CS 201: Data Structures
Minimum Spanning Trees

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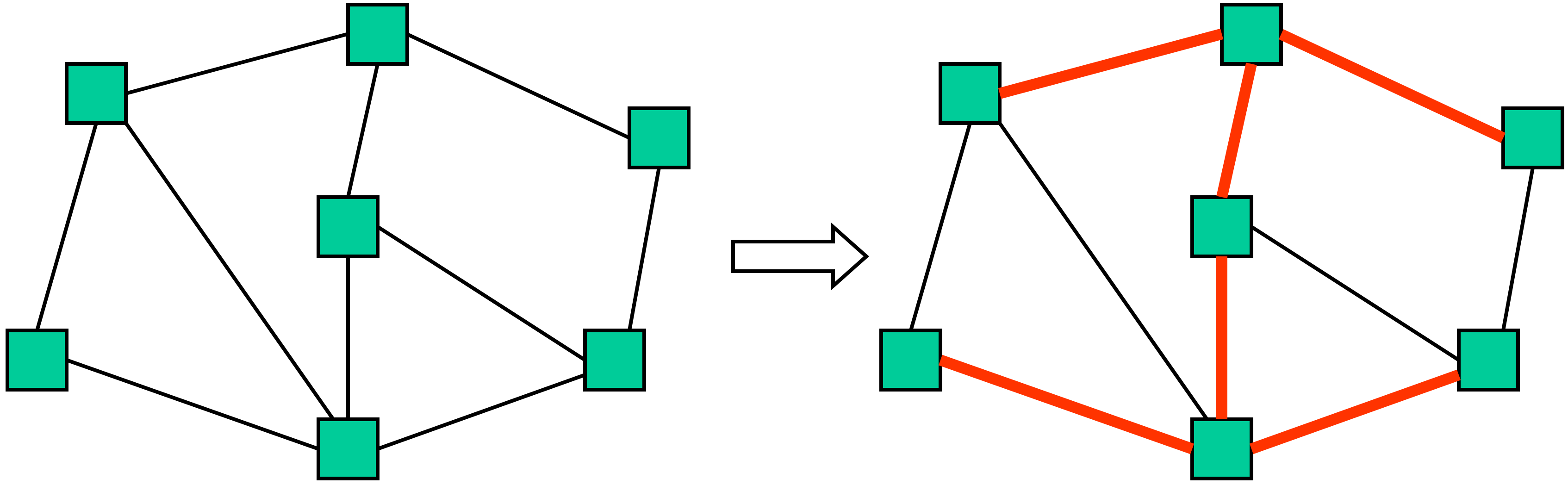
Spanning Trees

- A simple problem: Given a *connected* undirected graph **G**=(**V**,**E**), find a minimal subset of edges such that **G** is still connected
  - A graph **G2**=(**V**,**E2**) such that **G2** is connected and removing any edge from **E2** makes **G2** disconnected



Observations

1. Any solution to this problem is a tree
   – Recall a tree does not need a root; just means acyclic
   – For any cycle, could remove an edge and still be connected

2. Solution not unique unless original graph was already a tree

3. Problem ill-defined if original graph not connected
   – So **|E| ≥ |V|-1**

4. A tree with **|V|** nodes has **|V|-1** edges
   – So every solution to the spanning tree problem has **|V|-1** edges

Motivation

A spanning tree connects all the nodes with as few edges as possible

- Example: want there to be ice-free paths between any two campus buildings—what is the minimum set of paved walks that need to be de-iced?

In most compelling uses, we have a *weighted* undirected graph and we want a tree of least total cost

- Example: Electrical wiring for a house or wires on a computer chip
- Example: A road network if you cared about asphalt cost rather than travel time

This is the minimum spanning tree problem

- Will do that next, after intuition from the simpler case

Two Approaches

Different algorithmic approaches to the spanning-tree problem:

1. Do a graph traversal (e.g., depth-first search, but any traversal will do), keeping track of edges that form a tree

2. Iterate through edges; add to output any edge that does not create a cycle

Spanning tree via DFS

```
spanning_tree(Graph G) {
  for each node i: i.marked = false
  for some node i: f(i)
}
f(Node i) {
  i.marked = true
  for each j adjacent to i:
    if(!j.marked) {
      add(i,j) to output
      f(j) // DFS
    }
}
```

Correctness: DFS reaches each node. We add one edge to connect it to the already visited nodes. Order affects result, not correctness.

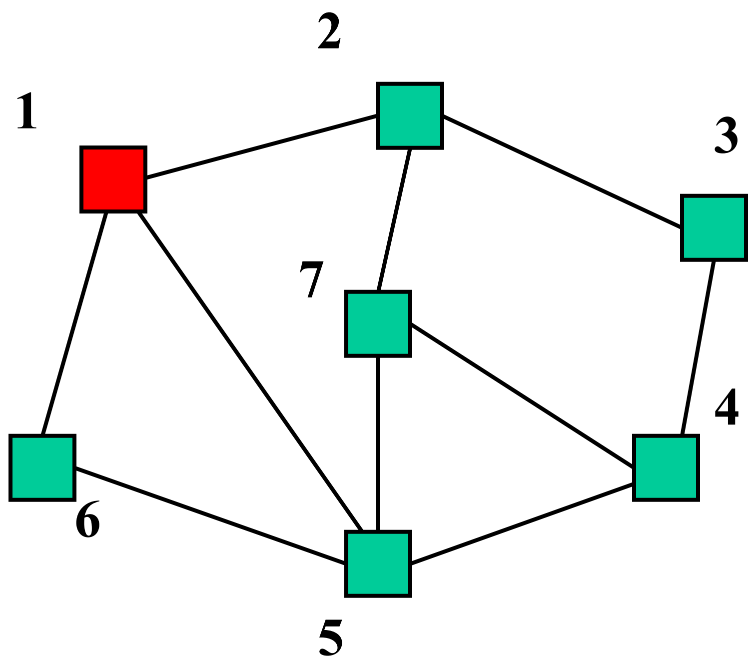
Time: $O(|\mathbf{E}|)$

Example

Stack

f(1)

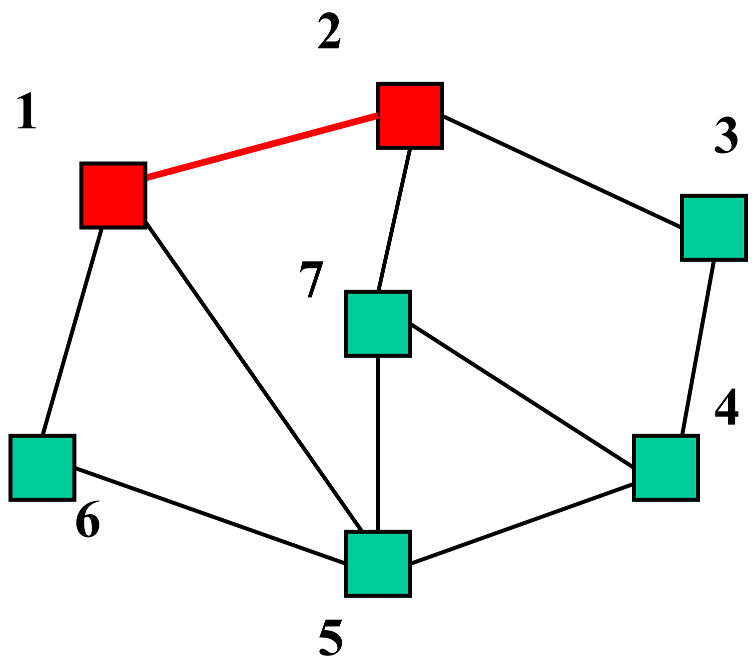
top of stack



Output:

