

Algorithms and Data Structures

Minimal Spanning Trees

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Die Energiewende

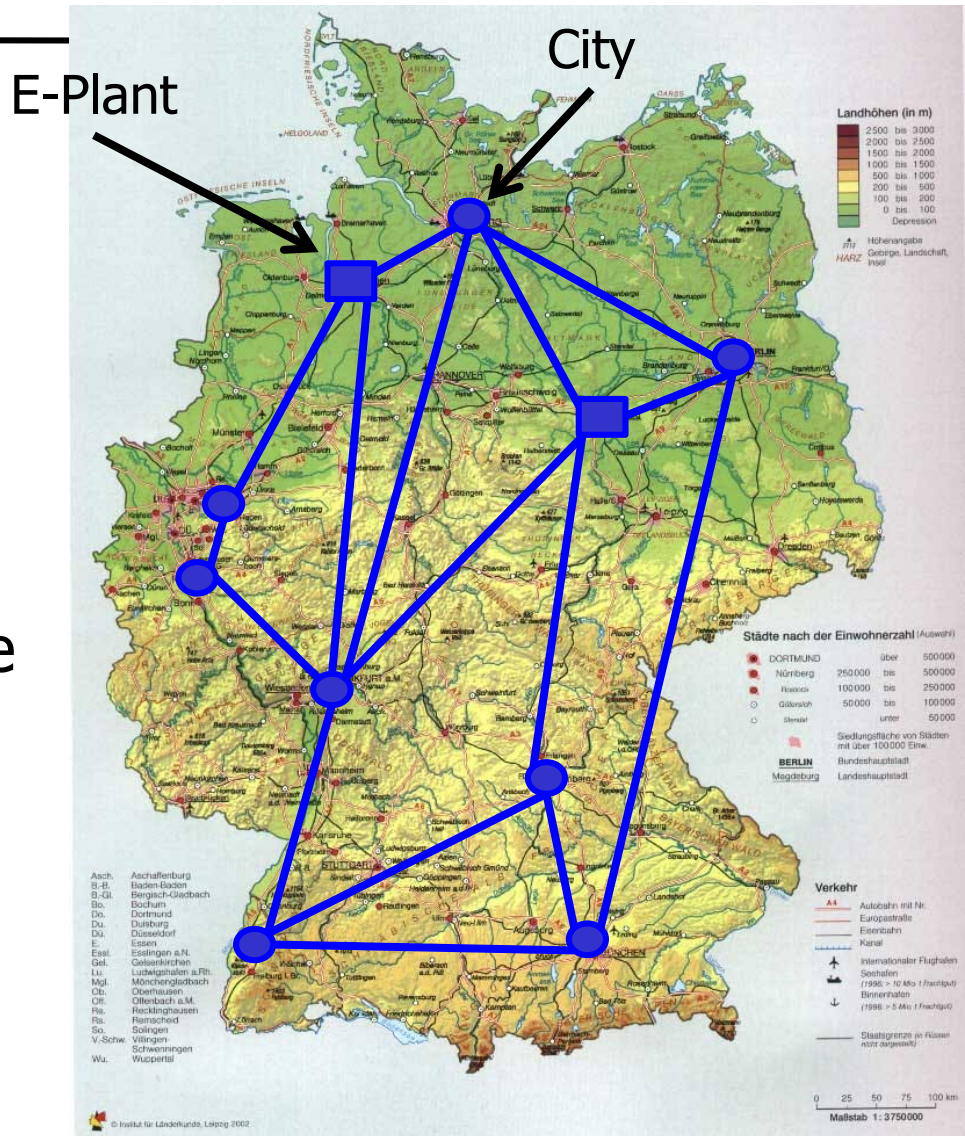
- Electricity is created in **many more places** than before
- Electricity is consumed in many places
- **Places of production** are not evenly distributed across the country
- We need to build **new electricity highways**

Source: <http://www.deutsche-mittelgebirge.de/>



Die Energiewende

- How can we do this **as cheap as possible?**
- Not all connections are possible
 - Mountains, rivers, ...
- Different connections have **different costs**



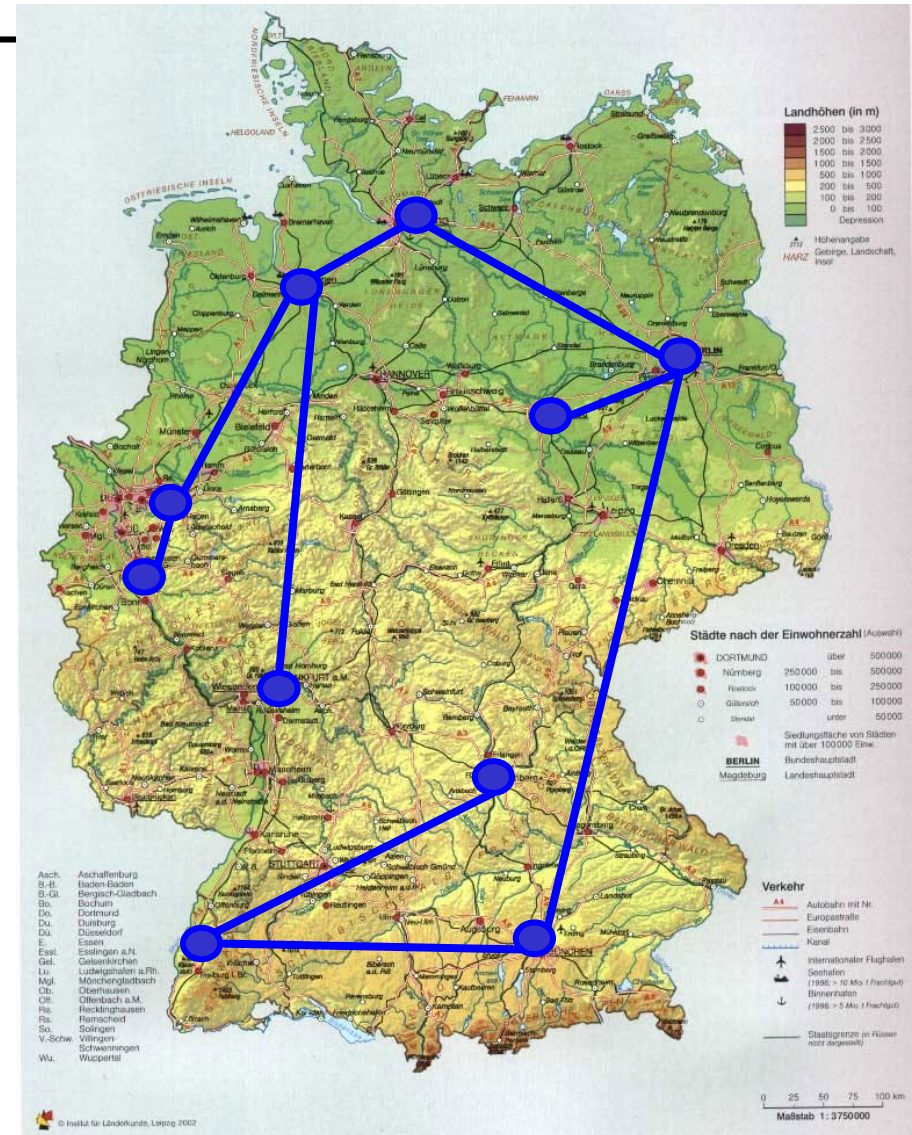
Die Energiewende

- Requirement for a solution:
Every city and every plant must be connected to the network
- We treat them uniformly
- We don't care about the length of a connection
- **One** solution



