Algorithms

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Algorithms

FOURTH EDITION

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https://algs4.cs.princeton.edu

4.3 MINIMUM SPANNING TREES

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

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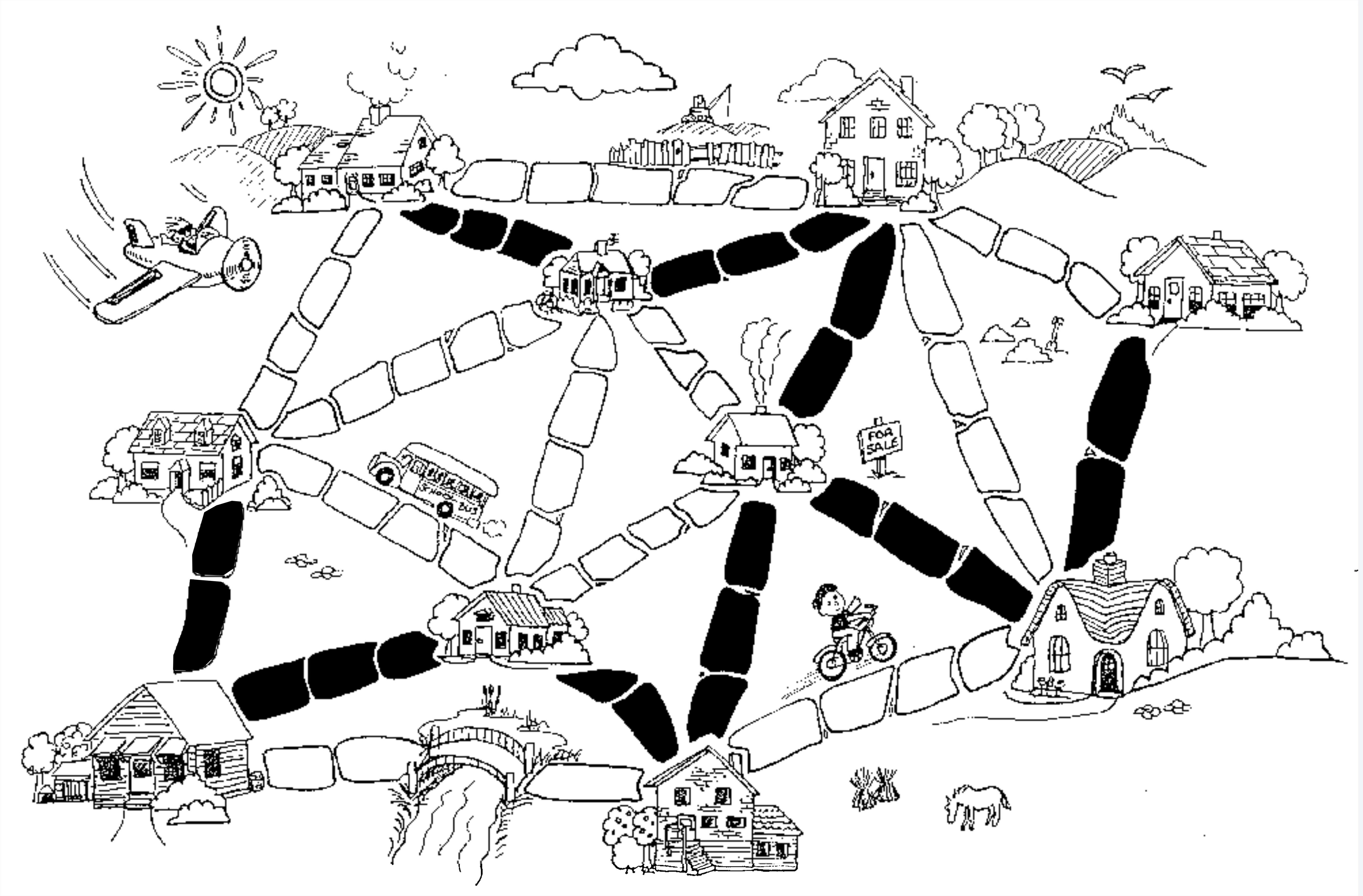
4.3 Minimum Spanning Trees

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

A motivating example

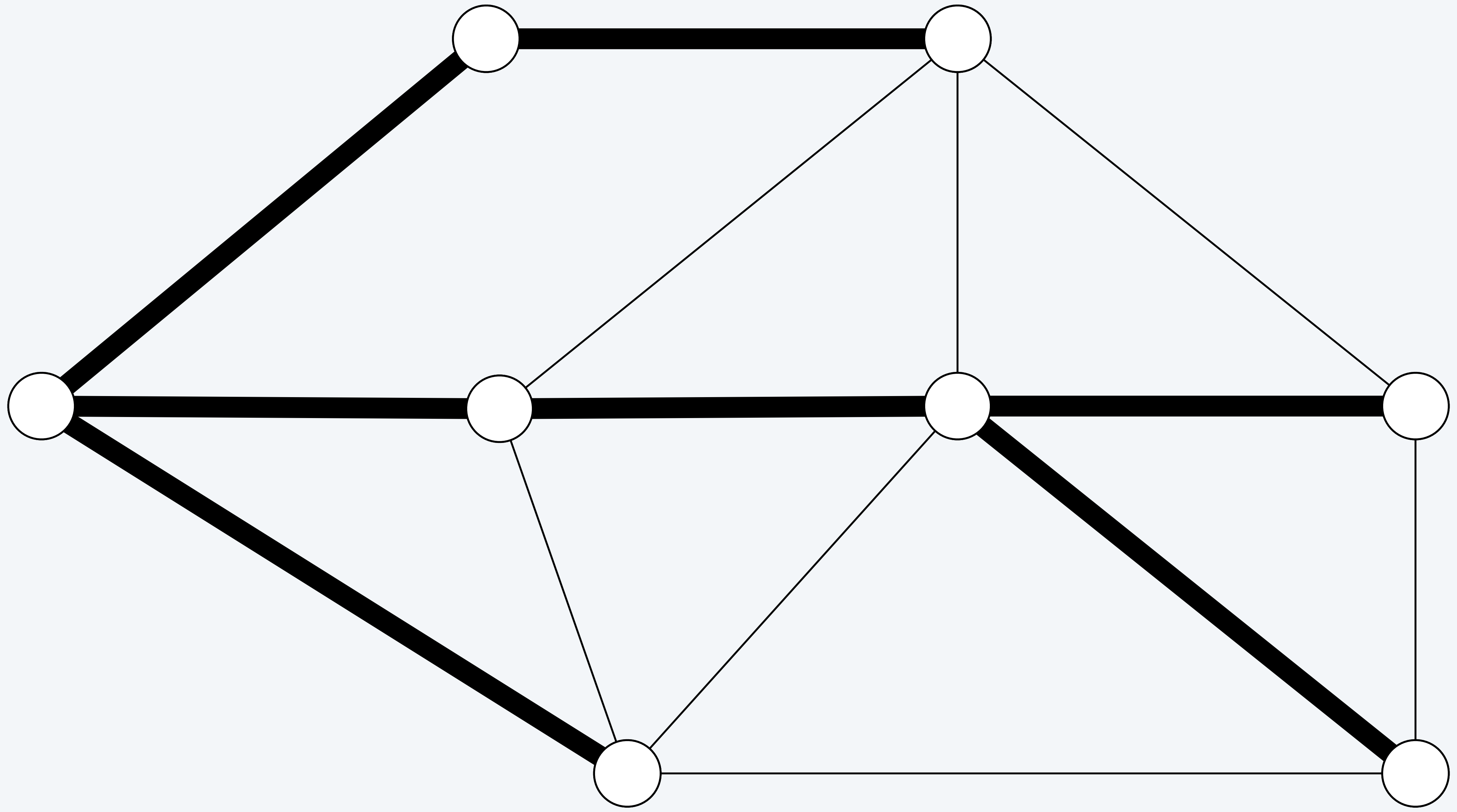
Install minimum number of paving stones to connect all of the houses.



Spanning tree

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

- A tree: connected and acyclic. ← *not to be confused with rooted trees in digraphs (such as BSTs)*
- Spanning: includes all of the vertices.



graph G

spanning tree T

Spanning tree

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

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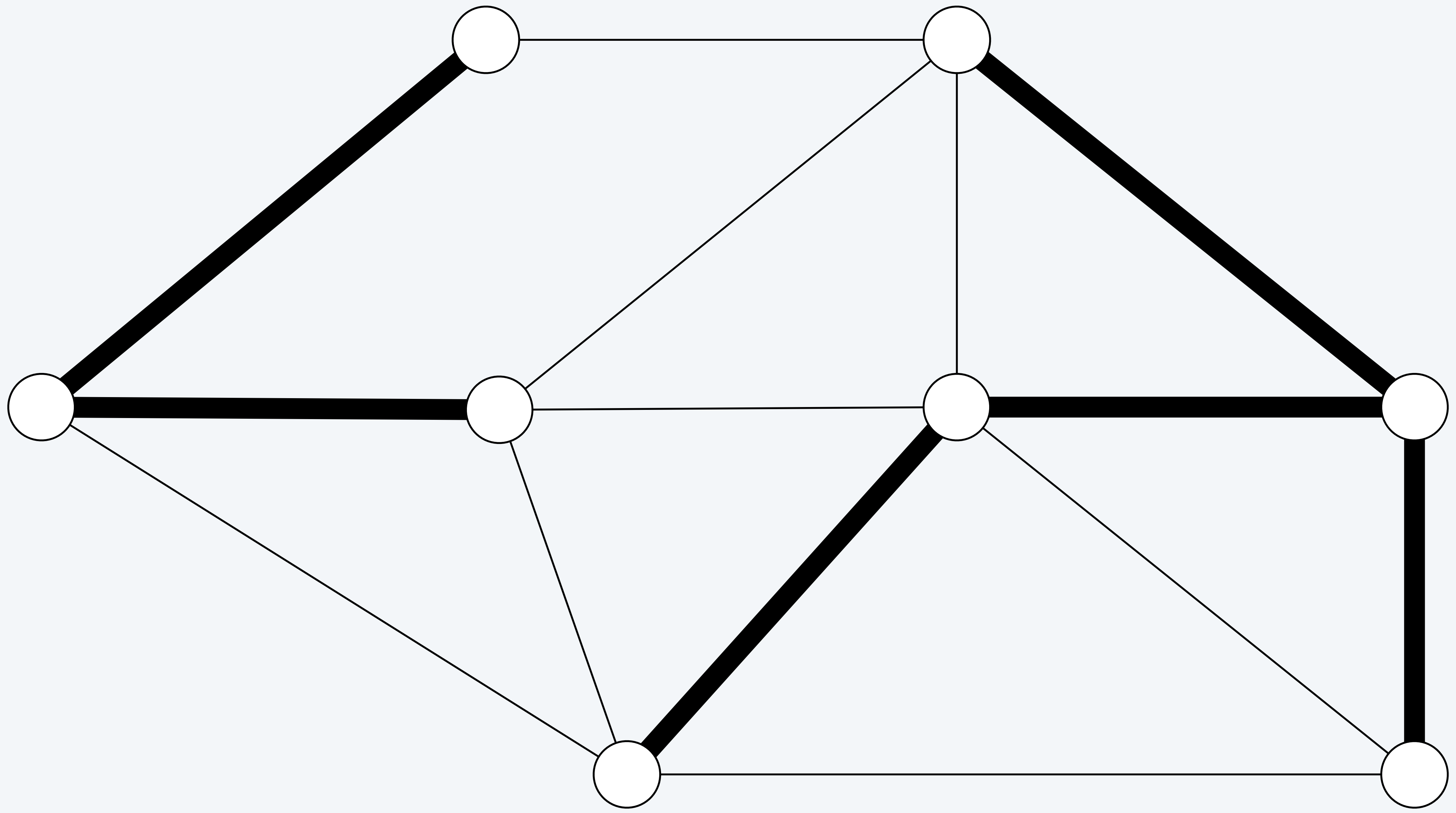

not a connected subgraph

Spanning tree

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

- A tree: connected and acyclic.
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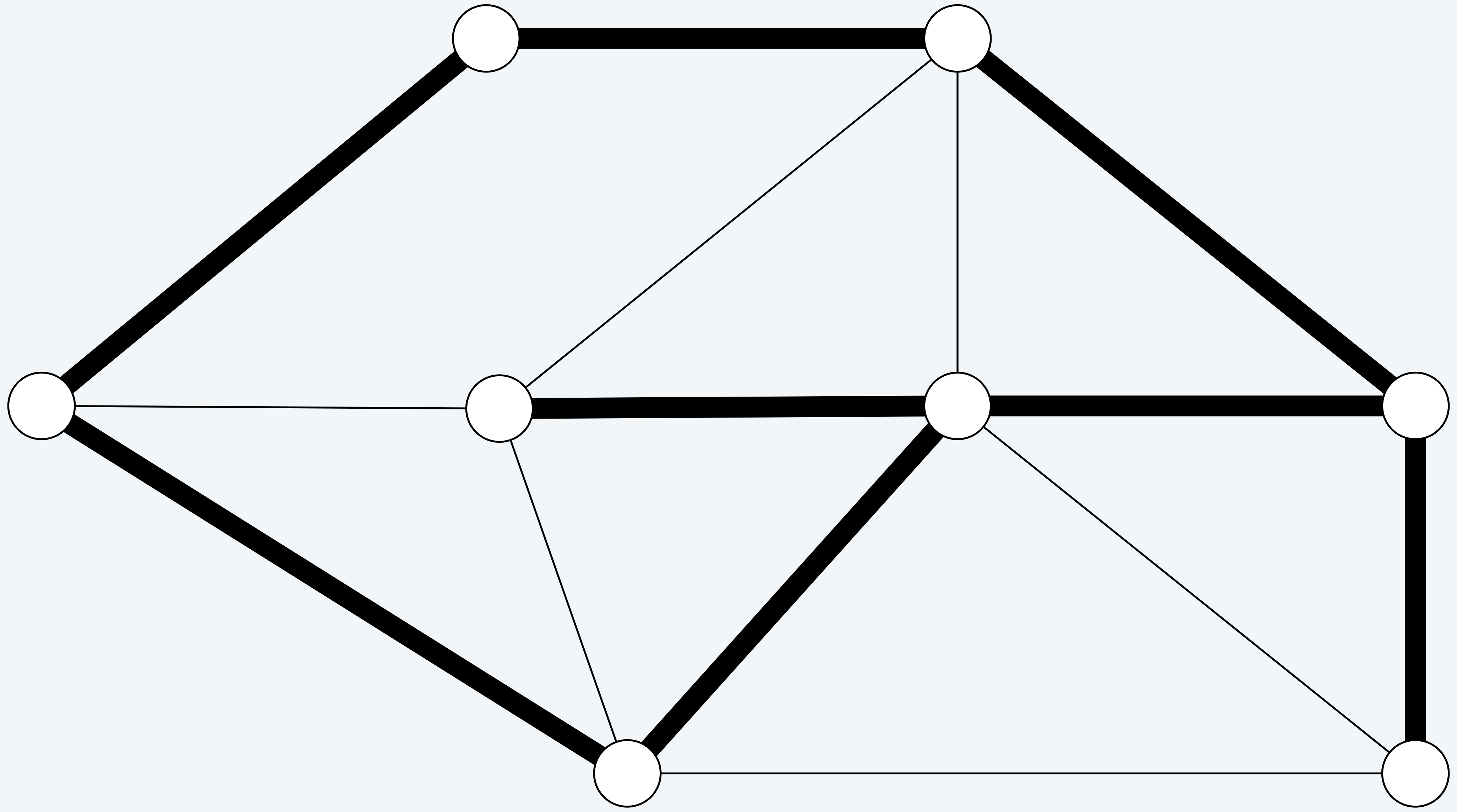
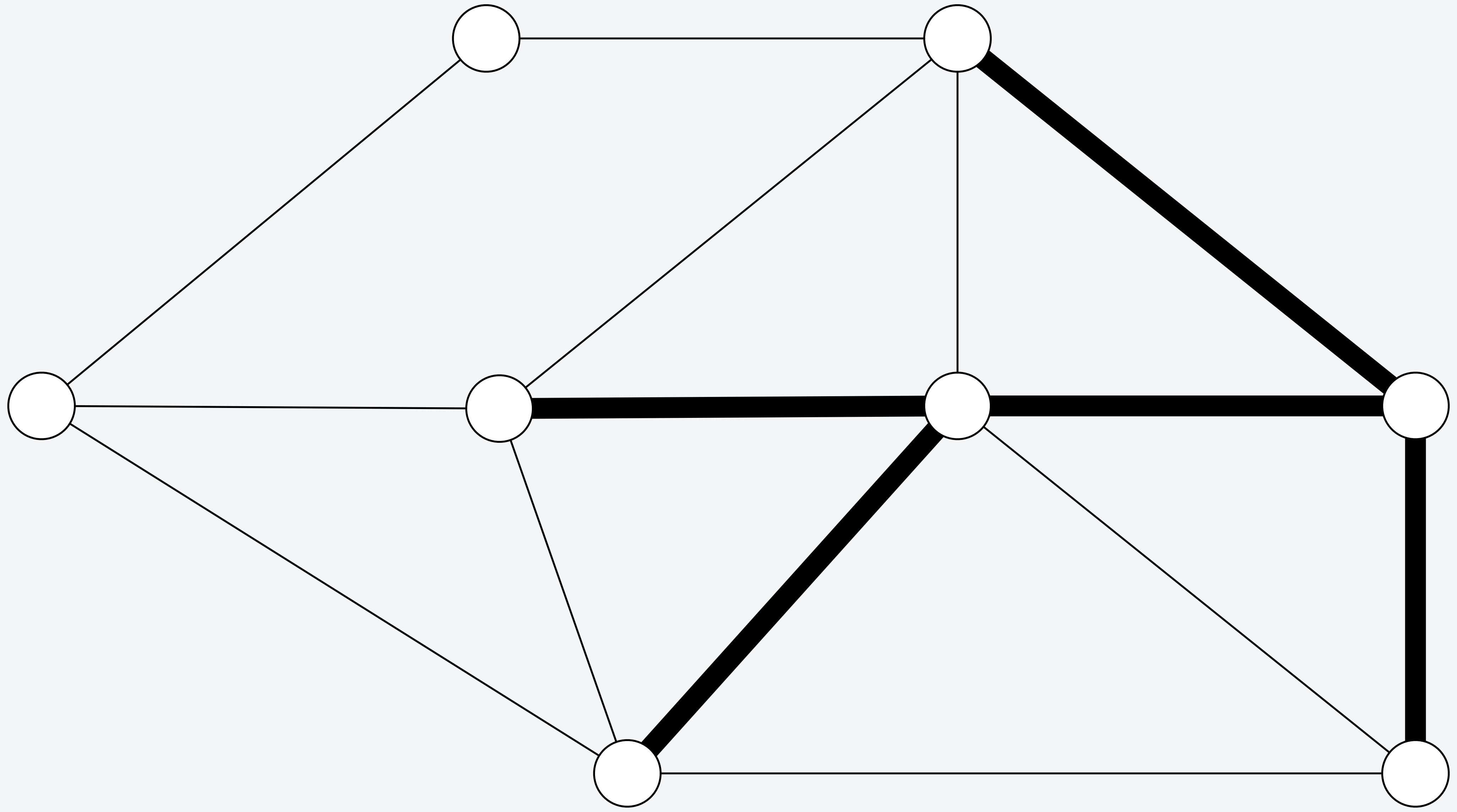


