Algorithms for Minimum Spanning Trees

Lecture 19

April 4, 2023

Part I

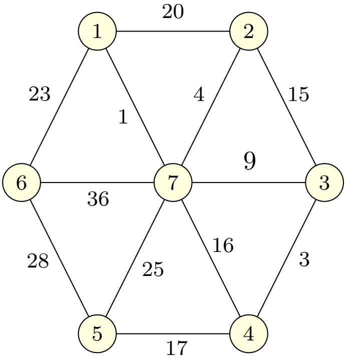
Algorithms for Minimum Spanning Tree

Minimum Spanning Tree

Input Connected graph $G = (V, E)$ with edge costs

Goal Find $T \subseteq E$ such that (V, T) is connected and total cost of all edges in T is smallest

1. T is the minimum spanning tree (MST) of G



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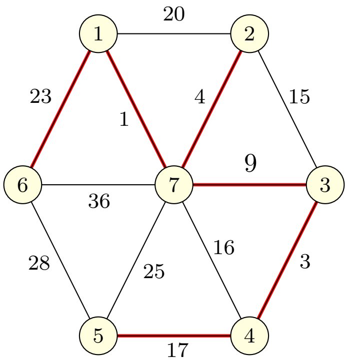


Applications

1. Network Design
   1. Designing networks with minimum cost but maximum connectivity
2. Approximation algorithms
   1. Can be used to bound the optimality of algorithms to approximate Traveling Salesman Problem, Steiner Trees, etc.
3. Cluster Analysis

Some basic properties of (Spanning) Trees

- A *tree* $T = (V, E)$ is a connected acyclic undirected graph
- A tree on n nodes has exactly $n - 1$ edges
- Every tree on $n > 1$ nodes has at least two leaves
- A tree T in a graph G is *spanning* if T includes every node of G
- G is connected implies that there is a path from u to v for all nodes u, v
- A graph G is connected iff it has a spanning tree (constructive proof via Basic Search)

A useful lemma

Lemma

Let $T = (V, E_T)$ *be a spanning tree of* $G = (V, E)$*. For every non-tree edge* $e \in E \setminus E_T$ *there is a unique cycle* C *in* $T + e$*. For every edge* $f \in C - \{e\}$*,* $T - f + e$ *is another spanning tree of* G*.*

Greedy Template

```
Initially E is the set of all edges in G
T is empty (* T will store edges of a MST *)
while E is not empty do
    choose e ∈ E
    if (e satisfies condition)
        add e to T
return the set T
```

Main Task: In what order should edges be processed? When should we add edge to spanning tree?

KA PA RD

Kruskal's Algorithm

Process edges in the order of their costs (starting from the least) and add edges to T as long as they don't form a cycle.

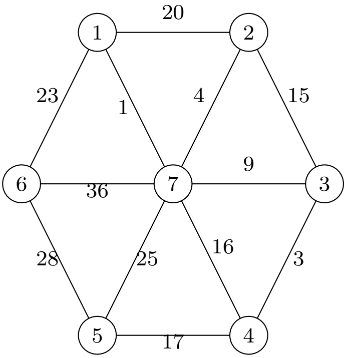
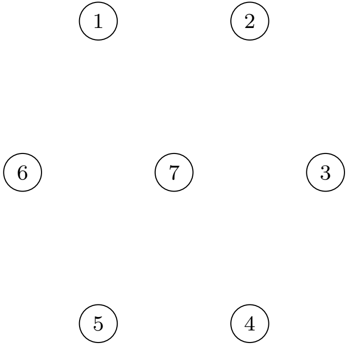


Figure: Graph G



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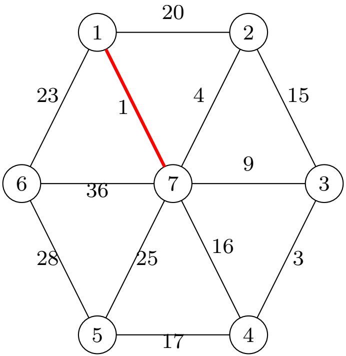

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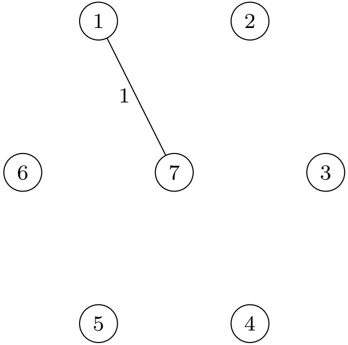

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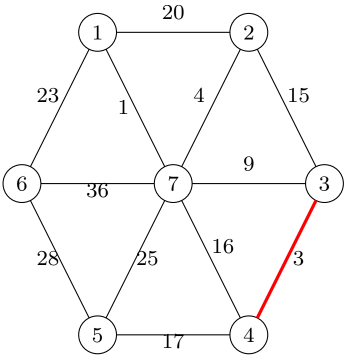

