be any spanning tree of a connected graph G with V vertices. Which of the following properties must hold?

A. T contains exactly $V - 1$ edges.

B. Removing any edge from T disconnects it.

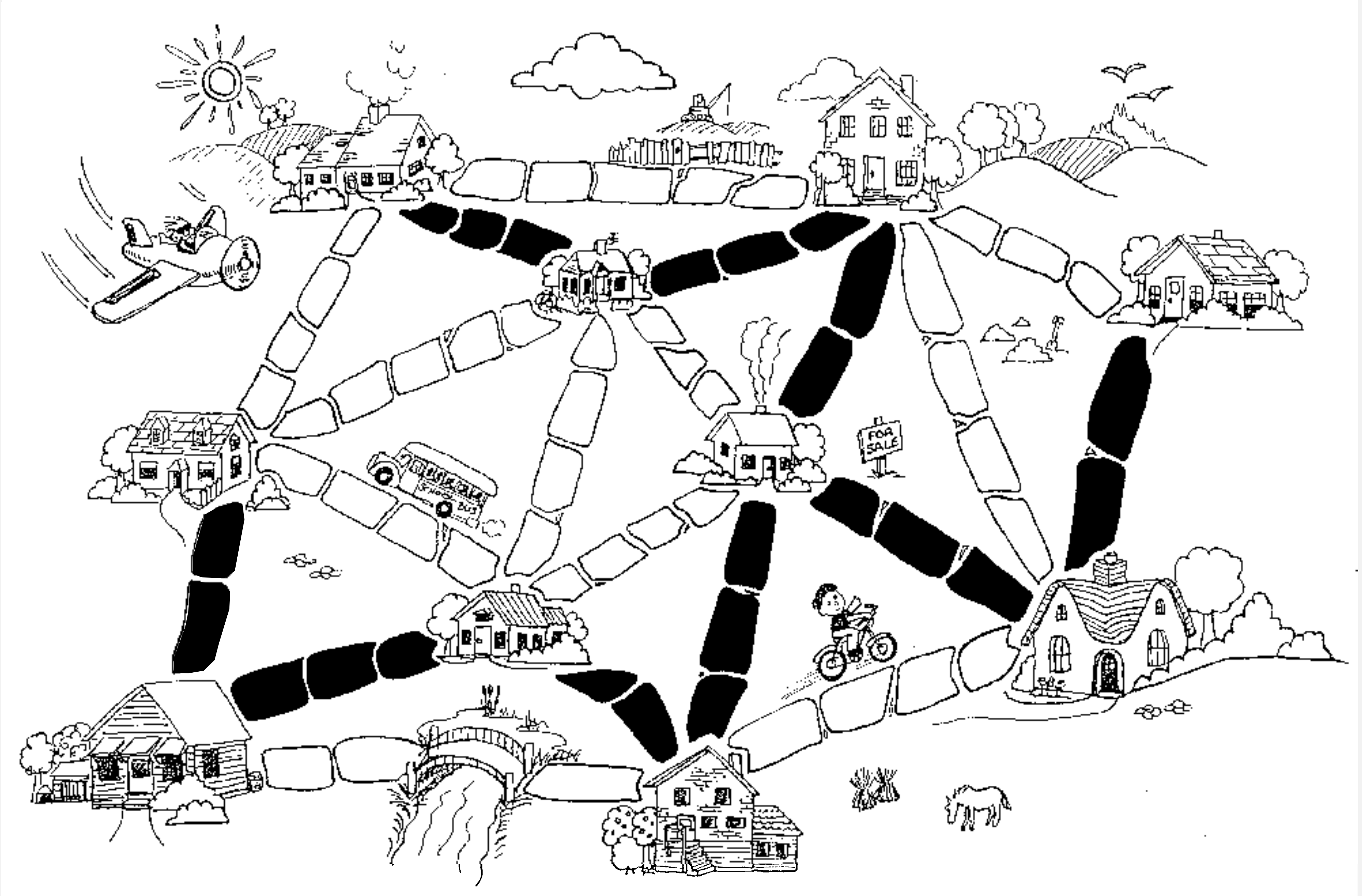
C. Adding any edge to T creates a cycle.

D. All of the above.



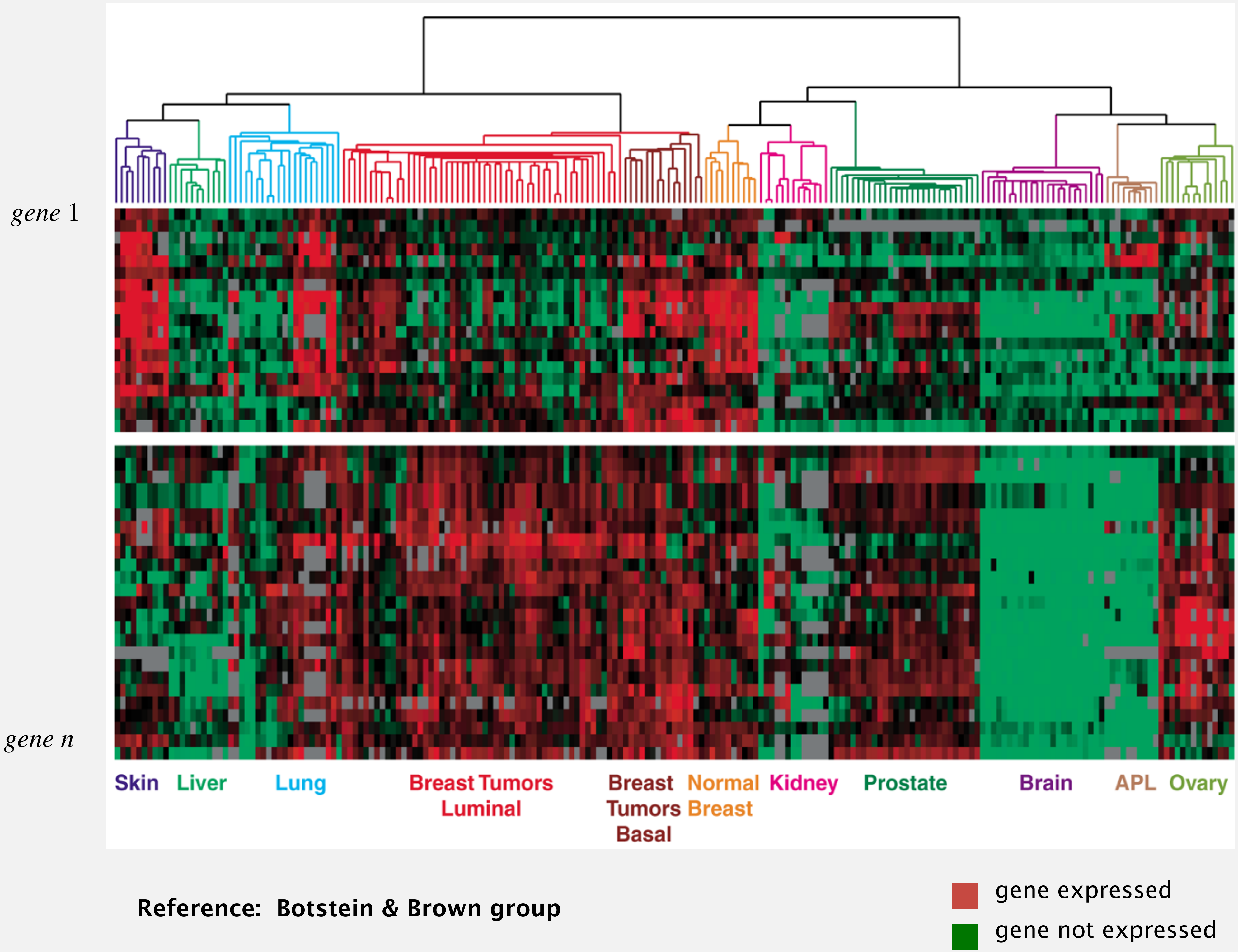
spanning tree T of graph G

Network design



https://www.utdallas.edu/~besp/teaching/mst-applications.pdf

Dendrogram of cancers in human



Reference: Botstein & Brown group

Applications

MST is fundamental problem with diverse applications.

- Cluster analysis.
- Real-time face verification.
- LDPC codes for error correction.
- Image registration with Renyi entropy.
- Curvilinear feature extraction in computer vision.
- Find road networks in satellite and aerial imagery.
- Handwriting recognition of mathematical expressions.
- Measuring homogeneity of two-dimensional materials.
  Model locality of particle interactions in turbulent fluid flows.
- Reducing data storage in sequencing amino acids in a protein.
- Autoconfig protocol for Ethernet bridging to avoid cycles in a network.
- Network design (communication, electrical, hydraulic, computer, road).
- Approximation algorithms for **NP**-hard problems (e.g., TSP, Steiner tree).

http://www.ics.uci.edu/~eppstein/gina/mst.html
http://www.utdallas.edu/~besp/teaching/mst-applications.pdf

