

Minimum spanning trees

The problem

Properties

The cut and the
cycle properties

A generic algorithm

Prim's algorithm

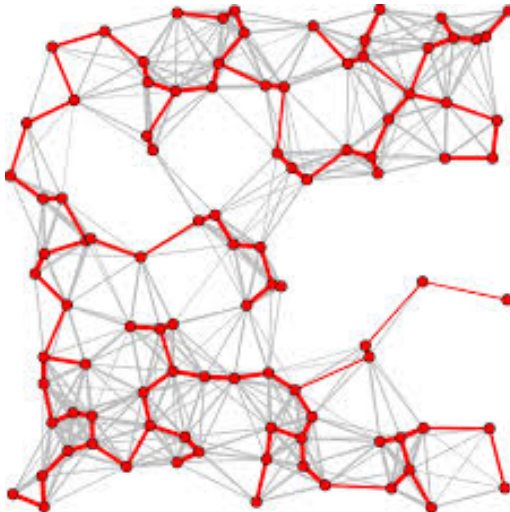
Kruskal's algorithm

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Union-Find
implementation

Cost

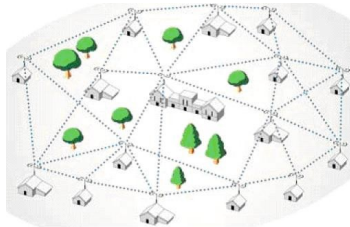
An application:
Clustering



A network construction problem: Minimum Spanning Tree

CLRS 23, KT 4.5, DPV 5.1

- We have a set of locations.
- For some pairs of locations it is possible to build a link connecting the two locations, but it has a cost.



- We want to build a network (if possible), connecting all the locations, with total minimum cost.
- So, the resulting network must be a tree.

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Network construction: Minimum Spanning Tree

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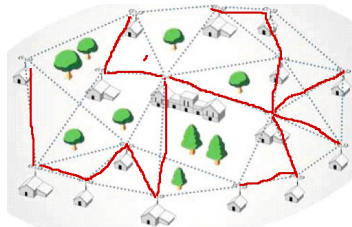
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- We have a set of locations. Build a link connecting the locations i and j has a cost $w(v_i, v_j)$.
- We want to build tree spanning all the locations with total minimum cost.



The MST

Properties of trees

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- A tree on n nodes has $n - 1$ edges.
- Any connected undirected graph with n vertices and $n - 1$ edges is a tree.
- An undirected graph is a tree iff there is a unique path between any pair of nodes.

Let $G = (V, E)$ be a (undirected) graph.

- $G' = (V', E')$ is a **subgraph** of G if $V' \subseteq V$ and $E' \subseteq E$.
- A subgraph $G' = (V', E')$ of G is **spanning** if $V' = V$.
- A **spanning tree** of G is a spanning subgraph that is a tree.

Any connected graph has a spanning tree

MINIMUM SPANNING TREE problem (MST)

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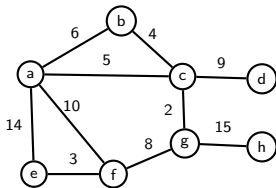
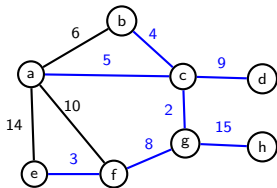
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Given as input an edge weighted graph $G = (V, E, w)$, where $w : E \rightarrow \mathbb{R}$. Find a tree $T = (V, E')$ with $E' \subseteq E$, such that it minimizes $w(T) = \sum_{e \in E(T)} w(e)$.



Some definitions

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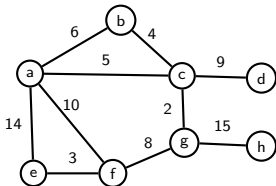
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For a graph $G = (V, E)$:

A **path** is a sequence of consecutive edges.

A **cycle** is a path ending in an edge connecting to the initial vertex, with no other repeated vertex.

A **cut** is a partition of V into two sets S and $V - S$.

The **cut-set** of a cut is the set of edges with one end in S and the other in $V - S$. $cut(S, V - S) = \{e = (u, v) \in E \mid u \in S \vee v \notin S\}$

MST: Properties

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Given a weighted graph $G = (V, E, w)$, assume that **all edge weights are different**.

A MST T in G has the following properties:

- **Cut property**

$e \in T \Leftrightarrow e$ is the **lightest** edge across some cut in G .

