

Let  $A \in \mathcal{V}$  source,  $B \in \mathcal{V}$  sink. For the following, we suppose that  $Turn_{j-1}$  has just finished and  $A = Player(j)$  is currently deciding  $Turn_j$ . We use the following notation:

$$\begin{aligned} c_{Av} &= DTr_{A \rightarrow v, j-1} \\ c'_{Av} &= DTr_{A \rightarrow v, j} \end{aligned}$$

Moreover,  $X$  and  $X'$  will be the flows returned by some execution of  $MaxFlow_{G_{j-1}}(A, B)$  and  $MaxFlow_{G_j}(A, B)$  respectively.

Furthermore, we suppose an arbitrary ordering of the members of  $N^+(A)$ . We set  $n = |N^+(A)|$ . Thus

$$N^+(A) = \{v_1, \dots, v_n\}$$

We use these subscripts to refer to the respective capacities (a.k.a. direct trusts) and flows. Thus

$$\begin{aligned} x_i &= x_{Av_i} \text{ , where } i \in [n] \\ c_i &= c_{Av_i} \text{ ,} \end{aligned}$$

**Definition 1 (Trust Reduction).**

*Trust Reduction on neighbour  $i$  is defined as  $\delta_i = c_i - c'_i$ .*

*Flow Reduction on neighbour  $i$  is defined as  $\Delta_i = x_i - c'_i$ .*

*We will also use the standard notation for 1-norm and  $\infty$ -norm:*

$$\begin{aligned} \|\delta_i\|_1 &= \sum_{i=1}^n \delta_i \\ \|\delta_i\|_\infty &= \max_{1 \leq i \leq n} \delta_i \end{aligned}$$

**Definition 2 (Restricted Flow).**

*Let  $i \in [n]$ . Let  $F_{A_i \rightarrow B}$  be  $x'_i$  when:*

$$\begin{aligned} c'_i &= c_i \text{ and} \\ \forall k \in [n] \setminus \{i\}, c'_k &= 0 \text{ .} \end{aligned}$$

*This definition can be rephrased equivalently as follows:*

*Let  $v \in N^+(A)$ . Let  $F_{A_v \rightarrow B}$  be  $x'_{Av}$  when:*

$$\begin{aligned} c'_{Av} &= c_{Av} \text{ and} \\ \forall w \in N^+(A) \setminus \{v\}, c'_{Aw} &= 0 \text{ .} \end{aligned}$$

Let  $L \subset [n]$ . Let  $F_{A \rightarrow B}$  be  $\sum_{i \in L} x'_i$  when:

$$\begin{aligned} \forall i \in L, c'_i &= c_i \text{ and} \\ \forall i \in [n] \setminus L, c'_i &= 0 . \end{aligned}$$

The latter definition can be rephrased equivalently as follows:

Let  $S \subset N^+(A)$ . Let  $F_{A \rightarrow B}$  be  $\sum_{v \in S} x'_{Av}$  when:

$$\begin{aligned} \forall v \in S, c'_{Av} &= c_{Av} \text{ and} \\ \forall v \in N^+(A) \setminus S, c'_{Av} &= 0 . \end{aligned}$$

The choice of the definition will depend on whether  $K$  in  $F_{A \rightarrow B}$  is a node, an index or a set of nodes or indices.

**Theorem 1 (Saturation theorem).**

$$(\forall i \in [n], c'_i \leq x_i) \Rightarrow (\forall i \in [n], x'_i = c'_i)$$

*Proof.* From the flow definition we know that

$$\forall i \in [n], x'_i \leq c'_i . \quad (1)$$

In turn  $j - 1$ , there exists some valid flow  $Y$  such that

$$\forall i \in [n], y_i = c'_i$$

with a flow value  $\sum_{i=1}^n y_i$ , which can be created as follows: We start from  $X$  and for each  $(A, v_i)$  edge we reduce the flow along paths starting from this edge for a total reduction of  $x_i - c'_i$  on all those paths.  $Y$  is also obviously valid for turn  $j$  and, since all capacities  $c'_i$  are saturated, there can be no more outgoing flow from the source, thus  $Y$  is a maximum flow in  $\mathcal{G}_j$ .  $\square$

**Theorem 2 (Trust transfer theorem (flow terminology)).**

Let  $A$  source,  $B$  sink. We create a new graph where

$$\begin{aligned} \forall i \in [n], c'_i &\leq x_i \text{ and} \\ \sum_{i=1}^n c'_i &= F - V . \end{aligned}$$

It then holds that  $\maxFlow_{\mathcal{G}_j}(A, B) = F' = F - V$ .