not an acyclic subgraph

Spanning tree

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

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

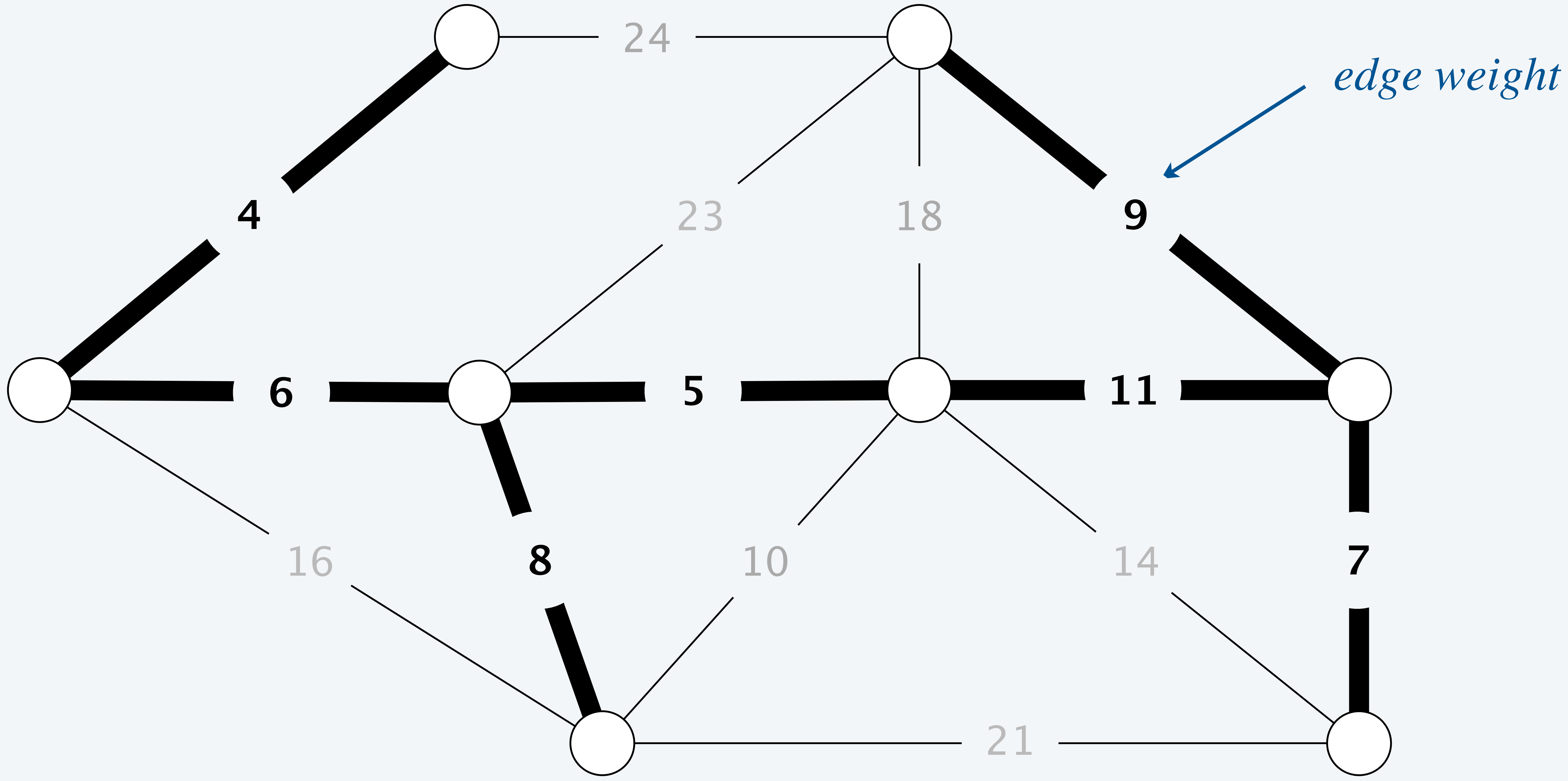


not a spanning subgraph

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?

Minimum spanning trees: quiz 1

Let T be any spanning tree of a connected graph G with V vertices.

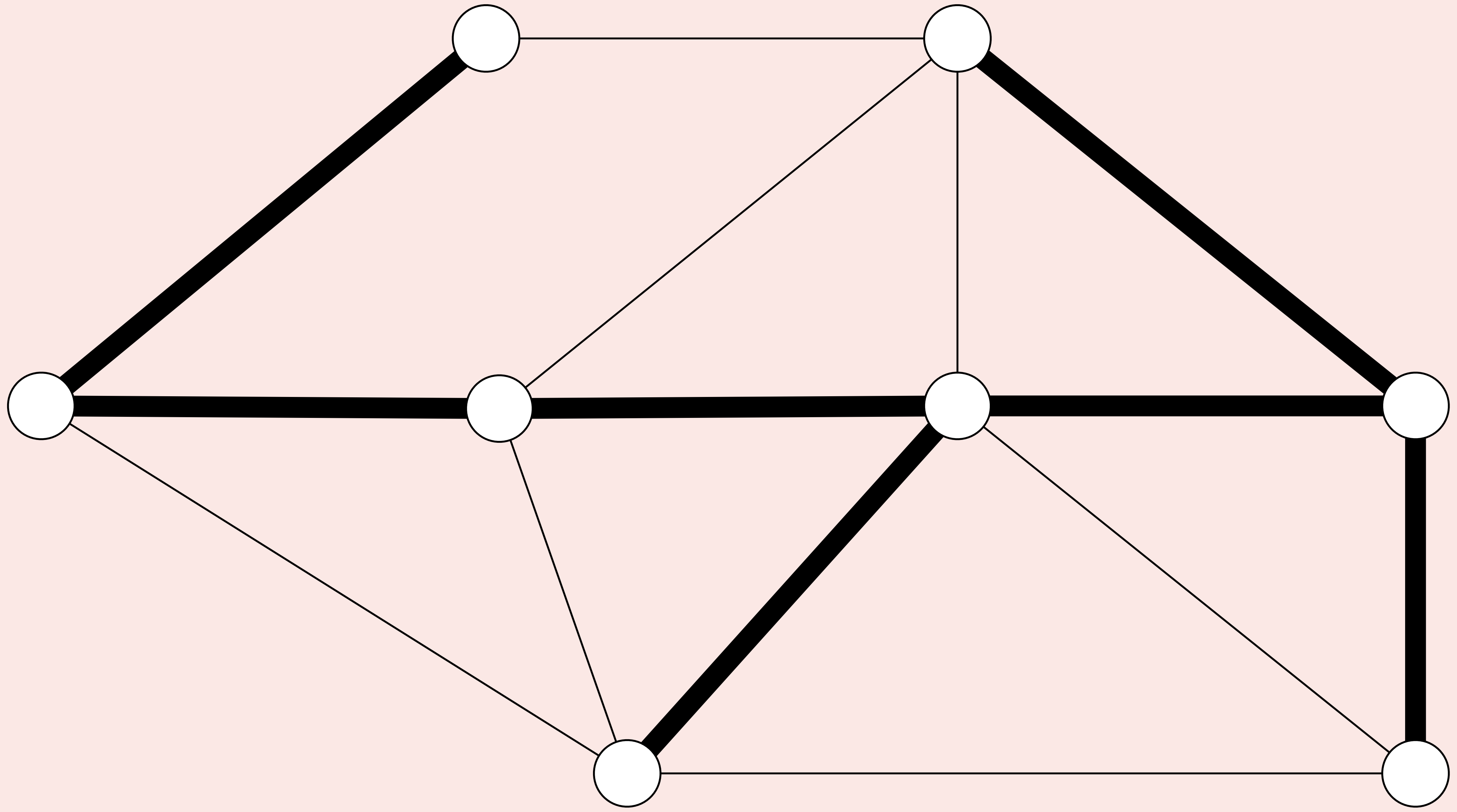
Which of the following properties must hold?