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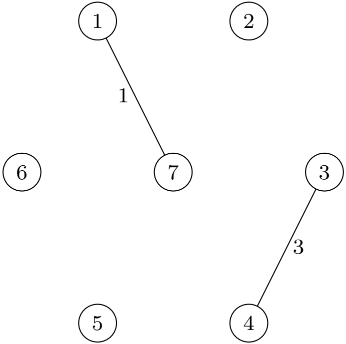

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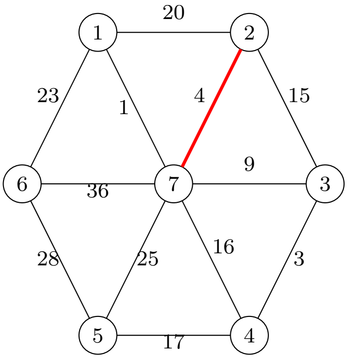

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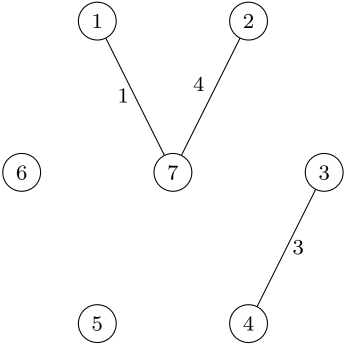

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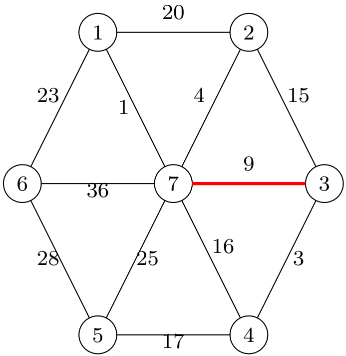

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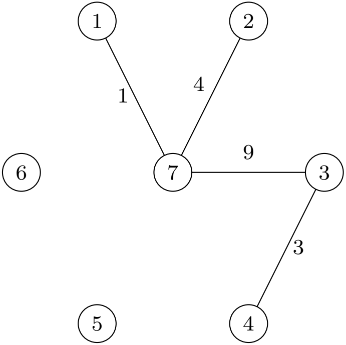

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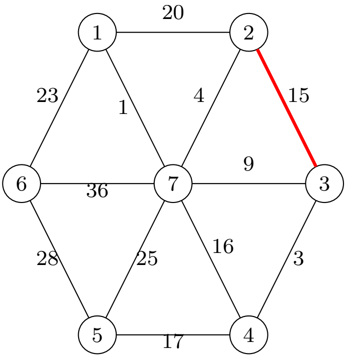

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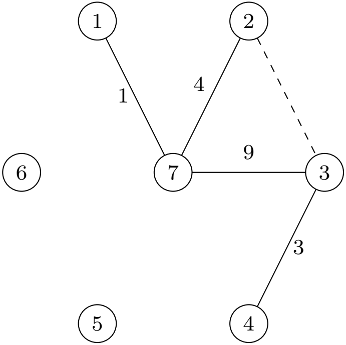

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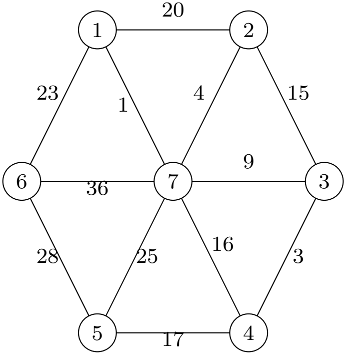

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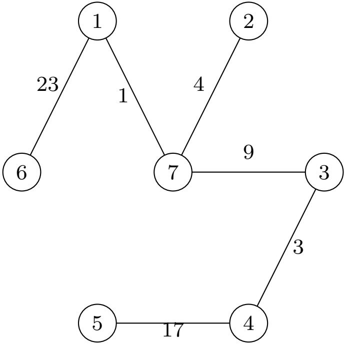

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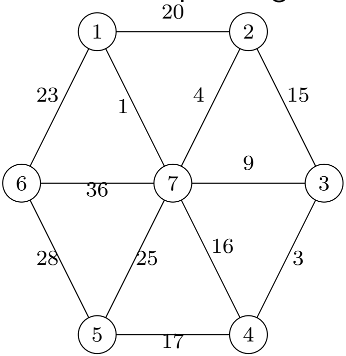
Prim's Algorithm

T maintained by algorithm will be a tree. Start with a node in T. In each iteration, pick edge with least attachment cost to T.



