Definition 1 (Trust Reduction).
*Let $A, B \in \mathcal{V}$ and x_i flow to $N^+(A)_i$ resulting from $maxFlow(A, B), u_i = DTr_{A \to N^+(A)_i, j-1}, u'_i = DTr_{A \to N^+(A)_i, j}$,
$i \in [|N^+(A)|], j \in \mathbb{N}$.*

1. *The Trust Reduction on neighbour i, δ_i is defined as $\delta_i = u_i - u'_i$.*
2. *The Flow Reduction on neigbour i, Δ_i is defined as $\Delta_i = x_i - u'_i$.*

We will also use the standard notation for 1-norm and ∞-norm, that is:

1. $||\delta_i||_1 = \sum\limits_{i \in N^+(A)} \delta_i$
2. $||\delta_i||_\infty = \max\limits_{i \in N^+(A)} \delta_i$.

Definition 2 (Restricted Flow).
Let $A, B \in \mathcal{V}, i \in [|N^+(A)|]$.

1. *Let $F_{A_i \to B}$ be the flow from A to $N^+(A)_i$ as calculated by the $maxFlow(A, B)$ (x'_i) when $u'_i = u_i$,
$u'_k = 0 \, \forall k \in [|N^+(A)|] \wedge k \neq i$.*
2. *Let $S \subset N^+(A)$. Let $F_{A_S \to B}$ be the sum of flows from A to S as calculated by the $maxFlow(A, B)$ ($\sum\limits_{i=1}^{|S|} x'_i$) when $u'_C = u_C \forall C \in S, u'_D = 0 \, \forall D \in N^+(A) \setminus S$.*

Theorem 1 (Saturation theorem).
Let s source, $n = |N^+(s)|, x_i, i \in [n]$, flows to s's neighbours as calculated by the maxFlow algorithm, u'_i new direct trusts to the n neighbours and x'_i new flows to the neighbours as calculated by the maxFlow algorithm with the new direct trusts, u'_i. It holds that $\forall i \in [n], u'_i \leq x_i \Rightarrow x'_i = u'_i$.

Proof. $\forall i \in [n], x'_i > u'_i$ is impossible because a flow cannot be higher than its corresponding capacity. Thus $\forall i \in [n], x'_i \leq u'_i$. (1)
In the initial configuration of u_i and according to the flow problem setting, a combination of flows y_i such that $\forall i \in [n], y_i = u'_i$ is a valid, albeit not necessarily maximum, configuration with a flow $\sum\limits_{i=1}^{n} y_i$. Suppose that $\exists k \in [n] : x'_k < u'_k$ as calculated by the maxFlow algorithm with the new direct trusts, u'_i. Then for the new maxFlow F' it holds that $F' = \sum\limits_{i=1}^{n} x'_i < \sum\limits_{i=1}^{n} y_i$ since $x'_k < y_k$ and (1) which is impossible because the configuration $\forall i \in [n], x'_i = y_i$ is valid since $\forall i \in [n], y_i = u'_i$ and also has a higher flow, thus the maxFlow algorithm will prefer the configuration with the higher flow. Thus we deduce that $\forall i \in [n], x'_i = u'_i$. □ □

Theorem 2 (Trust transfer theorem (flow terminology)).
Let s source, t sink, $n = N^{+}(s)$
$X = \{x_1, \ldots, x_n\}$ *outgoing flows from s,*
$U = \{u_1, \ldots, u_n\}$ *outgoing capacities from s,*
V *the value to be transferred.*
Nodes apart from s, t follow the conservative strategy.
Obviously $maxFlow = F = \sum_{i=1}^{n} x_i$.

```
          /                    ....                \
         / x_s1/u_s1                    x_1t/u_1t   \
        /                                            \
       /                                              \
      / x_s2/u_s2                         x_2t/u_2t    \
     s-------------            ....      ------------t
      \      .                                  .    /
       \     .                                  .   /
        \    .                                  .  /
         \ x_sn/u_sn           ....     x_mt/u_mt  /
          \                                       /
```

We create a new graph where

1. $\sum_{i=1}^{n} u'_i = F - V$
2. $\forall i \in [n]\ u'_i \leq x_i$

It holds that $maxFlow' = F' = F - V$.

