

Preflows

Definition 1

An (s, t) -preflow is a function $f : E \mapsto \mathbb{R}^+$ that satisfies

For each edge e

$$0 \leq f(e) \leq c(e)$$

(flow conservation)

for each $v \in V \setminus \{s, t\}$

$$\sum_{e \in E^+(v)} f(e) = \sum_{e \in E^-(v)} f(e)$$

Preflows

Definition 1

An (s, t) -preflow is a function $f : E \mapsto \mathbb{R}^+$ that satisfies

1. For each edge e

$$0 \leq f(e) \leq c(e) .$$

(capacity constraints)

2. For each $v \in V \setminus \{s, t\}$

$$\sum_{e \in \text{out}(v)} f(e) \leq \sum_{e \in \text{into}(v)} f(e) .$$

Definition 1

An (s, t) -preflow is a function $f : E \mapsto \mathbb{R}^+$ that satisfies

1. For each edge e

$$0 \leq f(e) \leq c(e) .$$

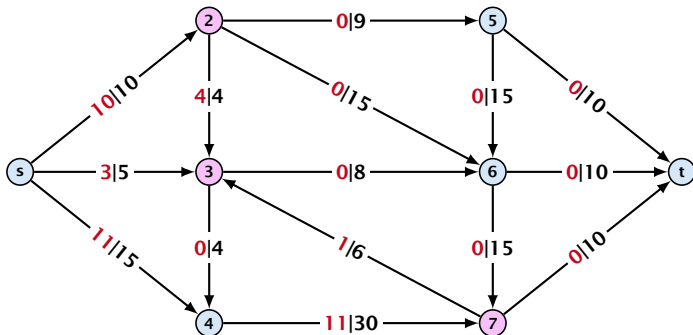
(capacity constraints)

2. For each $v \in V \setminus \{s, t\}$

$$\sum_{e \in \text{out}(v)} f(e) \leq \sum_{e \in \text{into}(v)} f(e) .$$

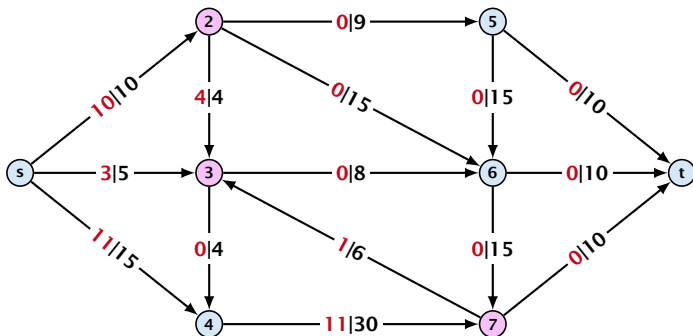
Preflows

Example 2



Preflows

Example 2



A node that has $\sum_{e \in \text{out}(v)} f(e) < \sum_{e \in \text{into}(v)} f(e)$ is called an **active node**.

Preflows

Preflows

Definition:

A **labelling** is a function $\ell : V \rightarrow \mathbb{N}$. It is **valid** for preflow f if

- ▶ $\ell(u) \leq \ell(v) + 1$ for all edges in the residual graph G_f (only non-zero capacity edges!!!)

Preflows

Definition:

A **labelling** is a function $\ell : V \rightarrow \mathbb{N}$. It is **valid** for preflow f if

- ▶ $\ell(u) \leq \ell(v) + 1$ for all edges in the residual graph G_f (only non-zero capacity edges!!!)
- ▶ $\ell(s) = n$

Preflows

Definition:

A **labelling** is a function $\ell : V \rightarrow \mathbb{N}$. It is **valid** for preflow f if

- ▶ $\ell(u) \leq \ell(v) + 1$ for all edges in the residual graph G_f (only non-zero capacity edges!!!)
- ▶ $\ell(s) = n$
- ▶ $\ell(t) = 0$

Preflows

Definition:

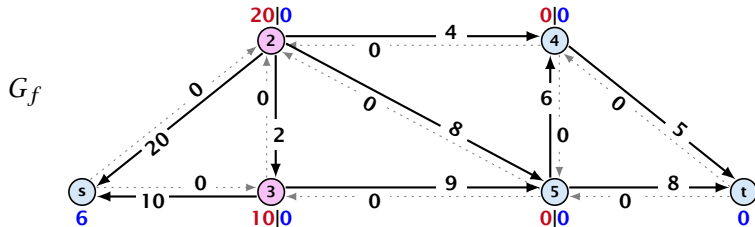
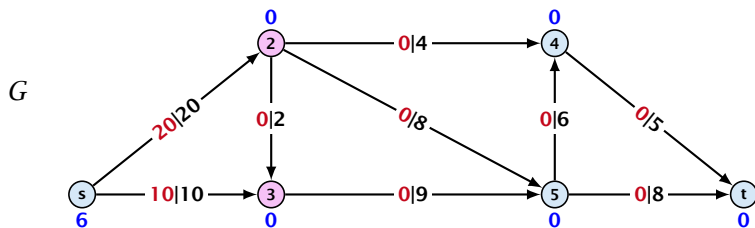
A **labelling** is a function $\ell : V \rightarrow \mathbb{N}$. It is **valid** for preflow f if

- ▶ $\ell(u) \leq \ell(v) + 1$ for all edges in the residual graph G_f (only non-zero capacity edges!!!)
- ▶ $\ell(s) = n$
- ▶ $\ell(t) = 0$

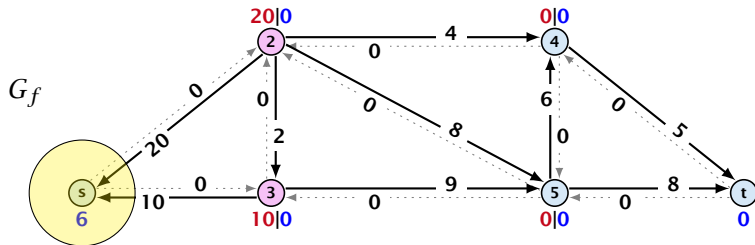
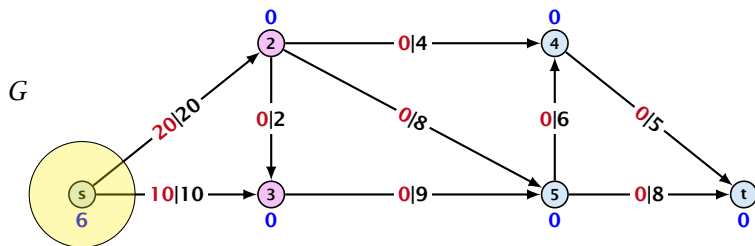
Intuition:

The labelling can be viewed as a height function. Whenever the height from node u to node v decreases by more than 1 (i.e., it goes very steep downhill from u to v), the corresponding edge must be saturated.

Preflows



Preflows



Preflows

Preflows

Lemma 3

A *preflow* that has a valid labelling saturates a cut.

Preflows

Lemma 3

A *preflow* that has a valid labelling saturates a cut.

Proof:

- ▶ There are n nodes but $n + 1$ different labels from $0, \dots, n$.

Preflows

Lemma 3

A *preflow* that has a valid labelling saturates a cut.

Proof:

- ▶ There are n nodes but $n + 1$ different labels from $0, \dots, n$.
- ▶ There must exist a label $d \in \{0, \dots, n\}$ such that none of the nodes carries this label.

Preflows

Lemma 3

A *preflow* that has a valid labelling saturates a cut.

Proof:

- ▶ There are n nodes but $n + 1$ different labels from $0, \dots, n$.
- ▶ There must exist a label $d \in \{0, \dots, n\}$ such that none of the nodes carries this label.
- ▶ Let $A = \{v \in V \mid \ell(v) > d\}$ and $B = \{v \in V \mid \ell(v) < d\}$.

Lemma 3

A *preflow* that has a valid labelling saturates a cut.

Proof:

- ▶ There are n nodes but $n + 1$ different labels from $0, \dots, n$.
- ▶ There must exist a label $d \in \{0, \dots, n\}$ such that none of the nodes carries this label.
- ▶ Let $A = \{v \in V \mid \ell(v) > d\}$ and $B = \{v \in V \mid \ell(v) < d\}$.
- ▶ We have $s \in A$ and $t \in B$ and there is no edge from A to B in the residual graph G_f ; this means that (A, B) is a saturated cut.

Preflows

Lemma 3

A *preflow* that has a valid labelling saturates a cut.

Proof:

- ▶ There are n nodes but $n + 1$ different labels from $0, \dots, n$.
- ▶ There must exist a label $d \in \{0, \dots, n\}$ such that none of the nodes carries this label.
- ▶ Let $A = \{v \in V \mid \ell(v) > d\}$ and $B = \{v \in V \mid \ell(v) < d\}$.
- ▶ We have $s \in A$ and $t \in B$ and there is no edge from A to B in the residual graph G_f ; this means that (A, B) is a saturated cut.

Lemma 4

A *flow* that has a valid labelling is a maximum flow.

Push Relabel Algorithms

Push Relabel Algorithms

Idea:

- ▶ start with some preflow and some valid labelling

Push Relabel Algorithms

Idea:

- ▶ start with some preflow and some valid labelling
- ▶ successively change the preflow while maintaining a valid labelling

Push Relabel Algorithms

Idea:

- ▶ start with some preflow and some valid labelling
- ▶ successively change the preflow while maintaining a valid labelling
- ▶ stop when you have a flow (i.e., no more active nodes)

Changing a Preflow

An arc (u, v) with $c_f(u, v) > 0$ in the residual graph is **admissible** if $\ell(u) = \ell(v) + 1$ (i.e., it goes downwards w.r.t. labelling ℓ).

The push operation

Consider an active node u with **excess flow**

$f(u) = \sum_{e \in \text{into}(u)} f(e) - \sum_{e \in \text{out}(u)} f(e)$ and suppose $e = (u, v)$ is an admissible arc with residual capacity $c_f(e)$.

We can send flow $\min\{c_f(e), f(u)\}$ along e and obtain a new preflow. The old labelling is still valid (!!!).

if $\min\{c_f(e), f(u)\} = c_f(e)$

the arc e is deleted from the residual graph

if $\min\{c_f(e), f(u)\} = f(u)$

the node u becomes inactive

Changing a Preflow

An arc (u, v) with $c_f(u, v) > 0$ in the residual graph is **admissible** if $\ell(u) = \ell(v) + 1$ (i.e., it goes downwards w.r.t. labelling ℓ).

The push operation

Consider an active node u with **excess flow**

$f(u) = \sum_{e \in \text{into}(u)} f(e) - \sum_{e \in \text{out}(u)} f(e)$ and suppose $e = (u, v)$ is an admissible arc with residual capacity $c_f(e)$.

We can send flow $\min\{c_f(e), f(u)\}$ along e and obtain a new preflow. The old labelling is still valid (!!!).

Let $\delta = \min\{c_f(e), f(u)\}$.

Then an arc e is removed from the residual graph

if $\delta = c_f(e)$ and $\delta = f(u)$ if $\delta = c_f(e) = f(u)$.

The node u becomes inactive

Changing a Preflow

An arc (u, v) with $c_f(u, v) > 0$ in the residual graph is **admissible** if $\ell(u) = \ell(v) + 1$ (i.e., it goes downwards w.r.t. labelling ℓ).

The push operation

Consider an active node u with **excess flow**

$f(u) = \sum_{e \in \text{into}(u)} f(e) - \sum_{e \in \text{out}(u)} f(e)$ and suppose $e = (u, v)$ is an admissible arc with residual capacity $c_f(e)$.

We can send flow $\min\{c_f(e), f(u)\}$ along e and obtain a new preflow. The old labelling is still valid (!!!).

Changing a Preflow

An arc (u, v) with $c_f(u, v) > 0$ in the residual graph is **admissible** if $\ell(u) = \ell(v) + 1$ (i.e., it goes downwards w.r.t. labelling ℓ).

The push operation

Consider an active node u with **excess flow**

$f(u) = \sum_{e \in \text{into}(u)} f(e) - \sum_{e \in \text{out}(u)} f(e)$ and suppose $e = (u, v)$ is an admissible arc with residual capacity $c_f(e)$.

We can send flow $\min\{c_f(e), f(u)\}$ along e and obtain a new preflow. The old labelling is still valid (!!!).

Changing a Preflow

An arc (u, v) with $c_f(u, v) > 0$ in the residual graph is **admissible** if $\ell(u) = \ell(v) + 1$ (i.e., it goes downwards w.r.t. labelling ℓ).

The push operation

Consider an active node u with **excess flow**

$f(u) = \sum_{e \in \text{into}(u)} f(e) - \sum_{e \in \text{out}(u)} f(e)$ and suppose $e = (u, v)$ is an admissible arc with residual capacity $c_f(e)$.

We can send flow $\min\{c_f(e), f(u)\}$ along e and obtain a new preflow. The old labelling is still valid (!!!).

- ▶ **saturating push**: $\min\{f(u), c_f(e)\} = c_f(e)$
the arc e is deleted from the residual graph
- ▶ **non-saturating push**: $\min\{f(u), c_f(e)\} = f(u)$
the node u becomes inactive

Changing a Preflow

An arc (u, v) with $c_f(u, v) > 0$ in the residual graph is **admissible** if $\ell(u) = \ell(v) + 1$ (i.e., it goes downwards w.r.t. labelling ℓ).

The push operation

Consider an active node u with **excess flow**

$f(u) = \sum_{e \in \text{into}(u)} f(e) - \sum_{e \in \text{out}(u)} f(e)$ and suppose $e = (u, v)$ is an admissible arc with residual capacity $c_f(e)$.

We can send flow $\min\{c_f(e), f(u)\}$ along e and obtain a new preflow. The old labelling is still valid (!!!).

