Preflows

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Definition 53

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

1. For each edge e

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(capacity constraints)

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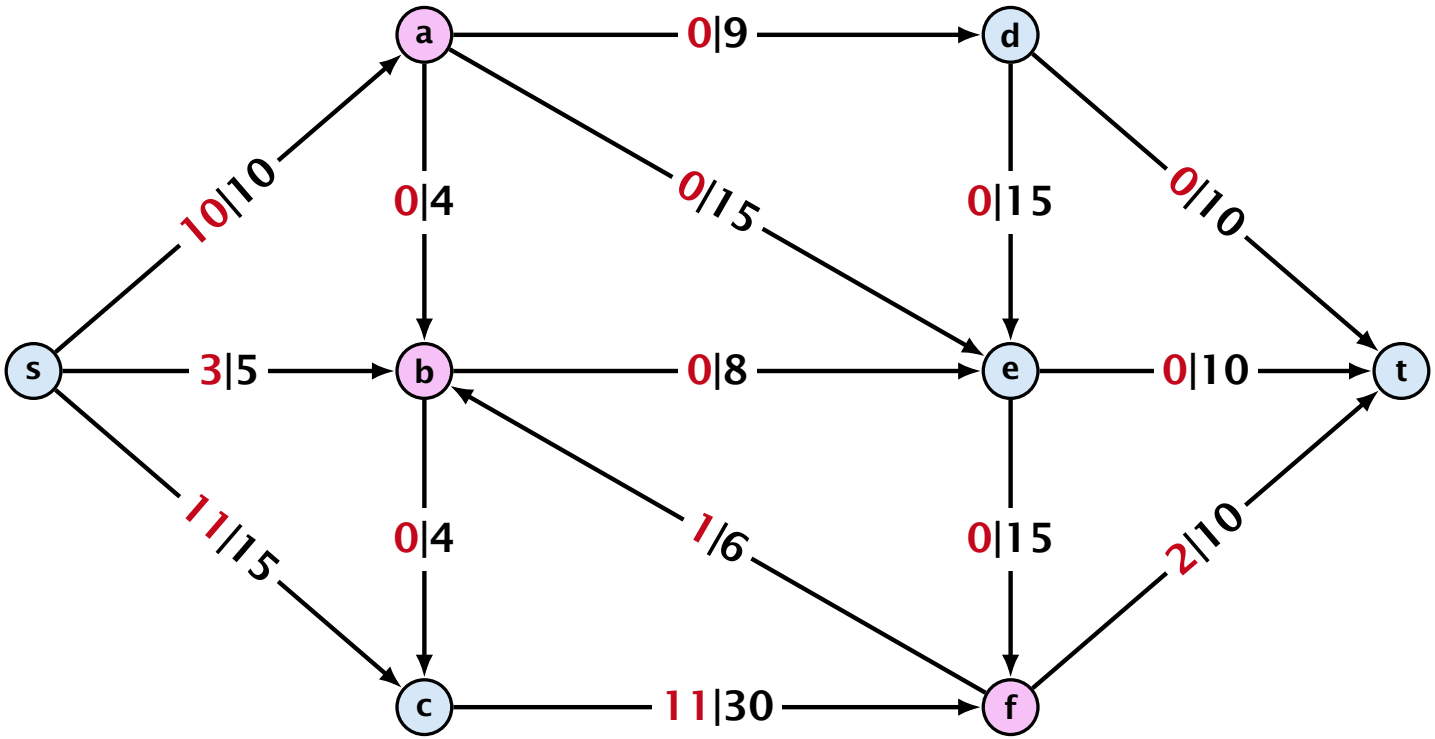
(capacity constraints)

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

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

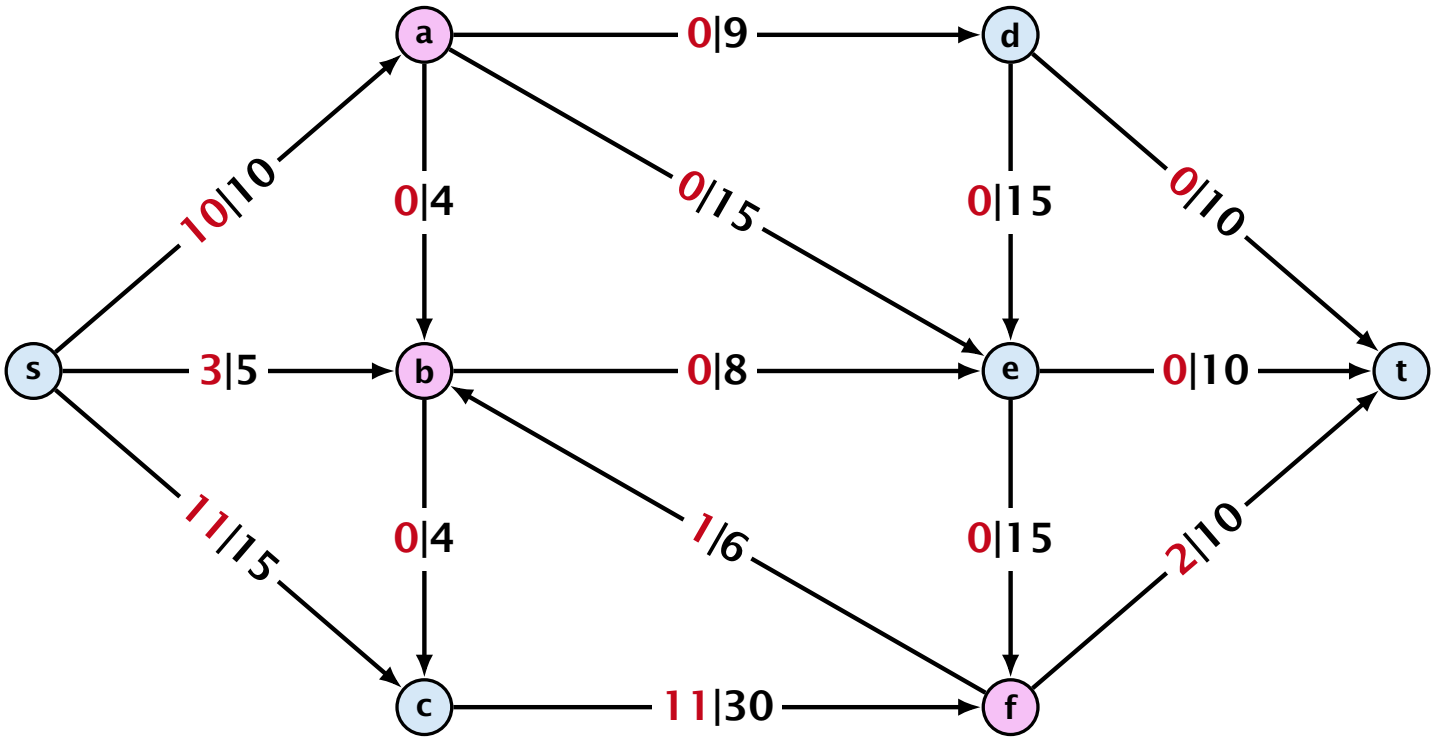
Preflows

Example 54



Preflows

Example 54



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

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Definition:

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

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

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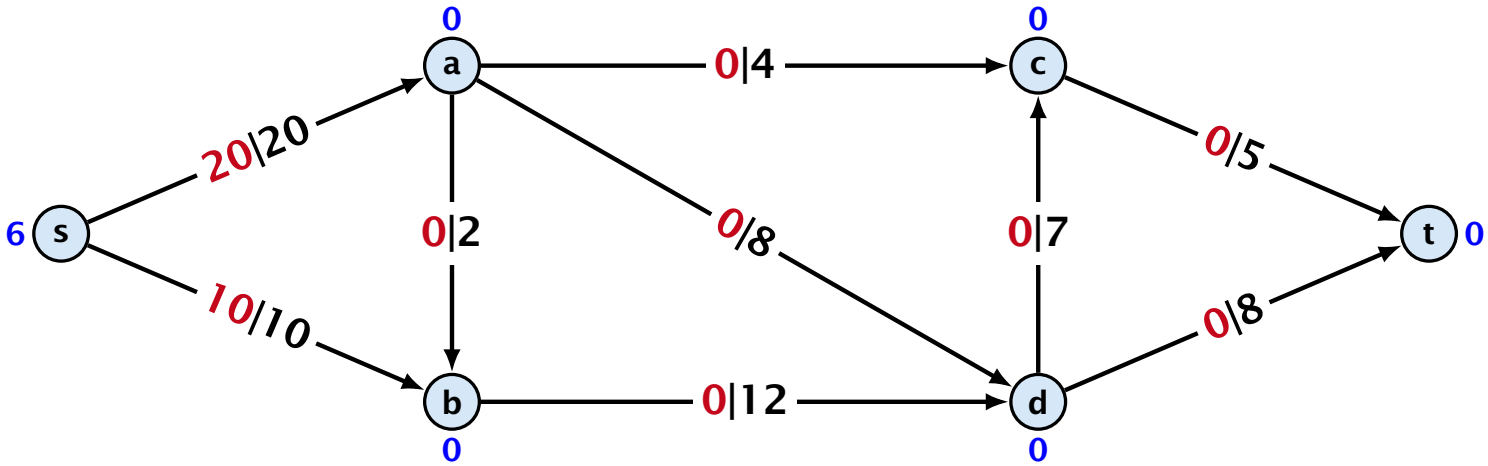
Intuition:

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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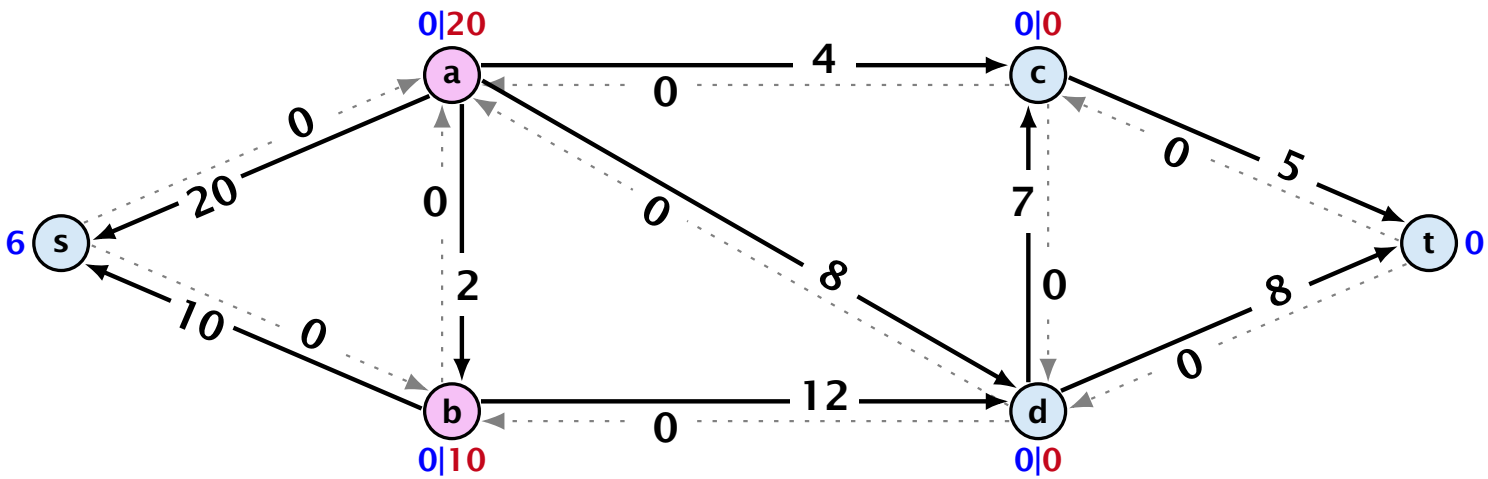
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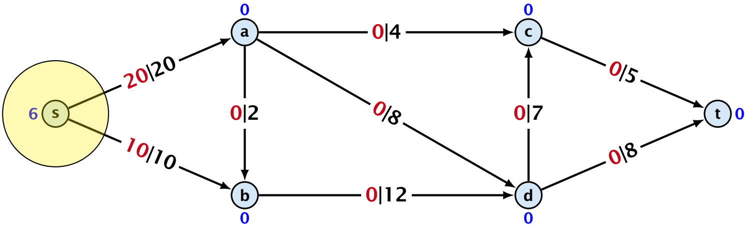
Preflows



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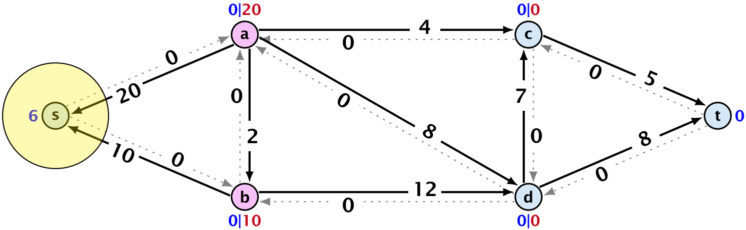

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Preflows

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Lemma 55

A preflow that has a valid labelling saturates a cut.

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Proof:

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

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- 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 56

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

Note that this is somewhat dual to an augmenting path algorithm. The former maintains the property that it has a feasible flow. It successively changes this flow until it saturates some cut in which case we conclude that the flow is maximum. A preflow push algorithm maintains the property that it has a saturated cut. The preflow is changed iteratively until it fulfills conservation constraints in which case we can conclude that we have a maximum flow.

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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)

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Changing a Preflow

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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).

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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 $c_f(e)$.

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

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

Note that a push-operation may be saturating **and** deactivating at the same time.

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

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Push Relabel Algorithms

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The relabel operation

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- 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 then 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; 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 saturating push along e pushes an amount of $c(e)$ flow along the edge, thereby saturating the edge (and making it dissappear from the residual graph).
- A deactivating 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 1 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:             push(G, e, f, c)
5:       else
6:             relabel(u)
7: return f
```

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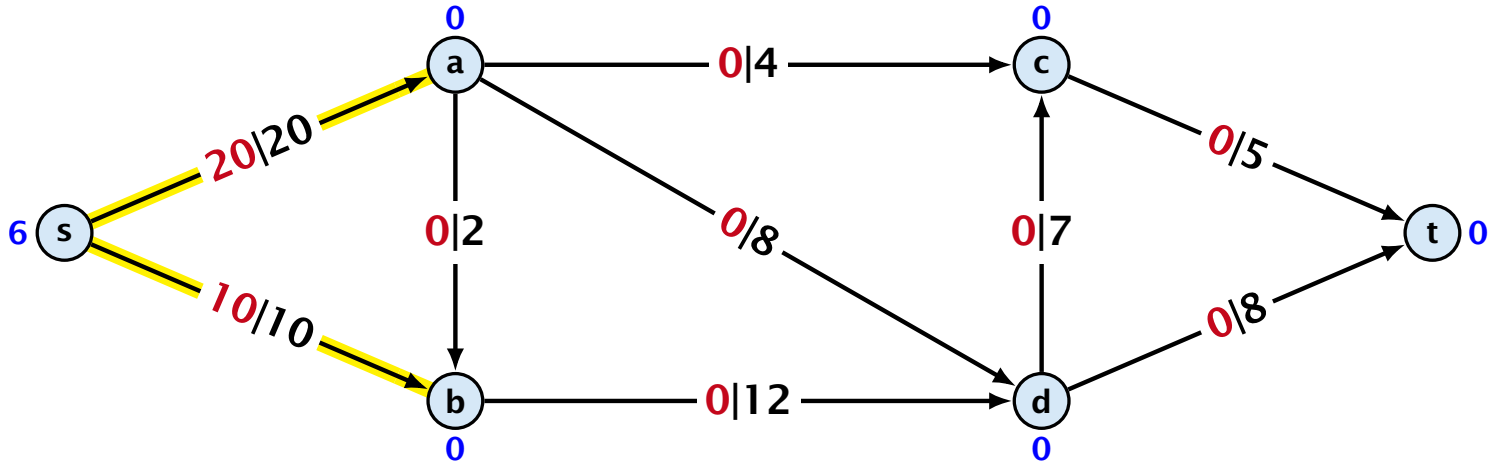
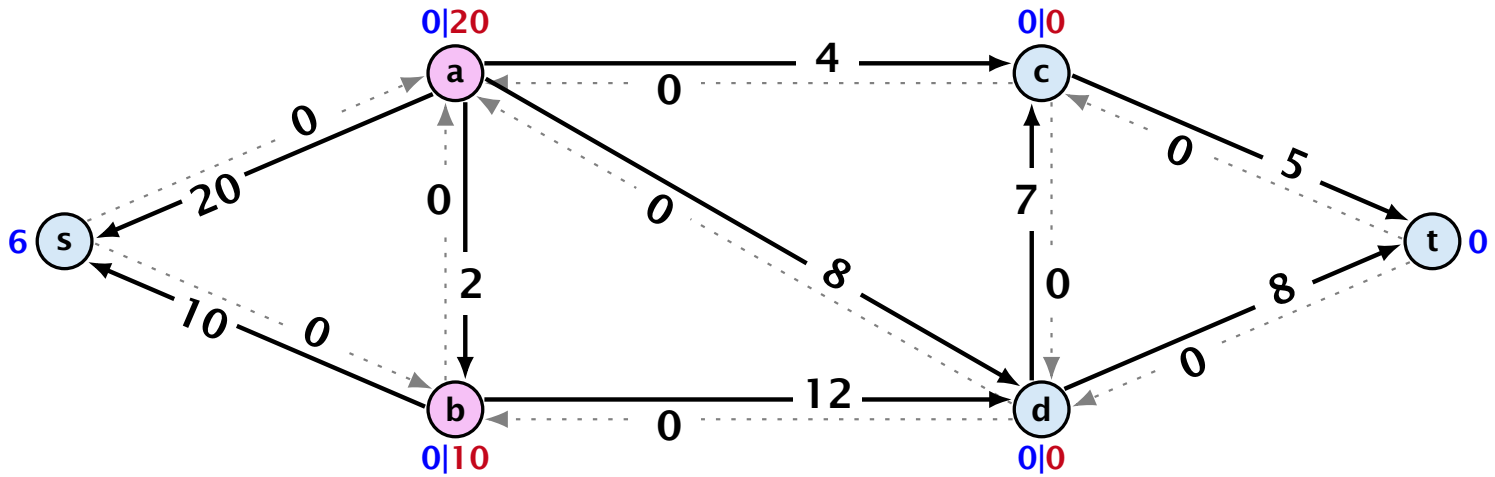
```

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

Preflow Push

The yellow edges indicate the cut that is introduced by the smallest missing label.





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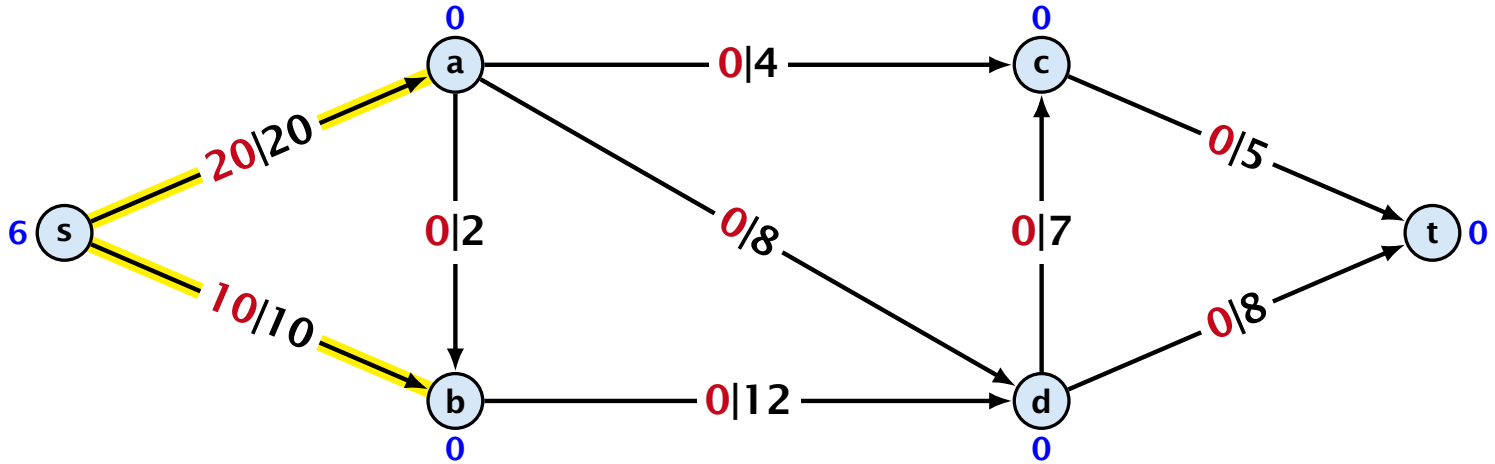

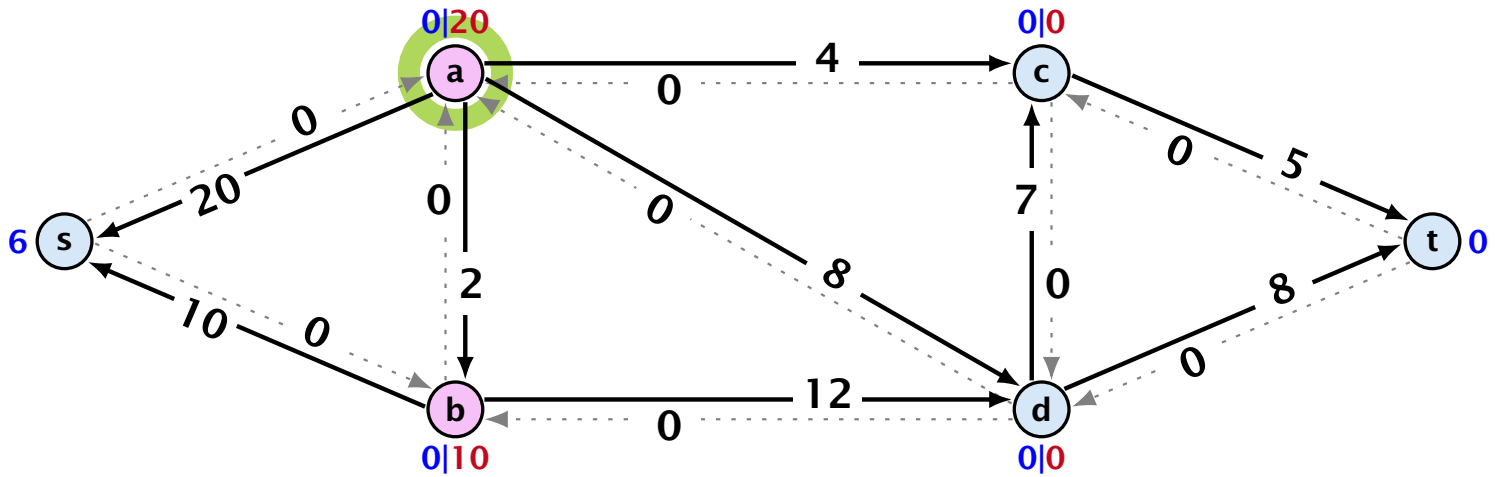

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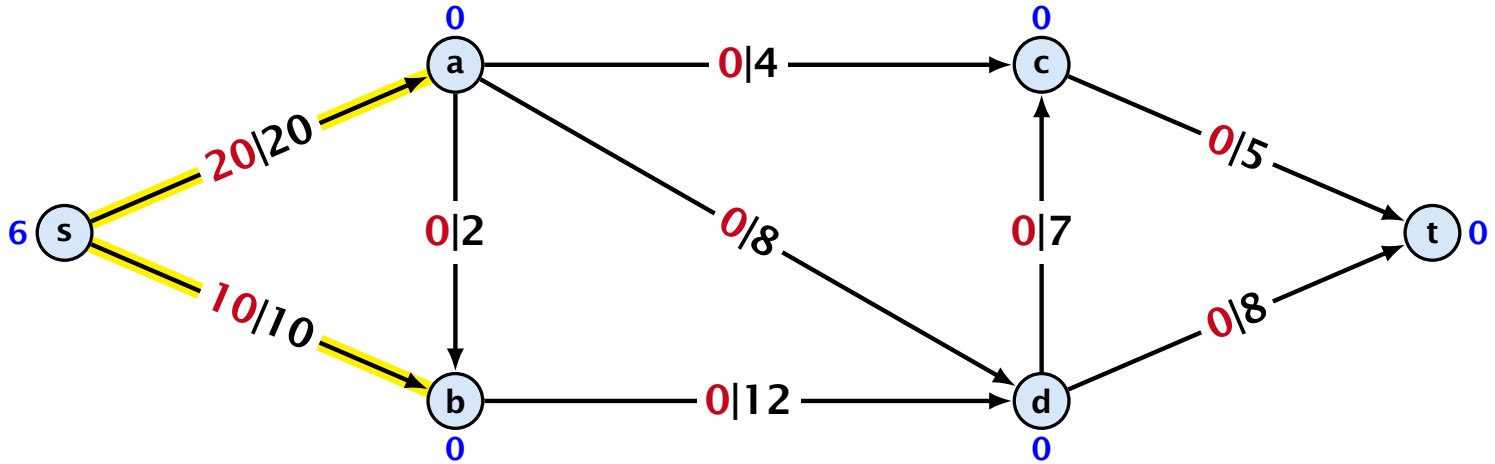
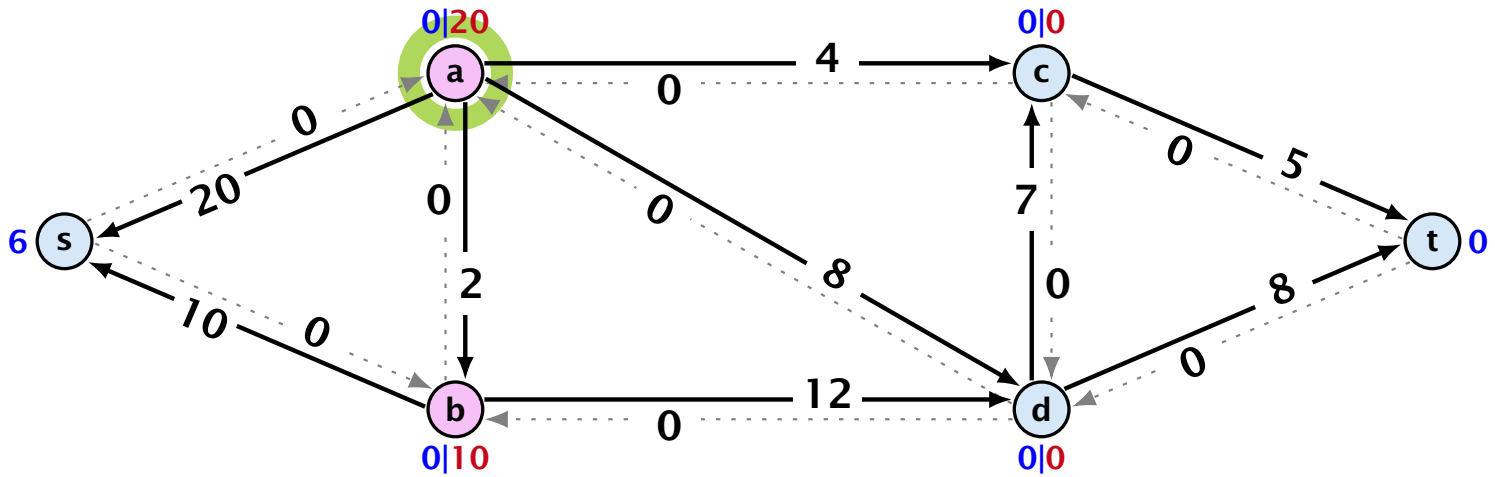


relabel to 1



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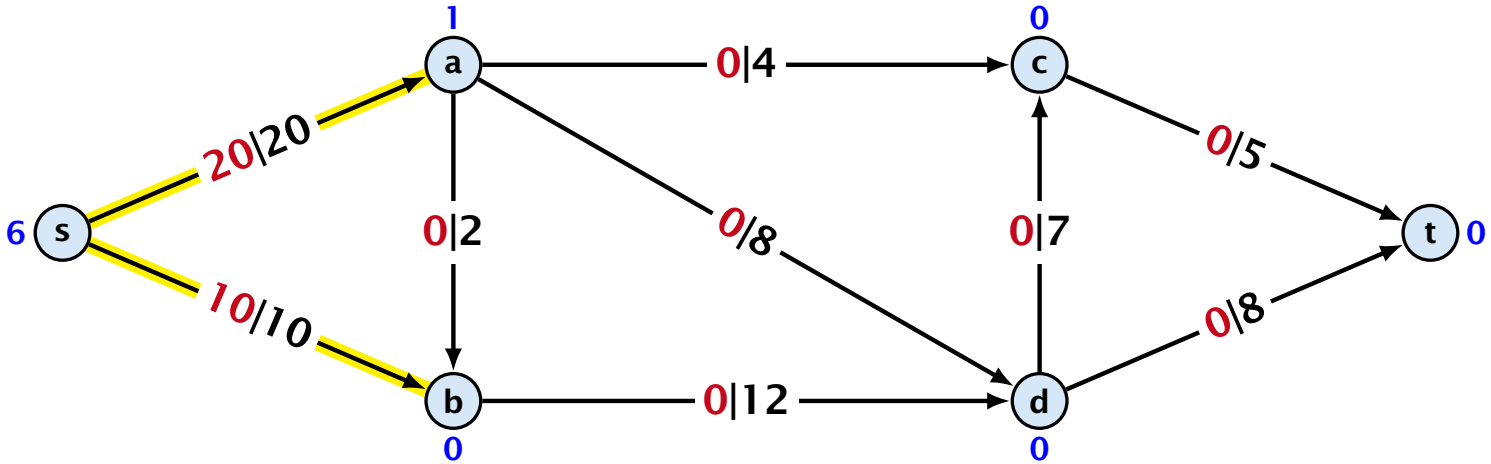

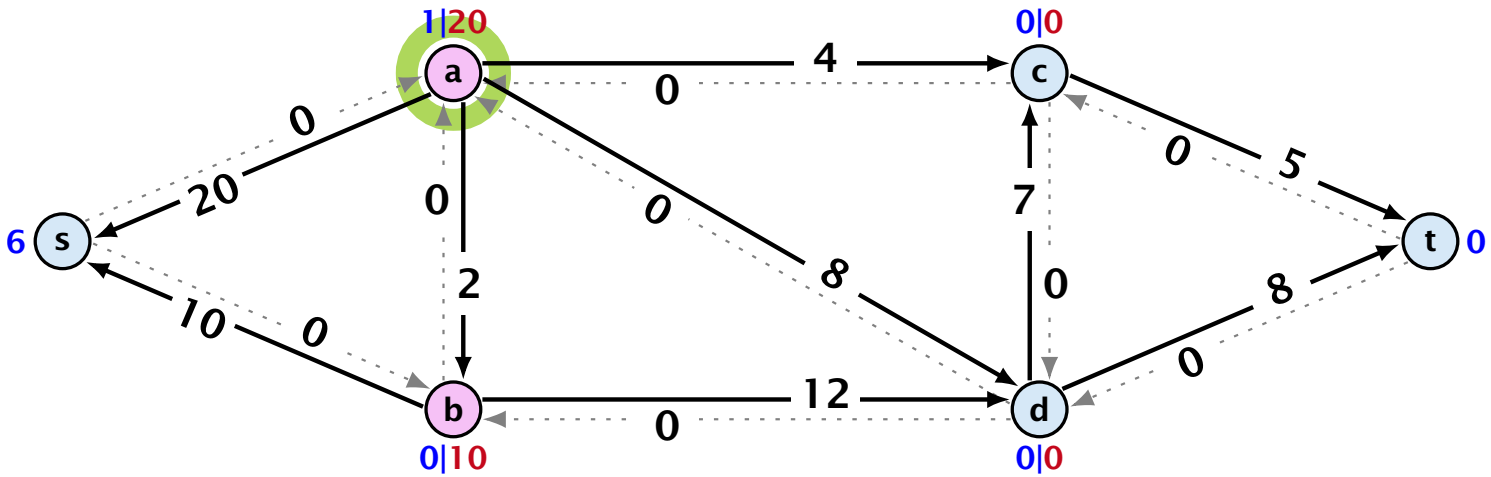

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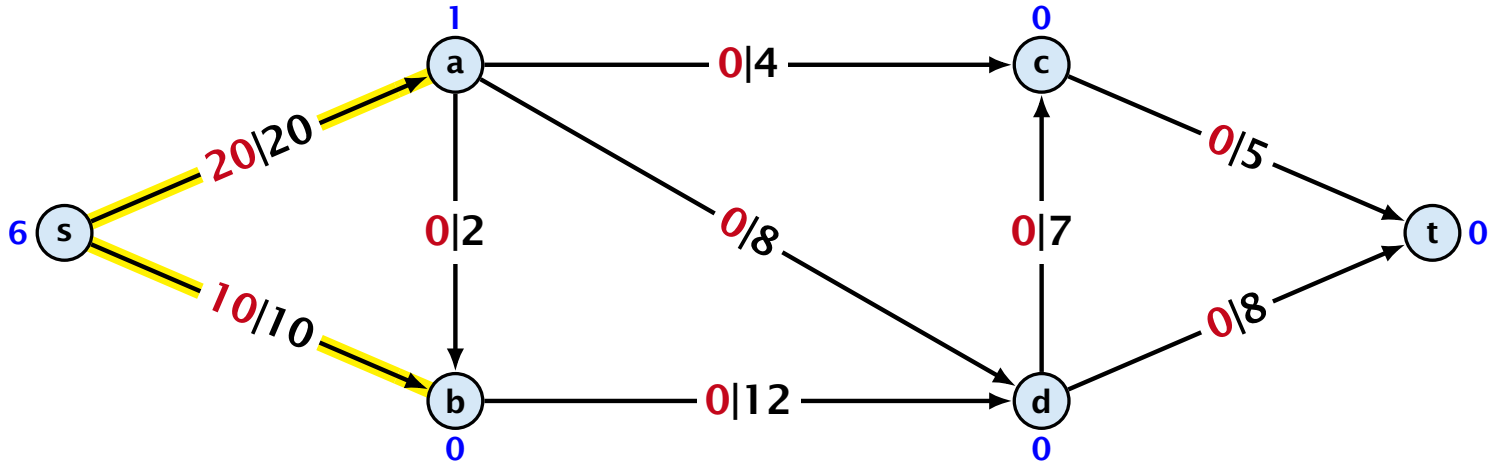
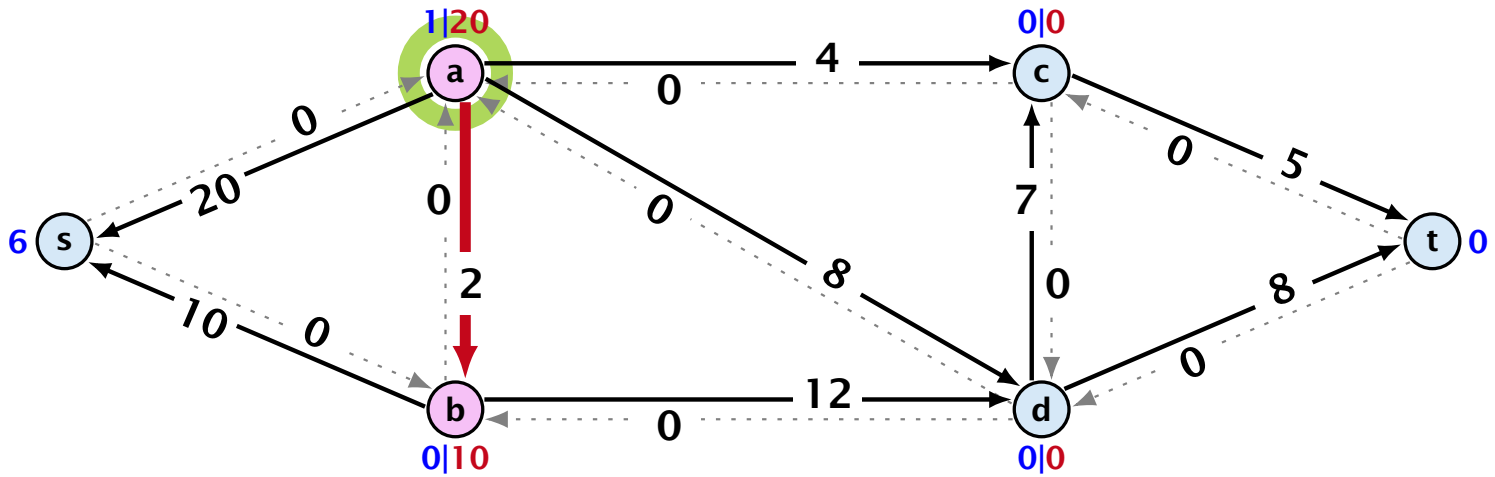


saturating push



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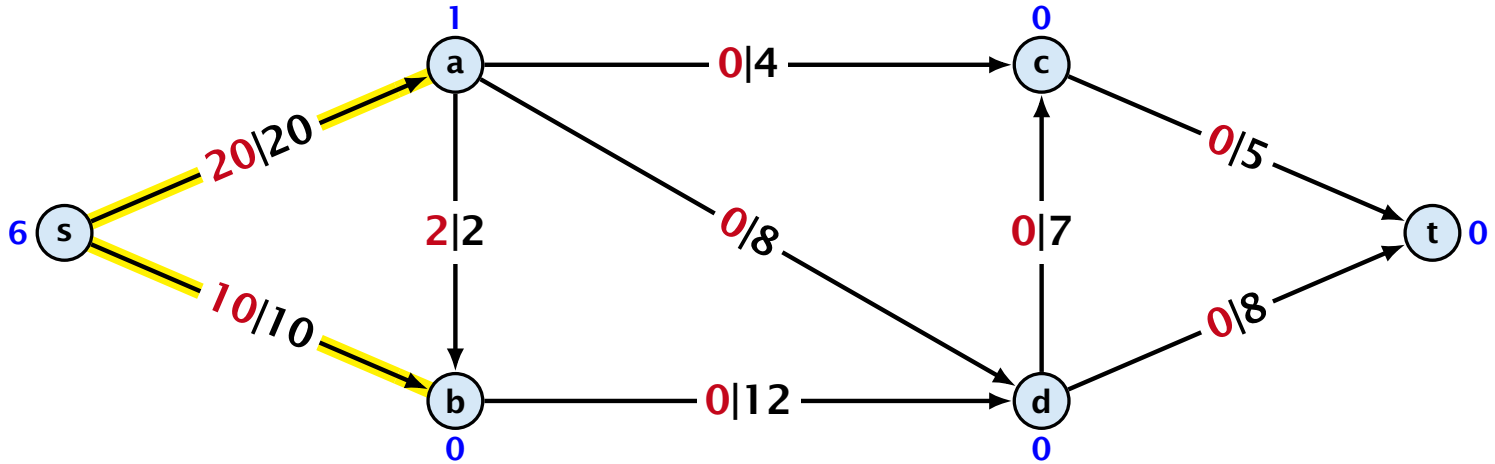