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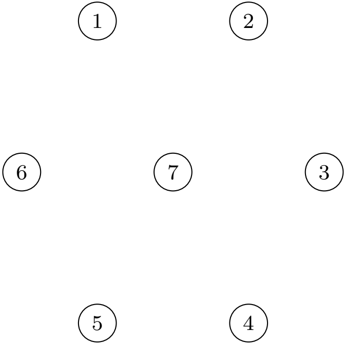

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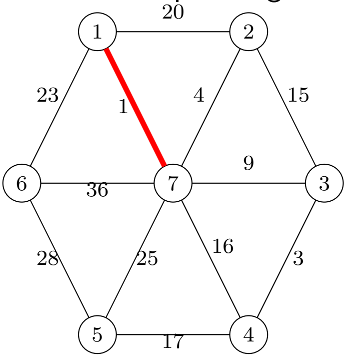

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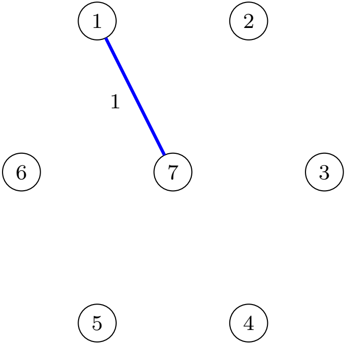

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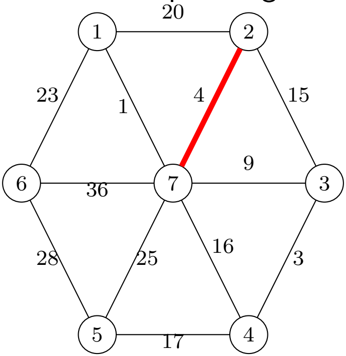

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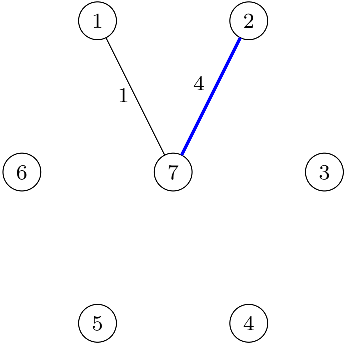

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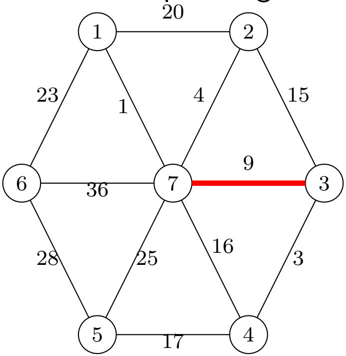

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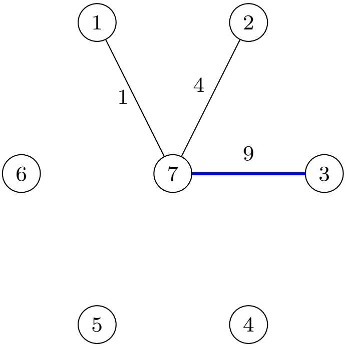

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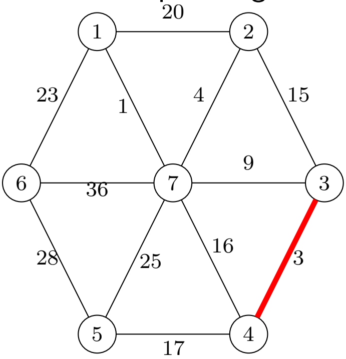

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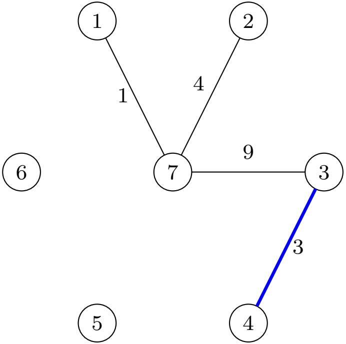

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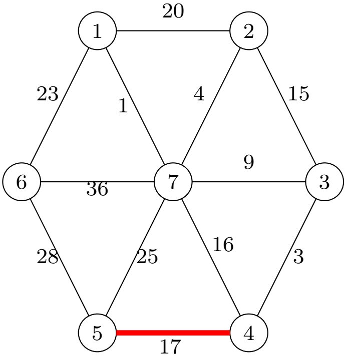

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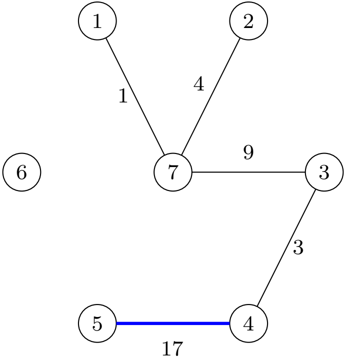

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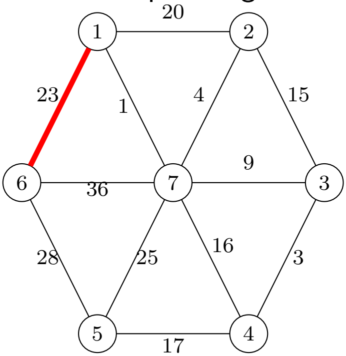

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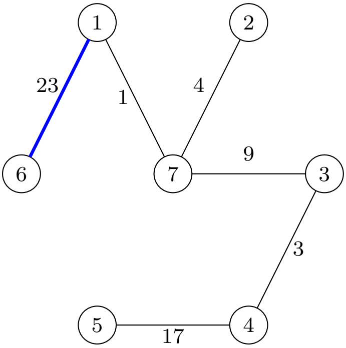


Figure: MST of ***G***

Back

Reverse Delete Algorithm

```
Initially E is the set of all edges in G
T is E (* T will store edges of a MST *)
while E is not empty do
    choose e ∈ E of largest cost
    if removing e does not disconnect T then
        remove e from T
return the set T
```

Returns a minimum spanning tree.