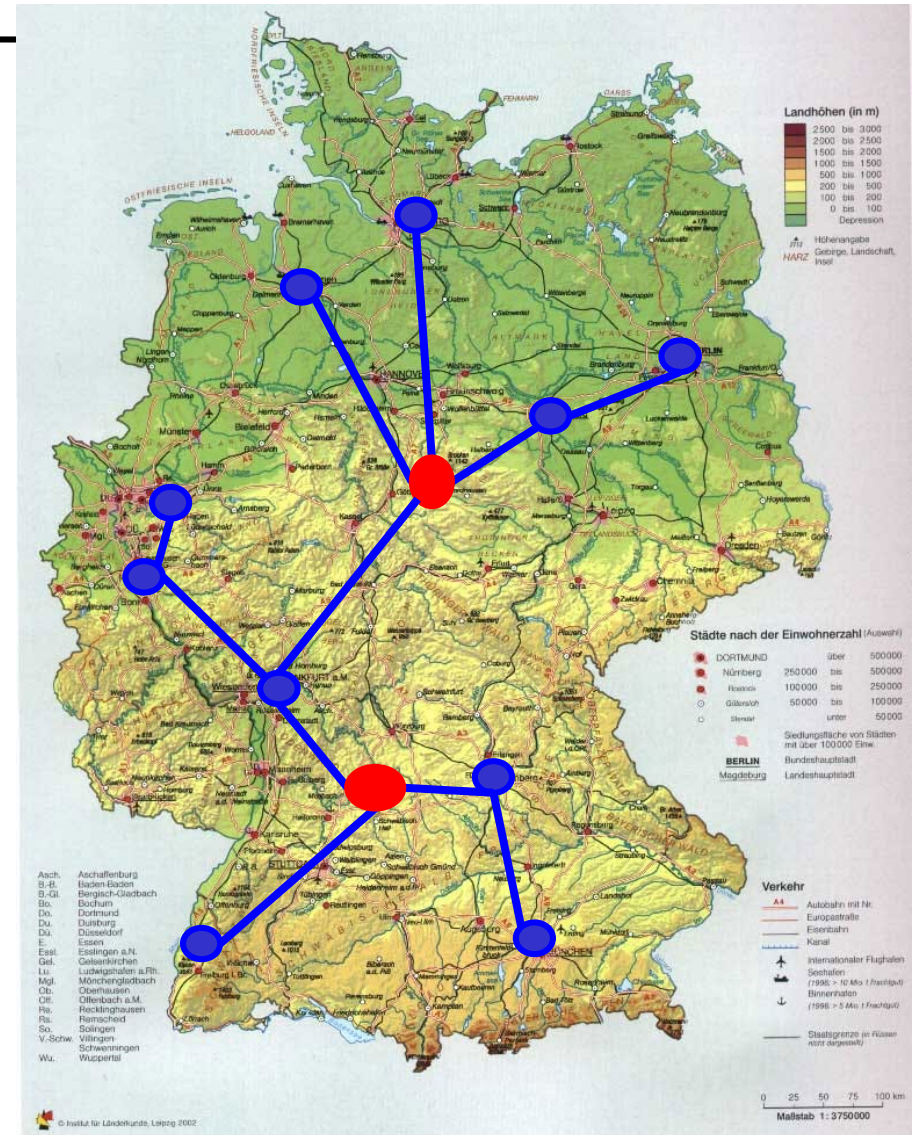
Die Energiewende

- Another solution
- Of course, in real life we may build **crossroads** outside cities



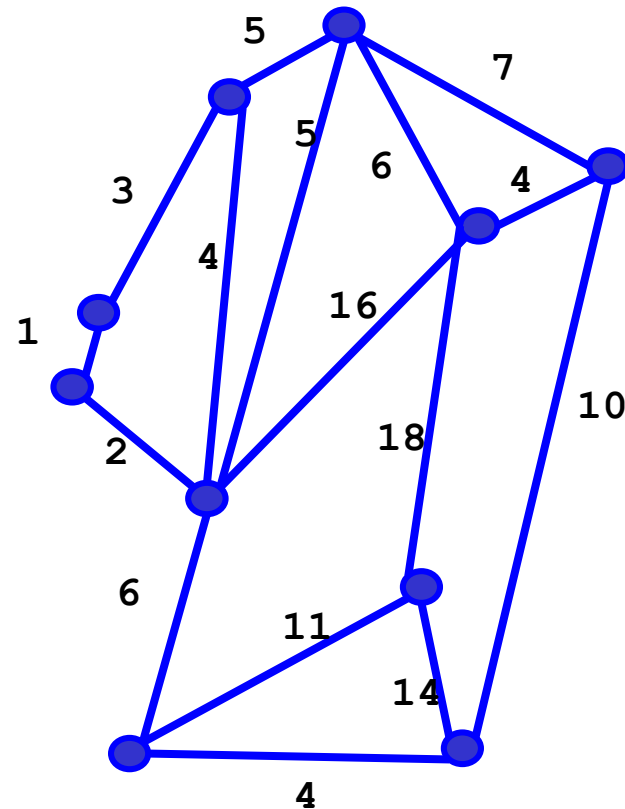
Die Energiewende

- This is the Steinerbaum-Problem
 - Some nodes must be connected, other nodes maybe connected
- Optimal solution is much harder to find
- Not considered here