https://algs4.cs.princeton.edu

4.3 MINIMUM SPANNING TREES

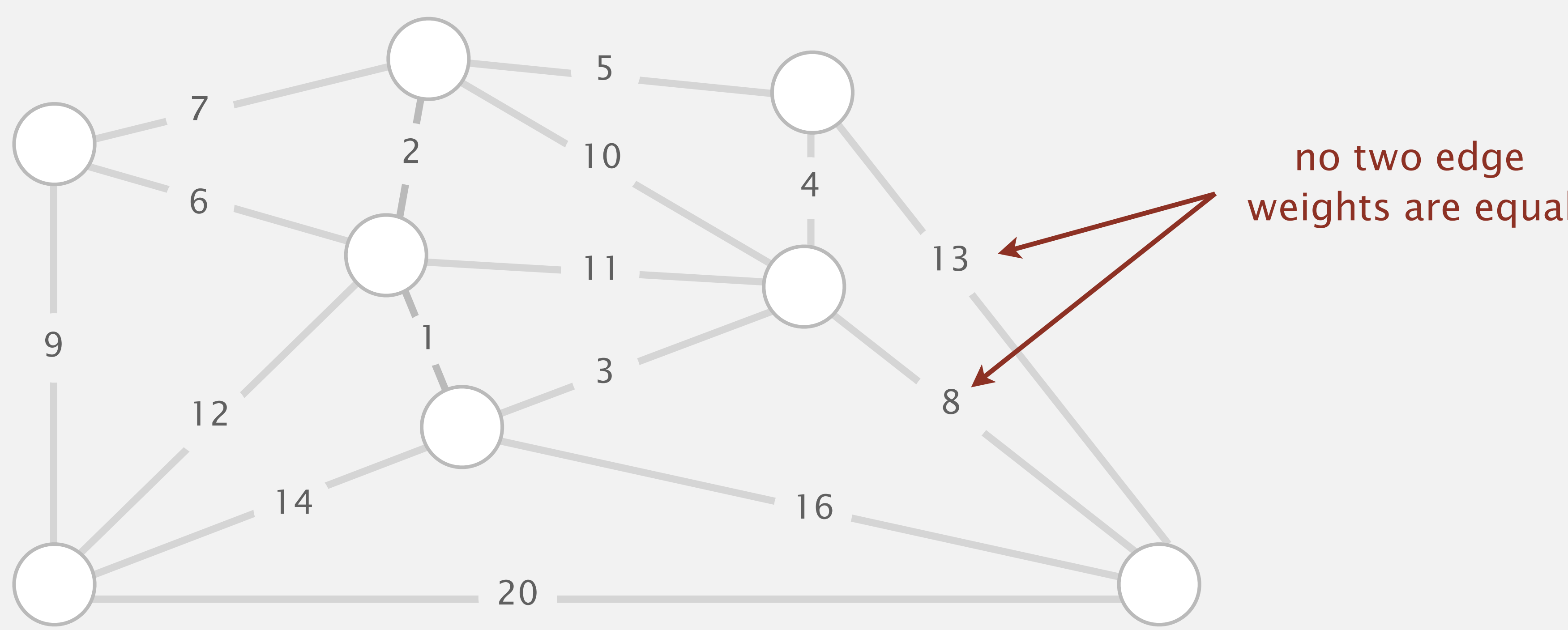
- *introduction*
- *cut property*
- *edge-weighted graph API*
- *Kruskal's algorithm*
- *Prim's algorithm*

Simplifying assumptions

For simplicity, we assume:

- The graph is connected. $\Rightarrow$ MST exists.
- The edge weights are distinct. $\Rightarrow$ MST is unique. ← see Exercise 4.3.3

Note. Algorithms still work even if duplicate edge weights.

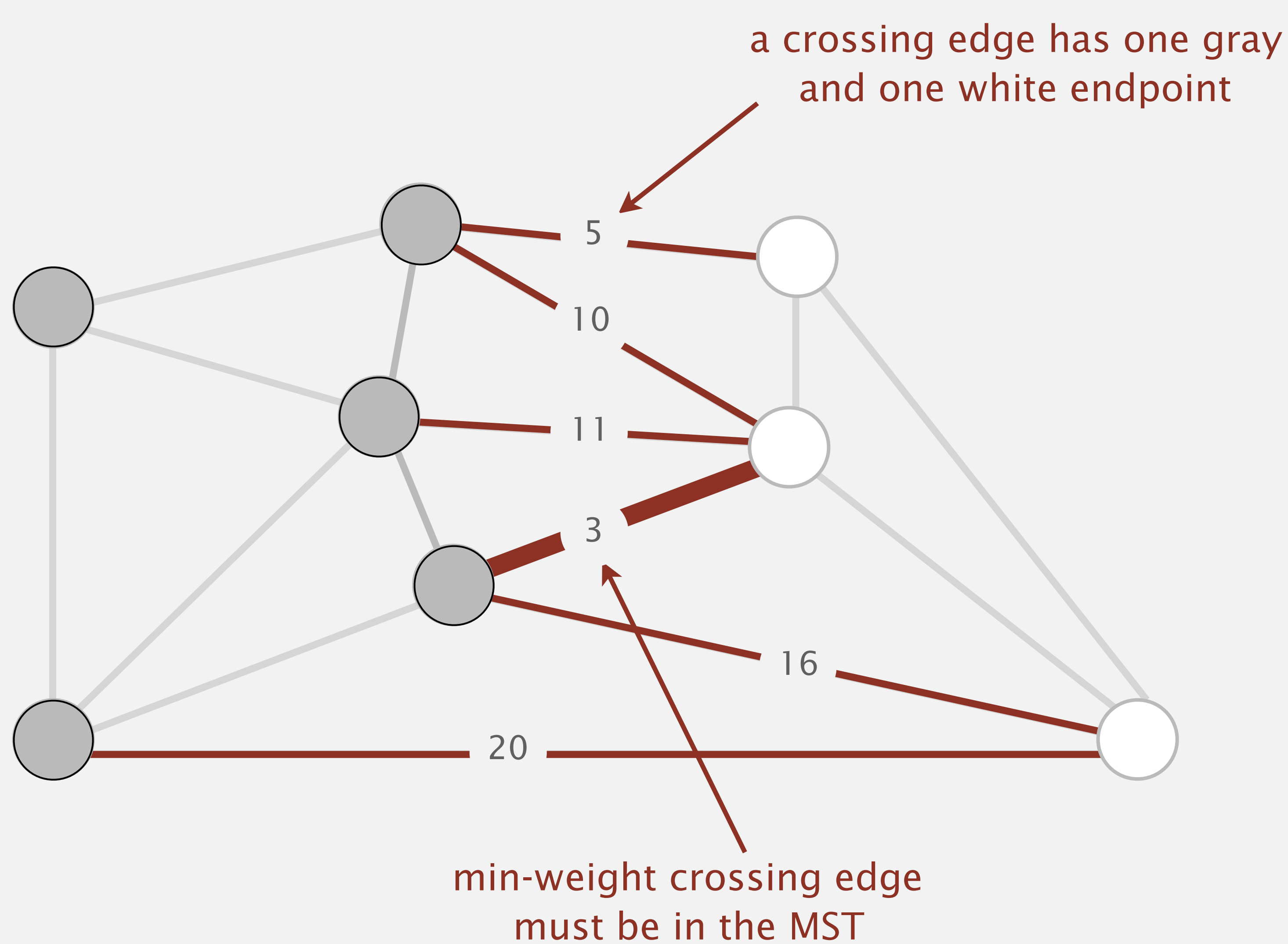


Cut property

Def. A cut in a graph is a partition of its vertices into two (nonempty) sets.

Def. A crossing edge is an edge that has one endpoint in each set.

Cut property. For any cut, the min-weight crossing edge is in the MST.



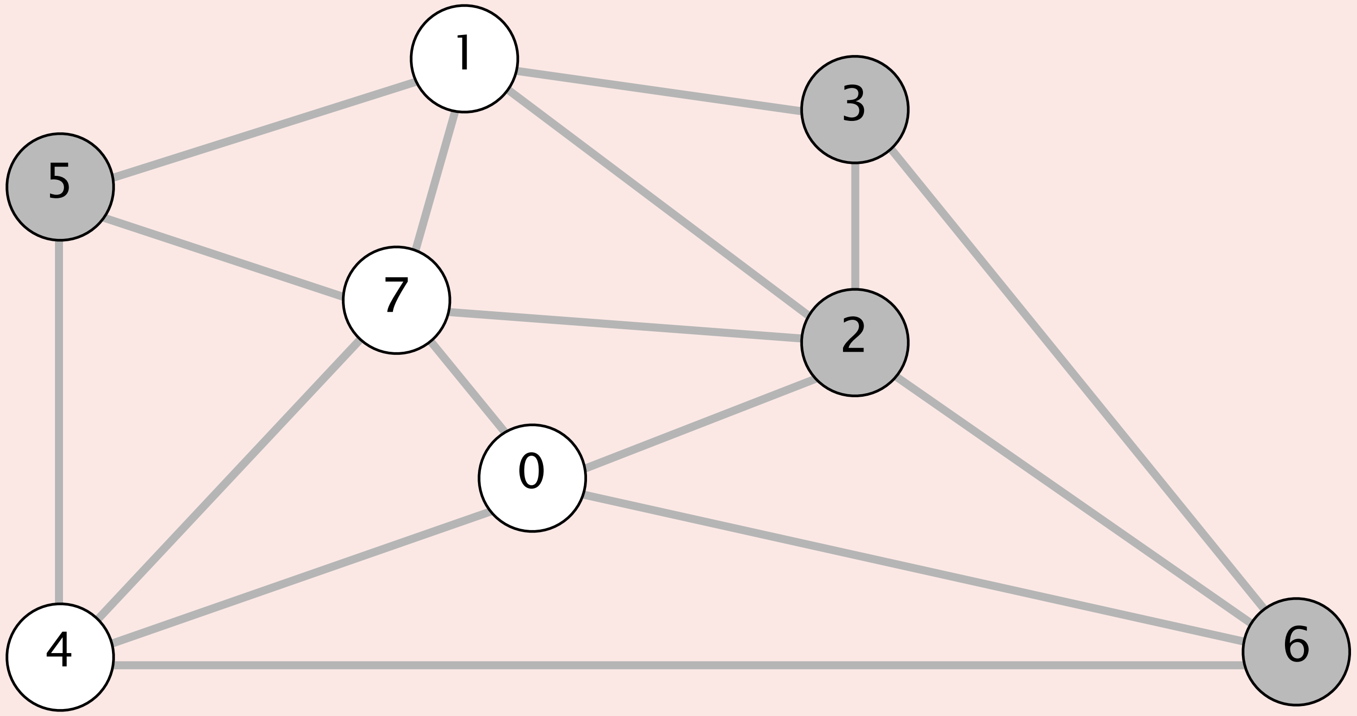
Which is the min-weight edge crossing the cut { 2, 3, 5, 6 } ?