Back

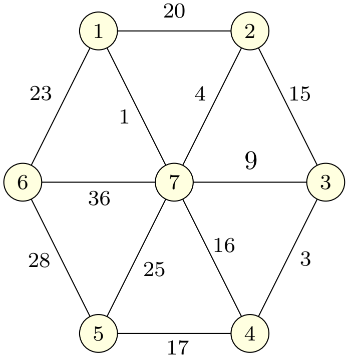
Borůvka's Algorithm

Simplest to implement. See notes.

Assume G is a connected graph.

```
T is ∅ (* T will store edges of a MST *)
while T is not spanning do
    X ← ∅
    for each connected component S of T do
        add to X the cheapest edge between S and V \ S
    Add edges in X to T
return the set T
```

Borůvka's Algorithm



Correctness of MST Algorithms

1. Many different MST algorithms
2. All of them rely on some basic properties of MSTs, in particular the **Cut Property** to be seen shortly.

Assumption

And for now ...

Assumption

Edge costs are distinct, that is no two edge costs are equal.

Cuts

Definition

Given a graph $G = (V, E)$, a **cut** is a partition of the vertices of the graph into two sets $(S, V \setminus S)$.

Cuts

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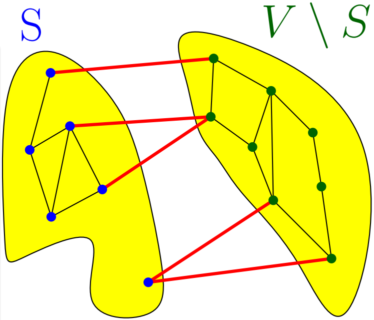
Given a graph $G = (V, E)$, a **cut** is a partition of the vertices of the graph into two sets $(S, V \setminus S)$.

Edges having an endpoint on both sides are the **edges of the cut**.

A cut edge is **crossing** the cut.



Safe and Unsafe Edges

Definition

An edge $e = (u, v)$ is a safe edge if there is some partition of V into S and $V \setminus S$ and e is the unique minimum cost edge crossing S (one end in S and the other in $V \setminus S$).

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An edge $e = (u, v)$ is an unsafe edge if there is some cycle C such that e is the unique maximum cost edge in C.

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Definition

An edge $e = (u, v)$ is an unsafe edge if there is some cycle C such that e is the unique maximum cost edge in C.

Proposition

If edge costs are distinct then every edge is either safe or unsafe.

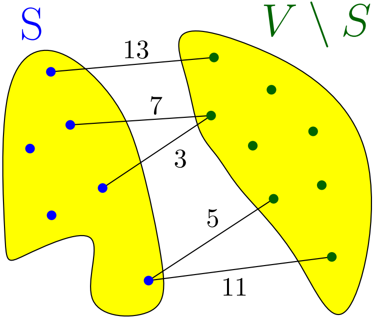
Proof.

Exercise. □

Safe edge

Example...

Every cut identifies one safe edge...



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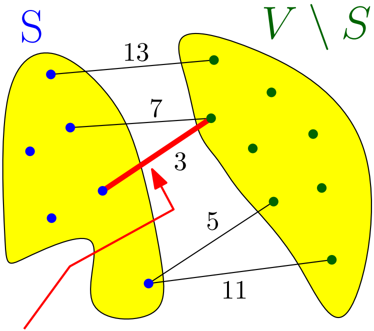


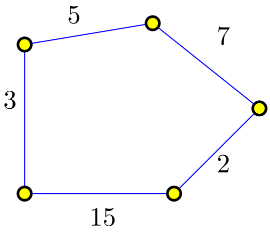
...the cheapest edge in the cut.

Note: An edge e may be a safe edge for *many* cuts!

Unsafe edge

Example...

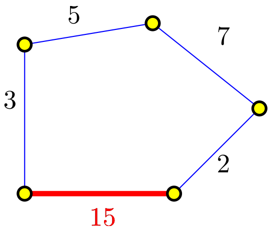
Every cycle identifies one **unsafe** edge...



Unsafe edge

Example...

Every cycle identifies one **unsafe** edge...



...the most expensive edge in the cycle.