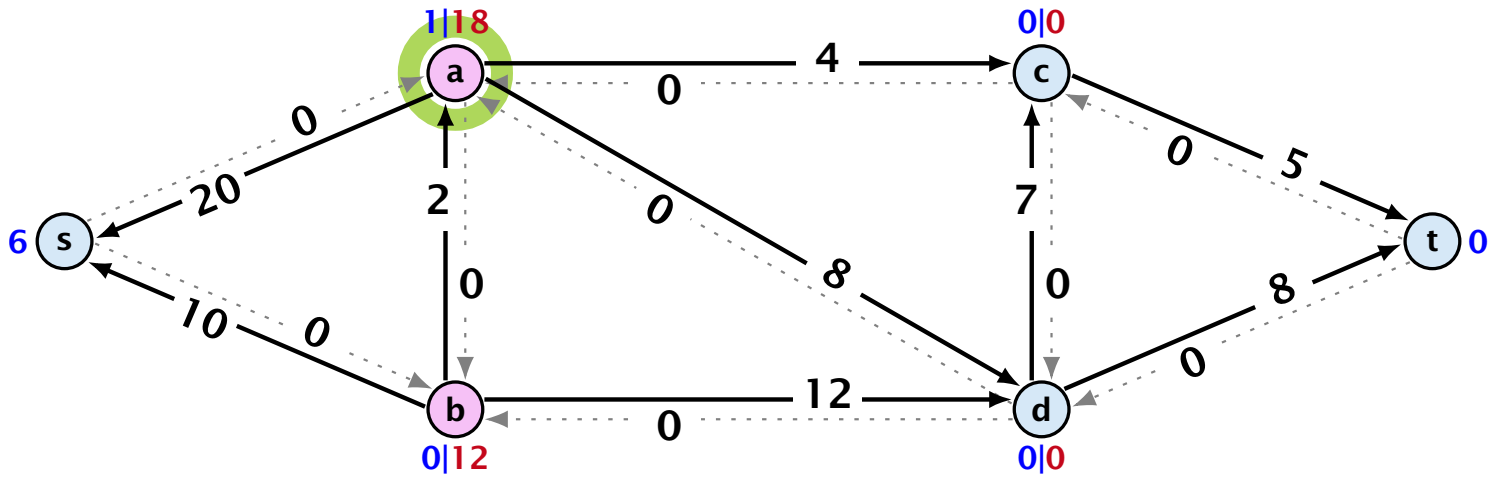

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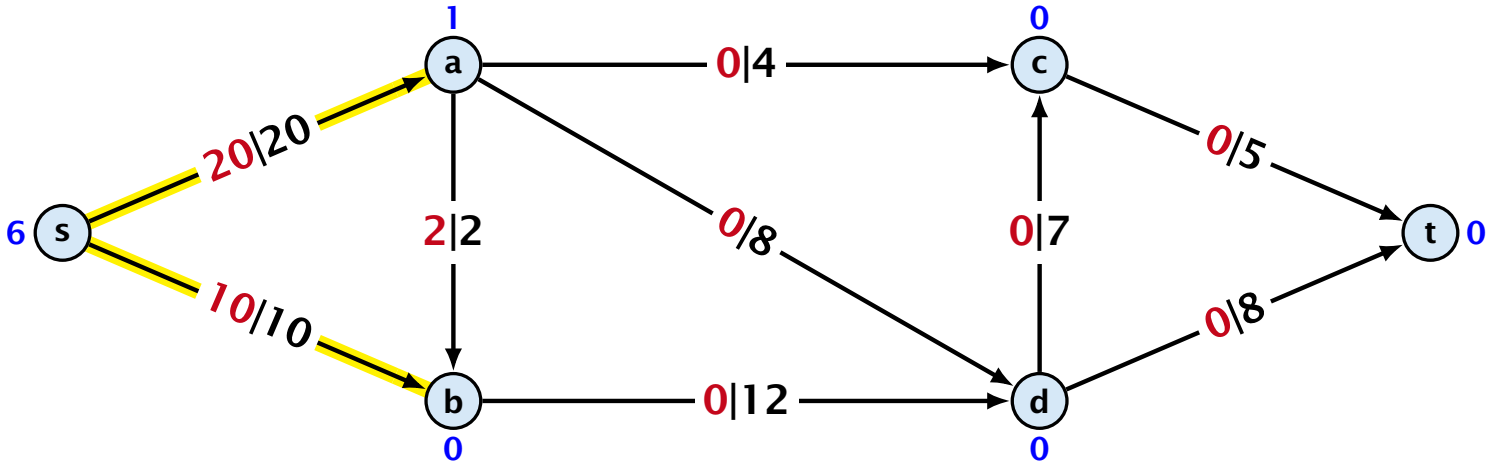
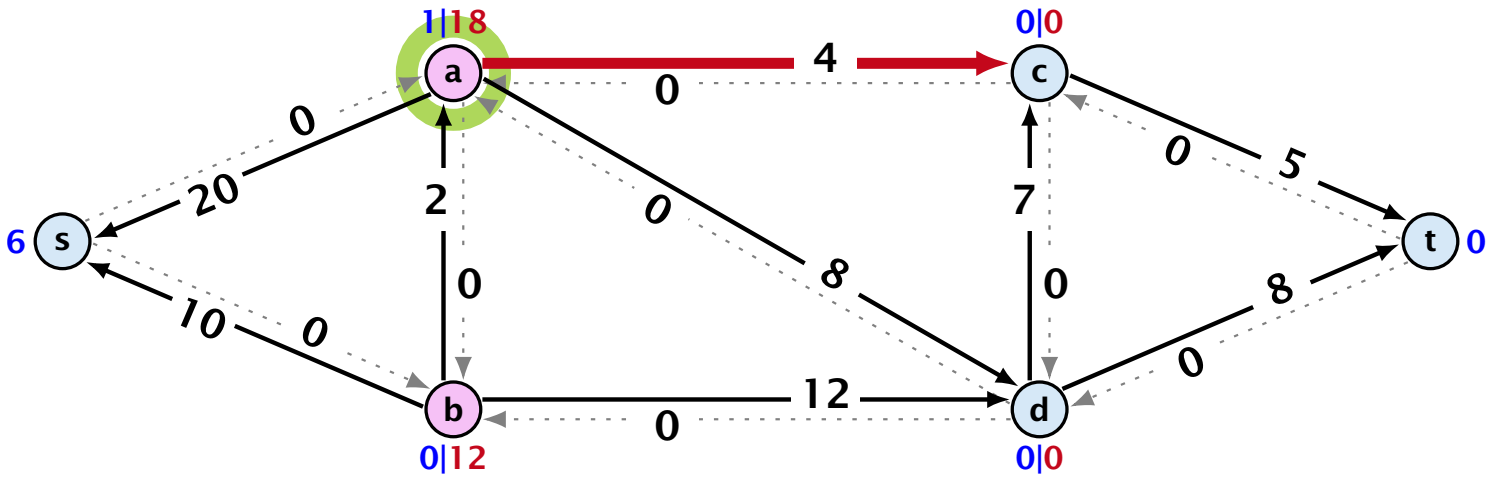


saturating push



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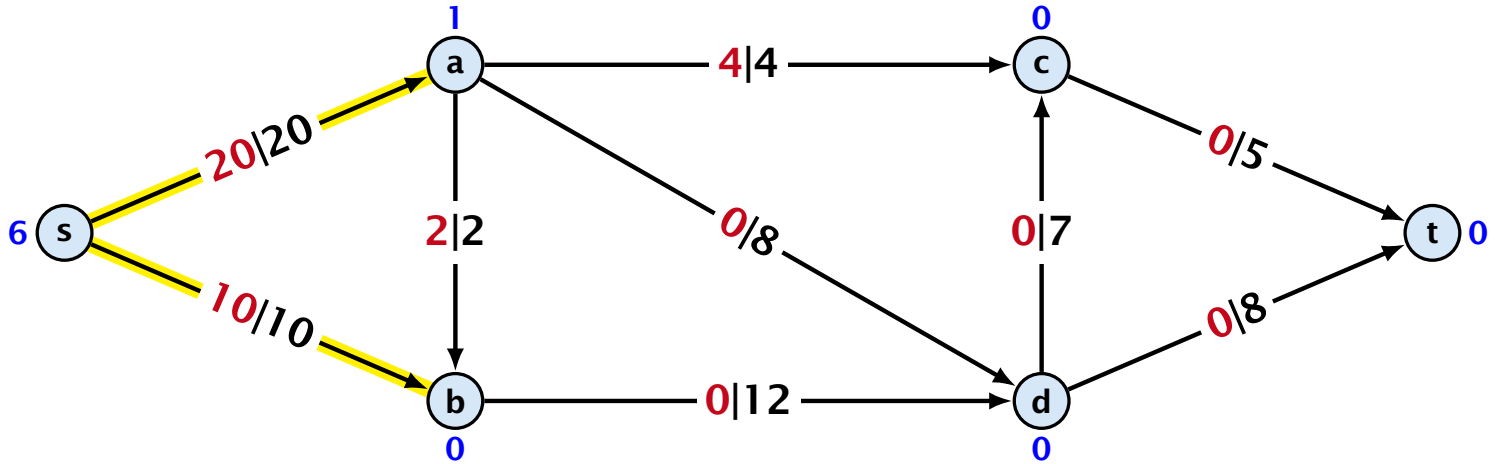

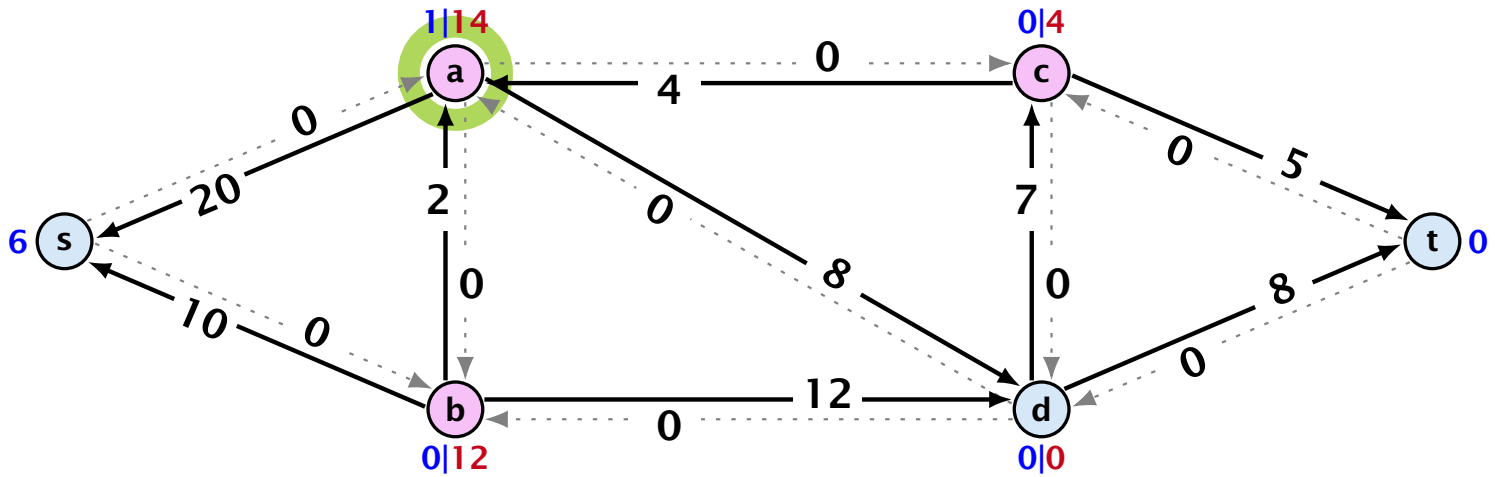

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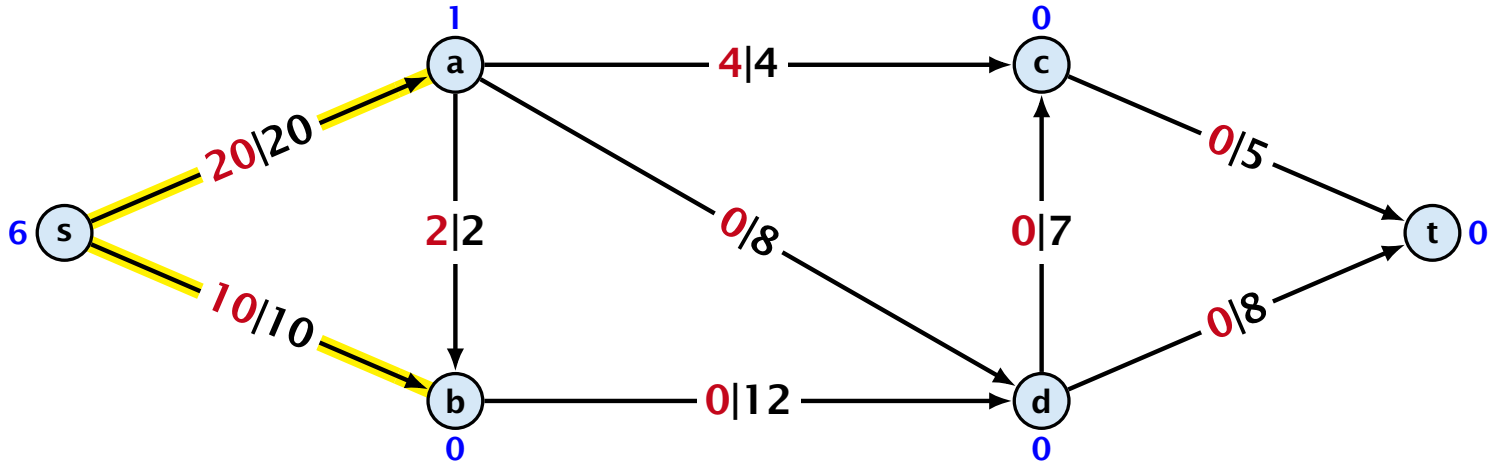

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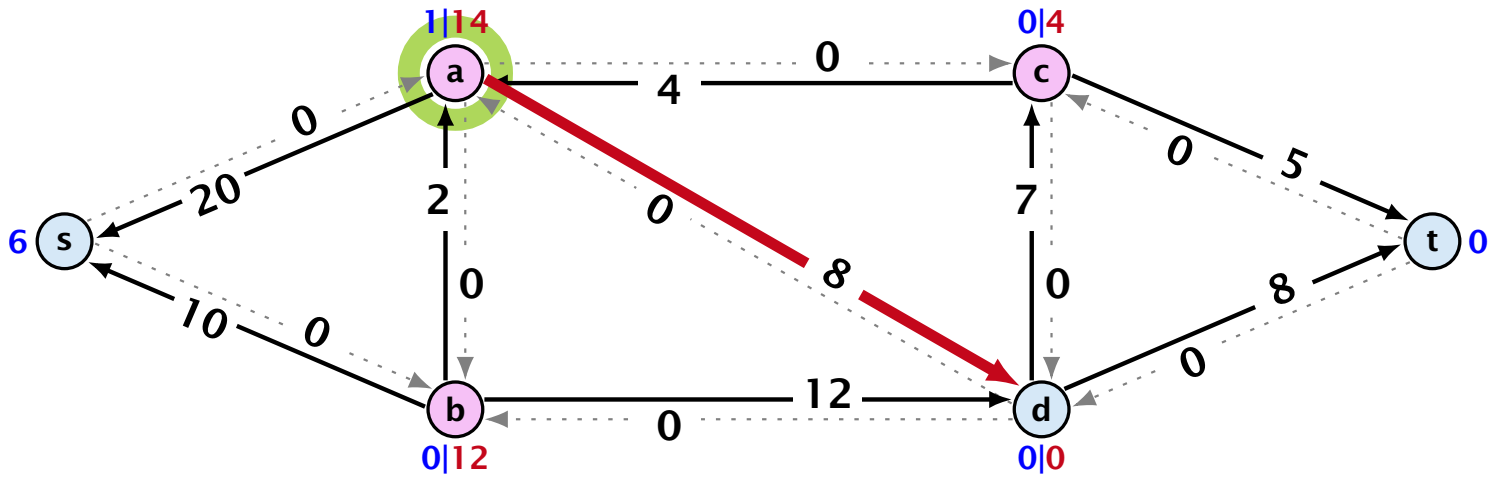

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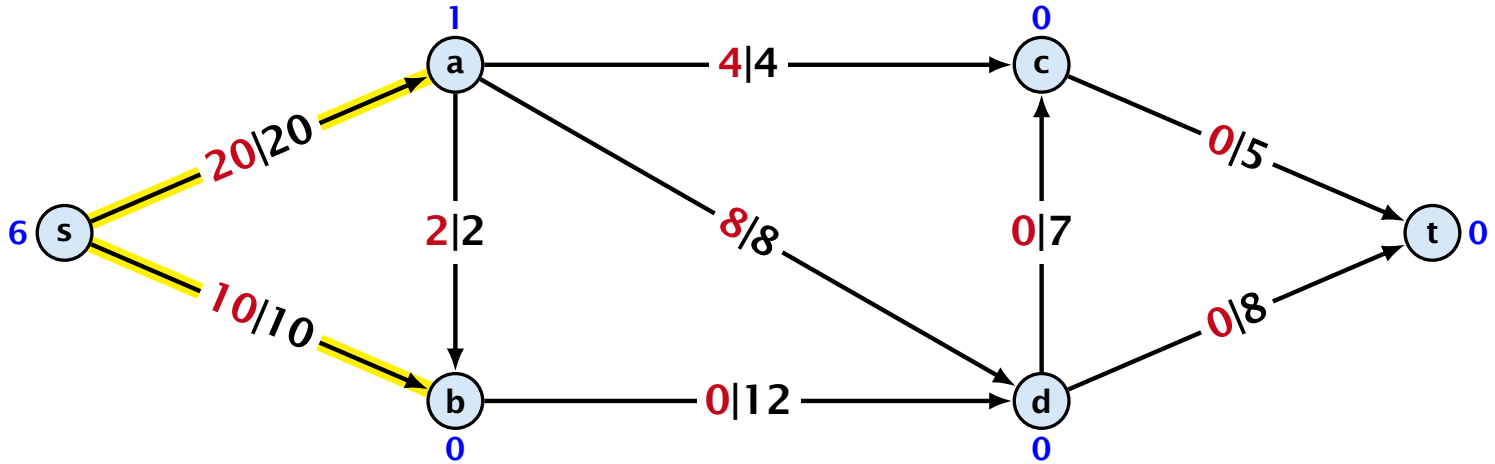

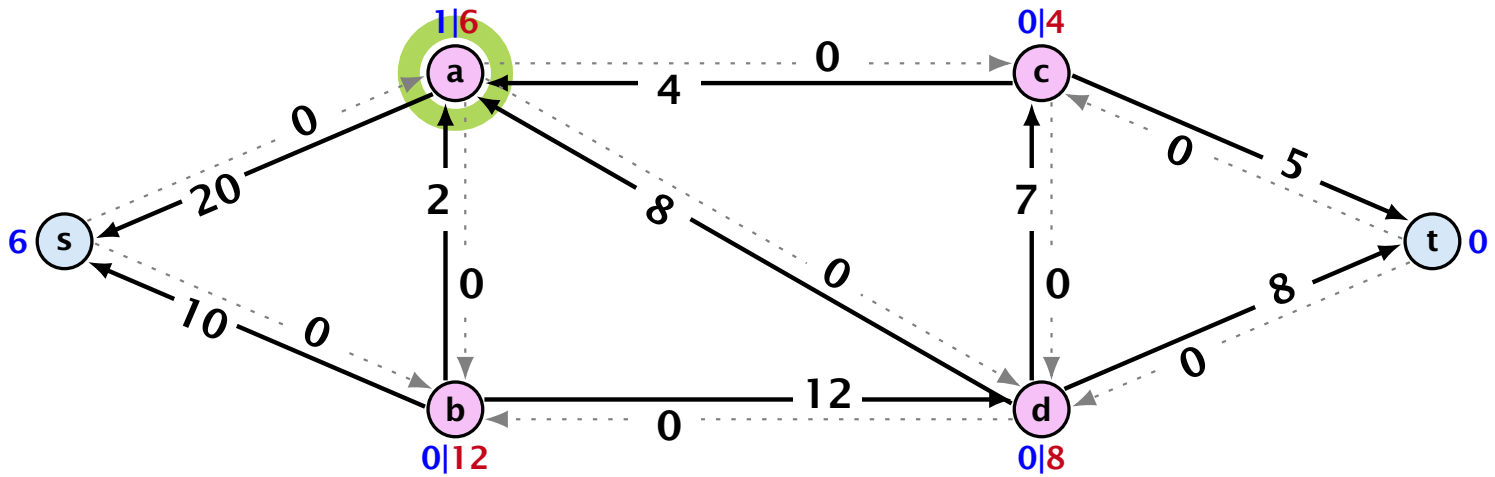

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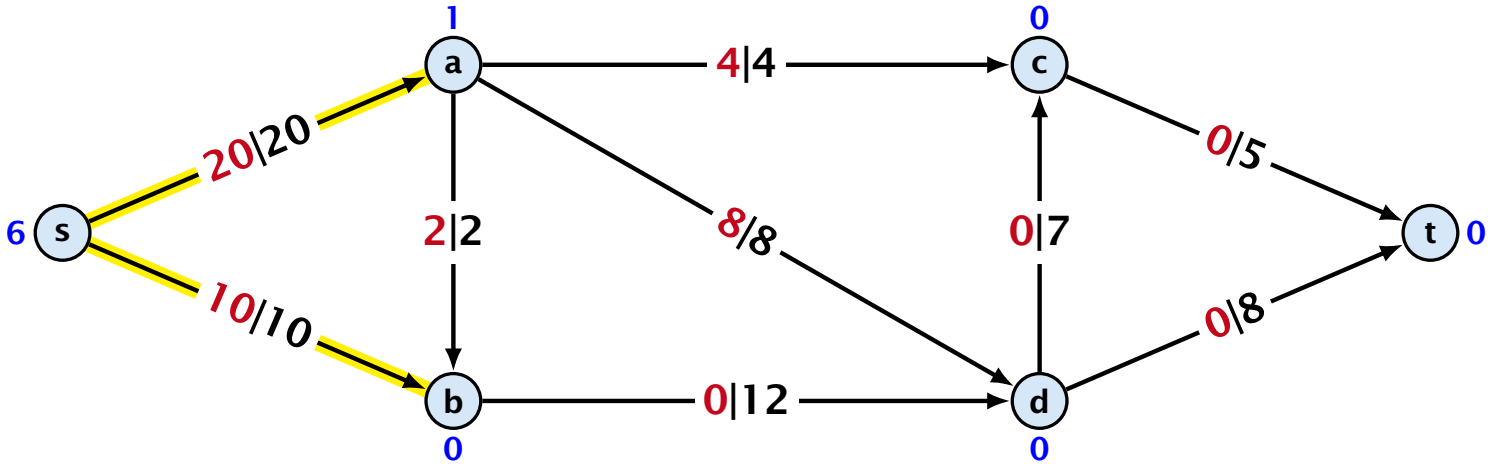
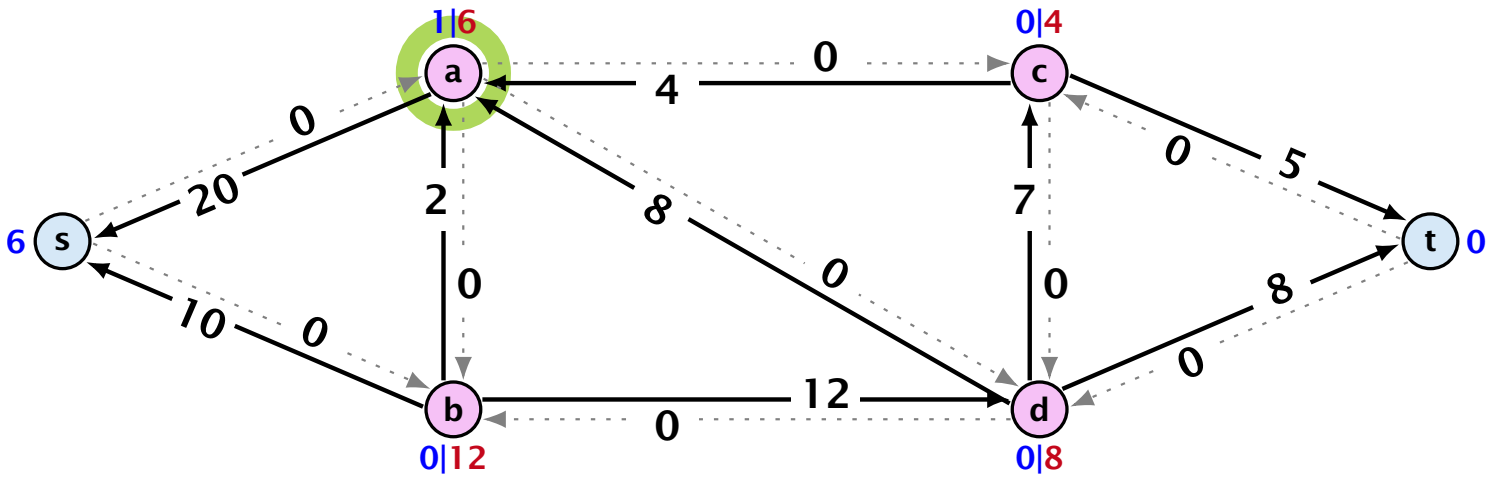


relabel to 7



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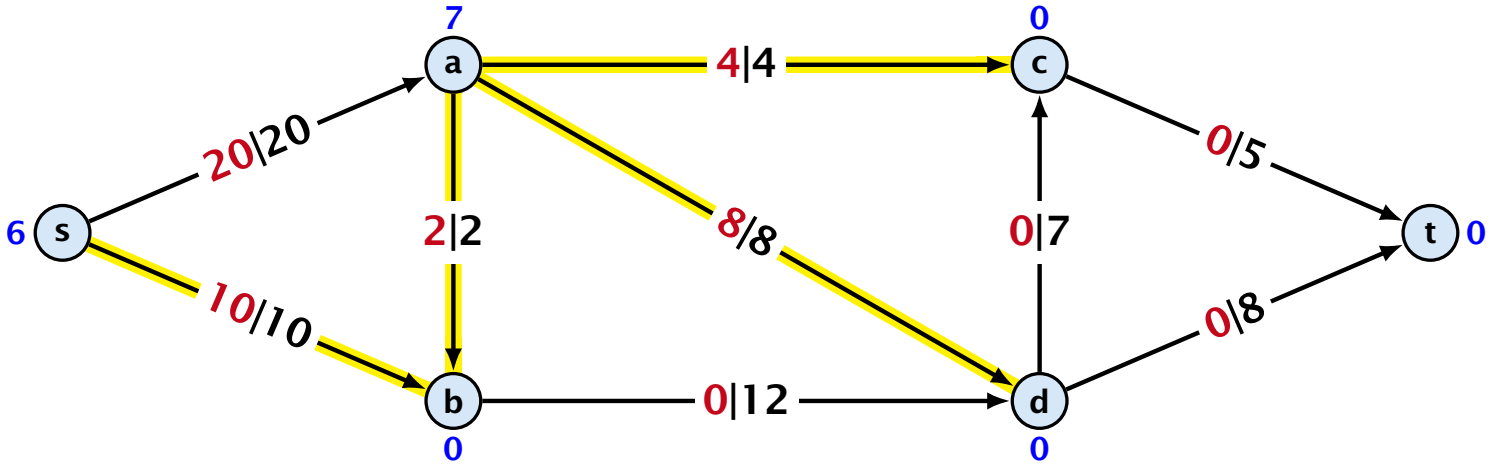
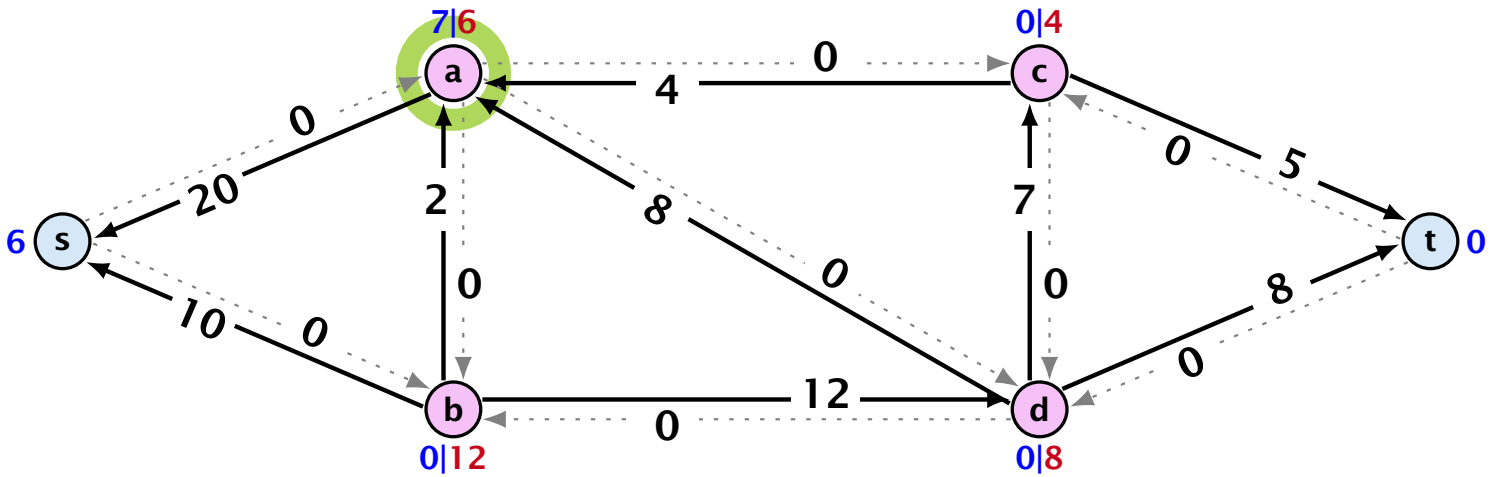
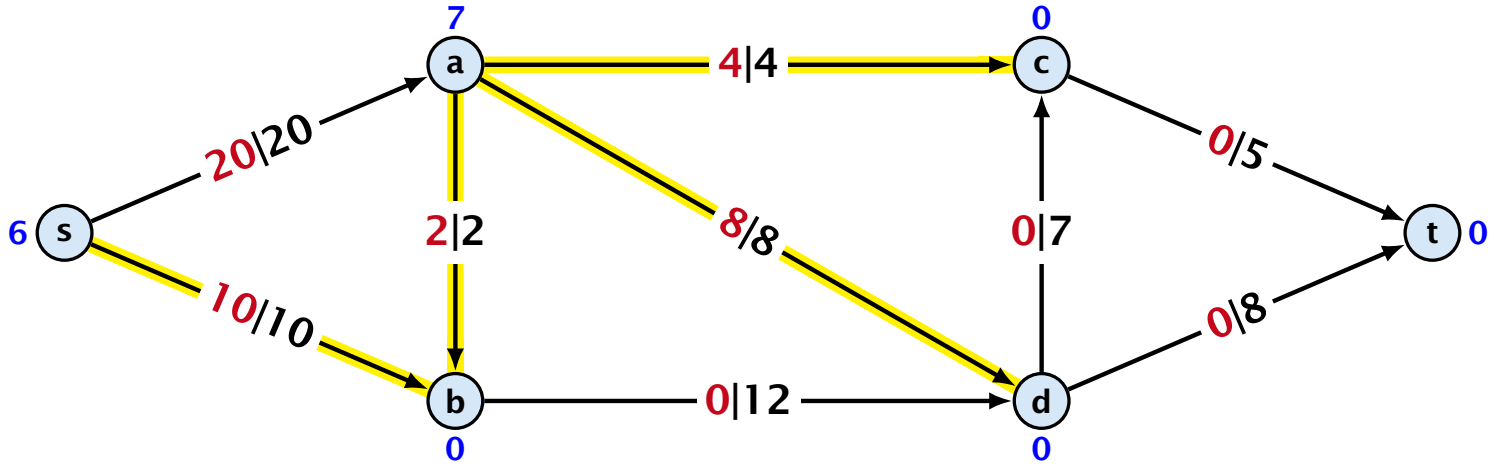


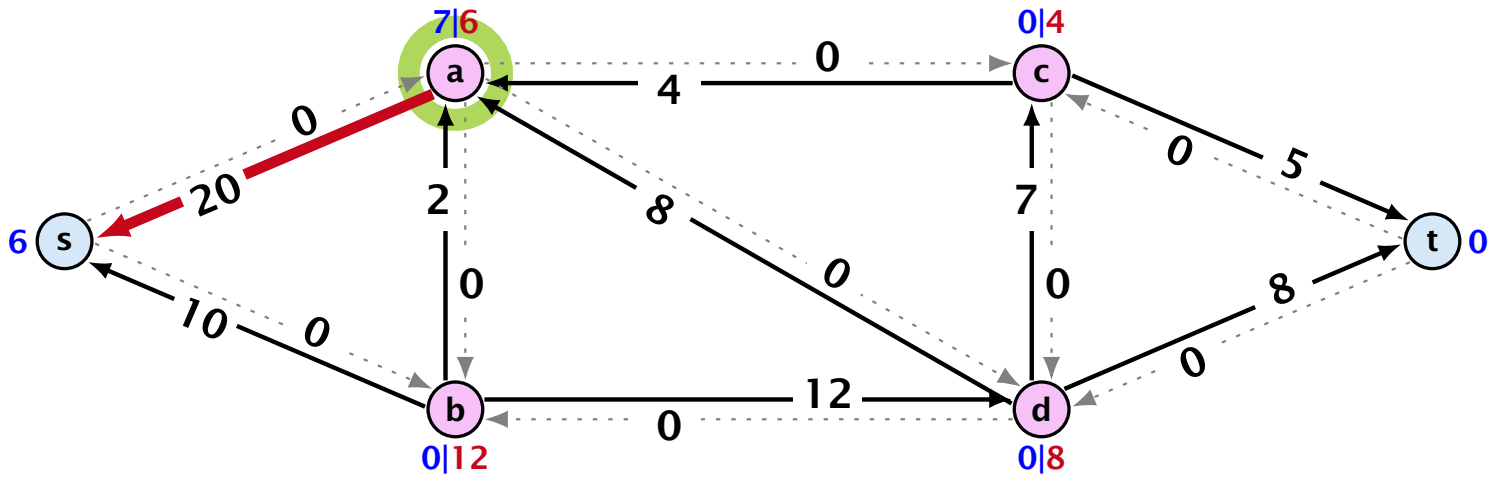


Preflow Push

The yellow edges indicate the cut that is introduced by the smallest missing label.



deactivating push



Preflow Push

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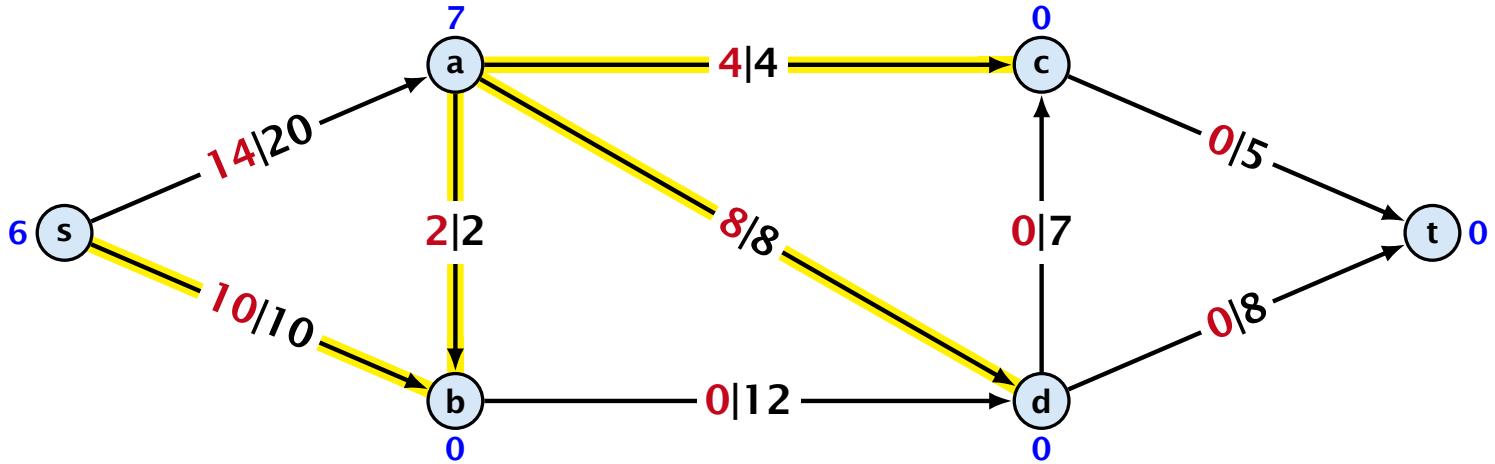