A. 0–7 (0.16)

B. 2–3 (0.17)

C. 0–2 (0.26)

D. 5–7 (0.28)



0-7	0.16
2-3	0.17
1-7	0.19
0-2	0.26
5-7	0.28
1-3	0.29
1-5	0.32
2-7	0.34
4-5	0.35
1-2	0.36
4-7	0.37
0-4	0.38
6-2	0.40
3-6	0.52
6-0	0.58
6-4	0.93

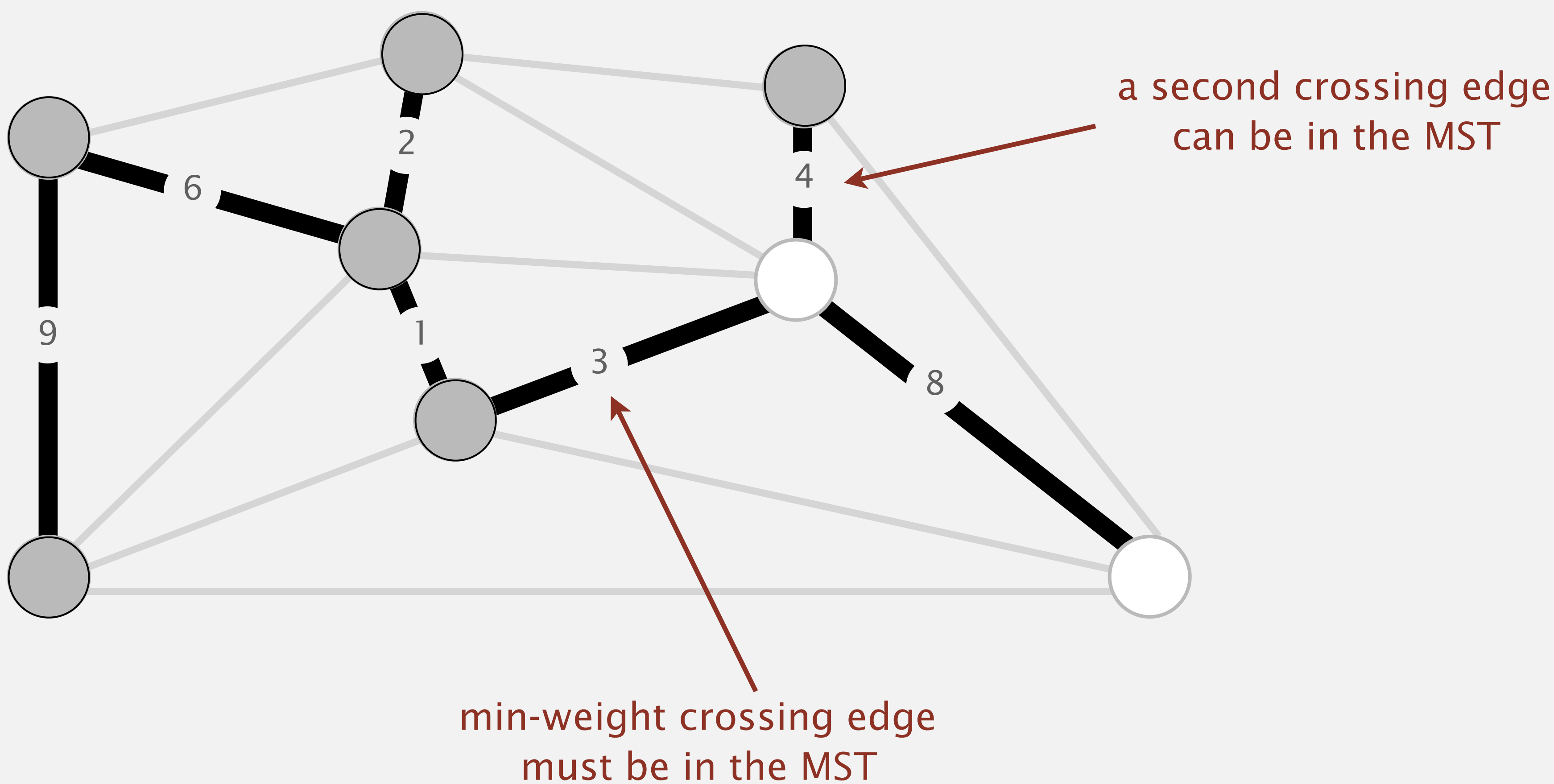
Cut property

Def. A cut in a graph is a partition of its vertices into two (nonempty) sets.

Def. A crossing edge is an edge that has one endpoint in each set.

Cut property. For any cut, the min-weight crossing edge e is in the MST.

Note. A cut may have multiple edges in the MST.



Cut property: correctness proof

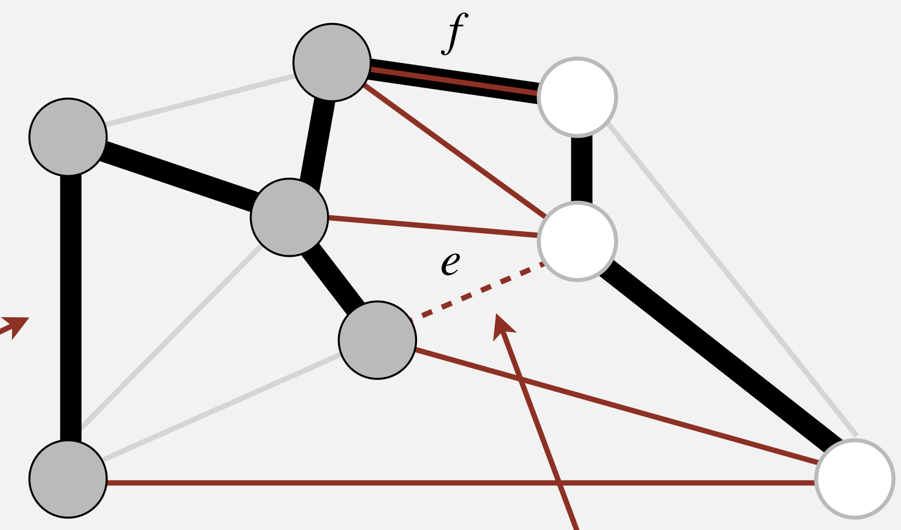
Def. A cut in a graph is a partition of its vertices into two (nonempty) sets.

Def. A crossing edge is an edge that has one endpoint in each set.

Cut property. For any cut, the min-weight crossing edge e is in the MST.

Pf. [by contradiction] Suppose e is not in the MST T.

- Adding e to the MST creates a cycle.
- Some other edge f in cycle must be a crossing edge.
- Removing f and adding e yields a different spanning tree T'.
- Since weight of e is less than the weight of f, the weight of T' is less than the weight of T.
- Contradiction. ▪



the MST T does not contain e

adding e to MST creates a unique cycle

Framework for minimum spanning tree algorithm

Generic algorithm (to compute MST)

T = ∅.

Repeat until T is a spanning tree: ← $V - 1$ edges

- **Find a cut in G.**
- **e ← min-weight crossing edge.**
- **T ← T ∪ { e }.**

Efficient implementations.

- Which cut? ← 2^{V-2} distinct cuts
- How to compute min-weight crossing edge.

Ex 1. Kruskal's algorithm.

Ex 2. Prim's algorithm.

Ex 3. Borüvka's algorithm.

https://algs4.cs.princeton.edu

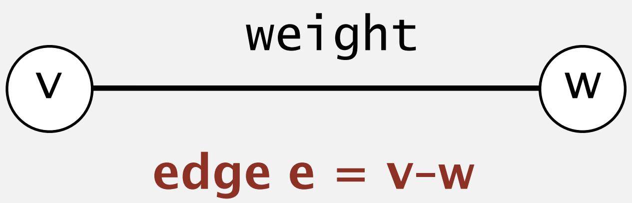
4.3 Minimum Spanning Trees

- *introduction*
- *cut property*
- *edge-weighted graph API*
- *Kruskal's algorithm*
- *Prim's algorithm*

Weighted edge API

Edge abstraction for weighted edges.

public class Edge implements Comparable<Edge>		
	`Edge(int v, int w, double weight)`	*create a weighted edge v–w*
`int`	`either()`	*either endpoint*
`int`	`other(int v)`	*the endpoint that's not v*
`int`	`compareTo(Edge that)`	*compare edges by weight*
	⋮	⋮



Idiom for processing an edge e. `int v = e.either(), w = e.other(v);`

Weighted edge: Java implementation

```
public class Edge implements Comparable<Edge>
{
   private final int v, w;
   private final double weight;

   public Edge(int v, int w, double weight)
   {
      this.v = v;
      this.w = w;
      this.weight = weight;
   }

   public int either()
   {  return v;  }

   public int other(int vertex)
   {
      if (vertex == v) return w;
      else return v;
   }

   public int compareTo(Edge that)
   {  return Double.compare(this.weight, that.weight);  }
}
```

constructor

either endpoint

other endpoint

compare edges by weight

Edge-weighted graph API

API. Same as `Graph` and `Digraph`, except with explicit `Edge` objects.

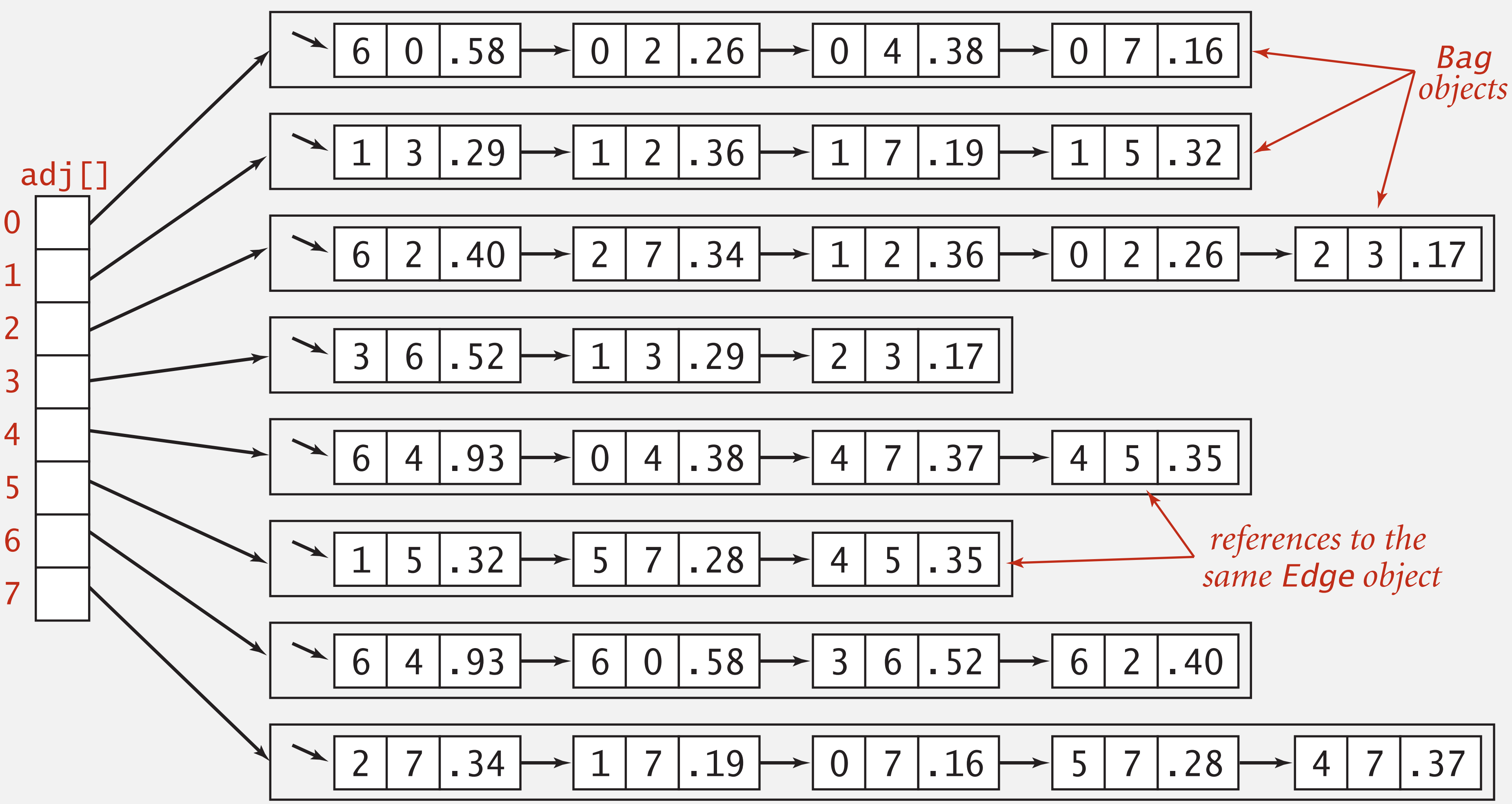
public class `EdgeWeightedGraph`		
	`EdgeWeightedGraph(int V)`	*create an empty graph with V vertices*
`void`	`addEdge(Edge e)`	*add weighted edge e to this graph*
`Iterable<Edge>`	`adj(int v)`	*edges incident to v*
	⋮	⋮