- ▶ **saturating push**: $\min\{f(u), c_f(e)\} = c_f(e)$
the arc e is deleted from the residual graph
- ▶ **non-saturating push**: $\min\{f(u), c_f(e)\} = f(u)$
the node u becomes inactive

Push Relabel Algorithms

Push Relabel Algorithms

The relabel operation

Consider an active node u that does not have an outgoing admissible arc.

Push Relabel Algorithms

The relabel operation

Consider an active node u that does not have an outgoing admissible arc.

Increasing the label of u by 1 results in a valid labelling.

Push Relabel Algorithms

The relabel operation

Consider an active node u that does not have an outgoing admissible arc.

Increasing the label of u by 1 results in a valid labelling.

- ▶ Edges (w, u) incoming to u still fulfill their constraint $\ell(w) \leq \ell(u) + 1$.

Push Relabel Algorithms

The relabel operation

Consider an active node u that does not have an outgoing admissible arc.

Increasing the label of u by 1 results in a valid labelling.

- ▶ Edges (w, u) incoming to u still fulfill their constraint $\ell(w) \leq \ell(u) + 1$.
- ▶ An outgoing edge (u, w) had $\ell(u) < \ell(w) + 1$ before since it was not admissible. Now: $\ell(u) \leq \ell(w) + 1$.

Push Relabel Algorithms

Intuition:

We want to send flow downwards, since the source has a height/label of n and the target a height/label of 0. If we see an active node u with an admissible arc we push the flow at u towards the other end-point that has a lower height/label. If we do not have an admissible arc but excess flow into u it should roughly mean that the level/height/label of u should rise. (If we consider the flow to be water than this would be natural).

Note that the above intuition is very incorrect as the labels are integral, i.e., they cannot really be seen as the height of a node.

Reminder

- ▶ In a **preflow** nodes may not fulfill conservation constraints but a node may have more incoming flow than outgoing flow.
- ▶ Such a node is called **active**.
- ▶ A labelling is **valid** if for every edge (u, v) in the residual graph $\ell(u) \leq \ell(v) + 1$.
- ▶ An arc (u, v) in residual graph is **admissible** if $\ell(u) = \ell(v) + 1$.
- ▶ A **saturation push** along e pushes an amount of $c(e)$ flow along the edge, thereby saturating the edge (and making it disappear from the residual graph).
- ▶ A **non-saturating push** along $e = (u, v)$ pushes a flow of $f(u)$, where $f(u)$ is the **excess flow** of u . This makes u inactive.

Push Relabel Algorithms

Algorithm 46 $\text{maxflow}(G, s, t, c)$

```
1: find initial preflow  $f$ 
2: while there is active node  $u$  do
3:     if there is admiss. arc  $e$  out of  $u$  then
4:          $\text{push}(G, e, f, c)$ 
5:     else
6:          $\text{relabel}(u)$ 
7: return  $f$ 
```

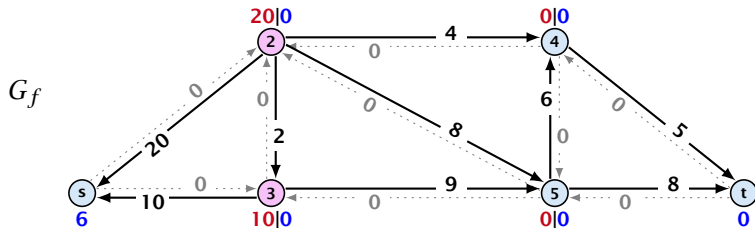
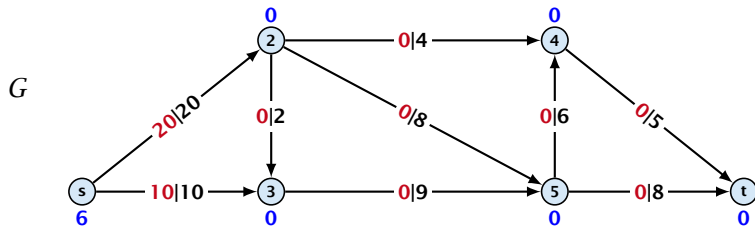
Push Relabel Algorithms

Algorithm 46 $\text{maxflow}(G, s, t, c)$

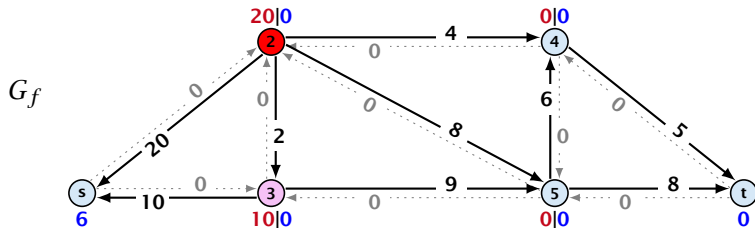
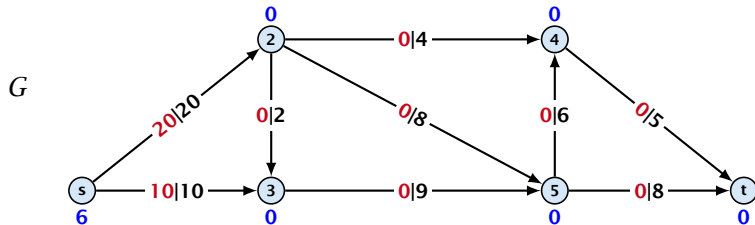
```
1: find initial preflow  $f$ 
2: while there is active node  $u$  do
3:     if there is admiss. arc  $e$  out of  $u$  then
4:          $\text{push}(G, e, f, c)$ 
5:     else
6:          $\text{relabel}(u)$ 
7: return  $f$ 
```

In the following example we always stick to the same active node u until it becomes inactive but this is not required.

Preflow Push Algorithm



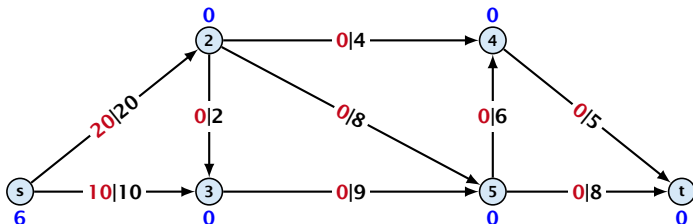
Preflow Push Algorithm



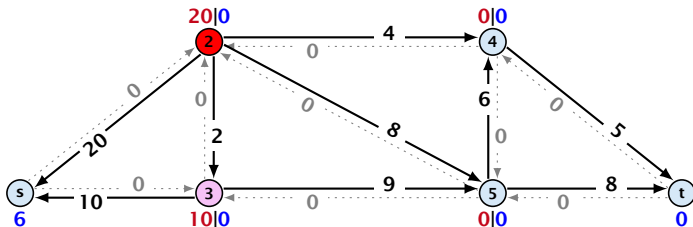
Preflow Push Algorithm

relabel

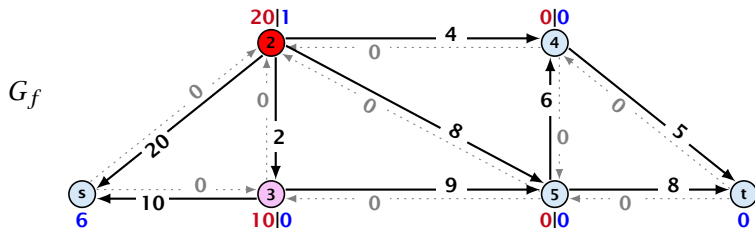
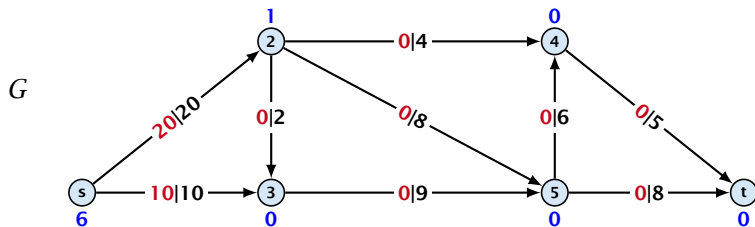
G



G_f



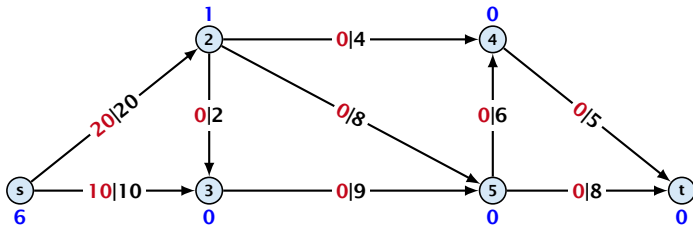
Preflow Push Algorithm



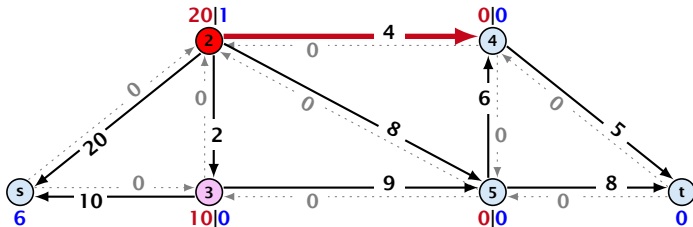
Preflow Push Algorithm

push

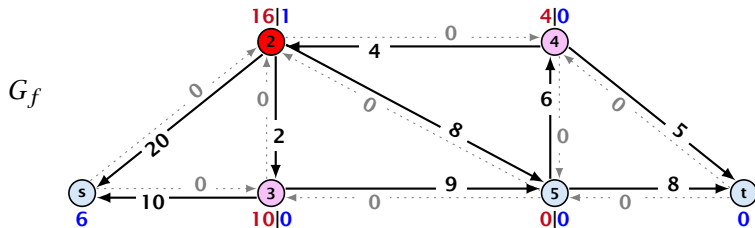
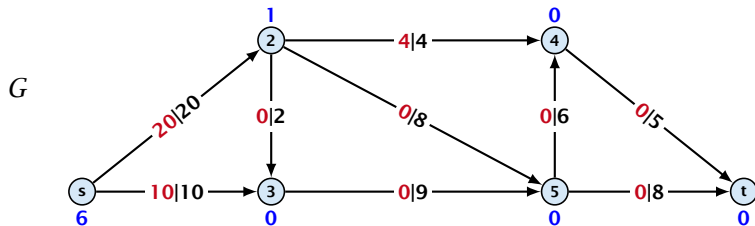
G



G_f



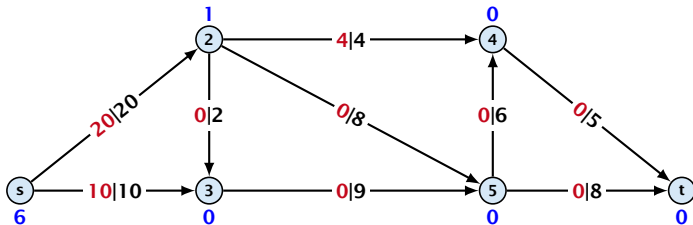
Preflow Push Algorithm



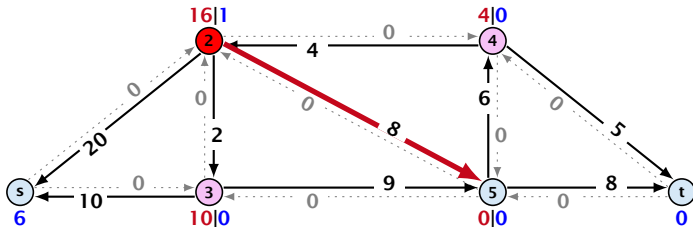
Preflow Push Algorithm

push

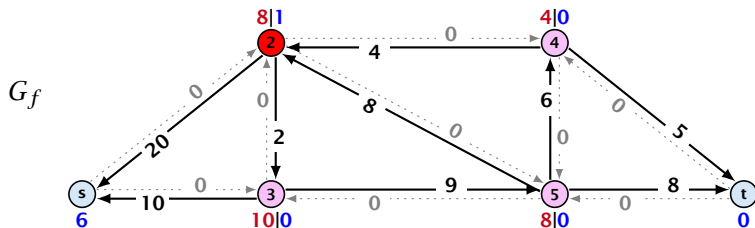
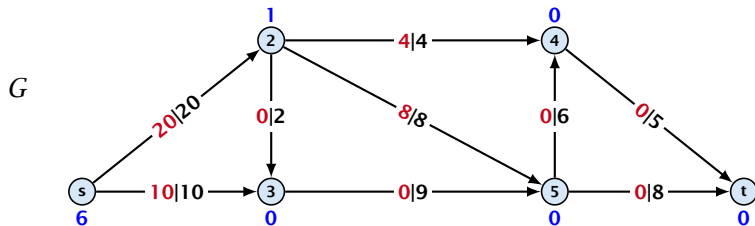
G