Example

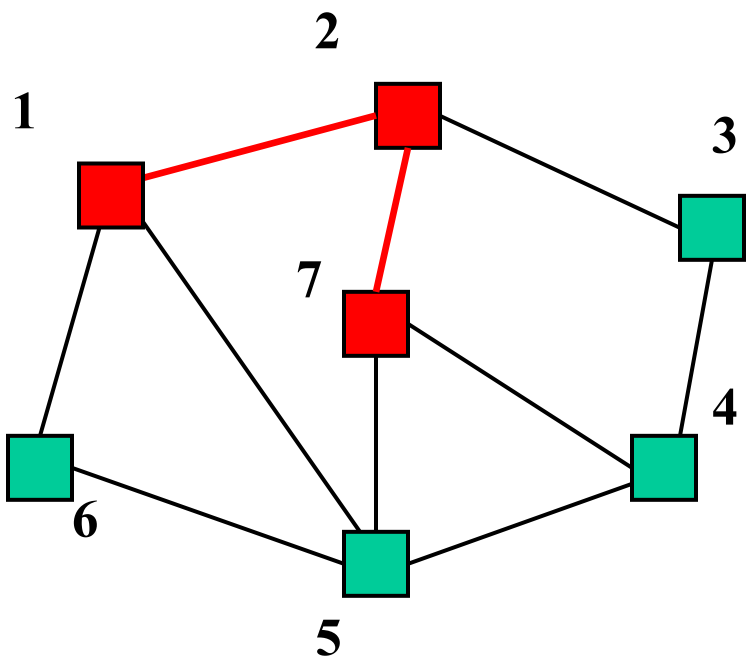
Stack
f(1)
f(2)
top



Output: (1,2)

Example

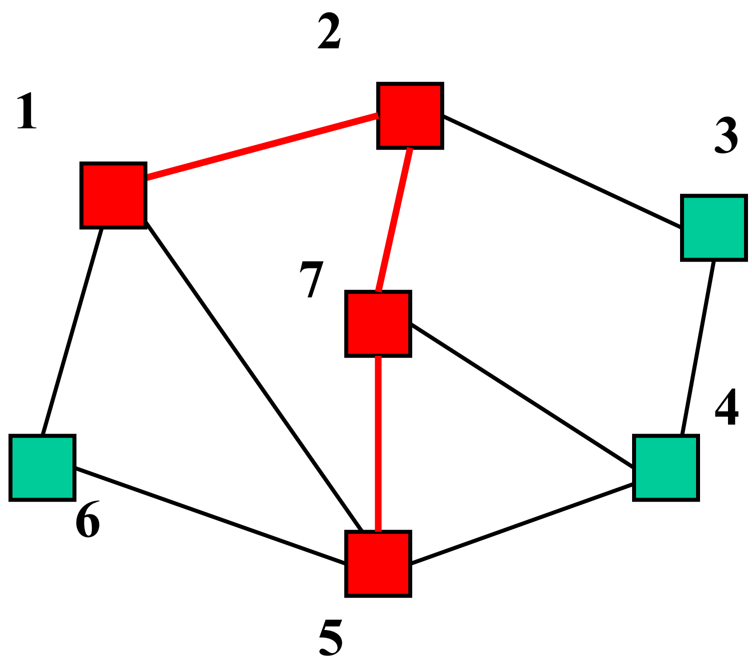
Stack
f(1)
f(2)
f(7)
top



Output: (1,2), (2,7)

Example

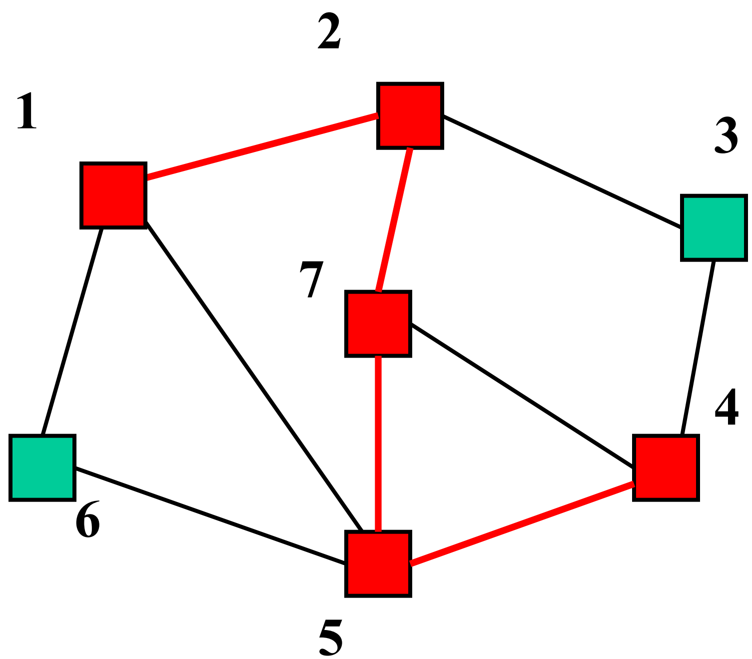
Stack
f(1)
f(2)
f(7)
f(5)
top



Output: (1,2), (2,7), (7,5)

Example

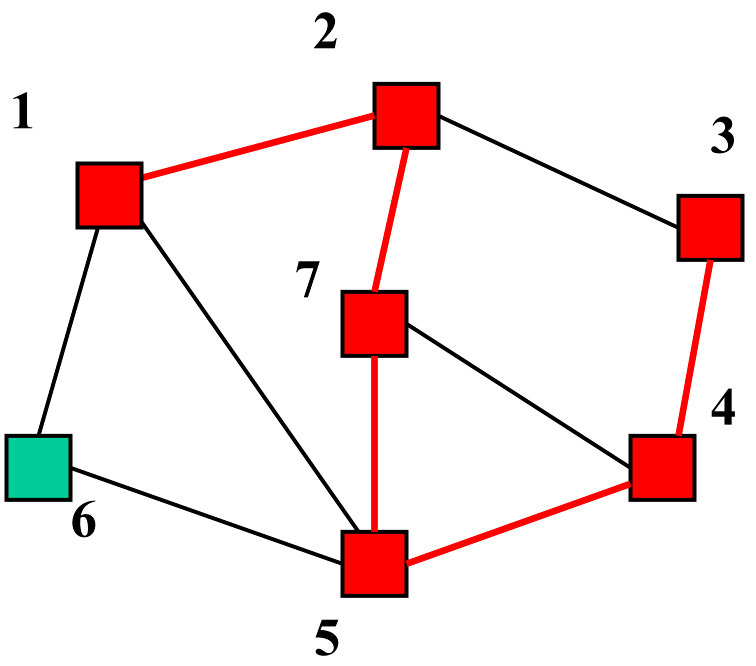
Stack
f(1)
f(2)
f(7)
f(5)
f(4)
top



Output: (1,2), (2,7), (7,5), (5,4)

Example

Stack
f(1)
f(2)
f(7)
f(5)
f(4)
f(3)
top



Output: (1,2), (2,7), (7,5), (5,4),(4,3)

Example

Stack

f(1)