Edge-weighted graph: adjacency-lists representation

Representation. Maintain vertex-indexed array of Edge lists.

tinyEWG.txt

```
V → 8
    16 ← E
    4 5  0.35
    4 7  0.37
    5 7  0.28
    0 7  0.16
    1 5  0.32
    0 4  0.38
    2 3  0.17
    1 7  0.19
    0 2  0.26
    1 2  0.36
    1 3  0.29
    2 7  0.34
    6 2  0.40
    3 6  0.52
    6 0  0.58
    6 4  0.93
```



Edge-weighted graph: adjacency-lists implementation

```
public class EdgeWeightedGraph
{
   private final int V;
   private final Bag<Edge>[] adj;

   public EdgeWeightedGraph(int V)
   {
      this.V = V;
      adj = (Bag<Edge>[]) new Bag[V];
      for (int v = 0; v < V; v++)
         adj[v] = new Bag<Edge>();
   }

   public void addEdge(Edge e)
   {
      int v = e.either(), w = e.other(v);
      adj[v].add(e);
      adj[w].add(e);
   }

   public Iterable<Edge> adj(int v)
   {  return adj[v];  }
}
```

same as Graph, but adjacency lists of Edge objects

constructor

add same Edge object to both adjacency lists

Minimum spanning tree API

Q. How to represent the MST?

A. Technically, an MST is an edge-weighted graph.
For convenience, we represent it as a set of edges.

public class MST		
	`MST(EdgeWeightedGraph G)`	*constructor*
`Iterable<Edge>`	`edges()`	*edges in MST*
`double`	`weight()`	*weight of MST*

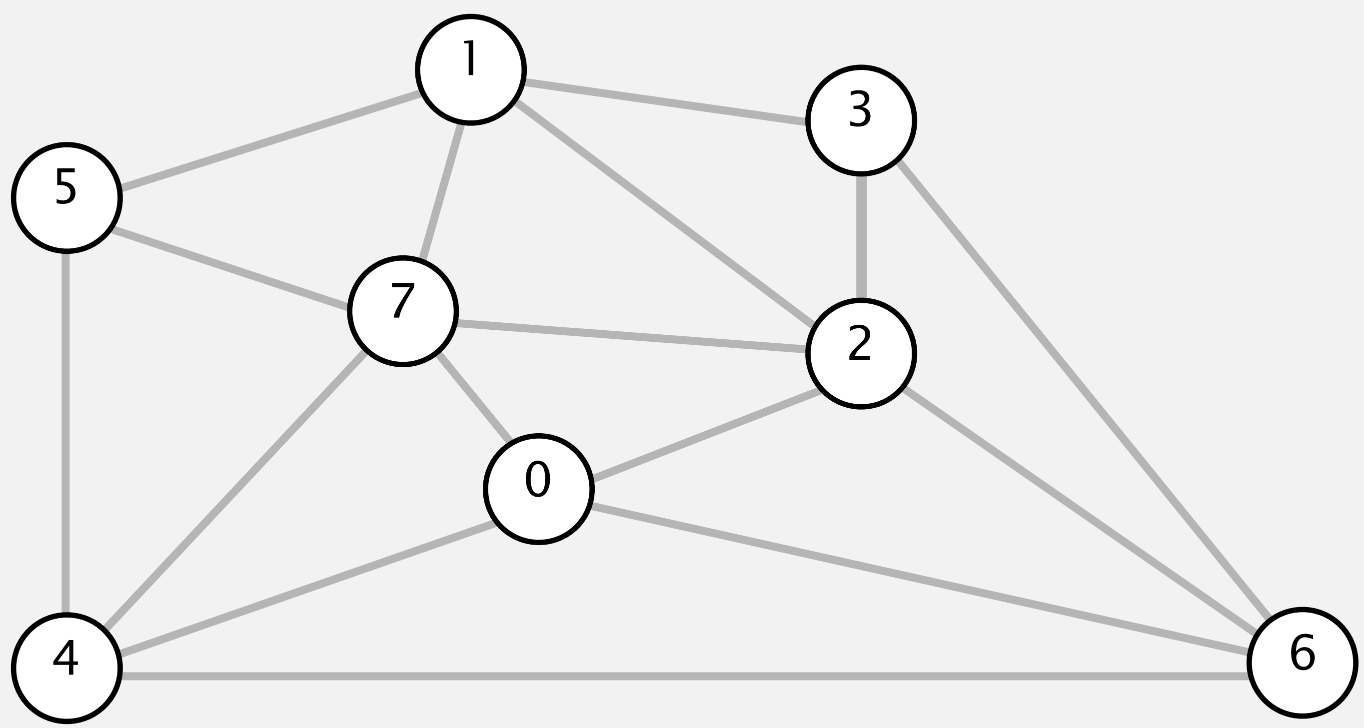
https://algs4.cs.princeton.edu

4.3 Minimum Spanning Trees

Kruskal's algorithm demo

Consider edges in ascending order of weight.

- Add next edge to T unless doing so would create a cycle.



an edge-weighted graph

graph edges sorted by weight

0-7	0.16
2-3	0.17
1-7	0.19
0-2	0.26
5-7	0.28
1-3	0.29
1-5	0.32
2-7	0.34
4-5	0.35
1-2	0.36
4-7	0.37
0-4	0.38
6-2	0.40
3-6	0.52
6-0	0.58
6-4	0.93

Minimum spanning trees: quiz 3

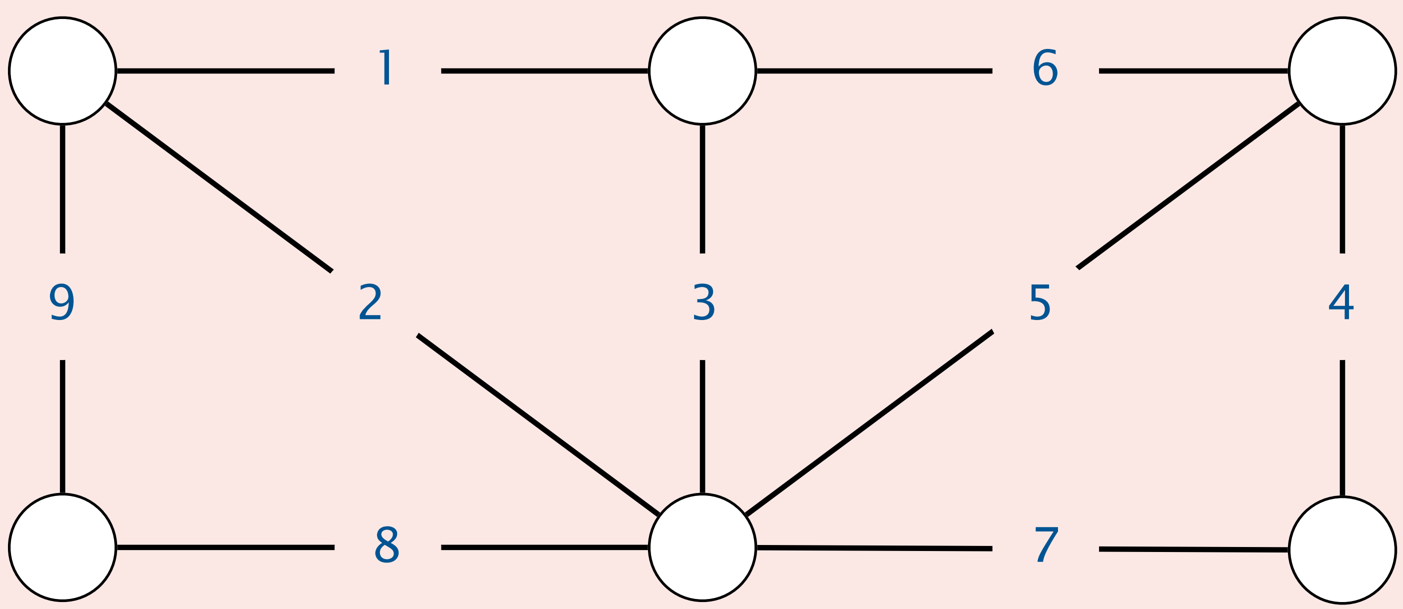
In which order does Kruskal's algorithm select edges in MST?

A. 1, 2, 4, 5, 6

B. 1, 2, 4, 5, 8

C. 1, 2, 5, 4, 8

D. 8, 2, 1, 5, 4



Kruskal's algorithm: visualization

Kruskal's algorithm: correctness proof

Proposition. [Kruskal 1956] Kruskal's algorithm computes the MST.

