Greedy Algorithms and Data Compression.

Curs 2016
Greedy Algorithms

An optimization problem: Given of \((\mathcal{S}, f)\), where \(\mathcal{S}\) is a set of feasible elements and \(f: \mathcal{S} \rightarrow \mathbb{R}\) is the objective function, find a \(u \in \mathcal{S}\), which optimizes (maximizes or minimizes) \(f\).

A greedy algorithm always makes a locally optimal choice in the (myopic) hope that this choice will lead to a globally optimal solution.

Greedy algorithms do not always yield optimal solutions, but for some problems they are very efficient.
Greedy Algorithms

- At each step we choose the best choice at the moment and then solve the subproblems that arise later.
- The choice may depend on previous choices, but not on future choices.
- At its choice, the algorithm reduces the problem into a smaller one.
- A greedy algorithm never backtracks.
Greedy Algorithms

For the greedy strategy to work well, it is necessary that the problem under consideration has two characteristics:

- **Greedy choice property**: We can arrive to the global optimum by selecting a local optimums.
- **Optimal substructure**: An optimal solution to the problem contains the optimal solutions to subproblems.
Buying of $n$ software licenses

A company needs to obtain licenses for $n$ different pieces of software. Due to budget restriction, they can only obtain at most one license per month. Each license is currently selling for 100 euros, however they become more expensive each month. If licenses are labelled as 1, 2, 3, ..., $n$, the cost of license $j$ increases by a factor $r_j > 1$ each month (so if the company buys license $j$ in $t$ months, the cost will be $100 \cdot r_j^t$). Assume all price rates are distinct ($r_i \neq r_j$ for $i \neq j$).

INPUT: Given a set of monthly appreciations $r_1, r_2, \ldots, r_n$

QUESTION: Compute the order in which to buy the licenses so that the total amount of money spent is minimized.
The buying of $n$ software licenses: Solution

Idea: Sort $\{r_i\}$! Increasing or decreasing order? Try by small example: let $r_1 = 2$, $r_2 = 3$, $r_3 = 4$:
Buying in increasing order has cost $100(2 + 3^2 + 4^3) = 7500$, in decreasing order has cost $100(4 + 3^2 + 2^3) = 2100$

Therefore increasing order not the best!
So the greedy algorithm seems to be sorting $\{r_i\}$ by decreasing order.

*Buy now the license with highest $r$, next month the license with the second most expensive $r$, etc.*

The complexity of this algorithm is: $T(n) = \mathcal{O}(n \log n)$
Correctness

Proof by contradiction
Let $S$ the solution given by the greedy algorithm, let $O$ be a different optimal solution.
As $S \neq O$ there are at least two months $t$ and $t+1$ s.t. for $S$: $r_i < r_j$ and we pay $r_i$ at $t$ and $r_j$ at $t+1$.
The cost of months $t$ and $t+1$ for $O$: $100(r^t_i + r^{t+1}_j)$
If we use the $S$ algorithm: $100(r^t_j + r^{t+1}_i)$
Therefore: as $r_i > 0 \ \forall i$ and $r_i < r_{i+1}$.
$r^t_i + r^{t+1}_j - (r^t_j + r^{t+1}_i) \Rightarrow r^t_j(r_j - 1) - r^t_i(r_i - 1) > 0$
and the cost of the solution $S < \text{cost of } O$. 
Exercise

Try the greedy approach to a variation of the previous problem: We want to sell licenses and we must exactly sell one every month. The cost of each license depreciates $r_i < 1$ per month. (i.e. the rates are now $< 1$ instead of $> 1$)

Try as input $(3/4, 1/2, 1/100)$
Does the greedy approach work?
Fractional knapsack problem

Fractional Knapsack
INPUT: a set $I = \{i\}_{1}^{n}$ of items that can be fractioned, each $i$ with weight $w_i$ and value $v_i$. A maximum weight $W$ permissible
QUESTION: select the items to maximize the profit, within allowed weight $W$

Example.

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>60</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>Weight</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

$Tw = 28$
Fractional knapsack

**Greedy for fractional knapsack** \((I, V, W)\)

Sort \(I\) in decreasing value of \(v_i/w_i\)

Take the maximum amount of the first \(i\)

**while** total weight taken \(\leq W\) **do**

Take the maximum amount of the next \(i\)

**end while**

If \(n\) is the number of items, The algorithm has a complexity of \(T(n) = O(n + n \log n)\).
Example.