- **Cycle property**

$e \notin T \Leftrightarrow e$ is the **heaviest** edge on some cycle in G .

The cut property

Let $G = (V, E, w)$, $w : E \rightarrow \mathbb{R}^+$, such that all weights are different. **Let T be a MST of G .**

Removing an edge $e = (u, v)$ from T yields two disjoint trees T_u and T_v , so that $V(T_u) = V - V(T_v)$, $u \in T_u$ and $v \in T_v$. Let us call $S_u = V(T_u)$ and $S_v = V(T_v)$.

Claim

$e \in E(T)$ is the min-weight edge among those in $\text{cut}(S_u, S_v)$.

Proof.

Otherwise, we can replace e by an edge in the cut with smaller weight. Thus, forming a new spanning tree with smaller weight. □

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The cut property

Claim (The cut rule)

For $S \subseteq V$, let $e = (u, v)$ be the min-weight edge in $\text{cut}(S, V - S)$, then $e \in T$.

Proof.

- Assume $e \notin T$, $u \in S$ and $v \notin S$.
- T is spanning, then a path $P(u, v)$ from u to v exists in T .
- $u \in S$ and $v \notin S$: there is $e' \in \text{cut}(S, V - S)$ in $P(u, v)$.
- Replacing e' with e produces another spanning tree.
- But then, as $w(e) > w(e')$, T was not optimal.



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For an edge $e \notin T$, adding it to T creates a graph $T + e$ having a unique cycle involving e . Let's call this cycle C_e .

Claim

For $e \notin E(T)$, e is the max-weight edge in C_e .

Proof.

Otherwise, removing any edge different from e in $T + e$ produces a spanning tree with smaller total weight. □

The cycle property

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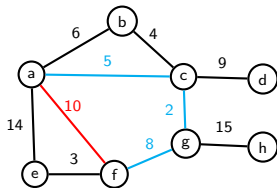
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Claim (The cycle rule)

For a cycle C in G , the edge $e \in C$ with max-weight can not be part of T .

Proof.

Observe that, as G is connected, $G' = (V, E - \{e\})$ is connected. Furthermore, a MST for G' is a MST for G . $\square$



MST: Rules

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The MST algorithms use two rules for adding/discarding edges.

The $\Leftarrow$ implication of the cut property yields the **blue rule** (**include**), which allow us to include safely in T a min weight edge from some identified cut.

The $\Rightarrow$ implication of the cycle property will yield the **red rule** (**exclude**) which allow us to exclude from T a max weight edge from some identified cycles.

Generic greedy for MST: Apply blue and/or red rules

- The two rules show the optimal substructure of the MST. So, we can design a greedy algorithm.
- Blue rule: Given a cut-set between S and $V - S$ with no blue edges, select from the cut-set a non-colored edge with min weight and paint it blue
- Red rule: Given a cycle C with no red edges, selected a non-colored edge in C with max weight and paint it red.
- *Greedy scheme:*
Given G , apply the red and blue rules until having $n - 1$ blue edges, those form the MST.