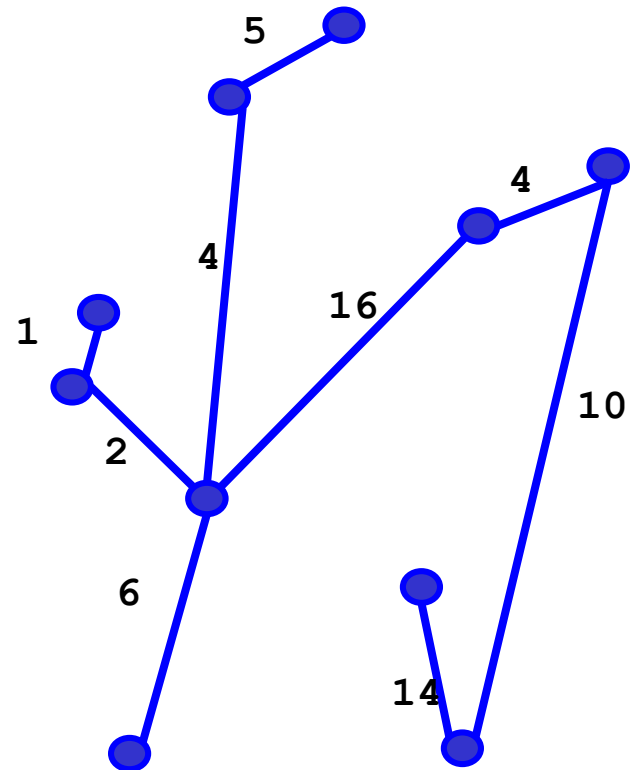
Abstraction

- Given an undirected, positively weighted, connected graph $G=(V,E)$
- Find a **subset** $E' \subseteq E$ such that $\text{cost}(E')$ is **minimal** and $G'=(V, E')$ is **connected**
 - $\text{cost}(E')$: Sum of the edge weights
- Every such E' (or G') is called a **minimum spanning tree** (MST) for G



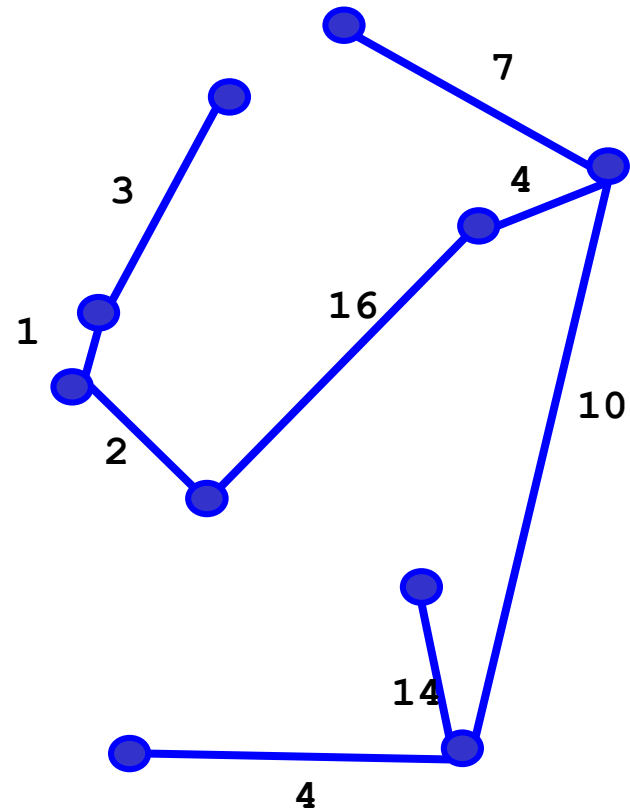
Example 1

- Cost = 62



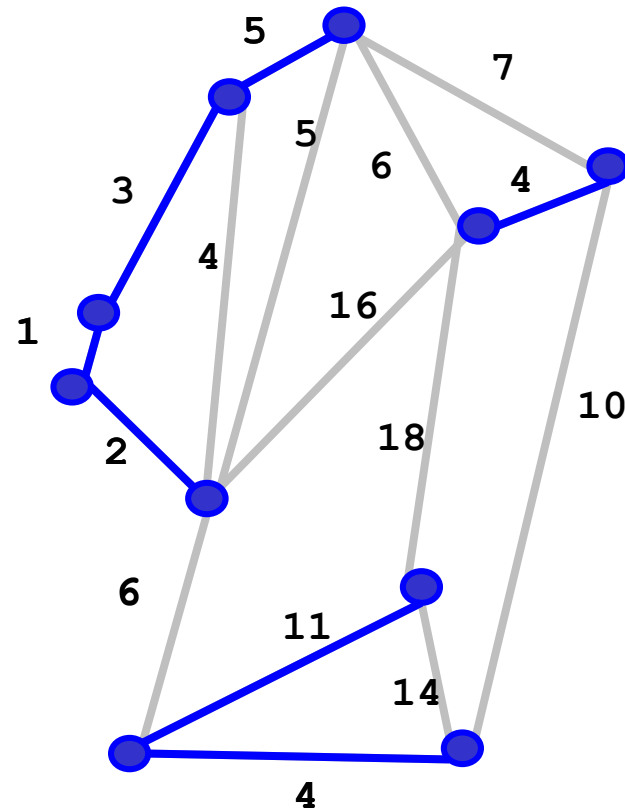
Example 2

- Cost = 61



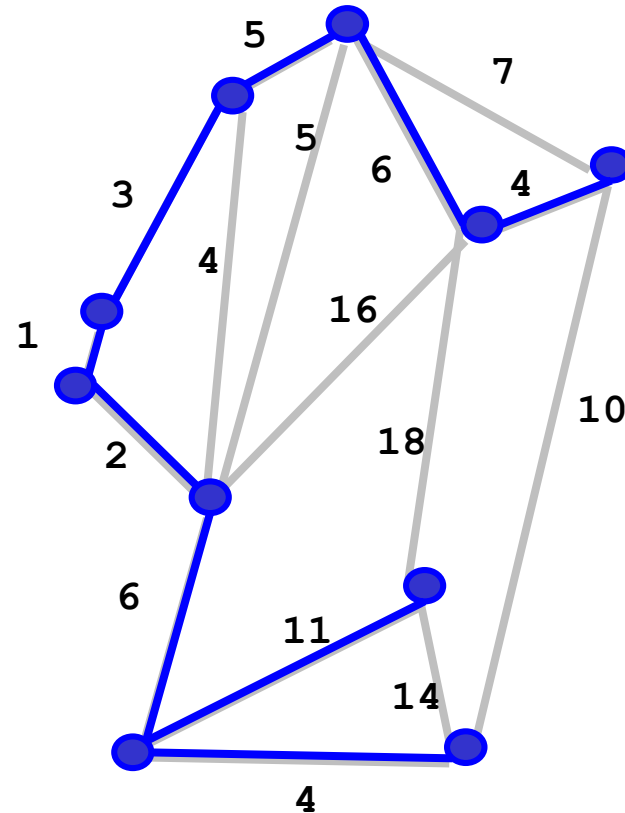
First Algorithm

- Let's try **greedy**
 - Sort edges by weight
 - Add the next cheapest edge to E' whenever it connects a new node to something already known
- Hmm



Second Algorithm

- Let's try greedy – **another way**
 - Sort edges by weight
 - Add cheapest edge to E'
 - Add all edges to E' in ascending order such that every new edge **adds a new node** to the graph **induced by E'**
 - Repeat until E' is complete
- Cost = 42
 - Is this optimal?
 - Does this **always work**?
 - How can we implement this **algorithm efficiently**?