*Proof.* From theorem 1 we can see that  $x'_i = c'_i$ . It holds that

$$F' = \sum_{i=1}^n x'_i = \sum_{i=1}^n c'_i = F - V \ .$$

□

**Lemma 1 (Flow limit lemma).**

$$\forall i \in [n], x_i \leq F_{A_i \rightarrow B}$$

*Proof.* Suppose a flow where  $\exists i \in [n] : x_i > F_{A_i \rightarrow B}$ . If for any  $k \neq i$  we choose  $c'_k < c_k$ , then  $x'_i \geq x_i$ . We set the new capacities as follows:

$$\begin{aligned} \forall k \neq i, c'_k &= 0 \text{ and} \\ c'_i &= c_i \ . \end{aligned}$$

Then for  $X'$  we will have

$$\begin{aligned} \forall k \neq i, x'_k &= 0 \text{ and} \\ x'_i &= x_i \ , \end{aligned}$$

which is also a valid flow for  $\mathcal{G}_{j-1}$  and thus by definition

$$F_{A_i \rightarrow B} = x'_i = x_i > F_{A_i \rightarrow B} \ ,$$

which is a contradiction. Thus the proposition holds. □

**Theorem 3 (Trust Saving Theorem).**

*Suppose some  $i \in [n]$  and two alternative capacities configurations, say  $C'_1$  and  $C'_2$  such that*

$$\begin{aligned} c'_{1,i} &= F_{A_i \rightarrow B} \ , \\ c'_{2,i} &= c_i \ , \\ \forall k \in [n] \setminus \{i\}, c'_{1,k} &= c'_{2,k} \ . \end{aligned}$$

*Then  $\maxFlow_1 = \maxFlow_2$ .*

*Proof.* From the Flow Limit lemma (1) we know that  $x_i \leq F_{A_i \rightarrow B}$ , thus we can see that any increase in  $c'_i$  beyond  $F_{A_i \rightarrow B}$  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).**

*If  $\forall i \in [n], c'_i \leq x_i$ , then  $\|\delta_i\|_1$  and  $\|\Delta_i\|_1$  are independent of  $x'_i, c'_i$ .*

*Proof.* Since  $\forall i \in [n], c'_i \leq x_i$ , by applying the Saturation theorem (1) we see that  $x'_i = c'_i$ , thus  $\delta_i = c_i - x'_i$  and  $\Delta_i = x_i - x'_i$ . We know that  $\sum_{i=1}^n x'_i = F - V$ , so we have

$$\begin{aligned} \|\delta_i\|_1 &= \sum_{i=1}^n \delta_i = \sum_{i=1}^n (c_i - x'_i) = \sum_{i=1}^n c_i - F + V \text{ and} \\ \|\Delta_i\|_1 &= \sum_{i=1}^n \Delta_i = \sum_{i=1}^n (x_i - x'_i) = \sum_{i=1}^n x_i - F + V . \end{aligned}$$

thus  $\|\delta_i\|_1, \|\Delta_i\|_1$  are independent from  $x'_i$  and  $c'_i$ .  $\square$

Until now *MaxFlow* has been viewed purely as an algorithm. This algorithm is not guaranteed to always return the same flow when executed multiple times on the same graph. However, the corresponding flow value, *maxFlow*, is always the same. Thus *maxFlow* can be also viewed as a function from a matrix of capacities to a positive real number. Under this perspective, we prove the following theorem. Let  $\mathcal{C}$  be the family of all capacity matrices  $C = [c_{vw}]_{V(\mathcal{G}) \times V(\mathcal{G})}$ .

**Theorem 5 (maxFlow continuity).**

*Let  $p \in \mathbb{N} \cup \{\infty\}$ . The function  $\text{maxFlow} : \mathcal{C} \rightarrow \mathbb{R}^+$  is continuous with respect to the  $\|\cdot\|_p$  norm.*

*Proof.* Let  $C_0 \in \mathcal{C}$ . We want to prove that

$$\forall \epsilon > 0, \exists \delta > 0 : 0 < \|C - C_0\|_p < \delta \Rightarrow |\text{maxFlow}(C) - \text{maxFlow}(C_0)| < \epsilon .$$

We will prove it by contradiction. Suppose that

$$\exists \epsilon > 0 : \forall \delta > 0, 0 < \|C - C_0\|_p < \delta \Rightarrow |\text{maxFlow}(C) - \text{maxFlow}(C_0)| \geq \epsilon .$$