G_f



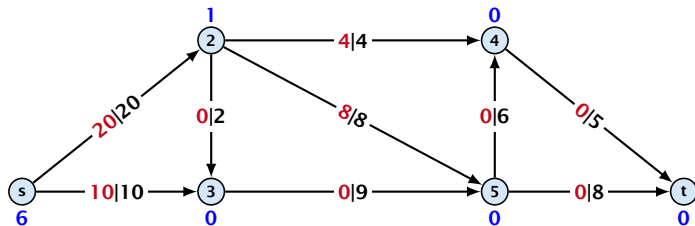
Preflow Push Algorithm



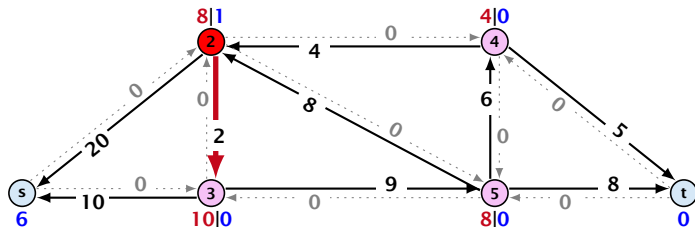
Preflow Push Algorithm

push

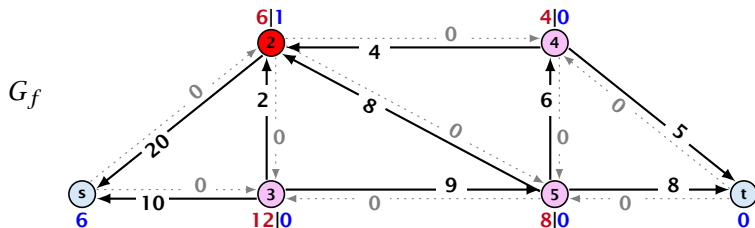
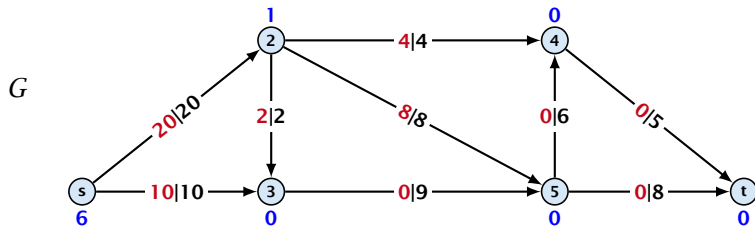
G



G_f



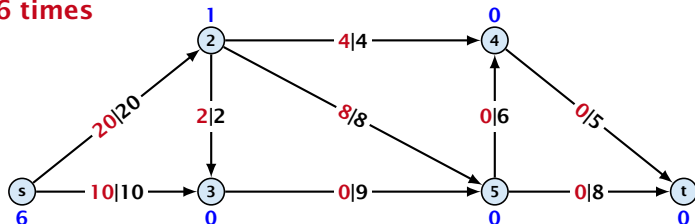
Preflow Push Algorithm



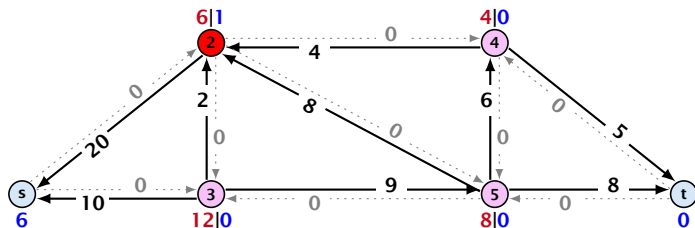
Preflow Push Algorithm

relabel 6 times

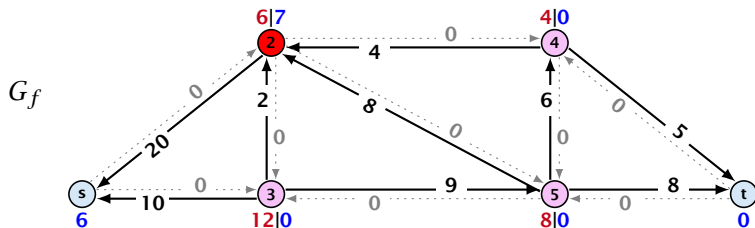
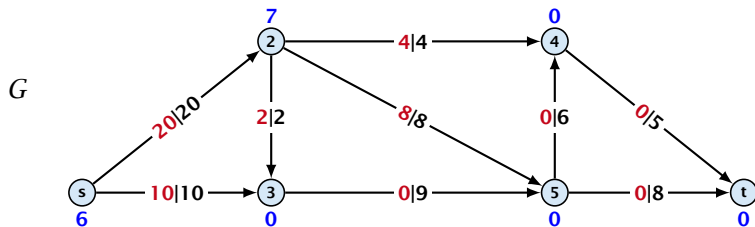
G



G_f



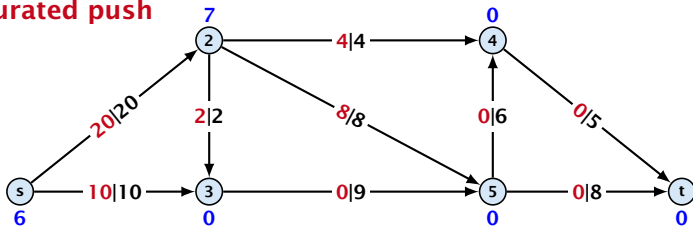
Preflow Push Algorithm



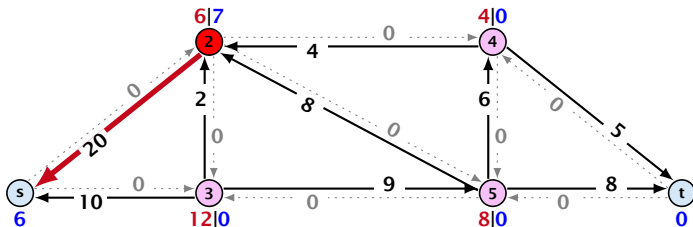
Preflow Push Algorithm

non-saturated push

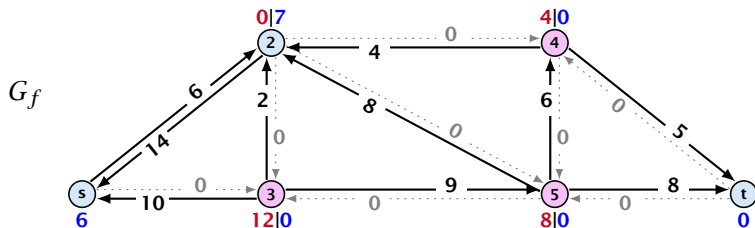
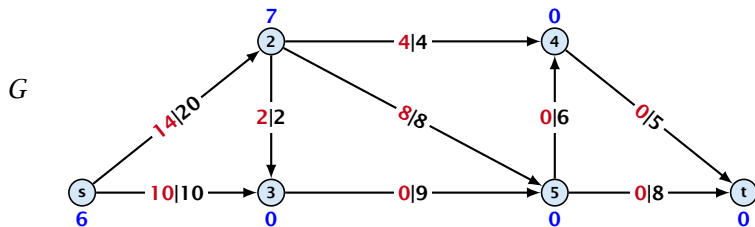
G



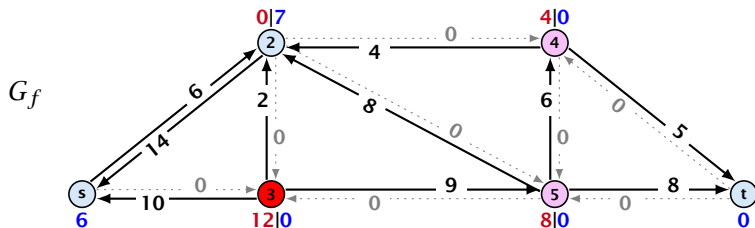
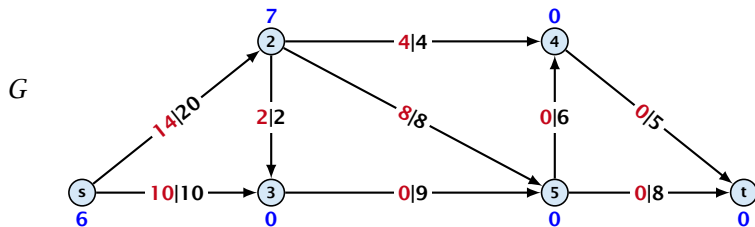
G_f



Preflow Push Algorithm



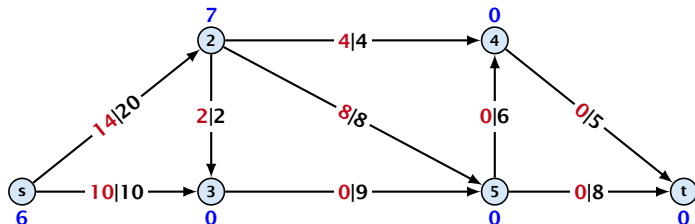
Preflow Push Algorithm



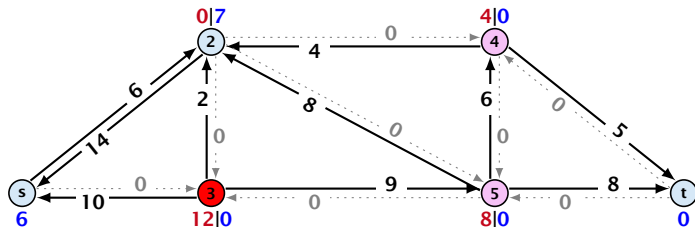
Preflow Push Algorithm

relabel

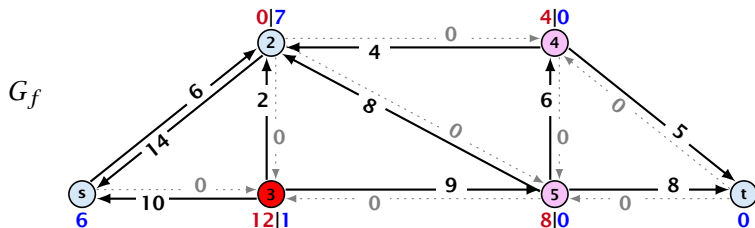
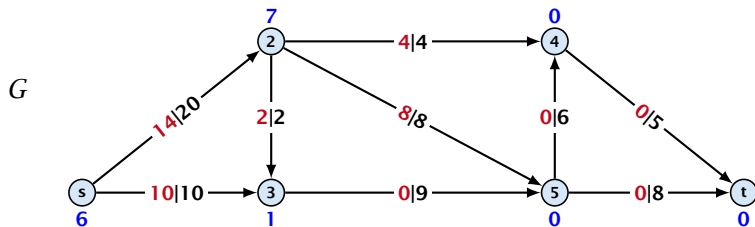
G



G_f



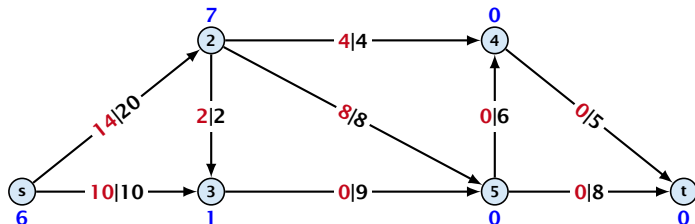
Preflow Push Algorithm



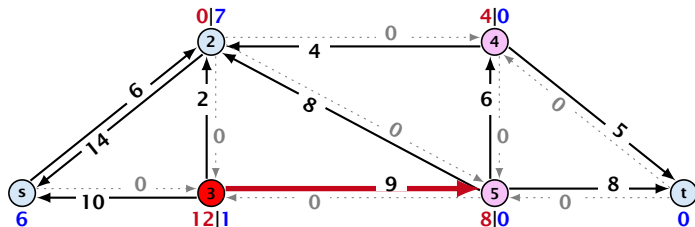
Preflow Push Algorithm

push

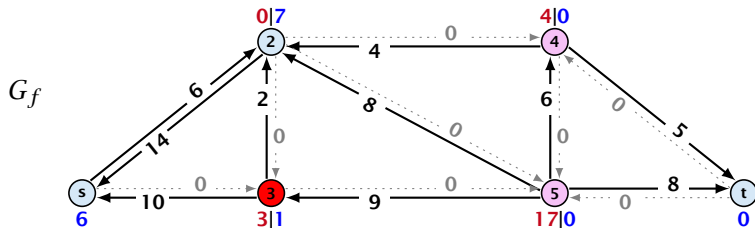
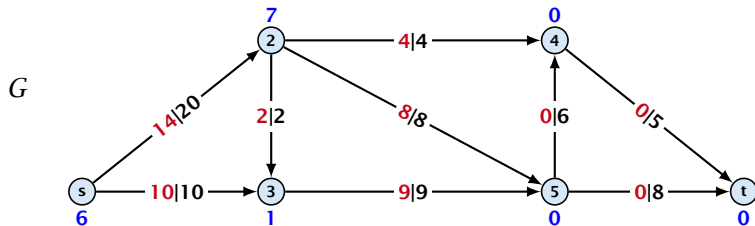
G



G_f



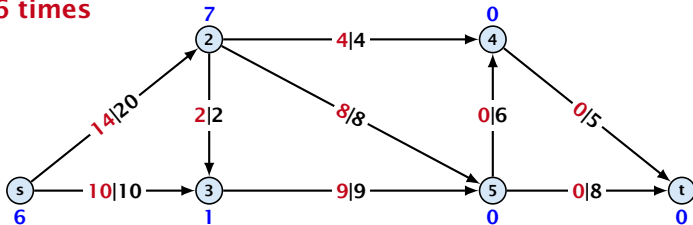
Preflow Push Algorithm



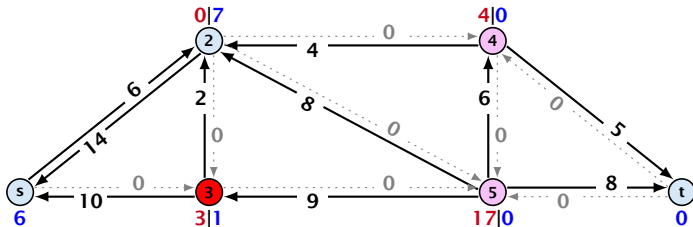
Preflow Push Algorithm

relabel 6 times

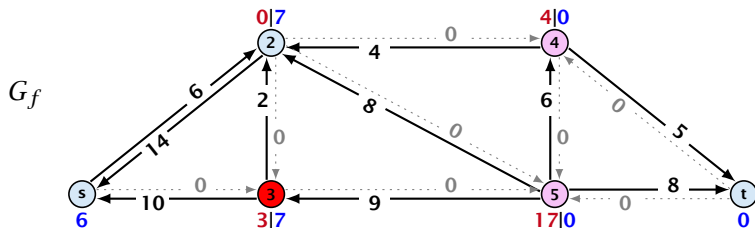
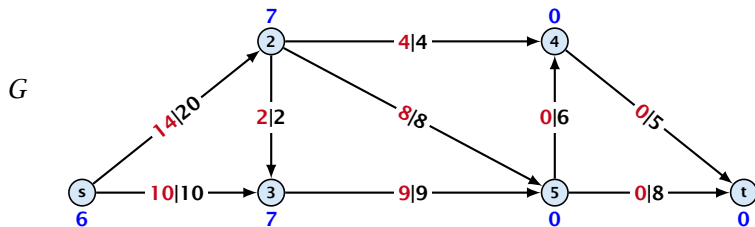
G