A. Removing any edge from T disconnects it.

B. Adding any edge to T creates a cycle.

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

D. All of the above.

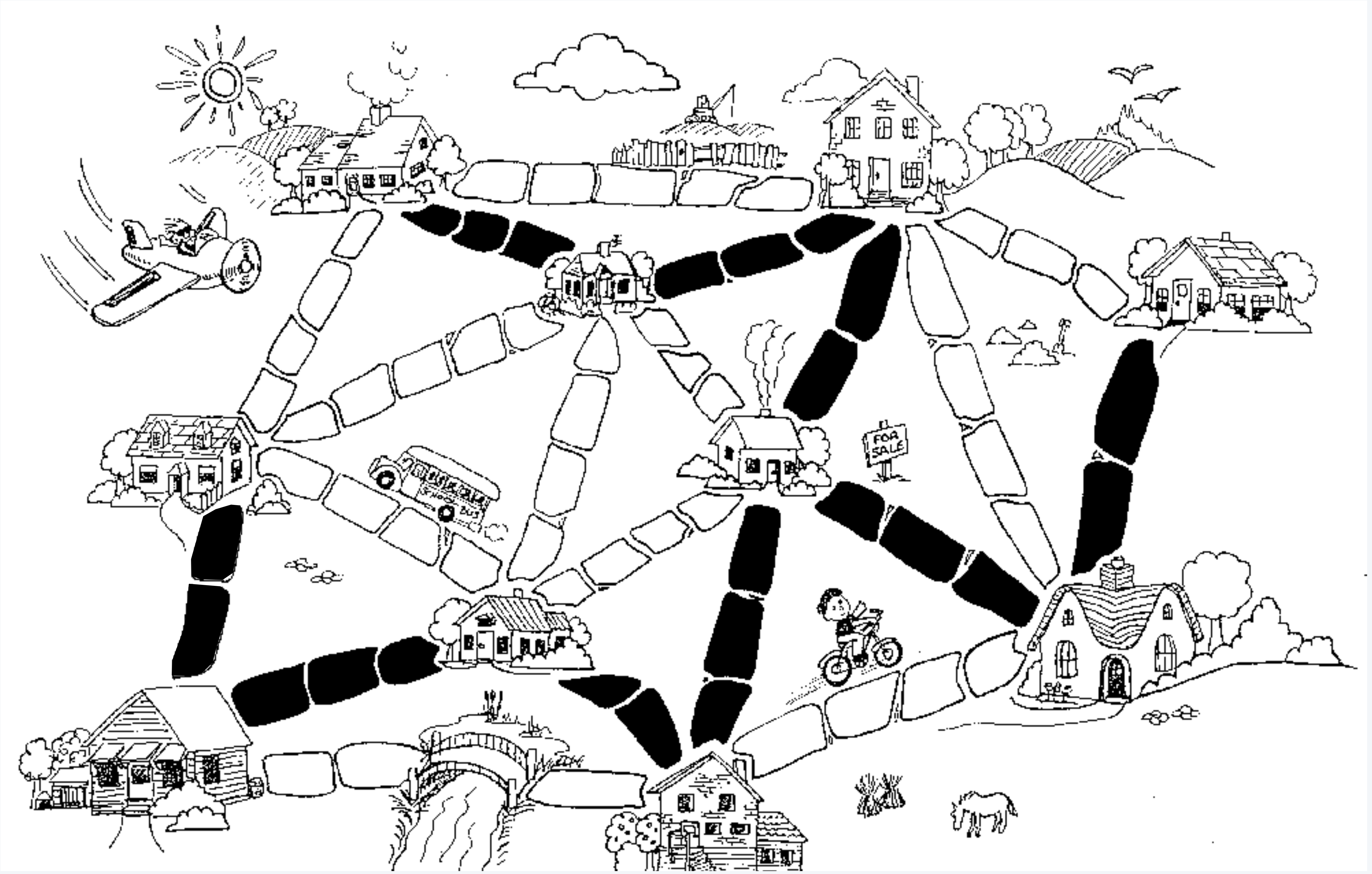


spanning tree T of graph G

Network design

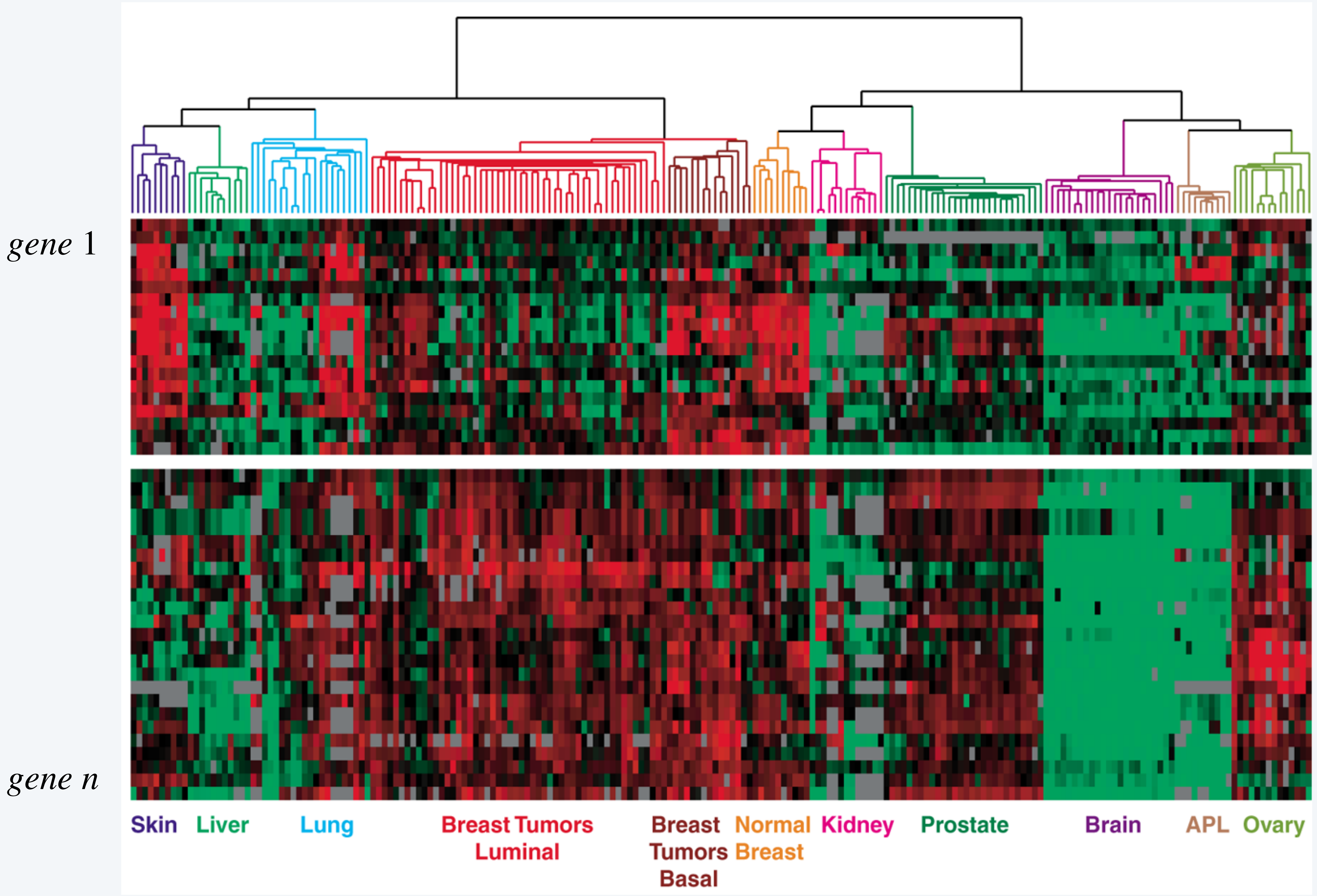
Network. Vertex = network component; edge = potential connection; edge weight = cost.

computer, transportation, electrical, telecommunication



Hierarchical clustering

Microarray graph. Vertex = cancer tissue; edge = all pairs; edge weight = dissimilarity.



Reference: Botstein & Brown group

🟥 *gene expressed*

🟩 *gene not expressed*

More MST applications

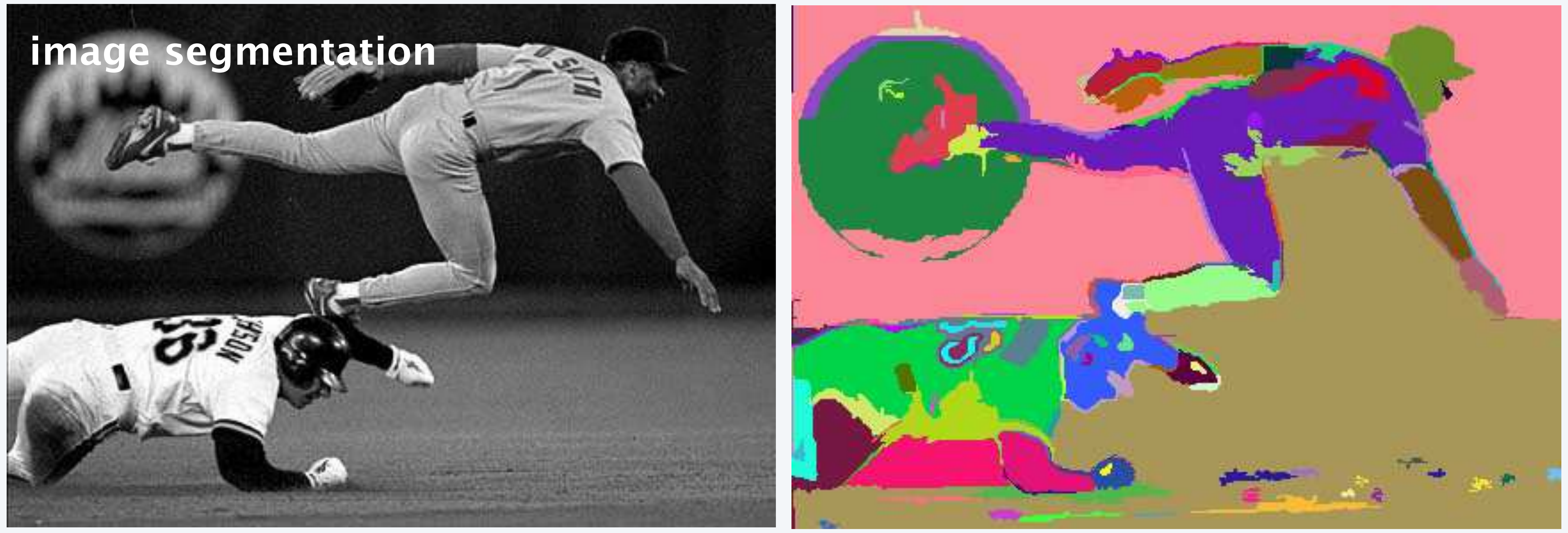
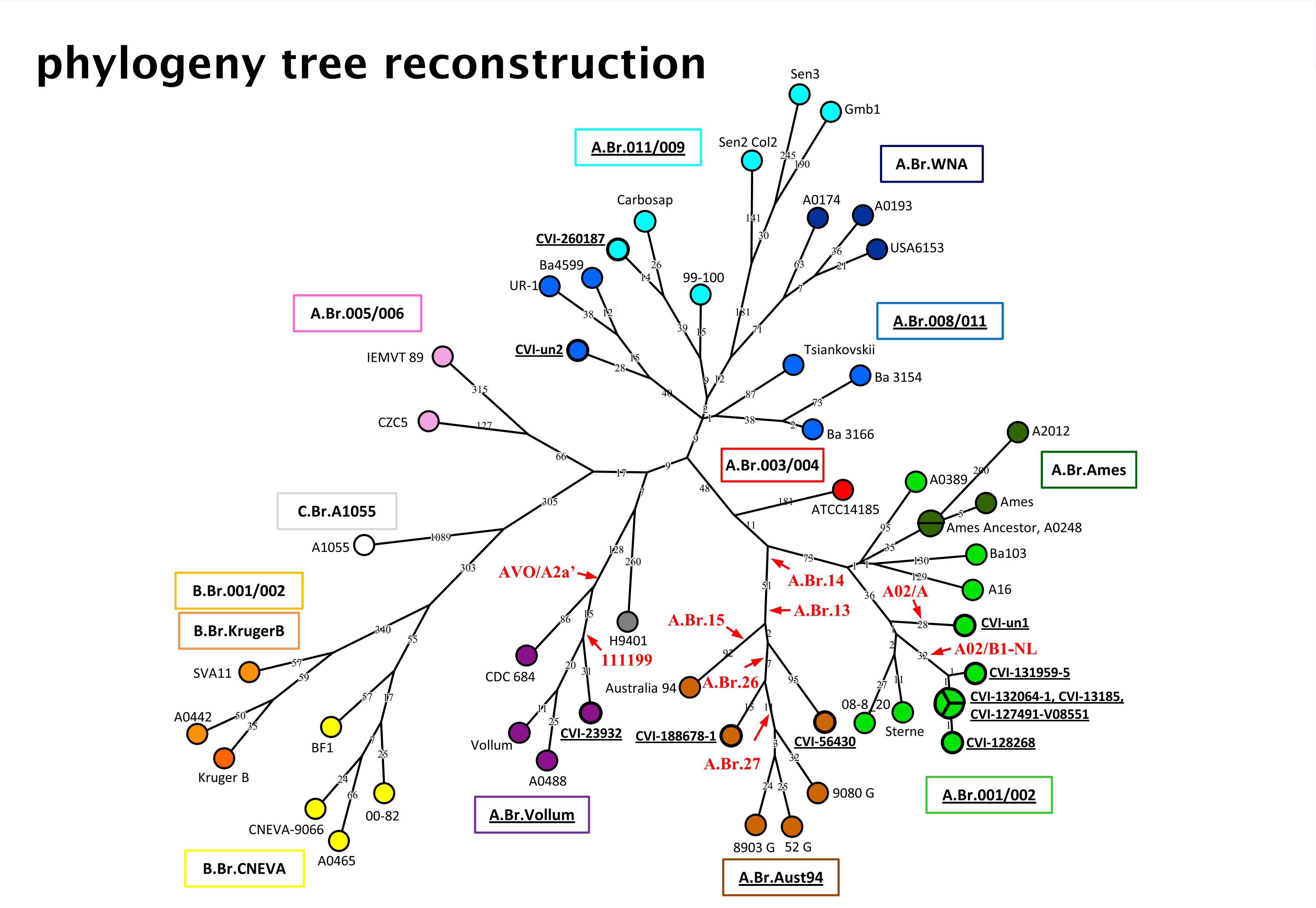
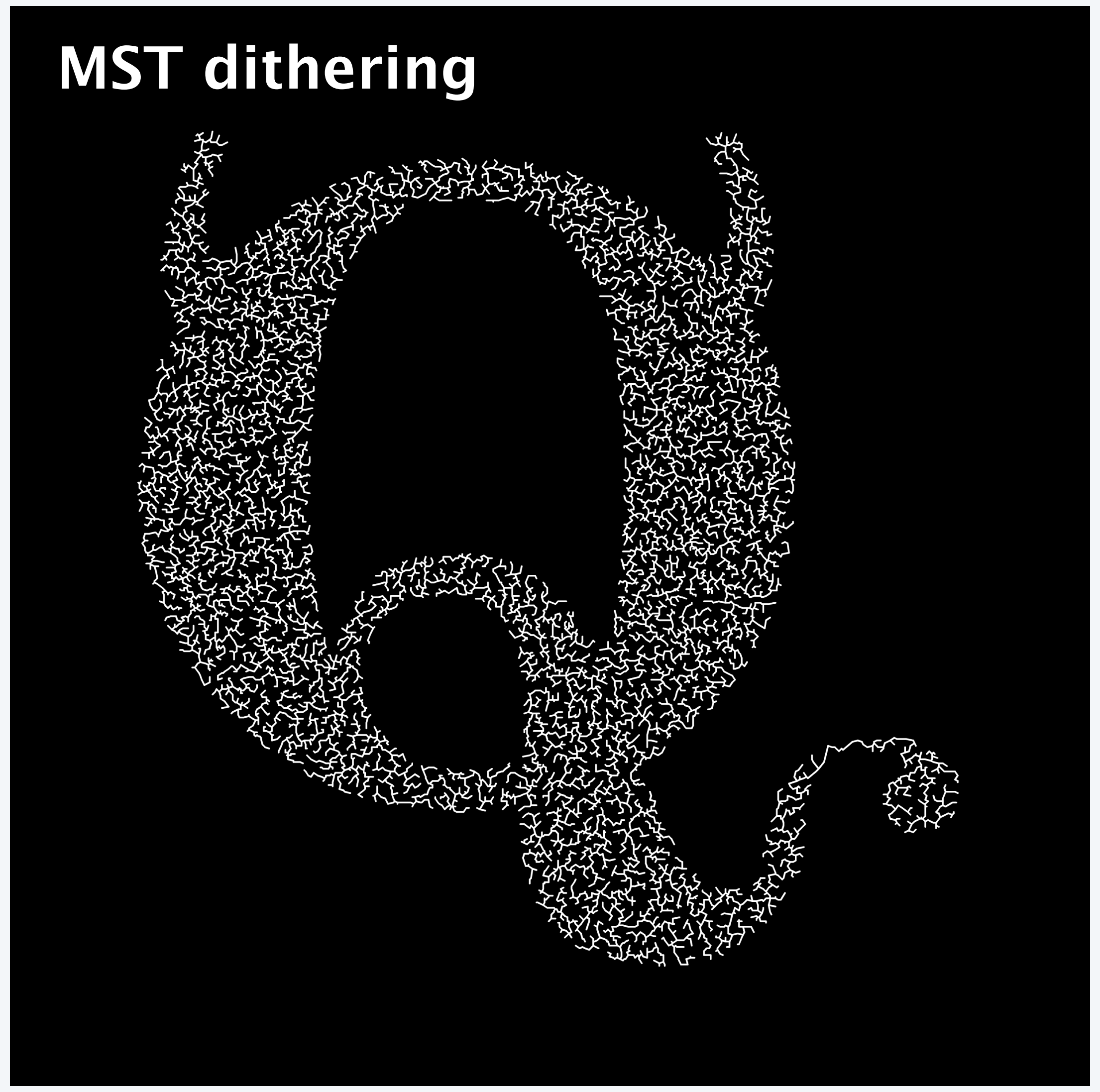
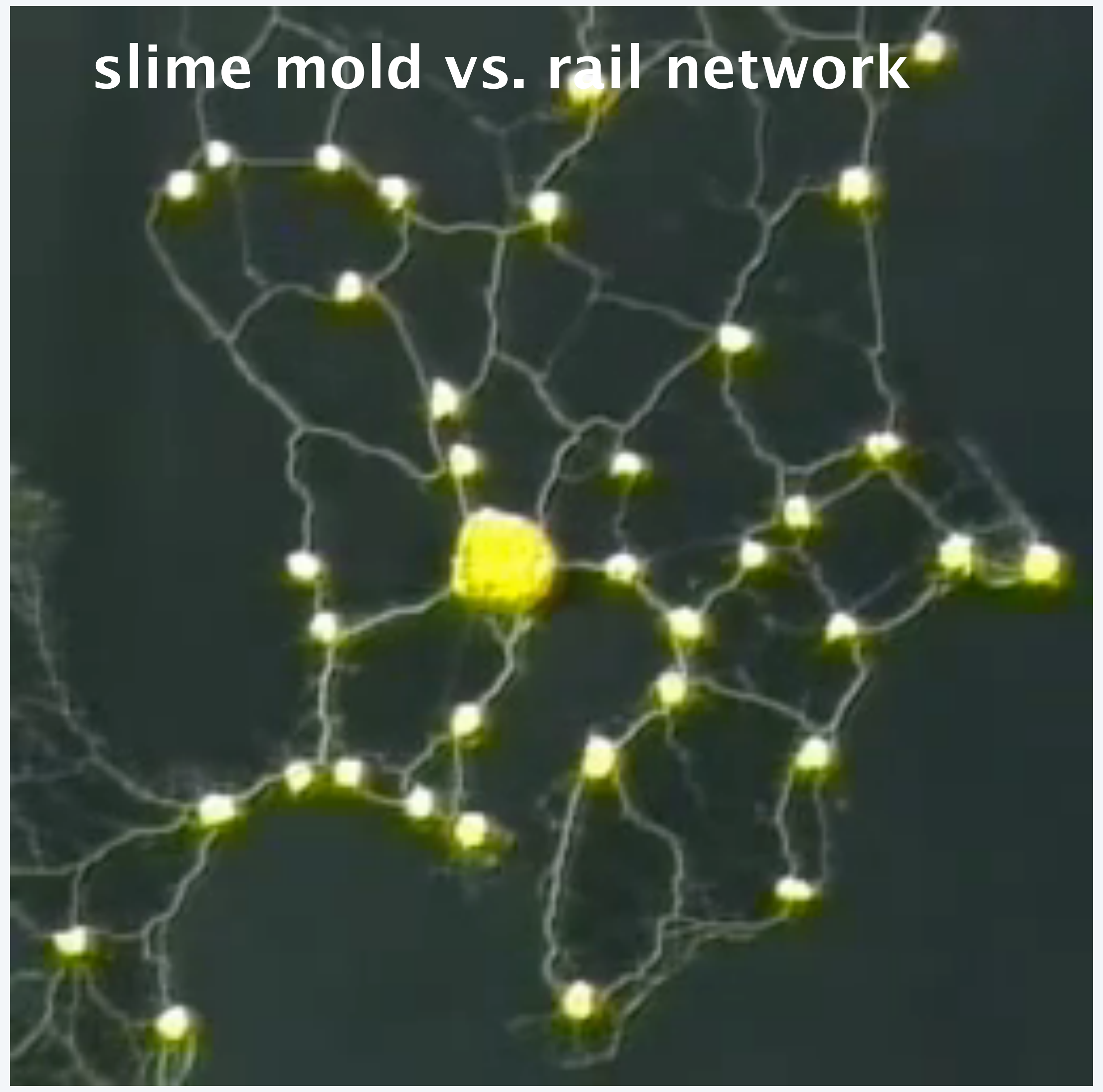