Example

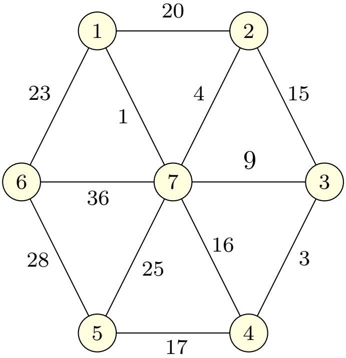
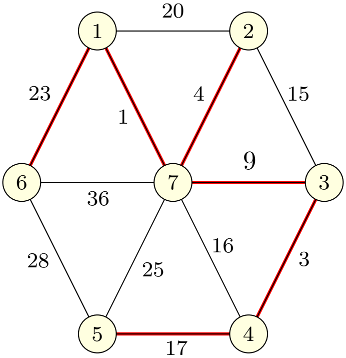


Figure: Graph with unique edge costs. Safe edges are red, rest are unsafe.

Example



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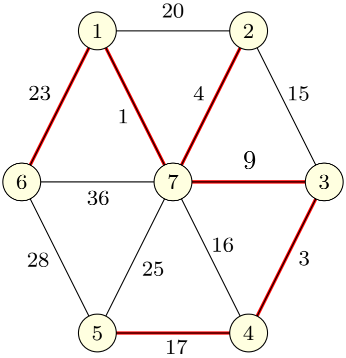

Figure: Graph with unique edge costs. Safe edges are red, rest are unsafe.

And all safe edges are in the MST in this case...

Key Observation: Cut Property

Lemma

If e is a safe edge then **every** *minimum spanning tree contains e.*

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If e is a safe edge then **every** *minimum spanning tree contains e.*

Proof.

1. Suppose (for contradiction) e is not in MST T.
2. Since e is safe there is an $S \subset V$ such that e is the unique min cost edge crossing S.
3. Since T is connected, there must be some edge f with one end in S and the other in $V \setminus S$
4. Since $c_f > c_e$, $T' = (T \setminus \{f\}) \cup \{e\}$ is a spanning tree of lower cost!

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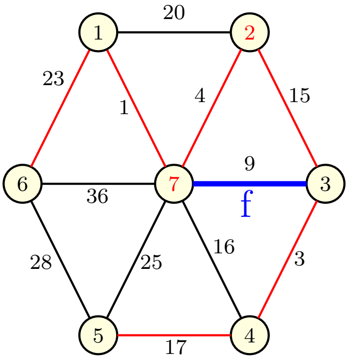
4. Since $c_f > c_e$, $T' = (T \setminus \{f\}) \cup \{e\}$ is a spanning tree of lower cost! Error: T' may not be a spanning tree!!

□

Error in Proof: Example

Problematic example. $S = \{1, 2, 7\}$, $e = (7, 3)$, $f = (1, 6)$. $T - f + e$ **is not a spanning tree.**



(A)

1. (A) Consider adding the edge ***f***.

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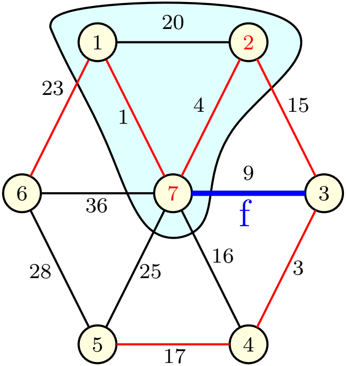

(B)

1. (A) Consider adding the edge ***f***.
2. (B) It is safe because it is the cheapest edge in the cut.

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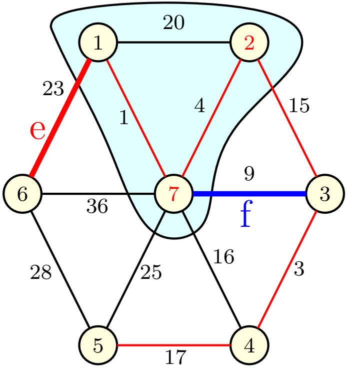

(C)

1. (A) Consider adding the edge f.
2. (B) It is safe because it is the cheapest edge in the cut.
3. (C) Lets throw out the edge e currently in the spanning tree which is more expensive than f and is in the same cut. Put it f instead...

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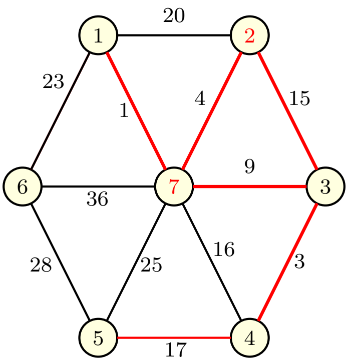

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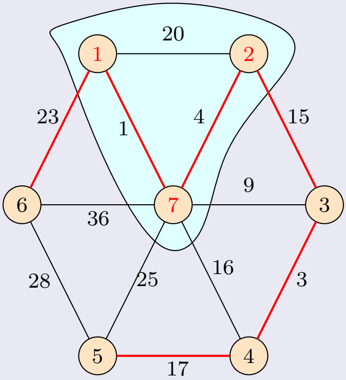
1. (A) Consider adding the edge f.
2. (B) It is safe because it is the cheapest edge in the cut.
3. (C) Lets throw out the edge e currently in the spanning tree which is more expensive than f and is in the same cut. Put it f instead...
4. (D) New graph of selected edges is not a tree anymore. BUG.