G_f



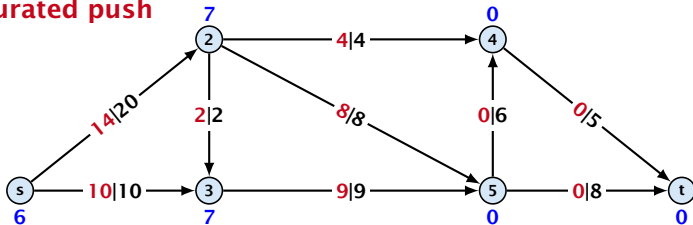
Preflow Push Algorithm



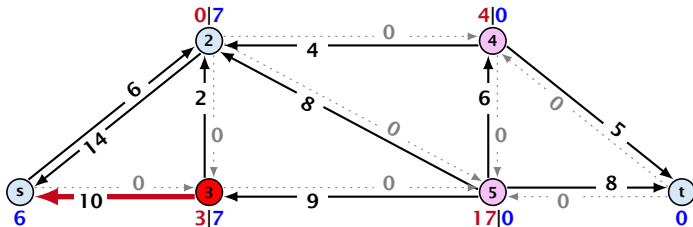
Preflow Push Algorithm

non-saturated push

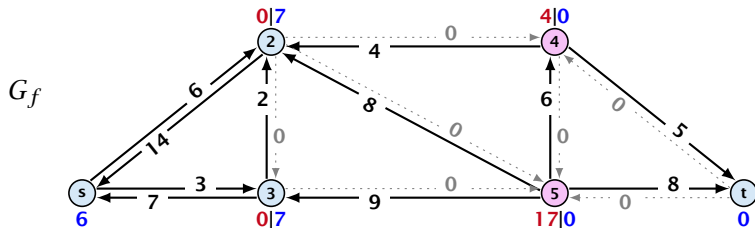
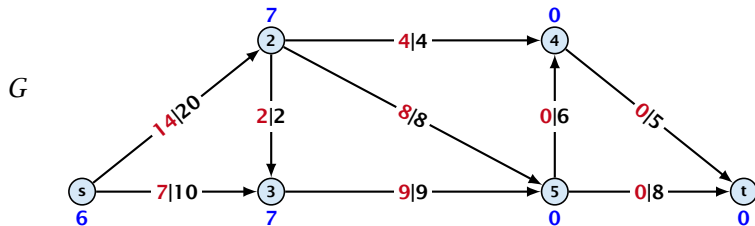
G



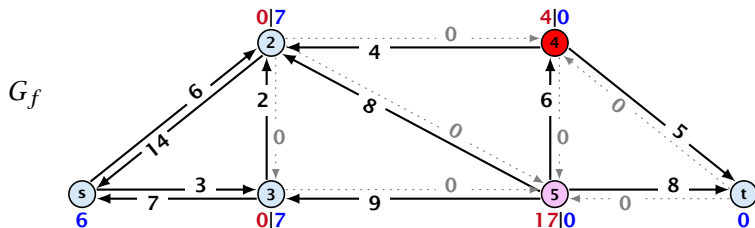
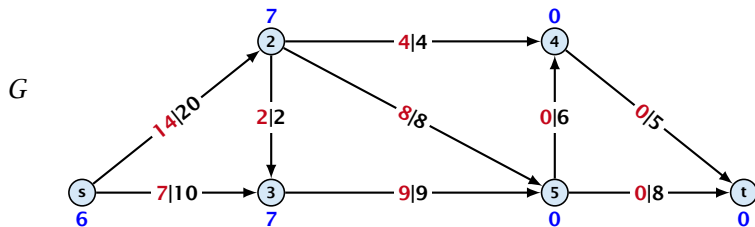
G_f



Preflow Push Algorithm



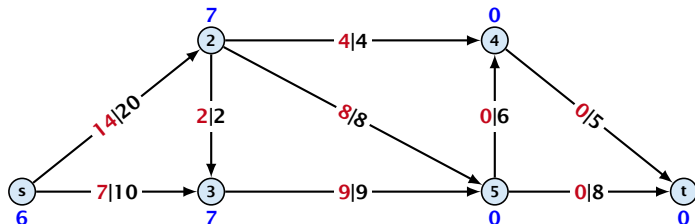
Preflow Push Algorithm



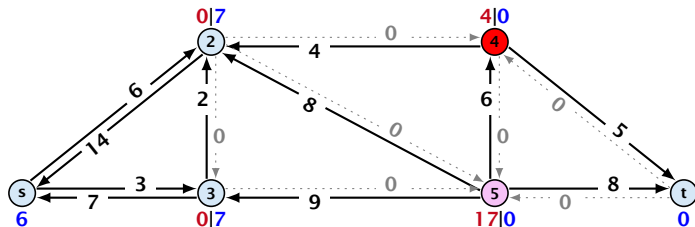
Preflow Push Algorithm

relabel

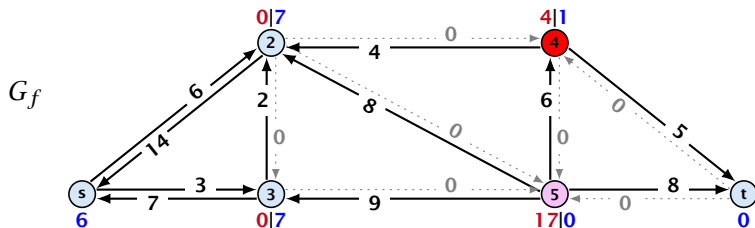
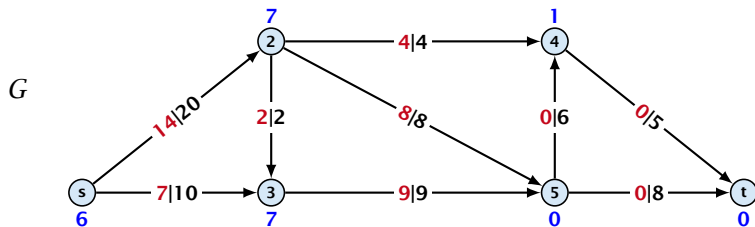
G



G_f

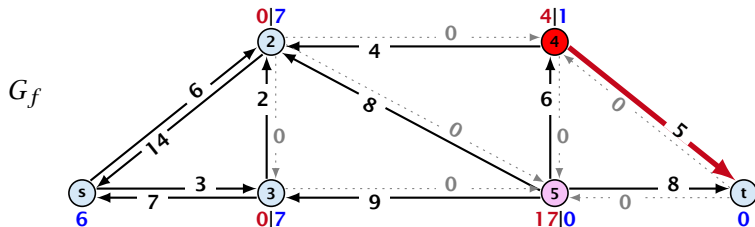
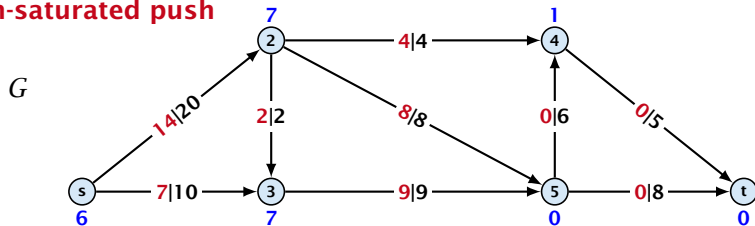


Preflow Push Algorithm

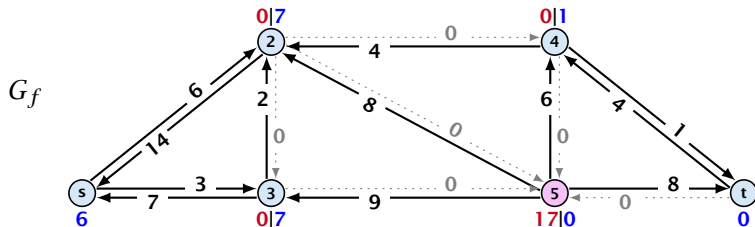
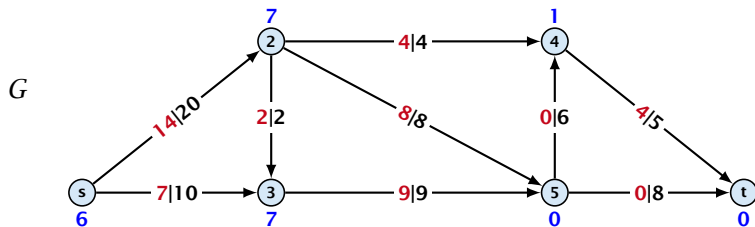


Preflow Push Algorithm

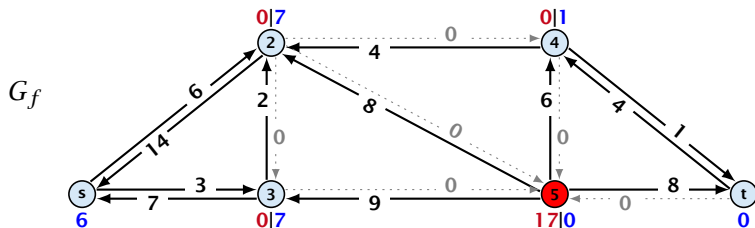
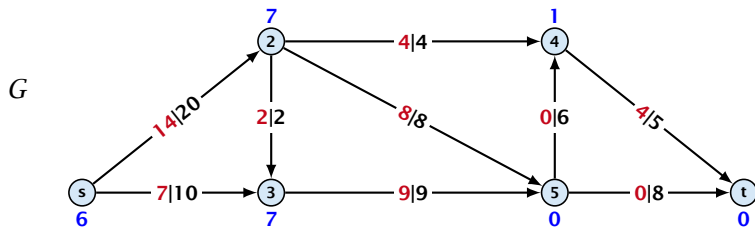
non-saturated push



Preflow Push Algorithm



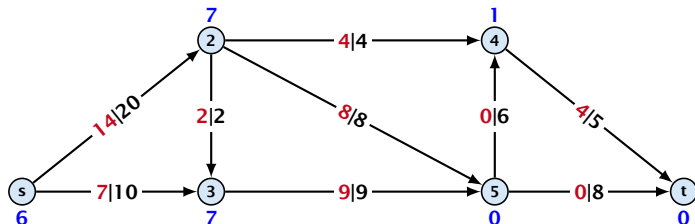
Preflow Push Algorithm



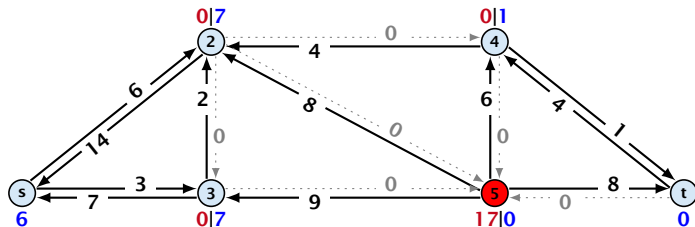
Preflow Push Algorithm

relabel

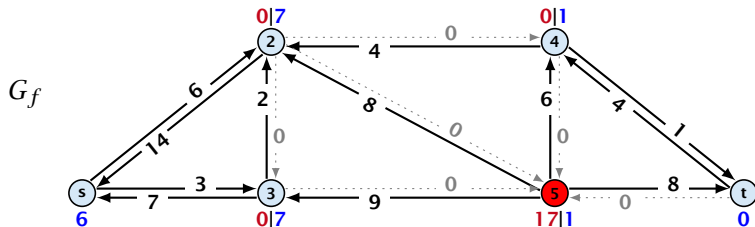
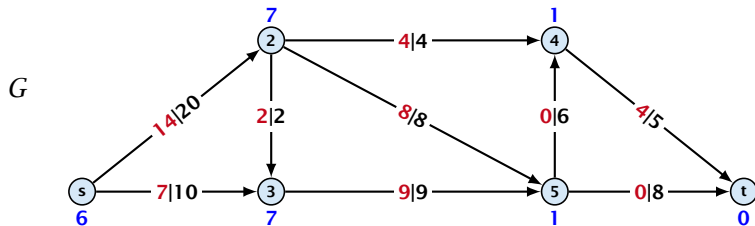
G



G_f

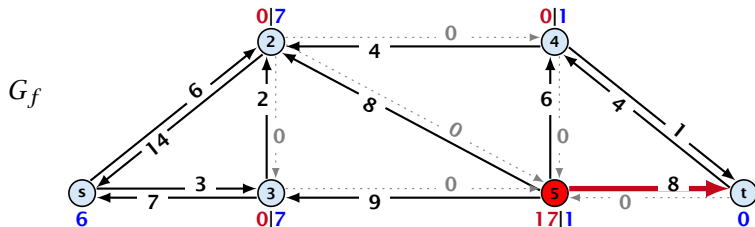
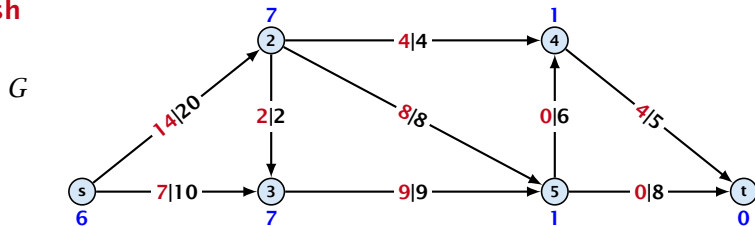