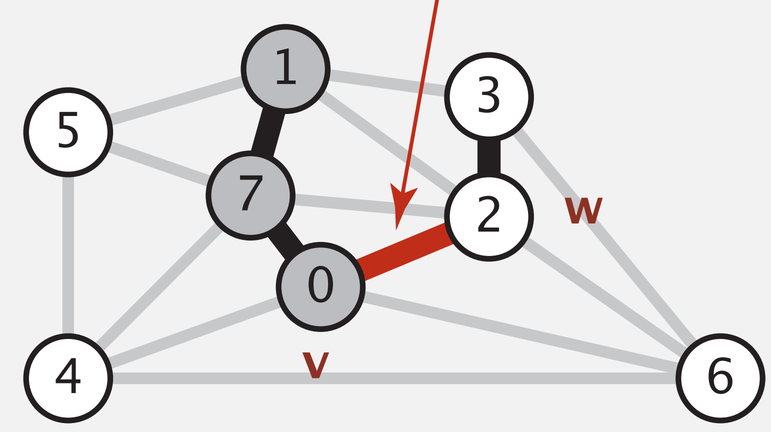
Pf. Let T be tree at some point during execution, and let e be next edge.

recall: consider edges in ascending order by weight

[Case 1] Kruskal's algorithm adds edge $e = v\text{–}w$ to T.

- Vertices v and w are in different connected components of T.
- Cut = set of vertices connected to v in T.
- By construction of cut, no edge crossing cut is currently in T.
- No edge crossing cut has lower weight. Why?
- Cut property $\Rightarrow$ edge e is in the MST.

add edge to tree



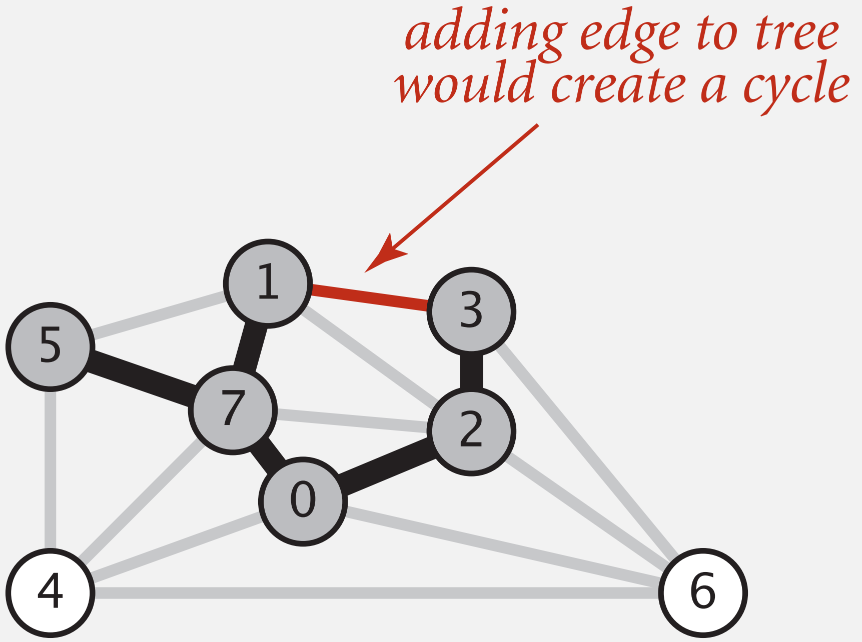
Kruskal's algorithm: correctness proof

Proposition. [Kruskal 1956] Kruskal's algorithm computes the MST.

Pf. Let T be tree at some point during execution, and let e be next edge.

[Case 2] Kruskal's algorithm discards edge $e = v–w$.

- From Case 1, all edges in T are in the MST.
- The MST can't contain a cycle. ▪

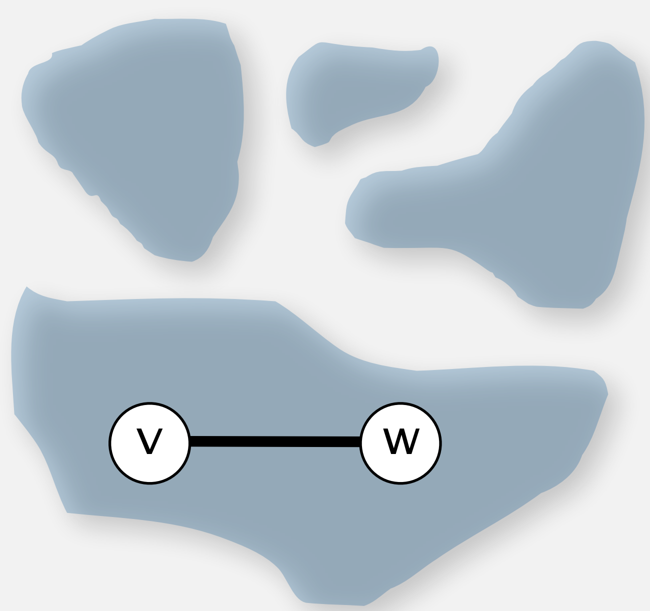


Kruskal's algorithm: implementation challenge

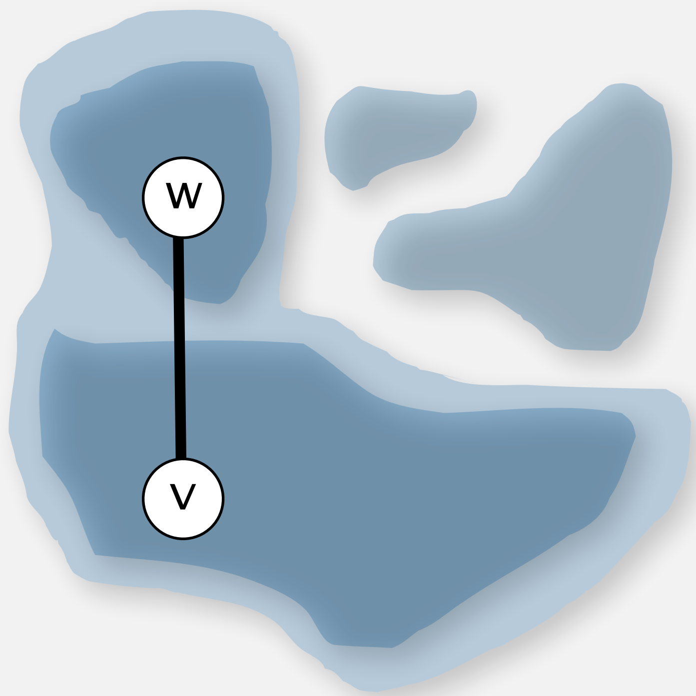
Challenge. Would adding edge $v–w$ to tree T create a cycle? If not, add it.

Efficient solution. Use the union–find data structure.

- Maintain a set for each connected component in T.
- If v and w are in same set, then adding $v–w$ would create a cycle.
- To add $v–w$ to T, merge sets containing v and w.



Case 2: adding v–w creates a cycle



Case 1: add v–w to T and merge sets containing v and w

Kruskal's algorithm: Java implementation

```
public class KruskalMST
{
   private Queue<Edge> mst = new Queue<Edge>();

   public KruskalMST(EdgeWeightedGraph G)
   {
      DirectedEdge[] edges = G.edges();
      Arrays.sort(edges);
      UF uf = new UF(G.V());

      for (int i = 0; i < G.E(); i++)
      {
         Edge e = edges[i];
         int v = e.either(), w = e.other(v);
         if (uf.find(v) != uf.find(w))
         {
            mst.enqueue(e);
            uf.union(v, w);
         }
      }
   }

   public Iterable<Edge> edges()
   {  return mst;  }
}
```

edges in the MST

sort edges by weight

maintain connected components

optimization: stop as soon as $V-1$ edges in T

greedily add edges to MST

edge v–w does not create cycle

add edge e to MST

merge connected components

Kruskal's algorithm: running time

Proposition. In the worst case, Kruskal's algorithm computes MST in time proportional to $E \log E$.

Pf.

- Bottlenecks are sort and union–find operations.

operation	frequency	time per op
SORT	1	$E \log E$
UNION	$V - 1$	$\log V$ †
FIND	$2E$	$\log V$ †

† using weighted quick union

- Total. $V \log V + E \log V + E \log E$.

dominated by $E \log E$
since graph is connected

Minimum spanning trees: quiz 4

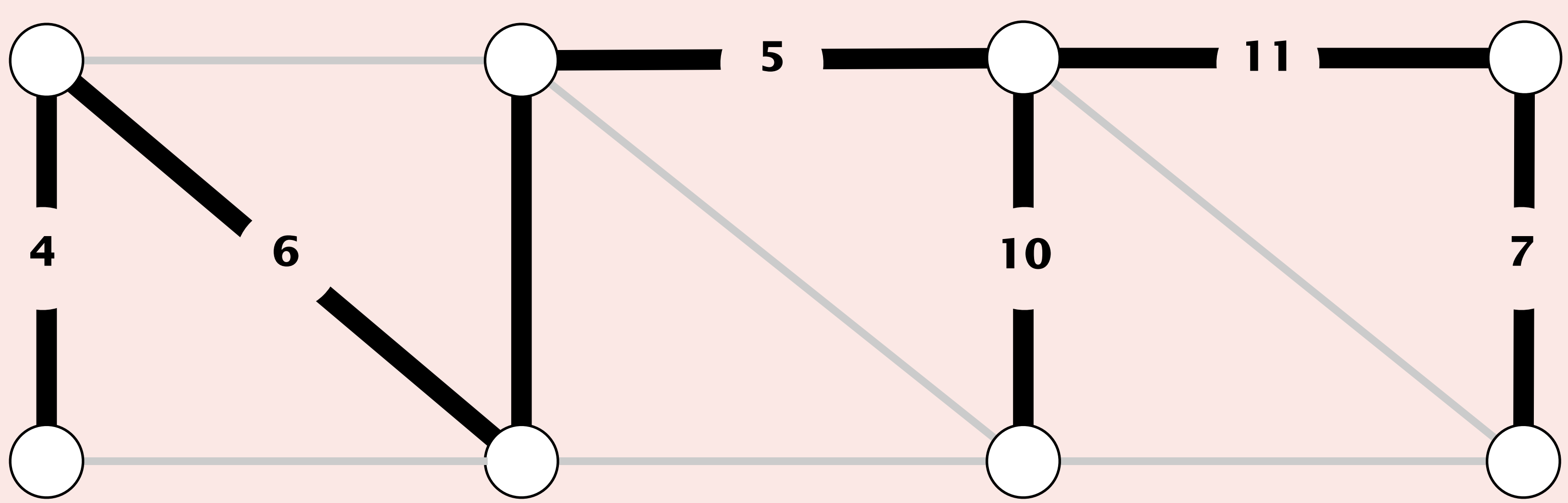
Given a graph with positive edge weights, how to find a spanning tree that minimizes the sum of the squares of the edge weights?