Overview

- First algorithms for computing MST date back to the 1920s
- Algorithms are not difficult; much research went into **efficient implementations**
- Actually, MSTs can be computed in a **greedy manner**
- Algorithms need not grow only one component; in general, we may have “**connected islands**” that all get connected to one component in the end
- In each step, one needs to decide which edge to add next to which island (or which edges not to add)
- What are **criteria for adding / not adding edges**?

Content of this Lecture

- Minimal Spanning Trees
- Basic Properties
 - Tree
 - Cuts
 - Cycles
- Algorithms
- Implementation

Minimal Spanning Trees

- Lemma

Let $G=(V, E)$ and $E' \subseteq E$ be the subset of E' with minimal cost such that G' , the graph induced by E' , is connected. Then G' is a tree.

- Proof

- Recall: A (undirected) tree is a undirected, connected acyclic graph
- By definition, G' is connected and undirected
- Imagine G' had a cycle. Then G' cannot have minimal cost, because removing any of the edges on the cycle from E' would create a subset E'' that has less cost, and the induced subgraph would still be connected
 - We assumed all edge weights to be positive

- Note: If all edge weights are distinct, the **MST is unique**

Cuts

- Definition

*Let $G=(V, E)$. A **cut is a binary partitioning** of V into two sets V_1, V_2 such that $V_1 \cap V_2 = \emptyset$ and $V_1 \cup V_2 = V$.*

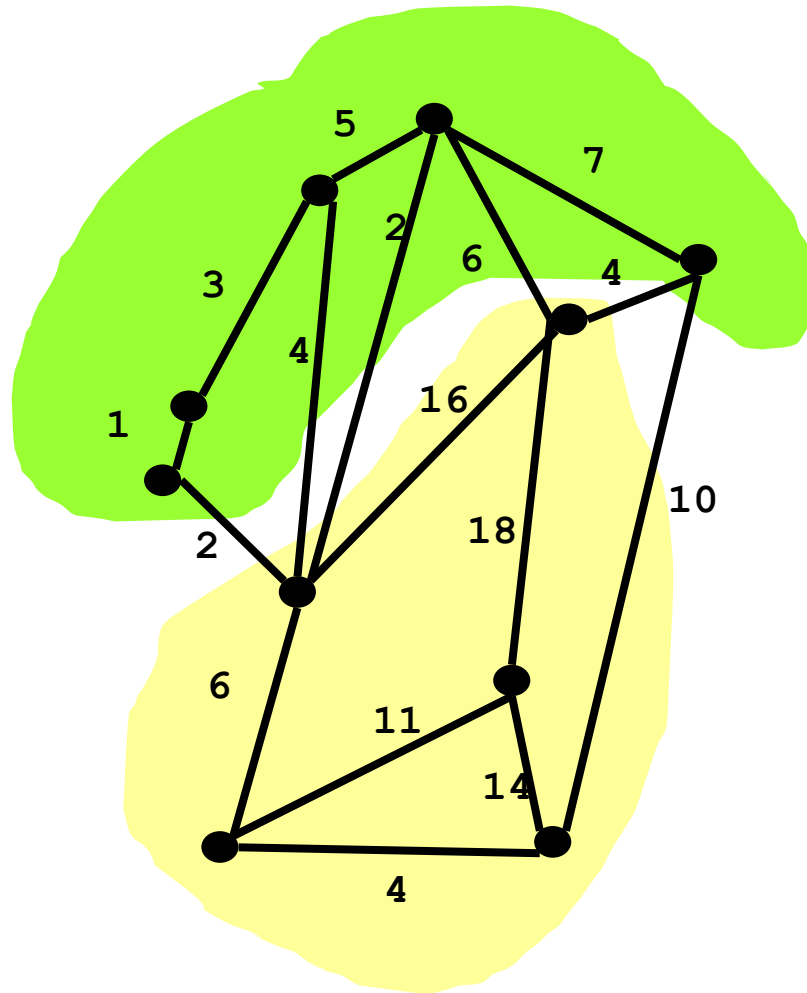
- Lemma

*Let $G=(V, E)$ and V_1, V_2 be a cut of V . Let F be the set of all edges going from any node in V_1 to any node in V_2 . Let F' be those edges of F with minimal weight. Then any MST G' of G **must contains one edge of F' , and every edge of F' is contained in at least one MST of G***

- Remarks

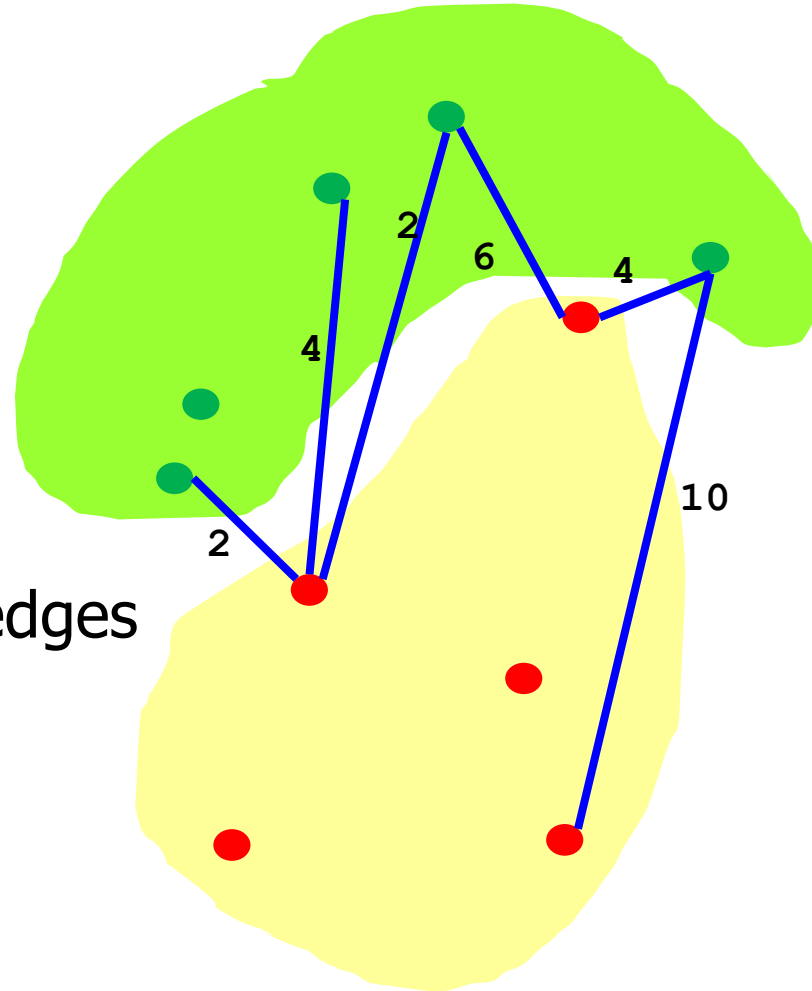
- This holds for arbitrary cuts – a very powerful statement
- Edges in F are called **crossing edges**