Proof of Cut Property

Proof.



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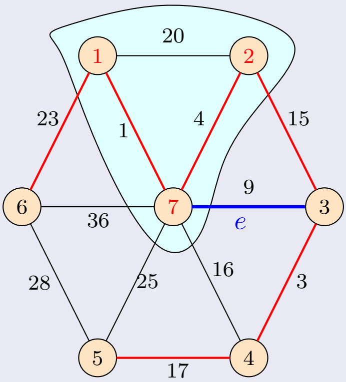

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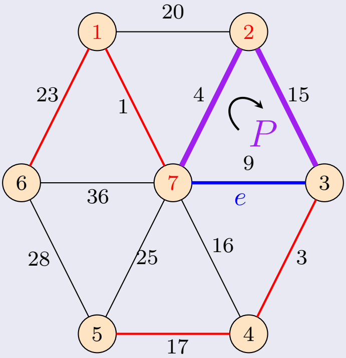

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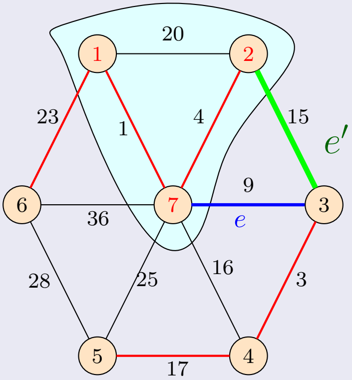

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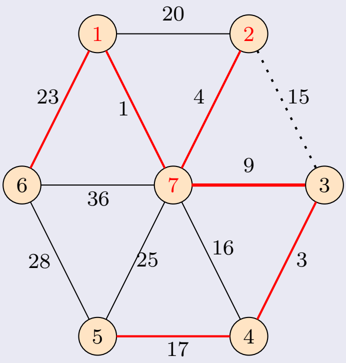
2. T is spanning tree: there is a unique path P from v to w in T
3. Let w' be the first vertex in P belonging to $V \setminus S$; let v' be the vertex just before it on P, and let $e' = (v', w')$

Proof of Cut Property

Proof.



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4. $T' = (T \setminus \{e'\}) \cup \{e\}$ is spanning tree of lower cost. (Why?) □

Proof of Cut Property (contd)

Observation

$T' = (T \setminus \{e'\}) \cup \{e\}$ *is a spanning tree.*

Proof.

T' is connected.

T' is a tree

$\square$

Proof of Cut Property (contd)

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T' is connected.

Removed $e' = (v', w')$ from T but v' and w' are connected by the path $P - f + e$ in T'. Hence T' is connected if T is.

T' is a tree

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Proof of Cut Property (contd)

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T' is a tree

T' is connected and has $n - 1$ edges (since T had $n - 1$ edges) and hence T' is a tree

□

Safe Edges form a Tree

Lemma

Let G be a connected graph with distinct edge costs, then the set of safe edges form a connected graph.

Proof.

1. Suppose not. Let S be a connected component in the graph induced by the safe edges.
2. Consider the edges crossing S, there must be a safe edge among them since edge costs are distinct and so we must have picked it.

□

Safe Edges form an MST

Corollary

Let G be a connected graph with distinct edge costs, then set of safe edges form the unique MST *of G.*

Safe Edges form an MST

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Let G be a connected graph with distinct edge costs, then set of safe edges form the unique MST *of G.*

Consequence: Every correct MST algorithm when G has unique edge costs includes exactly the safe edges.

Cycle Property

Lemma

If e is an unsafe edge then no MST *of G contains e.*

Proof.

Exercise. □

Note: Cut and Cycle properties hold even when edge costs are not distinct. Safe and unsafe definitions do not rely on distinct cost assumption.

Correctness of Prim's Algorithm

Prim's Algorithm

Pick edge with minimum attachment cost to current tree, and add to current tree.

Proof of correctness.

1. If e is added to tree, then e is safe and belongs to every MST.
2. Set of edges output is a spanning tree

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    1. Set of edges output forms a connected graph: by induction, S is connected in each iteration and eventually $S = V$.

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2. Set of edges output is a spanning tree
    1. Set of edges output forms a connected graph: by induction, S is connected in each iteration and eventually $S = V$.
    2. Only safe edges added and they do not have a cycle □

Correctness of Kruskal's Algorithm

Kruskal's Algorithm

Pick edge of lowest cost and add if it does not form a cycle with existing edges.

Proof of correctness.

1. If $e = (u, v)$ is added to tree, then e is safe

2. Set of edges output is a spanning tree : exercise

□

Correctness of Kruskal's Algorithm

Kruskal's Algorithm

Pick edge of lowest cost and add if it does not form a cycle with existing edges.

Proof of correctness.