Proof. From theorem 1 we can see that $x'_i = u'_i$. It holds that $F' = \sum_{i=1}^{n} x'_i = \sum_{i=1}^{n} u'_i = F - V$. □ □

Lemma 1 (Flow limit lemma).
It is impossible for the outgoing flow x_i from A to an out neighbour of A to be greater than $F_{A_i \to B}$. More formally, $x_i \leq F_{A_i \to B}$.

Proof. Suppose a configuration where $\exists i : x_i > F_{A_i \to B}$. If we reduce the capacities $u_k, k \neq i$ the flow that passes from i in no case has to be reduced. Thus we can set $\forall k \neq i, u'_k = 0$ and $u'_i = u_i$. Then $\forall k \neq i, x'_k = 0, x'_i = x_i$ is a valid configuration and thus by definition $F_{A_i \to B} = x'_i = x_i > F_{A_i \to B}$, which is a contradiction. Thus $\forall i \in [|N^{+}(A)|], x_i \leq F_{A_i \to B}$. □ □

Theorem 3 (Trust-saving Theorem).
A configuration $U' : u'_i = F_{A_i \to B}$ *for some* $i \in [|N^+(A)|]$ *can yield the same maxFlow with a configuration* $U'' : u''_i = u_i, \forall k \in [|N^+(A)|], k \neq i, u''_k = u'_k$.

Proof. We know that $x_i \leq F_{A_i \to B}$ (lemma 1), thus we can see that any increase in u'_i beyond $F_{A_i \to B}$ will not influence x_i and subsequently will not incur any change on the rest of the flows. □ □

Theorem 4 (Invariable trust reduction with naive algorithms).
Let A source, $n = |N^+(A)|$ *and* u'_i *new direct trusts. If* $\forall i \in [n], u'_i \leq x_i$, *Trust Reduction* $||\delta_i||_1$ *is independent of* x_i, u'_i $\forall$ *valid configurations of* x_i

Proof. Since $\forall i \in [n], u'_i \leq x_i$ it is (according to 1) $x'_i = u'_i$, thus $\delta_i = u_i - x'_i$. We know that $\sum\limits_{i=1}^{n} x'_i = F - V$, so we have $||\delta_i||_1 = \sum\limits_{i=1}^{n} \delta_i = \sum\limits_{i=1}^{n} (u_i - x'_i) = \sum\limits_{i=1}^{n} u_i - F + V$ independent from x'_i, u'_i □ □

Here we show three naive algorithms for calculating new direct trusts so as to maintain invariable risk when paying a trusted party. To prove the correctness of the algorithms, it suffices to prove that $\forall i \in [n]\ u'_i \leq x_i$ and that $\sum\limits_{i=1}^{n} u'_i = F - V$ where $F = \sum\limits_{i=1}^{n} x_i$.

Algorithm 1: First-come, first-served trust transfer

Input : x_i flows, $n = |N^+(s)|$, V value
Output: u'_i capacities

$F \leftarrow \sum\limits_{i=1}^{n} x_i$
if $F < V$ **then**
  return $\perp$
$F_{cur} \leftarrow F$
for $i \leftarrow 1$ *to* n **do**
  $u'_i \leftarrow x_i$
$i \leftarrow 1$
while $F_{cur} > F - V$ **do**
  $reduce \leftarrow \min(x_i, F_{cur} - F + V)$
  $F_{cur} \leftarrow F_{cur} - reduce$
  $u'_i \leftarrow x_i - reduce$
  $i \leftarrow i + 1$
return $U' = \bigcup\limits_{k=1}^{n} \{u'_k\}$

Proof of correctness for algorithm 1.