Let  $v_1, u_1 \in V(\mathcal{G})$ . Let  $C$  such that

$$\begin{aligned} c_{v_1 u_1} &= c_{0, v_1 u_1} + \frac{\epsilon}{2} \\ \forall (v, u) \in E(\mathcal{G}) \setminus \{(v_1, u_1)\}, c_{vu} &= c_{0, vu} . \end{aligned}$$

Due to the construction, for  $\delta = \epsilon$  we have

$$0 < \|C - C_0\|_p < \delta . \tag{2}$$

Any valid flow for  $C_0$  is also valid for  $C$ , thus

$$\text{maxFlow}(C_0) \leq \text{maxFlow}(C) . \tag{3}$$

Also, it is obvious by the way that  $C$  was constructed that

$$\maxFlow(C) \leq \maxFlow(C_0) + \frac{\epsilon}{2} \quad (4)$$

From (3) we have  $\maxFlow(C_0) \leq \maxFlow(C) + \frac{\epsilon}{2}$ , which, in combination with (4), gives

$$|\maxFlow(C) - \maxFlow(C_0)| \leq \frac{\epsilon}{2} < \epsilon ,$$

which, together with (2) contradicts our supposition. Thus  $\maxFlow$  is continuous on  $C_0$ . Since  $C_0$  is arbitrary, the result holds for all  $C_0 \in \mathcal{C}$ , thus  $\maxFlow$  is continuous with respect to  $\|\cdot\|_p$  for any  $p \in \mathbb{N} \cup \{\infty\}$ .  $\square$

Here we show three naive algorithms for calculating new direct trusts so as to maintain invariable risk when paying a trusted party. Let  $F = \sum_{i=1}^n x_i$ . To prove the correctness of the algorithms, it suffices to prove that

$$\forall i \in [n], c'_i \leq x_i \text{ and} \quad (5)$$

$$\sum_{i=1}^n c'_i = F - V . \quad (6)$$

**First Come First Served Trust Transfer**

Input : old flows  $x_i$ , value  $V$

Output : new capacities  $c'_i$

```

1 fcfs( $(x_i)$ ,  $V$ ) :
2    $n = \text{length}(x_i)$ 
3    $F_{cur} = F = \sum_{i=1}^n x_i$ 
4   if ( $F < V$ )
5     return( $\perp$ )
6   for ( $i = 1$  to  $n$ )
7      $c'_i = x_i$ 
8      $i = 1$ 
9   while ( $F_{cur} > F - V$ )
10     $\text{reduce} = \min(x_i, F_{cur} - (F - V))$ 
11     $F_{cur} = F_{cur} - \text{reduce}$ 
12     $c'_i = x_i - \text{reduce}$ 
13     $i += 1$ 
14  return( $\bigcup_{i=1}^n \{c'_i\}$ )
```

*Proof of correctness for fcfs.*

We will first show that at the end of the execution,  $i \leq n+1$ . Suppose that  $i > n+1$  on line 14. 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 4,  $F - V \geq 0$ . This means however that the **while** loop on line 9 will break, thus  $F_{cur,n+1}$  cannot exist and  $i = n+1$  on line 14, which is a contradiction, thus the first proposition holds. We can also note that, even if  $i = n+1$  at the end of the execution, the **while** loop will break right after the last incrementation, thus the algorithm will never try to read or write the nonexistent objects  $x_{n+1}, c'_{n+1}$ .

We will now show that  $\forall i \in [n], c'_i \leq x_i$ , as per the requirement (5). Let  $i \in [n]$ . In line 7 we can see that  $c'_i = x_i$  and the only other occurrence of  $c'_i$  is in line 12 where it is never increased ( $reduce \geq 0$ ), thus we see that the requirement (5) is satisfied.

We will finally show that  $\sum_{i=1}^n c'_i = F - V$ . From line 3 we see that  $F_{cur,0} = F$ . Let  $i \in [n]$  such that  $F_{cur,i}$  exists. If  $F_{cur,i} \leq F - V$ , then  $F_{cur,i+1}$  does not exist because the **while** loop (line 9) breaks after calculating  $F_{cur,i}$ . Else

$$F_{cur,i+1} = F_{cur,i} - \min(x_{i+1}, F_{cur,i} - F + V) \quad . \quad (\text{lines 10- 11})$$