1. If $e = (u, v)$ is added to tree, then e is safe
   1. When algorithm adds e let S and S' be the connected components containing u and v respectively
2. Set of edges output is a spanning tree : exercise

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Proof of correctness.

1. If $e = (u, v)$ is added to tree, then e is safe
   1. When algorithm adds e let S and S' be the connected components containing u and v respectively
   2. e is the lowest cost edge crossing S (and also S').
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   1. When algorithm adds e let S and S' be the connected components containing u and v respectively
   2. e is the lowest cost edge crossing S (and also S').
   3. If there is an edge e' crossing S and has lower cost than e, then e' would come before e in the sorted order and would be added by the algorithm to T
2. Set of edges output is a spanning tree : exercise

□

Correctness of Borůvka's Algorithm

Proof of correctness.

Argue that only safe edges are added. □

Correctness of Reverse Delete Algorithm

Reverse Delete Algorithm

Consider edges in decreasing cost and remove an edge if it does not disconnect the graph

Proof of correctness.

Argue that only unsafe edges are removed. □

When edge costs are not distinct

Heuristic argument: Make edge costs distinct by adding a small tiny and different cost to each edge

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Formal argument: Order edges lexicographically to break ties

1. $e_i \prec e_j$ if either $c(e_i) < c(e_j)$ or $(c(e_i) = c(e_j)$ and $i < j)$
2. Lexicographic ordering extends to sets of edges. If $A, B \subseteq E$, $A \neq B$ then $A \prec B$ if either $c(A) < c(B)$ or $(c(A) = c(B)$ and $A \setminus B$ has a lower indexed edge than $B \setminus A$)
3. Can order all spanning trees according to lexicographic order of their edge sets. Hence there is a unique MST.

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Prim's, Kruskal, and Reverse Delete Algorithms are optimal with respect to lexicographic ordering.

Edge Costs: Positive and Negative

1. Algorithms and proofs don't assume that edge costs are non-negative! MST algorithms work for arbitrary edge costs.
2. Another way to see this: make edge costs non-negative by adding to each edge a large enough positive number. Why does this work for MSTs but not for shortest paths?
3. Can compute *maximum* weight spanning tree by negating edge costs and then computing an MST.

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3. Can compute *maximum* weight spanning tree by negating edge costs and then computing an MST.
   Question: Why does this not work for shortest paths?

Part II

Data Structures for MST: Priority Queues and Union-Find

Implementing Borůvka's Algorithm

No complex data structure needed.

```
T is ∅ (* T will store edges of a MST *)
while T is not spanning do
    X ← ∅
    for each connected component S of T do
        add to X the cheapest edge between S and V \ S
    Add edges in X to T
return the set T
```

- $O(\log n)$ iterations of while loop. Why?

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- Each iteration can be implemented in $O(m)$ time.

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Running time: $O(m \log n)$ time.

Advantages of the algorithm: no data structures and easy to implement in parallel setting

Prim's Algorithm

T maintained by algorithm will be a tree. Start with a node in T. In each iteration, pick edge with least attachment cost to T.

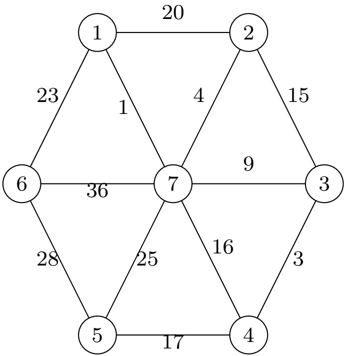

Figure: Graph G

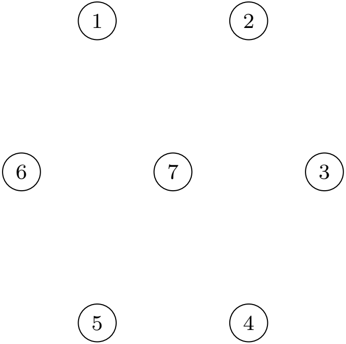

Figure: MST of G

```
Prim_ComputeMST
    E is the set of all edges in G
    S = {1}
    T is empty (* T will store edges of a MST *)
    while S ≠ V do
        pick e = (v, w) ∈ E such that
            v ∈ S and w ∈ V − S
            e has minimum cost
        T = T ∪ e
        S = S ∪ w
    return the set T
```

Analysis

Implementing Prim's Algorithm

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1. Number of iterations $= O(n)$, where n is number of vertices

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Analysis

1. Number of iterations $= O(n)$, where n is number of vertices
2. Picking e is $O(m)$ where m is the number of edges
3. Total time $O(nm)$

Implementing Prim's Algorithm

More Efficient Implementation

Prim_ComputeMST

```
    E is the set of all edges in G
    S = {1}
    T is empty (* T will store edges of a MST *)
    for v ∉ S, a(v) = min_{w∈S} c(w, v)
    for v ∉ S, e(v) = w such that w ∈ S and c(w, v) is minimum
    while S ≠ V do
        pick v with minimum a(v)
        T = T ∪ {(e(v), v)}
        S = S ∪ {v}
        update arrays a and e
    return the set T
```