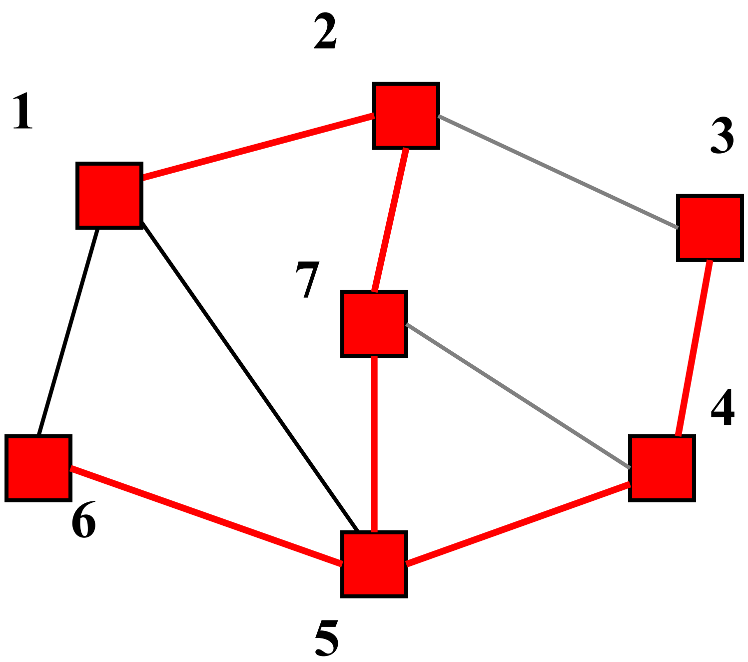
f(2)

f(7)

f(5)

f(4) f(6)

f(3)



Output: (1,2), (2,7), (7,5), (5,4), (4,3), (5,6)

Example

Stack

f(1)

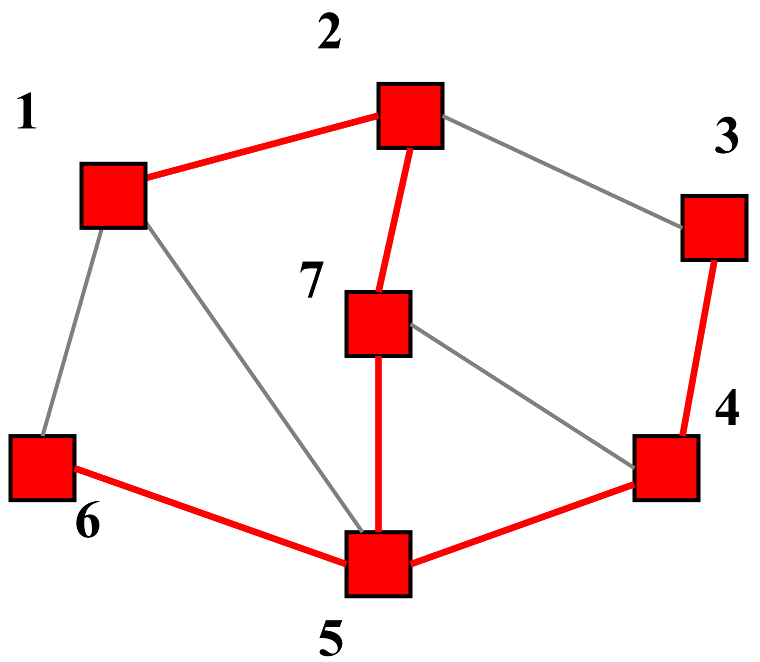
f(2)

f(7)

f(5)

f(4) f(6)

f(3)



Output: (1,2), (2,7), (7,5), (5,4), (4,3), (5,6)

Second Approach

Iterate through edges; output any edge that does not create a cycle

Correctness (hand-wavy):

- Goal is to build an acyclic connected graph
- When we add an edge, it adds a vertex to the tree
  - Else it would have created a cycle
- The graph is connected, so we reach all vertices

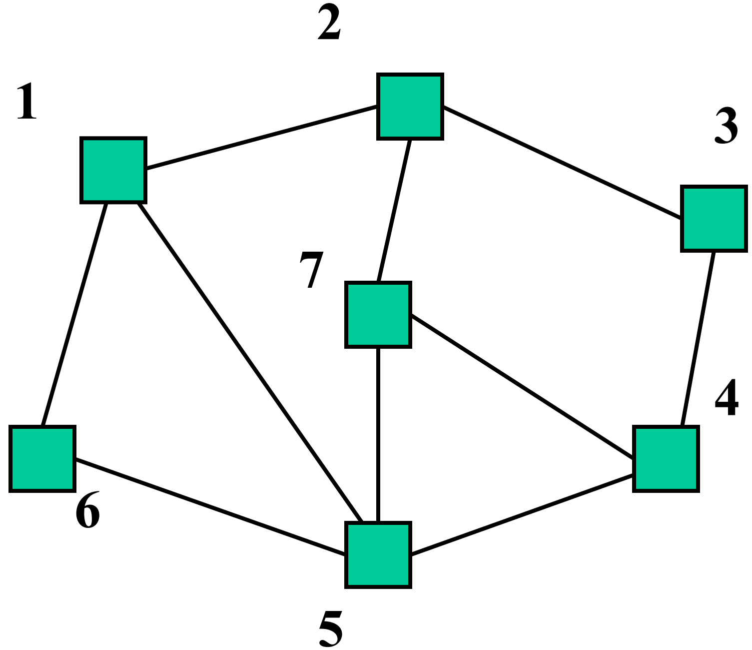
Efficiency:

- Depends on how quickly you can detect cycles
- Reconsider after the example

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7),(1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

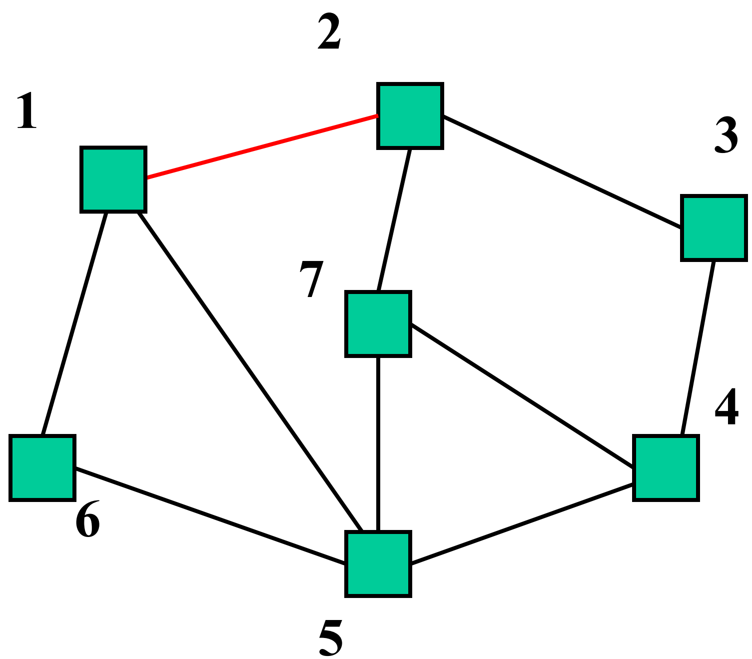


Output:

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7),(1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

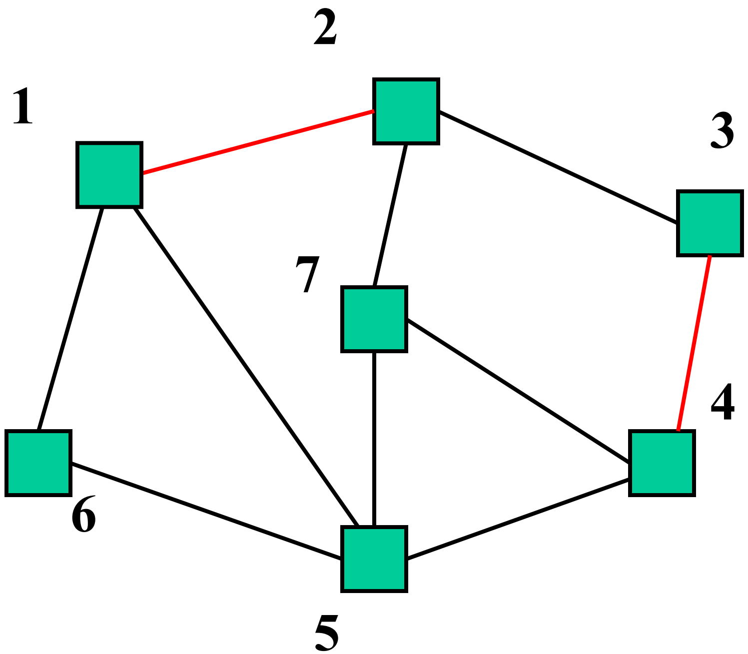


Output: (1,2)