- We will show that $\forall i \in [n]\ u'_i \leq x_i$.
  Let $i \in [n]$. In line 6 we can see that $u'_i = x_i$ and the only other occurence of u'_i is in line 11 where it is never increased ($\mathit{reduce} \geq 0$), thus we see that, when returned, $u'_i \leq x_i$.
- We will show that $\sum_{i=1}^{n} u'_i = F - V$.
  $F_{cur,0} = F$
  If $F_{cur,i} \geq F - V$, then $F_{cur,i+1}$ does not exist because the *while* loop breaks after calculating $F_{cur,i}$.
  Else $F_{cur,i+1} = F_{cur,i} - \min(x_{i+1}, F_{cur,i} - F + V)$.
  If for some $i, \min(x_{i+1}, F_{cur,i} - F + V) = F_{cur,i} - F + V$, then $F_{cur,i+1} = F - V$, so if $F_{cur,i+1}$ exists, then $\forall k < i, F_{cur,k} = F_{cur,k-1} - x_k \Rightarrow F_{cur,i} = F - \sum_{k=1}^{i} x_k$
  Furthermore, if $F_{cur,i+1} = F - V$ then $u'_{i+1} = x_{i+1} - F_{cur,i} + F - V = x_i - F + \sum_{k=1}^{i-1} x_k + F - V = \sum_{k=1}^{i} x_k - V$, $\forall k \leq i, u'_k = 0$ and $\forall k > i+1, u'_k = x_k$.
  In total, we have $\sum_{k=1}^{n} u'_k = \sum_{k=1}^{i} x_k - V + \sum_{k=i+1}^{n} x_k = \sum_{k=1}^{n} x_k - V \Rightarrow \sum_{k=1}^{n} u'_k = F - V$.

□ □

Complexity of algorithm 1.
First we will prove that on line 13 $i \leq n+1$. Suppose that $i > n+1$ on line 13. This means that $F_{cur,n}$ exists and $F_{cur,n} = F - \sum_{i=1}^{n} x_i = 0 \leq F - V$ since, according to the condition on line 2, $F - V \geq 0$. This means however that the *while* loop on line 8 will break, thus $F_{cur,n+1}$ cannot exist and $i = n+1$ on line 13, which is a contradiction, thus $i \leq n+1$ on line 13. Since i is incremented by 1 on every iteration of the *while* loop (line 12), the complexity of the *while* loop is $O(n)$ in the worst case. The complexity of lines 2 - 4 and 7 is $O(1)$ and the complexity of lines 1, 5 - 6 and 13 is $O(n)$, thus the total complexity of algorithm 1 is $O(n)$. □ □

Algorithm 2: Absolute equality trust transfer ($||\Delta_i||_\infty$ minimizer)

Input : x_i flows, $n = |N^+(s)|$, V value
Output: u'_i capacities

1 $F \leftarrow \sum_{i=1}^{n} x_i$
2 **if** $F < V$ **then**
3   **return** $\perp$
4 **for** $i \leftarrow 1$ *to* n **do**
5     $u'_i \leftarrow x_i$
6 $reduce \leftarrow \frac{V}{n}$
7 $reduction \leftarrow 0$
8 $empty \leftarrow 0$
9 $i \leftarrow 0$
10 **while** $reduction < V$ **do**
11   **if** $u'_i > 0$ **then**
12   **if** $x_i < reduce$ **then**
13             $empty \leftarrow empty + 1$
14   **if** $empty < n$ **then**
15                 $reduce \leftarrow reduce + \frac{reduce - x_i}{n - empty}$
16             $reduction \leftarrow reduction + u'_i$
17             $u'_i \leftarrow 0$
18   **else if** $x_i \geq reduce$ **then**
19             $reduction \leftarrow reduction + u'_i - (x_i - reduce)$
20             $u'_i \leftarrow x_i - reduce$
21     $i \leftarrow (i + 1) mod\, n$
22 **return** $U' = \bigcup_{k=1}^{n} \{u'_k\}$

We will start by showing some results useful for the following proofs. Let j be the number of iterations of the **while** loop for the rest of the proofs for algorithm 2 (think of i from line 21 without the $mod\, n$).
First we will show that $empty \leq n$. *empty* is only modified on line 13 where it is incremented by 1. This happens only when $u'_i > 0$ (line 11), which is assigned the value 0 on line 17. We can see that the incrementation of *empty* can happen at most n times because $|U'| = n$. Since $empty_0 = 0$, $empty \leq n$ at all times of the execution.
Next we will derive the recursive formulas for the various variables.
$empty_0 = 0$

$$empty_{j+1} = \begin{cases} empty_j, & u'_{(j+1)\ mod\ n} = 0 \\ empty_j + 1, & u'_{(j+1)\ mod\ n} > 0 \wedge x_{(j+1)\ mod\ n} < reduce_j \\ empty_j, & u'_{(j+1)\ mod\ n} > 0 \wedge x_{(j+1)\ mod\ n} \geq reduce_j \end{cases}$$