Robert Tarjan: Data Structures and Network Algorithms, SIAM, 1984

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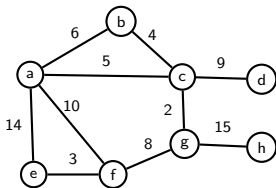
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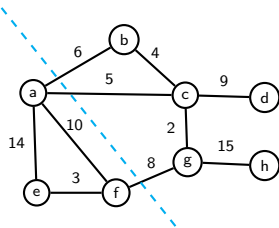
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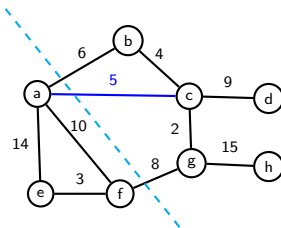
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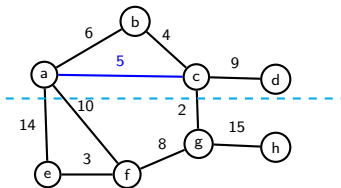
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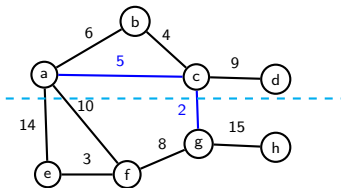
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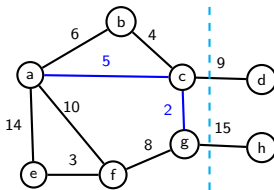
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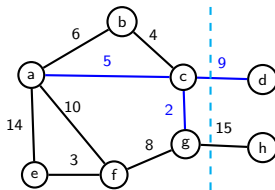
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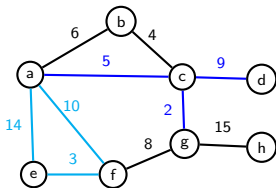
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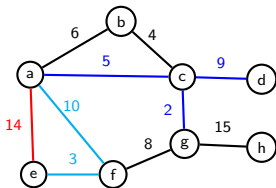
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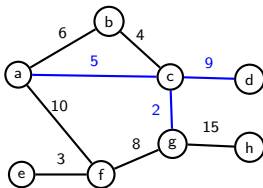
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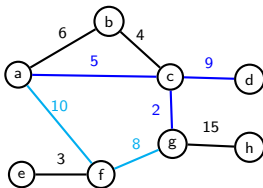
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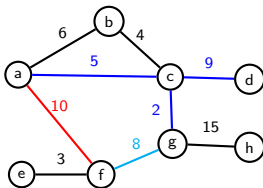
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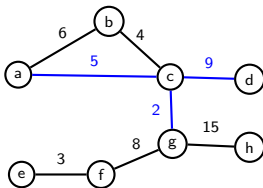
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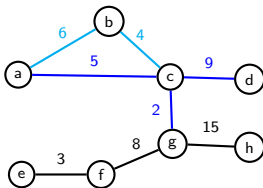
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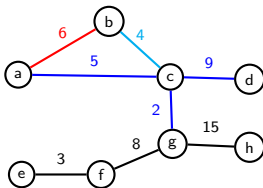
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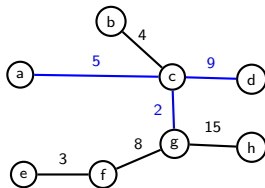
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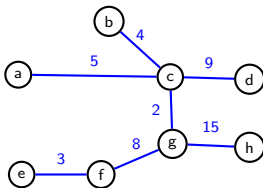
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Greedy for MST: Correctness

Theorem

The greedy scheme finishes in at most m steps and at the end of the execution the blue edges form a MST

Sketch.

- As in each iteration an edge is added or discarded, the algorithm finishes after at most m applications of the rules.
- As the red edges cannot form part of any MST and the blue ones belong to some MST, the selections are correct.
- A set of $n - 1$ required edges form a spanning tree!



We need implementations for the algorithm!

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A short history of MST implementation

There has been extensive work to obtain the most efficient algorithm to find a MST in a given graph:

- O. Borůvka gave the first greedy algorithm for the MST in 1926. V. Jarník gave a different greedy for MST in 1930, which was re-discovered by R. Prim in 1957. In 1956 J. Kruskal gave a different greedy algorithms for the MST. All those algorithms run in $O(m \lg n)$.
- Fredman and Tarjan (1984) gave a $O(m \log^* n)$ algorithm, introducing a new data structure for priority queues, the Fibonacci heap. Recall $\log^* n$ is the number of times we have to apply iteratively the log operator to n to get a value ≤ 1 , for ex. $\log^* 1000 = 2$.
- Gabow, Galil, Spencer and Tarjan (1986) improved Fredman-Tarjan to $O(m \log(\log^* n))$.
- Karger, Klein and Tarjan (1995) $O(m)$ randomized algorithm.
- In 1997 B. Chazelle gave an $O(m\alpha(n))$ algorithm, where $\alpha(n)$ is a very slowly growing function, the inverse of the Ackermann function.

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Basic algorithms for MST

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- **Jarník-Prim (Serial centralized)** Starting from a vertex v , grows T adding each time the lighter edge already connected to a vertex in T , using the blue rule.
Uses a priority queue
- **Kruskal (Serial distributed)** Considers every edge, in order of increasing weight, to grow a **forest** by using the blue and red rules. The algorithm stops when the forest became a tree.
Uses a union-find data structure.



Jarník–Prim greedy algorithm.

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V. Jarník, 1936, R. Prim, 1957

- The algorithm keeps a tree T and adds one edge (and one node) to T at each step until it became spanning.
- Initially the tree T has one arbitrary node r , and no edges.
- At each step T is enlarged adding a minimum weight edge in the set $\text{cut}(V(T), V - V(T))$.
- The algorithm is correct as it applies always the blue rule.