Example



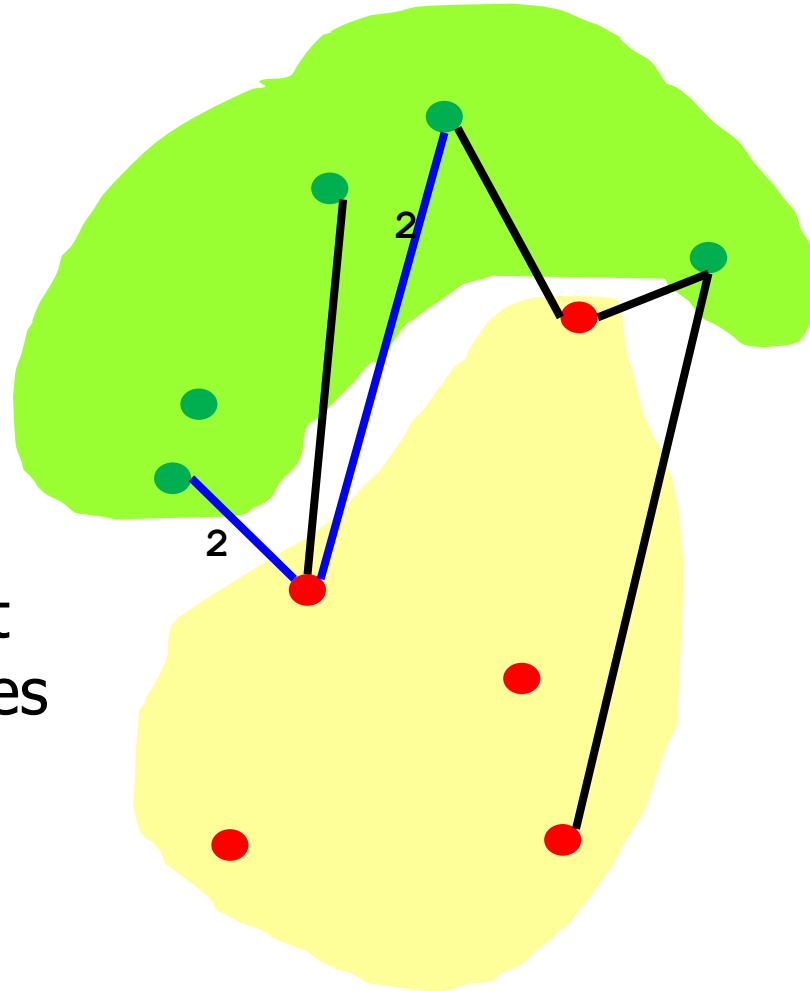
Example

- F:
All crossing edges



Example

- F' :
The cheapest crossing edges

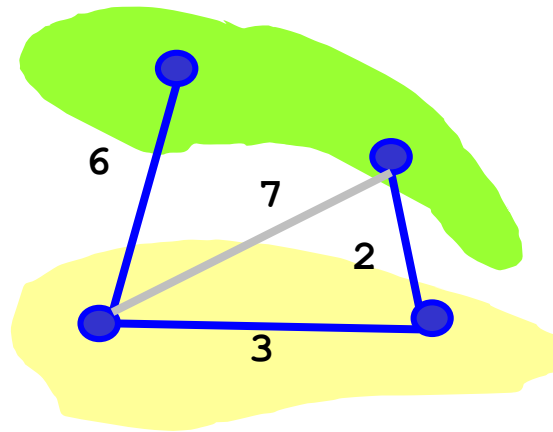


Proof

- Every MST G' contains **one $f \in F'$**
 - Imagine a G' that has no such f . Still, G' must be connected, so it must contain at least one of the crossing edges from F . Assume it contains only one such edge, h . h must have a higher weight than f because $h \notin F'$. Further, V_1 and V_2 must be connected in themselves. Then G' cannot be minimal, because removing h and adding some $f \in F$ would create a cheaper MST – contradiction.
 - Same argument holds if G' contains more than one crossing edge, all of which are not minimal
- Every $f \in F'$ is **contained in at least one MST**
 - Imagine f is not contained in any MST. Let G' be a MST and h be the edge in G' connecting V_1 and V_2 . h must be in F' , or G' is not minimal. Thus, the MST formed by removing h and adding f also is a MST – contradiction.

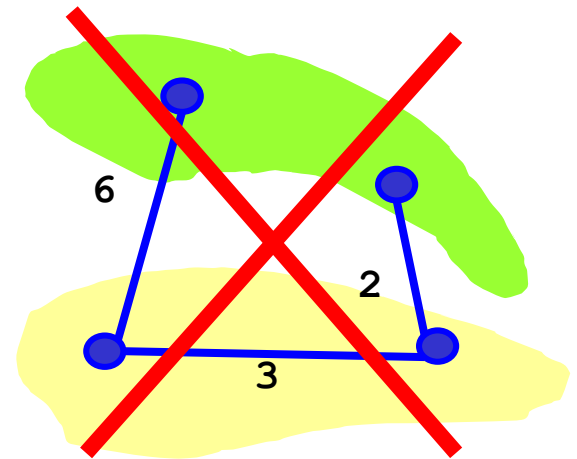
Beware

- For a given cut V_1, V_2 , a MST G' may contain **more than one crossing edge** (and at least one must have minimal weight)