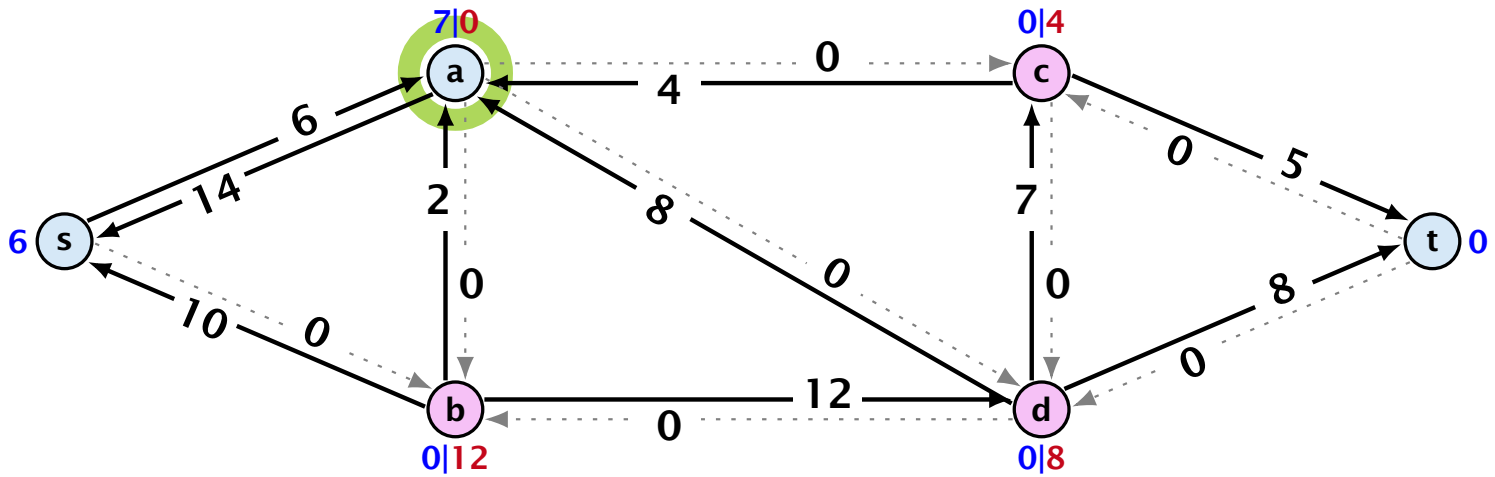

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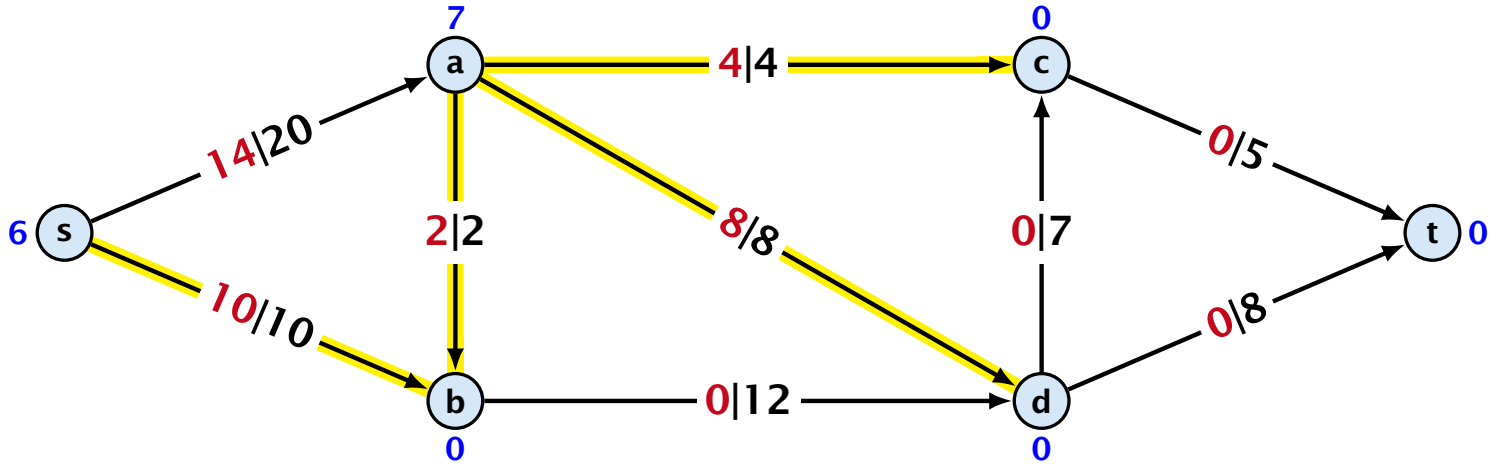

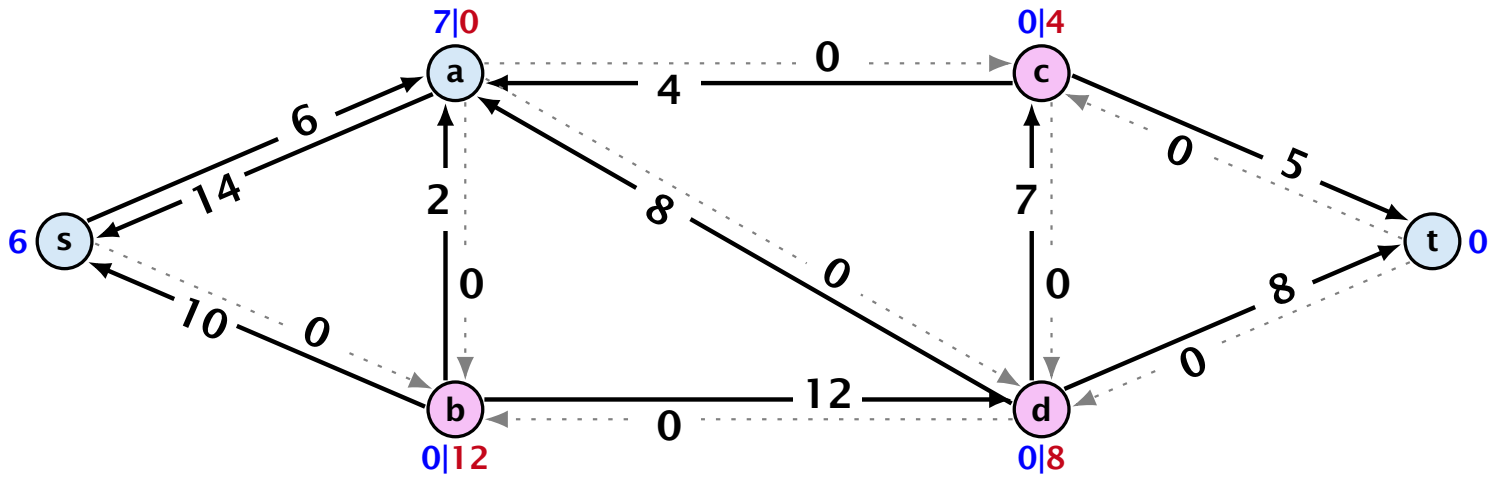

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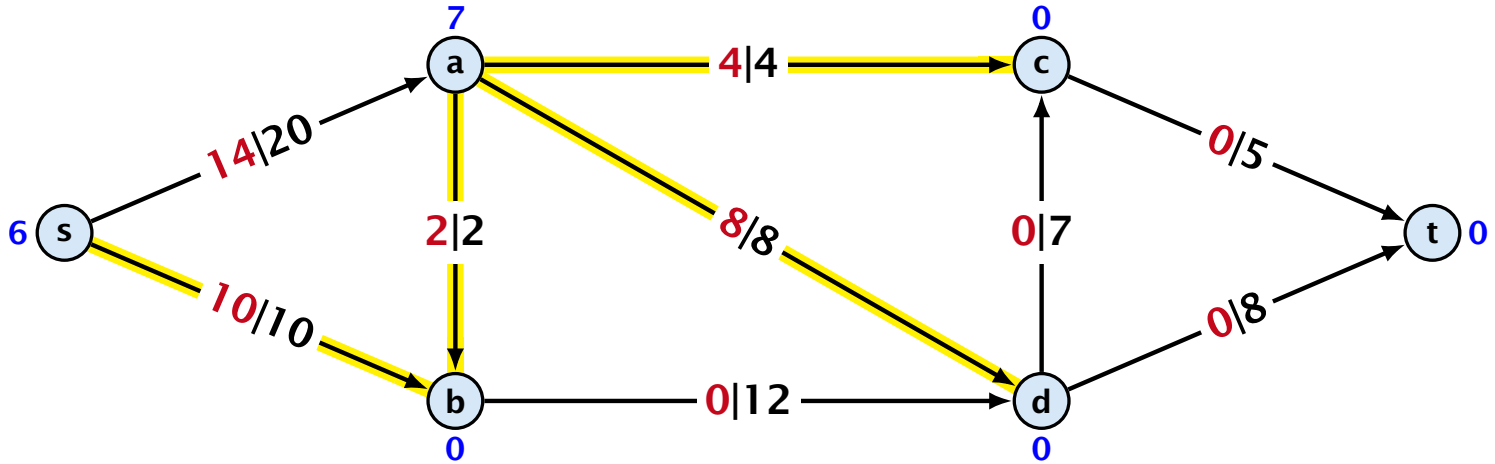

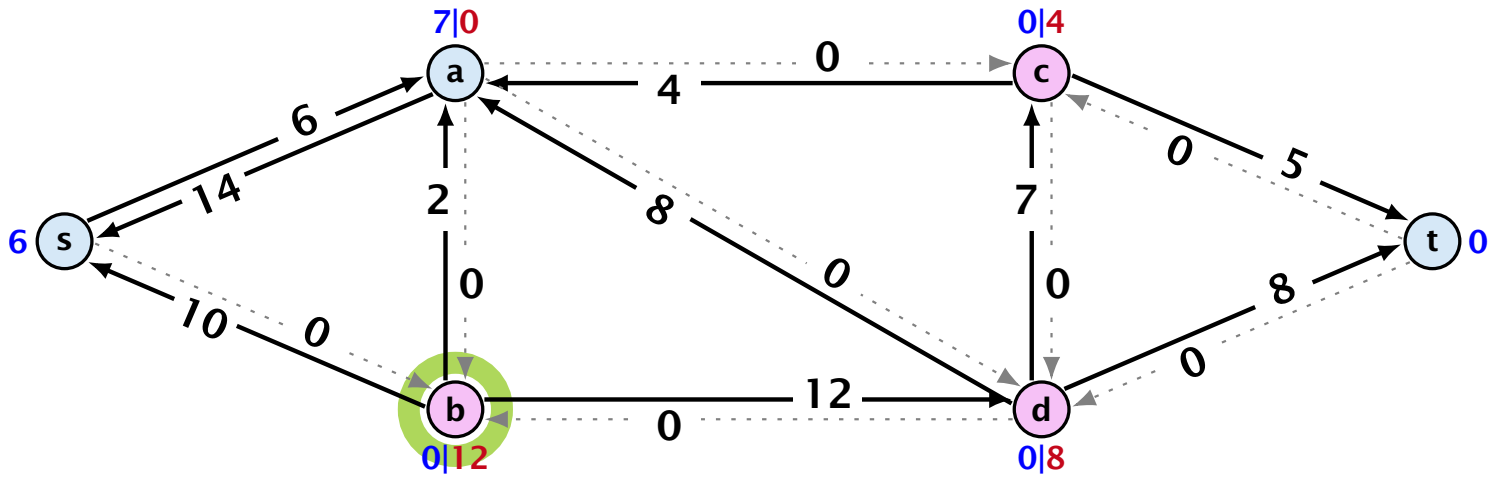

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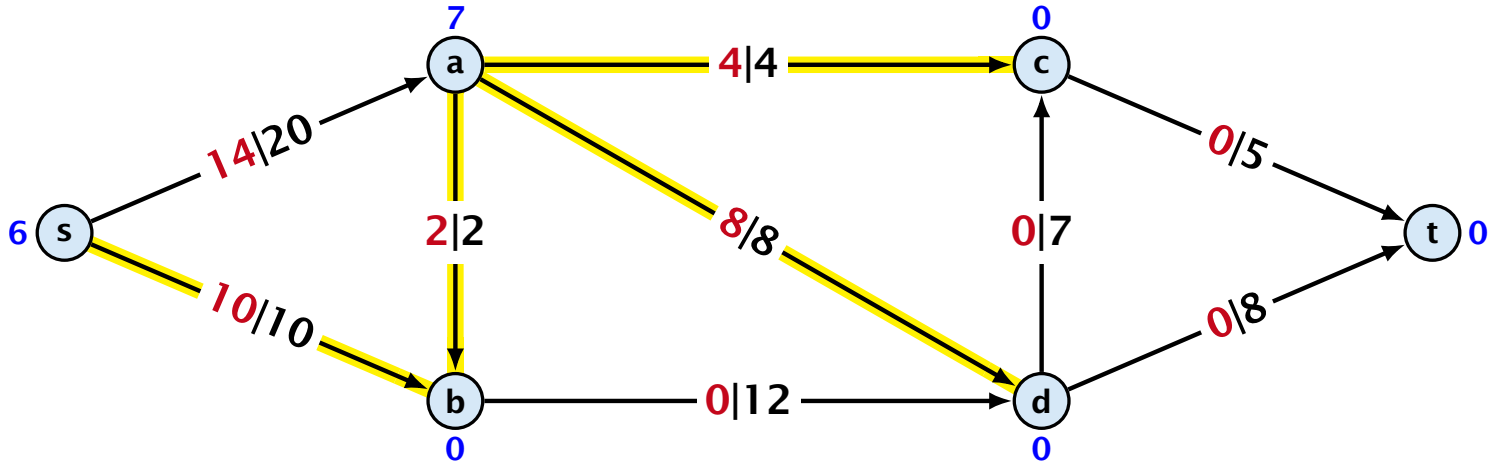
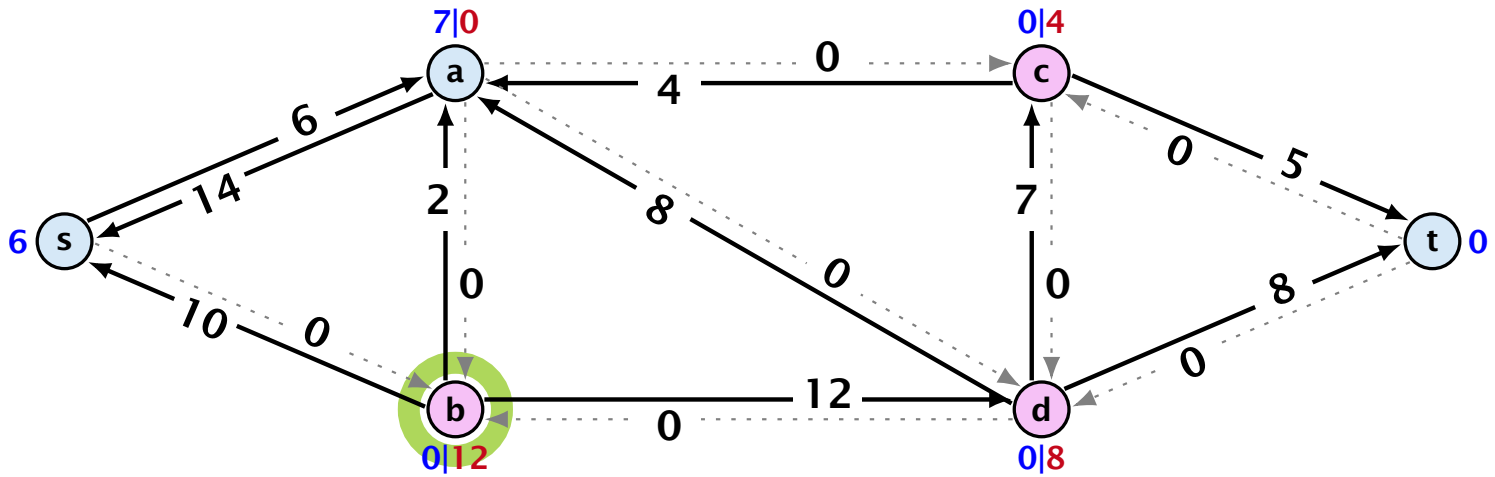


relabel to 1



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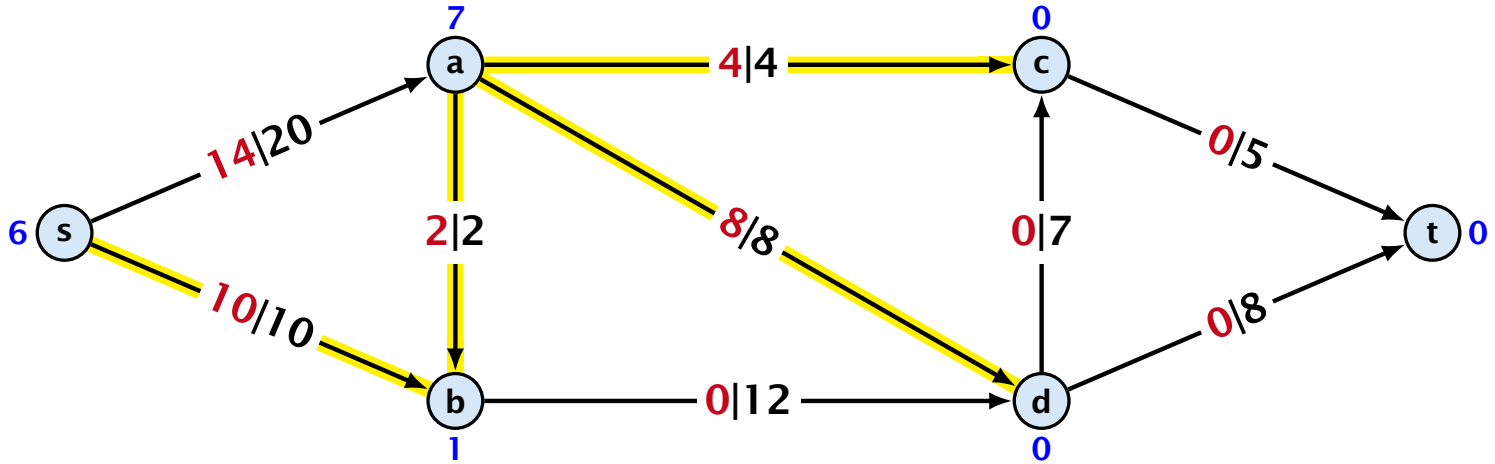

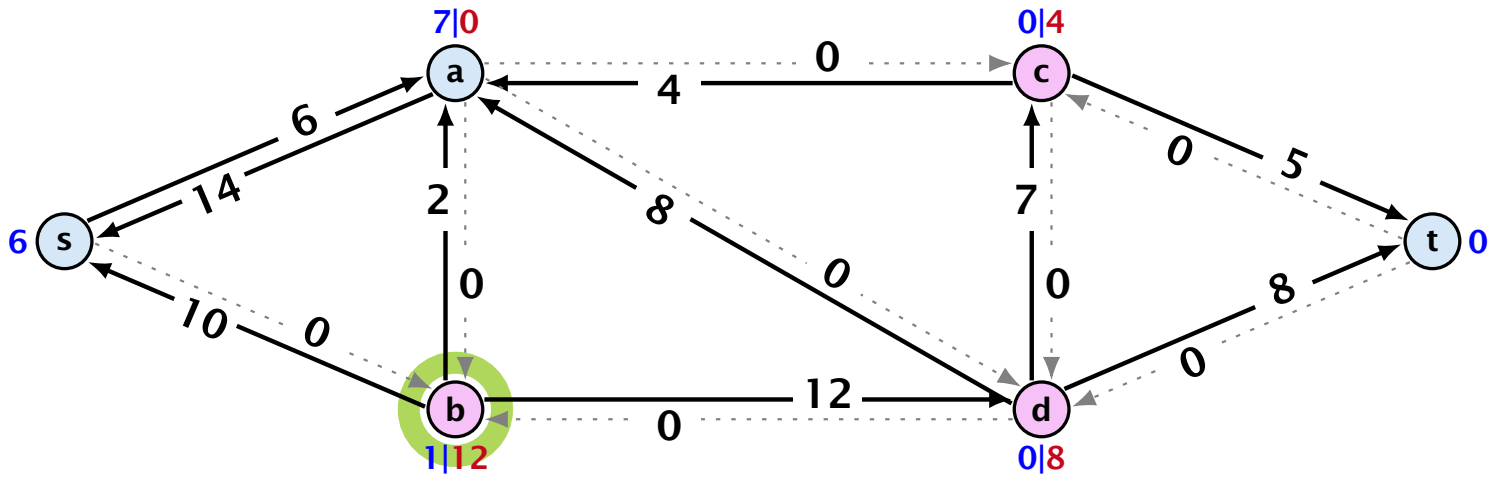

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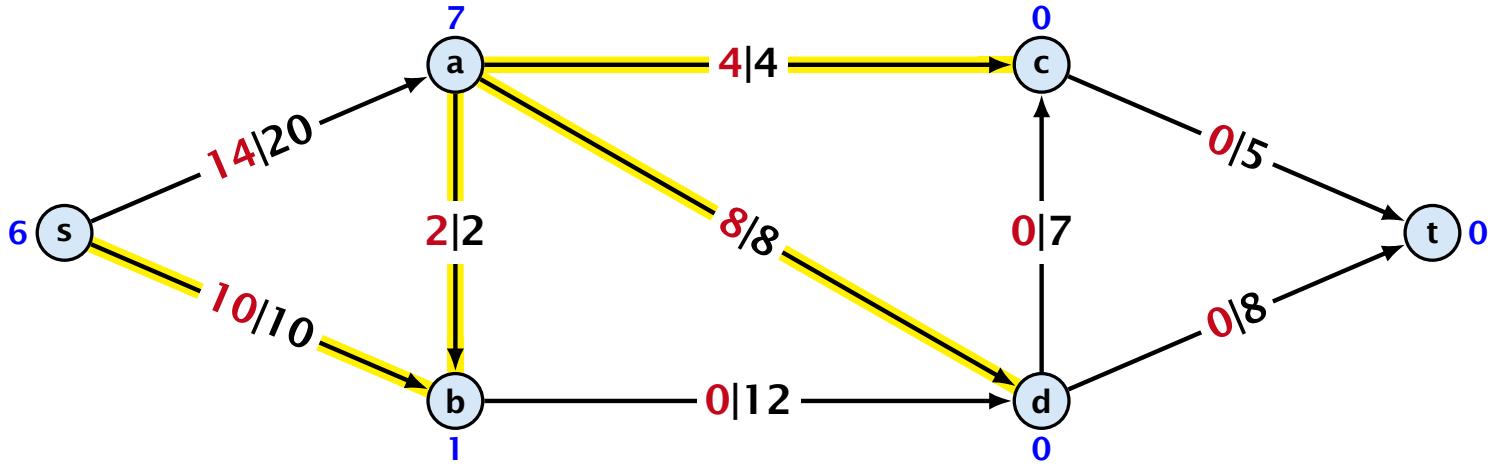
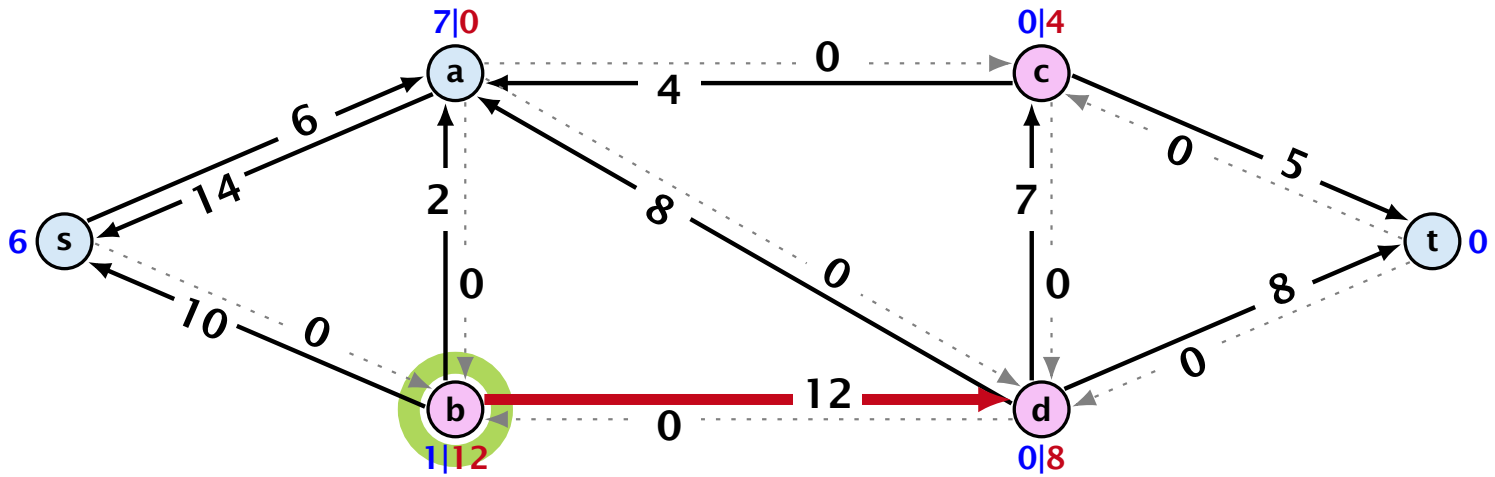


saturating and deactivating push



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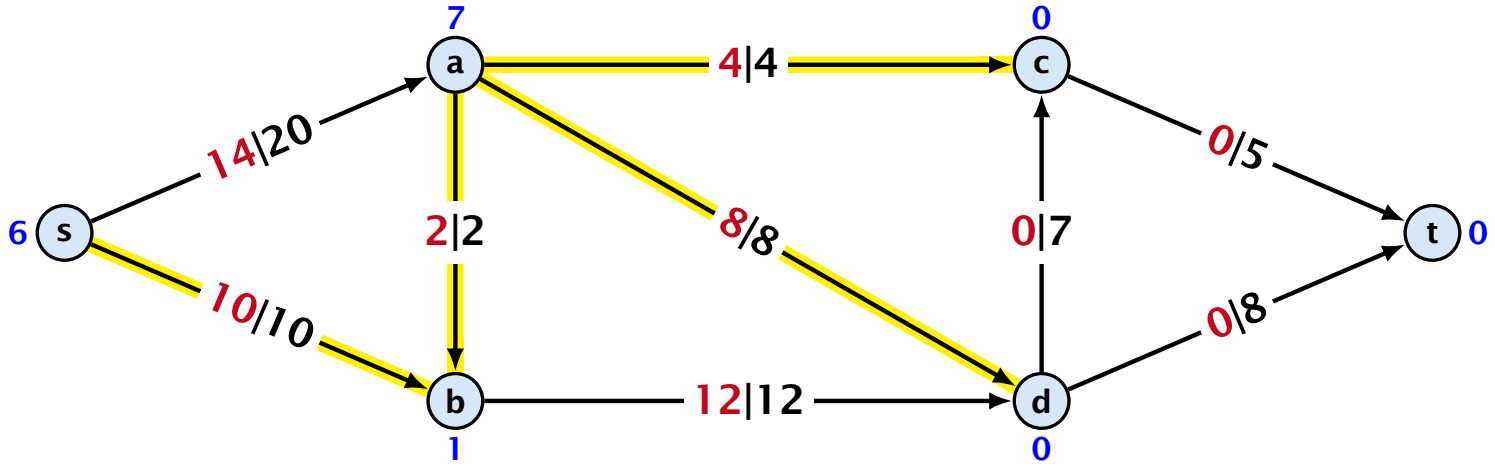

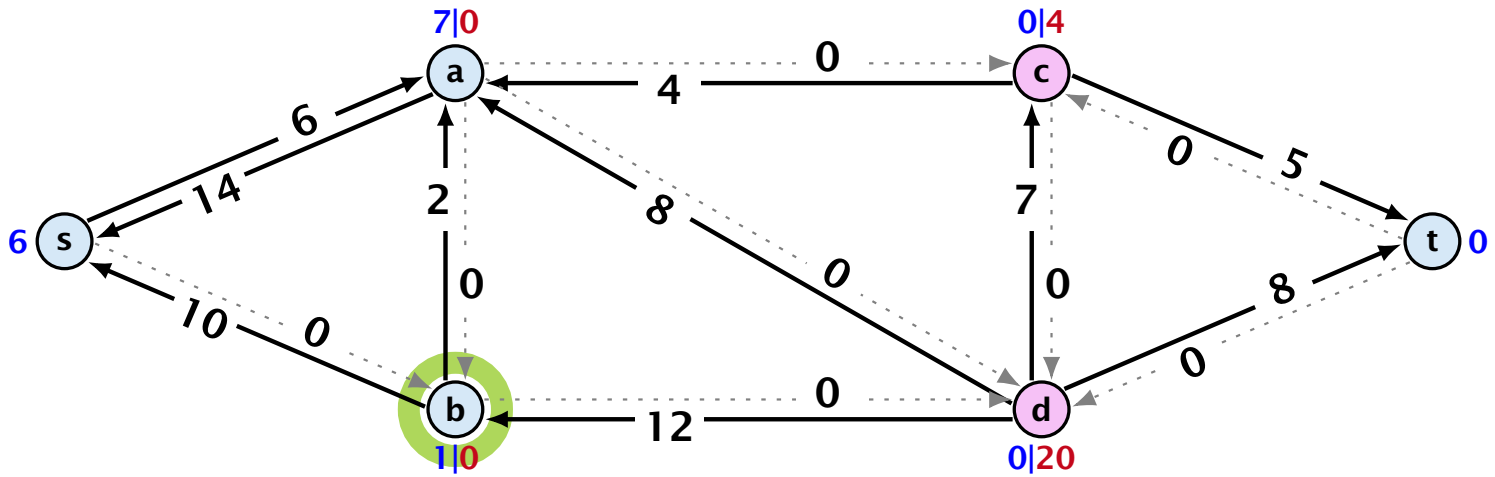

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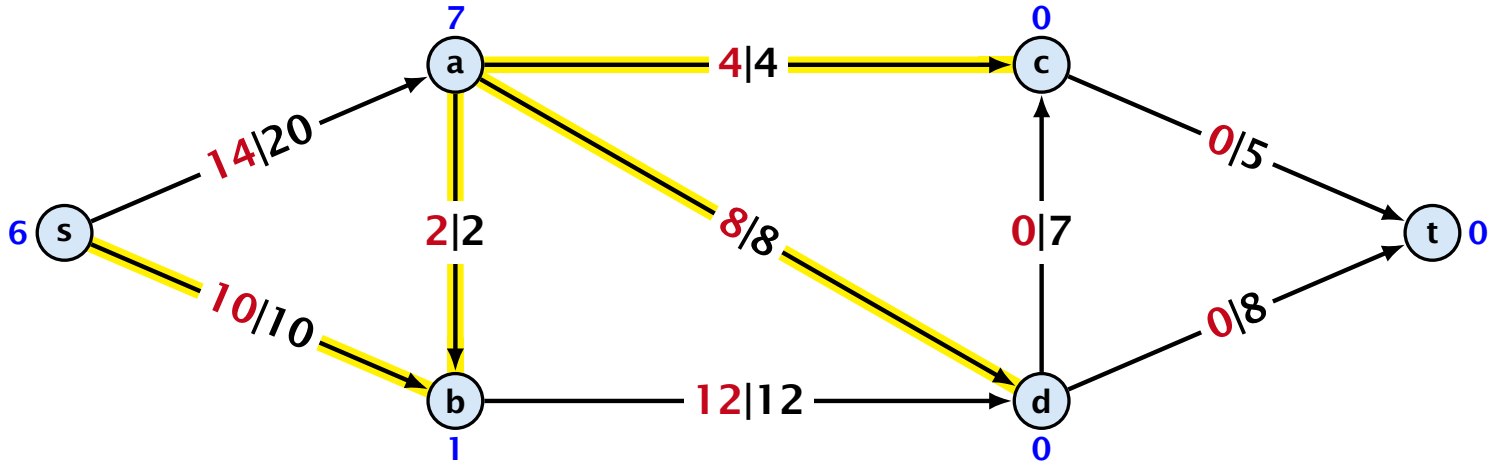

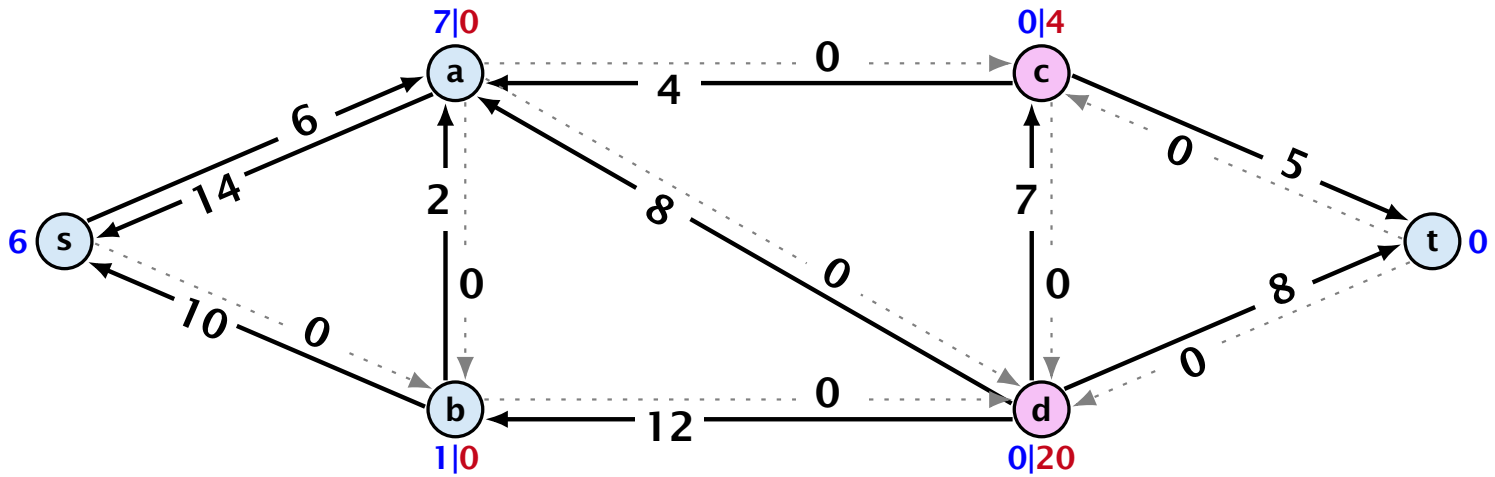

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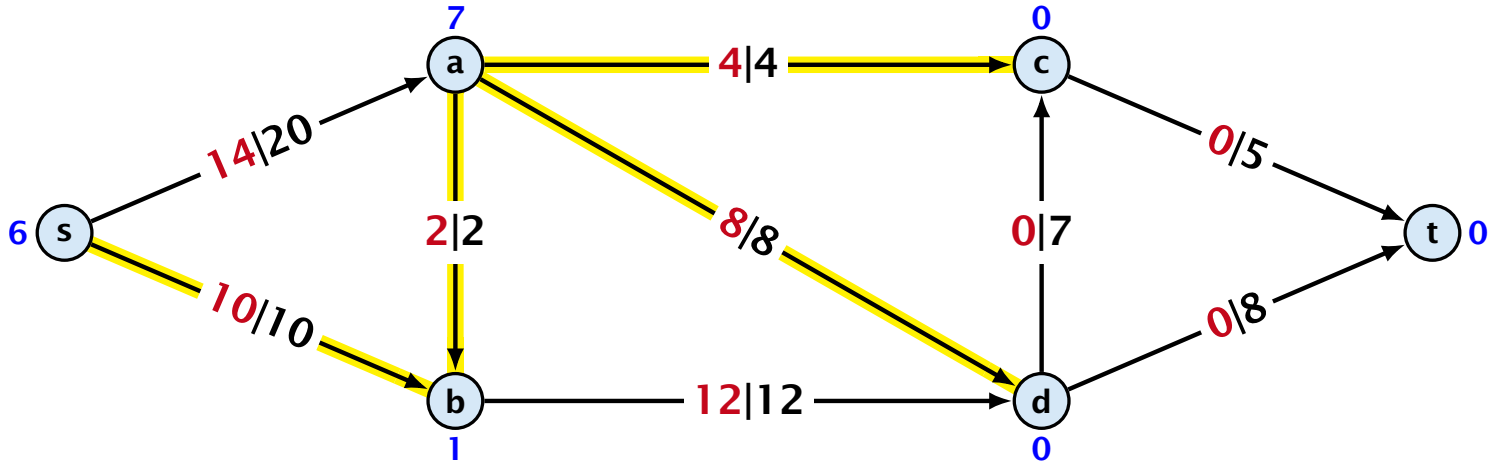