Jarník - Prim greedy algorithm.

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MST (G, w, r)

$T = \{r\}$

for $i = 2$ **to** $|V|$ **do**

Let e be a min weight edge in the $cut(V(T), V - V(T))$

$T = T \cup \{e\}$

end for

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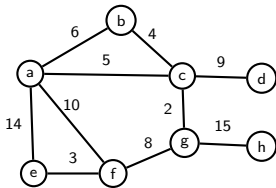
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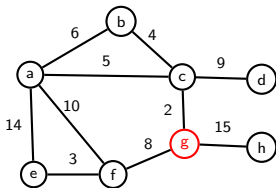
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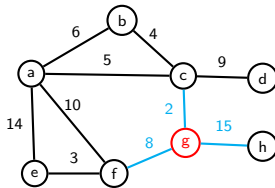
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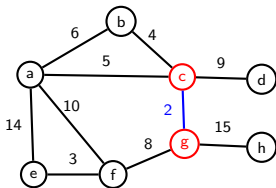
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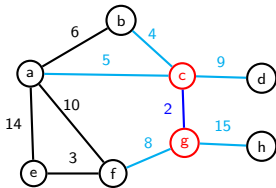
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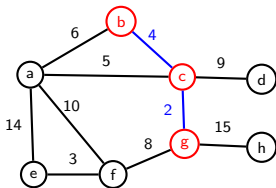
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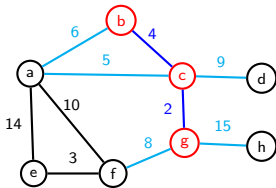
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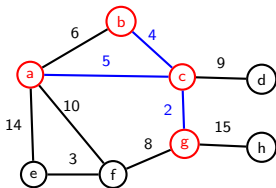
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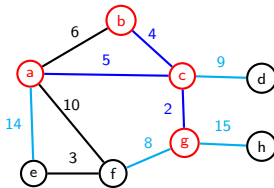
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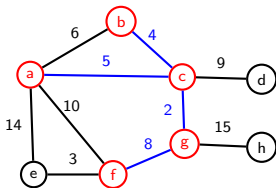
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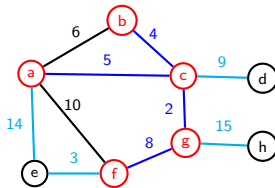
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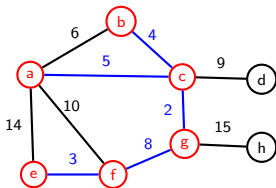
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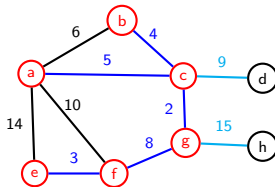
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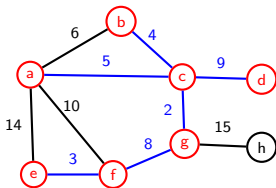
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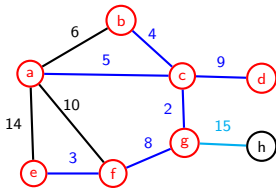
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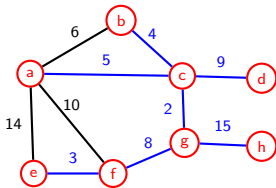
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Jarník–Prim: Implementation

Use a priority queue to choose min weight e in the cut set. In doing so we have to **discard some edges**

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MST (G, w, r)

$T = (\{r\}, \emptyset); Q = \emptyset; s = 0$

Insert in Q all edges $e = (r, v)$ with key $w(r, v)$

while $s < n - 1$ and Q is not empty **do**

$(u, v, w) = Q.pop()$

if $u \notin V(T)$ or $v \notin V(T)$ **then**

 Let u' be the vertex from (u, v) that is not in T

 Insert in Q all the edges $e = (u', v') \in E(G)$ for

$v' \notin V(T)$ with key $w(e)$

 add e to T ; $++s$

end if

end while

Jarník - Prim greedy algorithm: Correctness

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- **The algorithm discards edge e :**

Such an edge $e = (u, v)$ has $u, v \in V(T)$, so it forms a cycle with the edges in T . But, e is the edge with highest weight in this cycle. This is an application of the **red rule**.

- **The algorithm adds to T edge e :**

Then e has minimum weight among all edges in Q , as Q contains all edges in the cut-set($V(T), V - V(T)$). This is the **blue rule**

- Therefore the algorithm computes a MST.