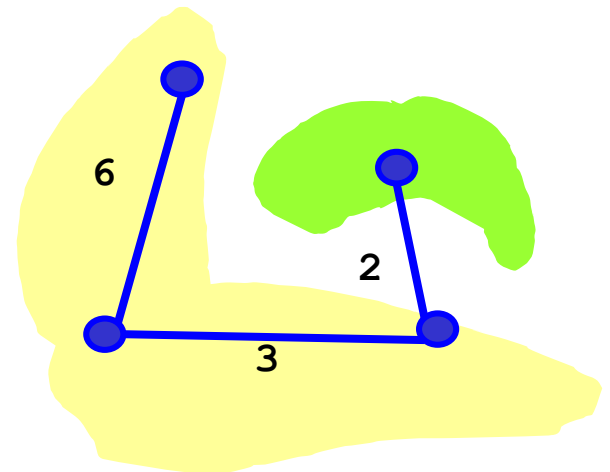
Consequences

- The cut property is a **powerful tool** for computing MSTs
- Lemma (cut property)
*Let $G=(V, E)$ and $G'=(V, E')$ be a MST of G . Then every $e \in E'$ has **minimal cost among all crossing edges of the cut** V_1, V_2 formed by removing e from G' .*
- Proof
 - Since G' is a tree, every edge from E' "cuts" G
 - Rest follows from previous lemma
- Can be used to check whether a given E' is a MST



Consequences

- The cut property is a **strong help** for computing MSTs
- Lemma (cut property)
*Let $G=(V, E)$ and $G'=(V, E')$ be a MST of G . Then every $e \in E'$ has **minimal cost among all crossing edges of the cut** V_1, V_2 formed by removing e from G' .*
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- Minimal Spanning Trees
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 - Cycles
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Cycles

- Lemma (cycle property)

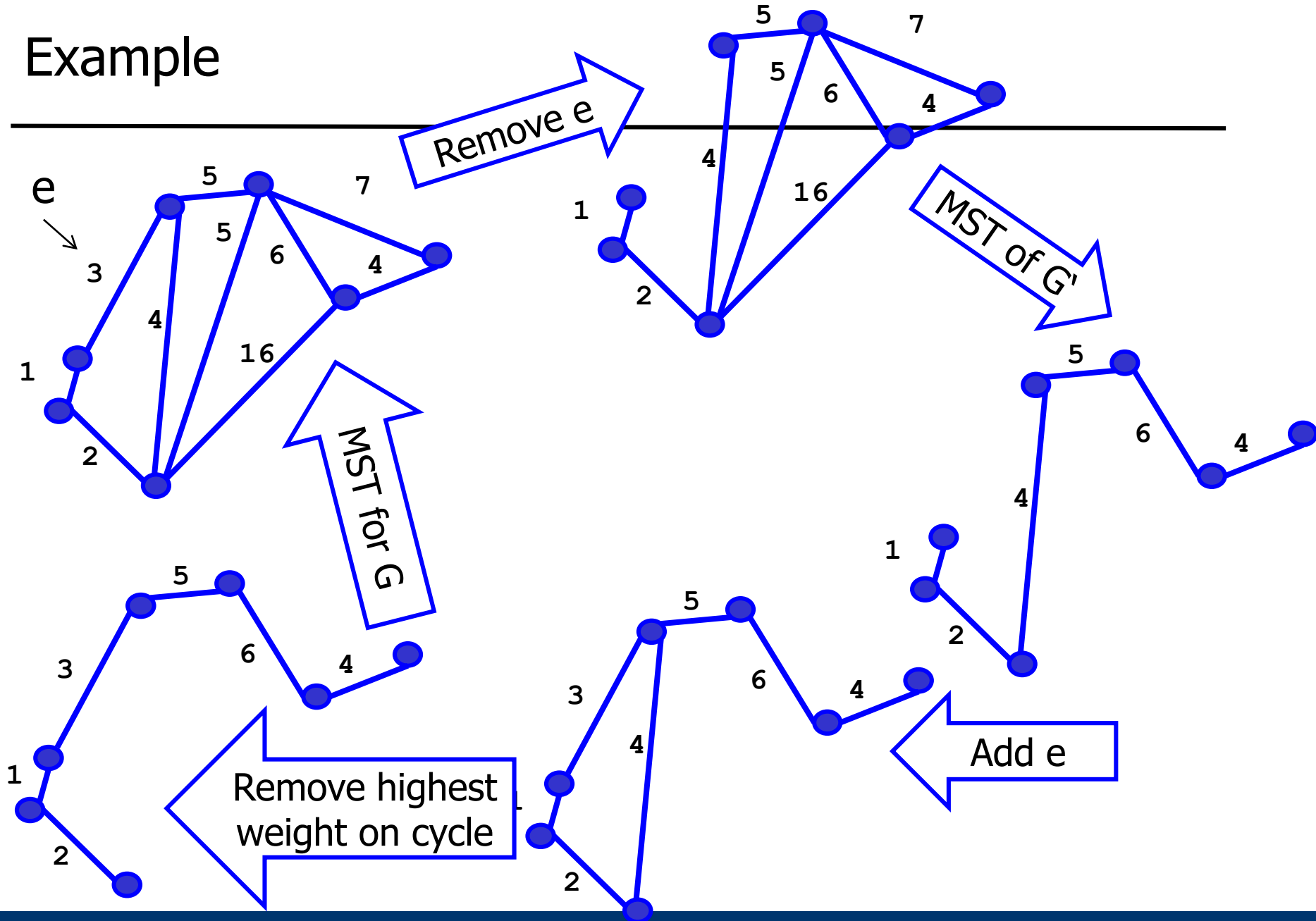
Let $G=(V, E)$ and $G'=(V, E')$ with $E'=E\setminus e$ for some edge e such that G' still is connected. Let T' be a MST for G' .

*When we add e to T' and **remove the edge with the highest weight on the then introduced cycle in T'** , forming T , then T is a MST for G .*

- Proof idea

- Adding e to T' must build a cycle because T' is a MST over V
- Removing any of the edges on the cycle still leaves a connected tree
- Removing the most expensive one leaves the minimal tree

Example



Implications

- T' is a MST for G without e
- Imagine we would enumerate edges in some order
- Taking into account a new edge e may allow us to replace an edge in T' with a **cheaper one**, creating a “better” MST for G
 - If e is not the edge with the highest weight on the cycle
- This means that **an edge with maximal weight on a cycle** in G cannot be part of any MST of G