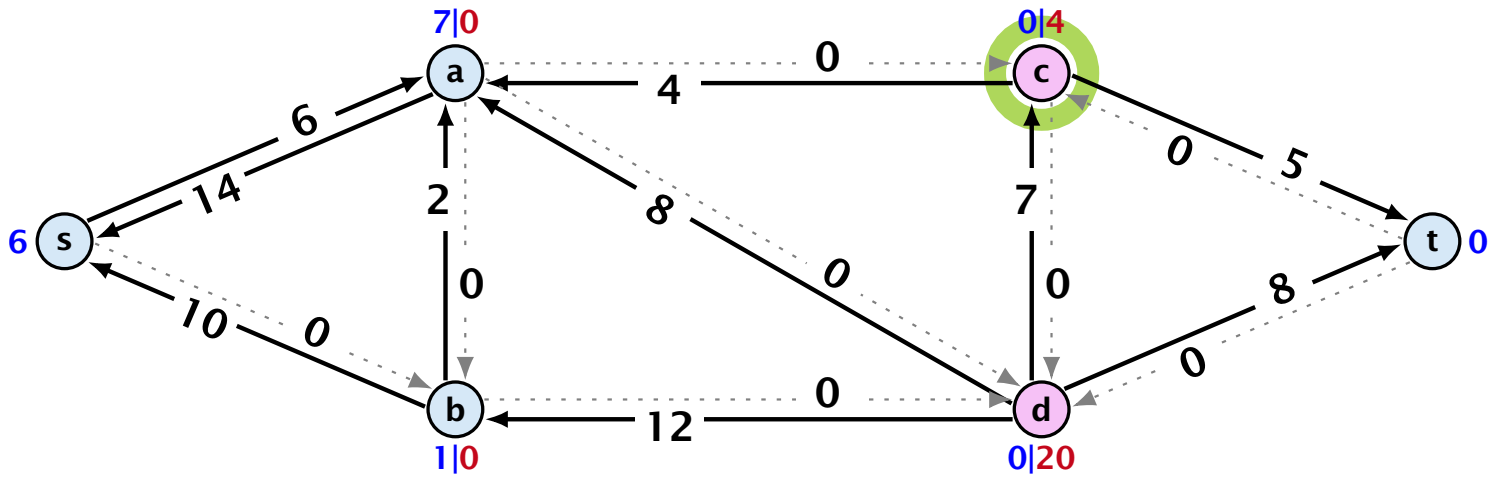

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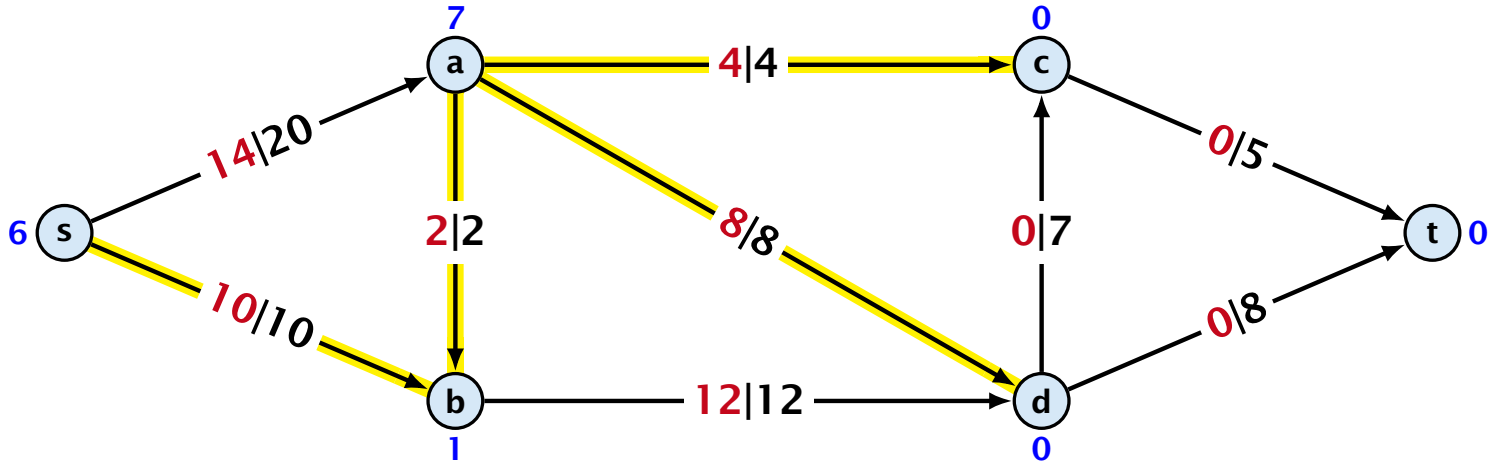
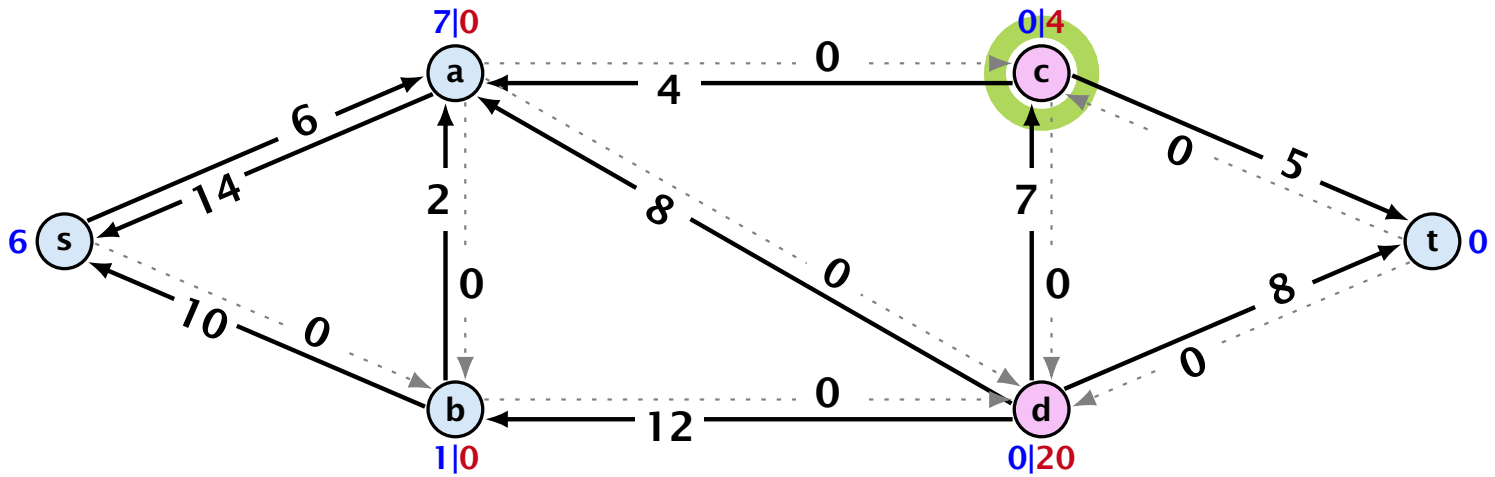


relabel to 1



Preflow Push

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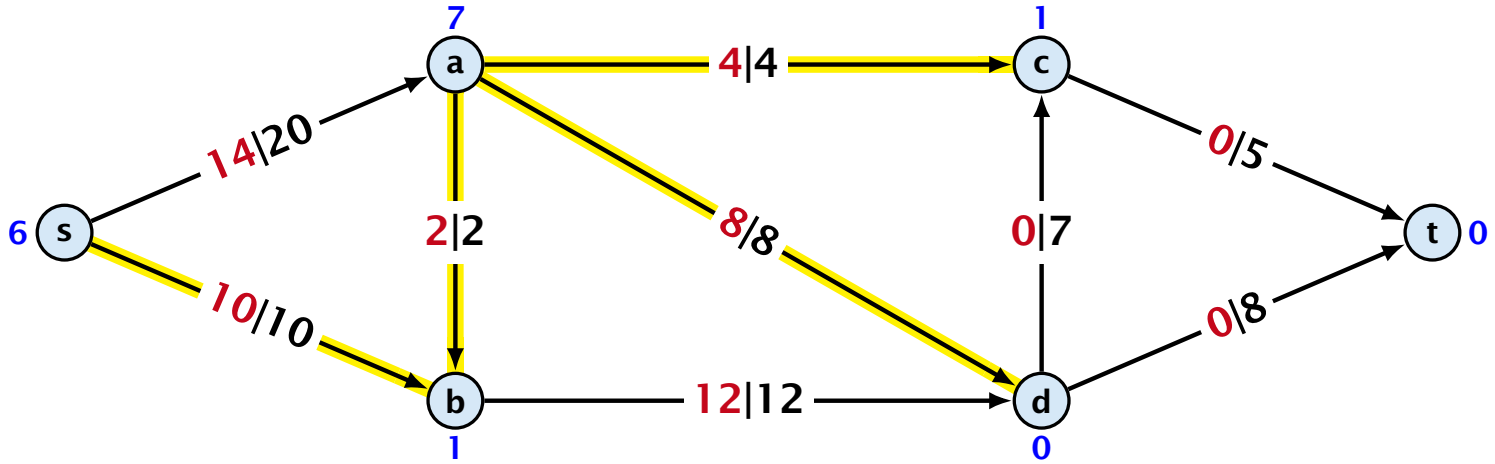

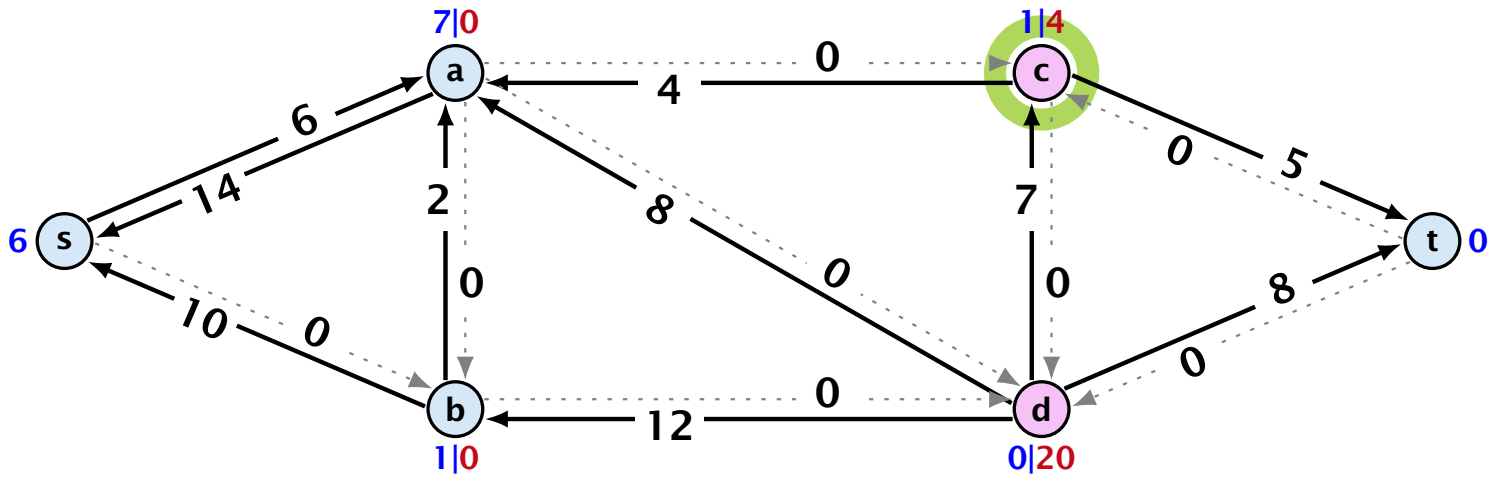

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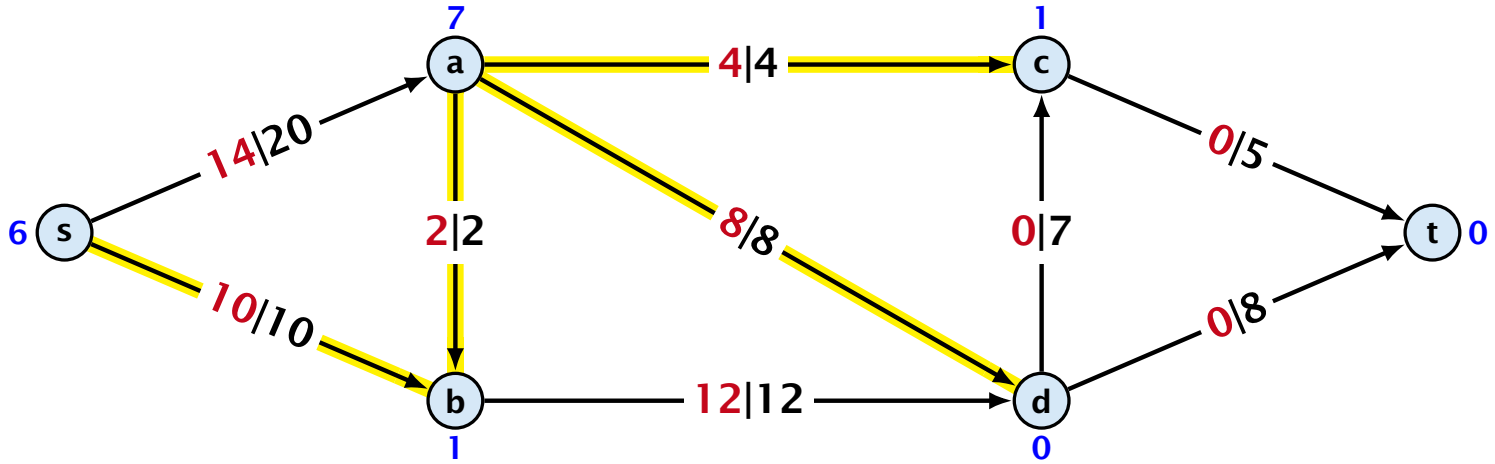
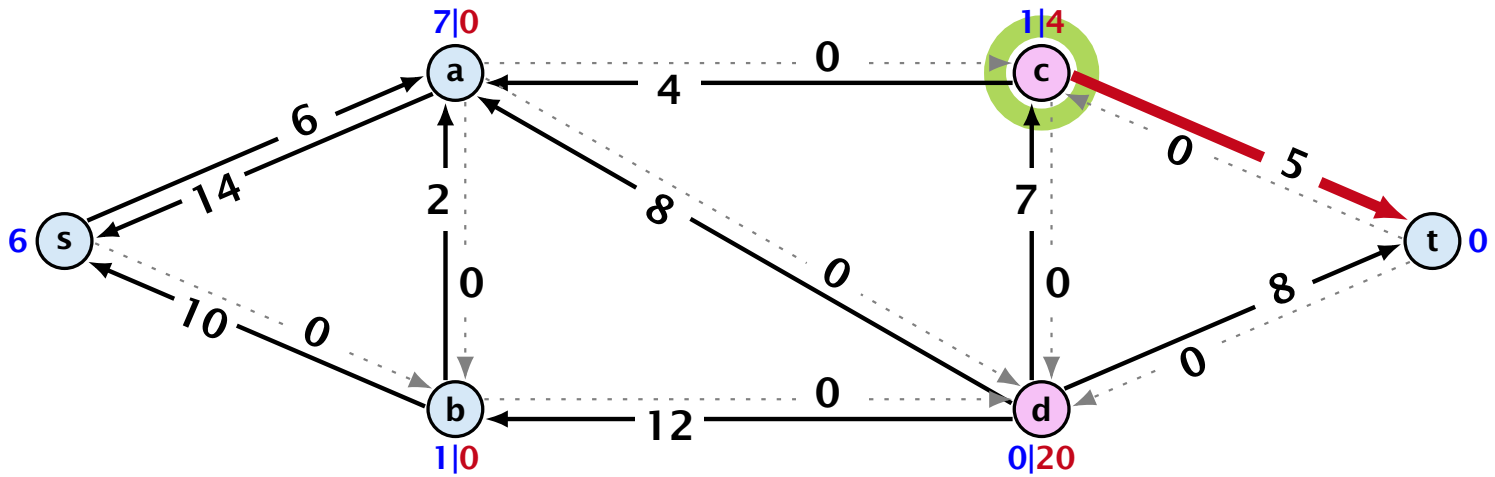


deactivating push



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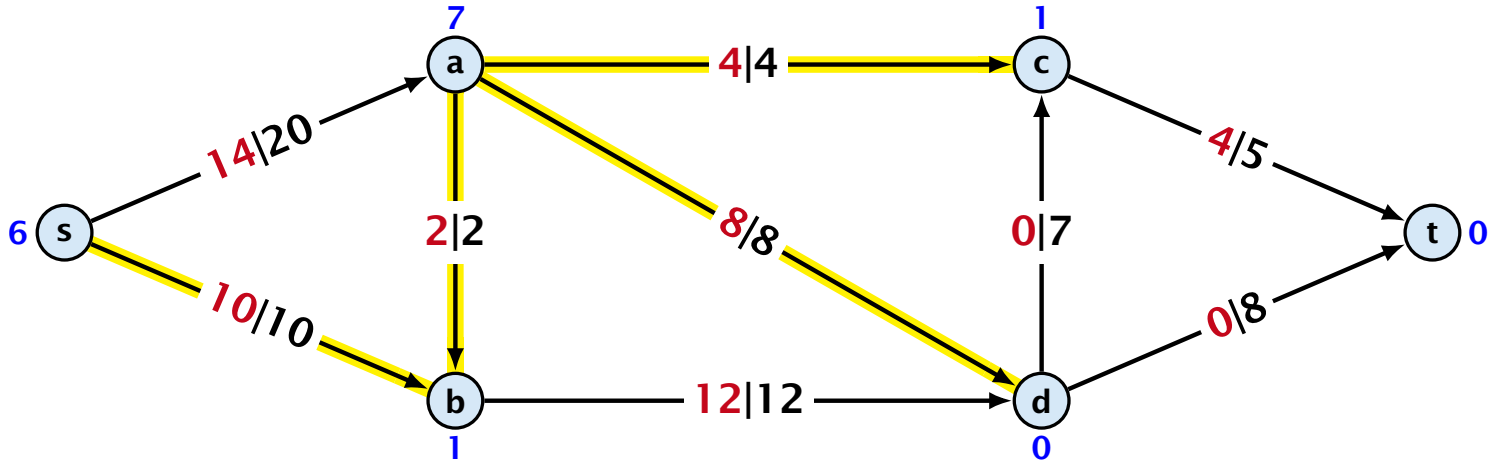

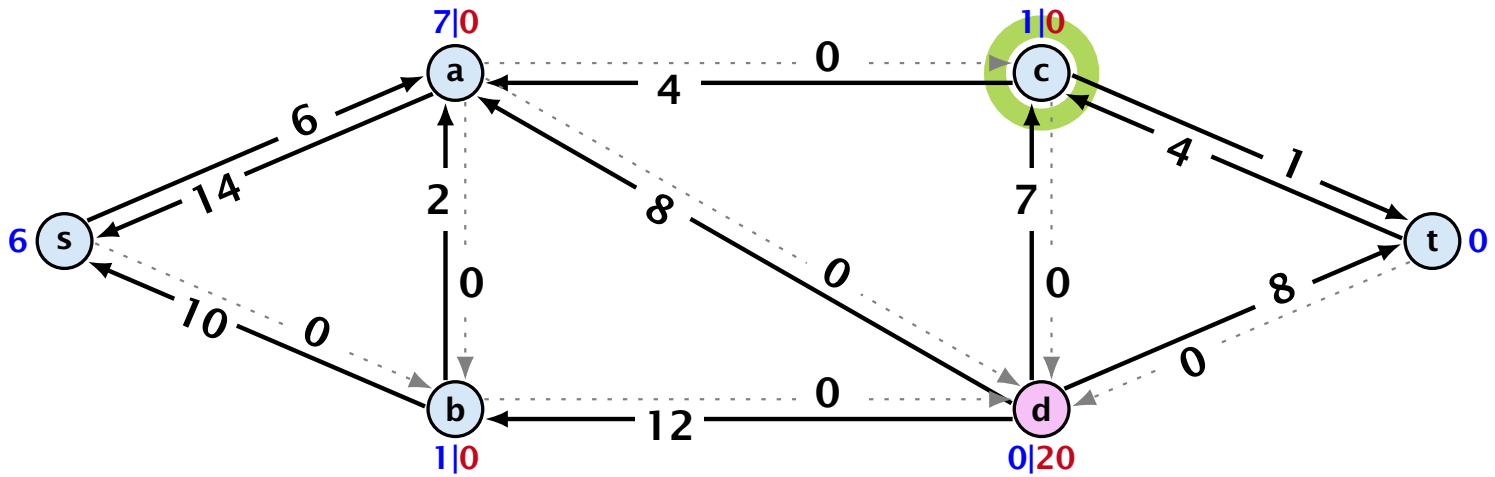

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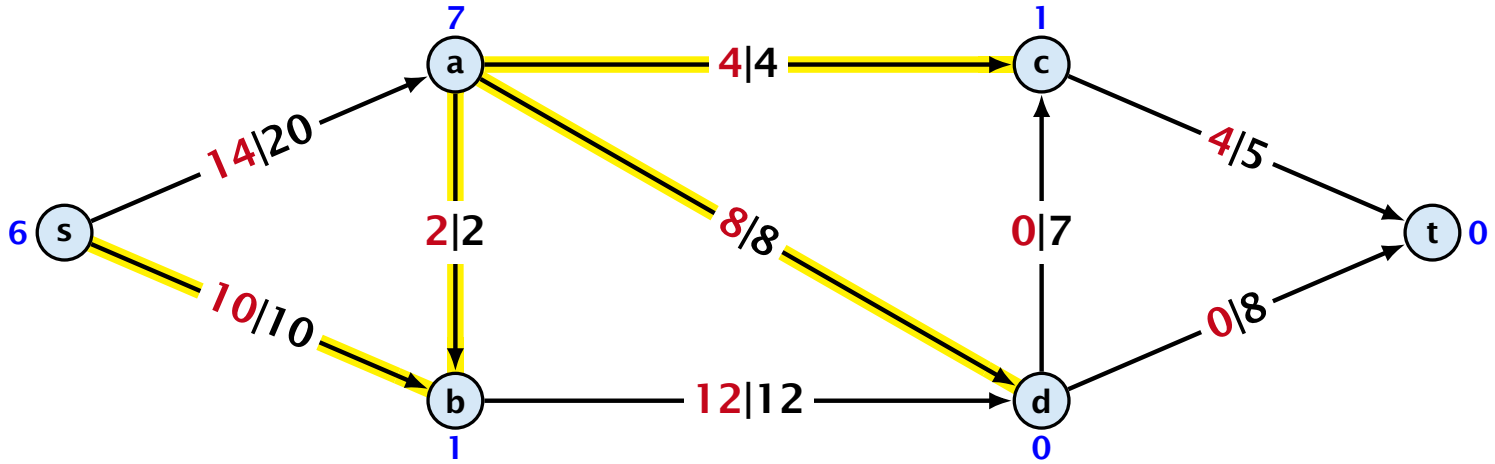

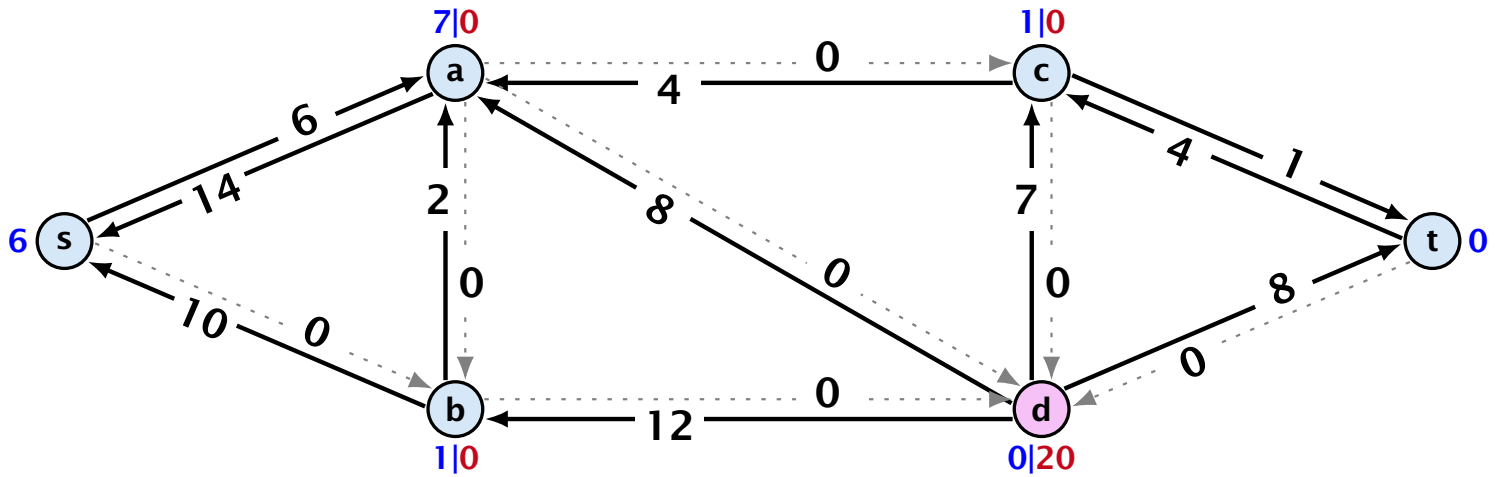

Preflow Push

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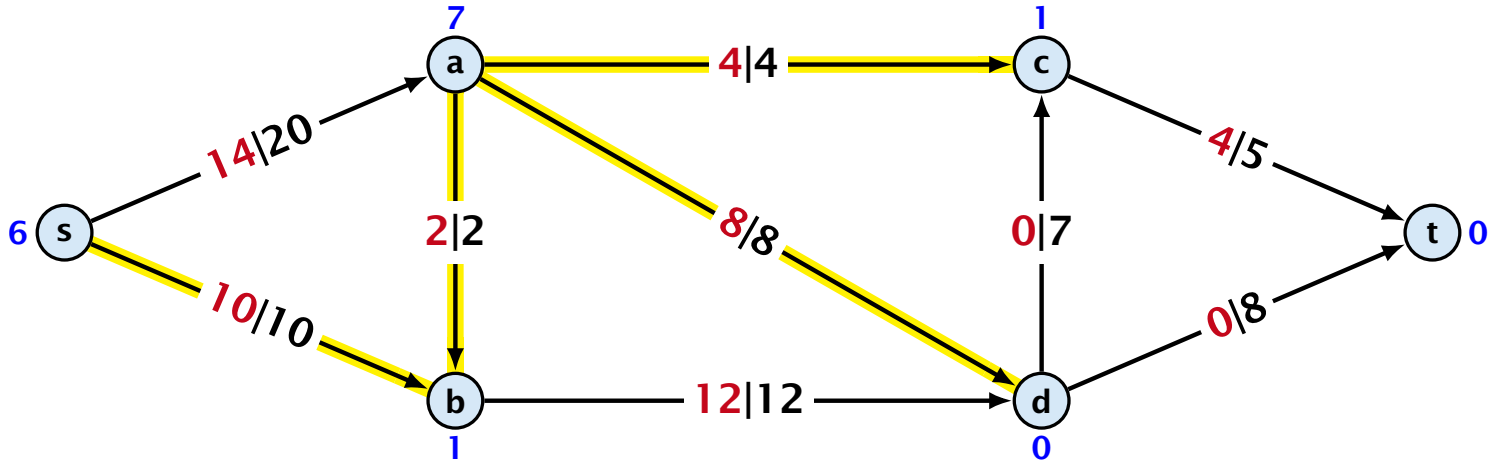

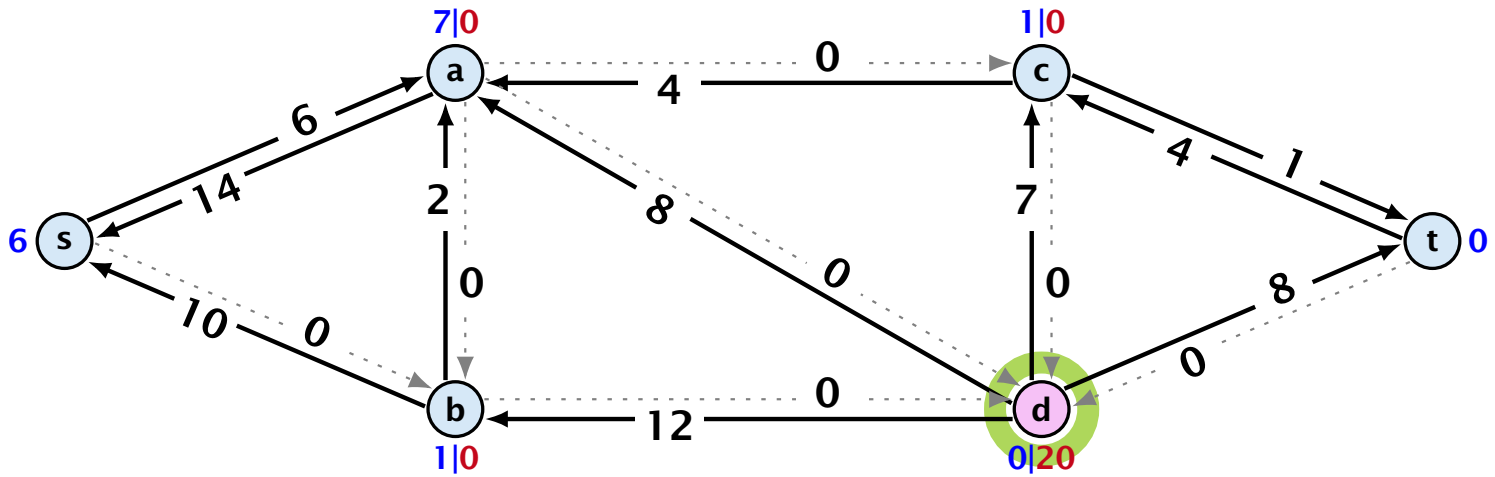

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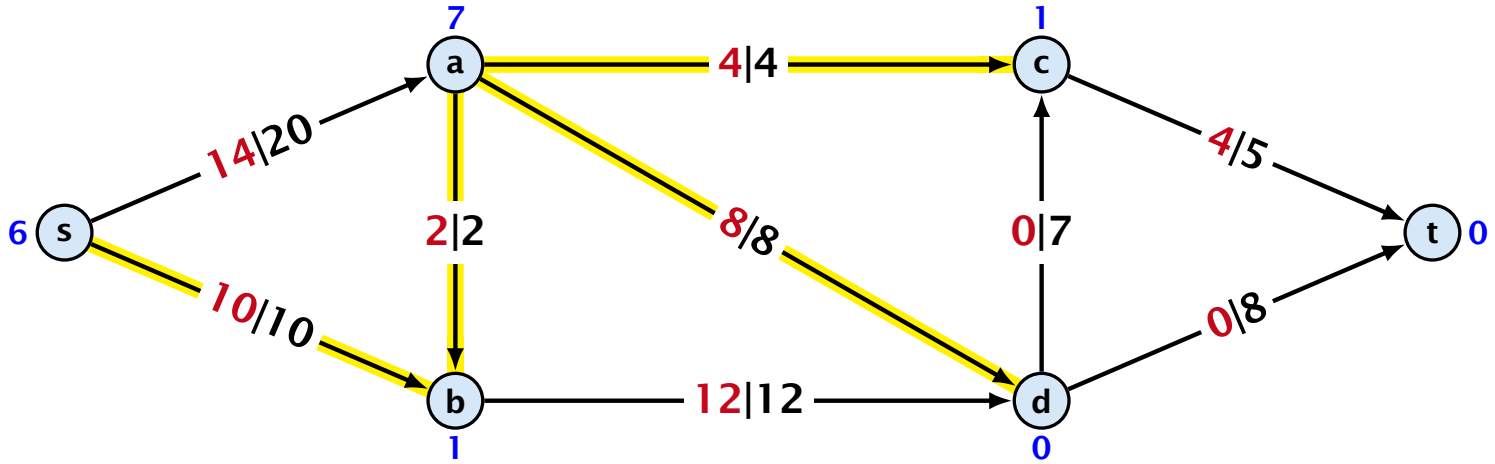
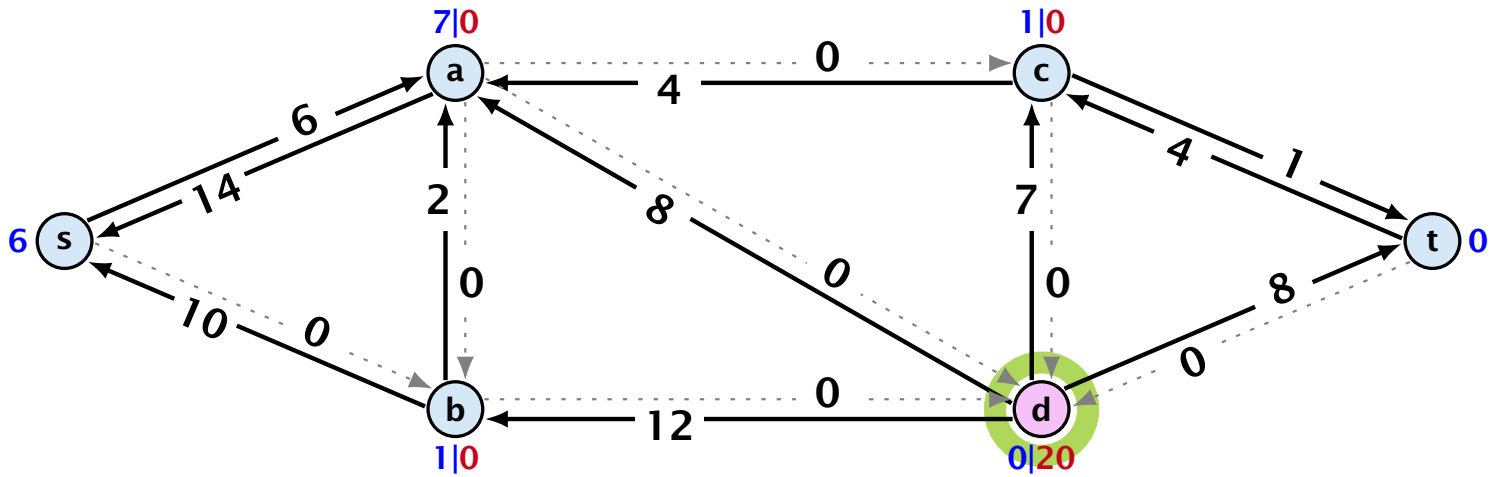


relabel to 1



Preflow Push

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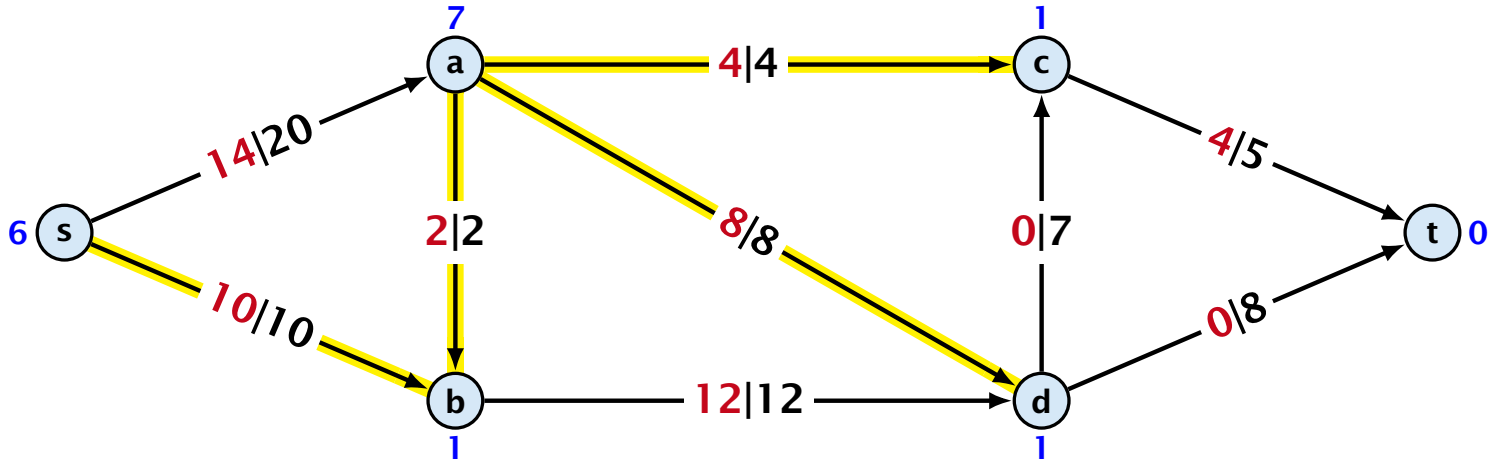