If  $\nexists i \in [n] : \min(x_i, F_{cur,i-1} - (F - V)) = F_{cur,i-1} - (F - V)$ , then  $\forall i \in [n], \min(x_i, F_{cur,i} - (F - V)) = x_i$ , thus from line 12 it will be  $\forall i \in [n], c'_i = 0$  and from line 11,  $F_{cur,n} = 0$ . However, we have

$$\left. \begin{array}{l} \min(x_n, F_{cur,n-1} - (F - V)) \neq F_{cur,n-1} - (F - V) \\ F_{cur,n-1} = x_n \end{array} \right\} \Rightarrow \\ \Rightarrow x_n < x_n - (F - V) \Rightarrow F < V$$

which is a contradiction, since if this were the case the algorithm would have failed on lines 4 - 5. Thus

$$\exists i \in [n] : \min(x_{i+1}, F_{cur,i} - (F - V)) = F_{cur,i} - (F - V)$$

That is the only  $i \in [n]$  such that  $F_{cur,i+1} = F - V$ , so

$$\forall 0 < k < i, F_{cur,k} = F_{cur,k-1} - x_k \Rightarrow F_{cur,i} = F - \sum_{k=1}^{i-1} x_k \quad .$$

Furthermore, since  $F_{cur,i+1} = F - V$ , it is

$$\begin{aligned} c'_{i+1} &= x_{i+1} - F_{cur,i} + F - V = x_i - F + \sum_{k=1}^{i-1} x_k + F - V \Rightarrow \\ &\Rightarrow c'_{i+1} = \sum_{k=1}^i x_k - V, \\ &\forall k \leq i, c'_k = 0 \text{ and} \\ &\forall k > i + 1, c'_k = x_k. \end{aligned}$$

In total, we have

$$\sum_{k=1}^n c'_k = \sum_{k=1}^i x_k - V + \sum_{k=i+1}^n x_k = \sum_{k=1}^n x_k - V \Rightarrow \sum_{k=1}^n c'_k = F - V.$$

Thus the requirement (6) is satisfied.  $\square$

*Complexity of algorithm fcfs.* Since  $i$  is incremented by 1 on every iteration of the **while** loop (line 13) and  $i < n + 1$  at the end of the execution, the complexity of the **while** loop is  $O(n)$  in the worst case. The complexity of lines 4 - 5 and 8 is  $O(1)$  and the complexity of lines 3, 6 - 7 and 14 is  $O(n)$ , thus the total complexity of algorithm is  $O(n)$ .  $\square$

**Absolute Equality Trust Transfer (  $\|\Delta_i\|_\infty$  minimizer)**

Input : old flows  $x_i$ , value  $V$

Output : new capacities  $c'_i$

```

1  abs(( $x_i$ ), V) :
2    n = length( $x_i$ )
3     $F_{cur} = F = \sum_{i=1}^n x_i$ 
4    if ( $F < V$ )
5      return( $\perp$ )
6    X = preprocess( $x_i$ )
7    empty = 0
8    reduction = 0
9    while ( $F_{cur} > F - V$ )
10     ( $i, X$ ) = popMin(X)
11      $F_{prov} = F_{cur} - (n - \text{empty}) * (x_i - \text{reduction})$ 
12     if ( $F_{prov} > F - V$ )
13       reduction =  $x_i$ 
14       empty += 1
```

```

15     Fcur = Fprov
16   else
17     aux = reduction
18     reduction +=  $\frac{F_{cur} - (F - V)}{n - \text{empty}}$ 
19     Fcur -= (n - empty)*(reduction - aux)
20     #lines 17 & 19 can be replaced by break. In this
21     #case, the loop (line 9) can become while (TRUE).
22   for (i = 1 to n)
23     c'i = max(0, xi - reduction)
24   return( $\bigcup_{i=1}^n \{c'_i\}$ )

```

The function `preprocess(xi)` returns a data structure **X** containing the set of flows (x<sub>i</sub>), such that the corresponding function `popMin(X)` is able to repeatedly return the index of a tuple consisting of the index of the minimum element and a new data structure missing exactly the minimum element. Examples of such pairs of functions are:

$$\begin{cases} \text{preprocess} = \text{quickSort} \\ \text{popMin} = (x_1, X \setminus x_1) \end{cases} \quad \text{and} \quad \begin{cases} \text{preprocess} = \text{FibonacciHeap} \\ \text{popMin} = (\text{find-min}(X), \text{delete-min}(X)) \end{cases} .$$

*Proof of correctness of abs.* We will first show that  $\forall i \in [n], c'_i \leq x_i$ , as per the requirement (5). From line 23, we see that it suffices to prove that `reduction`  $\geq 0$ . On line 8, `reduction` is initialized to 0. On line 13, `reduction` is set to x<sub>i</sub>, which is always a non-negative value. The last line where `reduction` is modified is 18.

