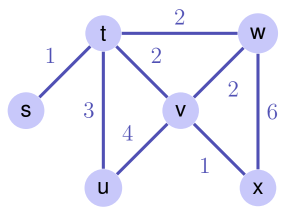
15. Minimum Spanning Trees

Motivation, Greedy, Algorithm Kruskal, General Rules, ADT Union-Find, Algorithm Jarnik, Prim, Dijkstra, [Ottman/Widmayer, Kap. 9.6, 6.2, 6.1, Cormen et al, Kap. 23, 19]

Problem

Given: Undirected, weighted, connected graph $G = (V, E, c)$.

Wanted: Minimum Spanning Tree $T = (V, E')$: connected, cycle-free subgraph $E' \subset E$, such that $\sum_{e \in E'} c(e)$ minimal.



Application Examples

- Network-Design: find the cheapest / shortest network that connects all nodes.
- Approximation of a solution of the travelling salesman problem: find a round-trip, as short as possible, that visits each node once.[25]

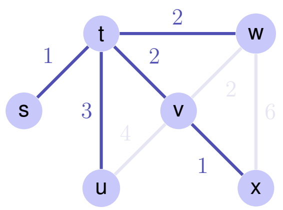
[25] The best known algorithm to solve the TS problem exactly has exponential running time.

Greedy Procedure

- Greedy algorithms compute the solution stepwise choosing locally optimal solutions.
- Most problems cannot be solved with a greedy algorithm.
- The Minimum Spanning Tree problem can be solved with a greedy strategy.

Greedy Idea (Kruskal, 1956)

Construct T by adding the cheapest edge that does not generate a cycle.



(Solution is not unique.)

Algorithm MST-Kruskal(G)

Input: Weighted Graph $G = (V, E, c)$
Output: Minimum spanning tree with edges A.

Sort edges by weight $c(e_1) \leq ... \leq c(e_m)$
$A \leftarrow \emptyset$
for $k = 1$ **to** $|E|$ **do**
  if $(V, A \cup \{e_k\})$ acyclic **then**
    $A \leftarrow A \cup \{e_k\}$

return (V, A, c)

[Correctness]

At each point in the algorithm (V, A) is a forest, a set of trees.

MST-Kruskal considers each edge e_k exactly once and either chooses or rejects e_k

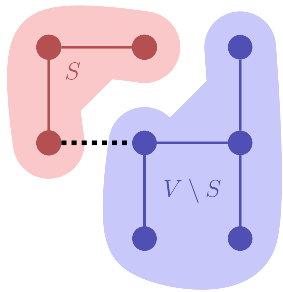
Notation (snapshot of the state in the running algorithm)

- A: Set of selected edges
- R: Set of rejected edges
- U: Set of yet undecided edges

[Cut]

A cut of G is a partition $S, V - S$ of V. ($S \subseteq V$).

An edge crosses a cut when one of its endpoints is in S and the other is in $V \setminus S$.



[Rules]

1. Selection rule: choose a cut that is not crossed by a selected edge. Of all undecided edges that cross the cut, select the one with minimal weight.
2. Rejection rule: choose a circle without rejected edges. Of all undecided edges of the circle, reject those with minimal weight.

[Rules]

Kruskal applies both rules:

1. A selected e_k connects two connection components, otherwise it would generate a circle. e_k is minimal, i.e. a cut can be chosen such that e_k crosses and e_k has minimal weight.
2. A rejected e_k is contained in a circle. Within the circle e_k has minimal weight.

[Correctness]

Theorem

Every algorithm that applies the rules above in a step-wise manner until $U = \emptyset$ is correct.

Consequence: MST-Kruskal is correct.

[Selection invariant]

Invariant: At each step there is a minimal spanning tree that contains all selected and none of the rejected edges.

If both rules satisfy the invariant, then the algorithm is correct. Induction:

- At beginning: $U = E$, $R = A = \emptyset$. Invariant obviously holds.
- Invariant is preserved at each step of the algorithm.
- At the end: $U = \emptyset$, $R \cup A = E \Rightarrow (V, A)$ is a spanning tree.

Proof of the theorem: show that both rules preserve the invariant.

[Selection rule preserves the invariant]

At each step there is a minimal spanning tree T that contains all selected and none of the rejected edges.