Preflow Push Algorithm

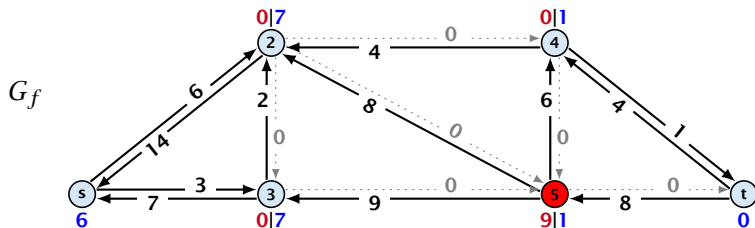
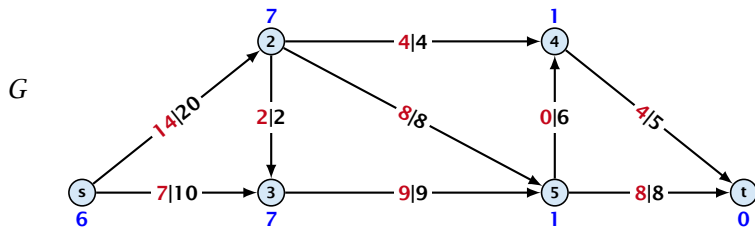


Preflow Push Algorithm

push



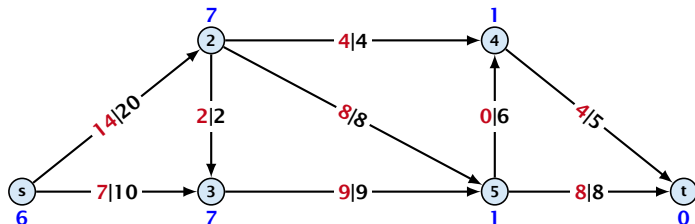
Preflow Push Algorithm



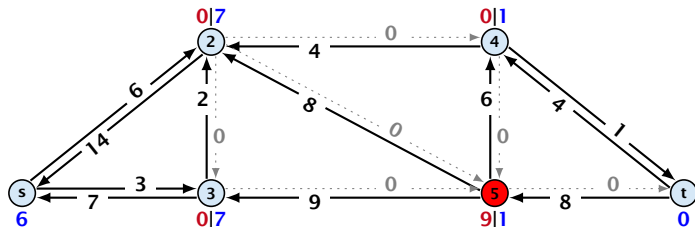
Preflow Push Algorithm

relabel

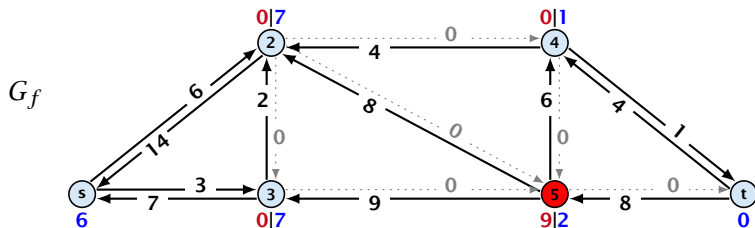
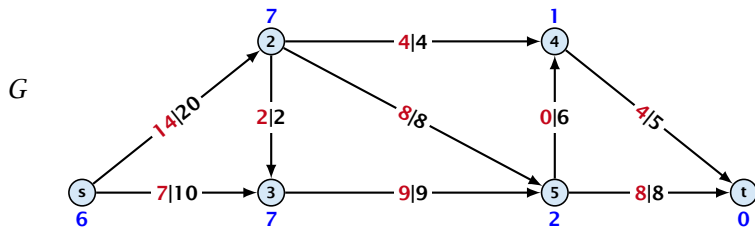
G



G_f



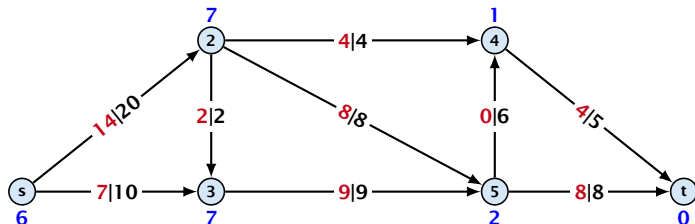
Preflow Push Algorithm



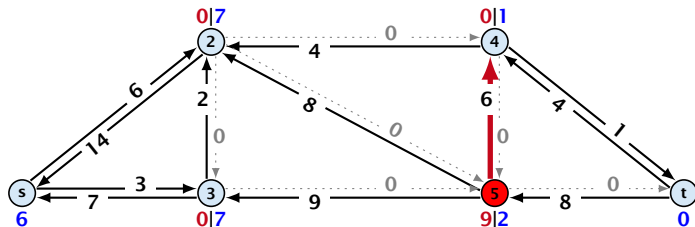
Preflow Push Algorithm

push

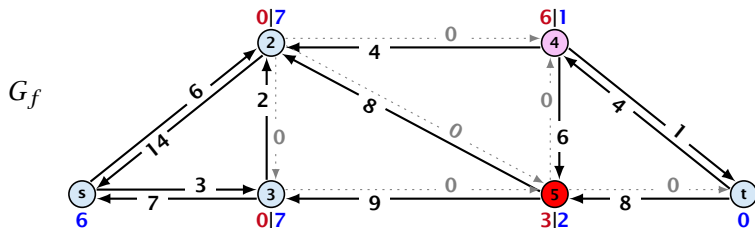
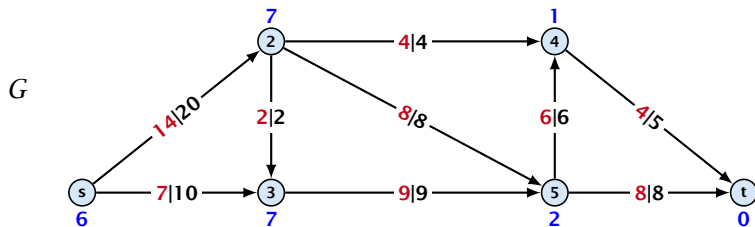
G



G_f



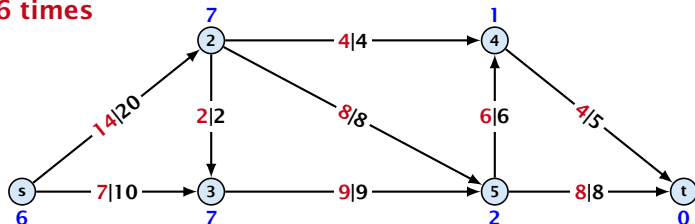
Preflow Push Algorithm



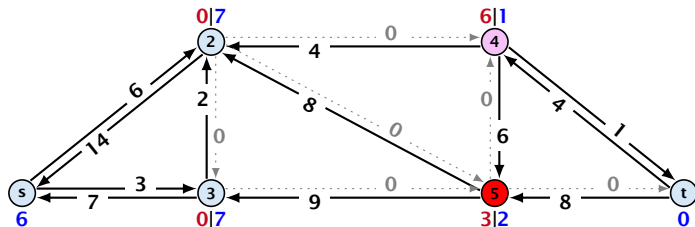
Preflow Push Algorithm

relabel 6 times

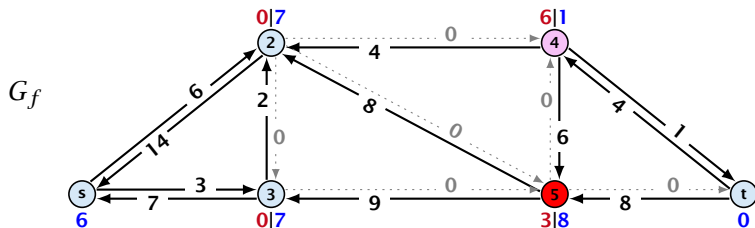
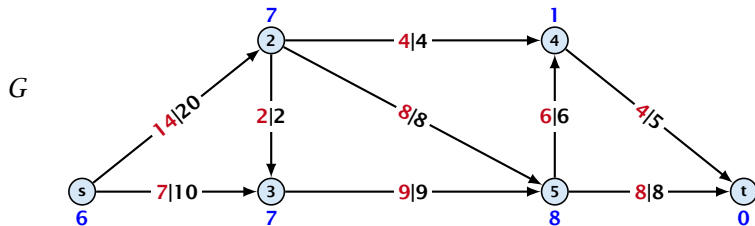
G



G_f



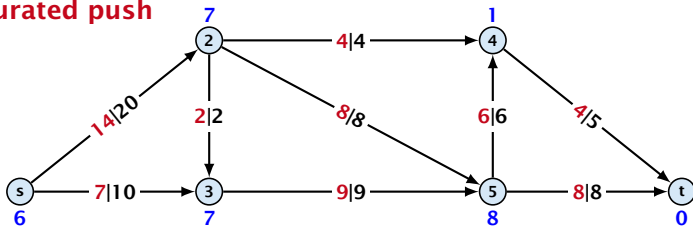
Preflow Push Algorithm



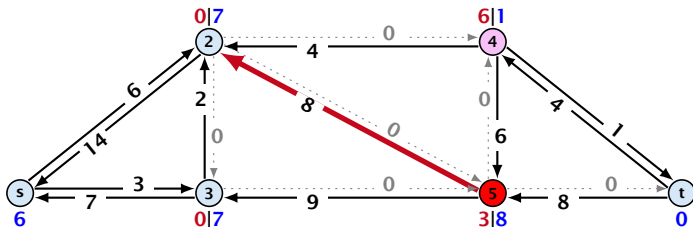
Preflow Push Algorithm

non-saturated push

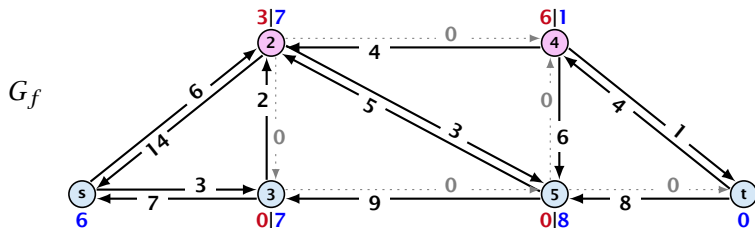
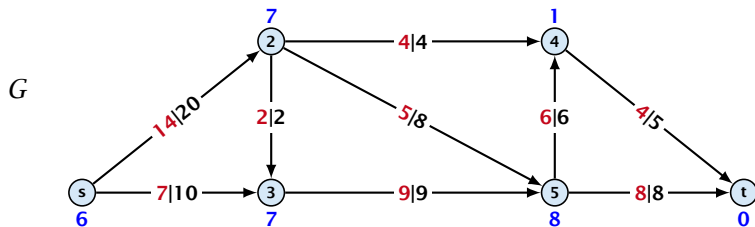
G



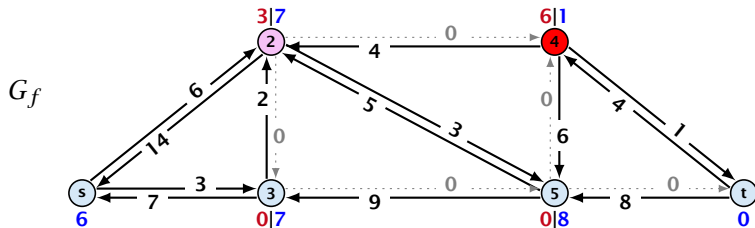
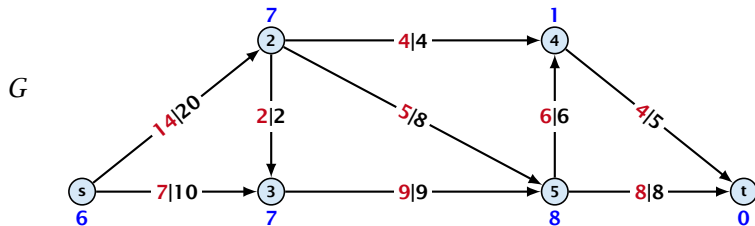
G_f



Preflow Push Algorithm



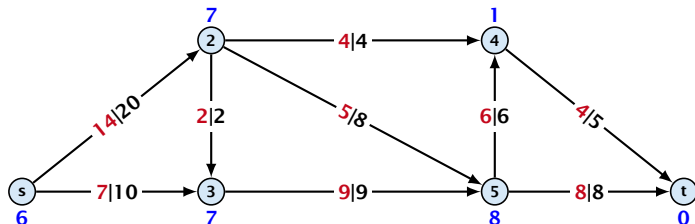
Preflow Push Algorithm



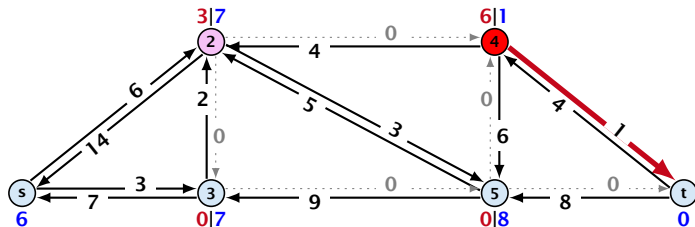
Preflow Push Algorithm

push

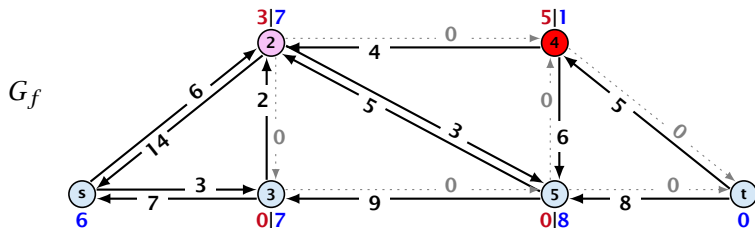
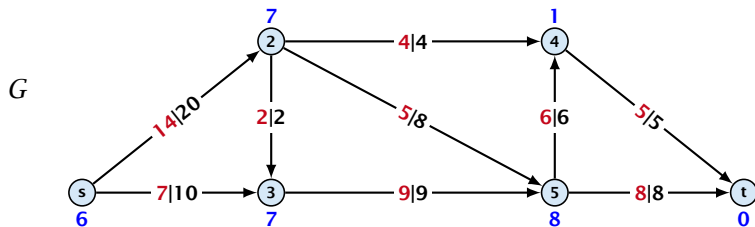
G