<table>
<thead>
<tr>
<th>Item (l)</th>
<th>Cost (V)</th>
<th>Weight (w)</th>
<th>v/w</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>30</td>
<td>4</td>
</tr>
</tbody>
</table>

As Tw = 28 then take 10 of 1 and 18 of 2
Greedy does not always work (2).

0-1 Knapsack

INPUT: a set $I = \{i\}_{1}^{n}$ of items that can NOT be fractioned, each $i$ with weight $w_i$ and value $v_i$. A maximum weight $W$ permissible

QUESTION: select the items to maximize the profit, within allowed weight $W$.

For example

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
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<td>Cost</td>
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<td>120</td>
</tr>
<tr>
<td>Weight</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>$v/w$</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

$Tw = 50$.

Then any solution which includes item 1 is not optimal. The optimal solution consists of items 2 and 3.
The activity selection problem

Activity Selection Problem
INPUT: a set $S = \{1, 2, \ldots, n\}$ of activities to be processed by a single resource. Each activity $i$ has a start time $s_i$ and a finish time $f_i$, with $f_i > s_i$.
QUESTION: Maximize the set of mutually compatible activities where activities $i$ and $j$ are compatible if $[s_i, f_i) \cap (s_j, f_j] = \emptyset$.

Notice, $\mathcal{S} = \{A | A \subseteq S, A \text{ is compatible} \}$ (where $A$ is a subset of activities) and $f(A) = |A|$.
Example.

Activity (A): \[1 \ 2 \ 3 \ 4 \ 5 \ 6 \ 7 \ 8\]
Start (s): \[3 \ 2 \ 2 \ 1 \ 8 \ 6 \ 4 \ 7\]
Finish (f): \[5 \ 5 \ 3 \ 5 \ 9 \ 9 \ 5 \ 8\]
To apply the greedy technique to a problem, we must take into consideration the following,

- A local criteria to allow the selection,
- a condition to determine if a partial solution can be completed,
- a procedure to test that we have the optimal solution.
The Activity Selection problem.

Given a set $A$ of activities, wish to maximize the number of compatible activities.

**Activity selection $A$**
Sort $A$ by increasing order of $f_i$
Let $a_1, a_2, \ldots, a_n$ the resulting sorted list of activities
$S := \{a_1\}$
$j := 1$ \{pointer in sorted list\}
for $i = 2$ to $n$ do
  if $s_i \geq f_j$ then
    $S := S \cup \{a_i\}$ and $j := i$
  end if
end for
return $S$.

$A : 3 \ 1 \ 2 \ 7 \ 8 \ 5 \ 6; \ f_i : 3 \ 5 \ 5 \ 5 \ 8 \ 9 \ 9$
⇒ SOL: 3 1 8 5
Notice: In the activity problem we are maximizing the number of activities, independently of the occupancy of the resource under consideration. For example in:

solution 3185 is as valid as 3785 (but the algorithm gives the first one). If we were asking for maximum occupancy 456 will be a solution.

How would you modify the previous algorithm to deal with the occupancy problem?
Theorem

The previous algorithm produces an optimal solution to the activity selection problem.

There is an optimal solution that includes the activity with earlier finishing time.

Proof.

Given $A = \{1, \ldots, n\}$ sorted by finishing time, we must show there is an optimal solution that begins with activity 1. Let $S = \{k, \ldots, m\}$ be a solution. If $k = 1$ done. Otherwise, define $B = (S - \{k\}) \cup \{1\}$. As $f_1 \leq f_k$ the activities in $B$ are disjoint. As $|B| = |S|$, $B$ is also an optimal solution. If $S$ is an optimal solution to $A$, then $S' = A - \{1\}$ is an optimal solution for $A' = \{i \in A|s_i \geq f_1\}$. Therefore, after each greedy choice we are left with an optimization problem of the same form as the original. Induction on the number of choices, the greedy strategy produces an optimal solution.
Notice the **the optimal substructure** of the problem: If an optimal solution $S$ to a problem includes $a_k$, then the partial solutions excluding $a_k$ from $S$ should also be optimal in their corresponding domains.
Greedy does not always work.

Weighted Activity Selection Problem
INPUT: a set $S = \{1, 2, \ldots, n\}$ of activities to be processed by a single resource. Each activity $i$ has a start time $s_i$ and a finish time $f_i$, with $f_i > s_i$, and a weight $w_i$.