Jarník–Prim greedy algorithm: Cost

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Time: depends on the implementation of the priority queue Q .
We have $\leq m$ insertions on the priority queue.

Q an unsorted array: $T(n) = O(|V|^2)$;

Q a heap: $T(n) = O(|E| \lg |V|)$.

Q a Fibonacci heap: $T(n) = O(|E| + |V| \lg |V|)$

Kruskal's algorithm.

J. Kruskal, 1956

Similar to Jarník–Prim, but chooses **minimum weight edge**, in some cut. The selected edges form a forest until the last step.

MST-K (G, w, r)

$T = \emptyset$

for $i = 1$ **to** $|V|$ **do**

Let $e \in E$: with minimum weight among those that do not form a cycle with T

$T = T \cup \{e\}$

end for

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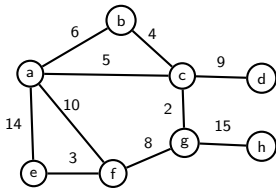
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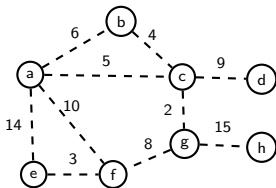
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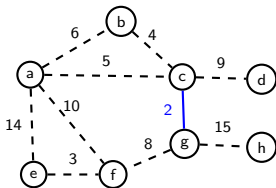
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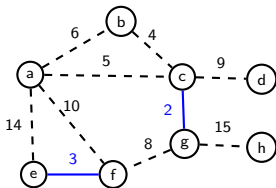
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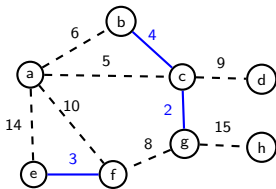
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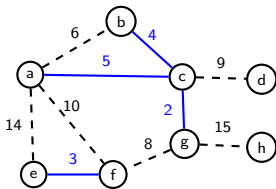
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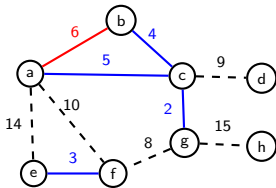
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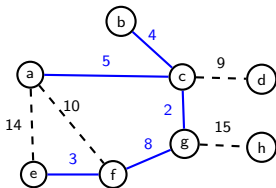
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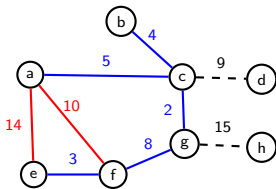
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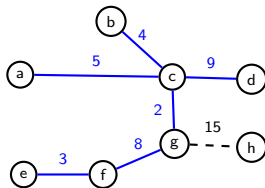
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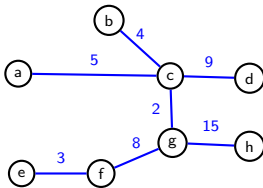
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Kruskal's algorithm: Efficient Implementation

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MST-K2 (G, w, r)

Sort E by increasing weight

$T = \emptyset$

for $e \in E$ in sorted order **do**

if e does not form a cycle with T **then**

$T = T \cup \{e\}$

end if

end for

The output is the same as for **MST-K** but we do not need to examine the remaining edges at intermediate steps.

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- We have a cost of $O(m \lg m)$ to sort the edges.
But as $m \leq n^2$, $O(m \lg m) = O(m \lg n)$.
- We need an efficient implementation of the algorithm selecting an adequate data structure.
- Let us look to some properties of the objects constructed along the execution of the algorithm.

A data structure for Kruskal algorithm

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- Kruskal evolves by building spanning forests, merging two trees (blue rule) or discarding an edge (red rule) so as to do not create a cycle.
- The connectivity relation is an equivalence relation: $u\mathcal{R}_F v$ iff there is a path between u and v .
- Kruskal, starts with a partition of V into n sets and ends with a partition of V into one set.
- $\mathcal{R}$ partition the elements of V in **equivalence classes**, which are the connected components of the forest

The Union-Find data structure

B. Galler, M. Fisher: An improved equivalence algorithm. ACM Comm., 1964; R.Tarjan 1979-1985

- Is a data structure to maintain a **dynamic partition** of a set.
- One of the most elegant in the algorithmic toolkit.
- It makes possible to design **almost linear** time algorithms for problems that otherwise would be unfeasible.
- Union-Find is a first introduction to an active research field in algorithmics: **Self organizing data structures** used in **data stream computation**.