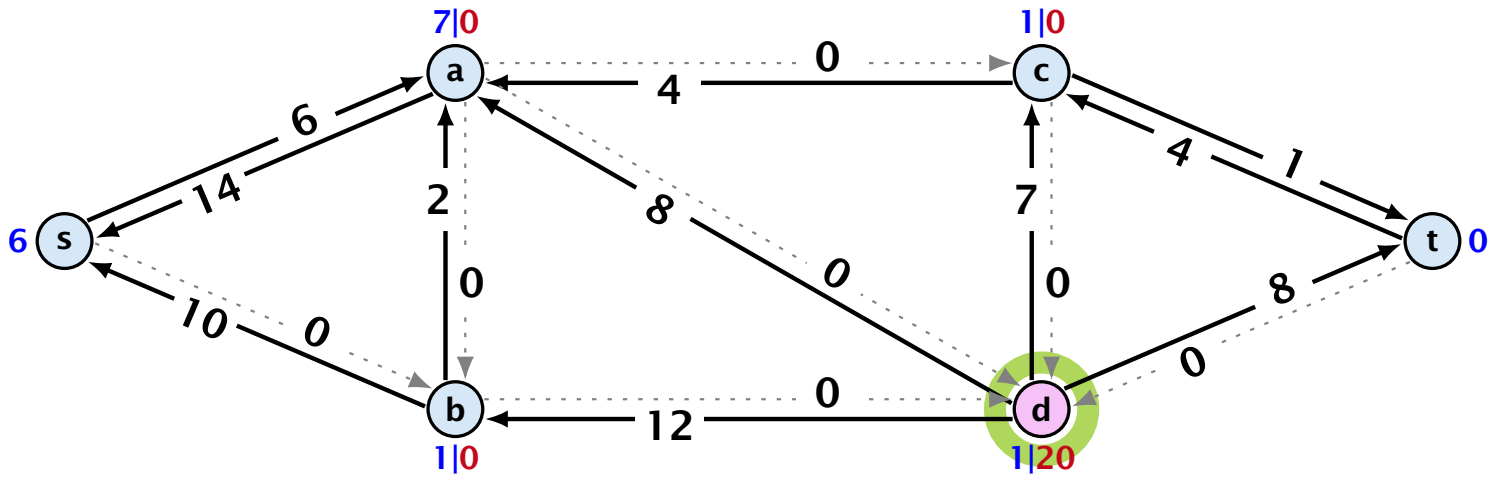

Preflow Push

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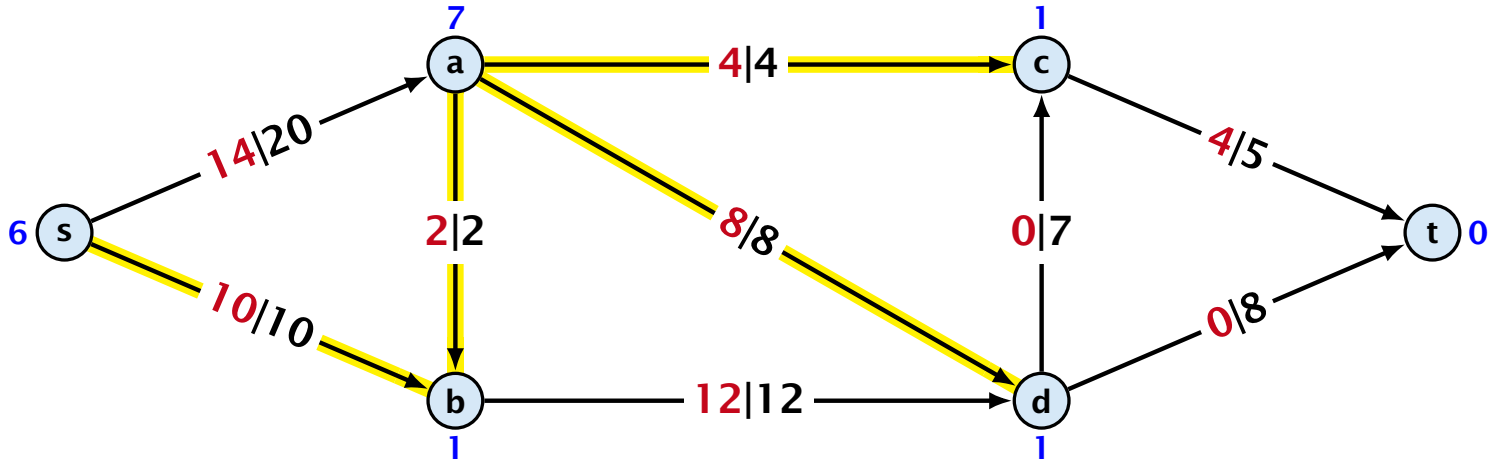
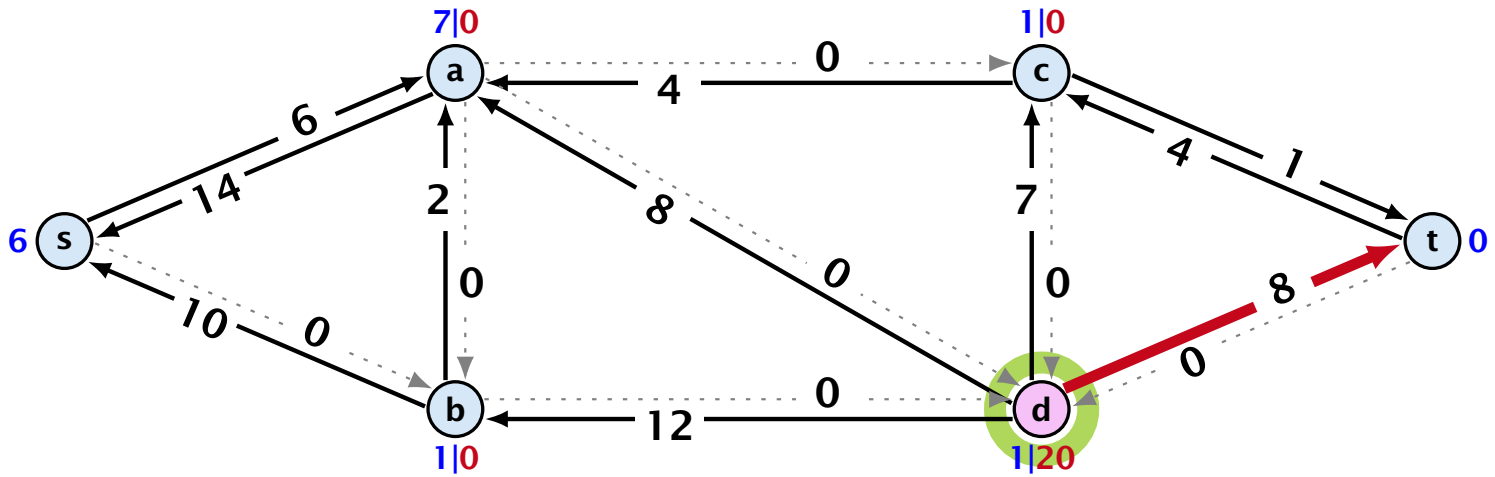


saturating push



Preflow Push

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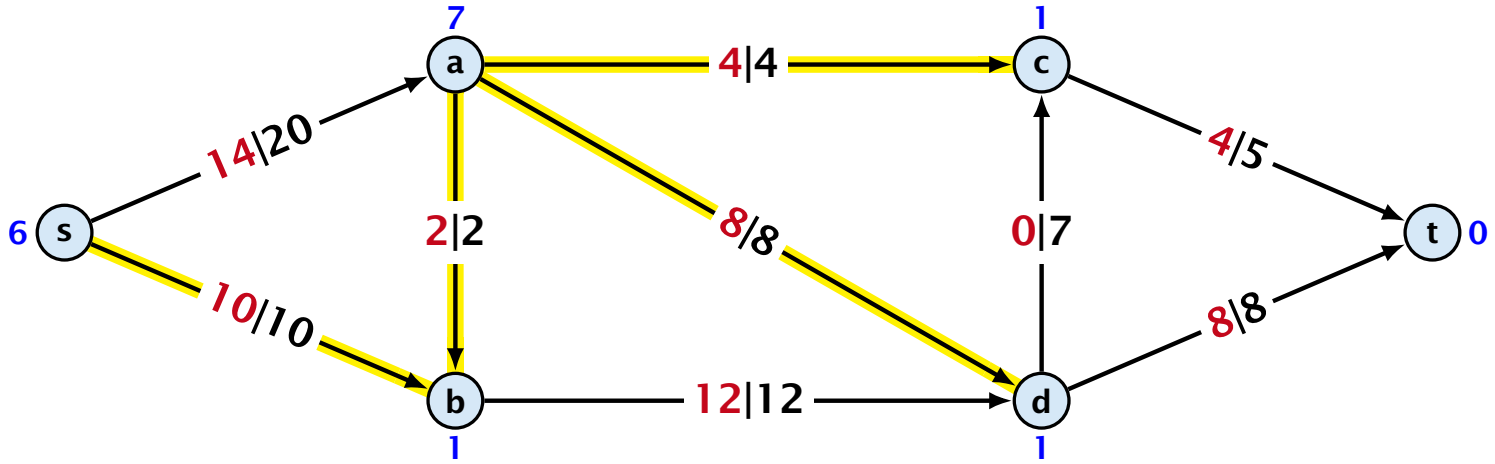

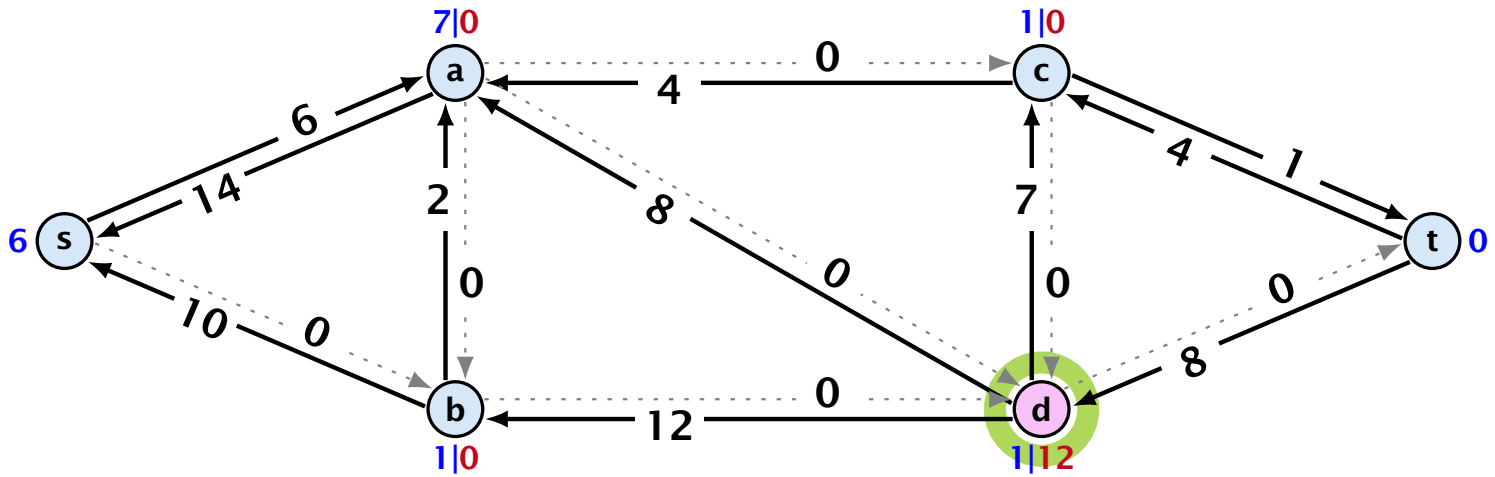

Preflow Push

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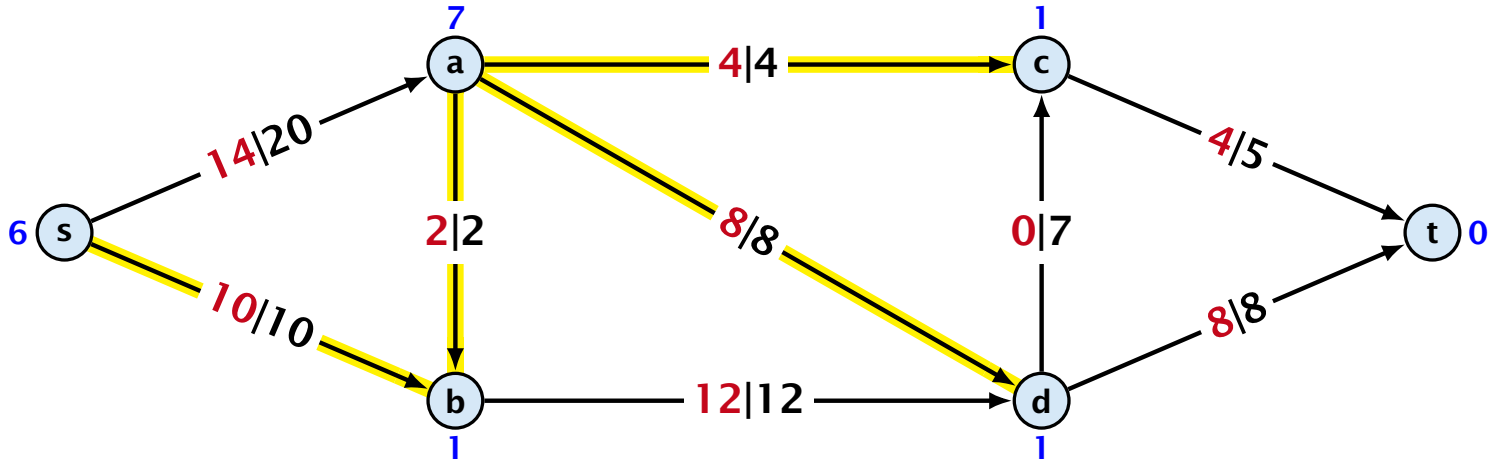
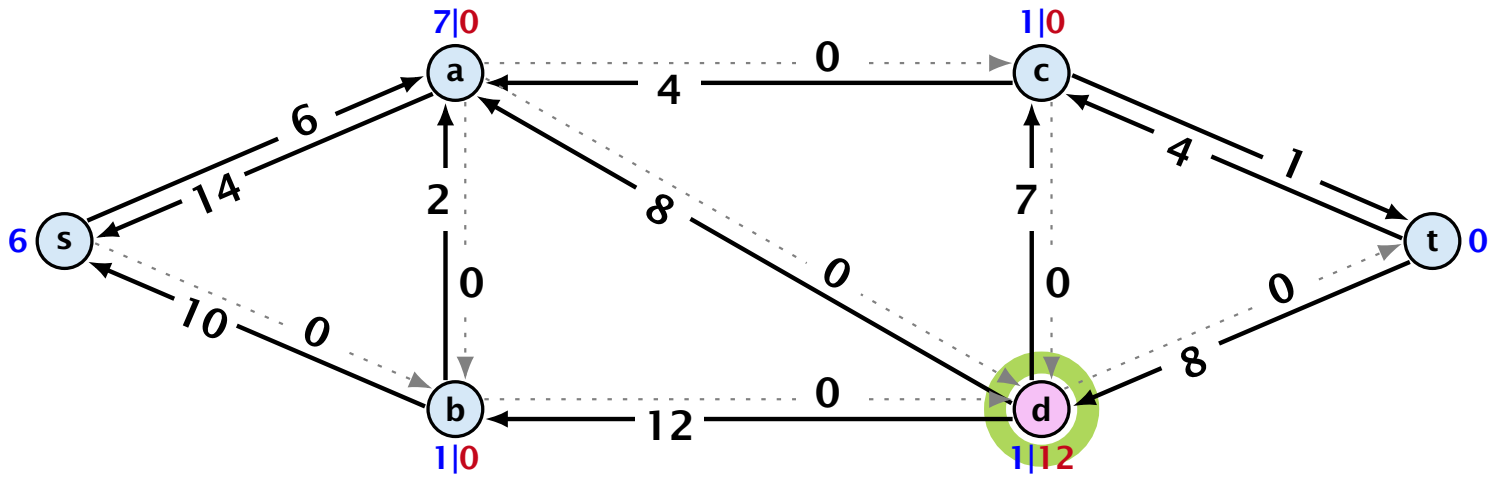


relabel to 2



Preflow Push

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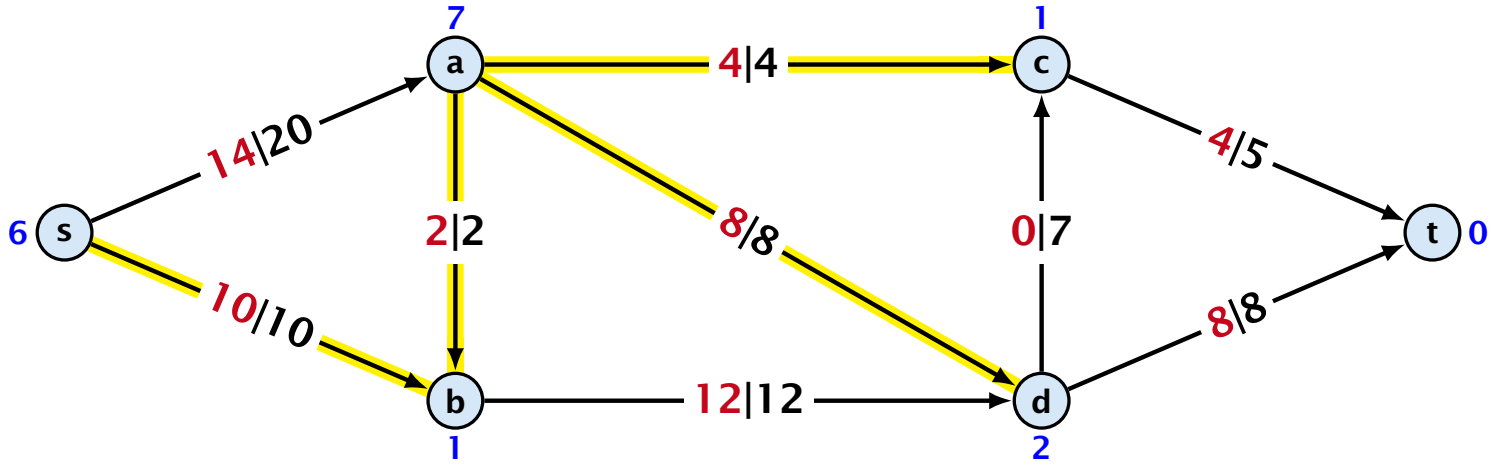

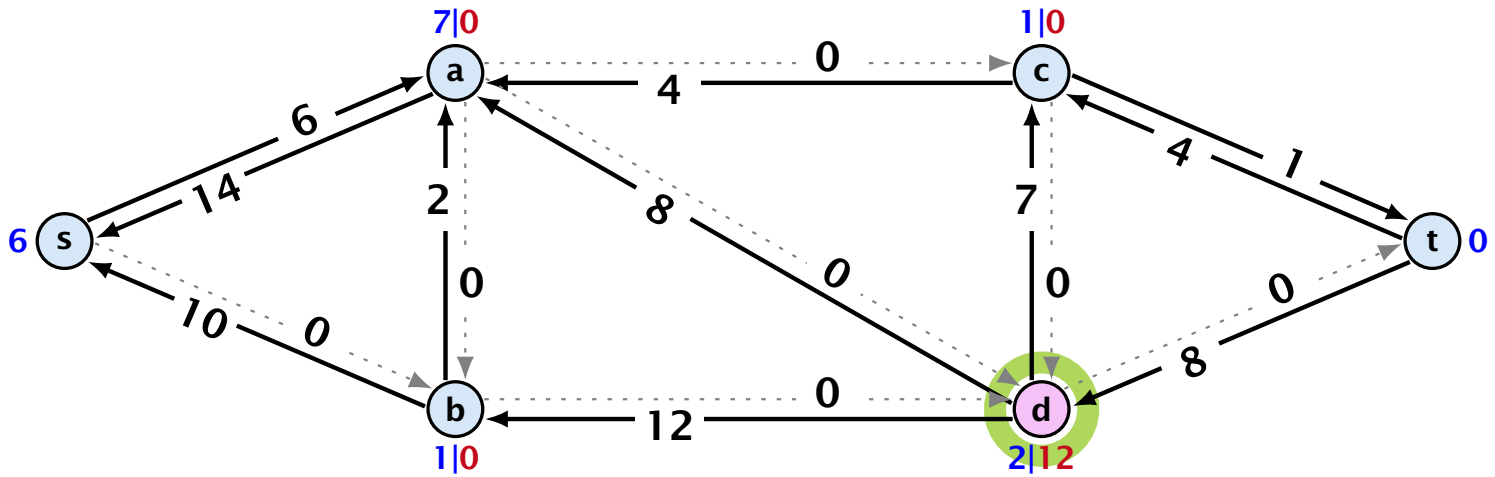

Preflow Push

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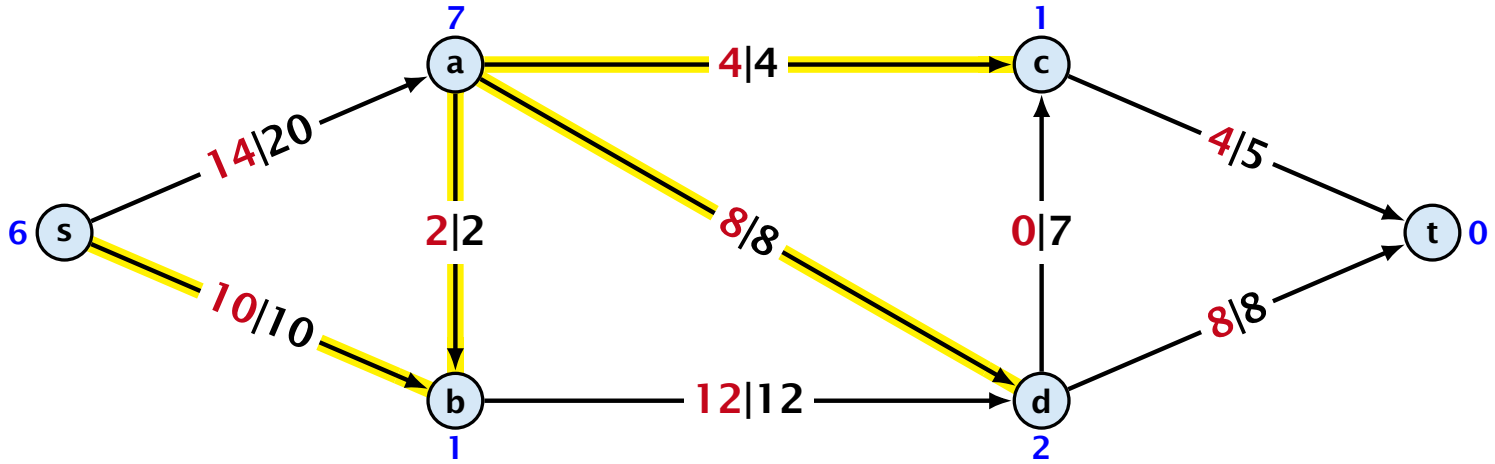
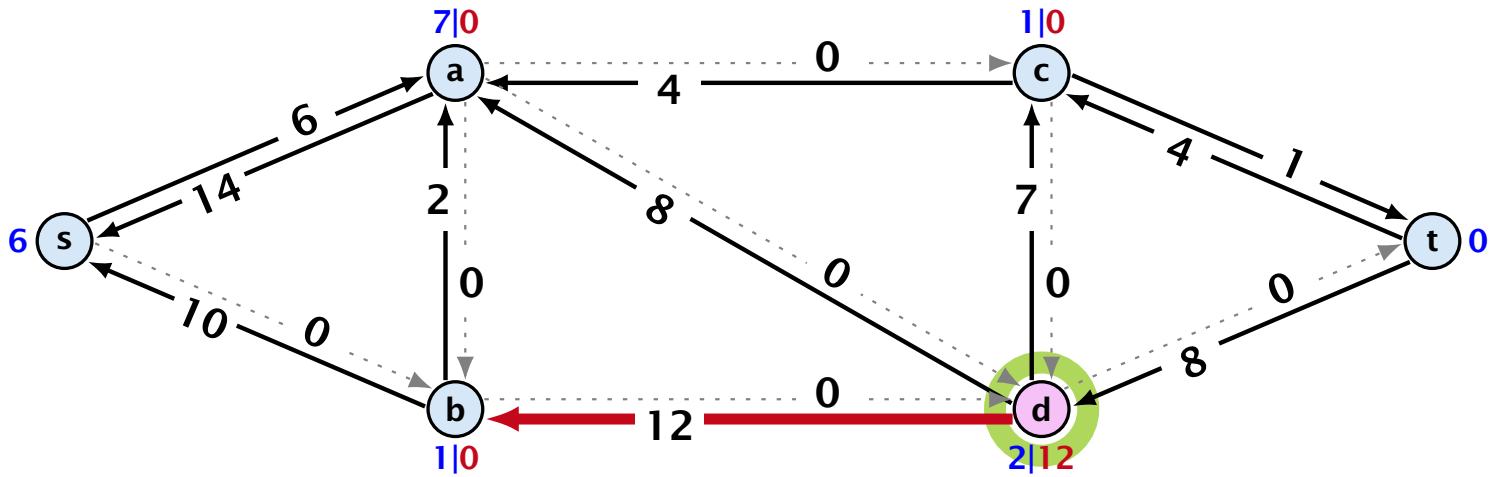


saturating and deactivating push



Preflow Push

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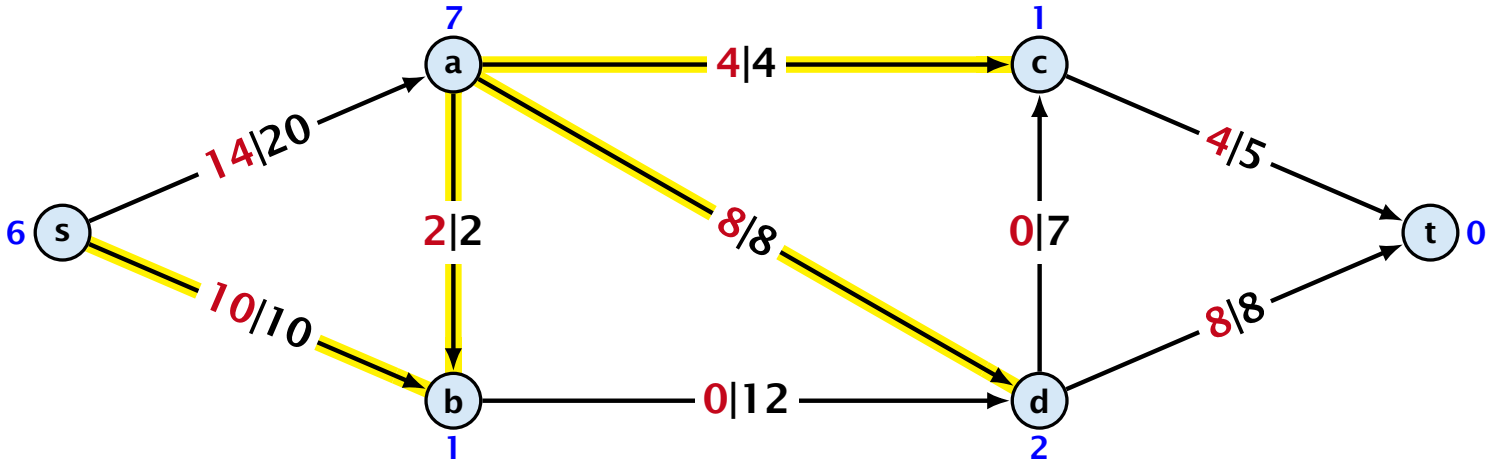

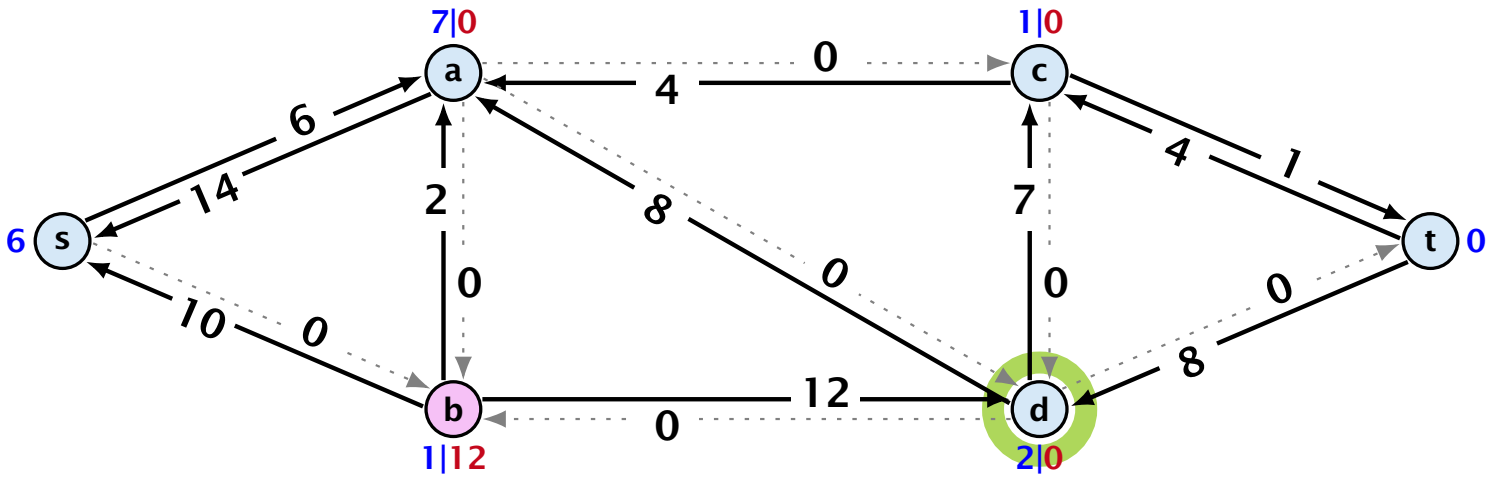

Preflow Push

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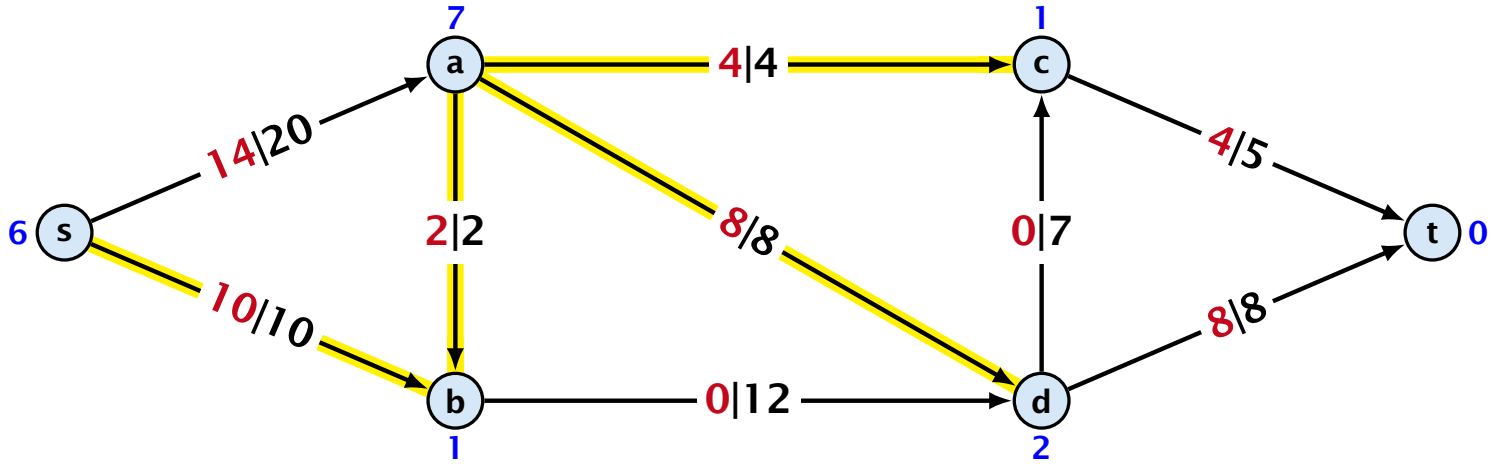

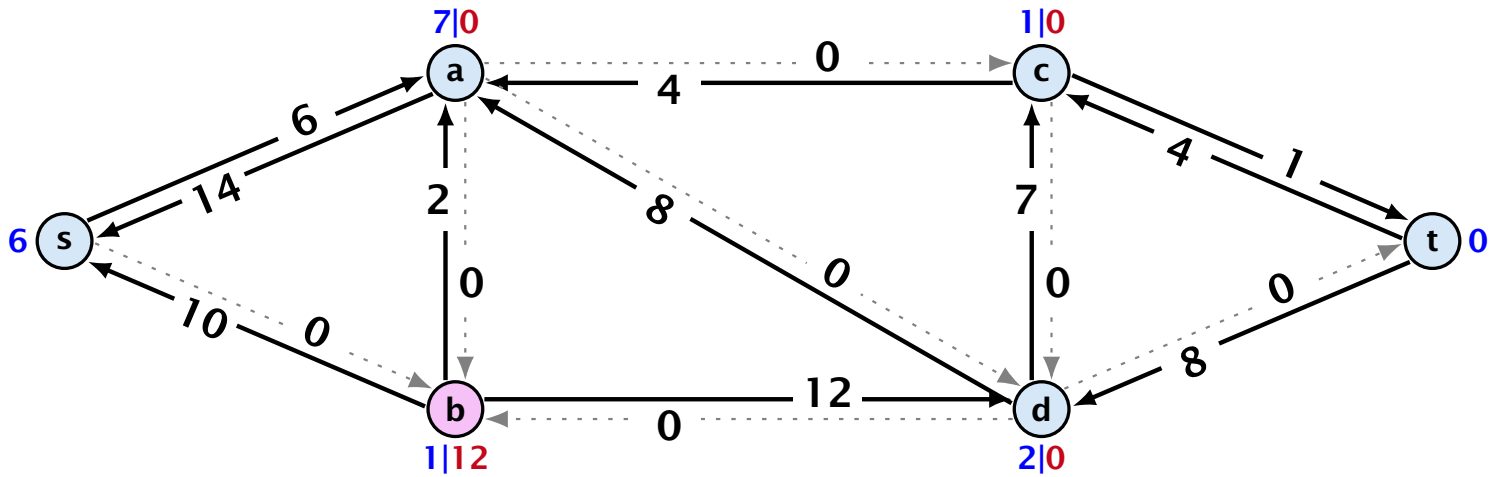

Preflow Push

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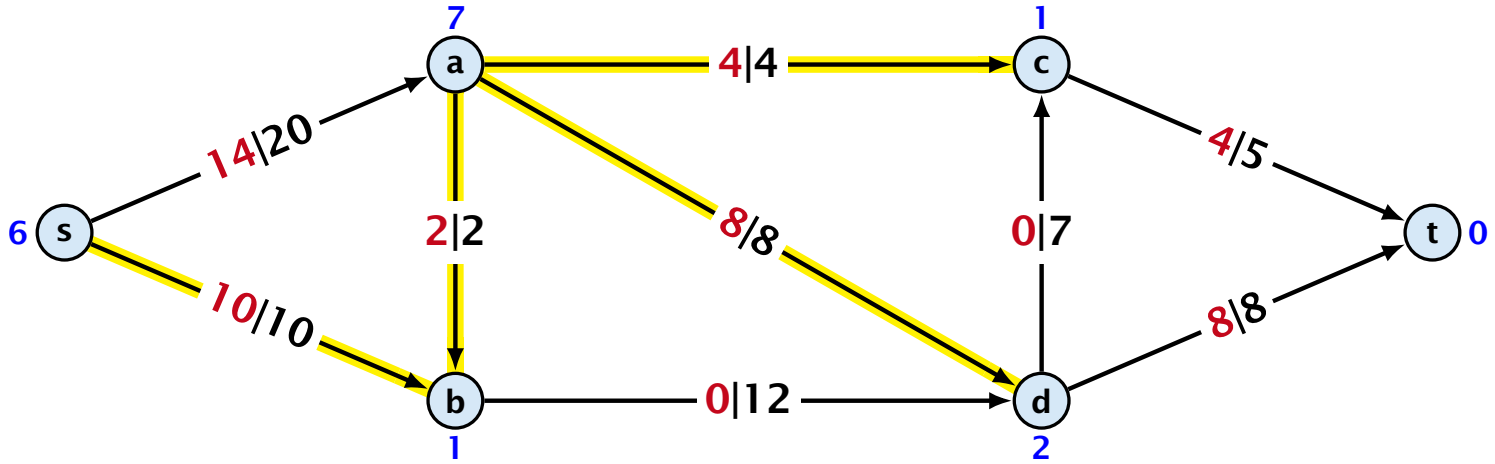
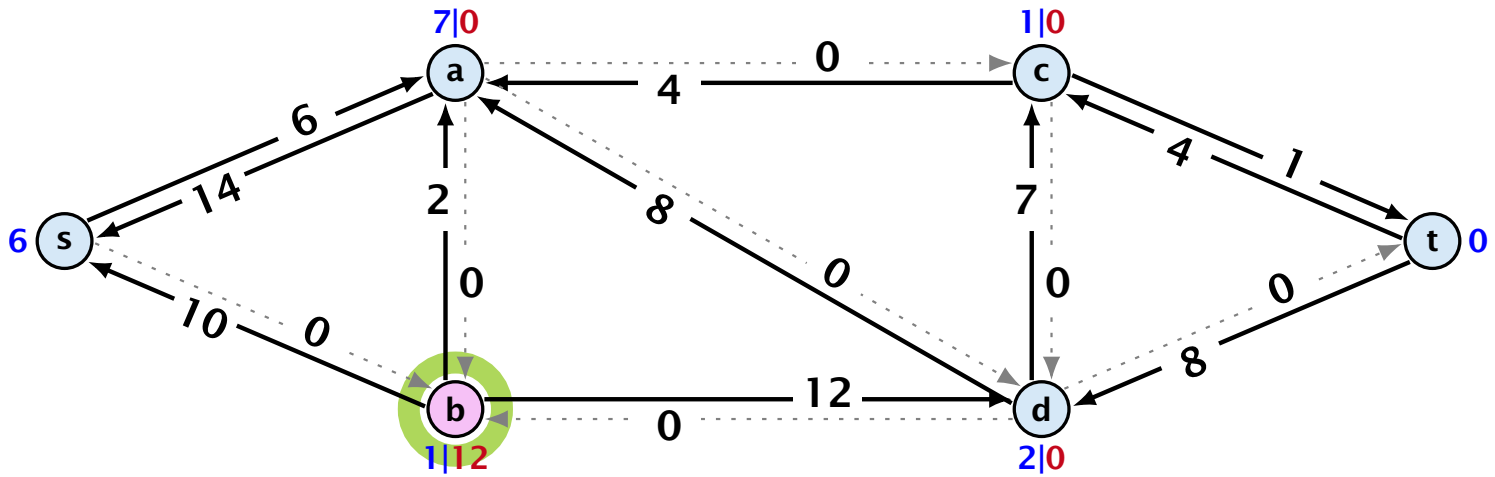
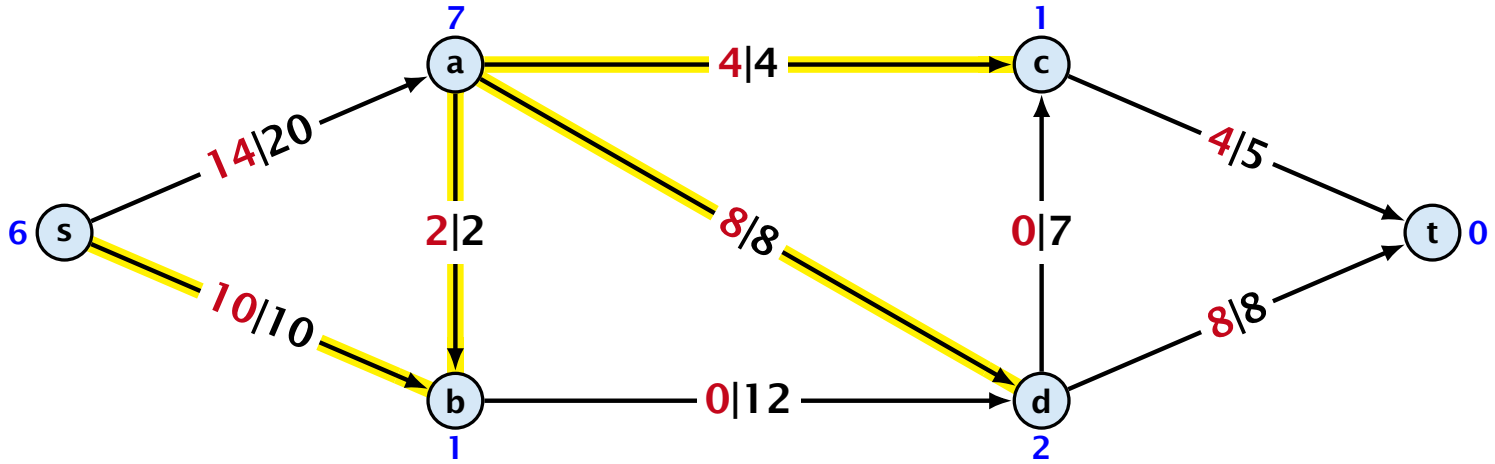