A. Run Kruskal's algorithm using the original edge weights.

B. Run Kruskal's algorithm using the squares of the edge weights.

C. Run Kruskal's algorithm using the square roots of the edge weights.

D. All of the above.

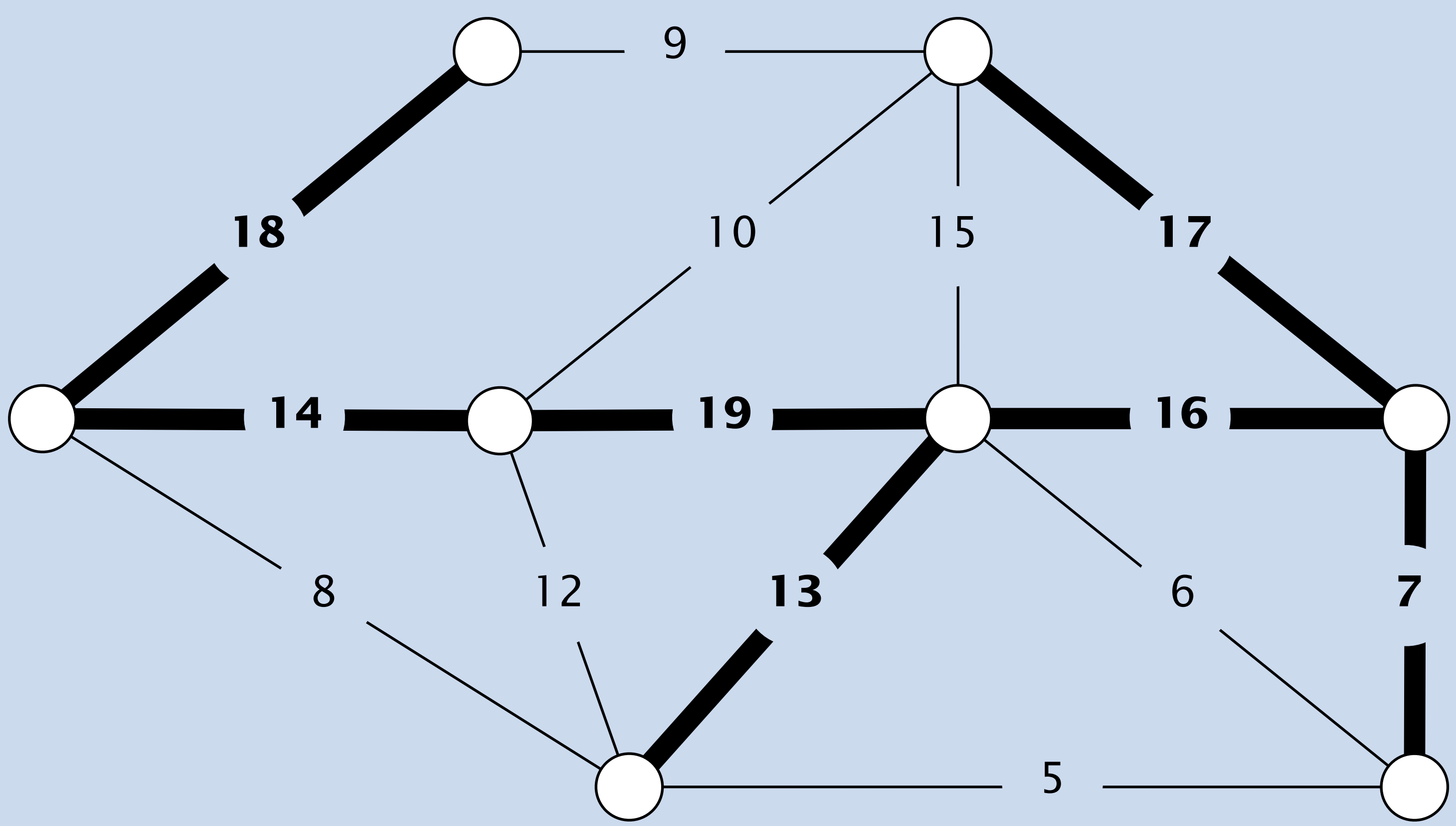


sum of squares $= 4^2 + 6^2 + 5^2 + 10^2 + 11^2 + 7^2 = 347$

Maximum Spanning Tree

Problem. Given an undirected graph G with positive edge weights, find a spanning tree that maximizes the sum of the edge weights.

Goal. Design algorithm with $E \log E$ running time.



maximum spanning tree T (weight = 104)

Greed is good

Gordon Gecko (Michael Douglas) evangelizing the importance of greed (in algorithm design?)

Wall Street (1986)

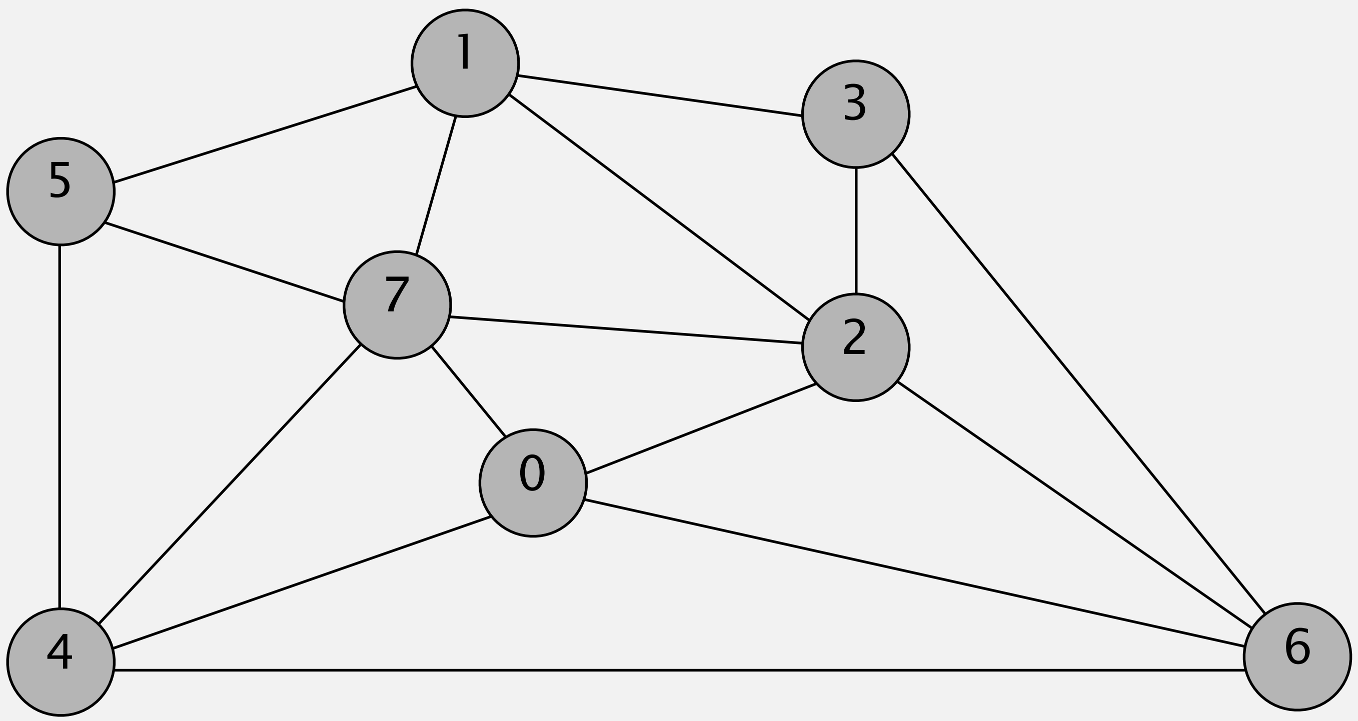
https://algs4.cs.princeton.edu

4.3 Minimum Spanning Trees

- *introduction*
- *cut property*
- *edge-weighted graph API*
- *Kruskal's algorithm*
- *Prim's algorithm*

Prim's algorithm demo

- Start with vertex 0 and grow tree T.
- Repeat until $V - 1$ edges:
  - add to T the min-weight edge with exactly one endpoint in T



an edge-weighted graph

0-7	0.16
2-3	0.17
1-7	0.19
0-2	0.26
5-7	0.28
1-3	0.29
1-5	0.32
2-7	0.34
4-5	0.35
1-2	0.36
4-7	0.37
0-4	0.38
6-2	0.40
3-6	0.52
6-0	0.58
6-4	0.93

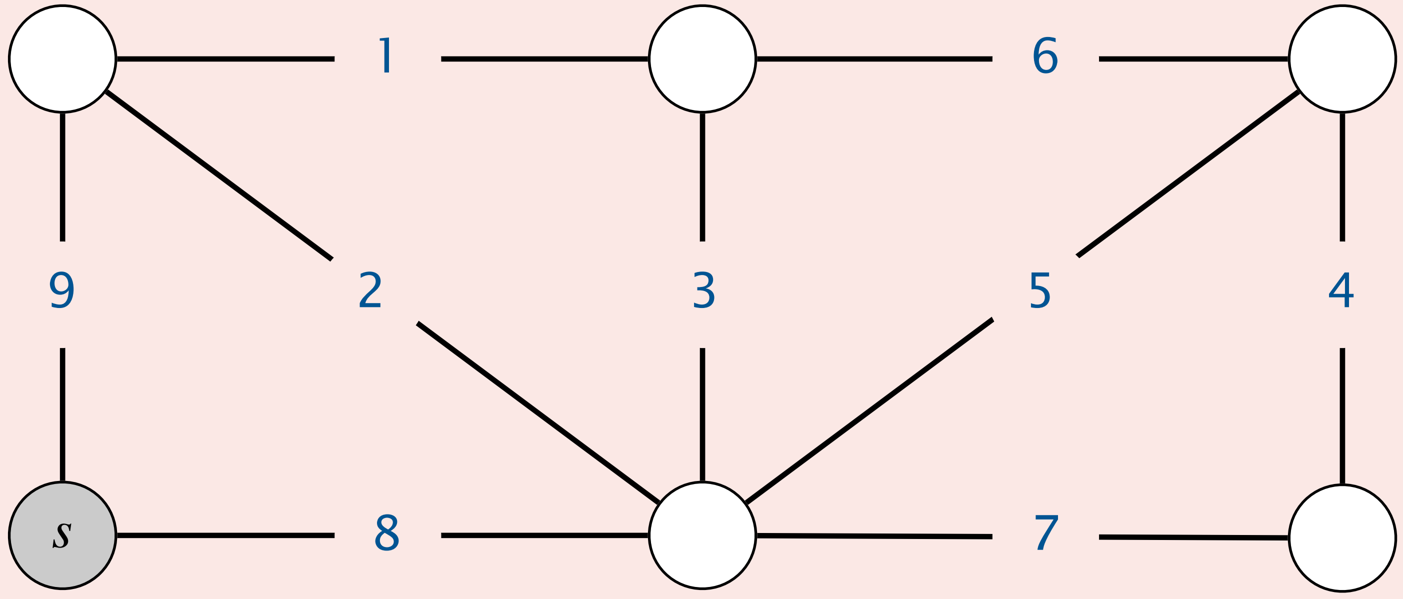
In which order does Prim's algorithm select edges in the MST? Assume it starts from vertex s.