Choose a cut that is not crossed by a selected edge. Of all undecided edges that cross the cut, select the egde e with minimal weight.

- Case 1: $e \in T$ (done)
- Case 2: $e \notin T$. Then $T \cup \{e\}$ contains a circle that contains e Circle must have a second edge e' that also crosses the cut.[26] Because $e' \notin R$, $e' \in U$. Thus $c(e) \leq c(e')$ and $T' = T \setminus \{e'\} \cup \{e\}$ is also a minimal spanning tree (and $c(e) = c(e')$).

[26] Such a circle contains at least one node in S and one node in $V \setminus S$ and therefore at lease to edges between S and $V \setminus S$.

[Rejection rule preserves the invariant]

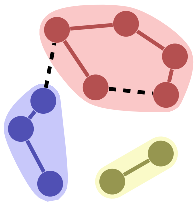
At each step there is a minimal spanning tree T that contains all selected and none of the rejected edges.

Choose a circle without rejected edges. Of all undecided edges of the circle, reject an edge e with minimal weight.

- Case 1: $e \notin T$ (done)
- Case 2: $e \in T$. Remove e from T, This yields a cut. This cut must be crossed by another edge e' of the circle. Because $c(e') \leq c(e)$, $T' = T \setminus \{e\} \cup \{e'\}$ is also minimal (and $c(e) = c(e')$).

Implementation Issues

Consider a set of sets $i \equiv A_i \subset V$. To identify cuts and circles: membership of the both ends of an edge to sets?



Implementation Issues

General problem: partition (set of subsets) .e.g. $\{\{1,2,3,9\},\{7,6,4\},\{5,8\},\{10\}\}$

Required: Abstract data type “Union-Find” with the following operations

- Make-Set(i): create a new set represented by i.
- Find(e): name of the set i that contains e .
- Union(i, j): union of the sets with names i and j.

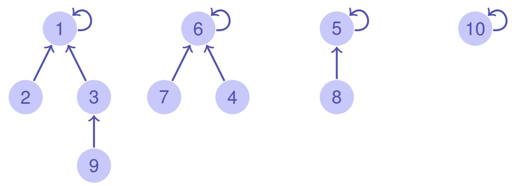
Union-Find Algorithm MST-Kruskal(G)

Input: Weighted Graph $G = (V, E, c)$
Output: Minimum spanning tree with edges A.

Sort edges by weight $c(e_1) \leq ... \leq c(e_m)$
$A \leftarrow \emptyset$
for $k = 1$ **to** $|V|$ **do**
  MakeSet(k)
for $k = 1$ **to** m **do**
  $(u, v) \leftarrow e_k$
  if Find(u) $\neq$ Find(v) **then**
    Union(Find(u), Find(v))
    $A \leftarrow A \cup e_k$
  else // conceptual: $R \leftarrow R \cup e_k$
return (V, A, c)

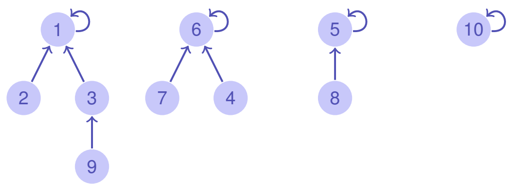
Implementation Union-Find

Idea: tree for each subset in the partition,e.g. $\{\{1, 2, 3, 9\}, \{7, 6, 4\}, \{5, 8\}, \{10\}\}$



roots = names (representatives) of the sets,
trees = elements of the sets

Implementation Union-Find



Representation as array:

Index	1	2	3	4	5	6	7	8	9	10
Parent	1	1	1	6	5	6	5	5	3	10

Implementation Union-Find

Index	1	2	3	4	5	6	7	8	9	10
Parent	1	1	1	6	5	6	5	5	3	10

Make-Set(i)	$p[i] \leftarrow i$; **return** i
Find(i)	**while** $(p[i] \neq i)$ **do** $i \leftarrow p[i]$ **return** i
Union(i, j) [27]	$p[j] \leftarrow i$;

[27] i and j need to be names (roots) of the sets. Otherwise use Union(Find(i),Find(j))

Optimisation of the runtime for Find

Tree may degenerate. Example: Union$(8, 7)$, Union$(7, 6)$, Union$(6, 5)$, ...