QUESTION: Find the set of mutually compatible such that it maximizes $\sum_{i \in S} w_i$

```latex
\begin{align*}
S &:= \emptyset \\
sort W = \{w_i\} &\text{by decreasing value} \\
\text{choose the max. weight } &w_m \\
\text{add } m = (l_m, u_m) &\text{ to } S \\
\text{remove all intervals overlapping with } &m \\
\textbf{while} &\text{ there are intervals } \textbf{do} \\
\quad &\text{repeat the greedy procedure} \\
\textbf{end while} \\
\textbf{return} &S
\end{align*}
```

Prove the correctness of the greedy algorithm
Greedy does not always work.

The previous greedy does not always solve the problem!

The algorithm chooses the interval \((1, 10)\) with weight 10, and the solution is the intervals \((2, 5)\) and \((5, 9)\) with total weight of 12.
Minimize Lateness problem

We have a single resource and \( n \) requests to use the resource, each request \( i \) taking a time \( t_i \).

In contrast to the previous problem, each request instead of having an starting and finishing time, it has a deadline \( d_i \). The goal is to schedule the tasks as to minimize the total amount the total time exceeding the deadlines.
Minimize Lateness

- We have a single processor that can process 1 job at the time
- We have \( n \) jobs such that job \( i \):
  - requires \( t_i \) units of processing time,
  - it has to be finished by time \( d_i \),
  - it starts at \( s_i \) (therefore finishes at \( f_i = s_i + t_i \))
- define lateness of \( i \): \( L_i = \max\{0, f_i - d_i\} \)
- we want to \( \min_i \max L_i \)

Goal: schedule the jobs to minimize lateness.
Minimize Lateness

Schedule jobs according to some ordering

(1.-) Sort in increasing order of $t_i$:
Process jobs with short time first

\[
\begin{array}{ccc}
  i & t_i & d_i \\
  1 & 1 & 2 \\
  2 & 5 & 5 \\
\end{array}
\]

(2.-) Sort in increasing order of $d_i - t_i$:
Process first jobs with less slack time

\[
\begin{array}{ccc}
  i & t_i & d_i \\
  1 & 1 & 2 \\
  2 & 10 & 10 \\
\end{array}
\]

$L=1$

$L=9$
Process urgent jobs first

(3.-) Sort in increasing order of $d_i$.

**Lateness** $\{i, t_i, d_i\}$

SORT by increasing order of $d_i$:

$\{d_1, d_2, \ldots, d_n\}$

Rearrange the jobs $i: 1, 2, \ldots, n$

$t = 0$

for $i = 2$ to $n$ do

Assign job $i$ to $[t, t + t_i]$

$t = t + t_i$

$s_i = t; f_i = t + t_i$

end for

return $S = \{[s_1, f_1], \ldots [s_n, f_n]\}$.
Complexity and idle time

Time complexity
Running-time of the algorithm without sorting: $O(n)$
Total running-time: $O(n \lg n)$

Idle steps
From an optimal schedule with idle steps, we always can eliminate gaps to obtain another optimal schedule:

There exists an optimal schedule with no idle steps.
Inversions and exchange argument

We say an schedule has an inversion if job $i$ is scheduled before job $j$ with $d_j < d_i$.

![Diagram of inversions and exchange](image)

**Lemma**

Exchanging two inverted jobs reduces the number of inversions by 1 and does not increase the max lateness.

**Proof** Let $L =$ lateness before exchange and let $L'$ be the lateness after the exchange.

Note, $\forall k \neq i, j \ L'_k = L_k$ and $L'_i = L_i$

If job $j$ is late: $L'_j = f'_j - d_j = f_i - d_i \leq f_i - d_i \leq L_i$
Correctness of LatenessA

Notice the output $S$ produced by LatenessA has no inversions and no idle steps.

Theorem

*Algorithm LatenessA returns an optimal schedule $S$.*

Proof

Assume $\hat{S}$ is an optimal schedule with the minimal number of inversions (and no idle steps).

If $\hat{S}$ has 0 inversions then $\hat{S} = S$.

If number inversions in $\hat{S}$ is $> 0$, let $i - j$ be an adjacent inversion. Exchanging $i$ and $j$ does not increase lateness and decrease the number of inversions.