Content of this Lecture

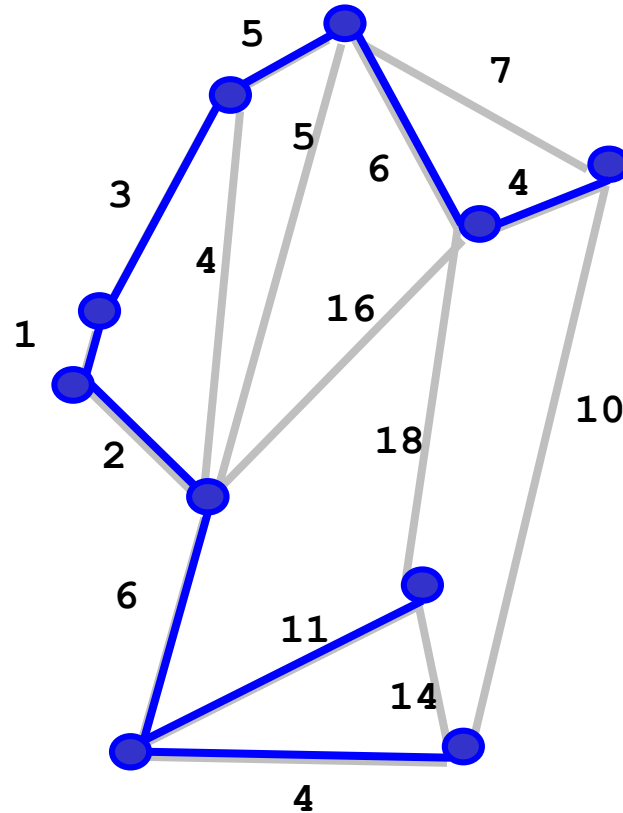
- Minimal Spanning Trees
- Basic Properties
- Algorithms
 - R.C. Prim: Shortest connection networks and some generalizations. Bell System Technical Journal, 1957
 - Also Jarník, Prim, Dijkstra: Jarník, 1930 – Prim, 1957 – Dijkstra, 1959
 - J. Kruskal: On the shortest spanning subtree and the traveling salesman problem. Proc. of the American Mathematical Soc., 1956
 - [Otakar Borůvka](#): O jistém problému minimálním (Über ein gewisses Minimierungsproblem), 1926
 - [Wikipedia, OW93]
- Implementation

Prim's Algorithm

Greedy; we never make mistakes

- Recall cut property: Every edge e in a MST is a minimal edge among the two partitions created by removing e
- **Prim's Algorithm**
*Start with an empty tree T . Continue adding the edge e with the **lowest cost to T** such that e connects T with a new node until all nodes of G are in T . Then T is a MST.*
- Proof
 - Consider, at each stage, nodes in T as one partition V_1 and all other nodes as the other partition V_2
 - By cut property, the cheapest crossing-edge between V_1 and V_2 must be in the MST
 - Since we only add those edges, T finally must be a MST

Example



Kruskal's Algorithm

- **Kruskal's Algorithm**

*Start with an **empty forest** F . Continue "adding" edges e to F in order of increasing cost until F becomes a tree. Adding an edge $e=(v, w)$ to F proceeds as follows:*

- *If F already contains a tree containing both v and w , then e is dropped*
- *If no tree in F contains either v or w , then a new tree formed by e is added to F*
- *If F contains a tree T containing either v or w and neither T nor any other tree in F contains the other node, then e is added to T*
- *If F contains a tree T containing either v or w and a tree T' containing the other node, then T , T' and e are merged into one tree*

Proof

- By induction (only central idea)
 - We show that all trees in F are a **MST of a subgraph** of G
 - Claim is true at the beginning (F empty)
 - Assume claim holds when we consider the next edge $e=(v, w)$
 - Case 1: Claim holds, because e would introduce a cycle, and e has the **highest cost on this cycle** (all cheaper edges were considered before). Thus, e cannot be in an MST for G
 - Case 2: Claim holds because e is the **cheapest edge** connecting v and w , and thus the new tree is a MST (for v and w)
 - Case 3: Claim holds because e is the cheapest edge connecting v (or w) and T , and thus the new tree is a MST
 - Case 4: Claim holds because e is the cheapest edge connecting T and T' , and thus the new tree is a MST

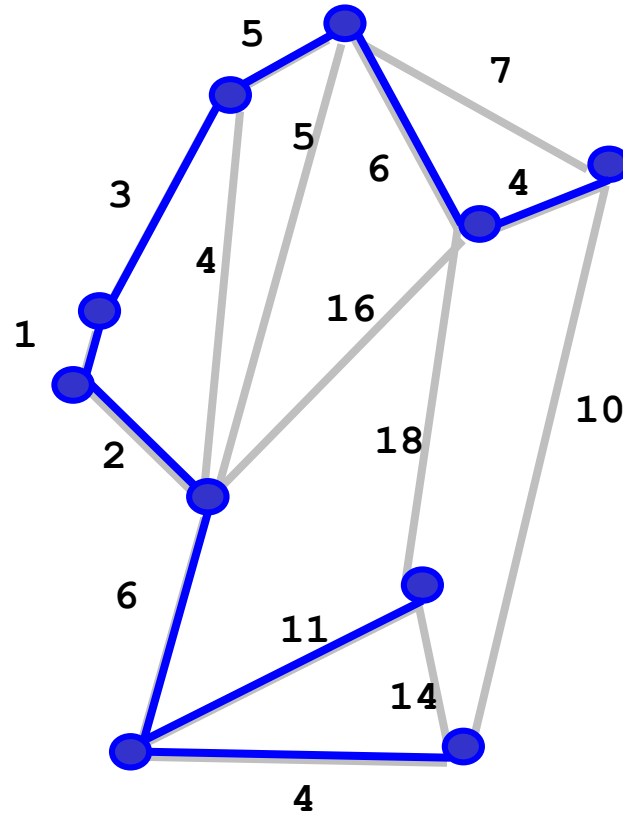
Boruvka's Algorithm

- Boruvka's Algorithm

Start with an empty forest F . Add all edges (at once) that connect a node with its "cheapest" neighbor (edge with least cost) – taking care of not introducing cycles. Then consider each pair of trees in F in order of the cost of connection and add cheapest crossing-edge until F becomes a unique tree.

- Proof (and details) omitted; see [Sed04]

Example



Communalities

- All three algorithms iteratively **choose an edge by the cut property** or reject an edge by the cycle property
 - Prim: Growing T is one partition, all other nodes the other (isolated nodes)
 - Kruskal: Each T that grows is one partition, all other nodes the other (islands of mini-MSTs)
 - Boruvka: Each T that grows is one partition, all other nodes the other (islands of mini-MSTs)
- Differences
 - The **order in which edges are chosen** – there are always many candidates
 - The **data structures** that these algorithms need to maintain