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- Union-Find maintains a partition of a set i.e. a collection of pairwise disjoint sets.
- A set is represented by a rooted tree with labels. The root of the tree the **representative** of the tree (set).
- Internally a partition is a **spanning forest**.

Union-Find

Union-Find supports three operations on partitions of a set:

- **MAKESET(x)**: creates a new set containing the single element x .
Creates a tree with only one node, the root, associated with x .
- **UNION(x, y)**: Merge the sets containing x and y , by using their union.
Define how to merge the trees and choose the root of the merged trees.
- **FIND(x)**: Return the representative of the set containing x .
Find the root of the tree containing x and return the associated element.

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Warning about UNION operation

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- **Warning:** For any $x, y \in S$, we might need to do $\text{UNION}(x, y)$, for x, y that are not representatives. Depending on the implementation this might or might not be allowed.
- To determine the complexity under different implementations, we consider that

$$\text{UNION}(x, y) = \text{UNION}(\text{FIND}(x), \text{FIND}(y)).$$

Union-Find implementation for Kruskal

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MST ($G(V, E), w, r$), $|V| = n, |E| = m$

Sort E by increasing weight: $\{e_1, \dots, e_m\}$

$T = \emptyset$

for all $v \in V$ **do**

MAKESET(v)

end for

for $i = 1$ **to** m **do**

 Assume that $e_i = (u, v)$

if **FIND**(u) $\neq$ **Find**(v) **then**

$T = T \cup \{e_i\}$

UNION(u, v)

end if

end for

- Sorting takes time $O(m \log n)$.
- The remaining part of the algorithm is a sequence of n **MAKESET** and $O(m)$ operations of type **FIND/UNION**

Amortized analysis

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(See for ex. Sect. 17-1 to 17.3 in CLRS)

- An **amortized analysis** is any strategy for analyzing a sequence of operations on a Data Structure, to provide the "average" cost per operation, even though a single operation within the sequence might be expensive.
- An amortized analysis guarantees the average performance of each operation is the worst case on the sequence.
- The easier way to think about amortized analysis is to consider **total cost** of the steps, for a sequence of operations, divided by its size.

Union Find implementations: Amortized Costs

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(4.6 KT)

For a set with n elements.

- Using an array holding the representative of each element.
 - MAKESET and FIND takes $O(1)$
 - UNION takes $O(n)$.
- Using an array holding the representative, a list by set, and in a UNION keeping the representative of the larger set.
 - MAKESET and FIND takes $O(1)$
 - any sequence of k UNION takes $O(k \log k)$.

Complexity of Union Find implementations:

Amortized cost

For a set with n elements.

- Using a rooted tree by set, in a UNION keeping the representative of the larger set.
 - MAKESET and UNION takes $O(1)$
 - FIND takes $O(\log n)$.
- Using a rooted tree by set, in a UNION keeping the representative of the larger set, and doing path compression during a FIND.
 - MAKESET takes $O(1)$
 - any intermixed sequence of k FIND and UNION takes $O(k\alpha(n))$.

$\alpha(n)$ is the **inverse Ackerman's function** which grows extremely slowly. For practical applications it behaves as a constant.

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MST ($G(V, E), w, r$), $|V| = n, |E| = m$

Sort E by increasing weight: $\{e_1, \dots, e_m\}$

$T = \emptyset$

for all $v \in V$ **do**

MAKESET(v)

end for

for $i = 1$ **to** m **do**

 Assume that $e_i = (u, v)$

if **FIND**(u) $\neq$ **Find**(v) **then**

$T = T \cup \{e_i\}$

UNION(u, v)

end if

end for

- Sorting take time $O(m \log n)$.
- The remaining part of the algorithm has cost $n + O(m\alpha(n)) = O(n + m)$.

But due to the sorting instruction, cost is $O(n + m \lg n)$.

Some applications of Union-Find

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- **Kruskal's algorithm for MST.**
- Dynamic graph connectivity in networks with a large number of edges.
- Cycle detection in undirected graphs.
- Random maze generation and exploration.
- Strategies for games: Hex and Go.
- Least common ancestor.
- Compiling equivalence statements.
- Equivalence of finite state automata.