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7),(1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

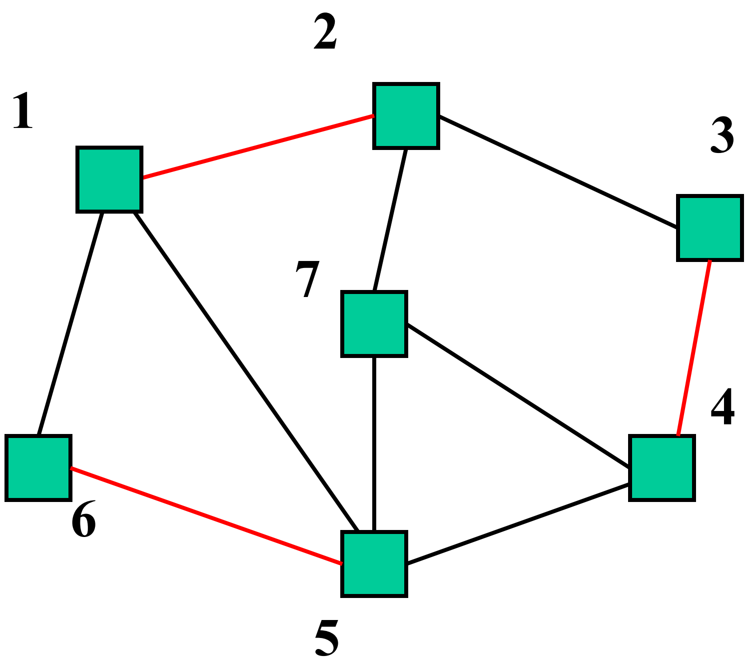


Output: (1,2), (3,4)

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7),(1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

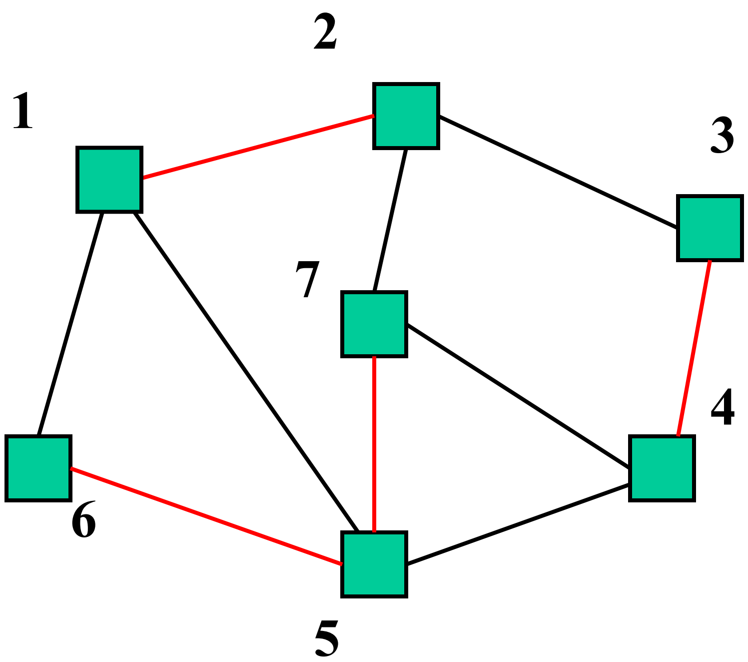


Output: (1,2), (3,4), (5,6),

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7),(1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

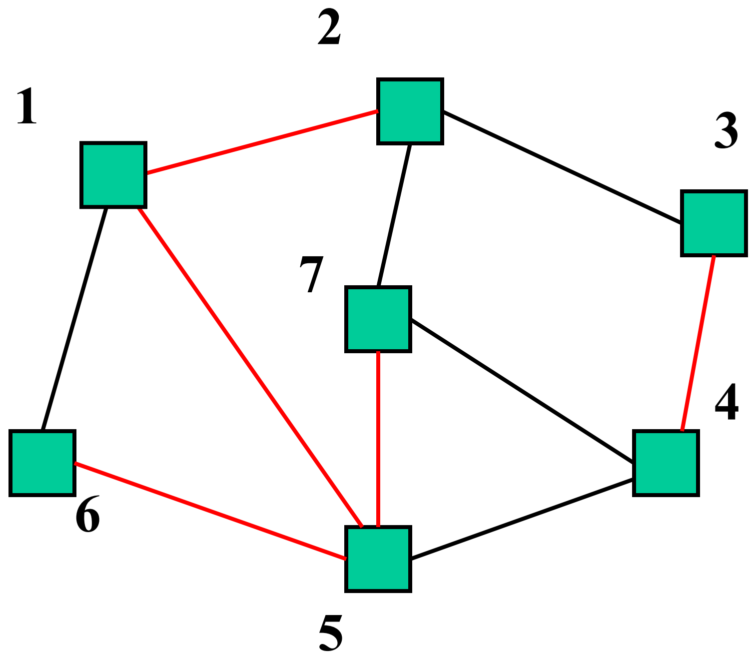


Output: (1,2), (3,4), (5,6), (5,7)

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7), (1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

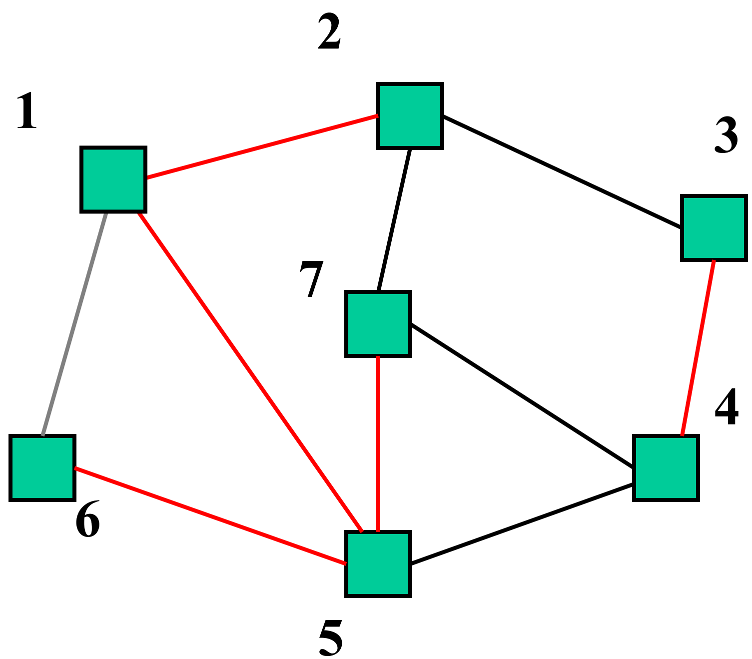


Output: (1,2), (3,4), (5,6), (5,7), (1,5)

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7), (1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