$$reduce_0 = \frac{V}{n}$$

$$reduce_{j+1} = \begin{cases} reduce_j, & u'_{(j+1)\ mod\ n} = 0 \\ reduce_j + \frac{reduce_j - x_{(j+1)\ mod\ n}}{n - empty_{j+1}}, & u'_{(j+1)\ mod\ n} > 0 \wedge x_{(j+1)\ mod\ n} < reduce_j \\ reduce_j, & u'_{(j+1)\ mod\ n} > 0 \wedge x_{(j+1)\ mod\ n} \geq reduce_j \end{cases}$$

$$reduction_0 = 0$$

$$reduction_{j+1} = \begin{cases} reduction_j, & u'_{(j+1)\ mod\ n} = 0 \\ reduction_j + u'_{(j+1)\ mod\ n}, & u'_{(j+1)\ mod\ n} > 0 \wedge x_{(j+1)\ mod} \\ reduction_j + u'_{(j+1)\ mod\ n} - x_{(j+1)\ mod\ n} + reduce_{j+1}, & u'_{(j+1)\ mod\ n} > 0 \wedge x_{(j+1)\ mod} \end{cases}$$

In the end, $r = reduce$ is such that $r = \frac{V - \sum\limits_{x \in S} x}{n - |S|}$ where $S = \{$flows y from s to $N^+(s)$ according to ma $y < r\}$. Also, $\sum\limits_{i=1}^{n} u'_i = \sum\limits_{i=1}^{n} \max(0, x_i - r)$. TOPROVE

Proof of correctness for algorithm 2.

– We will show that $\forall i \in [n]\ u'_i \leq x_i$.
  On line 5, $\forall i \in [n]\ u'_i = x_i$. Subsequently u'_i is modified on line 17, where it becomes equal to 0 and on line 20, where it is assigned $x_i - reduce$. It holds that $x_i - reduce \leq x_i$ because initially $reduce = \frac{V}{n} \geq 0$ and subsequently $reduce$ is modified only on line 15 where it is increased ($n > empty$ because of line 14 and $reduce > x_i$ because of line 12, thus $\frac{reduce - x_i}{n - empty} > 0$). We see that $\forall i \in [n], u'_i \leq x_i$.

– We will show that $\sum\limits_{i=1}^{n} u'_i = F - V$.
  The variable *reduction* keeps track of the total reduction that has happened and breaks the **while** loop when $reduction \geq V$. We will first show that $reduction = \sum\limits_{i=1}^{n} (x_i - u'_i)$ at all times and then we will prove that $reduction = V$ at the end of the execution. Thus we will have proven that $\sum\limits_{i=1}^{n} u'_i = \sum\limits_{i=1}^{n} x_i - V = F - V$.

  - On line 5, $u'_i = x_i \Rightarrow \sum\limits_{i=1}^{n} (x_i - u'_i) = 0$ and $reduction = 0$.

    On line 17, u'_i is reduced to 0 thus $\sum\limits_{i=1}^{n} (x_i - u'_i)$ is increased by u'_i. Similarly, on line 16 *reduction* is increased by u'_i, the same as the increase in $\sum_{i=1}^{n}(x_i - u'_i)$.

On line 20, u'_i is reduced by $u'_i - x_i + reduce$ thus $\sum_{i=1}^{n}(x_i - u'_i)$ is increased by $u'_i - x_i + reduce$. On line 19, *reduction* is increased by $u'_i - x_i + reduce$, which is equal to the increase in $\sum_{i=1}^{n}(x_i - u'_i)$. We also have to note that neither u'_i nor *reduction* is modified in any other way from line 10 and on, thus we conclude that $reduction = \sum_{i=1}^{n}(x_i - u'_i)$ at all times.

- Suppose that $reduction_j > V$ on the line 22. Since $reduction_j$ exists, $reduction_{j-1} < V$. If $x_{j\, mod\, n} < reduce_{j-1}$ then $reduction_j = reduction_{j-1} + u'_{j\, mod\, n}$. Since $reduction_j > V$, $u'_{j\, mod\, n} > V - reduction_{j-1}$. TOCOMPLETE

□ □

Complexity of algorithm 2.
In the worst case scenario, each time we iterate over all capacities only the last non-zero capacity will become zero and every non-zero capacity must be recalculated. This means that every n steps exactly 1 capacity becomes zero and eventually all capacities (maybe except for one) become zero. Thus we need $O(n^2)$ steps in the worst case. □ □

A variation of this algorithm using a Fibonacci heap with complexity $O(n)$ can be created, but that is part of further research.