image segmentation


phylogeny tree reconstruction


MST dithering


slime mold vs. rail network

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4.3 Minimum Spanning Trees

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

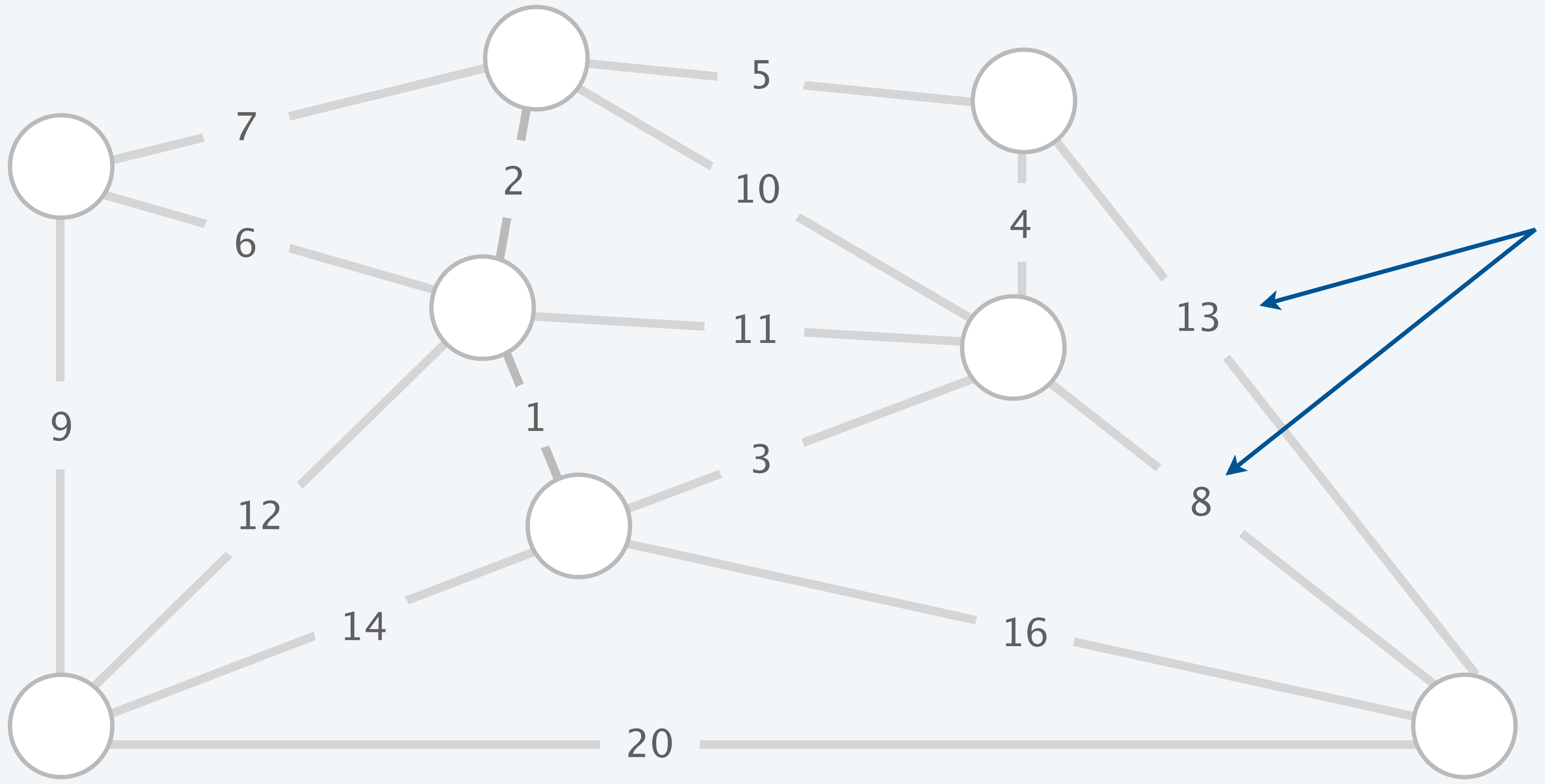
Simplifying assumptions

For simplicity, we assume:

- The graph is connected. ⟹ MST exists.
- The edge weights are distinct. ⟹ MST is unique. ← *see Exercise 4.3.3 (solution on booksite)*

Note. Today's algorithms all work even if edge weights are not distinct.

assumption simplifies the analysis and exposition



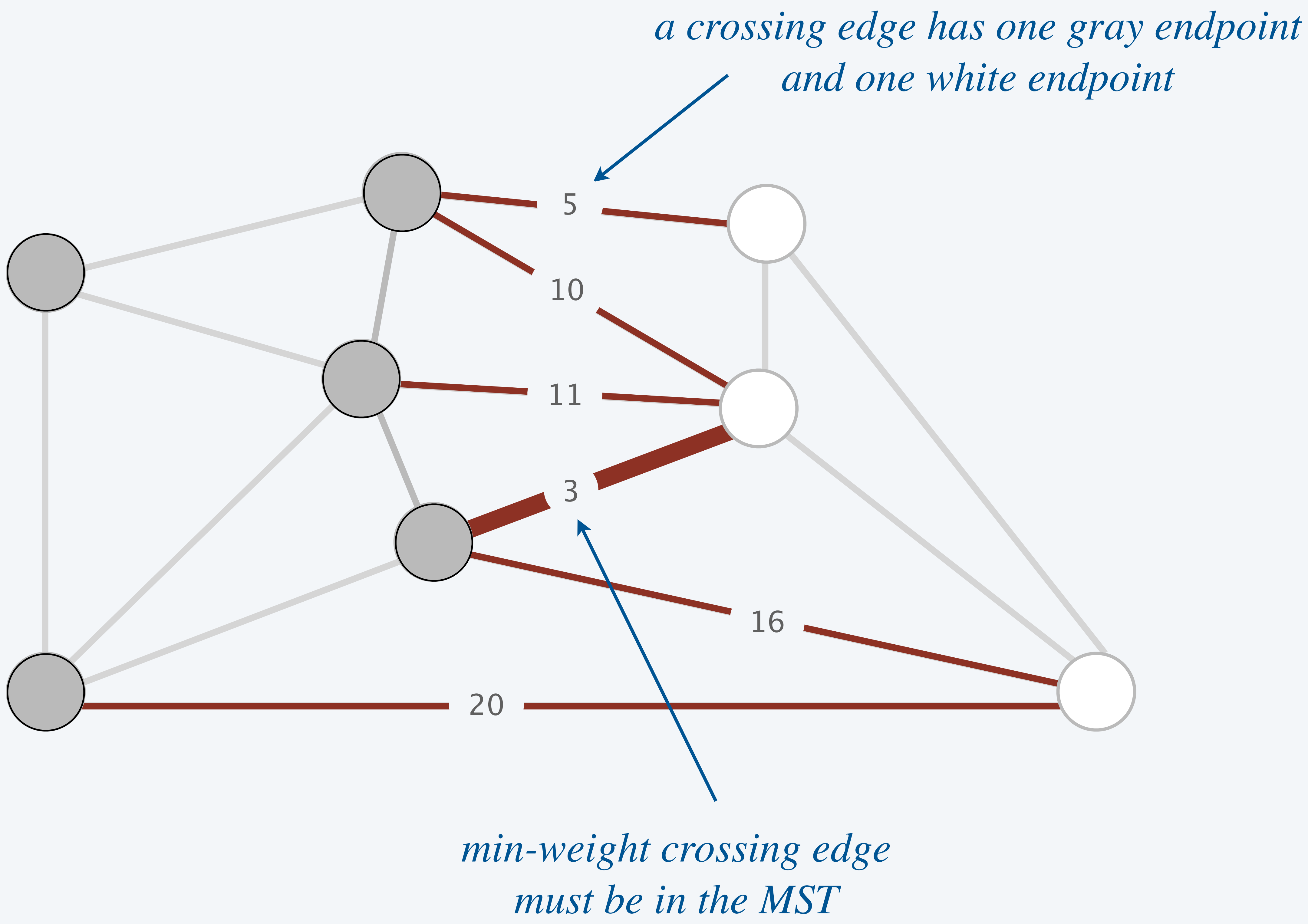
no two edge weights are equal

Cut property

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

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

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



a crossing edge has one gray endpoint and one white endpoint

min-weight crossing edge must be in the MST

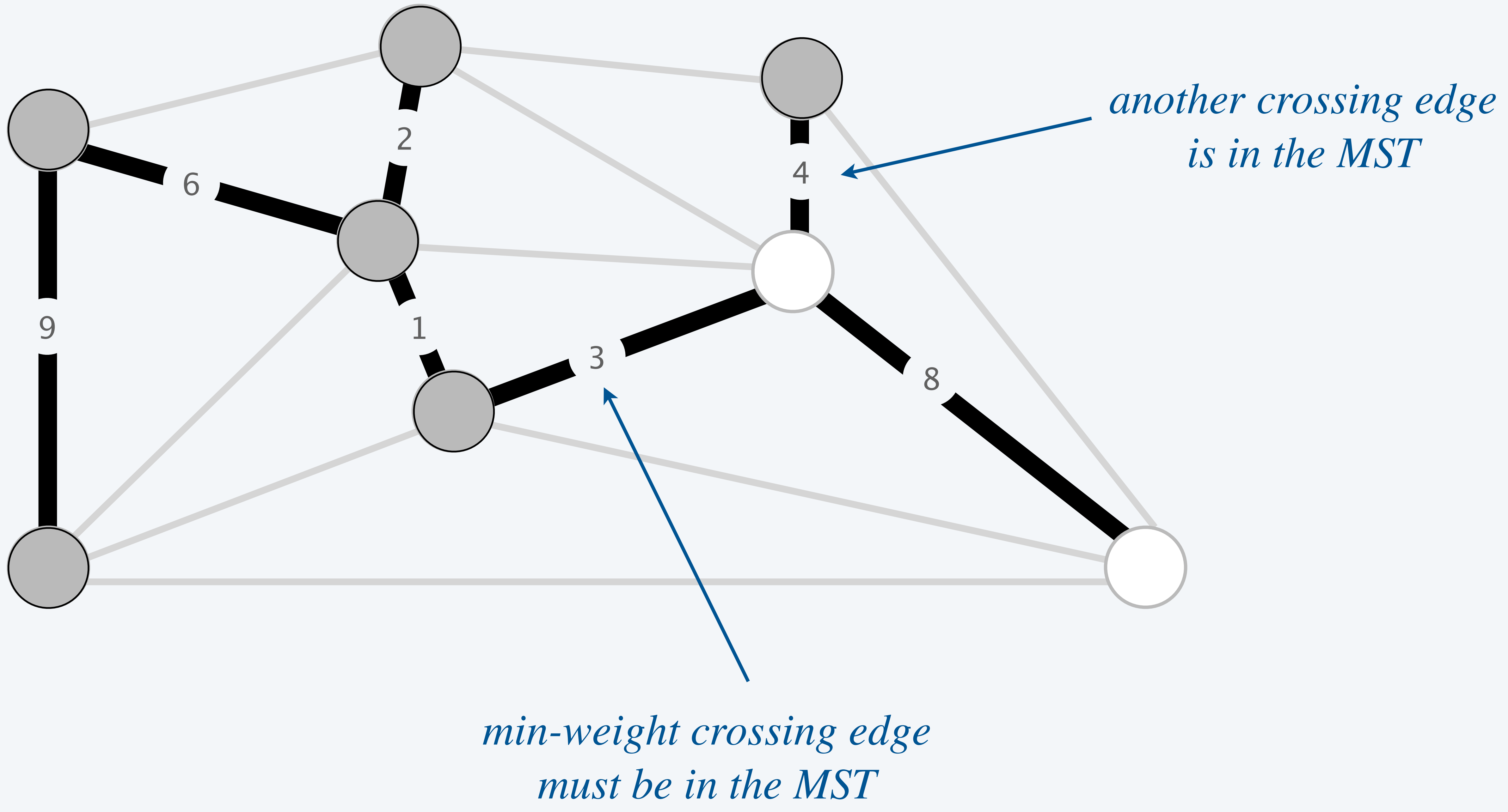
Cut property

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

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

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

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



another crossing edge is in the MST

min-weight crossing edge must be in the MST

Minimum spanning trees: quiz 2

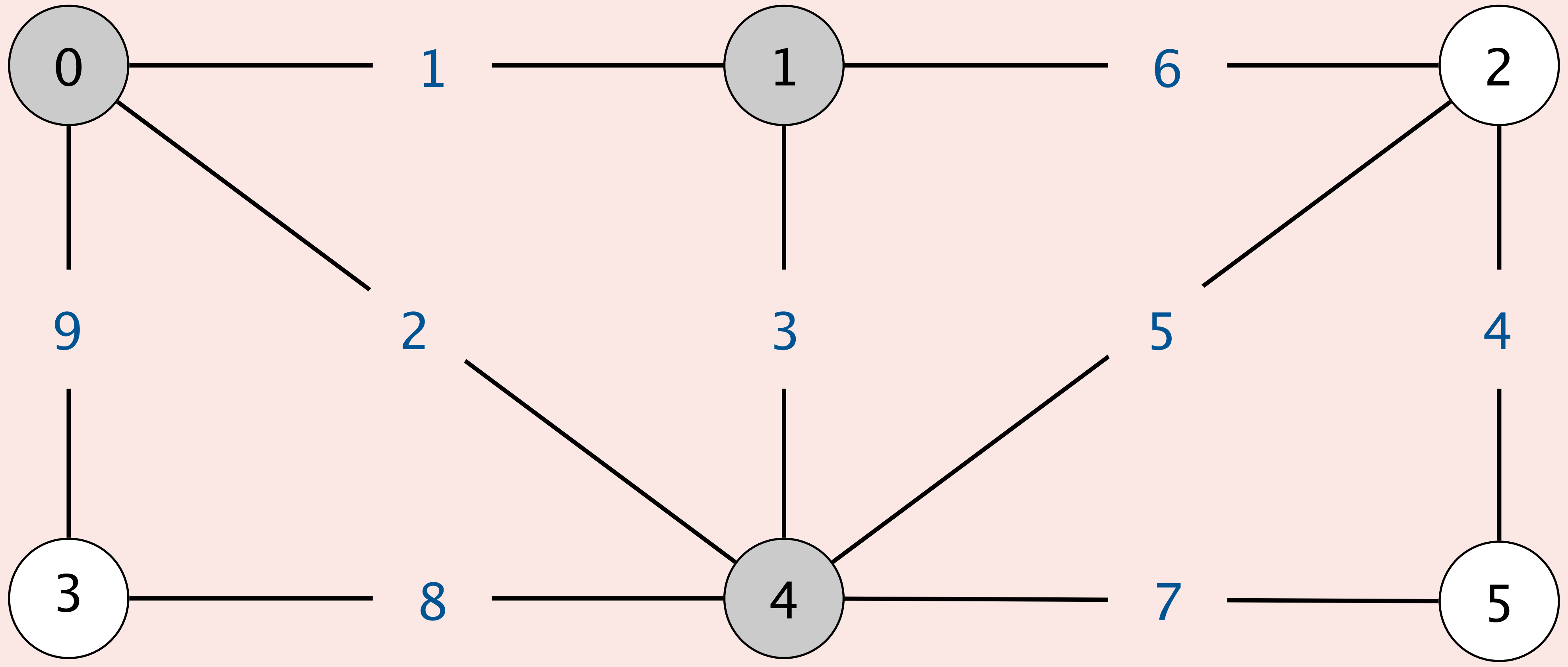
Which is the min-weight crossing edge for the cut { 2, 3, 5 } ?