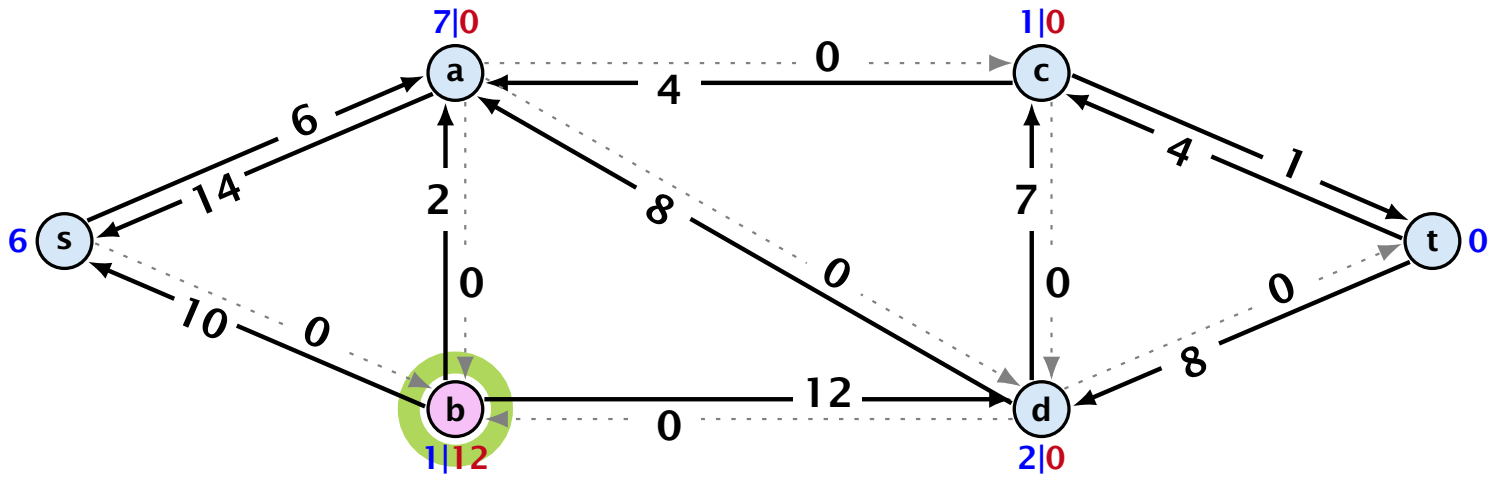


Preflow Push

The yellow edges indicate the cut that is introduced by the smallest missing label.



relabel to 3



Preflow Push

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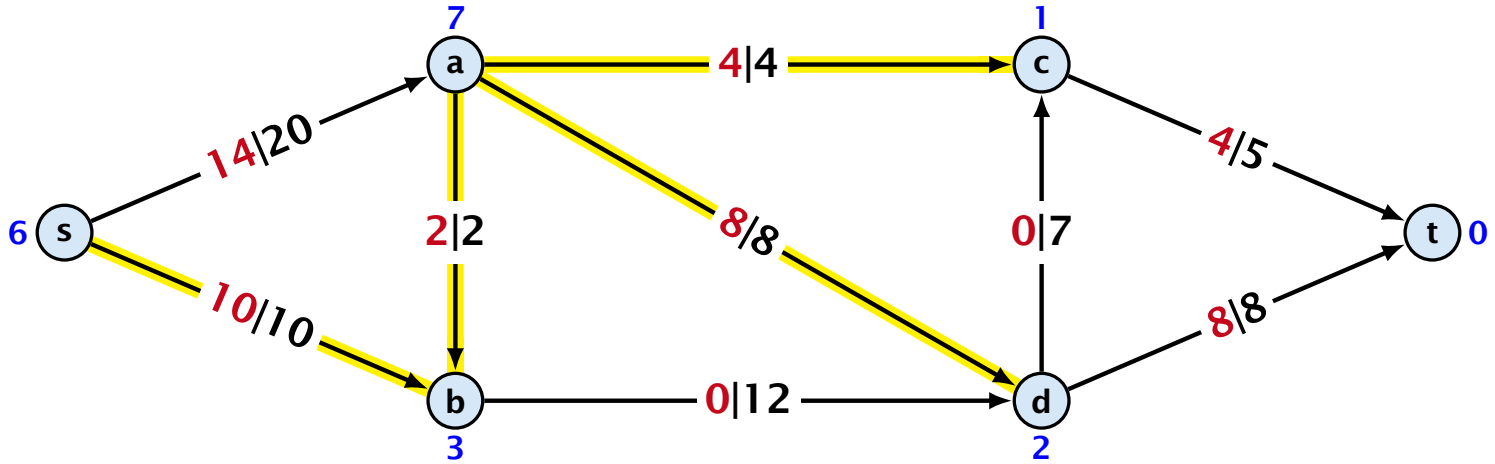
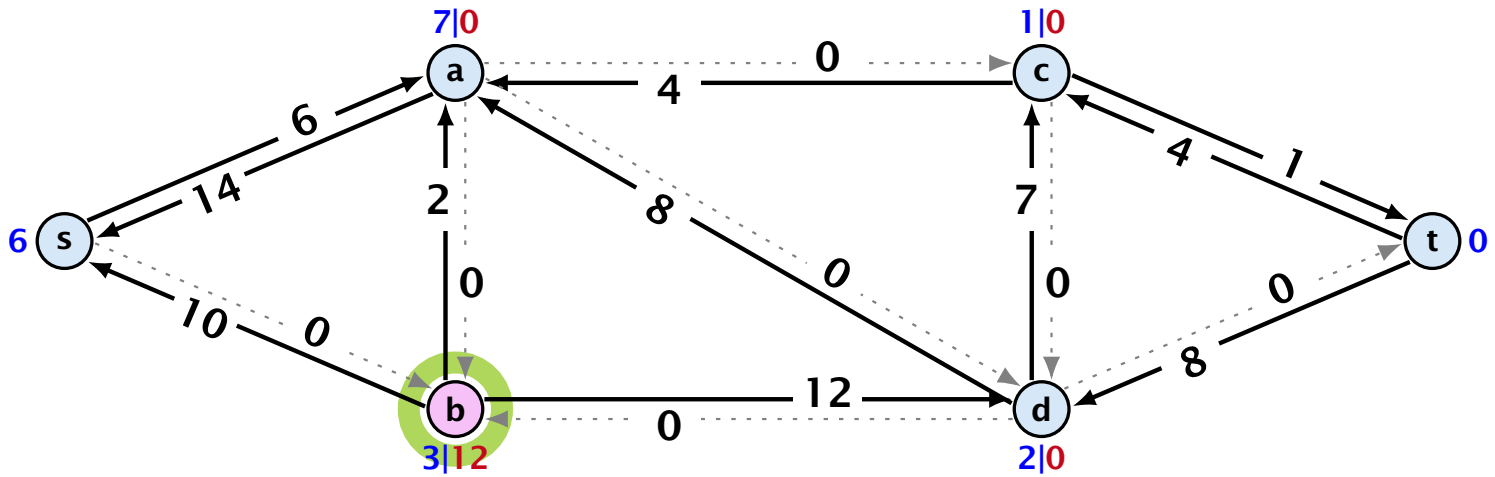
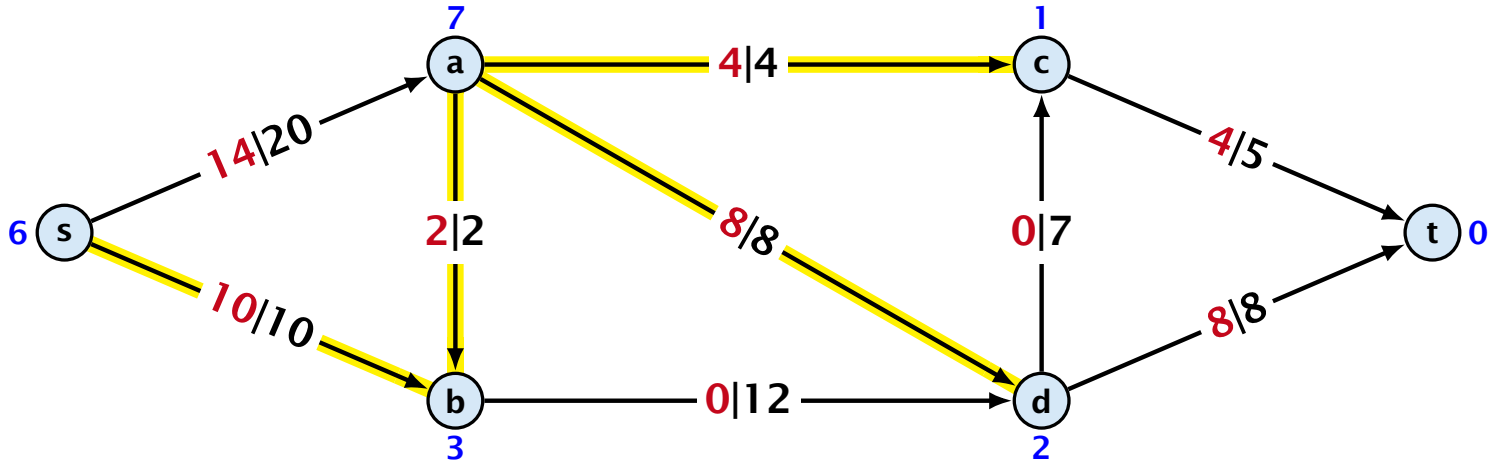


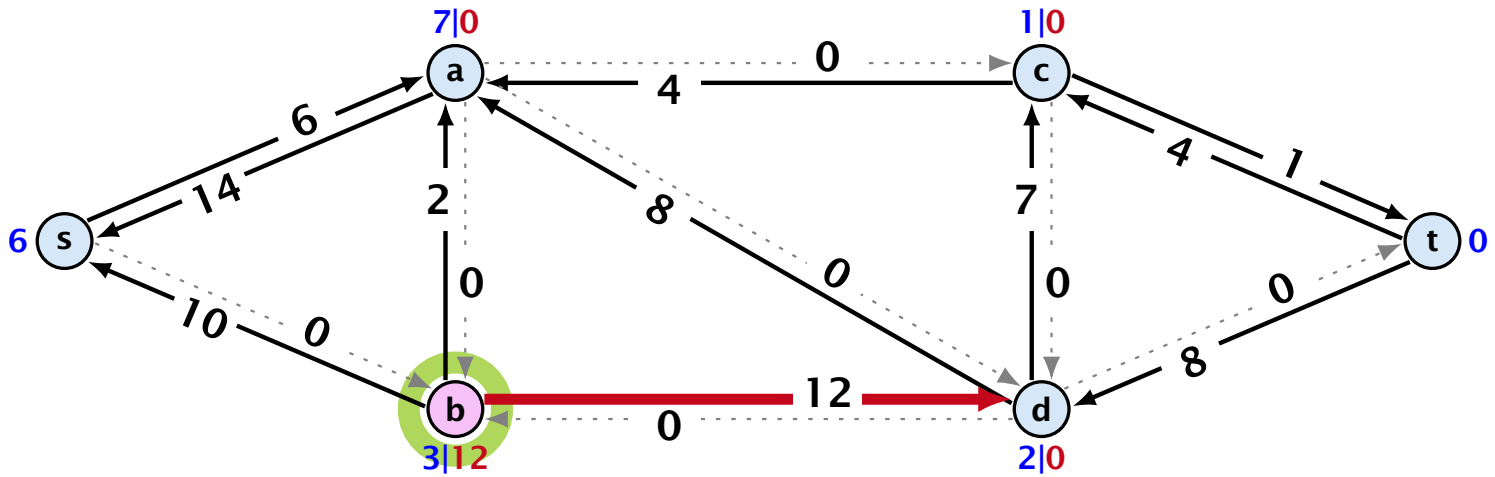


Preflow Push

The yellow edges indicate the cut that is introduced by the smallest missing label.



saturating and deactivating push



Preflow Push

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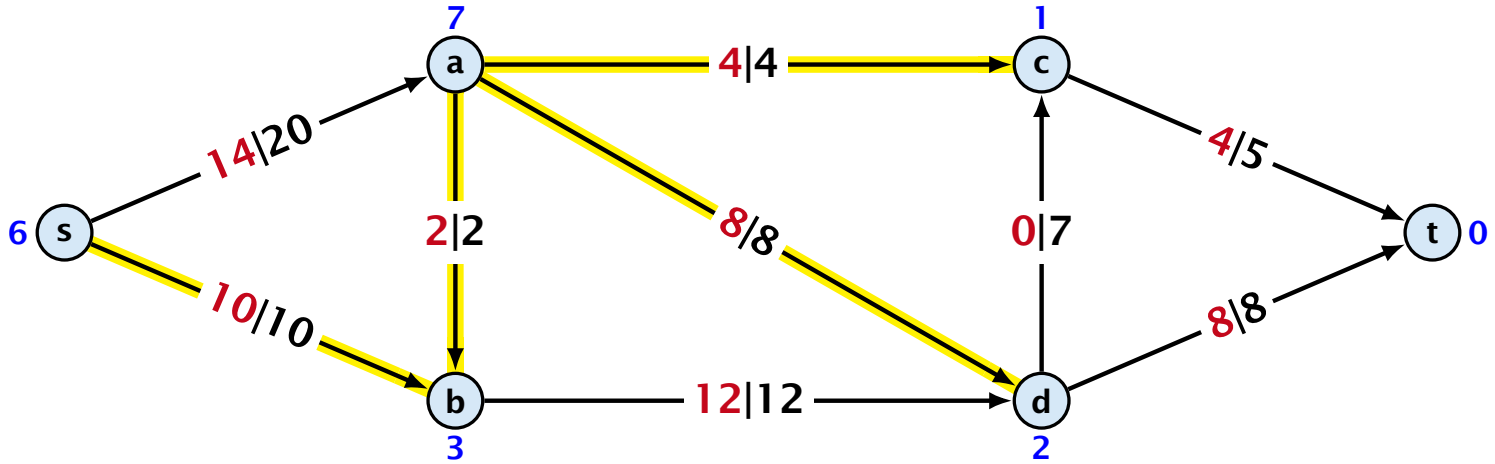

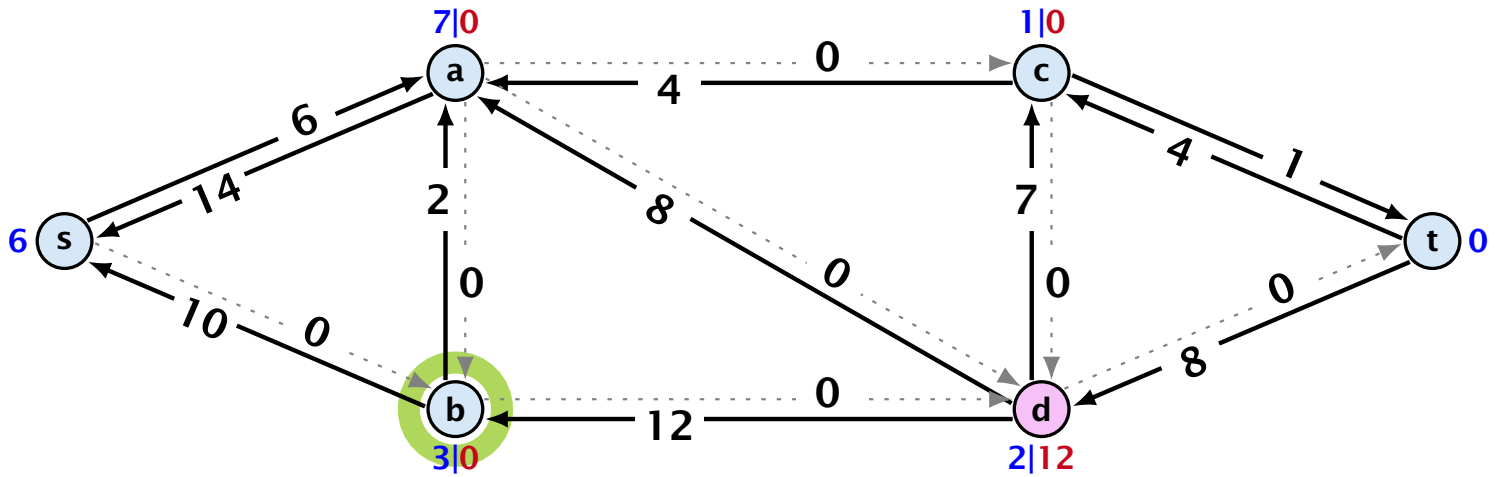

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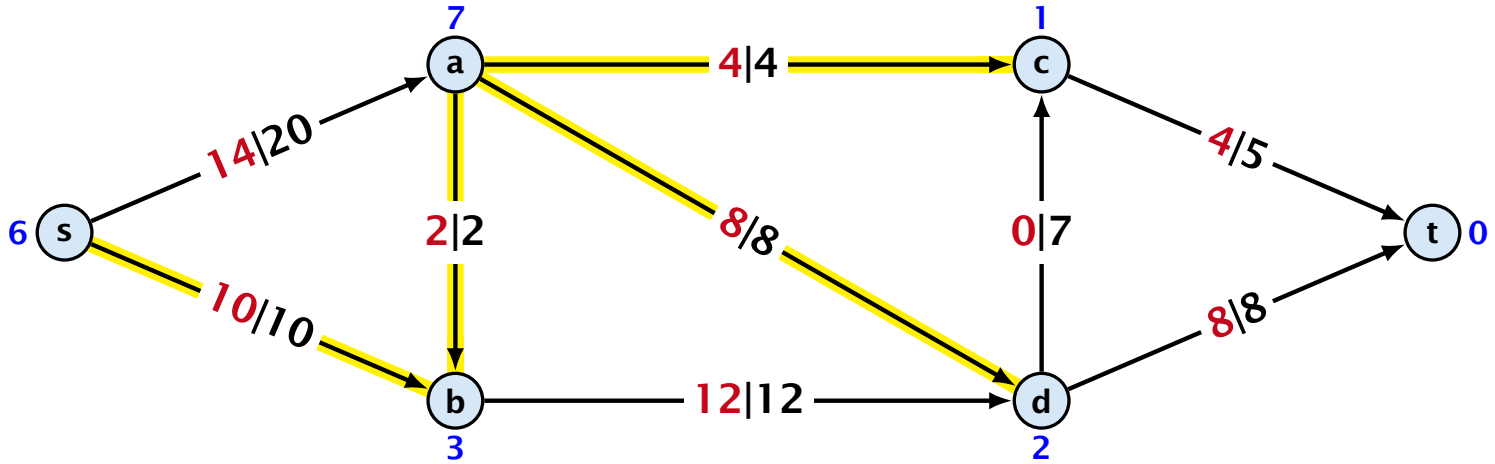

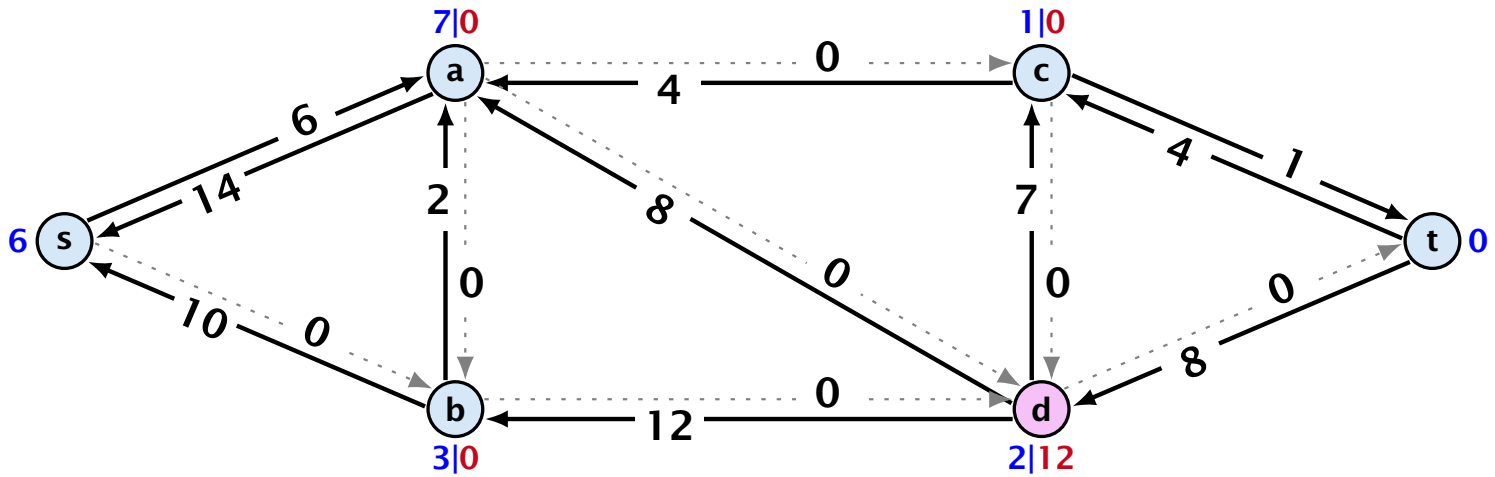

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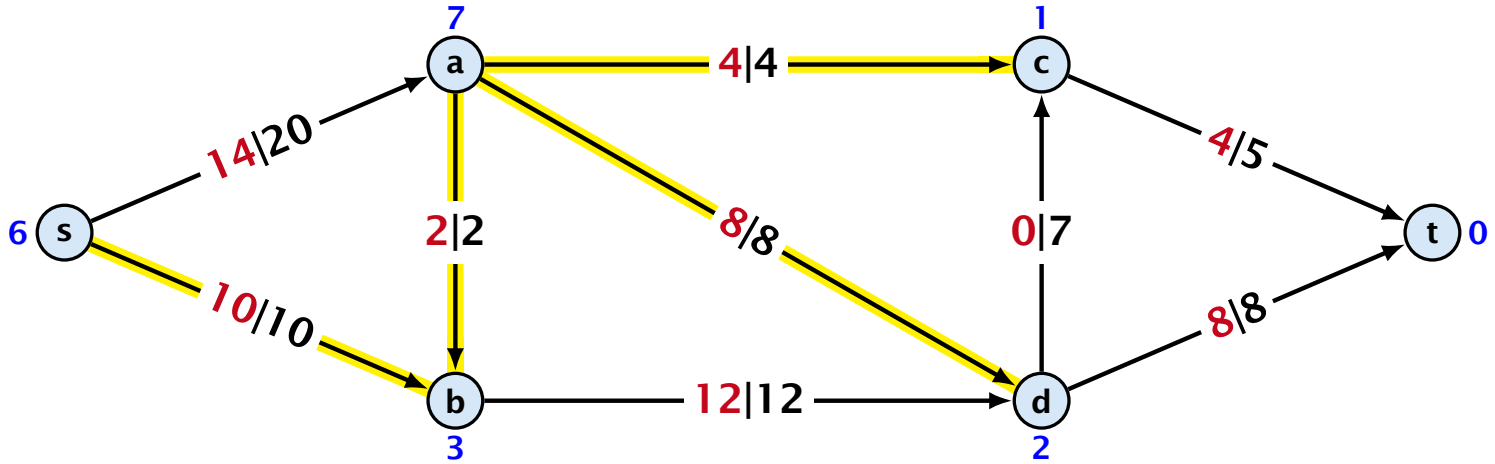

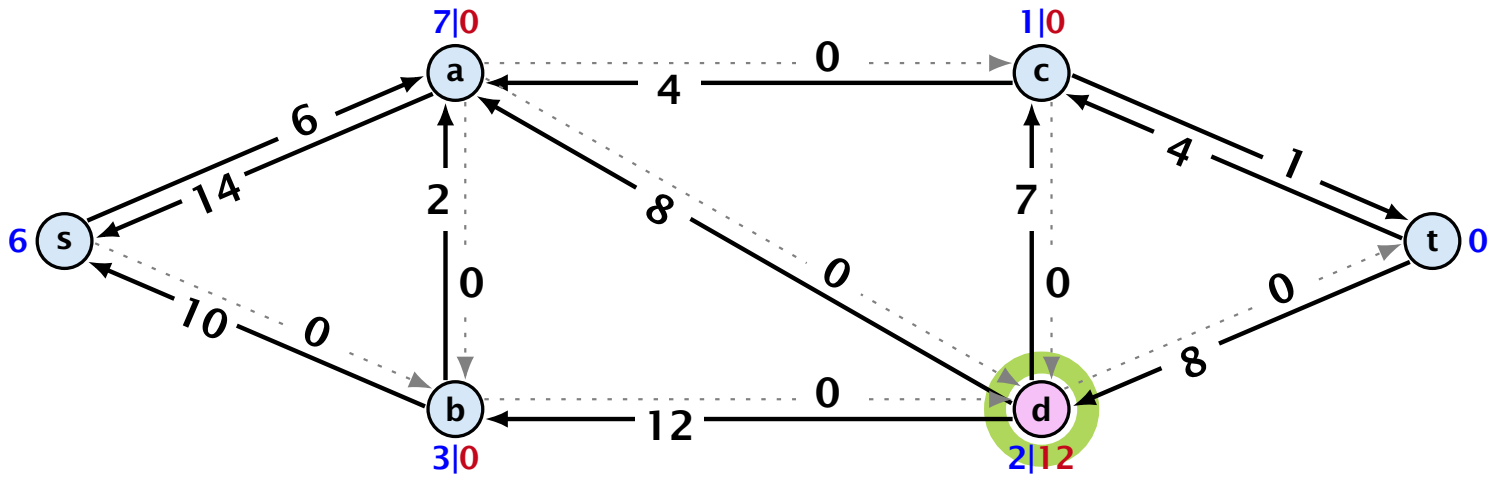

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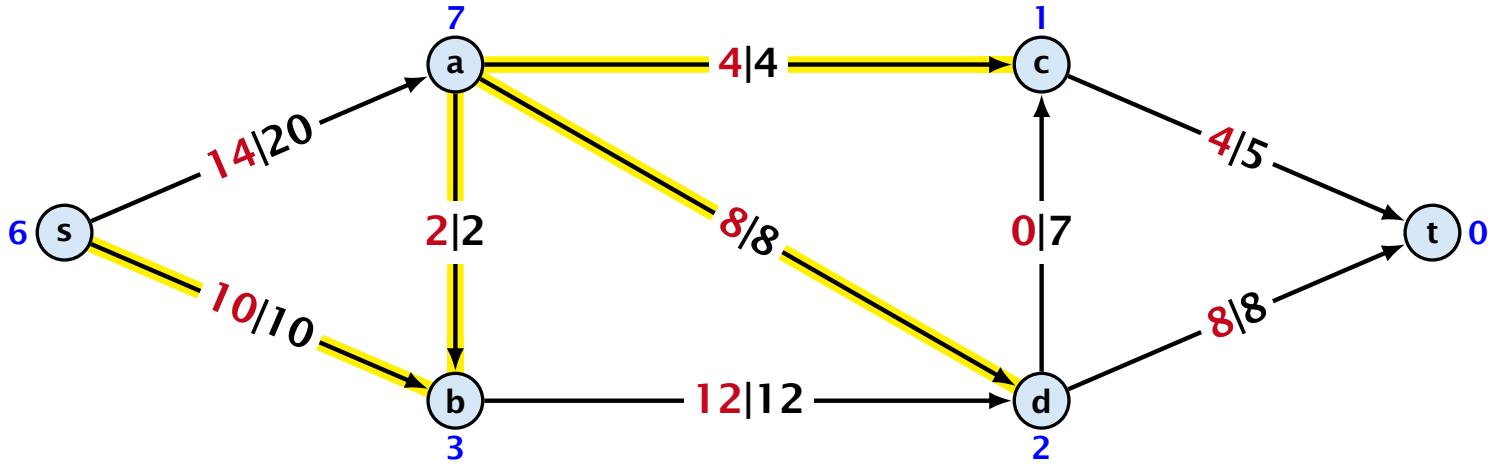
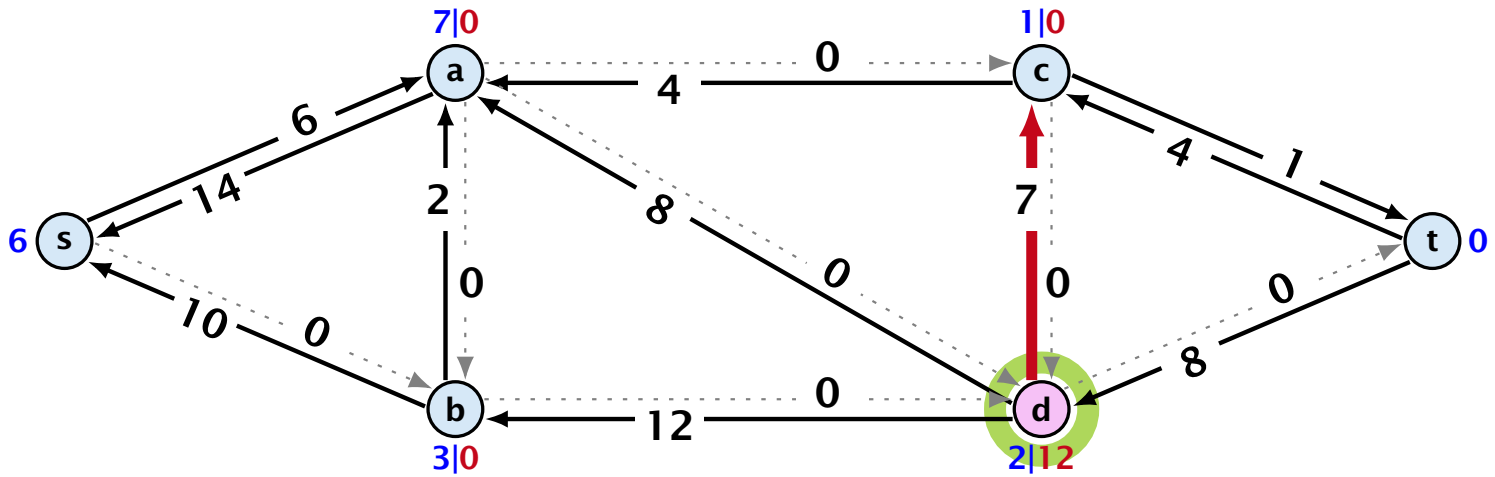


saturating push



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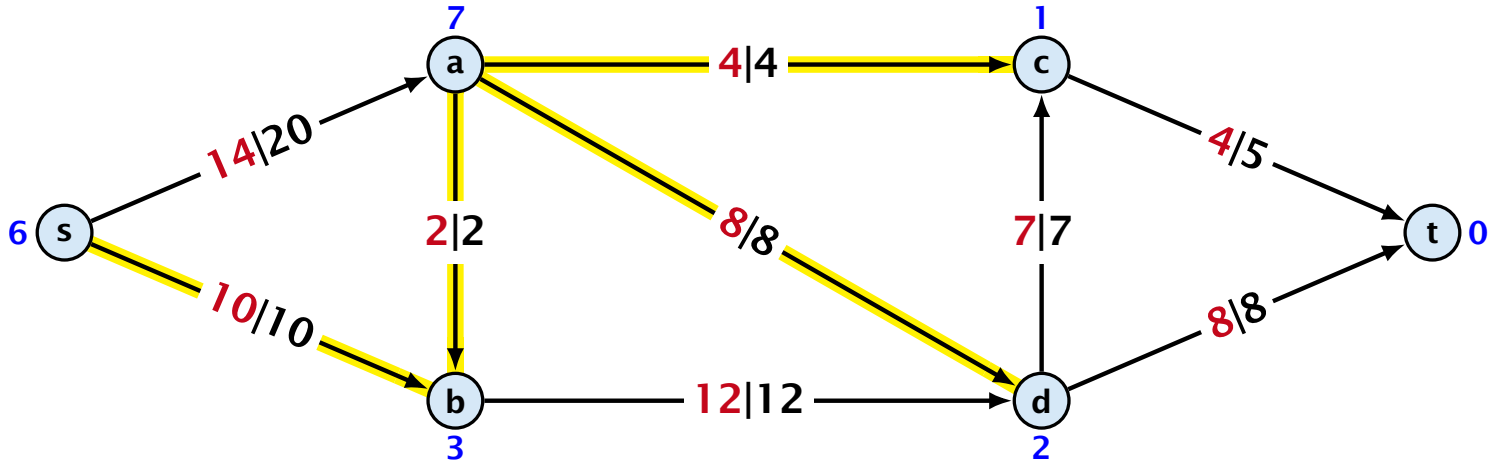