Implementing Prim's Algorithm

More Efficient Implementation

Prim_ComputeMST

E is the set of all edges in G
$S = \{1\}$
T is empty (* T will store edges of a MST *)
for $v \notin S$, $a(v) = \min_{w \in S} c(w, v)$
for $v \notin S$, $e(v) = w$ such that $w \in S$ and $c(w, v)$ is minimum
while $S \neq V$ **do**
    pick v with minimum $a(v)$
    $T = T \cup \{(e(v), v)\}$
    $S = S \cup \{v\}$
    update arrays a and e
return the set T

Implementing Prim's Algorithm

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Maintain vertices in $V \setminus S$ in a priority queue with key $a(v)$.

Priority Queues

Data structure to store a set S of n elements where each element $v \in S$ has an associated real/integer key $k(v)$ such that the following operations

1. **makeQ**: create an empty queue
2. **findMin**: find the minimum key in S
3. **extractMin**: Remove $v \in S$ with smallest key and return it
4. **add**$(v, k(v))$: Add new element v with key $k(v)$ to S
5. **Delete**(v): Remove element v from S
6. **decreaseKey** $(v, k'(v))$: *decrease* key of v from $k(v)$ (current key) to $k'(v)$ (new key). Assumption: $k'(v) \leq k(v)$
7. **meld**: merge two separate priority queues into one

Prim's using priority queues

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while S ≠ V do
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1. Requires $O(n)$ **extractMin** operations

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```

Maintain vertices in $V \setminus S$ in a priority queue with key $a(v)$

1. Requires $O(n)$ **extractMin** operations
2. Requires $O(m)$ **decreaseKey** operations

Running time of Prim's Algorithm

$O(n)$ **extractMin** operations and $O(m)$ **decreaseKey** operations

1. Using standard Heaps, **extractMin** and **decreaseKey** take $O(\log n)$ time. Total: $O((m + n) \log n)$
2. Using Fibonacci Heaps, $O(\log n)$ for **extractMin** and $O(1)$ (amortized) for **decreaseKey**. Total: $O(n \log n + m)$.

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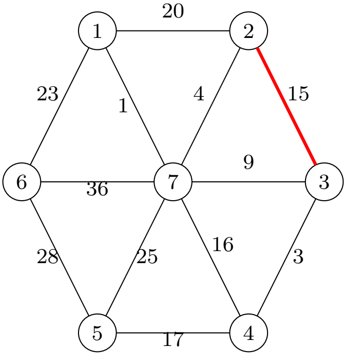
Prim's algorithm and Dijkstra's algorithms are similar. Where is the difference?

Kruskal's Algorithm

Process edges in the order of their costs (starting from the least) and add edges to T as long as they don't form a cycle.



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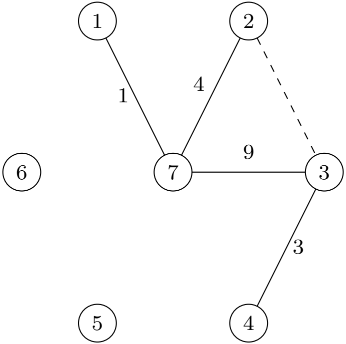

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Kruskal's Algorithm

Kruskal_ComputeMST

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Initially E is the set of all edges in G
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while E is not empty do
    choose e ∈ E of minimum cost
    if (T ∪ {e} does not have cycles)
        add e to T
return the set T
```

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1. Presort edges based on cost. Choosing minimum can be done in $O(1)$ time

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2. Do **BFS**/**DFS** on $T \cup \{e\}$. Takes $O(n)$ time
3. Total time $O(m \log m) + O(mn) = O(mn)$

Implementing Kruskal's Algorithm Efficiently

```
Kruskal_ComputeMST
    Sort edges in E based on cost
    T is empty (* T will store edges of a MST *)
    each vertex u is placed in a set by itself
    while E is not empty do
        pick e = (u, v) ∈ E of minimum cost
        if u and v belong to different sets
            add e to T
            merge the sets containing u and v
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Need a data structure to check if two elements belong to same set and to merge two sets.

Using Union-Find data structure can implement Kruskal's algorithm in $O((m+n)\log m)$ time.

Best Known Asymptotic Running Times for MST

Prim's algorithm using Fibonacci heaps: $O(n \log n + m)$.
If m is $O(n)$ then running time is $\Omega(n \log n)$.

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1. $O(m \log^* m)$ time **[Fredman, Tarjan 1987]**
2. $O(m + n)$ time using bit operations in RAM model **[Fredman, Willard 1994]**
3. $O(m + n)$ expected time (randomized algorithm) **[Karger, Klein, Tarjan 1995]**
4. $O((n + m)\alpha(m, n))$ time **Chazelle 2000]**
5. Still open: Is there an $O(n + m)$ time deterministic algorithm in the comparison model?