G_f



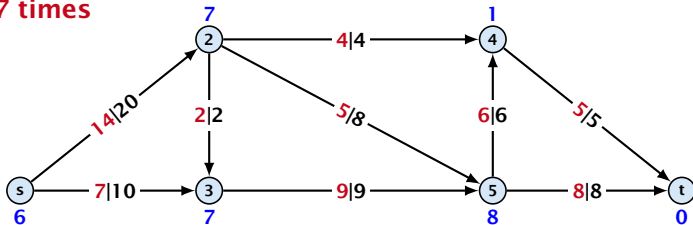
Preflow Push Algorithm



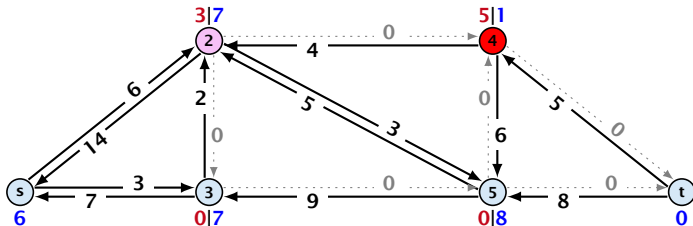
Preflow Push Algorithm

relabel 7 times

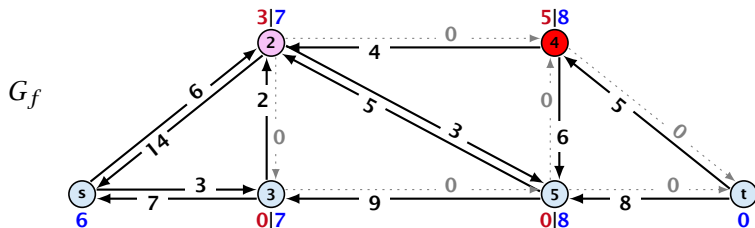
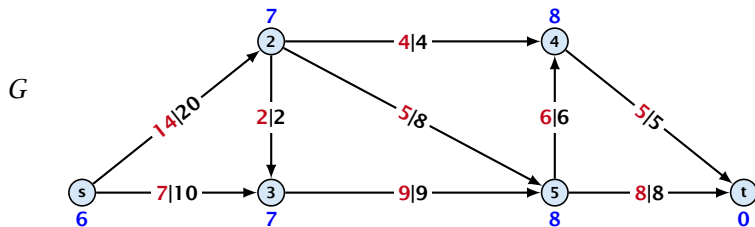
G



G_f

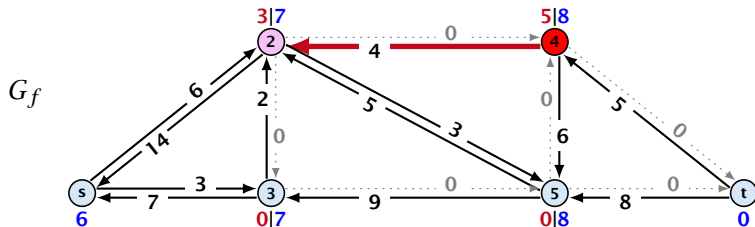
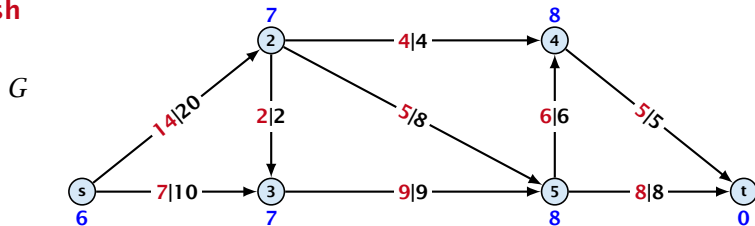


Preflow Push Algorithm

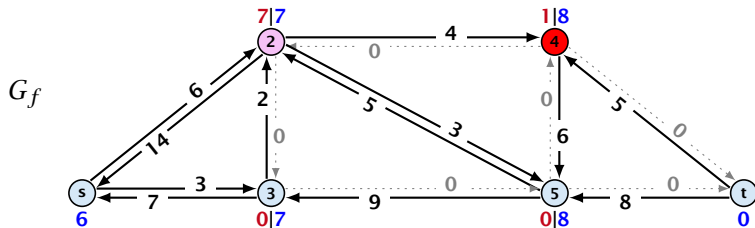
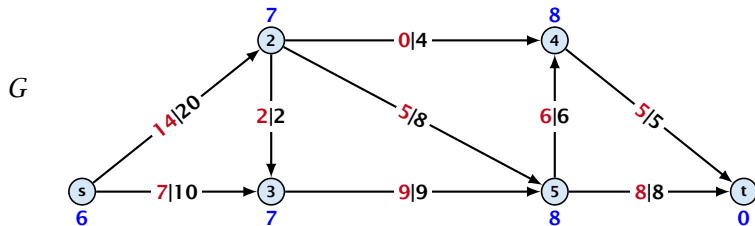


Preflow Push Algorithm

push



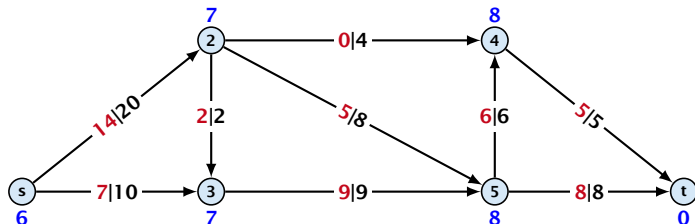
Preflow Push Algorithm



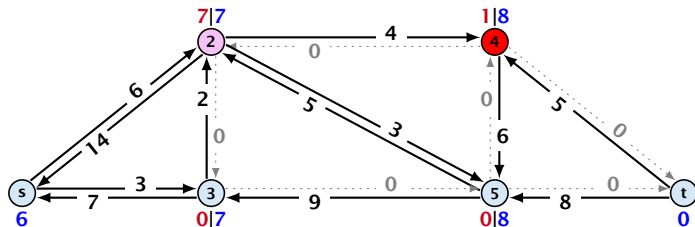
Preflow Push Algorithm

relabel

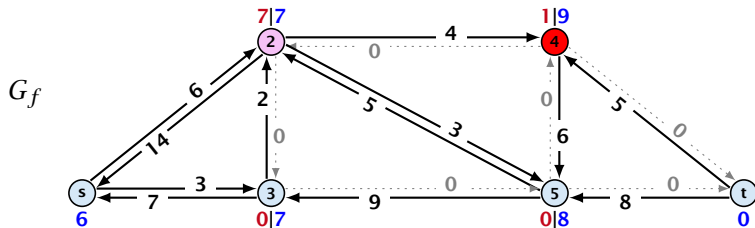
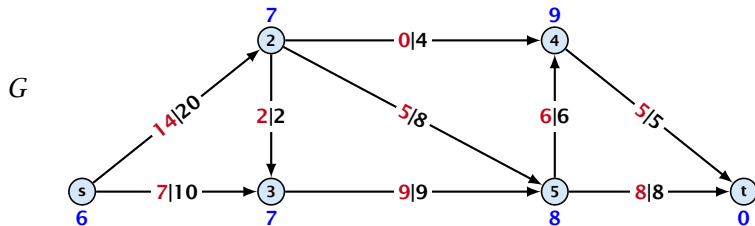
G



G_f



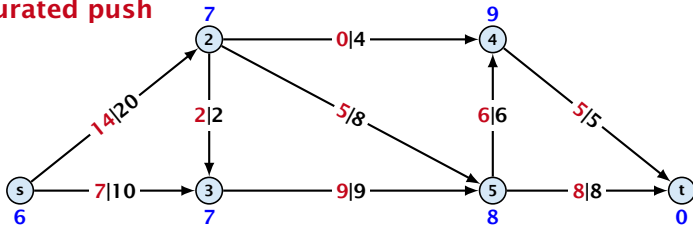
Preflow Push Algorithm



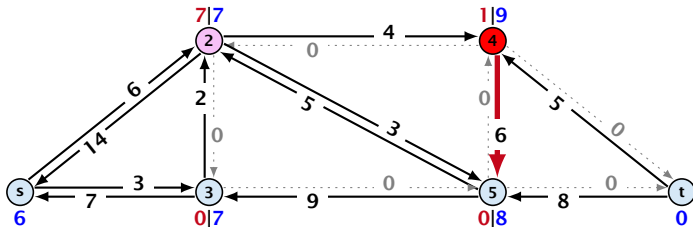
Preflow Push Algorithm

non-saturated push

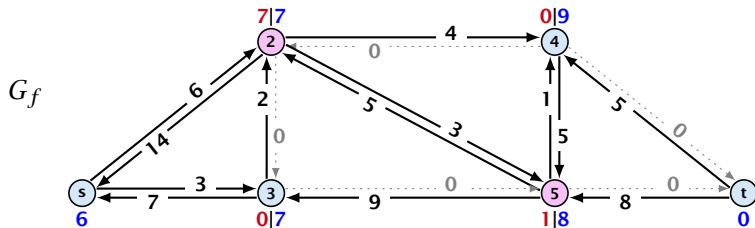
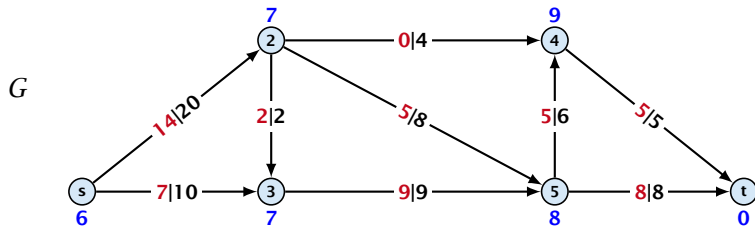
G



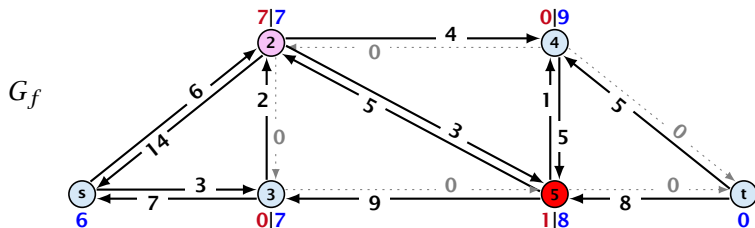
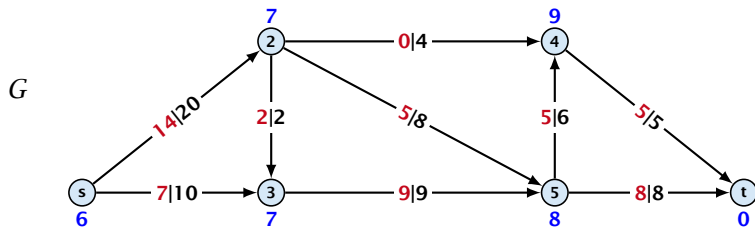
G_f



Preflow Push Algorithm



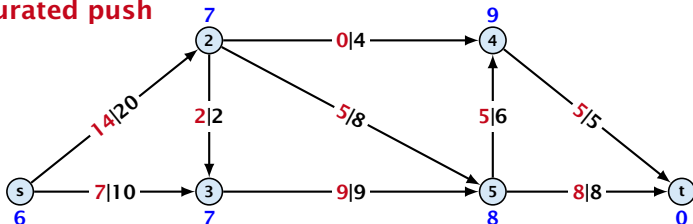
Preflow Push Algorithm



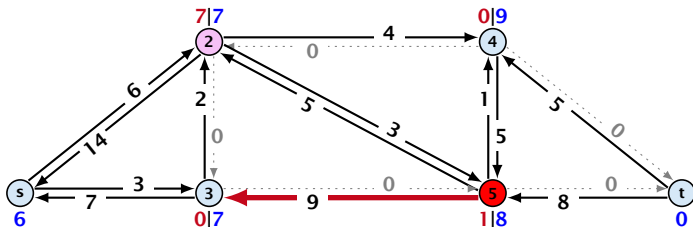
Preflow Push Algorithm

non-saturated push

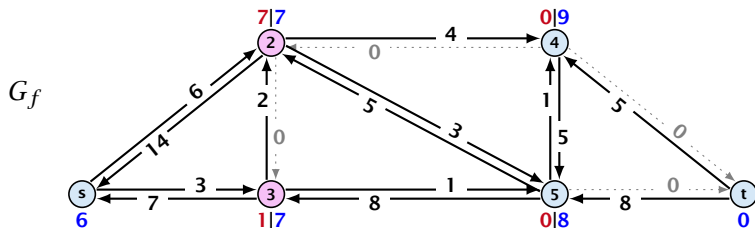
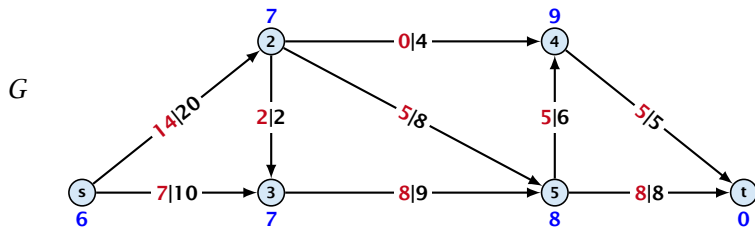
G