A. 1, 2, 3, 4, 5

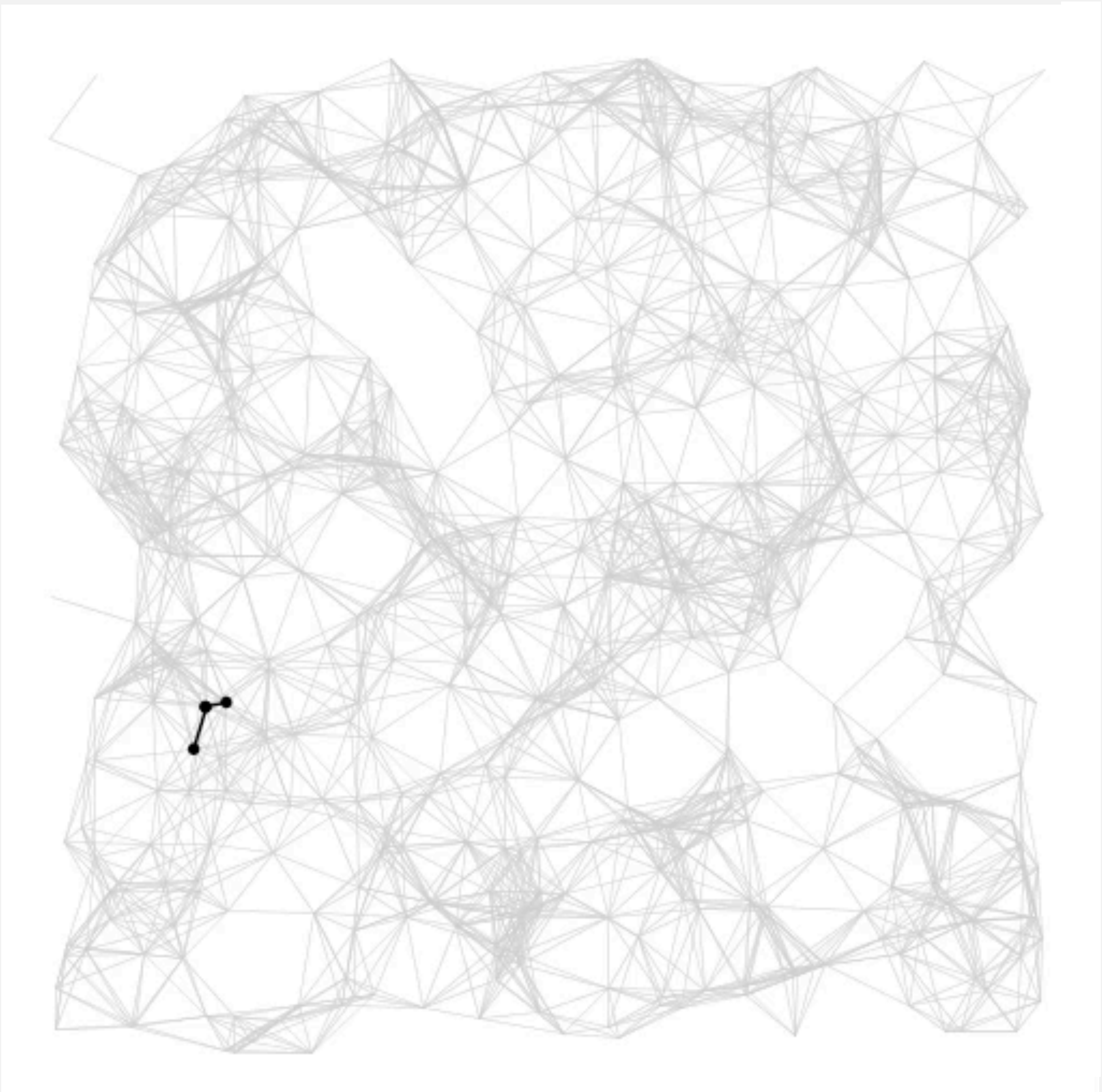
B. 1, 2, 5, 4, 8

C. 8, 2, 1, 5, 4

D. 8, 5, 4, 2, 1



Prim's algorithm: visualization



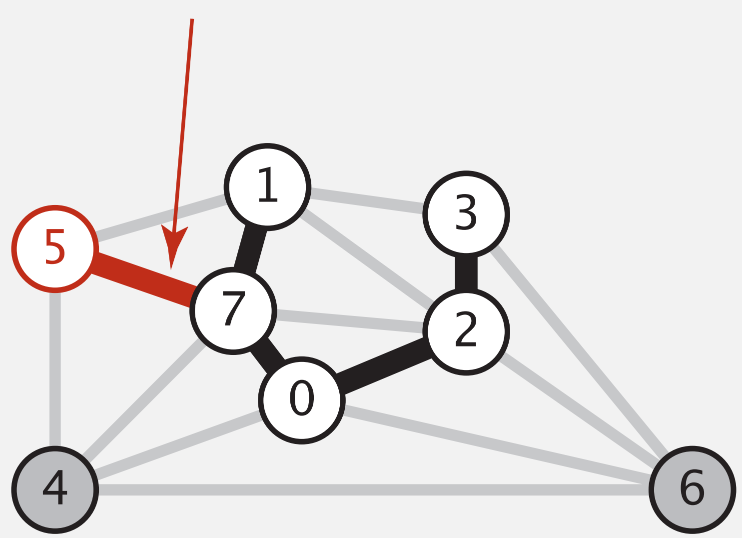
Prim's algorithm: proof of correctness

Proposition. [Jarník 1930, Dijkstra 1957, Prim 1959]
Prim's algorithm computes the MST.

Pf. Let e = min-weight edge with exactly one endpoint in T.

- Cut = set of vertices in T.
- No crossing edge is in T.
- No crossing edge has lower weight.
- Cut property $\Rightarrow$ edge e is in the MST. ▪

edge e = 7-5 added to tree



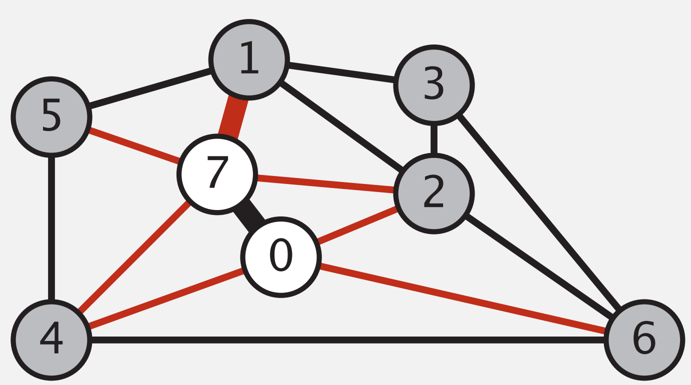
Prim's algorithm: lazy implementation

Challenge. Find the min-weight edge with exactly one endpoint in T.

Lazy solution. Maintain a PQ of edges with (at least) one endpoint in T.

- Key = edge; priority = weight of edge.
- DELETE-MIN to determine next edge $e = v–w$ to add to T.
- If both endpoints v and w are marked (both in T), disregard.
- Otherwise, let w be the unmarked vertex (not in T):
  - add e to T and mark w
  - add to PQ any edge incident to w (assuming other endpoint not in T)