Therefore, $\max \text{lateness } S \leq \max \text{lateness } \hat{S}$. \qed
Network construction: Minimum Spanning Tree

- We have a set of locations $V = \{v_1, \ldots, v_n\}$,
- we want to build a communication network on top of them
- we want that any $v_i$ can communicate with any $v_j$,
- for any pair $(v_i, v_j)$ there is a cost $w(v_i, v_j)$ of building a direct link,
- if $E$ is the set of all $n^2/2$ possible edges, we want to find a subset $T(E) \subseteq E$ s.t. $(V, T(E))$ is connected and minimizes $\sum_{e \in T(E)} w(e)$. 
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Construct the MST
Minimum Spanning Tree (MST).

INPUT: An edge weighted graph $G = (V, E)$, $|V| = n, \forall e \in E, w(e) \in \mathbb{R}$,

QUESTION: Find a tree $T$ with $V(T) = V$ and $E(T) \subseteq E$, such that it minimizes $w(T) = \sum_{e \in E(T)} w(e)$.
Some previous definitions

Given \( G = (V, E) \):
A path is a sequence of consecutive edges. A cycle is a path with no repeated vertices other than the one that it starts and ends.
A cut is a partition of \( V \) into \( S \) and \( V - S \).
The cut-set of the cut is the edges with one end in \( S \) and the other in \( V - S \).
Overall strategy

Given a MST $T$ in $G$, with different edge weights, $T$ has the following properties:

- **Cut property**
  
  $e \in T \iff e$ is the lighted edge across some cut in $G$.

- **Cycle property**

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

The MST algorithms are methods for ruling edges in or out of $G$.

The $\iff$ implication of the cut property will yield the blue (include) rule, which allow us to include a min weight edge in $T$ for $\exists$ cut.

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

The MST problem has the property of the optimal substructure: Given an optimal MST $T$, removing middle edge $e$ yields $T_1$ and $T_2$ which are optimal.

Theorem (The cut rule)

Given $G = (V, E), w : E \rightarrow \mathbb{R}$, let $T$ be a MST of $G$ and $S \subseteq T$. Let $e = (u, v)$ an min-weight edge in $G$ connecting $S$ to $V - S$. Then $e \in T$.

Proof.
Assume $e \notin T$. Consider a path from $u$ to $v$ in $T$. Replacing the first edge in the path, which is not in $S$, by $e$, must give a spanning tree of equal or less weight.
The cycle rule (Red rule)

The MST problem has the property that the optimal solution must be a tree.

Theorem (The cycle rule)

Given $G = (V, E), w : E \rightarrow \mathbb{R}$, let $C$ be a cycle in $G$, the edge $e \in C$ with greater weight cannot be part of the optimal MST $T$.

Proof.
Let $C$ be a cycle spanning through vertices $\{v_i, \ldots, v_l\}$, then removing the max weighted edge gives a better solution. Consider a path from $u$ to $v$ in $T$. Replacing the first edge in the path, which is not in $S$, by $e$, must give a spanning tree of equal or less weight.

C=cycle spanning {a,c,d,f}
Greedy for MST

*The Min. Spanning Tree problem has the optimal substructure problem we can apply greedy.*

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

Blue rule: Given a cut-set between $S$ and $V - S$ with no blue edges, select a non-colored edge with min weight and paint it blue.

Red rule: Given cycle $C$ with no red edges, select an non-colored edge in $C$ with max weight and paint it blue.

*Greedy scheme:*

Given $G$, $V(G) = n$, apply the red and blue rules until having $n - 1$ blue edges, those form the MST.
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*Greedy scheme:*
Given $G$, $V(G) = n$, apply the red and blue rules until having $n - 1$ blue edges, those form the MST.
Greedy for MST : Correctness

Theorem

There exists a MST $T$ containing only all blue edges. Moreover the algorithm finishes and finds a MST

Sketch of proof Induction on number of iterations for blue and red rules. The base case (no edges colored) is trivial. The induction step is the same that in the proofs of the cut and cycle rules. Moreover if we have an $e$ not colored, if ends are in different blue tree, apply blue rule, otherwise color red $e$. 

We need implementations for the algorithm! The ones we present use only the blue rule
A short history of MSP 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 MSP 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 $O(m \log n)$.

- Fredman and Tarjan (1984) gave a $O(m \log^* n)$ algorithm, introducing a new data structure for priority queues, the Fibonacci heap.

- Gabow, Galil, Spencer and Tarjan (1986) improved Fredman-Tarjan to $O(m \log(\log^* n))$.


- In 1997 B. Chazelle gave an $O(m\alpha(n))$ algorithm.
Basic algorithms

Use the greedy

- **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’s rule. Uses a heap to store the edges to be added and retrieve the lighter one.