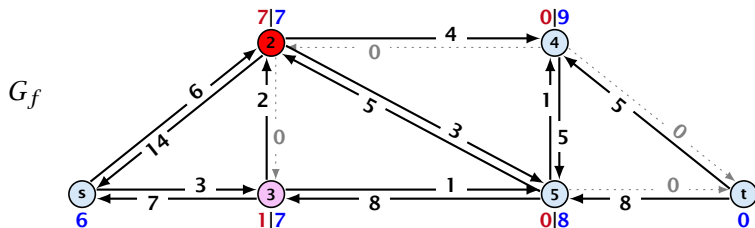
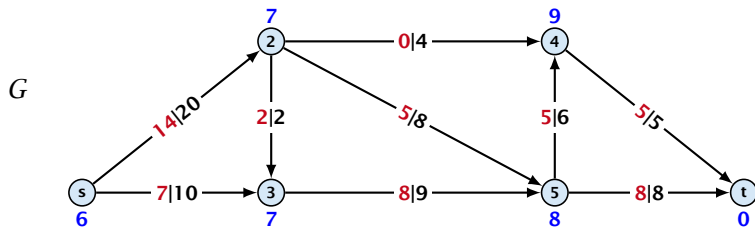
G_f



Preflow Push Algorithm



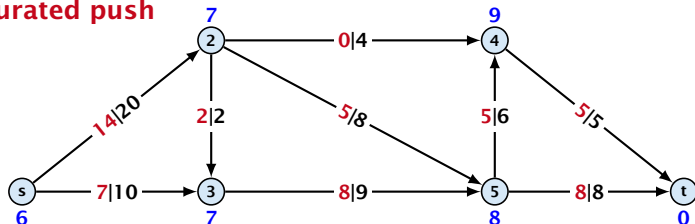
Preflow Push Algorithm



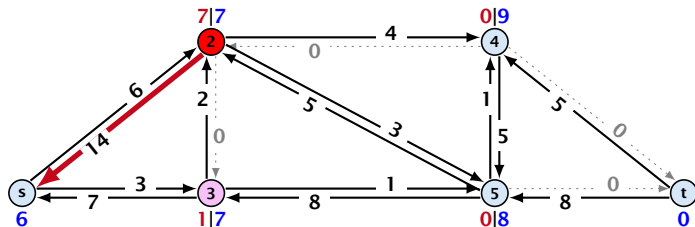
Preflow Push Algorithm

non-saturated push

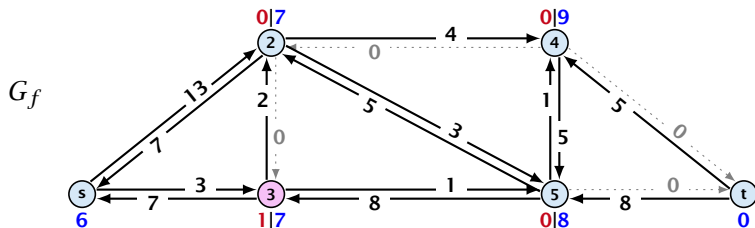
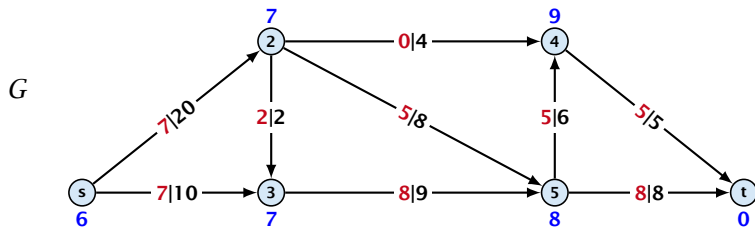
G



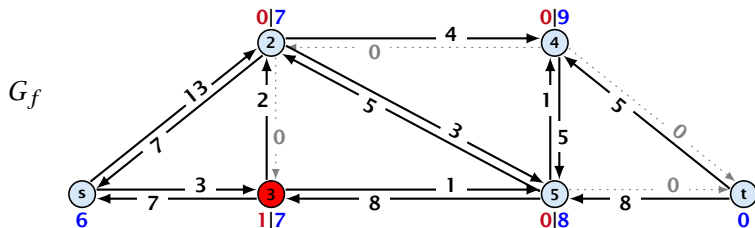
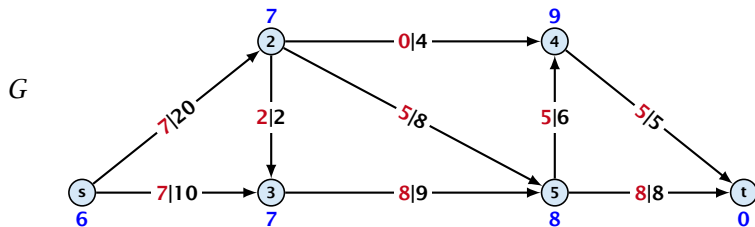
G_f



Preflow Push Algorithm



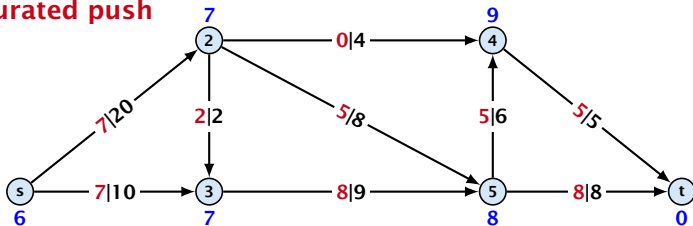
Preflow Push Algorithm



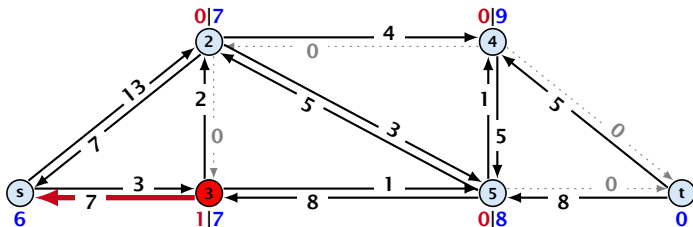
Preflow Push Algorithm

non-saturated push

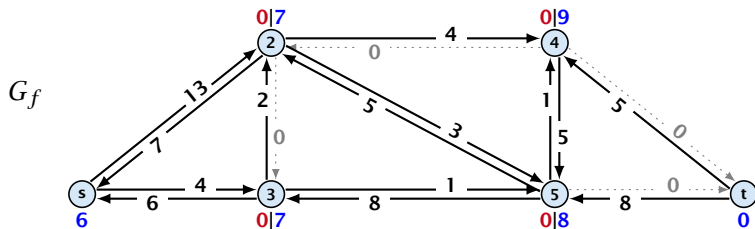
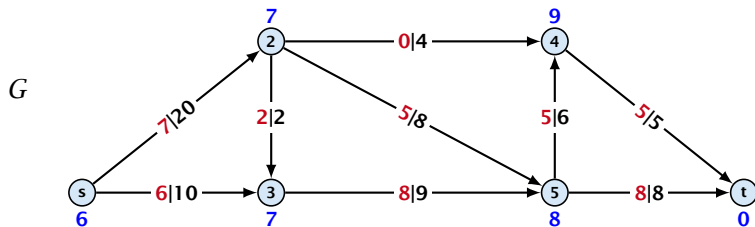
G



G_f



Preflow Push Algorithm



Analysis

Lemma 5

An active node has a path to s in the residual graph.

Analysis

Lemma 5

An active node has a path to s in the residual graph.

Proof.

- ▶ Let A denote the set of nodes that can reach s , and let B denote the remaining nodes. Note that $s \in A$.

Analysis

Lemma 5

An active node has a path to s in the residual graph.

Proof.

- ▶ Let A denote the set of nodes that can reach s , and let B denote the remaining nodes. Note that $s \in A$.
- ▶ In the following we show that a node $b \in B$ has excess flow $f(b) = 0$ which gives the lemma.

Analysis

Lemma 5

An active node has a path to s in the residual graph.

Proof.

- ▶ Let A denote the set of nodes that can reach s , and let B denote the remaining nodes. Note that $s \in A$.
- ▶ In the following we show that a node $b \in B$ has excess flow $f(b) = 0$ which gives the lemma.
- ▶ In the residual graph there are no edges into A , and, hence, no edges leaving A /entering B can carry any flow.

Lemma 5

An active node has a path to s in the residual graph.

Proof.

- ▶ Let A denote the set of nodes that can reach s , and let B denote the remaining nodes. Note that $s \in A$.
- ▶ In the following we show that a node $b \in B$ has excess flow $f(b) = 0$ which gives the lemma.
- ▶ In the residual graph there are no edges into A , and, hence, no edges leaving A /entering B can carry any flow.
- ▶ Let $f(B) = \sum_{v \in B} f(v)$ be the excess flow of all nodes in B .

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$f(B)$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$f(B) = \sum_{b \in B} f(b)$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \sum_{b \in B} \sum_{v \in A} f(v, b) - \sum_{b \in B} \sum_{v \in A} f(b, v) + \sum_{b \in B} \sum_{v \in B} f(v, b) - \sum_{b \in B} \sum_{v \in B} f(b, v) \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \sum_{b \in B} \sum_{v \in A} f(v, b) - \sum_{b \in B} \sum_{v \in A} f(b, v) + \sum_{b \in B} \sum_{v \in B} f(v, b) - \sum_{b \in B} \sum_{v \in B} f(b, v) \\ &= 0 \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \sum_{b \in B} \sum_{v \in A} f(v, b) - \sum_{b \in B} \sum_{v \in A} f(b, v) \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \sum_{b \in B} \sum_{v \in A} f(v, b) - \sum_{b \in B} \sum_{v \in A} f(b, v) \\ &= 0 \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \sum_{b \in B} \sum_{v \in A} f(v, b) - \sum_{b \in B} \sum_{v \in A} f(b, v) \\ &= \mathbf{0} \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \sum_{b \in B} \sum_{v \in A} f(b, v) \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \sum_{b \in B} \sum_{v \in A} f(b, v) \\ &\quad \geq 0 \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \qquad \qquad \qquad - \sum_{b \in B} \sum_{v \in A} f(b, v) \\ &\leq 0 \end{aligned}$$

Let $f : E \rightarrow \mathbb{R}_0^+$ be a preflow. We introduce the notation

$$f(x, y) = \begin{cases} 0 & (x, y) \notin E \\ f((x, y)) & (x, y) \in E \end{cases}$$

We have

$$\begin{aligned} f(B) &= \sum_{b \in B} f(b) \\ &= \sum_{b \in B} \left(\sum_{v \in V} f(v, b) - \sum_{v \in V} f(b, v) \right) \\ &= \sum_{b \in B} \left(\sum_{v \in A} f(v, b) + \sum_{v \in B} f(v, b) - \sum_{v \in A} f(b, v) - \sum_{v \in B} f(b, v) \right) \\ &= \qquad \qquad \qquad - \sum_{b \in B} \sum_{v \in A} f(b, v) \\ &\leq 0 \end{aligned}$$

Hence, the excess flow $f(b)$ must be 0 for every node $b \in B$.

Analysis

Lemma 6

The label of a node cannot become larger than $2n - 1$.

Analysis

Lemma 6

The label of a node cannot become larger than $2n - 1$.

Proof.

- ▶ When increasing the label at a node u there exists a path from u to s of length at most $n - 1$. Along each edge of the path the height/label can at most drop by 1, and the label of the source is n .

Analysis

Lemma 6

The label of a node cannot become larger than $2n - 1$.

Proof.

- ▶ When increasing the label at a node u there exists a path from u to s of length at most $n - 1$. Along each edge of the path the height/label can at most drop by 1, and the label of the source is n .

Lemma 7

There are only $\mathcal{O}(n^2)$ relabel operations.

Analysis

Lemma 8

The number of *saturating pushes* performed is at most $\mathcal{O}(mn)$.

Analysis

Lemma 8

The number of *saturating pushes* performed is at most $\mathcal{O}(mn)$.

Proof.

- ▶ Suppose that we just made a saturating push along (u, v) .

Analysis

Lemma 8

The number of *saturating pushes* performed is at most $\mathcal{O}(mn)$.

Proof.

- ▶ Suppose that we just made a saturating push along (u, v) .
- ▶ Hence, the edge (u, v) is deleted from the residual graph.

Analysis

Lemma 8

The number of *saturating pushes* performed is at most $\mathcal{O}(mn)$.

Proof.

- ▶ Suppose that we just made a saturating push along (u, v) .
- ▶ Hence, the edge (u, v) is deleted from the residual graph.
- ▶ For the edge to appear again, a push from v to u is required.

Analysis

Lemma 8

The number of *saturating pushes* performed is at most $\mathcal{O}(mn)$.

Proof.

- ▶ Suppose that we just made a saturating push along (u, v) .
- ▶ Hence, the edge (u, v) is deleted from the residual graph.
- ▶ For the edge to appear again, a push from v to u is required.
- ▶ Currently, $\ell(u) = \ell(v) + 1$, as we only make pushes along admissible edges.

Analysis

Lemma 8

The number of *saturating pushes* performed is at most $\mathcal{O}(mn)$.

Proof.

- ▶ Suppose that we just made a saturating push along (u, v) .
- ▶ Hence, the edge (u, v) is deleted from the residual graph.
- ▶ For the edge to appear again, a push from v to u is required.
- ▶ Currently, $\ell(u) = \ell(v) + 1$, as we only make pushes along admissible edges.
- ▶ For a push from v to u the edge (v, u) must become admissible. The label of v must increase by at least 2.

Analysis

Lemma 8

The number of *saturating pushes* performed is at most $\mathcal{O}(mn)$.

Proof.

- ▶ Suppose that we just made a saturating push along (u, v) .
- ▶ Hence, the edge (u, v) is deleted from the residual graph.
- ▶ For the edge to appear again, a push from v to u is required.
- ▶ Currently, $\ell(u) = \ell(v) + 1$, as we only make pushes along admissible edges.
- ▶ For a push from v to u the edge (v, u) must become admissible. The label of v must increase by at least 2.
- ▶ Since the label of v is at most $2n - 1$, there are at most n pushes along (u, v) .