Content of this Lecture

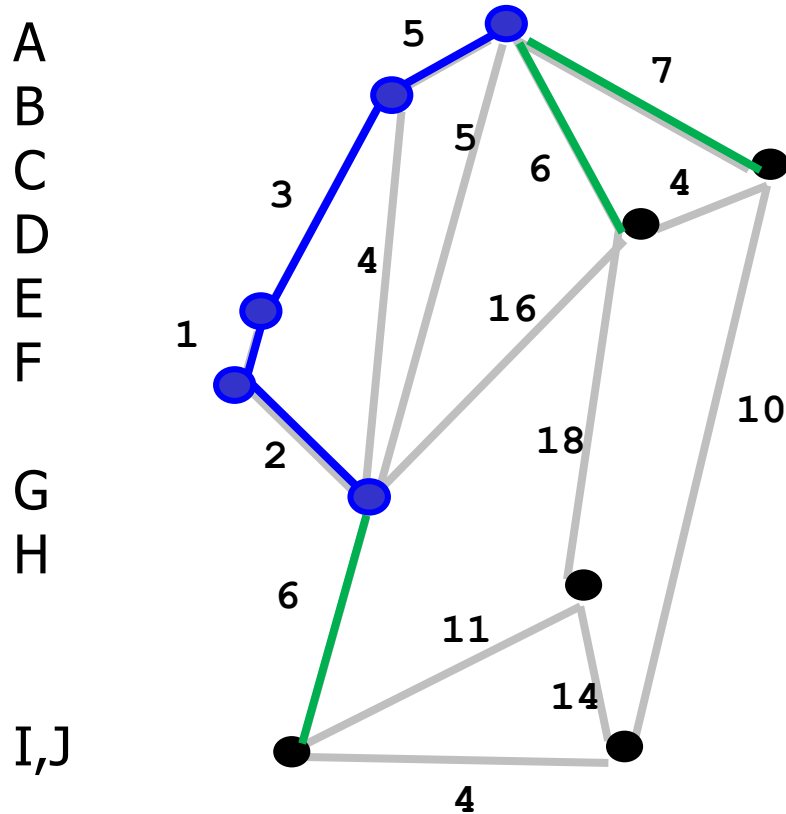
- Minimal Spanning Trees
- Basic Properties
- Algorithms
- **Implementation**
 - Prim's, Kruskal's

Implementing Prim's Algorithm

- ChooseCheapest: Choose cheapest edge from R connecting a **node in T to a node not yet in T**
- Brute force: Search all such edges in every step
- Better
 - Maintain a **PQ of nodes** reachable by one edge from T sorted by cost
 - When adding a new node to T, look at its neighbors and add them to the PQ (if not reachable before) or update costs (if now there is a cheaper edge reaching them)

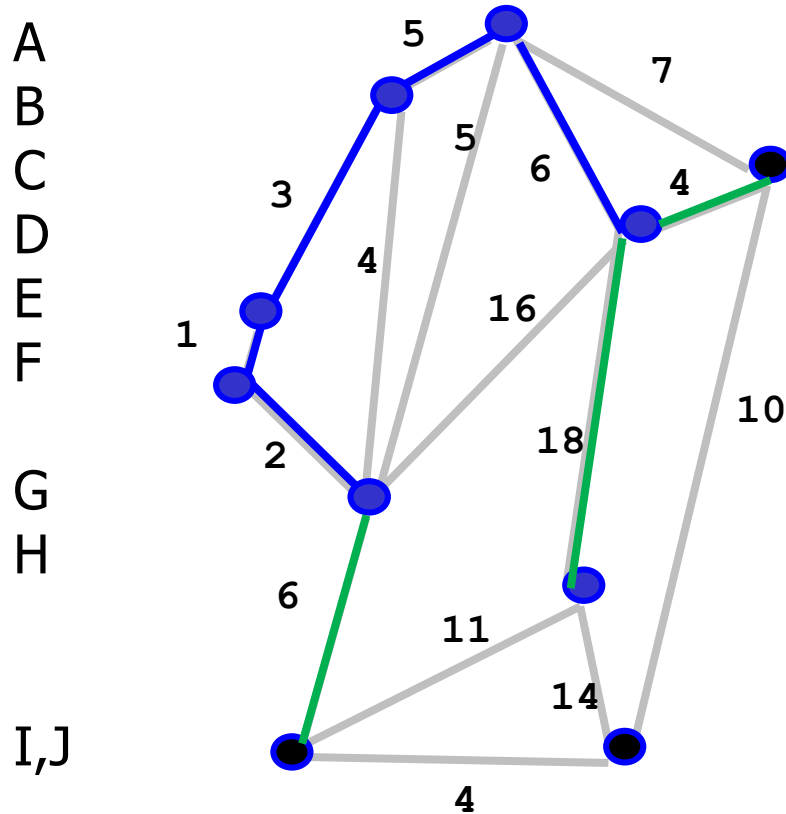
```
G := (V, E);
T := ∅;      # Growing T
R := E;      # Remaining edges
for i = 1 to |V|-1 do
    e := chooseCheapest( T, R);
    T := T ∪ e;
    R := R \ e;
end for;
```

Example



- $T = \{A, F, E, B, G\}$
- $PQ = \{(D,6), (I, 6), (C, 7)\}$
- Choose (A-D, 6)

Example



- $T = \{A, F, E, B, G\}$
- $PQ = \{(D,6), (I, 6), (C, 7)\}$
- Choose (A-D, 6)
- New $T: \{A, F, E, B, G, D\}$
- $PQ = \{(C,4), (I, 6), (H, 18)\}$

Complexity

- $n = |V|$, $m = |E|$
- Prim' algorithm runs in $O((n+m)*\log(n))$
 - n times through the loop, performing altogether at most m PQ-operations in $\log(n)$
- In dense graphs ($m \sim n^2$), this means $O(m*\log(n))$

Implementing Kruskal's Algorithm

- ChooseCheapest: Simply choose cheapest edge in E
 - I.e., sort E at the beginning
- This is called a **UNION-FIND** data structure
 - Maintains a set of sets (all trees T)
 - Needs a method for quickly **finding the set** containing a given element (find)
 - Needs a method for **quickly merging two sets** (union)
- Can be implemented in $O(m \cdot \log(n))$

```
G := (V, E);
F := ∅;
repeat
  (v,w) := chooseCheapest( E );
  E := E \ (v,w);
  T := find( v );
  T' := find( w );
  if T=T'=∅ then
    F.add( { (v,w) } );
  else if T'=∅ then
    T.add ( {v,w} );
  else if T=∅ then
    T'.add ( {v,w} );
  else if T≠T' then
    T := T ∪ T';
  end if;
until |T|=|V|;
```

Exemplary Examination Questions

- Correctly formulate and prove the Cut-property, a tool for computing MSTs
- Compute a MST for the following graph ... using Prim's algorithm. After each step, show the sets T , R , and the state of the priority queue Q
- Prove or falsify: If all edge weights of a graph G are pairwise distinct, then G has only one MST
- Prove or falsify the correctness of the following algorithm for computing an MST for a graph G :
 - (1) Set $G'=G$;
 - (2) If G' contains no cycle, return G' as MST;
 - (3) Otherwise, chose an arbitrary cycle in G' and remove the edge with the highest weight on this cycle; then goto 2