- **Kruskal (Serial distributed)** Considers every edge and grows a forest $F$ by using the blue and red rules to include or discard $e$. The insight of the algorithm is to consider the edges in order of increasing weight. This makes the complexity of Kruskal’s to be dominated by $\Omega(m \lg m)$. At the end $F$ becomes $T$. The efficient implementation of the algorithm uses Union-find data structure.
Jarník-Prim vs. Kruskal

Jarník-Prim: How blue man can spread his message to everybody

Kruskal: How to stablish a min distance cost network about all men
Jarník-Prim vs. Kruskal

**Jarník-Prim:** How blue man can spread his message to everybody
(first 6 steps)

**Kruskal:** How to establish a min distance cost network about all men
(6 first edges)
Jarník - Prim greedy algorithm.

V. Jarník, 1936, R. Prim, 1957

Greedy on vertices with Priority queue

Starting with an arbitrary node \( r \), at each step build the MST by incrementing the tree with an edge of minimum weight, which does not form a cycle.

\[
\text{MST} \ (G, w, r) \\
T := \emptyset \\
\text{for } i = 1 \text{ to } |V| \text{ do} \\
\quad \text{Let } e \in E : e \text{ touches } T, \text{ it has min weight, and do not form a cycle} \\
\quad T := T \cup \{e\} \\
\text{end for}
\]
Use a priority queue to choose min e connected to the tree already formed.

For every $v \in V - T$, let $k[v] =$ minimum weight of any edge connecting $v$ to any vertex in $T$.

Start with $k[v] = \infty$ for all $v$.

For $v \in T$, let $\pi[v]$ be the parent of $v$. During the algorithm $T = \{(v, \pi[v]) : v \in V - \{r\} - Q\}$

where $r$ is the arbitrary starting vertex and $Q$ is a min priority queue storing $k[v]$. The algorithm finishes when $Q = \emptyset$. 
\[ w(T) = 52 \]

**Time:** depends on the implementation of \( Q \).

- **\( Q \) 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 greedy algorithm.

J. Kruskal, 1956

Similar to Jarník - Prim, but chooses minimum weight edges, without keeping the graph connected.

**MST** \((G, w, r)\)

Sort \(E\) by increasing weight

\(T := \emptyset\)

for \(i = 1\) to \(|V|\) do

Let \(e \in E\) : with minimum weight and do not form a cycle with \(T\)

\(T := T \cup \{e\}\)

end for

We have an \(O(m \lg m)\) from the sorting the edges. Useful to implement the adding of edges to \(T\) we use **Union-Find** data structure.
Example.
A data structure: Union-Find


A disjoint-set data structure that maintains a collection \( \{S_1, \ldots, S - k\} \) of disjoint dynamic sets, each set identified by a representative.

Union find supports three operations on a set of:
- **Make-set** \((x)\): creates a new set containing \(x\).
- **Union** \((x, y)\): Merge the sets containing \(x\) and \(y\).
- **Find** \((x)\): find to which set \(x\) belongs.
  (i.e. given \(x\) find its representative)

Union-find manipulates all types of objects: names, integers, web-pages, computes ID, . . .

Union-find can be used in a myriad of applications, for ex. to compute the connected components of a graph or implement Kruskal.
Union-find implementation: First idea

Given \{S_1, \ldots, S - k\}, use double links

- Each set \(S_i\) represented by a double linked list.
- The representant of \(S_i\) is defined to be the element at the head of the list representing the set.

- **Make-set** \((x)\): Initializes \(x\) as a lone list. Worst time \(\Theta(1)\).
- **Union** \((x, y)\): Goes to the tail of \(S_x\) and points to head of \(S_y\), concatenating both lists. Worst time \(\Theta(n)\)
- **Find** \((x)\): Goes left from \(x\) to the head of \(S_x\). Worst case \(\Theta(n)\).

Can we do it more efficient?
Union-find implementation: Forest of Trees

Represent each set as a tree of elements:
- The root contains the representative.
- Make-set \((x)\): \(\Theta(1)\)
- Find \((x)\): find the root of the tree containing \(x\). \(\Theta(\text{height})\)
- Union \((x, y)\): make the root on one tree point to the root of the other. How?
Link by rank

Any singleton element has rank=0
Union rule: Link the root of smaller rank tree to the root of larger rank tree.