A. 0–1 (1)

B. 1–2 (6)

C. 2–4 (5)

D. 2–5 (4)



Cut property: correctness proof

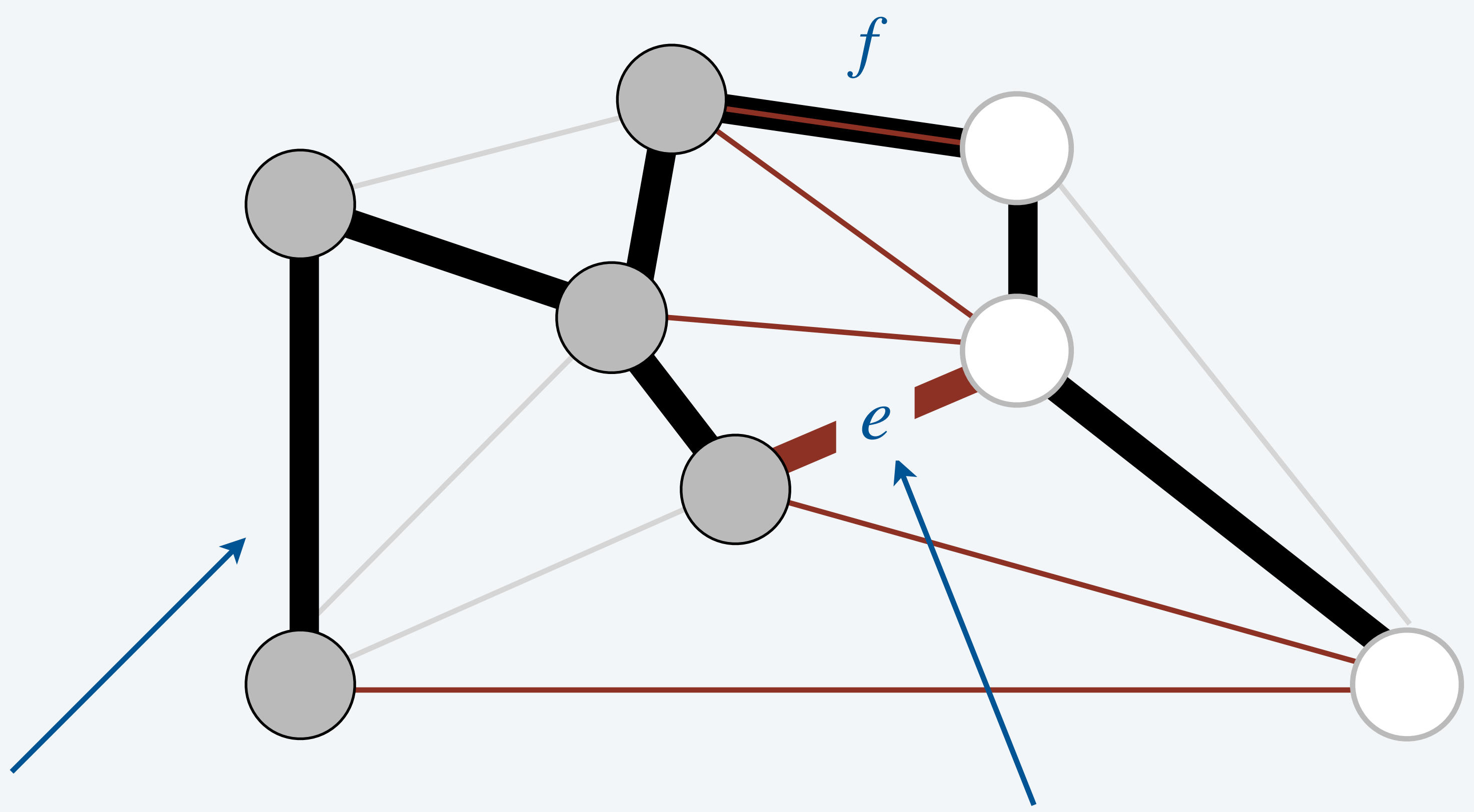
Def. A cut in an undirected graph is a partition of its vertices into two nonempty sets.

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

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

Pf. [by contradiction]

- Suppose e is not in the MST T^*.
- Adding e to T^* creates a unique cycle.
- Some other edge f in cycle must also be a crossing edge.
- Replacing f with e in T^* yields a different spanning tree T'.
- Since $weight(e) < weight(f)$, we have $weight(T') < weight(T^*)$.
- Contradiction.



the MST T does not contain e*

adding e to MST T creates a unique cycle*

Framework for minimum spanning tree algorithms

Generic algorithm (to compute MST in G)

```
T = $\varnothing$.
Repeat until T is a spanning tree:   $\longleftarrow$ $V - 1$ edges
    - Find a cut in G.
    - e $\leftarrow$ min-weight crossing edge.
    - T $\leftarrow$ T $\cup$ { e }.
```

Efficient implementations.

- Which cut? $\longleftarrow$ 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.

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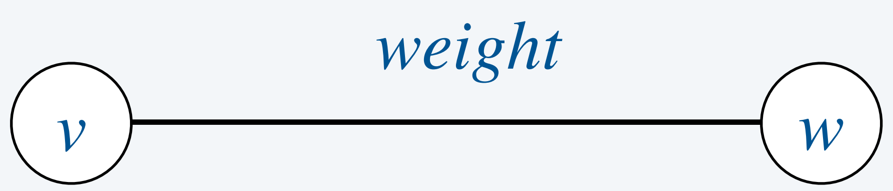
Weighted edge API

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*
`double`	`weight()`	*weight of edge*
`int`	`compareTo(Edge that)`	*compare edges by weight*
	⋮	⋮



edge e = v-w

```
int v = e.either();
int w = e.other(v);
double weight = e.weight();
```

idiom for processing an edge e

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

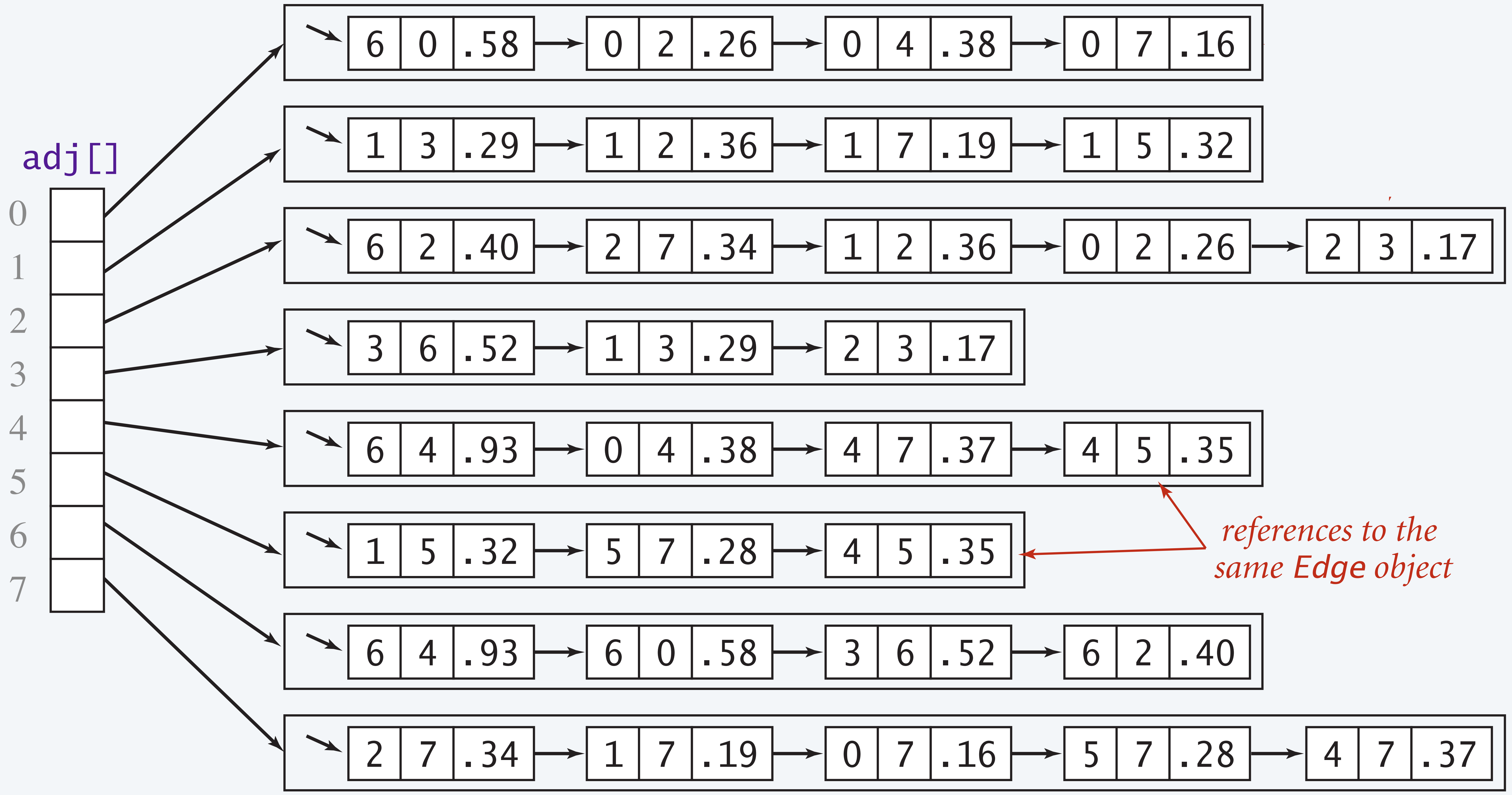
API. Same as `Graph` and `Digraph`, except with explicit `Edge` objects.

`public class EdgeWeightedGraph`

	`EdgeWeightedGraph(int V)`	*edge-weighted graph with V vertices (and no edges)*
`void`	`addEdge(Edge e)`	*add the weighted edge e*
`Iterable<Edge>`	`adj(int v)`	*edges incident with vertex v*
`int`	`V()`	*number of vertices*
`int`	`E()`	*number of edges*
	⋮	⋮

Edge-weighted graph: adjacency-lists representation

Maintain vertex-indexed array of lists: adj[v] contains edges incident with vertex *v*.