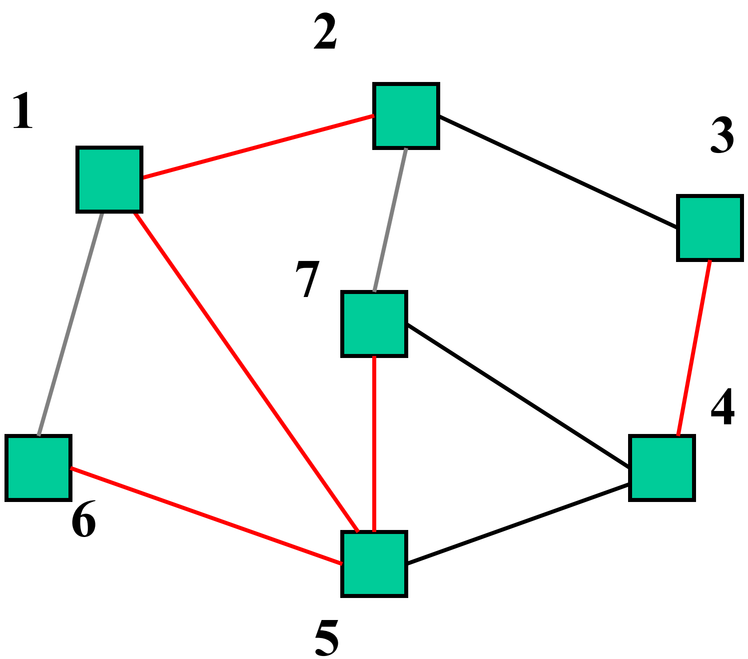


Output: (1,2), (3,4), (5,6), (5,7), (1,5)

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7), (1,5), (1,6), (2,7), (2,3), (4,5), (4,7)

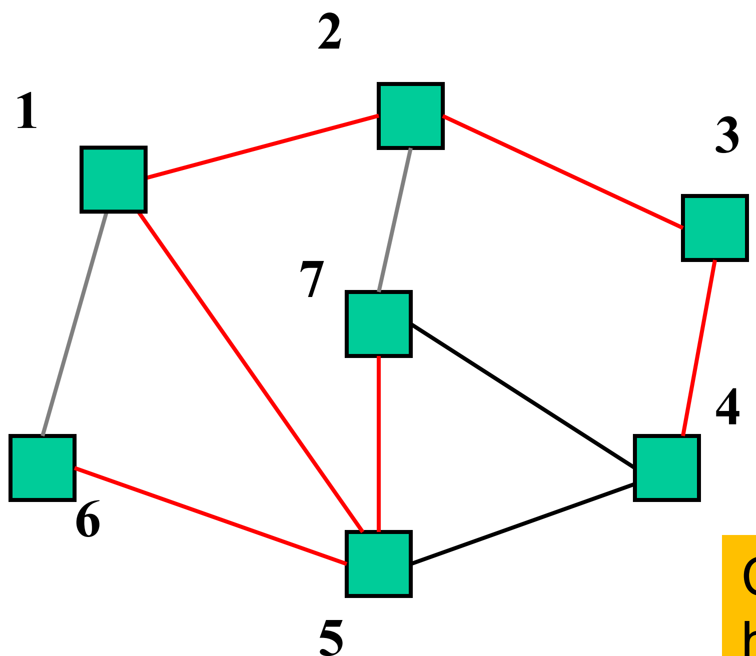


Output: (1,2), (3,4), (5,6), (5,7), (1,5)

Example

Edges in some arbitrary order:

(1,2), (3,4), (5,6), (5,7), (1,5), (1,6), (2,7), (2,3), (4,5), (4,7)



Can stop once we have **|V|-1** edges

Output: (1,2), (3,4), (5,6), (5,7), (1,5), (2,3)

Cycle Detection

- To decide if an edge could form a cycle is *O*(**|V|**) because we may need to traverse all edges already in the output

- So overall algorithm would be *O*(**|V||E|**)

- But there is a faster way we know: a data structure called union-find!
  - All we need to know is that it efficiently keeps track of which elements are connected (can check for cycle in about O(1))
  - All elements start out disconnected
  - union(int a, int b) connects a and b (like an edge in a graph)
  - connectedTo(int a, int b) returns whether a and b are connected (again like a graph, could be a→x→y→b)
  - Read Algorithms 1.5 for the details

Summary So Far

The spanning-tree problem

- Add nodes to partial tree approach is $O(|\mathbf{E}|)$
- Add acyclic edges approach is *almost* $O(|\mathbf{E}|)$
  - Using union-find "as a black box"

But really want to solve the minimum-spanning-tree problem

- Given a weighted undirected graph, give a spanning tree of minimum weight
- Same two approaches will work with minor modifications
- Both will be $O(|\mathbf{E}| \log |\mathbf{V}|)$

Getting to the Point

Algorithm #1

Shortest-path is to Dijkstra's Algorithm

as

Minimum Spanning Tree is to Prim's Algorithm

(Both based on expanding cloud of known vertices, basically using a priority queue instead of a DFS stack)

Algorithm #2

Kruskal's Algorithm for Minimum Spanning Tree

is

Exactly our 2nd approach to spanning tree

but process edges in cost order

Prim's Algorithm Idea

Idea: Grow a tree by adding an edge from the "known" vertices to the "unknown" vertices. *Pick the edge with the smallest weight that connects "known" to "unknown."*

Recall Dijkstra "picked edge with closest known distance to source"

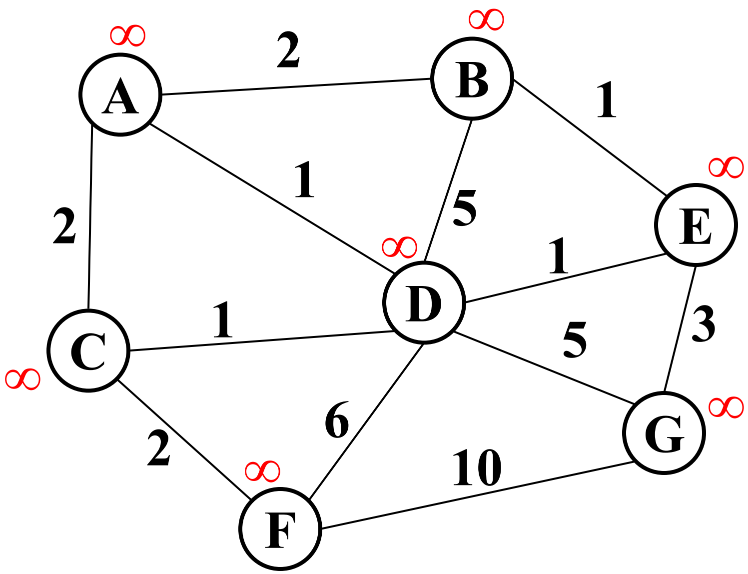
- That is not what we want here
- Otherwise identical (!)

The Algorithm

1. For each node **`v`**, set **`v.cost =`** ∞ and **`v.known = false`**
2. Choose any node **`v`**
   a) Mark **`v`** as known
   b) For each edge **`(v,u)`** with weight **`w`**, set **`u.cost=w`** and **`u.prev=v`**
3. While there are unknown nodes in the graph
   a) Select the unknown node **`v`** with lowest cost
   b) Mark **`v`** as known and add **`(v, v.prev)`** to output
   c) For each edge **`(v,u)`** with weight **`w`**,

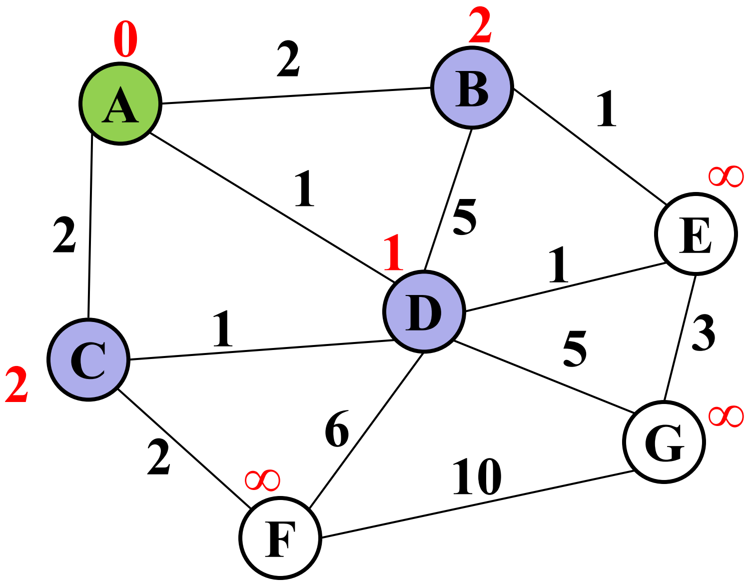
```
if(w < u.cost) {
  u.cost = w;
  u.prev = v;
}
```