Lemma 9

The number of *non-saturating pushes* performed is at most $\mathcal{O}(n^2m)$.

Lemma 9

The number of *non-saturating pushes* performed is at most $\mathcal{O}(n^2m)$.

Proof.

- ▶ Define a potential function $\Phi(f) = \sum_{\text{active nodes } v} \ell(v)$

Lemma 9

The number of *non-saturating pushes* performed is at most $\mathcal{O}(n^2m)$.

Proof.

- ▶ Define a potential function $\Phi(f) = \sum_{\text{active nodes } v} \ell(v)$
- ▶ A saturating push increases Φ by $\leq 2n$ (when the target node becomes active it may contribute at most $2n$ to the sum).

Lemma 9

The number of *non-saturating pushes* performed is at most $\mathcal{O}(n^2m)$.

Proof.

- ▶ Define a potential function $\Phi(f) = \sum_{\text{active nodes } v} \ell(v)$
- ▶ A saturating push increases Φ by $\leq 2n$ (when the target node becomes active it may contribute at most $2n$ to the sum).
- ▶ A relabel increases Φ by at most 1.

Lemma 9

The number of *non-saturating pushes* performed is at most $\mathcal{O}(n^2m)$.

Proof.

- ▶ Define a potential function $\Phi(f) = \sum_{\text{active nodes } v} \ell(v)$
- ▶ A saturating push increases Φ by $\leq 2n$ (when the target node becomes active it may contribute at most $2n$ to the sum).
- ▶ A relabel increases Φ by at most 1.
- ▶ A non-saturating push decreases Φ by at least 1 as the node that is pushed from becomes inactive and has a label that is strictly larger than the target.

Lemma 9

The number of *non-saturating pushes* performed is at most $\mathcal{O}(n^2m)$.

Proof.

- ▶ Define a potential function $\Phi(f) = \sum_{\text{active nodes } v} \ell(v)$
- ▶ A saturating push increases Φ by $\leq 2n$ (when the target node becomes active it may contribute at most $2n$ to the sum).
- ▶ A relabel increases Φ by at most 1.
- ▶ A non-saturating push decreases Φ by at least 1 as the node that is pushed from becomes inactive and has a label that is strictly larger than the target.
- ▶ Hence,

$$\begin{aligned} \# \text{non-saturating_pushes} &\leq \# \text{relabels} + 2n \cdot \# \text{saturating_pushes} \\ &\leq \mathcal{O}(n^2m) . \end{aligned}$$

Theorem 10

There is an implementation of the generic push relabel algorithm with running time $\mathcal{O}(n^2m)$.

Analysis

Proof:

For every node maintain a list of admissible edges starting at that node. Further maintain a list of active nodes.

A push along an edge (u, v) can be performed in constant time

- check whether edge (v, u) needs to be added or if
- check whether (u, v) needs to be deleted (aftering push)
- check whether u becomes inactive and has to be deleted from the set of active nodes

A relabel at a node u can be performed in time $\mathcal{O}(n)$

- check for all outgoing edges if they become inadmissible
- check for all incoming edges if they become inadmissible

Analysis

Proof:

For every node maintain a list of admissible edges starting at that node. Further maintain a list of active nodes.

A push along an edge (u, v) can be performed in constant time
check whether node v is active
check whether v is admissible
check whether v becomes inactive and has to be deleted from the set of active nodes

A relabel at a node u can be performed in time $\mathcal{O}(n)$
check for all outgoing edges if they become inadmissible
check for all incoming edges if they become inadmissible

Analysis

Proof:

For every node maintain a list of admissible edges starting at that node. Further maintain a list of active nodes.

A push along an edge (u, v) can be performed in constant time

- ▶ check whether edge (v, u) needs to be added to G_f
- ▶ check whether (u, v) needs to be deleted (saturating push)
- ▶ check whether u becomes inactive and has to be deleted from the set of active nodes

A relabel at a node u can be performed in time $\mathcal{O}(n)$

Analysis

Proof:

For every node maintain a list of admissible edges starting at that node. Further maintain a list of active nodes.

A push along an edge (u, v) can be performed in constant time

- ▶ check whether edge (v, u) needs to be added to G_f
- ▶ check whether (u, v) needs to be deleted (saturating push)
- ▶ check whether u becomes inactive and has to be deleted from the set of active nodes

A relabel at a node u can be performed in time $\mathcal{O}(n)$

Analysis

Proof:

For every node maintain a list of admissible edges starting at that node. Further maintain a list of active nodes.

A push along an edge (u, v) can be performed in constant time

- ▶ check whether edge (v, u) needs to be added to G_f
- ▶ check whether (u, v) needs to be deleted (saturating push)
- ▶ check whether u becomes inactive and has to be deleted from the set of active nodes

A relabel at a node u can be performed in time $\mathcal{O}(n)$

Analysis

Proof:

For every node maintain a list of admissible edges starting at that node. Further maintain a list of active nodes.

A push along an edge (u, v) can be performed in constant time

- ▶ check whether edge (v, u) needs to be added to G_f
- ▶ check whether (u, v) needs to be deleted (saturating push)
- ▶ check whether u becomes inactive and has to be deleted from the set of active nodes

A relabel at a node u can be performed in time $\mathcal{O}(n)$

- ▶ check for all outgoing edges if they become admissible
- ▶ check for all incoming edges if they become non-admissible

Analysis

Proof:

For every node maintain a list of admissible edges starting at that node. Further maintain a list of active nodes.

A push along an edge (u, v) can be performed in constant time

- ▶ check whether edge (v, u) needs to be added to G_f
- ▶ check whether (u, v) needs to be deleted (saturating push)
- ▶ check whether u becomes inactive and has to be deleted from the set of active nodes

A relabel at a node u can be performed in time $\mathcal{O}(n)$

- ▶ check for all outgoing edges if they become admissible
- ▶ check for all incoming edges if they become non-admissible

Analysis

For special variants of push relabel algorithms we organize the neighbours of a node into a linked list (possible neighbours in the residual graph G_f). Then we use the discharge-operation:

Algorithm 47 discharge(u)

```
1: while  $u$  is active do  
2:    $v \leftarrow u.current\text{-neighbour}$   
3:   if  $v = \text{null}$  then  
4:     relabel( $u$ )  
5:      $u.current\text{-neighbour} \leftarrow u.neighbour\text{-list-head}$   
6:   else  
7:     if  $(u, v)$  admissable then push( $u, v$ )  
8:     else  $u.current\text{-neighbour} \leftarrow v.next\text{-in-list}$ 
```

Note that $u.current\text{-neighbour}$ is a global variable. It is only changed within the discharge routine, but keeps its value between consecutive calls to discharge.

Lemma 11

If $v = \text{null}$ in Line 3, then there is no outgoing admissible edge from u .

Proof.

- ▶ While pushing from u the current-neighbour pointer is only advanced if the current edge is not admissible.
- ▶ The only thing that could make the edge admissible again would be a relabel at u .
- ▶ If we reach the end of the list ($v = \text{null}$) all edges are not admissible. □

This shows that $\text{discharge}(u)$ is correct, and that we can perform a relabel in line 4.

14.2 Relabel to Front

Algorithm 50 relabel-to-front(G, s, t)

```
1: initialize preflow
2: initialize node list  $L$  containing  $V \setminus \{s, t\}$  in any order
3: foreach  $u \in V \setminus \{s, t\}$  do
4:    $u.current\text{-neighbour} \leftarrow u.neighbour\text{-list}\text{-head}$ 
5:  $u \leftarrow L.head$ 
6: while  $u \neq \text{null}$  do
7:    $old\text{-height} \leftarrow \ell(u)$ 
8:   discharge( $u$ )
9:   if  $\ell(u) > old\text{-height}$  then // relabel happened
10:    move  $u$  to the front of  $L$ 
11:    $u \leftarrow u.next$ 
```

14.2 Relabel to Front

Lemma 12 (Invariant)

In Line 6 of the relabel-to-front algorithm the following invariant holds.

- 1. The sequence L is topologically sorted w.r.t. the set of admissible edges; this means for an admissible edge (x, y) the node x appears before y in sequence L .*
- 2. No node before u in the list L is active.*

Proof:

► Initialization:

1. In the beginning s has label $n \geq 2$, and all other nodes have label 0. Hence, no edge is admissible, which means that any ordering L is permitted.
2. We start with u being the head of the list; hence no node before u can be active

► Maintenance:

1.
 - Pushes do not create any new admissible edges. Therefore, if $\text{discharge}()$ does not relabel u , L is still topologically sorted.
 - After relabeling, u cannot have admissible incoming edges as such an edge (x, u) would have had a difference $\ell(x) - \ell(u) \geq 2$ before the re-labeling (such edges do not exist in the residual graph).
Hence, moving u to the front does not violate the sorting property for any edge; however it fixes this property for all admissible edges leaving u that were generated by the relabeling.

14.2 Relabel to Front

Proof:

► Maintenance:

2. If we do a relabel there is nothing to prove because the only node before u' (u in the next iteration) will be the current u ; the $\text{discharge}(u)$ operation only terminates when u is not active anymore.

For the case that we do not relabel, observe that the only way a predecessor could be active is that we push flow to it via an admissible arc. However, all admissible arcs point to successors of u .

Note that the invariant means that for $u = \text{null}$ we have a preflow with a valid labelling that does not have active nodes. This means we have a maximum flow.

14.2 Relabel to Front

Lemma 13

There are at most $\mathcal{O}(n^3)$ calls to $\text{discharge}(u)$.

Every discharge operation without a relabel advances u (the current node within list L). Hence, if we have n discharge operations without a relabel we have $u = \text{null}$ and the algorithm terminates.

Therefore, the number of calls to discharge is at most $n(\#\text{relabels} + 1) = \mathcal{O}(n^3)$.

14.2 Relabel to Front

Lemma 14

The cost for all relabel-operations is only $\mathcal{O}(n^2)$.

A relabel-operation at a node is constant time (increasing the label and resetting *u.current-neighbour*). In total we have $\mathcal{O}(n^2)$ relabel-operations.

14.2 Relabel to Front

Note that by definition a saturating push operation ($\min\{c_f(e), f(u)\} = c_f(e)$) can at the same time be a non-saturating push operation ($\min\{c_f(e), f(u)\} = f(u)$).

Lemma 15

*The cost for all saturating push-operations that are **not** also non-saturating push-operations is only $\mathcal{O}(mn)$.*

Note that such a push-operation leaves the node u active but makes the edge e disappear from the residual graph. Therefore the push-operation is immediately followed by an increase of the pointer $u.current-neighbour$.

This pointer can traverse the neighbour-list at most $\mathcal{O}(n)$ times (upper bound on number of relabels) and the neighbour-list has only $degree(u) + 1$ many entries (+1 for null-entry).

14.2 Relabel to Front

Lemma 16

The cost for all non-saturating push-operations is only $\mathcal{O}(n^3)$.

A non-saturating push-operation takes constant time and ends the current call to `discharge()`. Hence, there are only $\mathcal{O}(n^3)$ such operations.

Theorem 17

The push-relabel algorithm with the rule relabel-to-front takes time $\mathcal{O}(n^3)$.

14.3 Highest label

Algorithm 50 highest-label(G, s, t)

- 1: initialize preflow
- 2: **foreach** $u \in V \setminus \{s, t\}$ **do**
- 3: $u.current-neighbour \leftarrow u.neighbour-list-head$
- 4: **while** \exists active node u **do**
- 5: select active node u with highest label
- 6: discharge(u)

14.3 Highest label

Lemma 18

When using highest label the number of non-saturating pushes is only $\mathcal{O}(n^3)$.

A push from a node on level ℓ can only “activate” nodes on levels strictly less than ℓ .

This means, after a non-saturating push from u a relabel is required to make u active again.

Hence, after n non-saturating pushes without an intermediate relabel there are no active nodes left.

Therefore, the number of non-saturating pushes is at most $n(\#relabels + 1) = \mathcal{O}(n^3)$.

14.3 Highest label

Since a discharge-operation is terminated by a non-saturating push this gives an upper bound of $\mathcal{O}(n^3)$ on the number of discharge-operations.

The cost for relabels and saturating pushes can be estimated in exactly the same way as in the case of the generic push-relabel algorithm.

Question:

How do we find the next node for a discharge operation?

14.3 Highest label

Maintain lists L_i , $i \in \{0, \dots, 2n\}$, where list L_i contains active nodes with label i (maintaining these lists induces only constant additional cost for every push-operation and for every relabel-operation).

After a discharge operation terminated for a node u with label k , traverse the lists L_k, L_{k-1}, \dots, L_0 , (in that order) until you find a non-empty list.

Unless the last (non-saturating) push was to s or t the list $k - 1$ must be non-empty (i.e., the search takes constant time).

14.3 Highest label

Hence, the total time required for searching for active nodes is at most

$$\mathcal{O}(n^3) + n(\#non-saturating-pushes-to-s-or-t)$$

Lemma 19

The number of non-saturating pushes to s or t is at most $\mathcal{O}(n^2)$.

With this lemma we get

Theorem 20

The push-relabel algorithm with the rule highest-label takes time $\mathcal{O}(n^3)$.

14.3 Highest label

Proof of the Lemma.

- ▶ We only show that the number of pushes to the source is at most $\mathcal{O}(n^2)$. A similar argument holds for the target.
- ▶ After a node v (which must have $\ell(v) = n + 1$) made a non-saturating push to the source there needs to be another node whose label is increased from $\leq n + 1$ to $n + 2$ before v can become active again.
- ▶ This happens for every push that v makes to the source. Since, every node can pass the threshold $n + 2$ at most once, v can make at most n pushes to the source.
- ▶ As this holds for every node the total number of pushes to the source is at most $\mathcal{O}(n^2)$.