6 0 .58 → 0 2 .26 → 0 4 .38 → 0 7 .16

1 3 .29 → 1 2 .36 → 1 7 .19 → 1 5 .32

6 2 .40 → 2 7 .34 → 1 2 .36 → 0 2 .26 → 2 3 .17

3 6 .52 → 1 3 .29 → 2 3 .17

6 4 .93 → 0 4 .38 → 4 7 .37 → 4 5 .35

1 5 .32 → 5 7 .28 → 4 5 .35

6 4 .93 → 6 0 .58 → 3 6 .52 → 6 2 .40

2 7 .34 → 1 7 .19 → 0 7 .16 → 5 7 .28 → 4 7 .37

references to the same Edge *object*

Edge-weighted graph: adjacency-lists implementation

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

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

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

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

}
```

same as Graph *(but adjacency lists of* Edge *objects)*

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.

But, 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*
	⋮	⋮

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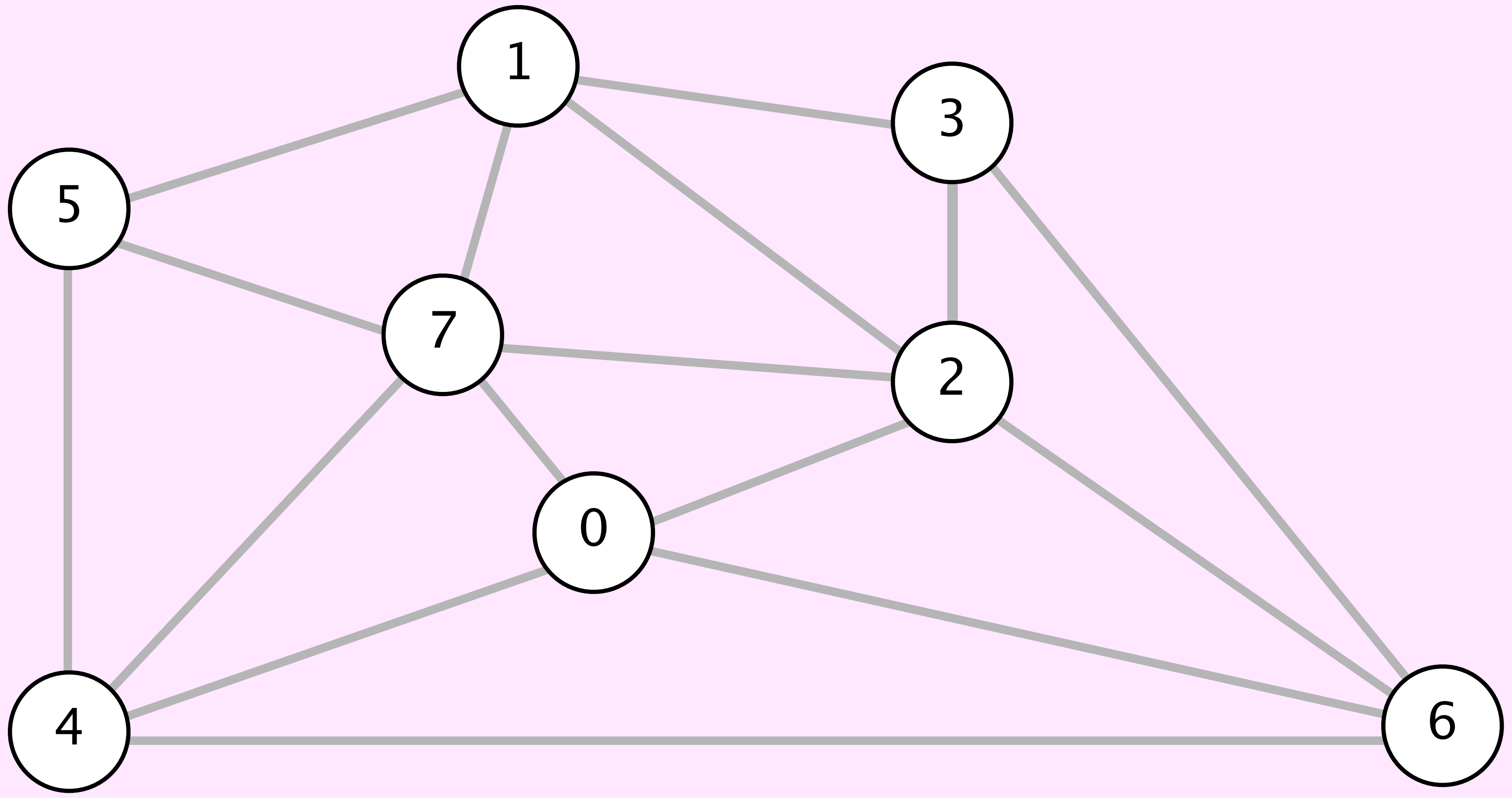
Kruskal's algorithm demo

Consider edges in ascending order by weight:

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



an edge-weighted 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

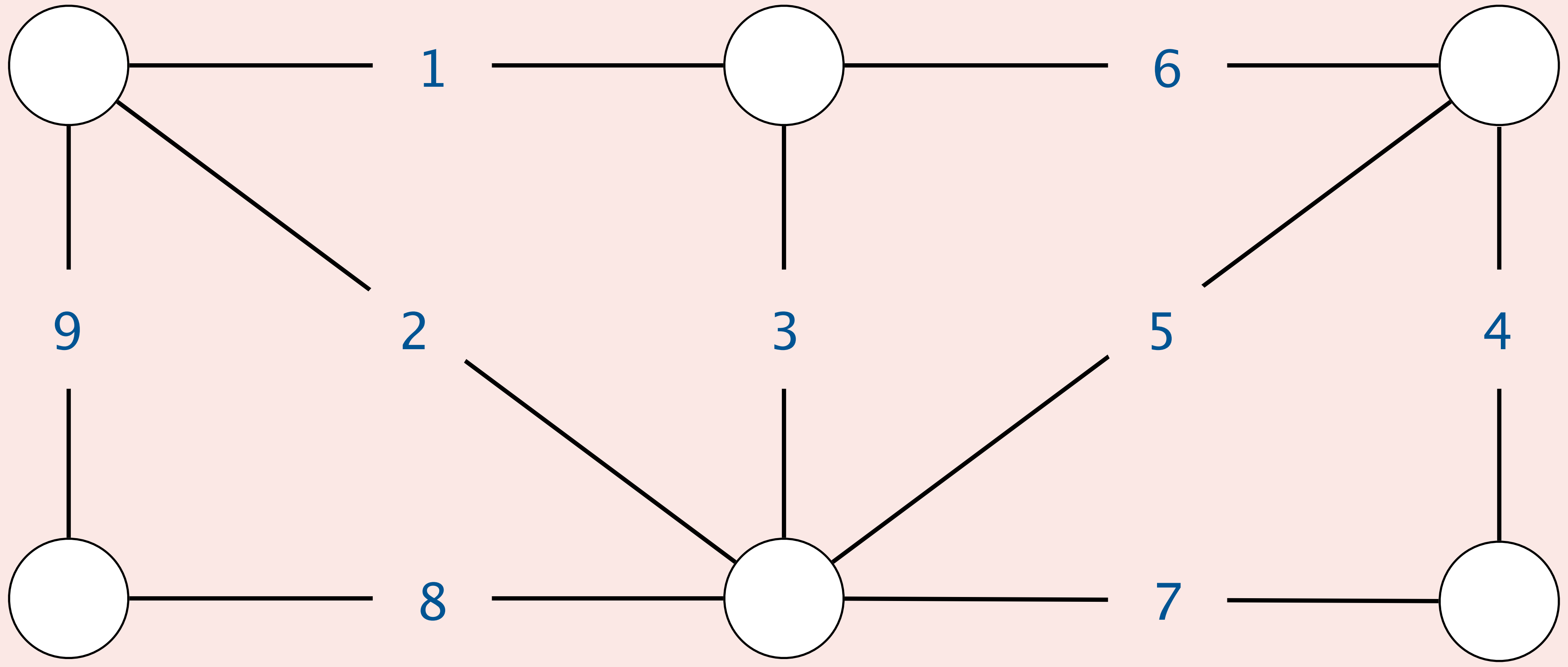
In which order does Kruskal's algorithm select edges in MST?

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: correctness proof

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

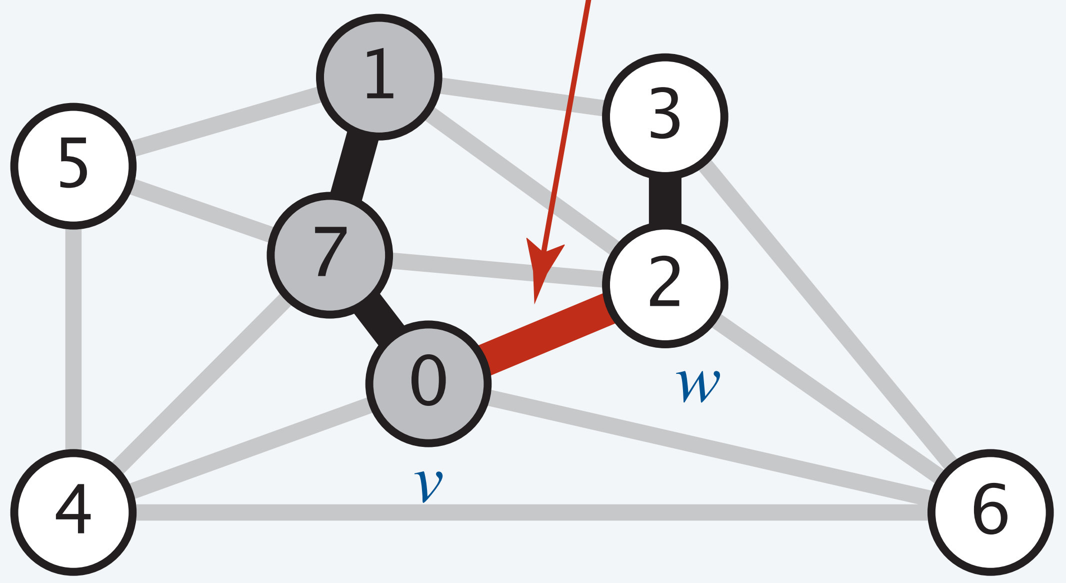
Pf. Kruskal's algorithm adds edge e to T if and only if e is in the MST.

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

- Vertices v and w are in different connected components of T.
- Cut = set of vertices connected to v in T.
- By definition of cut, e is a crossing edge; moreover,
  - no crossing edge is currently in T
  - no crossing edge was considered by Kruskal before e
- Thus, e is a min-weight crossing edge.
- Cut property $\Longrightarrow$ e is in the MST. ▪

Kruskal considers edges in ascending order by weight

add edge to tree



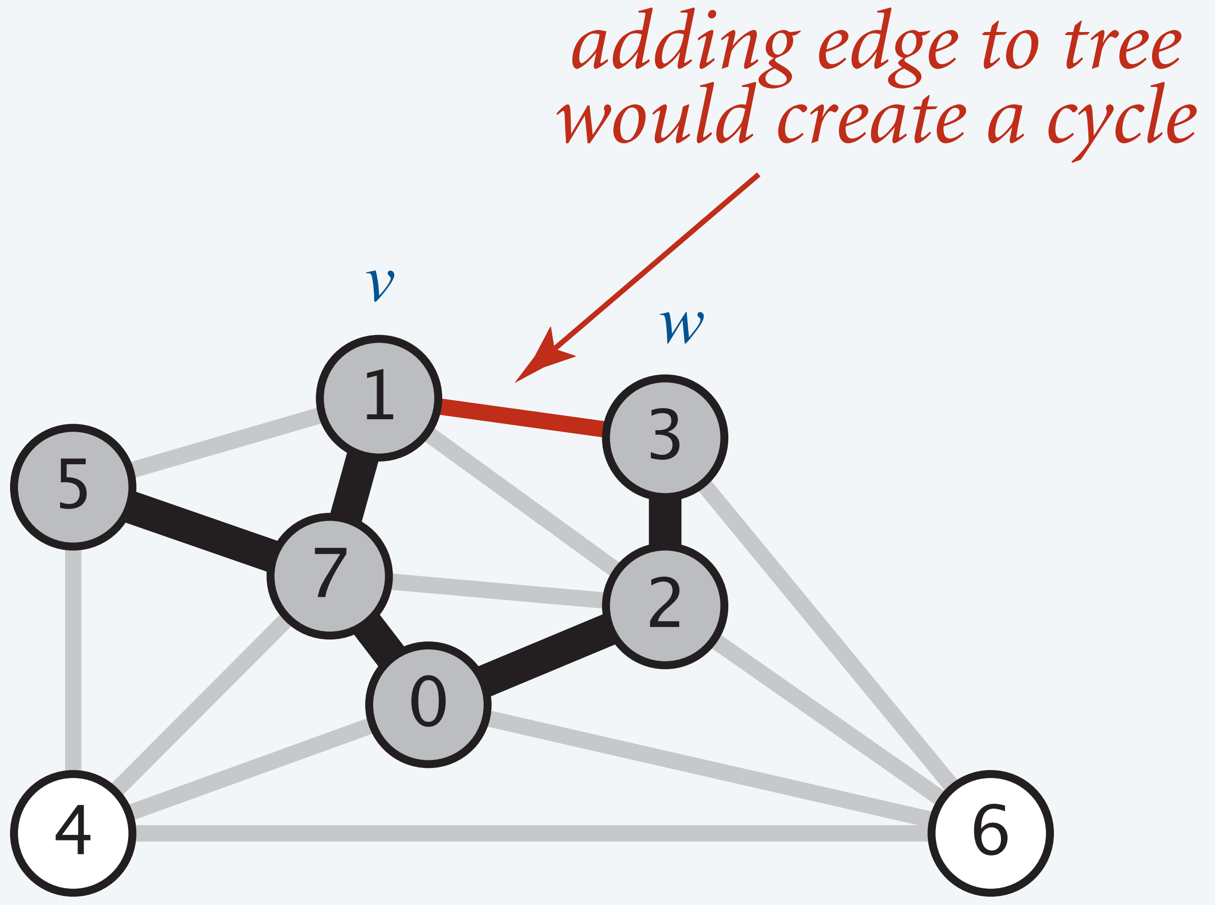
Kruskal's algorithm: correctness proof

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

Pf. Kruskal's algorithm adds edge e to T if and only if e is in the MST.

[Case 2 $\Longleftarrow$] Kruskal's algorithm discards edge $e = v\text{–}w$.

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

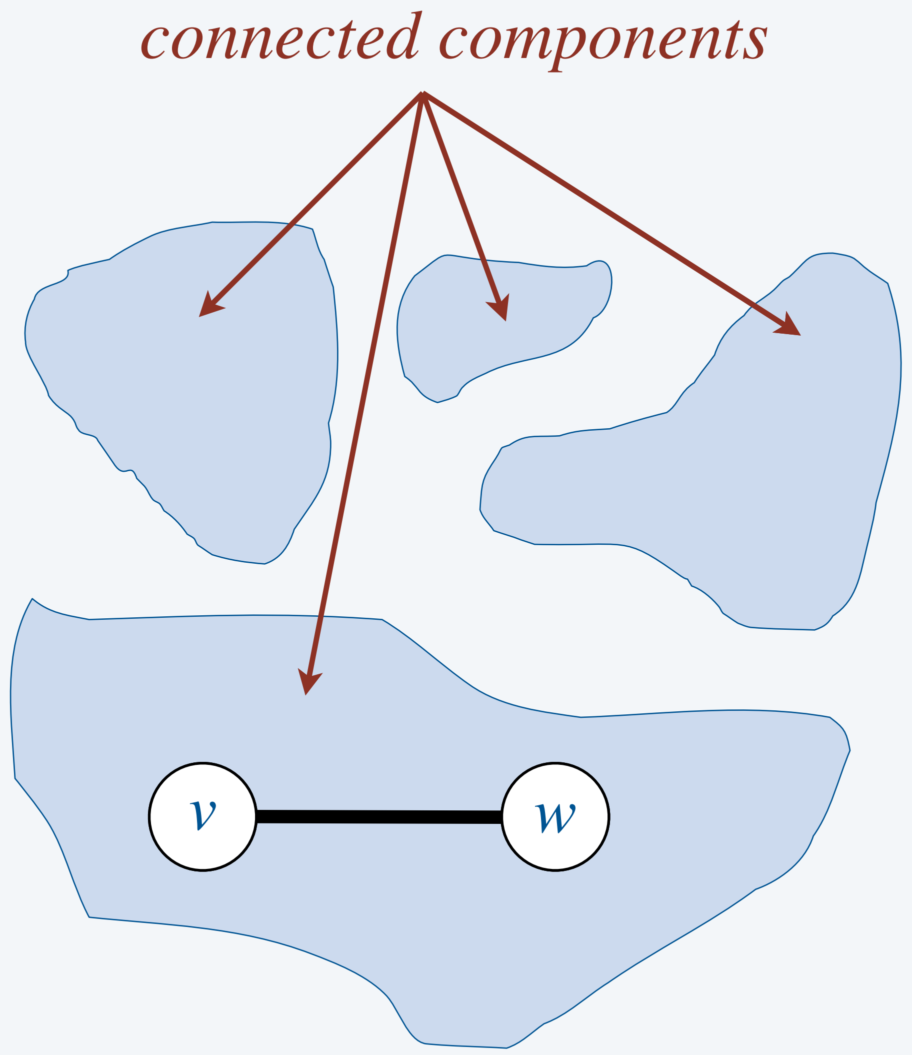


Kruskal's algorithm: implementation challenge

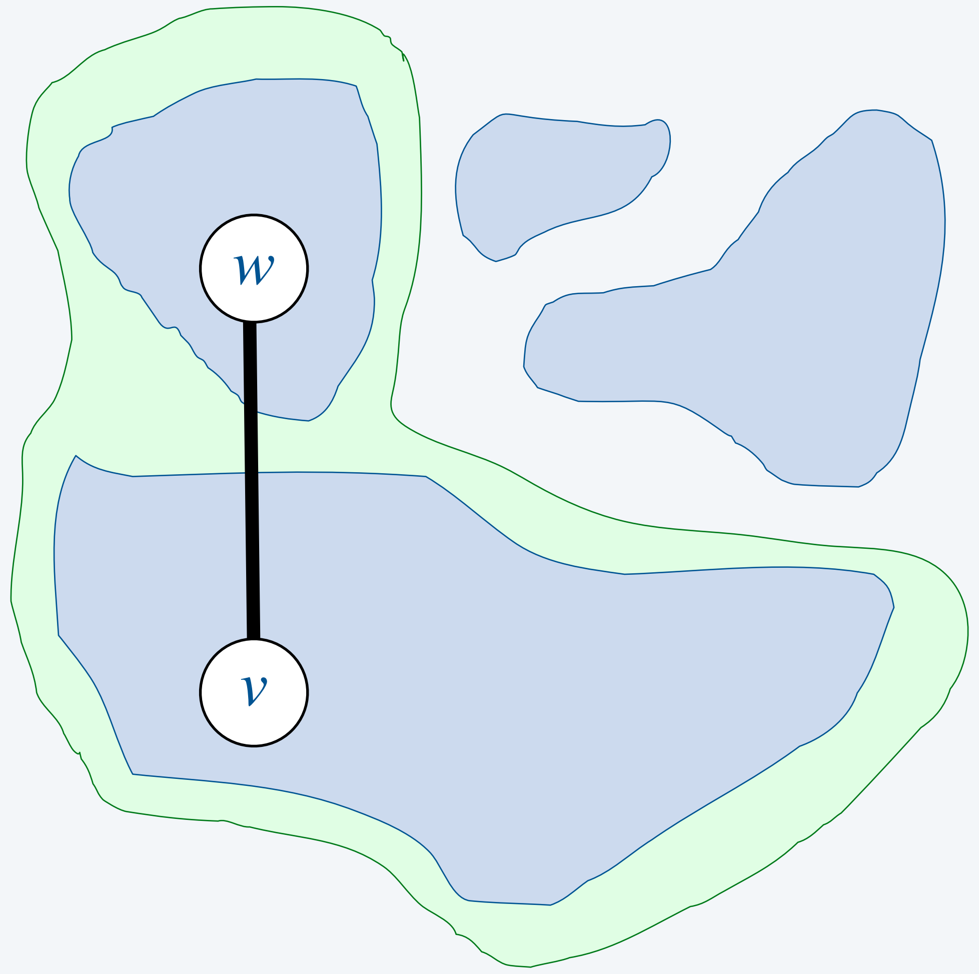
Challenge. Would adding edge $v\!-\!w$ to T create a cycle? If not, add it.

Efficient solution. Use the union-find data structure.

- Maintain a set for each connected component in T, with each vertex in its own set initially.
- If v and w are in same set, then adding edge $v\!-\!w$ to T would create a cycle. [Case 2]
- Otherwise, add edge $v\!-\!w$ to T and merge sets containing v and w. [Case 1]