Example



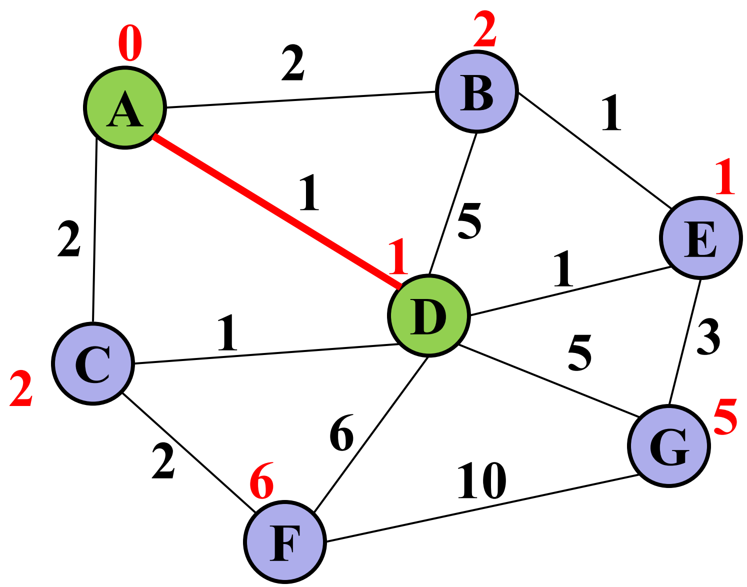
vertex	known?	cost	prev
A		??	
B		??	
C		??	
D		??	
E		??	
F		??	
G		??	

Example



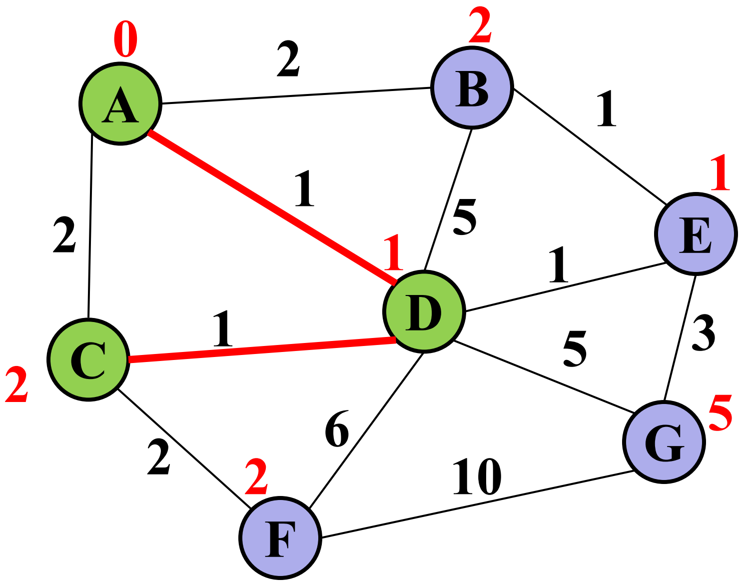
vertex	known?	cost	prev
A	Y	0	
B		2	A
C		2	A
D		1	A
E		??	
F		??	
G		??	

Example



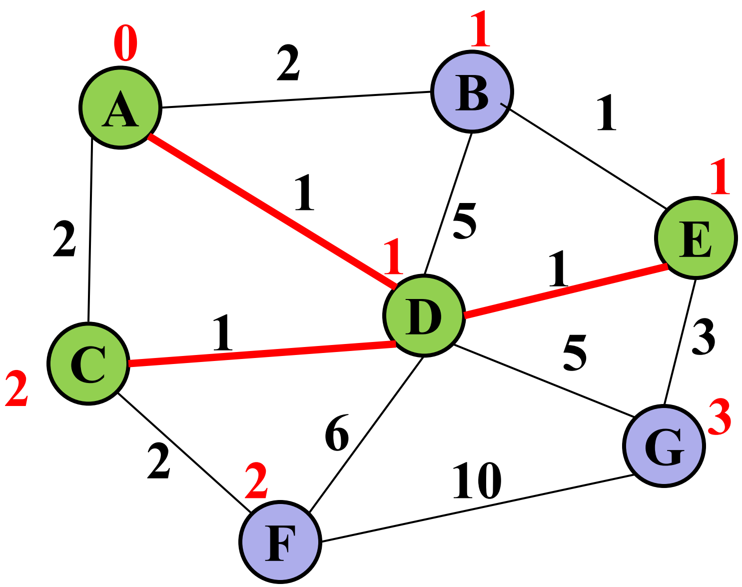
vertex	known?	cost	prev
A	Y	0	
B		2	A
C		1	D
D	Y	1	A
E		1	D
F		6	D
G		5	D

Example



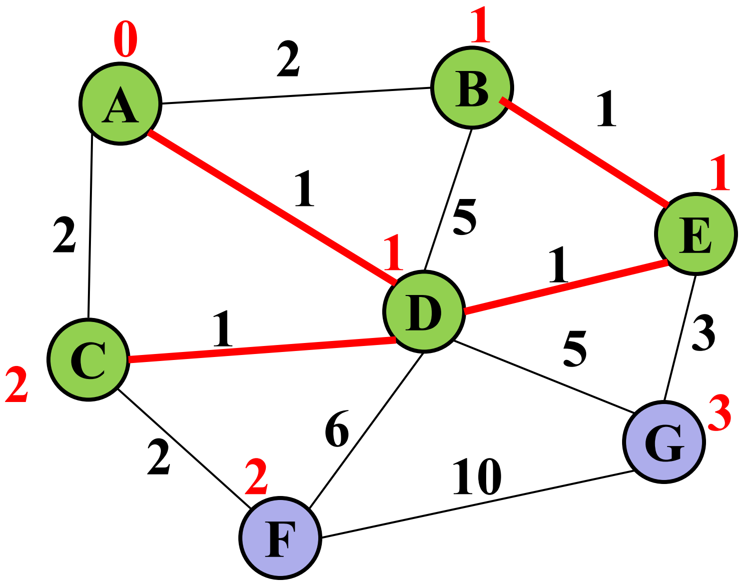
vertex	known?	cost	prev
A	Y	0	
B		2	A
C	Y	1	D
D	Y	1	A
E		1	D
F		2	C
G		5	D

Example



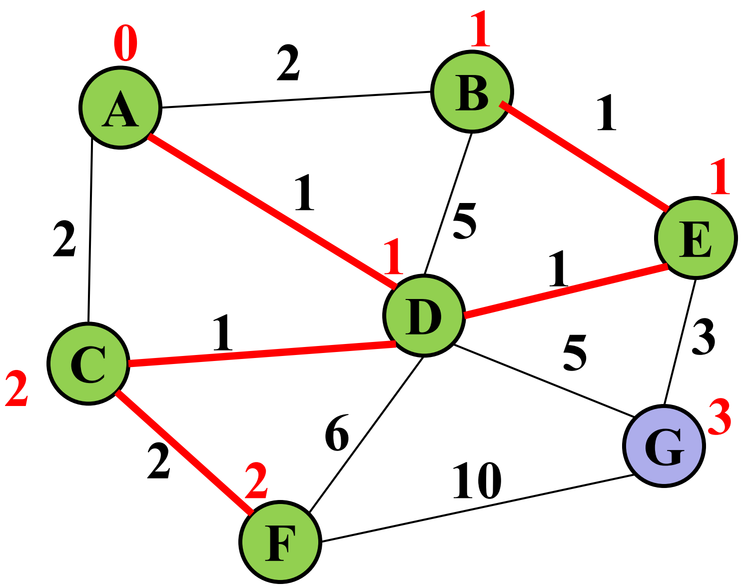
vertex	known?	cost	prev
A	Y	0	
B		1	E
C	Y	1	D
D	Y	1	A
E	Y	1	D
F		2	C
G		3	E