1-7 is min weight edge with exactly one endpoint in T

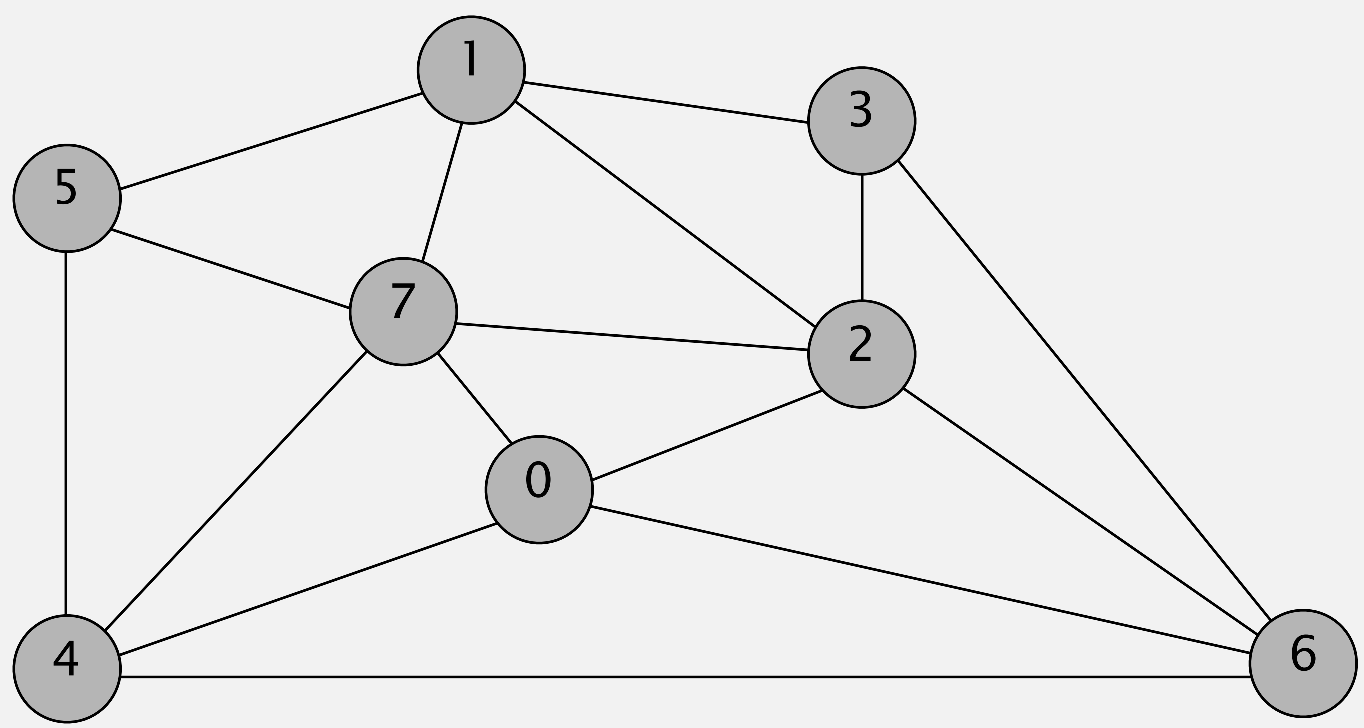


priority queue of crossing edges

```
1-7 0.19
0-2 0.26
5-7 0.28
2-7 0.34
4-7 0.37
0-4 0.38
6-0 0.58
```

Prim's algorithm: lazy implementation demo

- Start with vertex 0 and grow tree T.
- Repeat until $V - 1$ edges:
  - add to T the min-weight edge with exactly one endpoint in T



an edge-weighted graph

0-7	0.16
2-3	0.17
1-7	0.19
0-2	0.26
5-7	0.28
1-3	0.29
1-5	0.32
2-7	0.34
4-5	0.35
1-2	0.36
4-7	0.37
0-4	0.38
6-2	0.40
3-6	0.52
6-0	0.58
6-4	0.93

Prim's algorithm: lazy implementation

```
public class LazyPrimMST
{
   private boolean[] marked;    // MST vertices
   private Queue<Edge> mst;     // MST edges
   private MinPQ<Edge> pq;      // PQ of edges

    public LazyPrimMST(WeightedGraph G)
    {
        pq = new MinPQ<Edge>();
        mst = new Queue<Edge>();
        marked = new boolean[G.V()];
        visit(G, 0);

        while (!pq.isEmpty() && mst.size() < G.V() - 1)
        {
           Edge e = pq.delMin();
           int v = e.either(), w = e.other(v);
           if (marked[v] && marked[w]) continue;
           mst.enqueue(e);
           if (!marked[v]) visit(G, v);
           if (!marked[w]) visit(G, w);
        }

   }
}
```

assume graph G is connected

repeatedly delete the min-weight edge $e = v–w$ from PQ

ignore if both endpoints in tree T

add edge e to tree T

add either v or w to tree T

Prim's algorithm: lazy implementation

```
private void visit(WeightedGraph G, int v)
{
  marked[v] = true;
  for (Edge e : G.adj(v))
     if (!marked[e.other(v)])
        pq.insert(e);
}

public Iterable<Edge> mst()
{  return mst;  }
```

add vertex v to tree T

for each edge $e = v–w$:
add e to PQ if w not already in T

Lazy Prim's algorithm: running time

Proposition. In the worst case, lazy Prim's algorithm computes the MST in time proportional to $E \log E$ and extra space proportional to E.

can be improved to V with "eager" version

Pf.

- Bottlenecks are PQ operations.
- Each edge is added to PQ at most once.
- Each edge is deleted from PQ at most once.

operation	frequency	binary heap
INSERT	E	$\log E$
DELETE-MIN	E	$\log E$

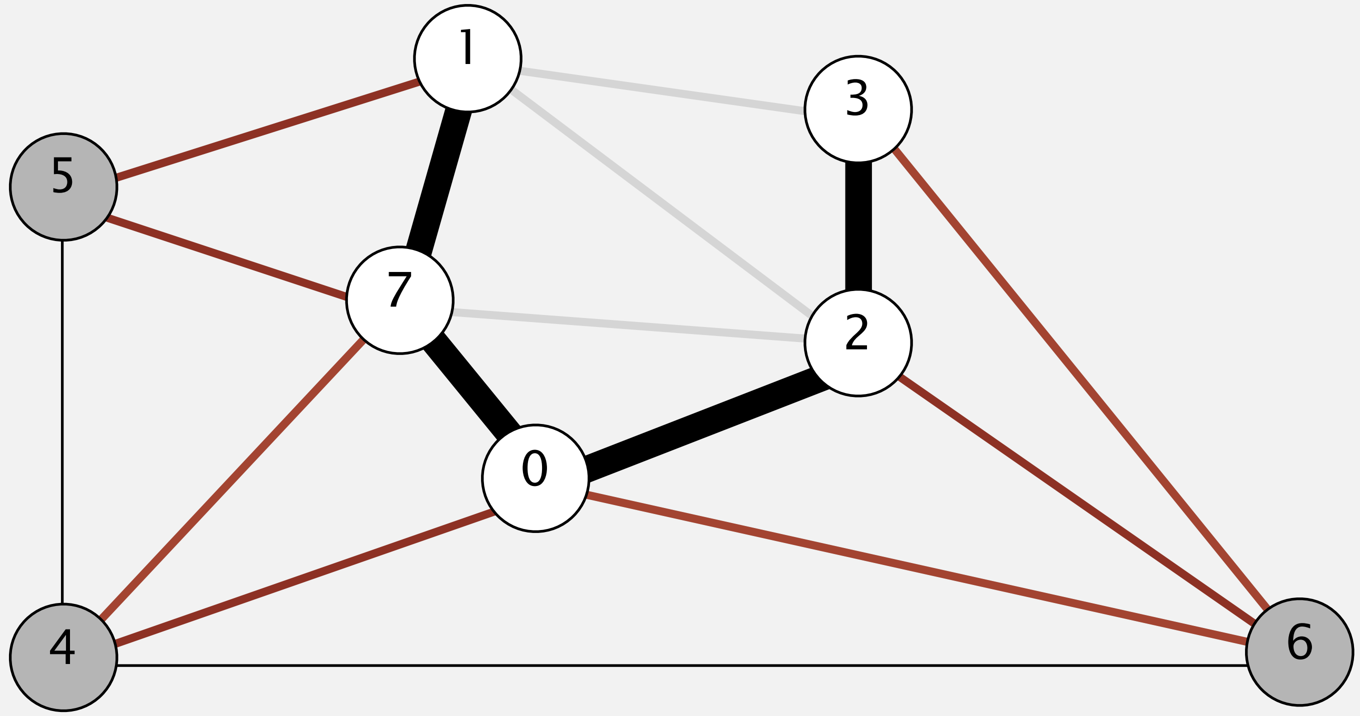
Prim's algorithm: eager implementation

Challenge. Find min-weight edge with exactly one endpoint in T.

Observation. For each vertex v, need only min-weight edge connecting v to T.

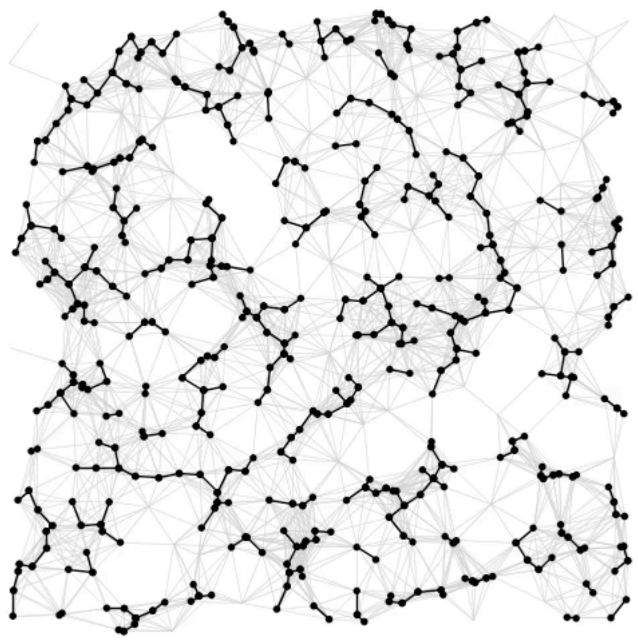
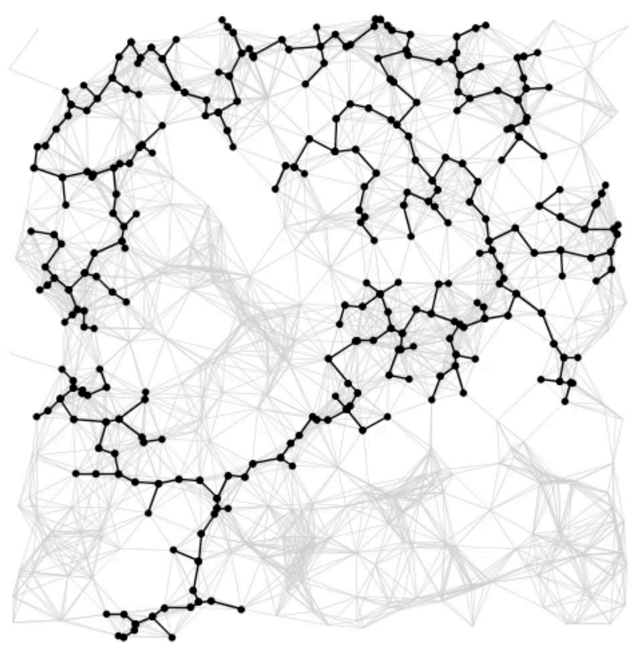
- MST includes at most one edge connecting v to T. Why?
- If MST includes such an edge, it must take lightest such edge. Why?

Impact. PQ of vertices; extra space at most V; running time $E \log V$.



see textbook for details

MST: algorithms of the day

algorithm	visualization	bottleneck	running time
Kruskal		sorting union–find	$E \log E$
Prim		priority queue	$E \log V$