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

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

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

      for (int i = 0; i < graph.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 the MST in an edge-weighted graph in $\Theta(E \log E)$ time and $\Theta(E)$ extra space.

Pf.

- Bottlenecks are sorting and union-find operations.

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

† *using weighted quick union*

- Total. $\Theta(V \log V) \;+\; \Theta(E \log V) \;+\; \Theta(E \log E)$.

dominated by $\Theta(E \log E)$
since graph is connected

Minimum spanning trees: quiz 4

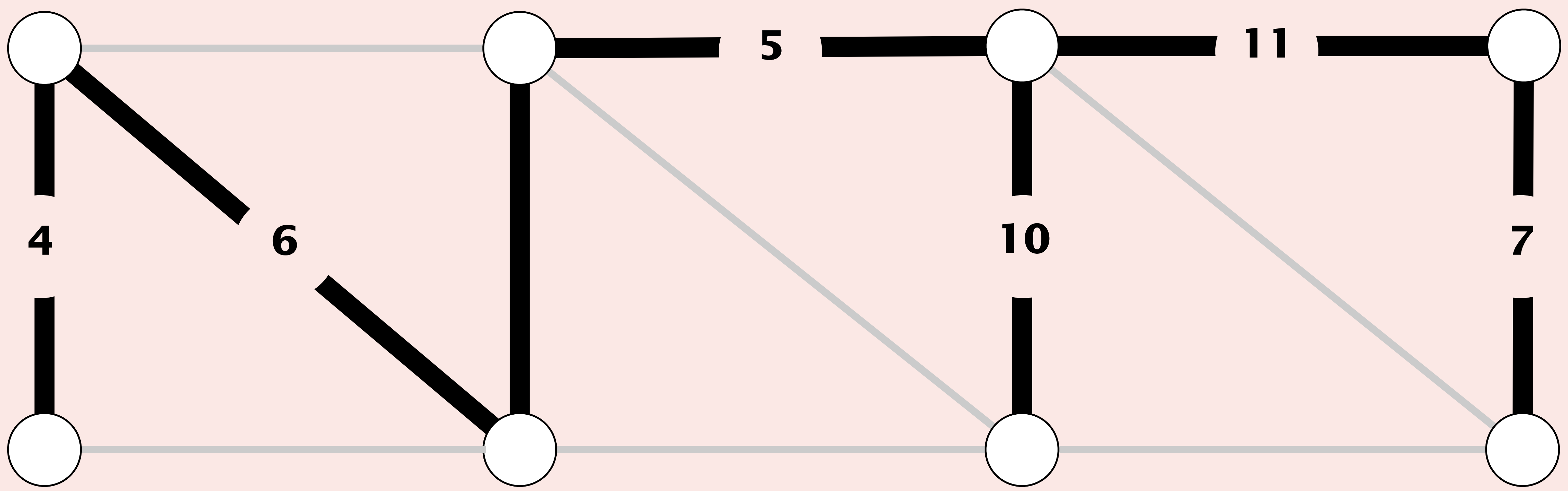
Given a graph with positive edge weights, how to find a spanning tree that minimizes the sum of the squares of the edge weights?

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.

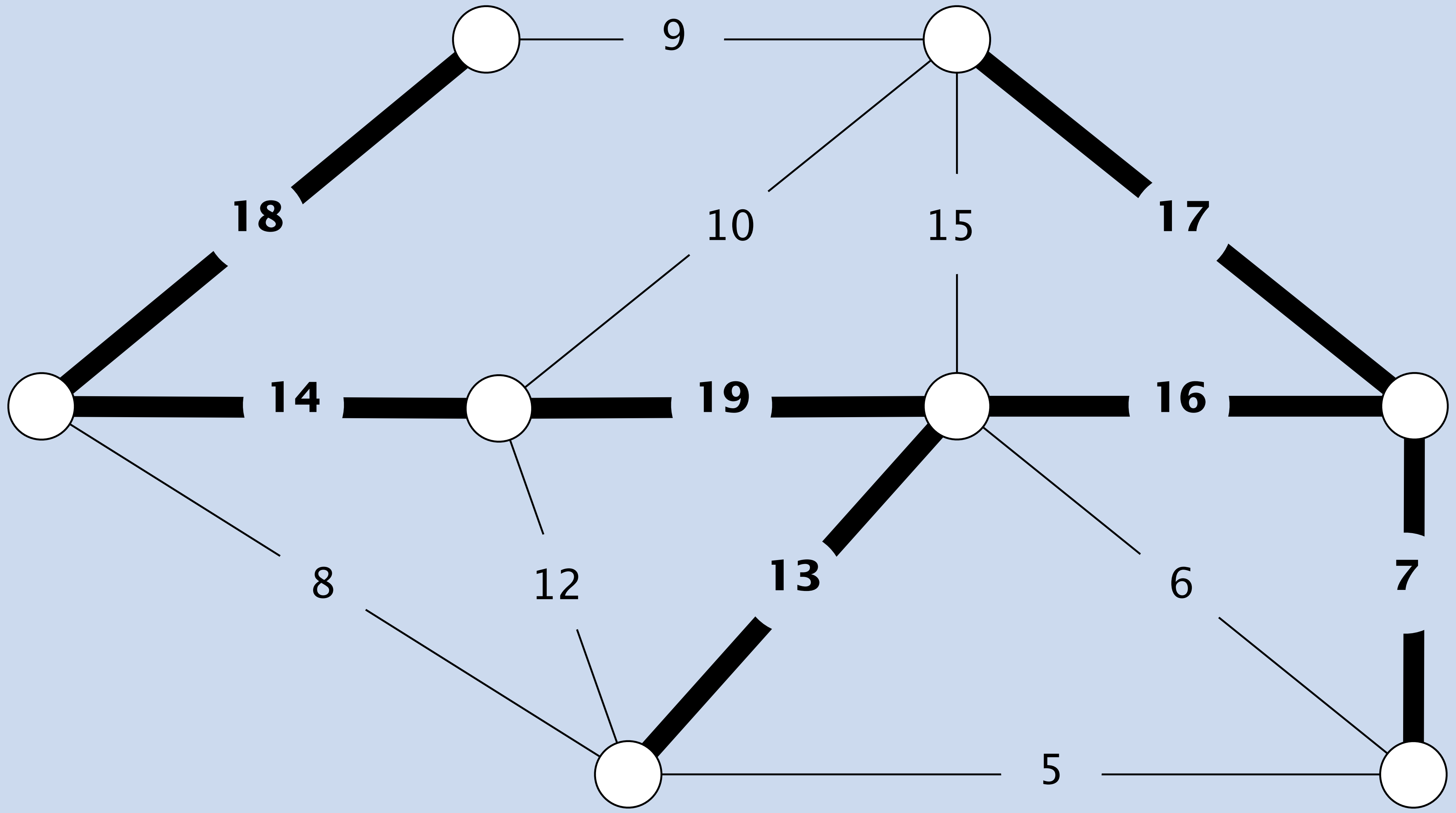


sum of squares = $4^2 + 6^2 + 5^2 + 10^2 + 11^2 + 7^2 = 347$

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 that takes $\Theta(E \log E)$ time in the worst case.



maximum spanning tree T* (weight = 104)

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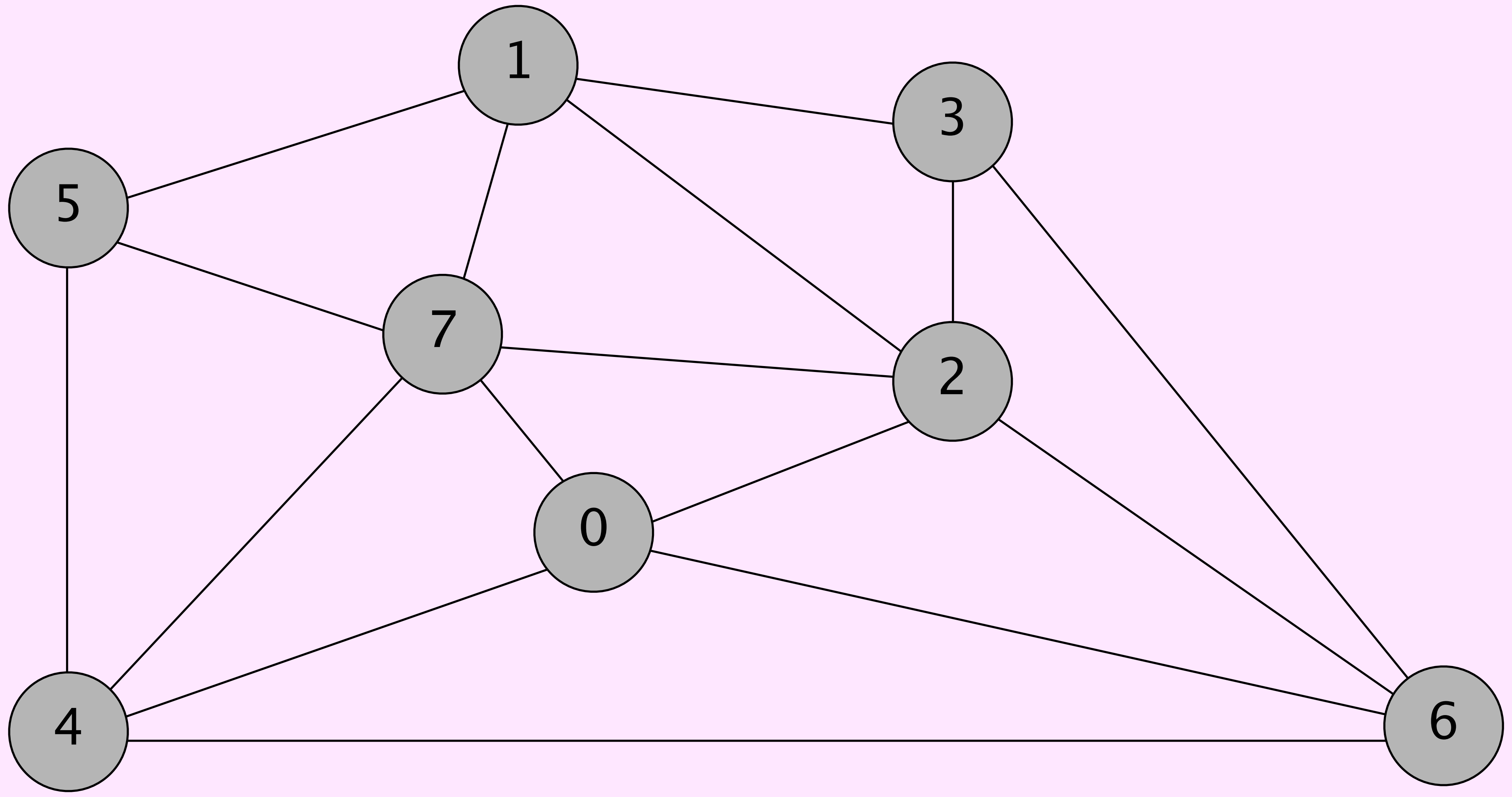
- ▸ ***Prim's algorithm***

Prim's algorithm demo

- Start with vertex 0 and grow tree T.
- Repeat until T contains $V - 1$ 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
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1-5	0.32
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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 5

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

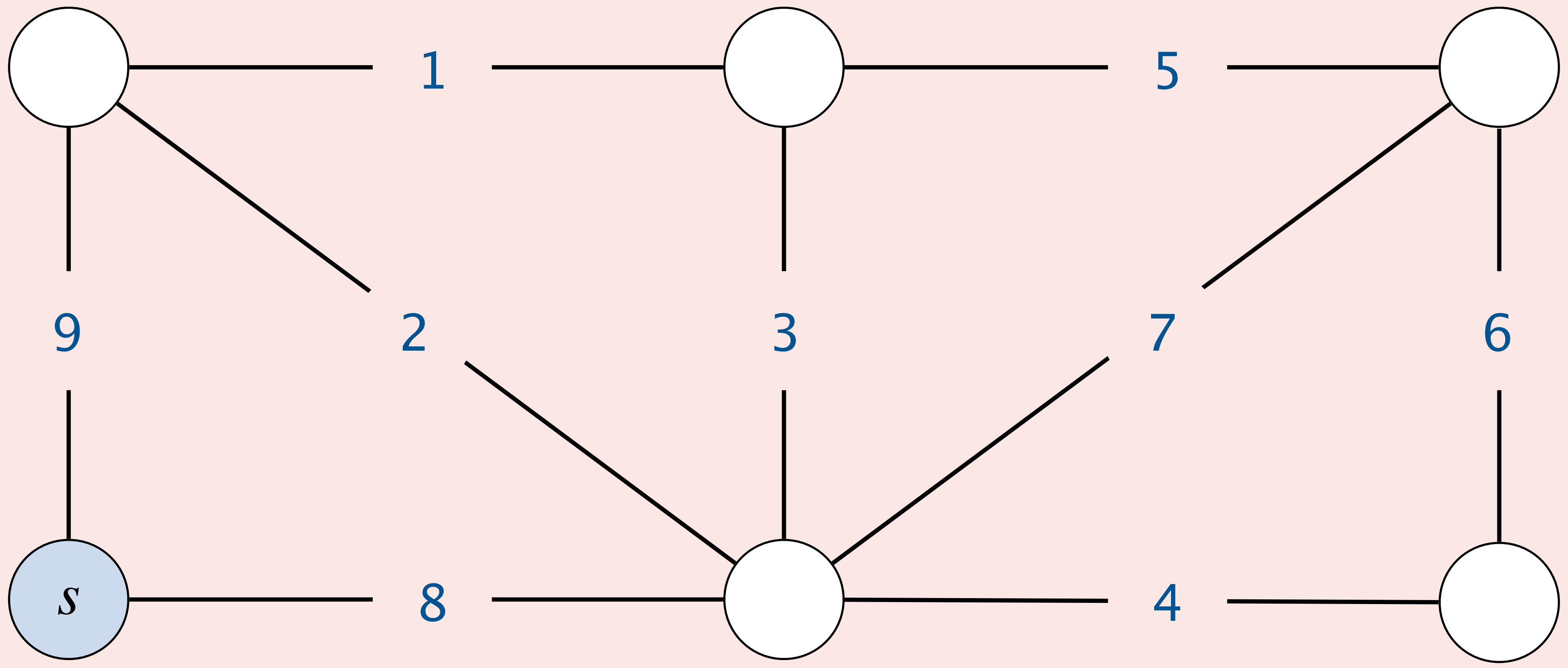
Assume it starts from vertex s.

A. 8, 2, 1, 4, 5

B. 8, 2, 1, 5, 4

C. 8, 2, 1, 5, 6

D. 8, 2, 3, 4, 5



Prim's algorithm: proof of correctness

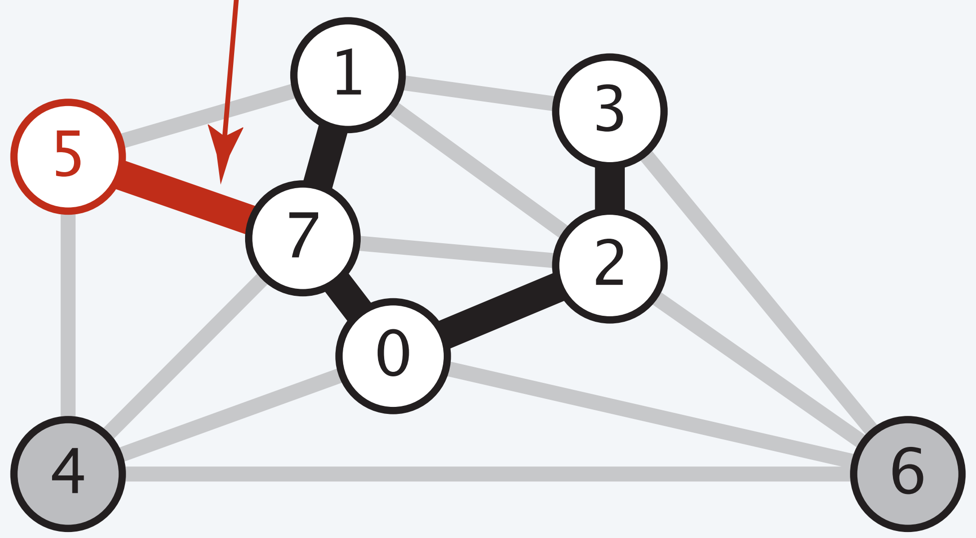
Proposition. [Jarník 1930, Dijkstra 1957, Prim 1959]

Prim's algorithm computes the MST.

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

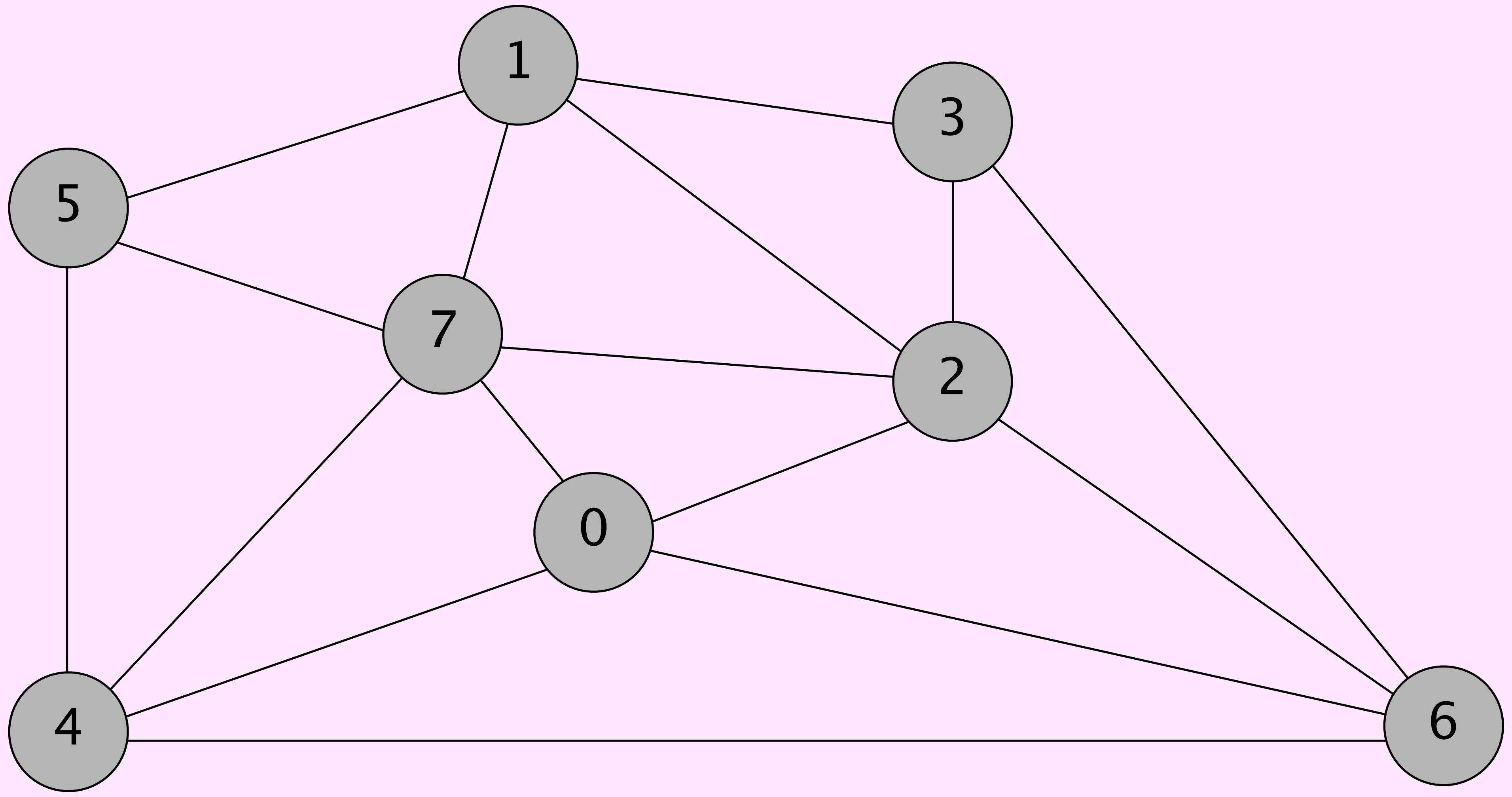
- Cut = set of vertices in T.
- Cut property $\Longrightarrow$ edge e is in the MST. ▪

Challenge. How to efficiently find min-weight edge with exactly one endpoint in T?



Prim's algorithm demo: lazy implementation

- Start with vertex 0 and grow tree T.
- Repeat until T contains $V - 1$ 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

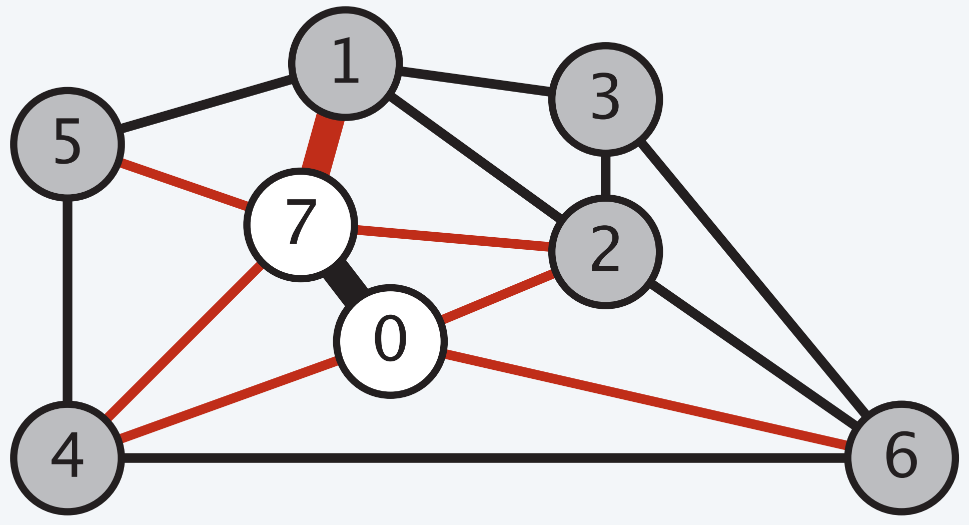
Prim's algorithm: lazy implementation

Challenge. How to efficiently find 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 with w ← *but don't bother if other endpoint is already 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

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

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

assume graph G is connected