Example



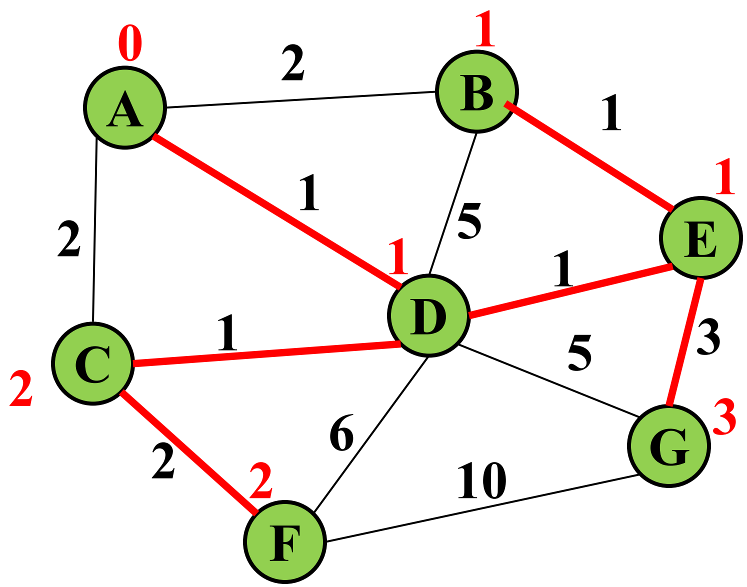
vertex	known?	cost	prev
A	Y	0	
B	Y	1	E
C	Y	1	D
D	Y	1	A
E	Y	1	D
F		2	C
G		3	E

Example



vertex	known?	cost	prev
A	Y	0	
B	Y	1	E
C	Y	1	D
D	Y	1	A
E	Y	1	D
F	Y	2	C
G		3	E

Example



vertex	known?	cost	prev
A	Y	0	
B	Y	1	E
C	Y	1	D
D	Y	1	A
E	Y	1	D
F	Y	2	C
G	Y	3	E

Analysis

- Run-time
  - Same as Dijkstra
  - $O(|E| \log |V|)$ using a priority queue
    - Costs/priorities are just edge-costs, not path-costs

Kruskal's Algorithm

Idea: Grow a forest out of edges that do not grow a cycle, just like for the spanning tree problem.

- But now consider the edges in order by weight

So:

- Sort edges: *O*(**|E|`log` |E|**)
- Iterate through edges using union-find for cycle detection almost *O*(**|E|**)

Somewhat better:

- Floyd's algorithm to build min-heap with edges *O*(**|E|**)
- Iterate through edges using union-find for cycle detection and **`deleteMin`** to get next edge *O*(**|E|`log`|E|**)
- Not better *worst-case* asymptotically, but often stop long before considering all edges

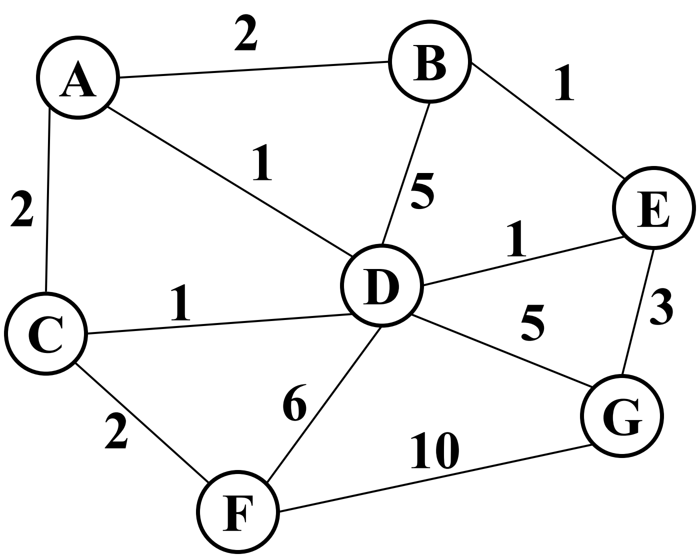
Pseudocode

1. Sort edges by weight (better: put in min-heap)
2. Union-find has each node disconnected
3. While output size **< |V|-1**
   - Consider next smallest edge **`(u,v)`**
   - if **`connectedTo(u,v)`** indicate **`u`** and **`v`** are disconnected
     - output **`(u,v)`**
     - **`union(u,v)`**

Recall invariant:

`u` and **`v`** in connected in union-find if and only if connected in output-so-far

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

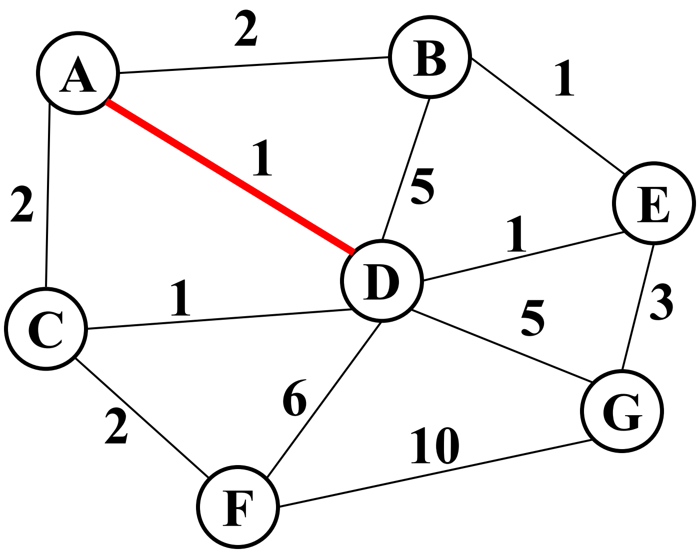
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output:

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

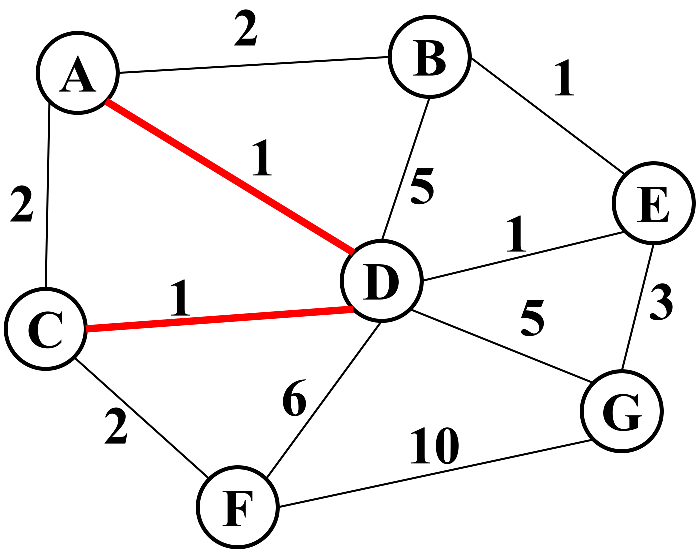
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D)