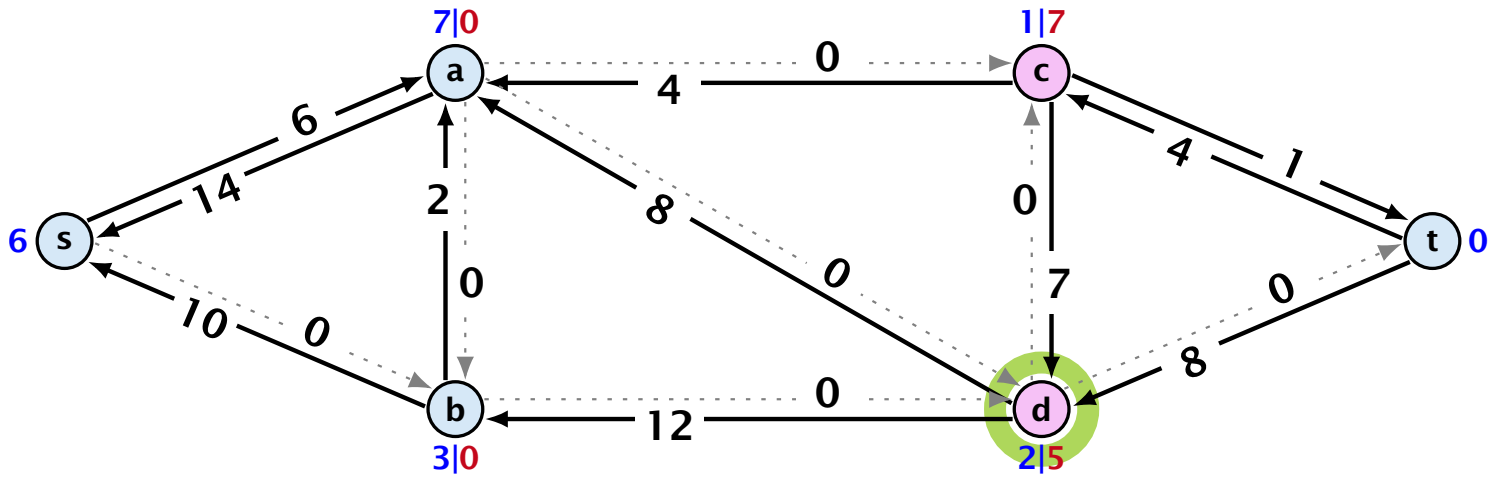

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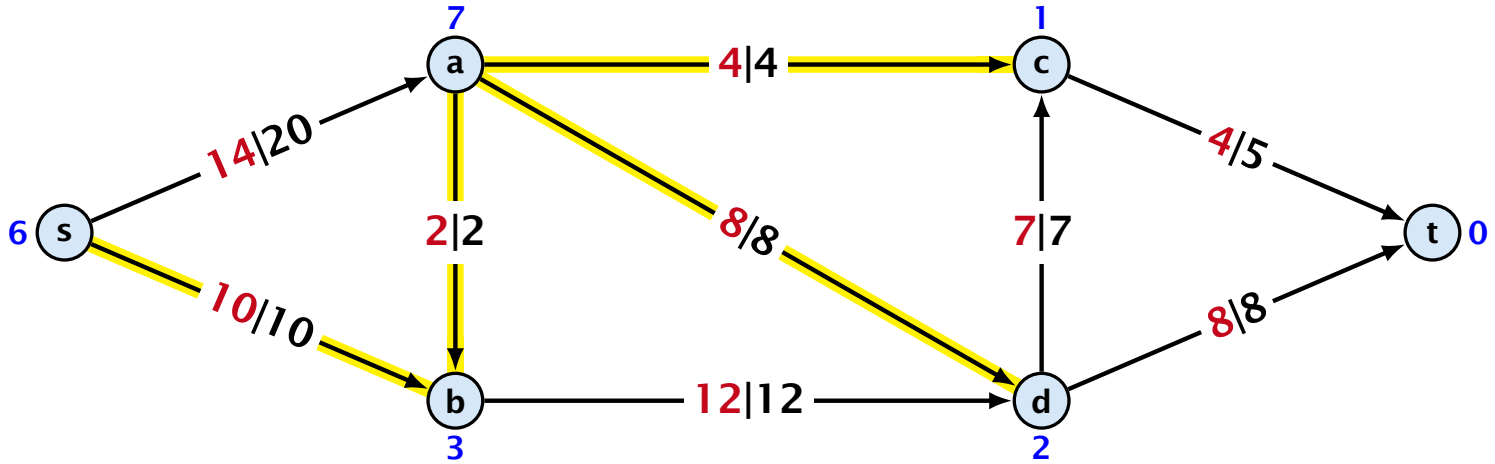
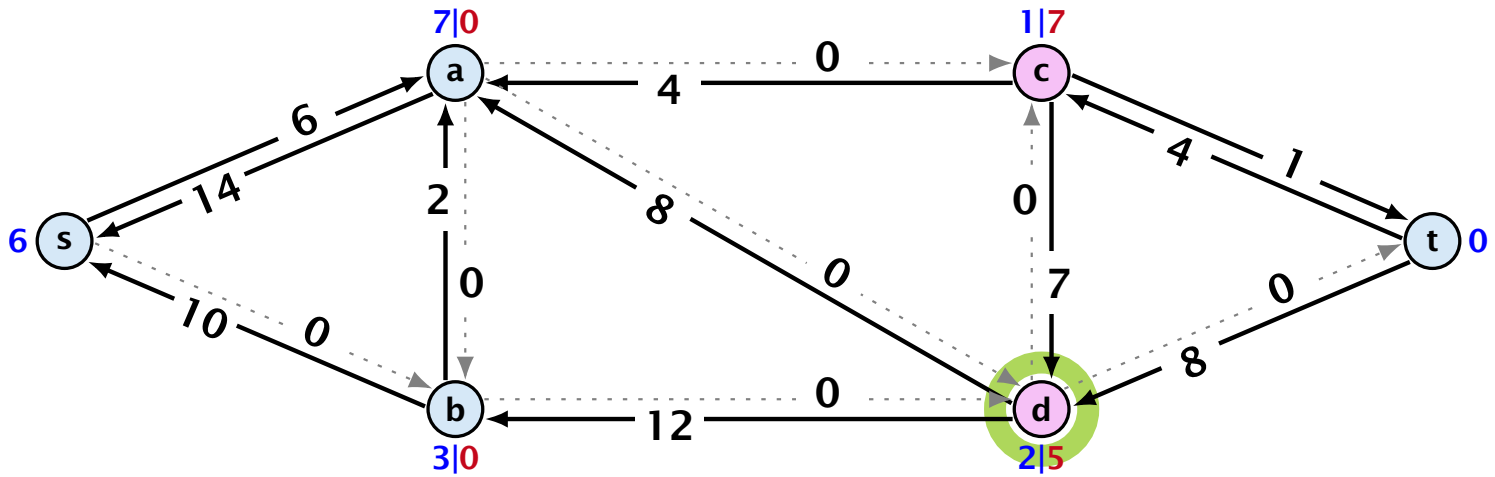


relabel to 4



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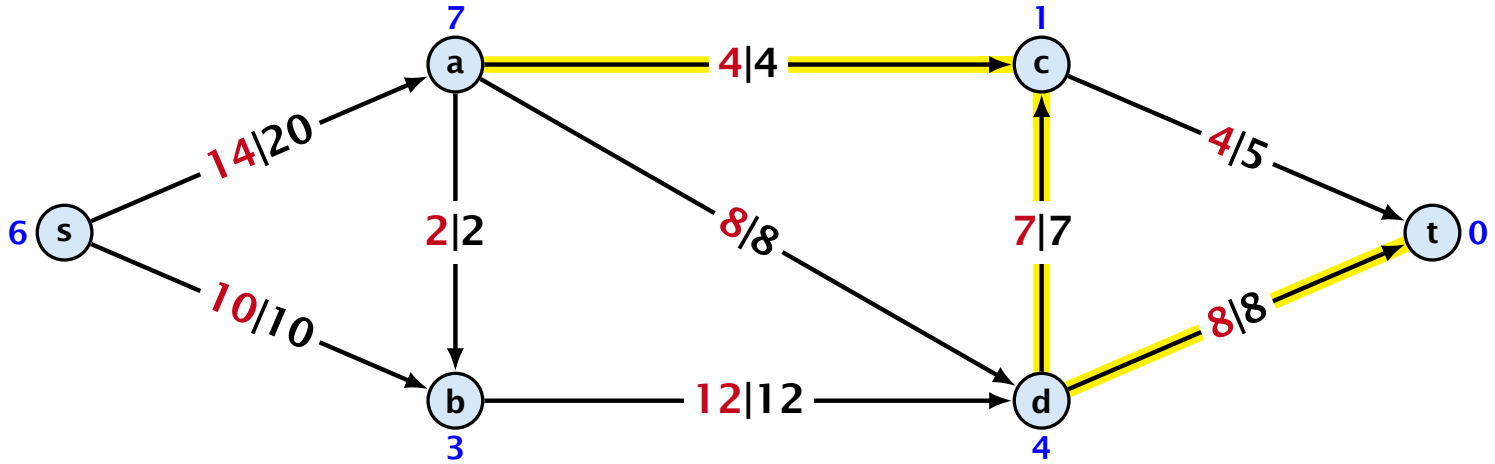

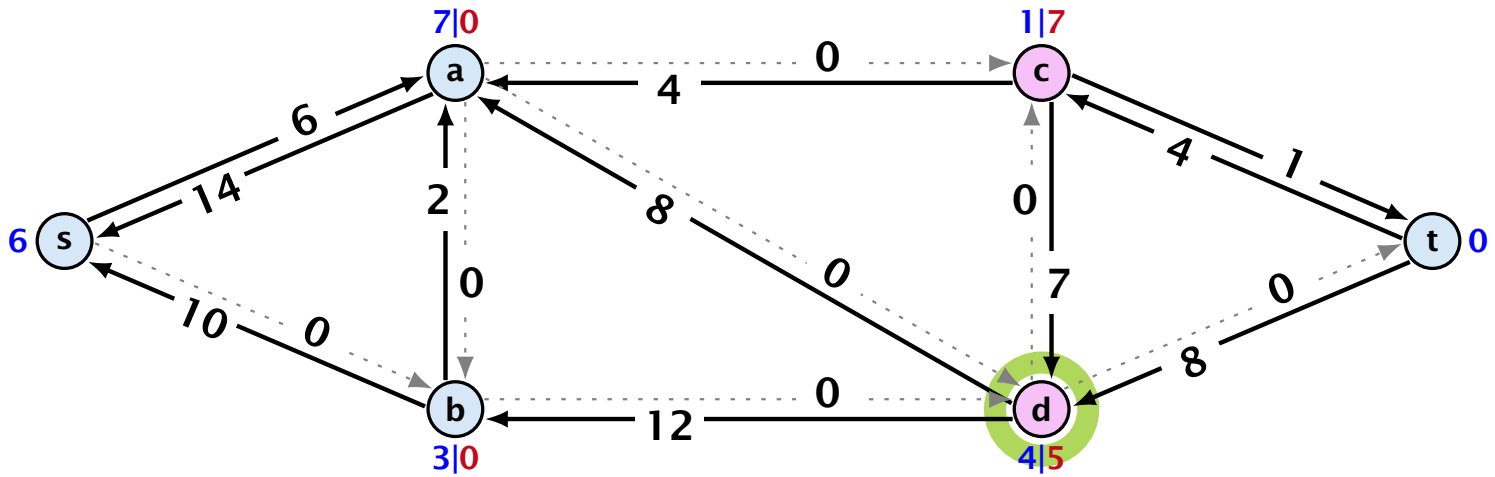

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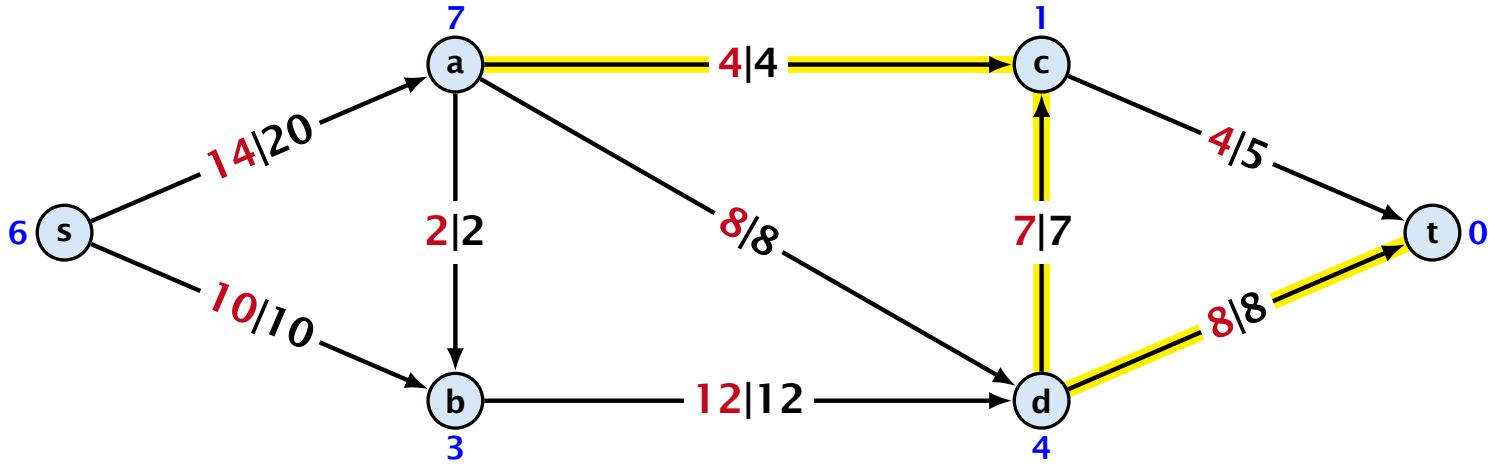
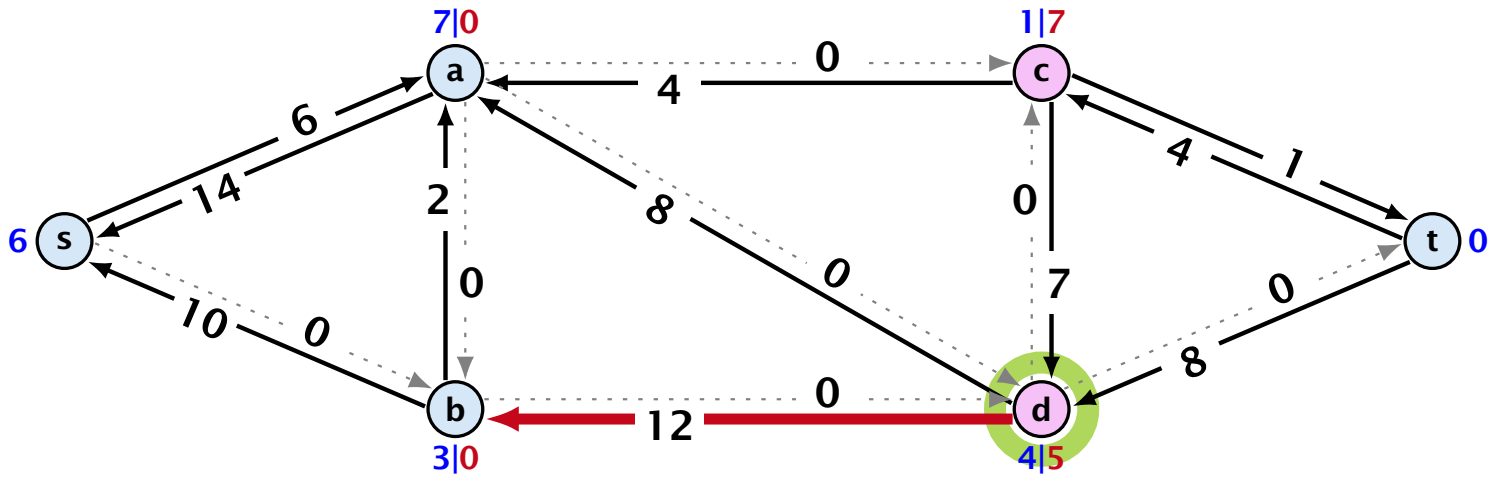


deactivating push



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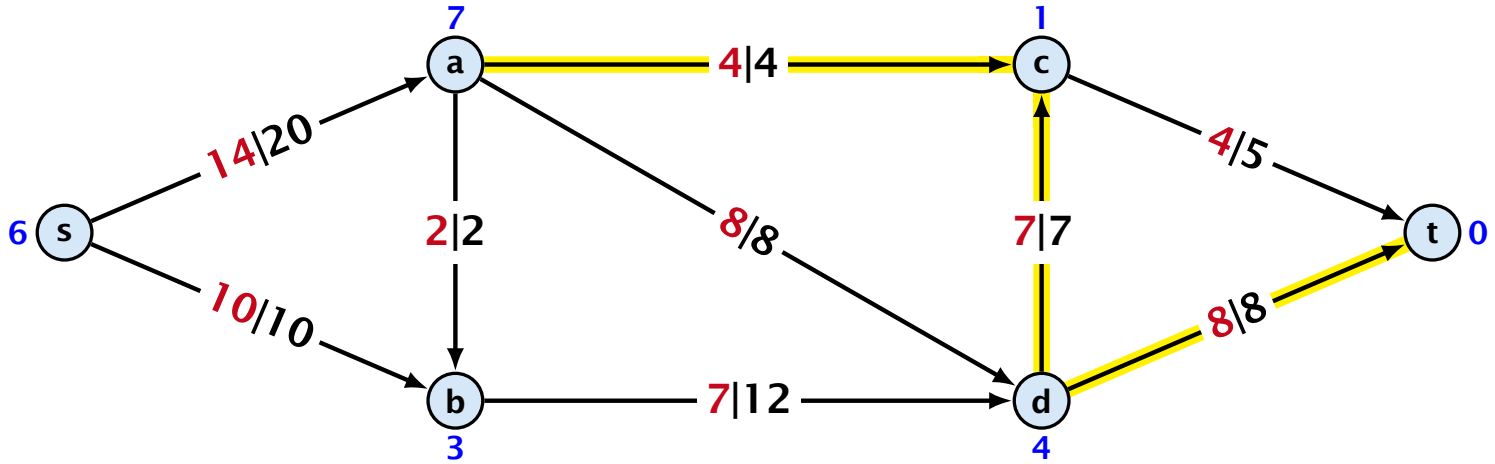

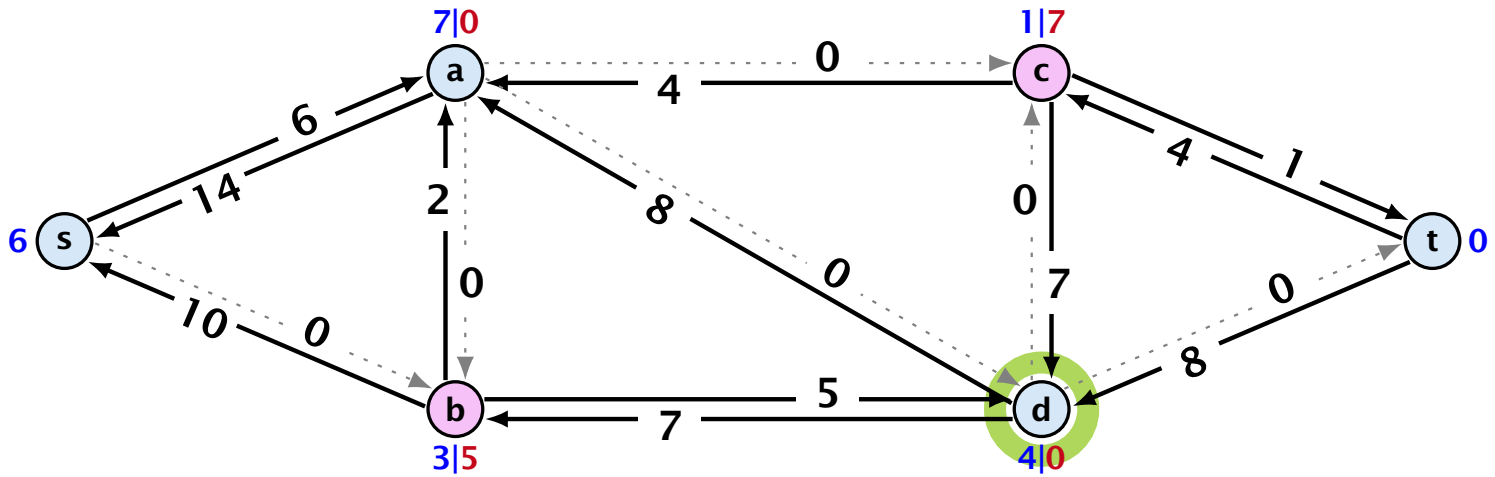

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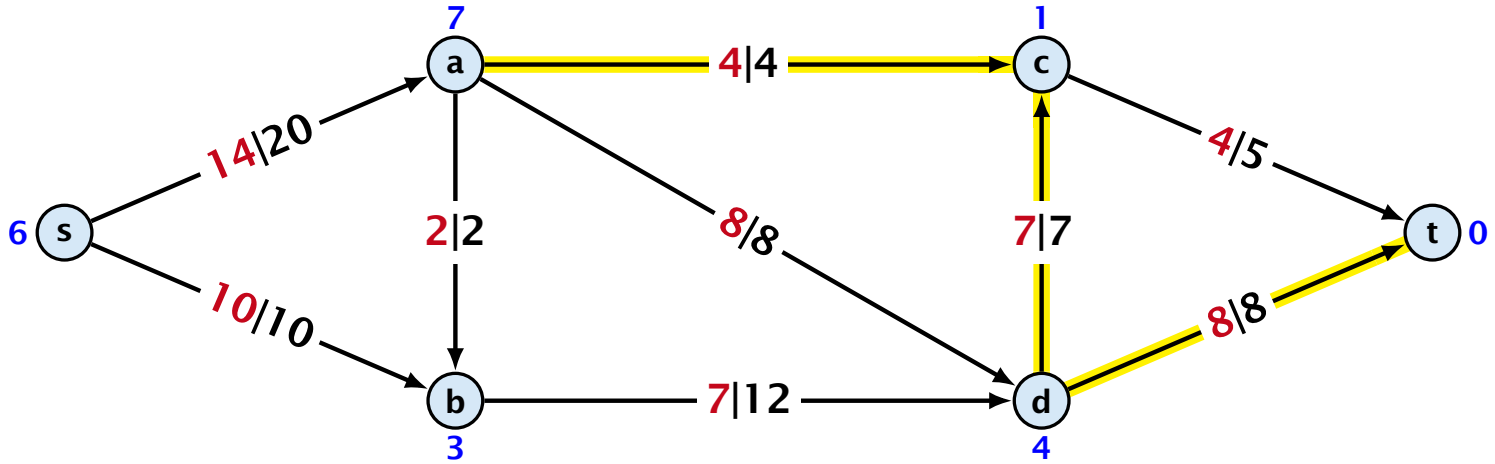

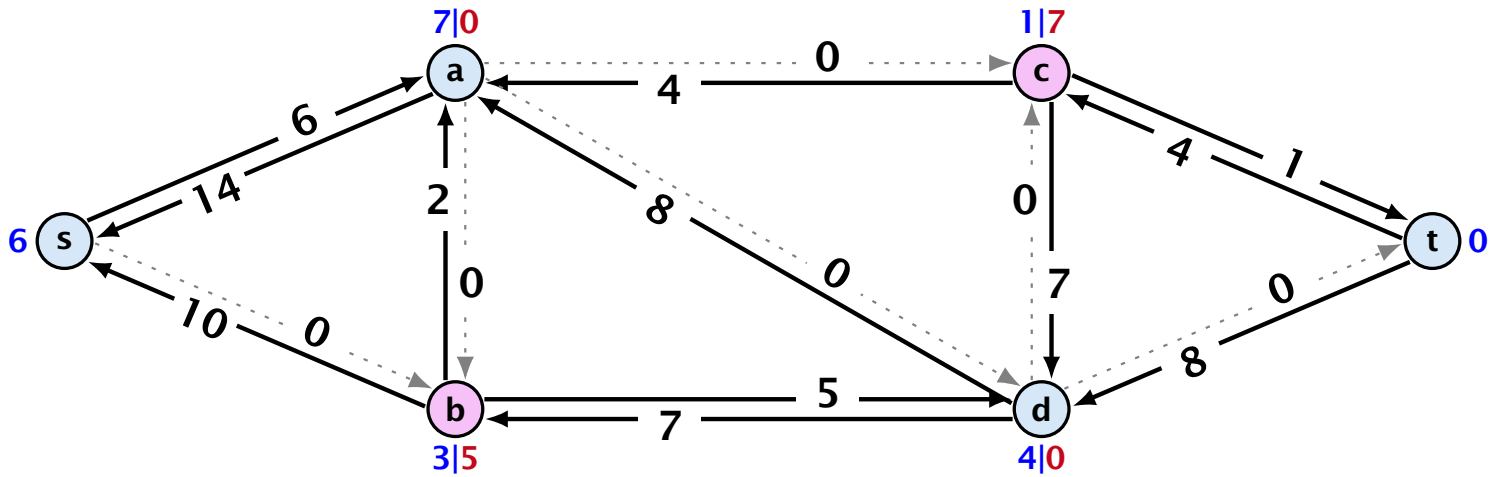

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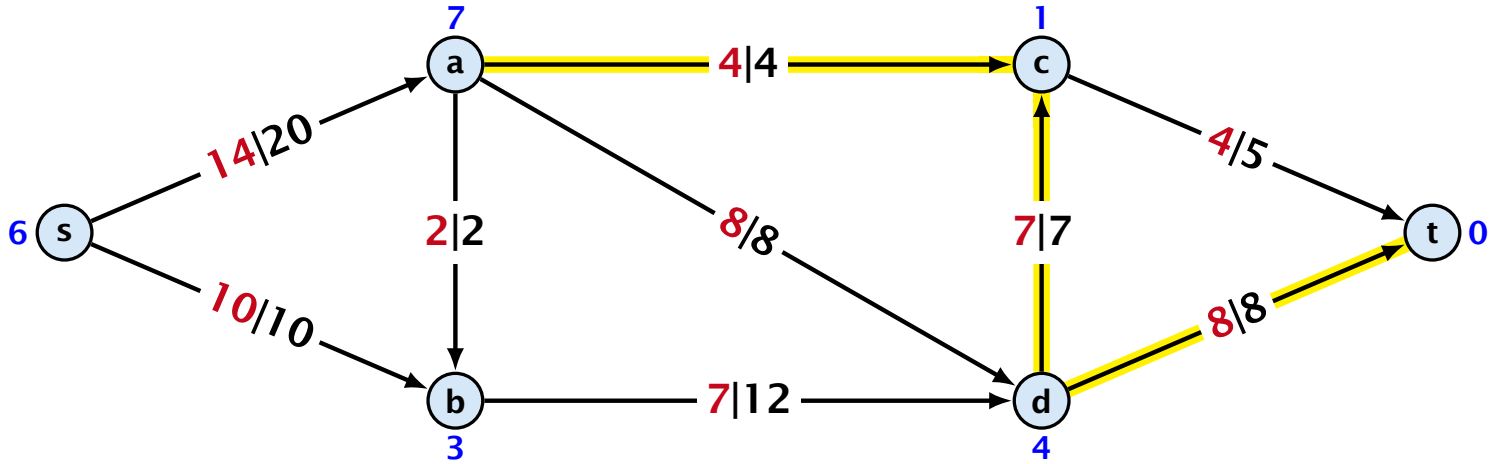

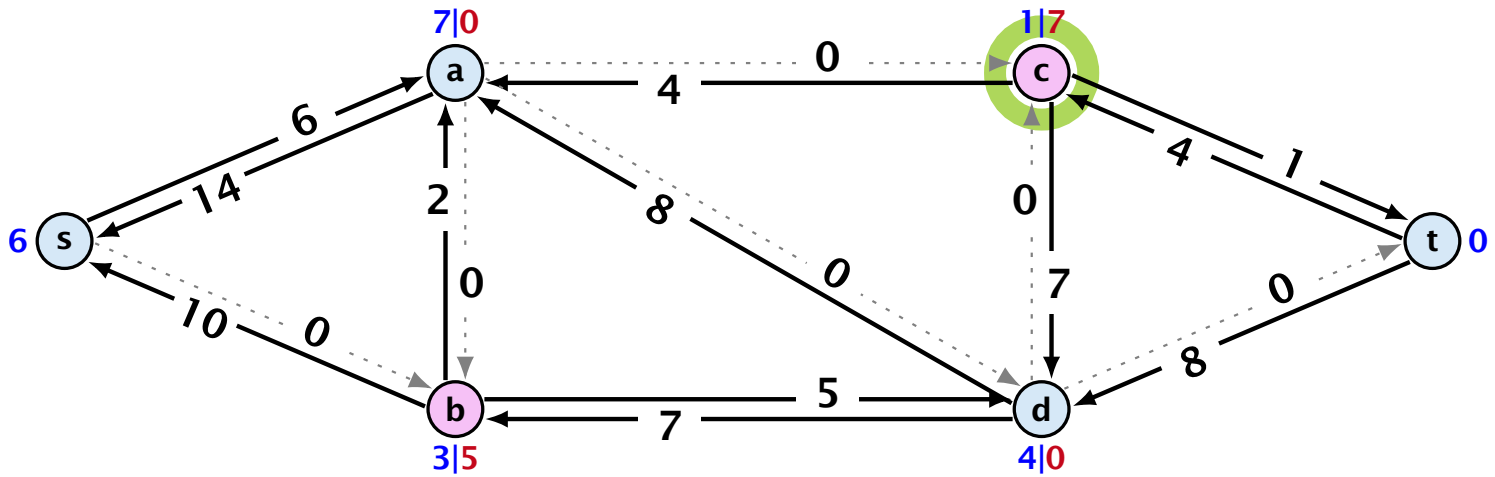

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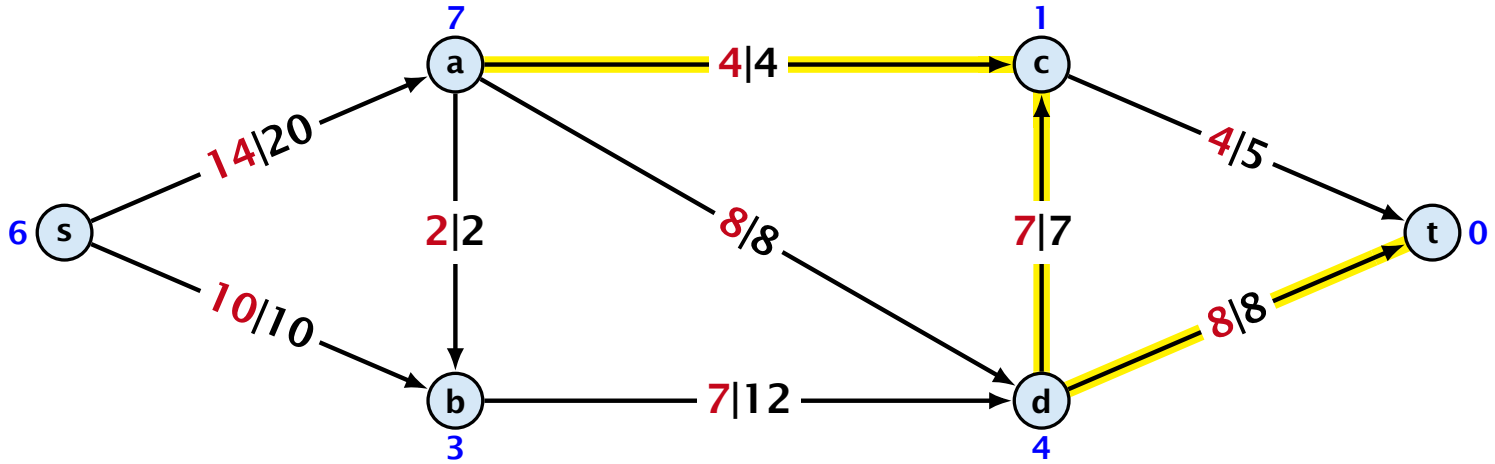
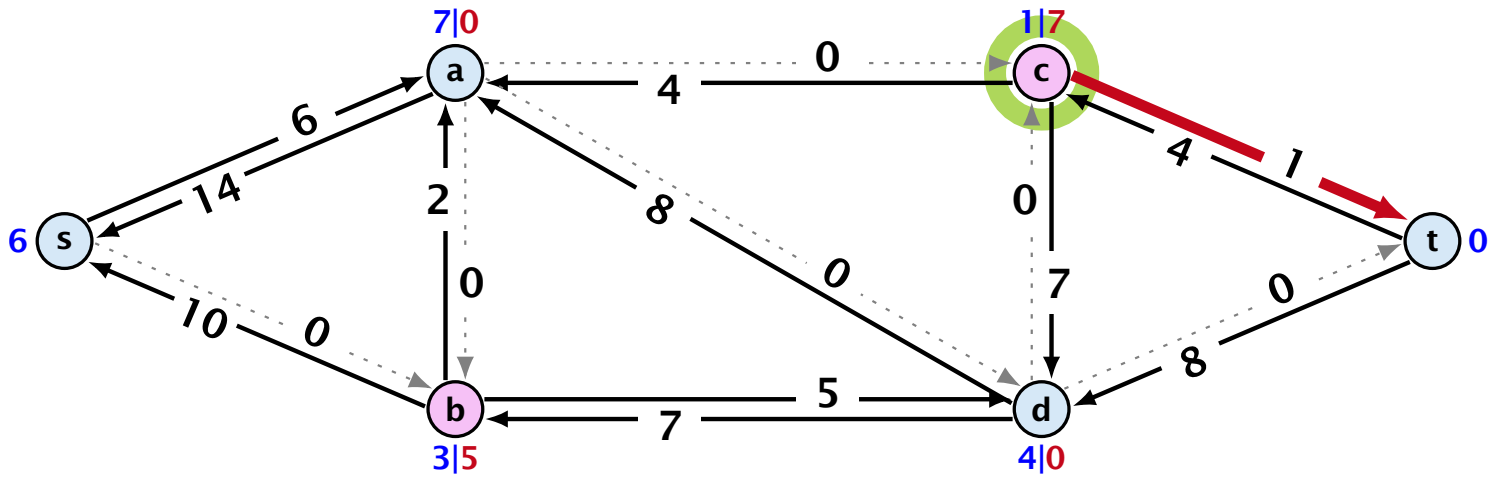


saturating push



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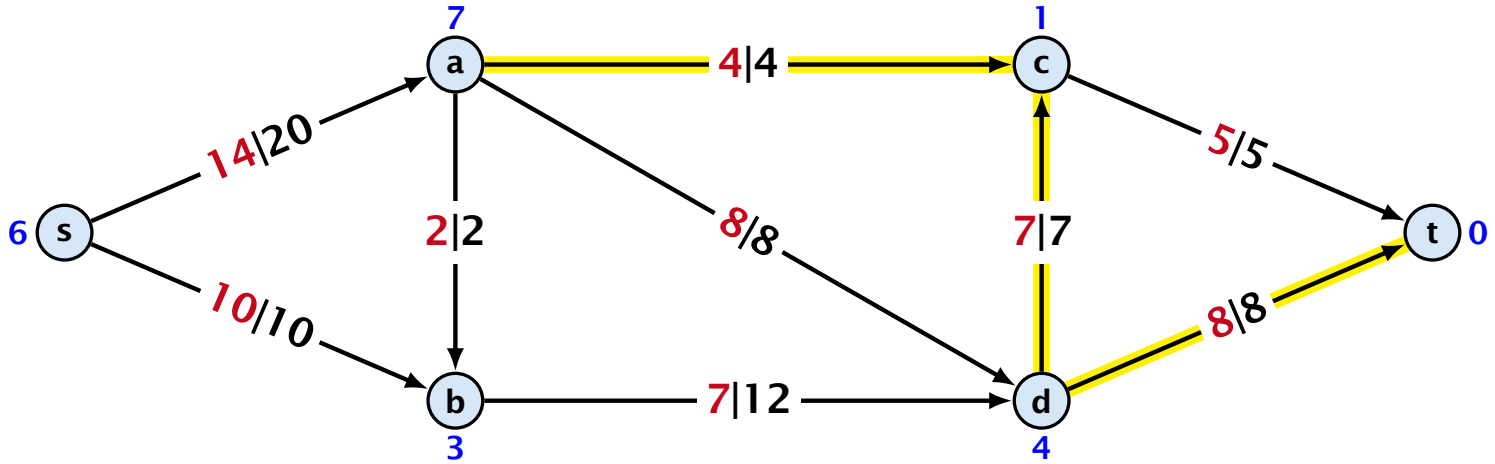