Index	1	2	3	4	5	6	7	8	..
Parent	1	1	2	3	4	5	6	7	..

Worst-case running time of Find in $\Theta(n)$.

Optimisation of the runtime for Find

Idea: always append smaller tree to larger tree. Requires additional size information (array) g

Make-Set(i)	$p[i] \leftarrow i$; $g[i] \leftarrow 1$; **return** i
Union(i, j)	**if** $g[j] > g[i]$ **then** swap(i, j) $p[j] \leftarrow i$ **if** $g[i] = g[j]$ **then** $g[i] \leftarrow g[i] + 1$

$\Rightarrow$ Tree depth (and worst-case running time for Find) in $\Theta(\log n)$

[Observation]

Theorem

The method above (union by size) preserves the following property of the trees: a tree of height h has at least 2^h nodes.

Immediate consequence: runtime Find = $\mathcal{O}(\log n)$.

[Proof]

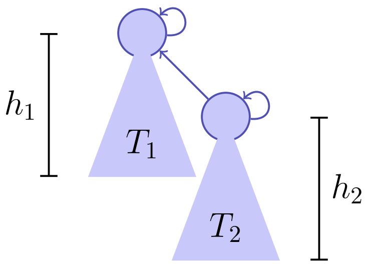
Induction: by assumption, sub-trees have at least 2^{h_i} nodes. WLOG: $h_2 \leq h_1$

- $h_2 < h_1$:

$$h(T_1 \oplus T_2) = h_1 \Rightarrow g(T_1 \oplus T_2) \geq 2^h$$

- $h_2 = h_1$:

$$g(T_1) \geq g(T_2) \geq 2^{h_2}$$
$$\Rightarrow g(T_1 \oplus T_2) = g(T_1) + g(T_2) \geq 2 \cdot 2^{h_2} = 2^{h(T_1 \oplus T_2)}$$



Further improvement

Link all nodes to the root when Find is called.

Find(i):

$j \leftarrow i$
while $(p[i] \neq i)$ **do** $i \leftarrow p[i]$
while $(j \neq i)$ **do**
  $t \leftarrow j$
  $j \leftarrow p[j]$
  $p[t] \leftarrow i$
return i

Cost: amortised *nearly* constant (inverse of the Ackermann-function).[28]

[28] We do not go into details here.

Running time of Kruskal's Algorithm

- Sorting of the edges: $\Theta(|E| \log |E|) = \Theta(|E| \log |V|)$. [29]
- Initialisation of the Union-Find data structure $\Theta(|V|)$
- $|E|\times$ Union(Find(x),Find(y)): $\mathcal{O}(|E| \log |E|) = \mathcal{O}(|E| \log |V|)$.

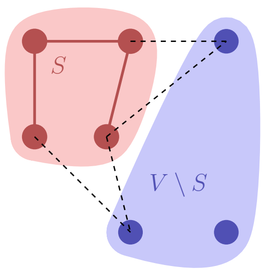
Overal $\Theta(|E| \log |V|)$.

[29] because G is connected: $|V| \leq |E| \leq |V|^2$

Algorithm of Jarnik (1930), Prim, Dijkstra (1959)

Idea: start with some $v \in V$ and grow the spanning tree from here by the acceptance rule.

$A \leftarrow \emptyset$
$S \leftarrow \{v_0\}$
for $i \leftarrow 1$ **to** $|V|$ **do**
  Choose cheapest (u, v) mit $u \in S$, $v \notin S$
  $A \leftarrow A \cup \{(u, v)\}$
  $S \leftarrow S \cup \{v\}$ // (Coloring)



Remark: a union-Find data structure is not required. It suffices to color nodes when they are added to S.

Running time

Trivially $\mathcal{O}(|V| \cdot |E|)$.

Improvement (like with Dijkstra's ShortestPath)

- With Min-Heap: costs
  - Initialization (node coloring) $\mathcal{O}(|V|)$
  - $|V|\times$ ExtractMin = $\mathcal{O}(|V| \log |V|)$,
  - $|E|\times$ Insert or DecreaseKey: $\mathcal{O}(|E| \log |V|)$,

$\mathcal{O}(|E| \cdot \log |V|)$