Clustering

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An application: Clustering

- Clustering: process of finding interesting structure in a set of data.
- Given a collection of objects, organize them into similar coherent groups with respect to some (distance function $d(\cdot, \cdot)$).
- The distance function not necessarily has to be the physical (Euclidean) distance. The interpretation of $d(\cdot, \cdot)$ is that for any two objects x, y , the larger that $d(x, y)$ is, the less similar that x and y are.
- If x, y are two species, we can define $d(x, y)$ as the years since they diverged in the course of evolution.

Generic k -clustering setting

Given a set of data points $\mathcal{U} = \{x_1, x_2, \dots, x_n\}$ together with a distance function d on X , and given a $k > 0$, a **k -clustering** is a partition of X into k disjoint subsets.

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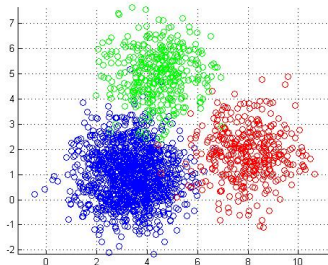
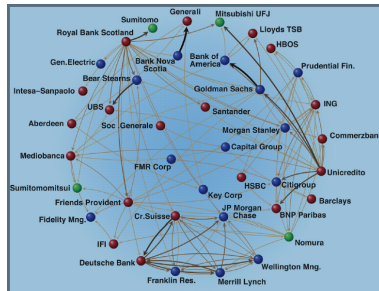
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The single-link clustering problem

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Let $\mathcal{U}$ be a set of n data points, assume $\{C_1, \dots, C_k\}$ is a k -clustering for $\mathcal{U}$.

Define the **spacing s** in the k -clustering as the **minimum** distance between any pair of points in different clusters.

The single-link clustering problem: Given $\mathcal{U} = \{x_1, x_2, \dots, x_n\}$, a distance function d , and $k > 0$, find a k -clustering of $\mathcal{U}$ maximizing the spacing s .

Notice there are exponentially many different k -clusterings of $\mathcal{U}$.

TrKruskal: An algorithm for the single-link clustering problem

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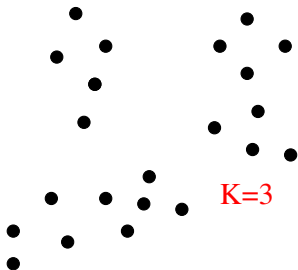
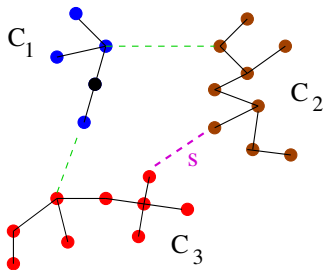
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- Represent $\mathcal{U}$ as vertices of an undirected graph where the edge (x, y) has weight $d(x, y)$.
- Apply Kruskal's algorithm until the forest has k trees.



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Theorem

TrKruskal solves the single-link clustering problem in $O(n^2 \lg n)$

Proof.

We have to create a complete graph and sort the n^2 edges.
Thus TrKruskal has cost $O(n^2 \lg n)$

Correctness

Let $\mathcal{C} = \{C_1, \dots, C_k\}$ be the k -clustering produced by TrKruskal, and let s be its spacing.

Assume there is another k -clustering $\mathcal{C}' = \{C'_1, \dots, C'_k\}$ with spacing s' and s.t. $\mathcal{C} \neq \mathcal{C}'$. We must show that $s' \leq s$.

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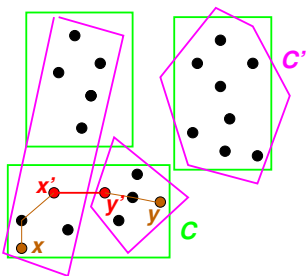
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- If $\mathcal{C} \neq \mathcal{C}'$, then $\exists C_r \in \mathcal{C}$ s.t.
 $\forall C'_t \in \mathcal{C}', C_r \not\subseteq C'_t$.
- Then $\exists x, y \in C_r$ s.t. $x \in C'_a, y \in C'_b$
and $a \neq b$.
- $\exists$ a path $x \rightsquigarrow y$ in C_r contained in the
spanning tree T_r obtained by
TrKruskal for C_r .
- Then, $\exists (x', y') \in E(T_r)$ with $x' \in C'_a$
and $y' \in C'_b$, so $s' \leq d(x', y')$.
- As $(x', y') \in E(T_r)$ $d(x', y') \leq s$ and
 $s' \leq s$.

End Proof