Proof that algorithm 2 minimizes the $||\Delta_i||_\infty$ norm.
Suppose that U' is the result of an execution of algorithm 2 that does not minimize the $||\Delta_i||_\infty$ norm. Suppose that W is a valid solution that minimizes the $||\Delta_i||_\infty$ norm. Let δ be the minimum value of this norm. There exists $i \in [n]$ such that $x_i - w_i = \delta$ and $u'_i < w_i$. Because both U' and W are valid solutions ($\sum_{i=1}^{n} u'_i = \sum_{i=1}^{n} w_i = F - V$), there must exist a set $S \subset U'$ such that $\forall u'_j \in S, u'_j > w_j$ TOCOMPLETE. □

Algorithm 3: Proportional equality trust transfer

Input : x_i flows, $n = |N^+(s)|$, V value

Output: u_i' capacities

1 $F \leftarrow \sum_{i=1}^{n} x_i$

2 **if** $F < V$ **then**

3   **return** $\perp$

4 **for** $i \leftarrow 1$ *to* n **do**

5     $u_i' \leftarrow x_i - \frac{V}{F} x_i$

6 **return** $U' = \bigcup_{k=1}^{n} \{u_k'\}$

Proof of correctness for algorithm 3.

- We will show that $\forall i \in [n]\ u_i' \leq x_i$.
  According to line 5, which is the only line where u_i' is changed, $u_i' = x_i - \frac{V}{F} x_i \leq x_i$ since $x_i, V, F > 0$ and $V \leq F$.
- We will show that $\sum_{i=1}^{n} u_i' = F - V$.
  With $F = \sum_{i=1}^{n} x_i$, on line 6 it holds that $\sum_{i=1}^{n} u_i' = \sum_{i=1}^{n} (x_i - \frac{V}{F} x_i) = \sum_{i=1}^{n} x_i - \frac{V}{F} \sum_{i=1}^{n} x_i = F - V$.

$\square$ $\square$

Complexity of algorithm 3.
The complexity of lines 1, 4 - 5 and 6 is $O(n)$ and the complexity of lines 2 - 3 is $O(1)$, thus the total complexity of algorithm 3 is $O(n)$. $\square$ $\square$

Naive algorithms result in $u_i' \leq x_i$, thus according to 4, $||\delta_i||_1$ is invariable for any of the possible solutions U', which is not necessarily the minimum (usually it will be the maximum). The following algorithms concentrate on minimizing two δ_i norms, $||\delta_i||_\infty$ and $||\delta_i||_1$.

Algorithm 4: $||\delta_i||_\infty$ minimizer

Input : $X = \{x_i\}$ flows, $n = |N^+(s)|$, V value, ϵ_1, ϵ_2
Output: u'_i capacities

if $\epsilon_1 < 0 \vee \epsilon_2 < 0$ **then**
  return $\perp$
$F \leftarrow \sum_{i=1}^{n} x_i$
if $F < V$ **then**
  return $\perp$
$\delta_{max} \leftarrow \max_{i \in [n]} \{u_i\}$
$\delta^* \leftarrow$ `BinSearch(`$0, \delta_{max}, F\text{-}V, n, X, \epsilon_1, \epsilon_2$`)`
for $i \leftarrow 1$ *to* n **do**
  $u'_i \leftarrow \max(u_i - \delta^*, 0)$
return $U' = \bigcup_{k=1}^{n} \{u'_k\}$

Since trust should be considered as a continuous unit and binary search dissects the possible interval for the solution on each recursive call, inclusion of the ϵ-parameters in `BinSearch` is necessary for the algorithm to complete in a finite number of steps.