Think of At the beginning, rank of \( x \) = height of the subtree rooted at \( x \) except for the root, a node does not change rank during the process

- Union \( (x, y) \): climbs to the roots of the tree containing \( x \) and \( y \) and merges sets by making the tree with less rank a subtree of the other tree. The new representant is the representant of the highest rank tree. This takes \( \Theta(\text{height}) \) steps.
Link by rank

Maintain an integer rank for each node, initially 0. Link root of smaller rank to root of larger rank; if a tie, increase rank of new root by 1.

**Make-set** \((x)\)
- parent\((x) = x\)
- rank\((x) = 0\)

**Find** \((x)\)
while \((x \neq \text{parent}(x))\)
do
\(x = \text{parent}(x)\)
end while

**Union** \((x, y)\)
- \(r_x = \text{Find}(x)\)
- \(r_y = \text{Find}(y)\)
if \(r_x = r_y\) then
  Stop
else if \((\text{rank})(r_x) > (\text{rank})(r_y)\) then
  parent\((r_y) = r_x\)
else if \((\text{rank})(r_x) < (\text{rank})(r_y)\) then
  parent\((r_x) = r_y\)
else
  parent\((r_x) = r_y\)
  \((\text{rank})(r_y) = (\text{rank})(r_y) + 1\)
end if
Example construction Union-find
Properties of Link by rank

P1.- If $x$ is not a root then
\[ \text{rank}(x) < \text{rank}(\text{parent}(x)) \]

P2.- If $\text{parent}(x)$ changes then $\text{rank}(\text{parent}(x))$ increases

P3.- Any root of rank $k$ has $\geq 2^k$ descendants.

\textbf{Proof} (Induction on $k$) True for $k = 0$, if true for $k - 1$ then a node of rank $k$ results from the merging of 2 nodes with rank $k - 1$

P4.- The highest rank of a root is $\leq \lfloor \lg n \rfloor$
Properties of Link by rank

P5.- For any $r \geq 0$, there are $\leq n/2^r$ nodes with rank $r$.

Theorem
Using Union-find with link-by-rank, the Union$(x, y)$ and Find$(x)$ operations take $O(\lg n)$ operations.

Proof The number of steps for each operation is bounded by the height of the tree, which is $O(\lg n)$. □
Back to Kruskal

\textbf{MST} \((G, w, r)\)
Sort \(E\) by increasing weight: \(\{e_1, \ldots, e_m\}\)
\(T := \emptyset\)
\textbf{for all} \(v \in V\) \textbf{do}
  \hspace{1em} \text{Make-set}(v)
\textbf{end for}
\textbf{for} \(i = 1\) \textbf{to} \(m\) \textbf{do}
  \hspace{1em} \text{Chose} \(e_i = (u, v)\) in order from \(E\)
  \hspace{1em} \textbf{if} \ \text{Find}(x) \neq \text{Find}(y) \ \textbf{then}
    \hspace{2em} T := T \cup \{e_i\}
    \hspace{2em} \text{Union}(u, v)
  \hspace{1em} \textbf{end if}
\textbf{end for}

Cost is dominated by \(O(m \lg m)\)
Example of Kruskal using Union-Find

\[ E = \{(f, d), (c, d), (e, f), (a, f), (a, e), (c, d), (f, g), (a, c), (a, b), (d, h)\}\]
Example of Kruskal

\[ E = \{(f, d), (c, d), (e, f), (a, f), (a, e), (c, d), (f, g), (a, c), (a, b), (d, h)\}\]
Data Compression

INPUT: Given a text $T$ over an finite alphabet $\Sigma$

QUESTION: Represent $T$ with as few bits as possible.

The goal of data compression is to reduce the time to transmit large files, and to reduce the space to store them. If we are using variable-length encoding we need a system easy to encode and decode.
Example.

\[
\begin{align*}
\text{AAACAGTTGCAT} & \cdots \text{GGTCCCTAGG} \\
130.000.000 \\
\end{align*}
\]

- **Fixed-length encoding:** $A = 00$, $C = 01$, $G = 10$ and $T = 11$. Needs 260Mbites to store.
- **Variable-length encoding:** If $A$ appears $7 \times 10^8$ times, $C$ appears $3 \times 10^6$ times, $G$ $2 \times 10^8$ and $T$ $37 \times 10^7$, better to assign a shorter string to $A$ and longer to $C$.
Prefix property

Given a set of symbols $\Sigma$, a prefix code, is $\phi : \Sigma \rightarrow \{0, 1\}^+$ (symbols to chain of bits) where for distinct $x, y \in \Sigma$, $\phi(x)$ is not a prefix of $\phi(y)$.