We will now show that  $\sum_{i=1}^n c'_i = F - V$ . □



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**Algorithm 1:** Proportional equality trust transfer

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**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  $U' = \bigcup_{k=1}^n \{u'_k\}$ 

```

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*Proof of correctness for algorithm 1.* – 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  $\sum_{i=1}^n u'_i = \sum_{i=1}^n (x_i - \frac{V}{F}x_i) = \sum_{i=1}^n x_i - \frac{V}{F} \sum_{i=1}^n x_i = F - V$ .

□

*Complexity of algorithm 1.* 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 1 is  $O(n)$ . □

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  $\delta_i$  norms,  $\|\delta_i\|_\infty$  and  $\|\delta_i\|_1$ .

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**Algorithm 2:**  $\|\delta_i\|_\infty$  minimizer

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**Input** :  $X = \{x_i\}$  flows,  $n = |N^+(s)|$ ,  $V$  value,  $\epsilon_1, \epsilon_2$   
**Output:**  $u'_i$  capacities

```

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

```

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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  $\epsilon$ -parameters in **BinSearch** is necessary for the algorithm to complete in a finite number of steps.

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**Algorithm 3:** \*

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**Input** :  $bot, top, F', n, X, \epsilon_1, \epsilon_2$   
**Output:**  $\delta^*$

```

1 function BinSearch if  $bot = top$  then
2   | return  $bot$ 
3 else
4   | for  $i \leftarrow 1$  to  $n$  do
5     |  $u'_i \leftarrow \max(0, u_i - \frac{top+bot}{2})$ 
6     | if  $maxFlow < F' - \epsilon_1$  then
7       | return BinSearch( $bot, \frac{top+bot}{2}, F', n, X, \epsilon_1, \epsilon_2$ )
8     | else if  $maxFlow > F' + \epsilon_2$  then
9       | return BinSearch( $\frac{top+bot}{2}, top, F', n, X, \epsilon_1, \epsilon_2$ )
10    | else
11      | return  $\frac{top+bot}{2}$ 

```

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*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

$\delta \leq \max_{i \in [n]} \{u_i\}$  such that  $\maxFlow(\delta) < F$ .

Suppose 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  $\sum_{i \in S_1} x_{i,2} < \sum_{i \in S_1} x_{i,1}$  and, since  $\maxFlow(\delta_1) \leq \maxFlow(\delta_2)$ ,

we conclude that for the same configurations,  $\sum_{i \in N^+(s) \setminus S_1} x_{i,2} > \sum_{i \in N^+(s) \setminus S_1} x_{i,1}$ .

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  $\sum_{i \in S_1} x''_{i,1} +$

$\sum_{i \in N^+(s) \setminus S_1} x''_{i,1} = \sum_{i \in S_1} x'_{i,1} + \sum_{i \in N^+(s) \setminus S_1} x'_{i,2} > \maxFlow(\delta_1)$ , contradiction.

Thus  $\maxFlow(\delta)$  is strictly decreasing.  $\square$

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

*Proof of correctness for function 3.* 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,  $\delta^*$  is always in the available interval, thus  $\maxFlow(\delta^*) \in [F' - \epsilon_1, F' + \epsilon_2]$ .  $\square$

*Complexity of function 3.* Lines 1 - 2 have complexity  $O(1)$ , lines 4 - 5 have complexity  $O(n)$ , lines 6 - 11 have complexity  $O(\maxFlow) + O(\text{BinSearch})$ . As we saw in the proof of correctness for function 3, we need at most  $\log_2(\frac{top - bot}{\epsilon_1 + \epsilon_2})$  recursive calls of **BinSearch**. Thus the function 3 has worst-case complexity  $O((\maxFlow + n) \log_2(\frac{top - bot}{\epsilon_1 + \epsilon_2}))$ .  $\square$

*Proof of correctness for algorithm 2.* We will show that  $\maxFlow \in [F - V - \epsilon_1, F - V + \epsilon_2]$ , with  $u'_i$  decided by algorithm 2. 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 3, we can directly see that  $\maxFlow(\delta^*) \in [F - V - \epsilon_1, F - V + \epsilon_2]$ , given that  $\epsilon_1, \epsilon_2$  are chosen so that  $F - V - \epsilon_1 \geq 0, F - V + \epsilon_2 \leq F$ , so as to satisfy the condition  $[F' - \epsilon_1, F' + \epsilon_2] \subset [\maxFlow(top), \maxFlow(bot)]$ .  $\square$

*Complexity of algorithm 2.* 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  $O(\text{BinSearch}) = O((\maxFlow + n) \log_2(\frac{\delta_{\max}}{\epsilon_1 + \epsilon_2}))$ , thus the total complexity of algorithm 2 is  $O((\maxFlow + n) \log_2(\frac{\delta_{\max}}{\epsilon_1 + \epsilon_2}))$ .  $\square$

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