```
         while (mst.size() < graph.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);
         }
   }
   ...
}
```

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

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

add v to tree T

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

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

Lazy Prim's algorithm: running time

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

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	time per op
INSERT	E	$\Theta(\log E)$ †
DELETE-MIN	E	$\Theta(\log E)$ †

† *using binary heap*

Prim's algorithm: eager implementation

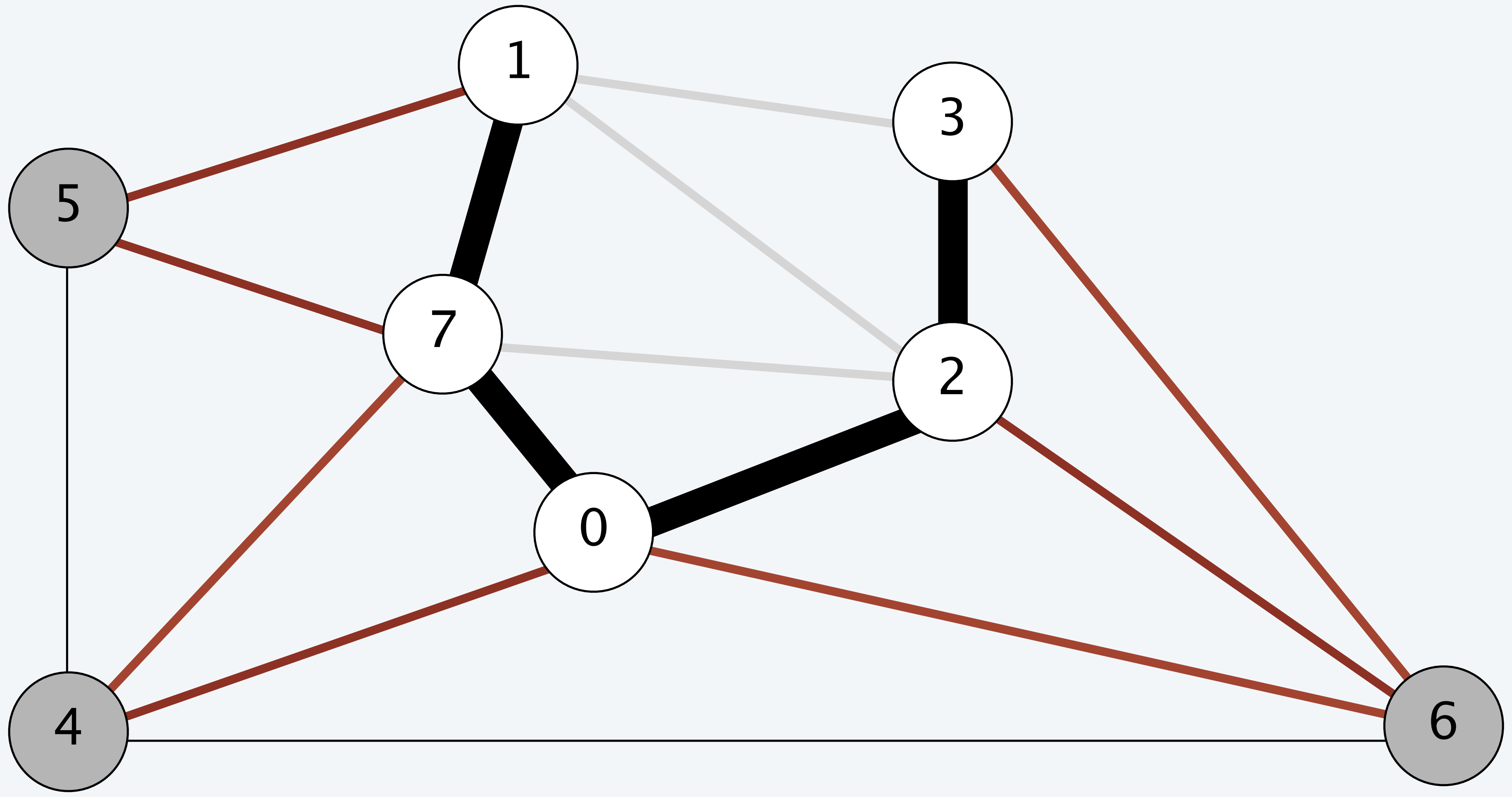
Challenge. Find min-weight edge with exactly one endpoint in T.

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?

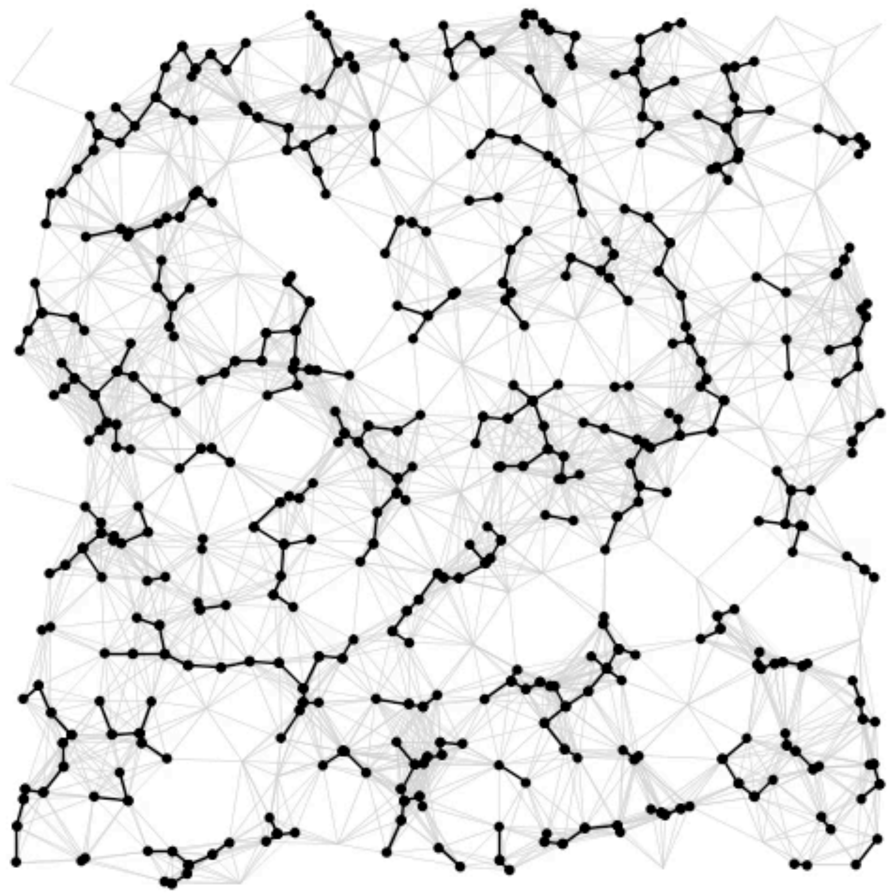
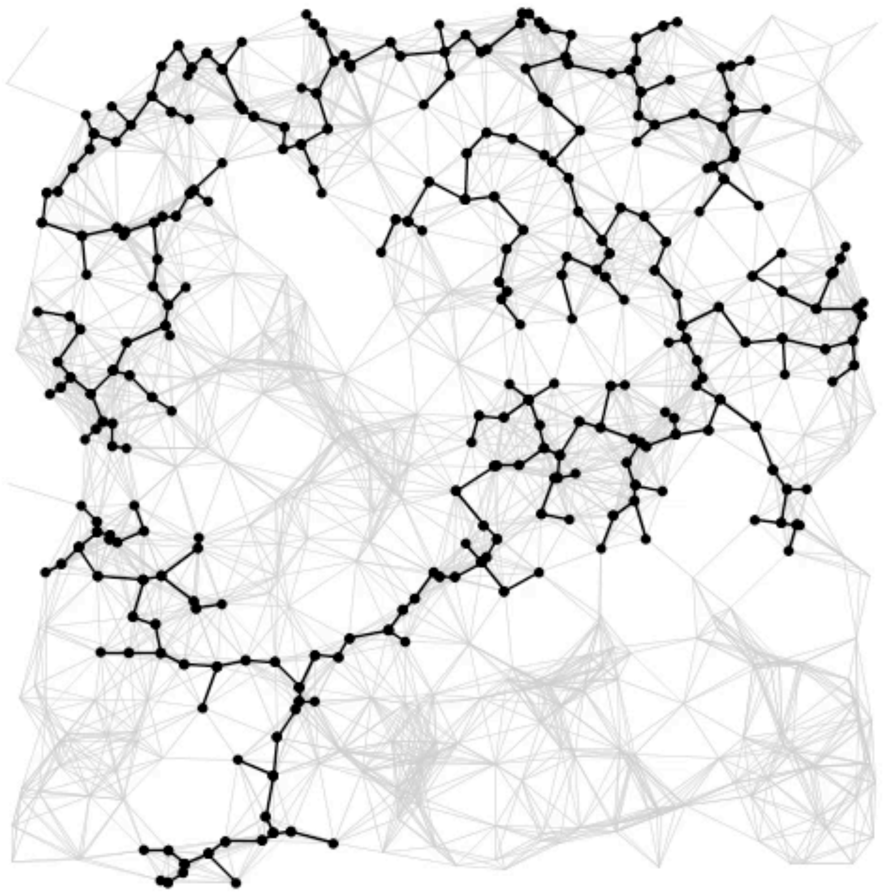
Impact. PQ of vertices; $\Theta(V)$ extra space; $\Theta(E \log V)$ running time in worst case.

instead of edges



see textbook for details

MST: algorithms of the day

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

Credits

media	source	license
Muddy City Problem	CS Unplugged	CC BY-NC-SA 4.0
Microarrays and Clustering	Botstein and Brown	by author
Image Segmentation	Felzenszwalb and Huttenlocher	
Phylogeny Tree	Derzelle et al.	
MST Dithering	Mario Klingemann	CC BY-NC 2.0
Slime Mold vs. Rail Network	Harvard Magazine	
Mona Singh	Princeton University	

A final thought

> “ *The algorithms we write are only as good as the questions we ask. And the best questions come from creative thinking and collaboration.* ” — Mona Singh