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

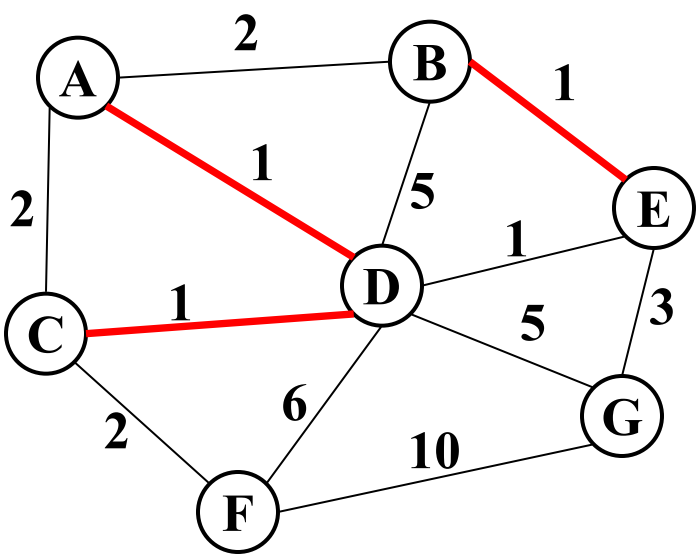
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D), (C,D)

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

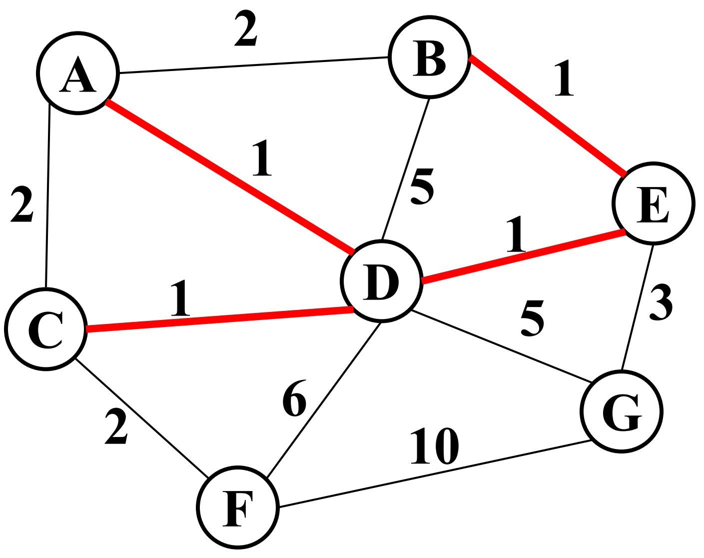
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D), (C,D), (B,E)

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

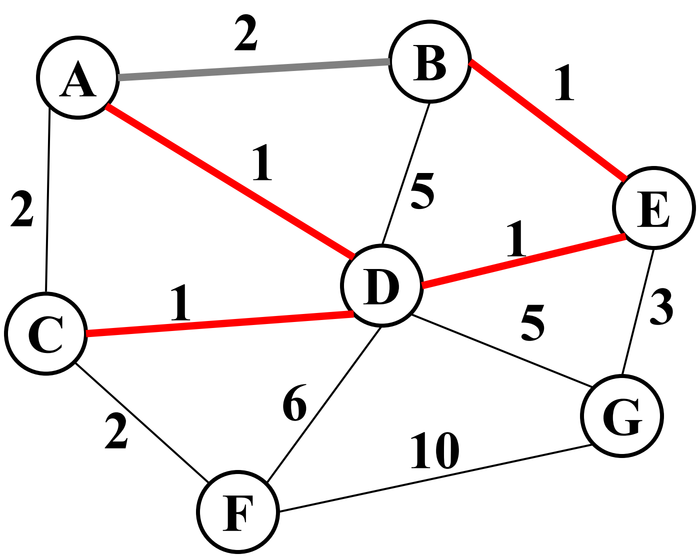
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D), (C,D), (B,E), (D,E)

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

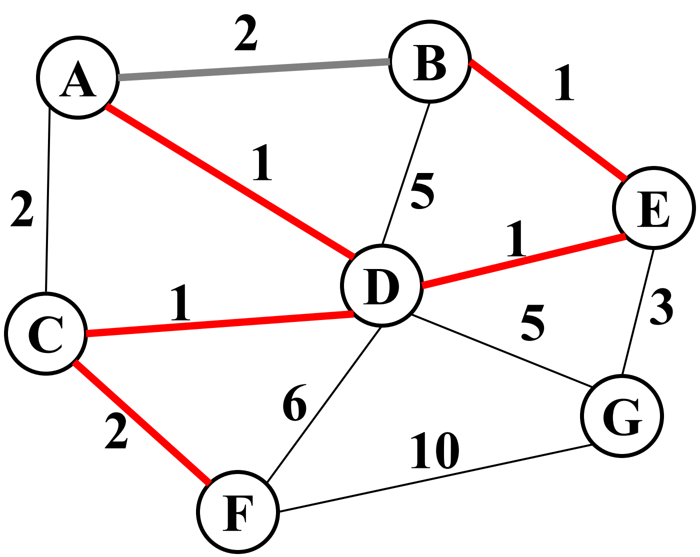
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D), (C,D), (B,E), (D,E)

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

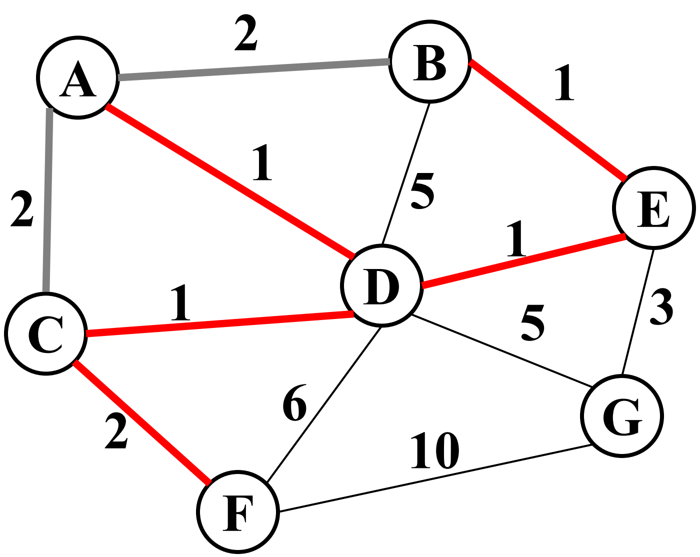
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D), (C,D), (B,E), (D,E), (C,F)

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

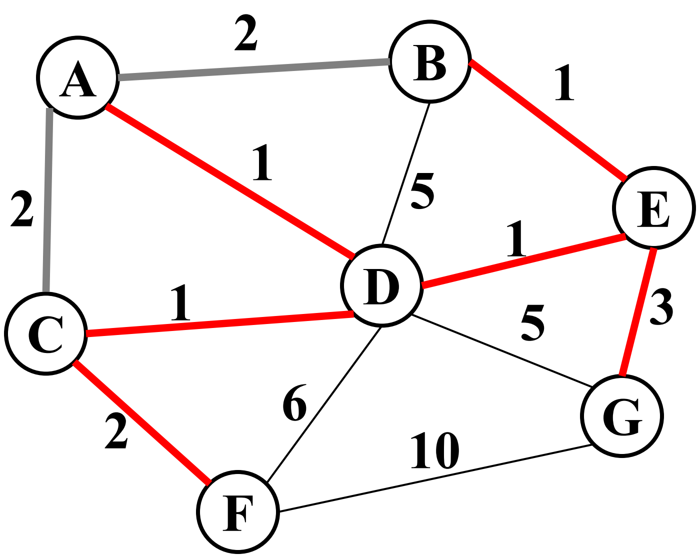
5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D), (C,D), (B,E), (D,E), (C,F)

Example



Edges in sorted order:

1: (A,D), (C,D), (B,E), (D,E)

2: (A,B), (C,F), (A,C)

3: (E,G)

5: (D,G), (B,D)

6: (D,F)

10: (F,G)

Output: (A,D), (C,D), (B,E), (D,E), (C,F), (E,G)