If $\phi(A) = 1$ and $\phi(C) = 101$ then $\phi$ is no prefix code.

$\phi(A) = 1, \phi(T) = 01, \phi(G) = 000, \phi(C) = 001$ is prefix code.

Prefix codes easy to decode (left-to-right):
000101100110100000101

```
  000 1 01 1 001 1 01 000 001 01
  G   A   T   A   C   A   T   G   C   T
```
Prefix tree.

Represent encoding with prefix property as a binary tree, the prefix tree:

A prefix tree $T$ is a binary tree with the following properties:

- One leaf for symbol,
- Left edge labeled 0 and right edge labeled 1,
- Labels on the path from the root to a leaf specify the code for that leaf.

For $\Sigma = \{A, T, G, C\}$
Frequency.

To find an efficient code, first given a text $S$ on $\Sigma$, with $|S| = n$, first we must find the frequencies of the alphabet symbols. $
\forall x \in \Sigma$, define the frequency

$$f(x) = \frac{\text{number occurrences of } x \in S}{n}$$

Notice: $\sum_{x \in \Sigma} f(x) = 1$.

Given a prefix code $\phi$, which is the total length of the encoding? The encoding length of $S$ is

$$B(S) = \sum_{x \in \Sigma} nf(x)|\phi(x)| = n \sum_{x \in \Sigma} f(x)|\phi(x)| \cdot \alpha$$
Given $\phi$, $\alpha = \sum_{x \in \Sigma} f(x)|\phi(x)|$ is the average number of bits required per symbol.

In terms of prefix tree of $\phi$, given $x$ and $f(x)$, the length of the codeword $|\phi(x)|$ is also the depth of $x$ in $T$, let us denote it by $d_x(T)$.

Let $B(T) = \sum_{x \in \Sigma} f(x)d_x(T)$. 

Example.

Let $\Sigma = \{a, b, c, d, e\}$ and let $S$ be a text over $\Sigma$.
Let $f(a) = .32, f(b) = .25, f(c) = .20, f(d) = .18, f(e) = .05$
If we use a fixed length code we need $\lceil \lg 5 \rceil = 3$ bits.
Consider the prefix-code $\phi_1$: $\phi_1(a) = 11, \phi_1(b) = 01, \phi_1(c) = 001, \phi_1(d) = 10, \phi_1(e) = 000$

\[
\alpha = .32 \cdot 2 + .25 \cdot 2 + .20 \cdot 3 + .18 \cdot 2 + .05 \cdot 3 = 2.25
\]
In average, $\phi_1$ reduces the bits per symbol over the fixed-length code from 3 to 2.25, about 25%
Is that the maximum reduction?
Consider the prefix-code $\phi_2$:

$\phi_2(a) = 11, \phi_2(b) = 10, \phi_2(c) = 01, \phi_2(d) = 001, \phi_2(e) = 000$

\[
\alpha = .32 \cdot 2 + .25 \cdot 2 + .20 \cdot 2 + .18 \cdot 3 + .05 \cdot 3 = 2.23
\]

is that the best? (the maximal compression)
Optimal prefix code.

Given a text, an optimal prefix code is a prefix code that minimizes the total number of bits needed to encode the text.

Note that an optimal encoding minimizes $\alpha$.

Intuitively, in the $T$ of an optimal prefix code, symbols with high frequencies should have small depth and symbols with low frequency should have large depth.

The search for an optimal prefix code is the search for a $T$, which minimizes the $\alpha$. 
Characterization of optimal prefix trees.

A binary tree $T$ is **full** if every interior node has two sons.

**Lemma**

*The binary prefix tree corresponding to an optimal prefix code is full.*

**Proof.**

Let $T$ be the prefix tree of an optimal code, and suppose it contains a $u$ with a son $v$.

If $u$ is the root, construct $T'$ by deleting $u$ and using $v$ com root. $T'$ will yield a code with less bits to code the symbols. Contradiction to optimality of $T$.

If $u$ is not the root, let $w$ be the father of $u$. Construct $T'$ by deleting $u$ and connecting directly $v$ to $w$. Again this decreases the number of bits, contradiction to optimality of $T$. 