Algorithm 5: *

Input : bot, top, F', n, X, ϵ_1, ϵ_2
Output: δ^*

function `BinSearch` **if** $bot = top$ **then**
  return bot
else
  for $i \leftarrow 1$ *to* n **do**
    $u'_i \leftarrow \max(0, u_i - \frac{top+bot}{2})$
  if $maxFlow < F' - \epsilon_1$ **then**
    return `BinSearch(`$bot, \frac{top+bot}{2}, F', n, X, \epsilon_1, \epsilon_2$`)`
  else if $maxFlow > F' + \epsilon_2$ **then**
    return `BinSearch(`$\frac{top+bot}{2}, top, F', n, X.\epsilon_1, \epsilon_2$`)`
  else
    return $\frac{top+bot}{2}$

Proof that $maxFlow(\delta)$ is strictly decreasing for $\delta : maxflow(\delta) < F$. Let $maxFlow(\delta)$ be the $maxFlow$ with $\forall i \in [n], u'_i = max(0, u_i - \delta)$. We will prove that the function $maxFlow(\delta)$ is strictly decreasing for all

$\delta \leq \max\limits_{i\in[n]}\{u_i\}$ such that $maxFlow(\delta) < F$.
Supppose that $\exists\delta_1,\delta_2 : \delta_1 < \delta_2 \wedge maxFlow(\delta_1) \leq maxFlow(\delta_2) < F$. We will work with configurations of $x'_{i,j}$ such that $x'_{i,j} \leq x_i, j \in \{1,2\}$.
Let $S_j = \{i \in N^+(s) : i \in MinCut_j\}$. It holds that $S_1 \neq \emptyset$ because otherwise $MinCut_1 = MinCut_{\delta=0}$ which is a contradiction because then $maxFlow(\delta_1) = F$. Moreover, it holds that $S_1 \subseteq S_2$, since $\forall u'_{i,2} > 0, u'_{i,2} < u'_{i,1}$. Every node in the $MinCut_j$ is saturated, thus $\forall i \in S_1, x'_{i,j} = u'_{i,j}$. Thus $\sum\limits_{i\in S_1} x_{i,2} < \sum\limits_{i\in S_1} x_{i,1}$ and, since $maxFlow(\delta_1) \leq maxFlow(\delta_2)$, we conclude that for the same configurations, $\sum\limits_{i\in N^+(s)\setminus S_1} x_{i,2} > \sum\limits_{i\in N^+(s)\setminus S_1} x_{i,1}$.
However, since $x'_{i,j} \leq x_i, j \in \{1,2\}$, the configuration $[x''_{i,1} = x'_{i,2}, i \in N^+(s)\setminus S_1], [x''_{i,1} = x'_{i,1}, i \in S_1]$ is valid for $\delta = \delta_1$ and then $\sum\limits_{i\in S_1} x''_{i,1} + \sum\limits_{i\in N^+(s)\setminus S_1} x''_{i,1} = \sum\limits_{i\in S_1} x'_{i,1} + \sum\limits_{i\in N^+(s)\setminus S_1} x'_{i,2} > maxFlow(\delta_1)$, contradiction.
Thus $maxFlow(\delta)$ is strictly decreasing. □ □

We can see that if $V > 0, F' = F - V < F$ thus if $\delta \in (0, \max\limits_{i\in[n]}\{u_i\}] : maxFlow(\delta) = F' \Rightarrow \delta = \min ||\delta_i||_\infty : maxFlow(||\delta_i||_\infty) = F'$.

Proof of correctness for function 5.
Supposing that $[F' - \epsilon_1, F' + \epsilon_2] \subset [maxFlow(top), maxFlow(bot)]$, or equivalently $maxFlow(top) \leq F' - \epsilon_1 \wedge maxFlow(bot) \geq F' + \epsilon_2$, we will prove that $maxFlow(\delta^*) \in [F' - \epsilon_1, F' + \epsilon_2]$.
First of all, we should note that if an invocation of `BinSearch` returns without calling `BinSearch` again (line 2 or 11), its return value will be equal to the return value of the initial invocation of `BinSearch`, as we can see on lines 7 and 9, where the return value of the invoked `BinSearch` is returned without any modification. The case where `BinSearch` is called again is analyzed next:

– If $maxFlow(\frac{top+bot}{2}) < F' - \epsilon_1 < F'$ (line 6) then, since $maxFlow(\delta)$ is strictly decreasing, $\delta^* \in [bot, \frac{top+bot}{2})$. As we see on line 7, the interval $(\frac{top+bot}{2}, top]$ is discarded when the next `BinSearch` is called. Since $F' + \epsilon_2 \leq maxFlow(bot)$, we have $[F' - \epsilon_1, F' + \epsilon_2] \subset [maxFlow(\frac{top+bot}{2}), maxFlow(bot)]$ and the length of the available interval is divided by 2.
– Similarly, if $maxFlow(\frac{top+bot}{2}) > F' + \epsilon_2 > F'$ (line 8) then $\delta^* \in (\frac{top+bot}{2}, top]$. According to line 9, the interval $[bot, \frac{top+bot}{2})$ is discarded when the next `BinSearch` is called. Since $F' - \epsilon_1 \geq maxFlow(top)$, we have $[F' - \epsilon_1, F' + \epsilon_2] \subset (maxFlow(top), maxFlow(\frac{top+bot}{2})]$ and the length of the available interval is divided by 2.

As we saw, $[F' - \epsilon_1, F' + \epsilon_2] \subset [maxFlow(top), maxFlow(bot)]$ in every recursive call and $top - bot$ is divided by 2 in every call. From topology we know that $A \subset B \Rightarrow |A| < |B|$, so the recursive calls cannot continue infinitely. $|[F' - \epsilon_1, F' + \epsilon_2]| = \epsilon_1 + \epsilon_2$. Let bot_0, top_0 the input values given to the initial invocation of `BinSearch`, bot_j, top_j the input values given to the j-th recursive call of `BinSearch` and $len_j = |[bot_j, top_j]| = top_j - bot_j$. We have $\forall j > 0, len_j = top_j - bot_j = \frac{top_{j-1} - bot_{j-1}}{2} \Rightarrow \forall j > 0, len_j = \frac{top_0 - bot_0}{2^j}$. We understand that in the worst case $len_j = \epsilon_1 + \epsilon_2 \Rightarrow 2^j = \frac{top_0 - bot_0}{\epsilon_1 + \epsilon_2} \Rightarrow j = \log_2(\frac{top_0 - bot_0}{\epsilon_1 + \epsilon_2})$. Also, as we saw earlier, δ^* is always in the available interval, thus $maxFlow(\delta^*) \in [F' - \epsilon_1, F' + \epsilon_2]$. □ □

Complexity of function 5.
Lines 1 - 2 have complexity $O(1)$, lines 4 - 5 have complexity $O(n)$, lines 6 - 11 have complexity $O(maxFlow) + O(BinSearch)$. As we saw in the proof of correctness for function 5, we need at most $\log_2(\frac{top - bot}{\epsilon_1 + \epsilon_2})$ recursive calls of `BinSearch`. Thus the function 5 has worst-case complexity $O((maxFlow + n)\log_2(\frac{top - bot}{\epsilon_1 + \epsilon_2}))$. □ □

Proof of correctness for algorithm 4.
We will show that $maxFlow \in [F - V - \epsilon_1, F - V + \epsilon_2]$, with u_i' decided by algorithm 4.
Obviously $maxFlow(0) = F, maxFlow(\max_{i \in [n]}\{u_i\}) = 0$, thus $\delta^* \in \max_{i \in [n]}\{u_i\}$.
According to the proof of correctness for function 5, we can directly see that $maxFlow(\delta^*) \in [F - V - \epsilon_1, F - V + \epsilon_2]$, given that ϵ_1, ϵ_2 are chosen so that $F - V - \epsilon_1 \geq 0, F - V + \epsilon_2 \leq F$, so as to satisfy the condition $[F' - \epsilon_1, F' + \epsilon_2] \subset [maxFlow(top), maxFlow(bot)]$. □ □

Complexity of algorithm 4.
The complexity of lines 1 - 2 and 4 - 5 is $O(1)$, the complexity of lines 3, 6, 8 - 9 and 10 is $O(n)$ and the complexity of line 7 is $O(BinSearch) = O((maxFlow + n)\log_2(\frac{\delta_{max}}{\epsilon_1 + \epsilon_2}))$, thus the total complexity of algorithm 4 is $O((maxFlow + n)\log_2(\frac{\delta_{max}}{\epsilon_1 + \epsilon_2}))$. □ □

However, we need to minimize $\sum_{i=1}^{n}(u_i - u_i') = ||\delta_i||_1$.