□
Greedy approach: Huffman code

Greedy approach due to David Huffman (1925-99) in 1952, while he was a PhD student at MIT.

Wish to produce a labeled binary full tree, in which the leaves are as close to the root as possible. Moreover symbols with low frequency will be placed deeper than the symbol with high frequency.
Greedy approach: Huffman code

- Given $S$ assume we computed $f(x)$ for every $x \in \Sigma$
- Sort the symbols by increasing $f$. Keep the dynamic sorted list in a priority queue $Q$.

- Construct a tree in bottom-up fashion, take two first elements of $Q$ join them by a new virtual node with $f$ the sum of the $f$’s of its sons, and place the new node in $Q$.

- When $Q$ is empty, the resulting tree will be prefix tree of an optimal prefix code.
Huffman Coding: Construction of the tree.

**Huffman** $\Sigma$, $S$
Given $\Sigma$ and $S$ \{compute the frequencies $\{f\}\}$
Construct priority queue $Q$ of $\Sigma$, ordered by increasing $f$

**while** $Q \neq \emptyset$ **do**

- create a new node $z$
- $x =$ Extract-Min ($Q$)
- $y =$ Extract-Min ($Q$)
- make $x, y$ the sons of $z$
- $f(z) = f(x) + f(y)$
- Insert ($Q, z$)

**end while**

If $Q$ is implemented by a Heap, the algorithm has a complexity $O(n \lg n)$. 
Consider the text: 

\textit{for each rose, a rose is a rose, the rose.}

with \( \Sigma = \{\text{for/ each/ rose/ a/ is/ the/ ,/ b}\} \)

Frequencies: \( f(\text{for}) = 1/21, \ f(\text{rose}) = 4/21, \ f(\text{is}) = 1/21, \)
\( f(\text{a}) = 2/21, \ f(\text{each}) = 1/21, \ f(,) = 2/21, \ f(\text{the}) = 1/21, \)
\( f(b) = 9/21. \)

Priority Queue:
\( Q= (\text{for}(1/21), \ \text{each}(1/21), \ \text{a}(1/21), \ \text{is}(1/21), \ ,(2/21), \ \text{the}(2/21), \)
\( \ \text{rose}(4/21), \ \text{b}(9/21)) \)

\[ Q= (\text{a}(1/21), \ \text{is}(1/21), \ ,(2/21), \ \text{the}(2/21), \ \text{z1}(2/21), \ \text{rose}(4,21), \ \text{b}(9/21)) \]
Example.
Example

Therefore \textit{for each rose, a rose is a rose, the rose} is Huffman codified:
\[100001001011011001010011001011010100110110011110110\]

Notice with a fix code we will use 4 bits per symbol $\Rightarrow$ 84 bits instead of the 53 we use.

Why does the Huffman’s algorithm produce an optimal prefix code?
Correctness.

Theorem (Greedy property)

Let \( \Sigma \) be an alphabet, and \( x, y \) two symbols with the lowest frequency. Then, there is an optimal prefix code in which the code for \( x \) and \( y \) have the same length and differ only in the last bit.

Proof.
For \( T \) optimal with \( a \) and \( b \) sibblings at max. depth. Assume \( f(b) \leq f(a) \). Construct \( T' \) by exchanging \( x \) with \( a \) and \( y \) with \( b \). As \( f(x) \leq f(a) \) and \( f(y) \leq f(b) \) then \( B(T') \leq B(T) \). \( \square \)
Theorem (Optimal substructure)
Assume $T'$ is an optimal prefix tree for $(\Sigma - \{x, y\}) \cup \{z\}$ where $x, y$ are symbols with lowest frequency, and $z$ has frequency $f(x) + f(y)$. The $T$ obtained from $T'$ by making $x$ and $y$ children of $z$ is an optimal prefix tree for $\Sigma$.

Proof.
Let $T_0$ be any prefix tree for $\Sigma$. Must show $B(T) \leq B(T_0)$.
We only need to consider $T_0$ where $x$ and $y$ are siblings. Let $T'_0$ be obtained by removing $x, y$ from $T_0$. As $T'_0$ is a prefix tree for $(\Sigma - \{x, y\}) \cup \{z\}$, then $B(T'_0) \geq B(T')$.
Comparing $T_0$ with $T'_0$ we get,
$B(T'_0) + f(x) + f(y) = B(T_0)$ and $B(T') + f(x) + f(y) = B(T)$.
Putting together the three identities, we get $B(T) \leq B(T_0)$. \qed