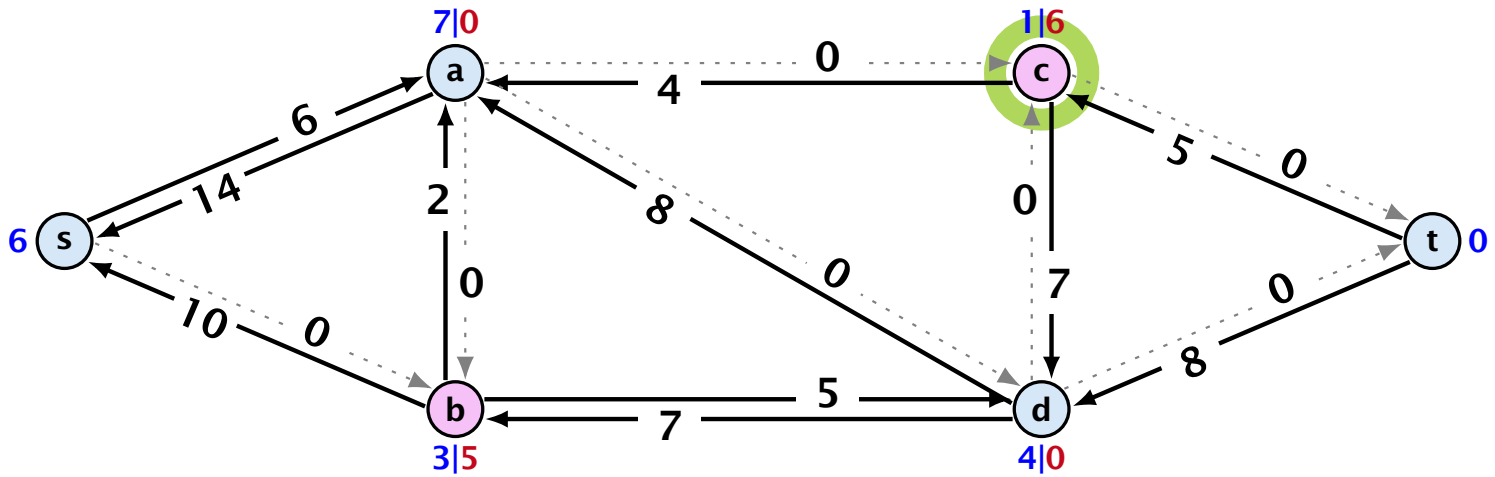

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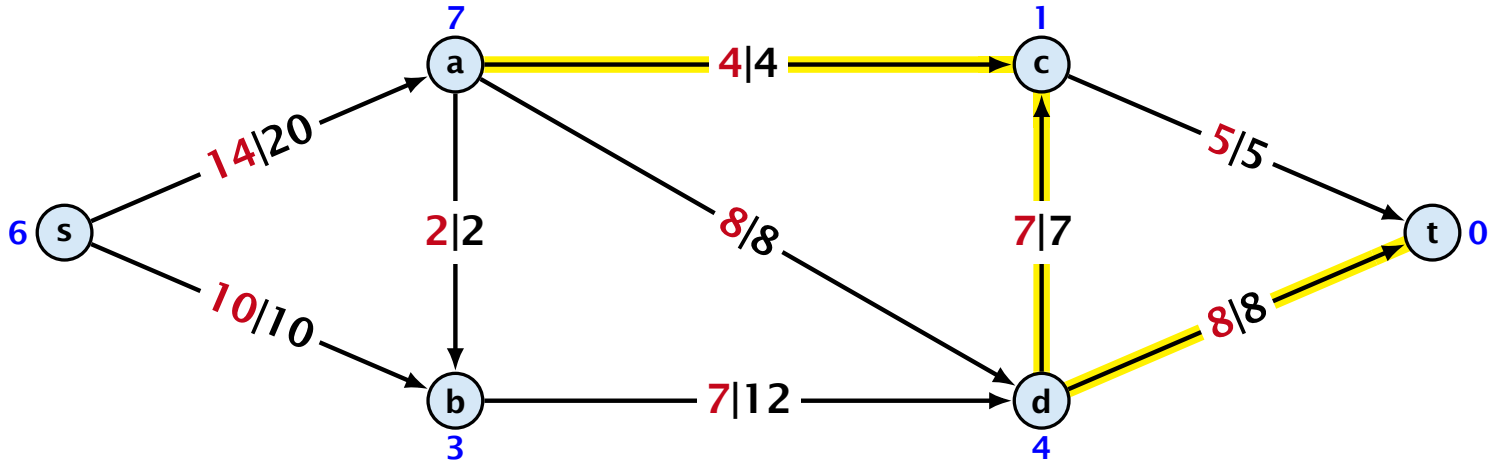
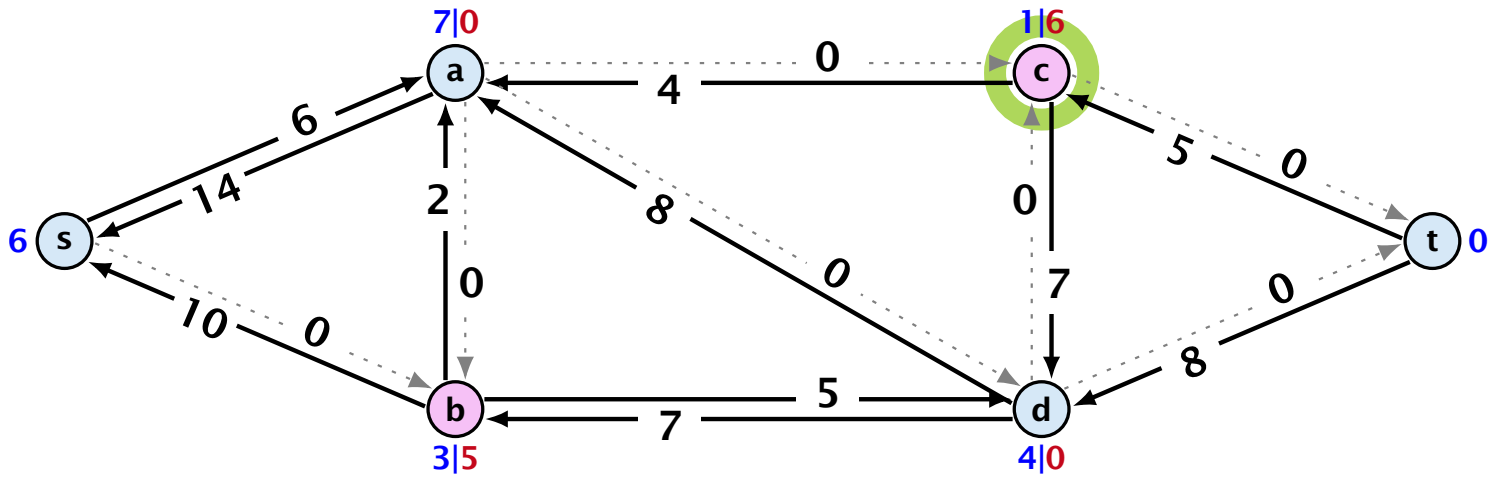


relabel to 5



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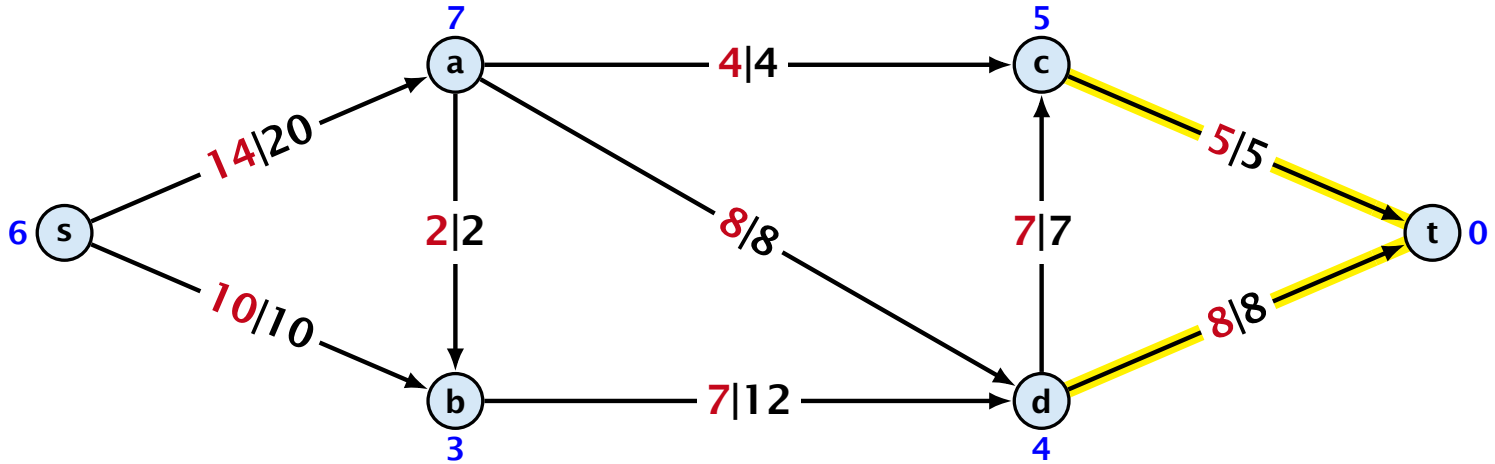

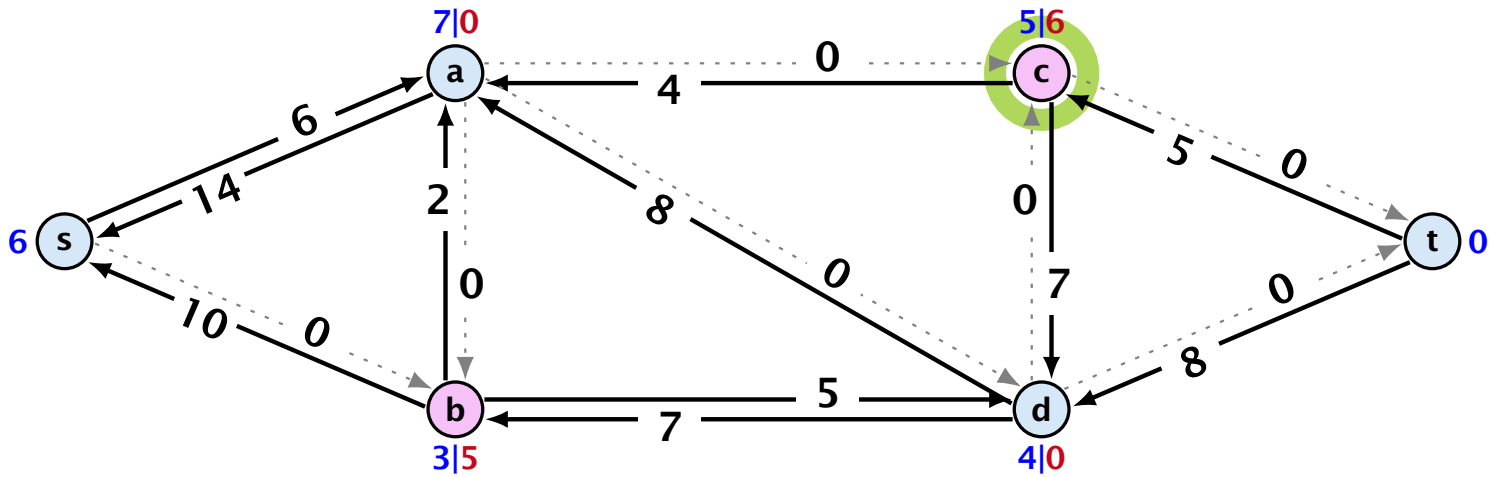

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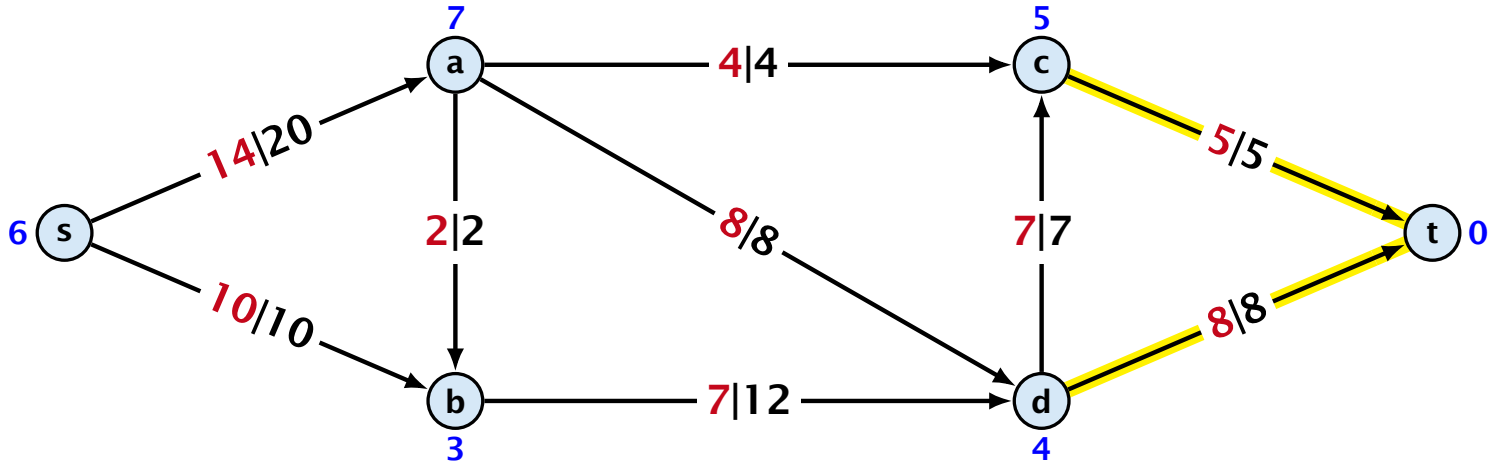
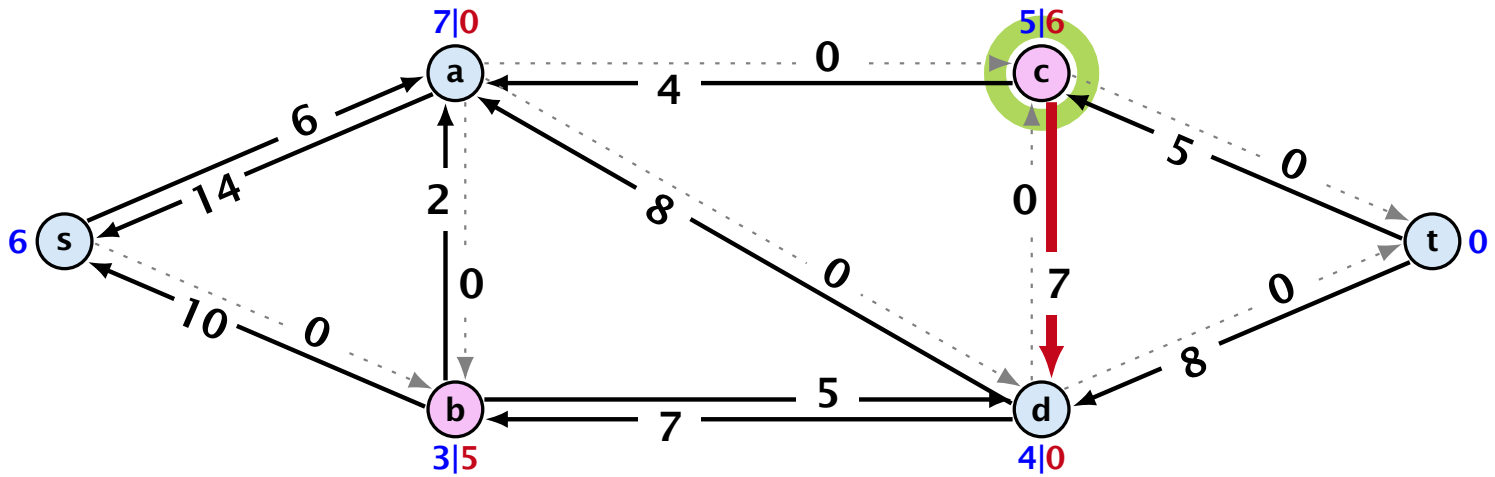


deactivating push



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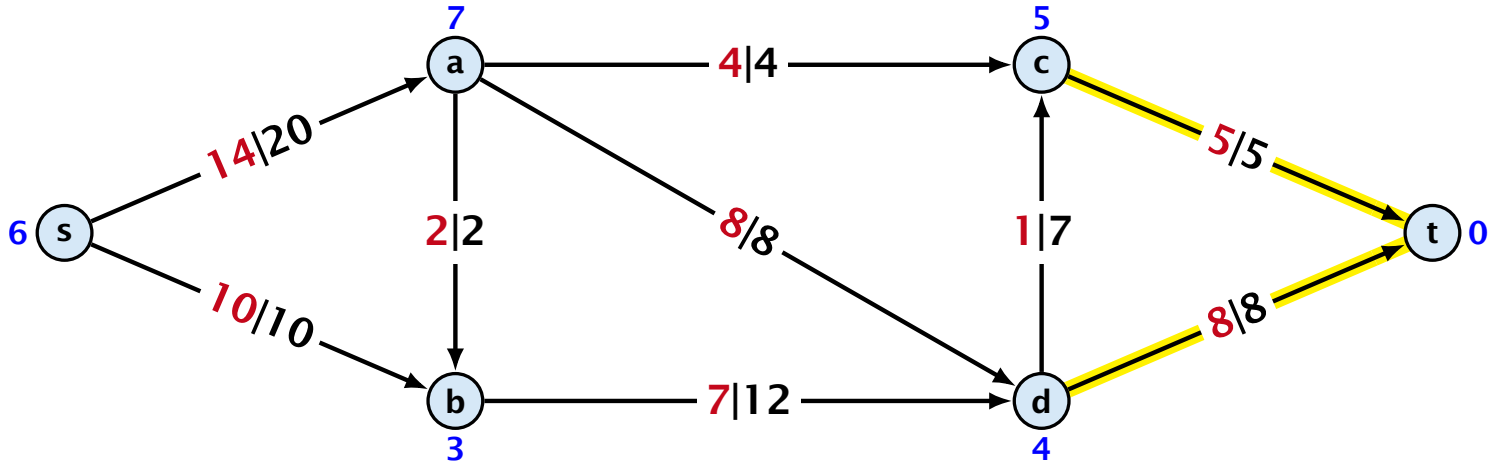

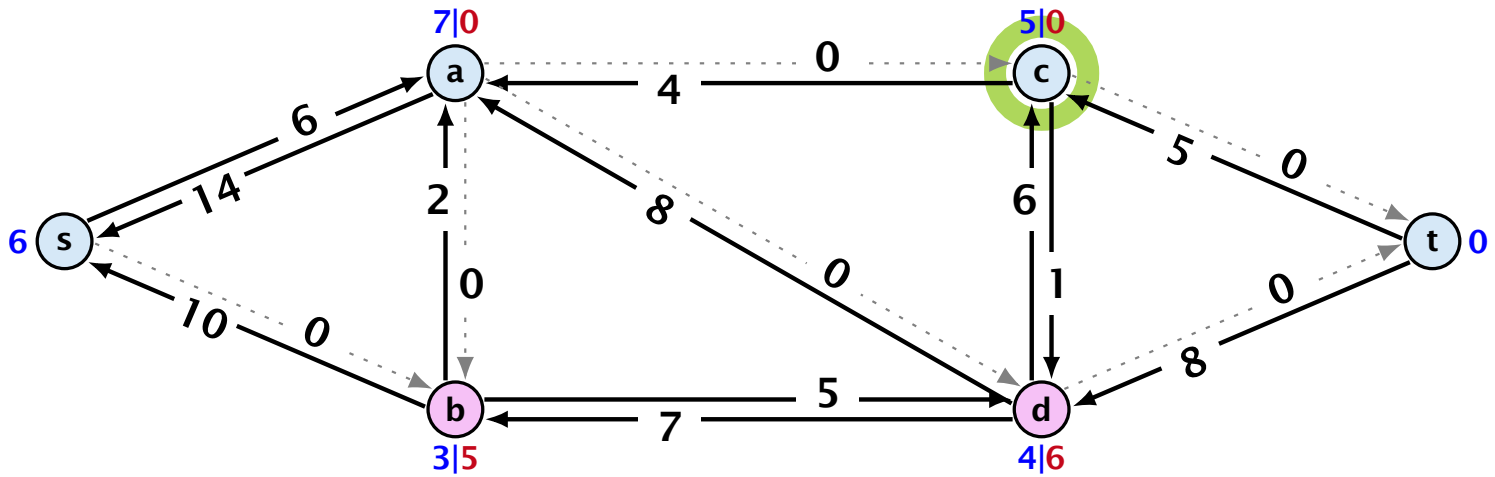

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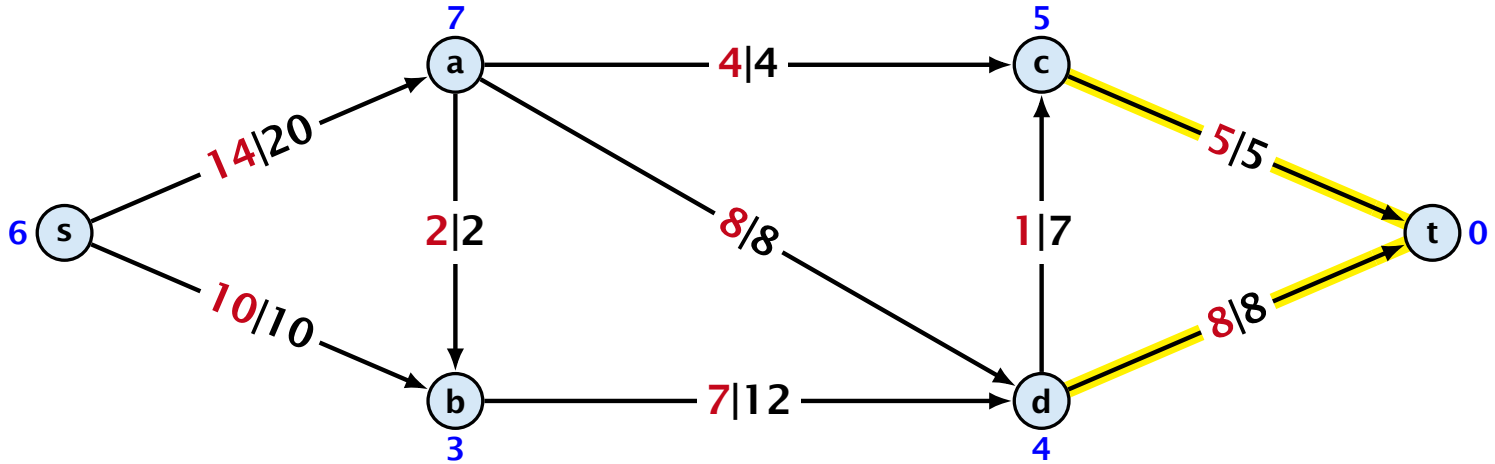

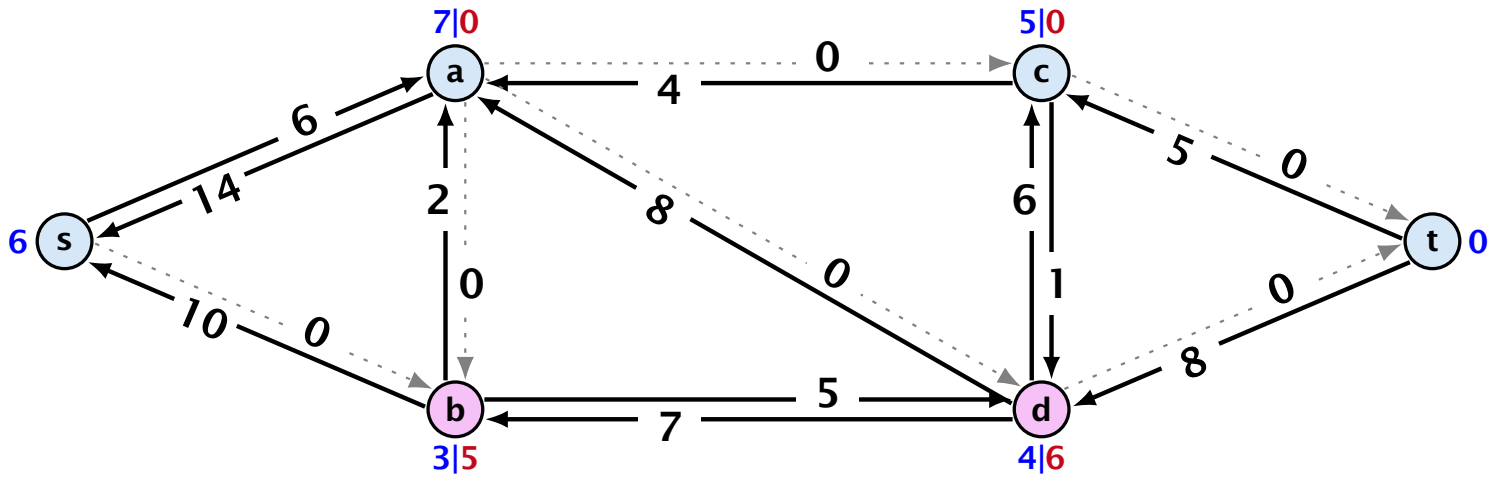

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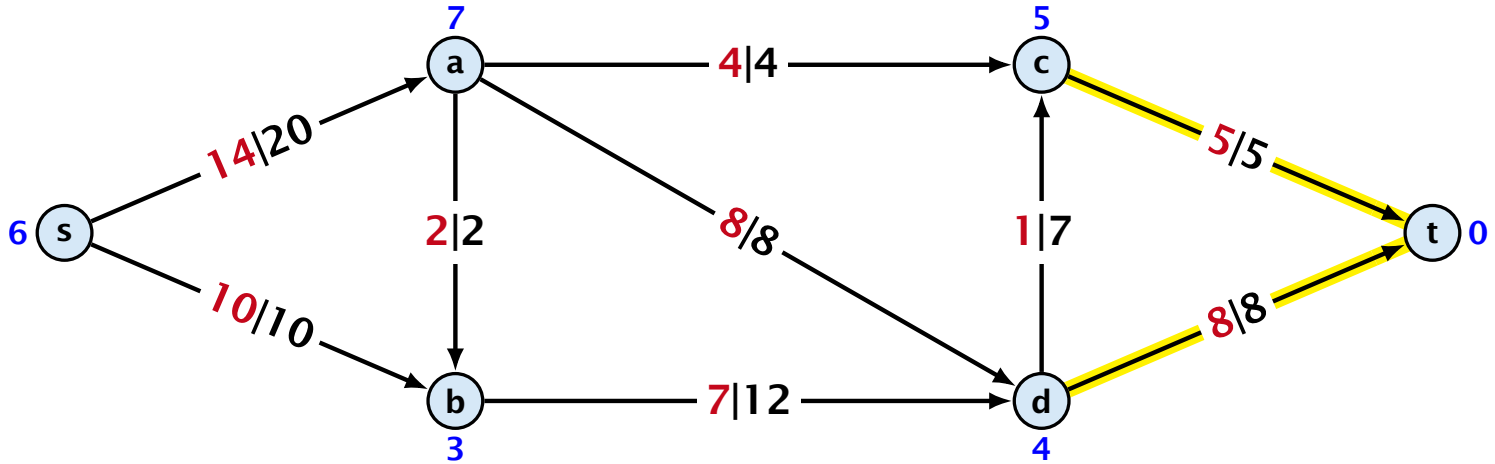

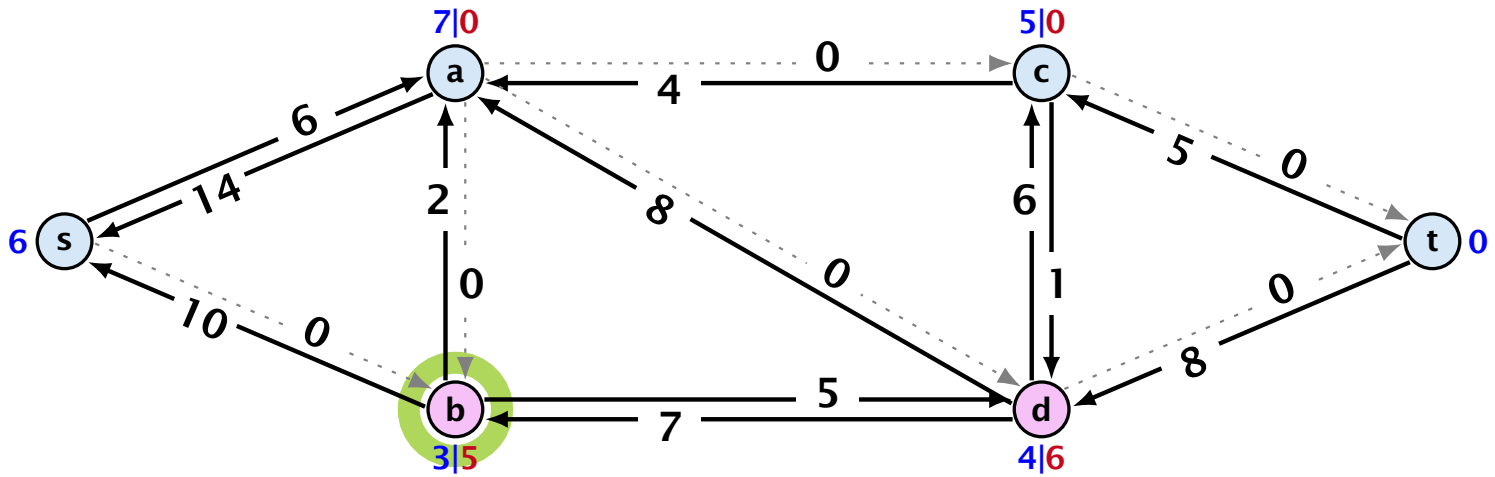

Preflow Push

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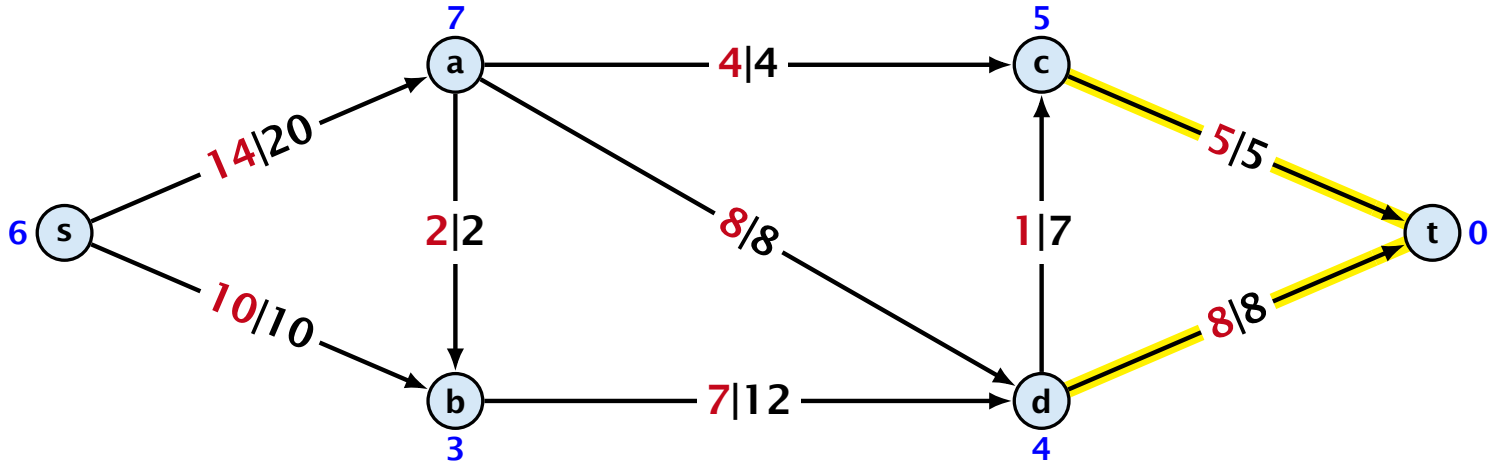
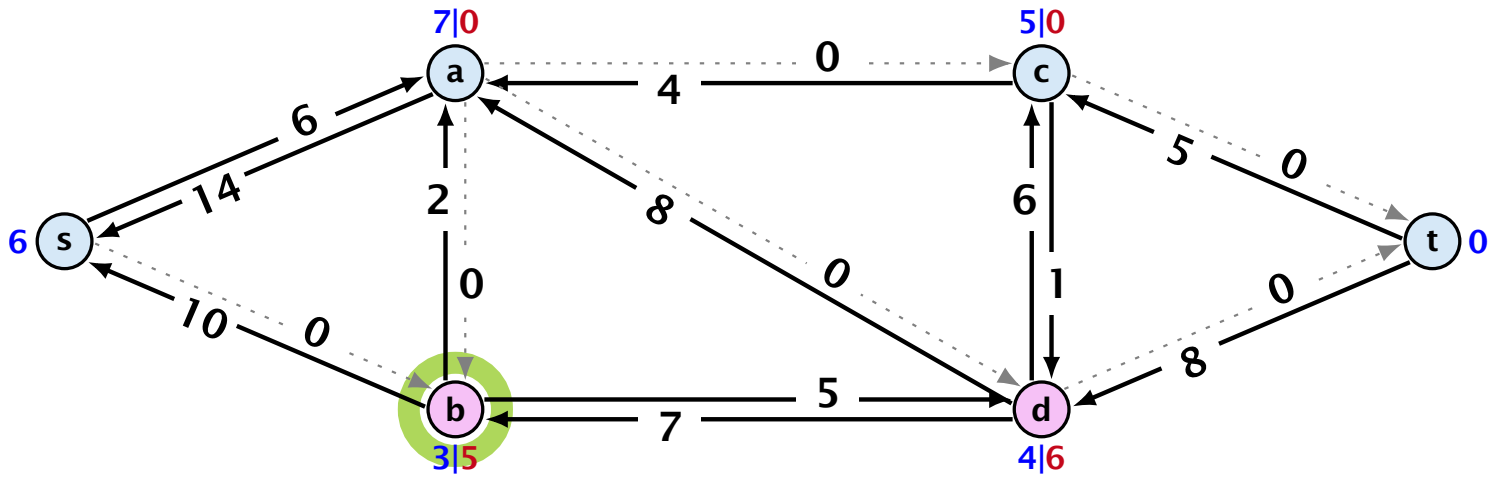


relabel to 5



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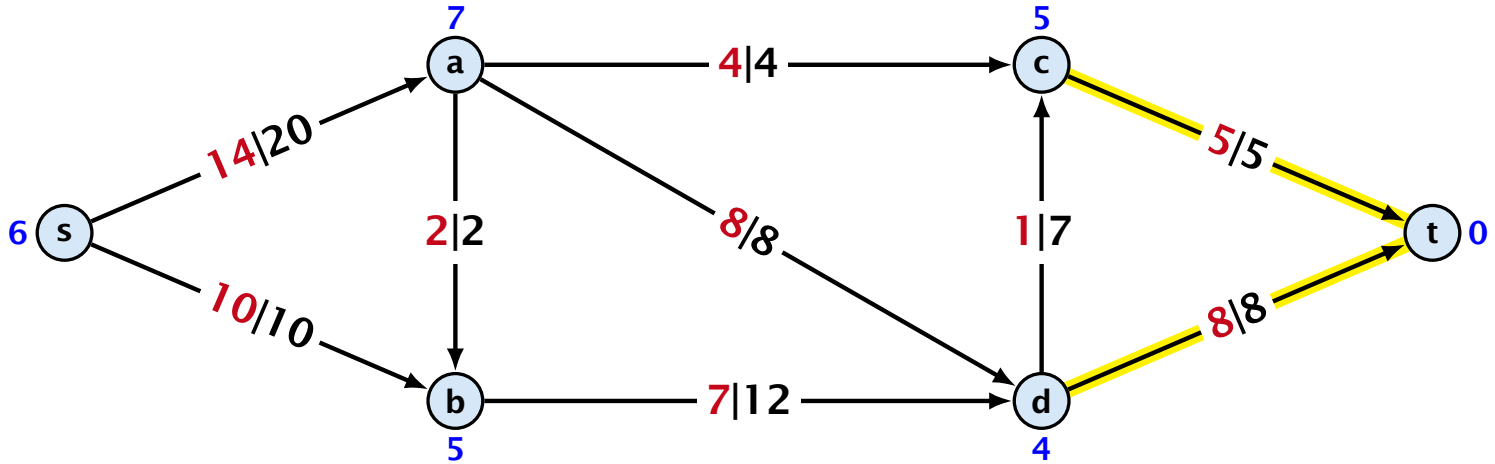

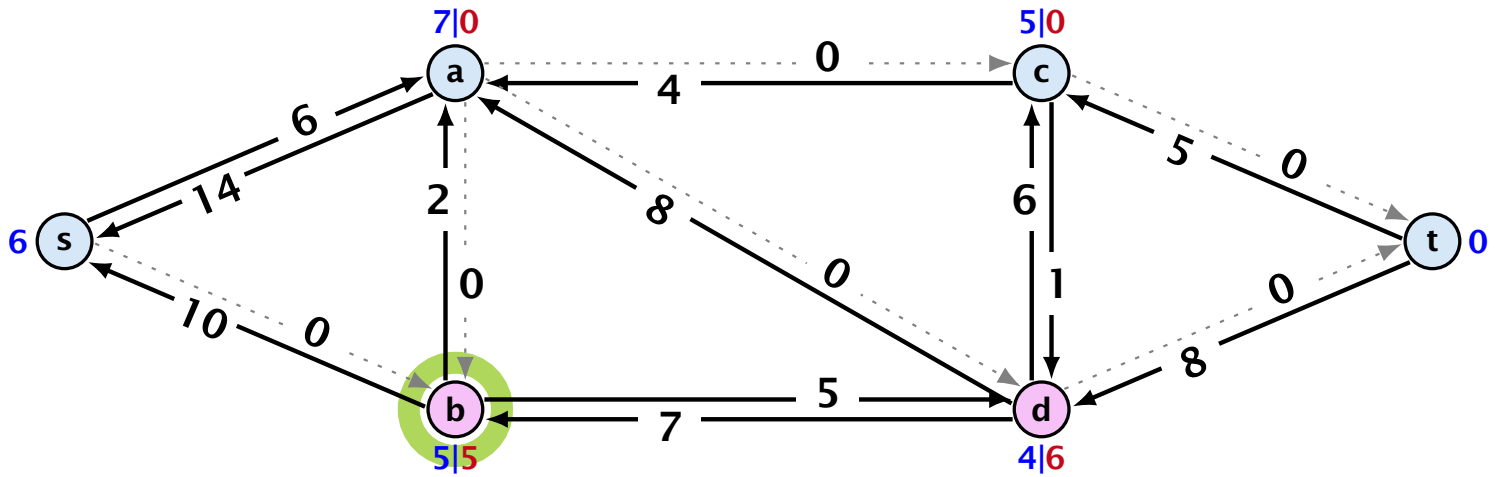

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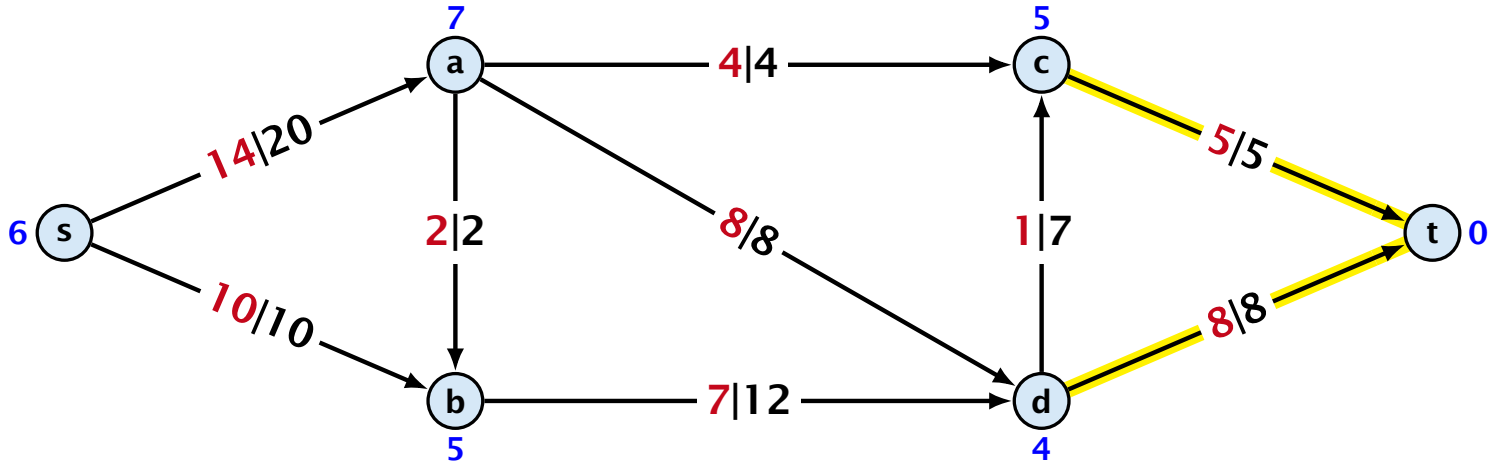
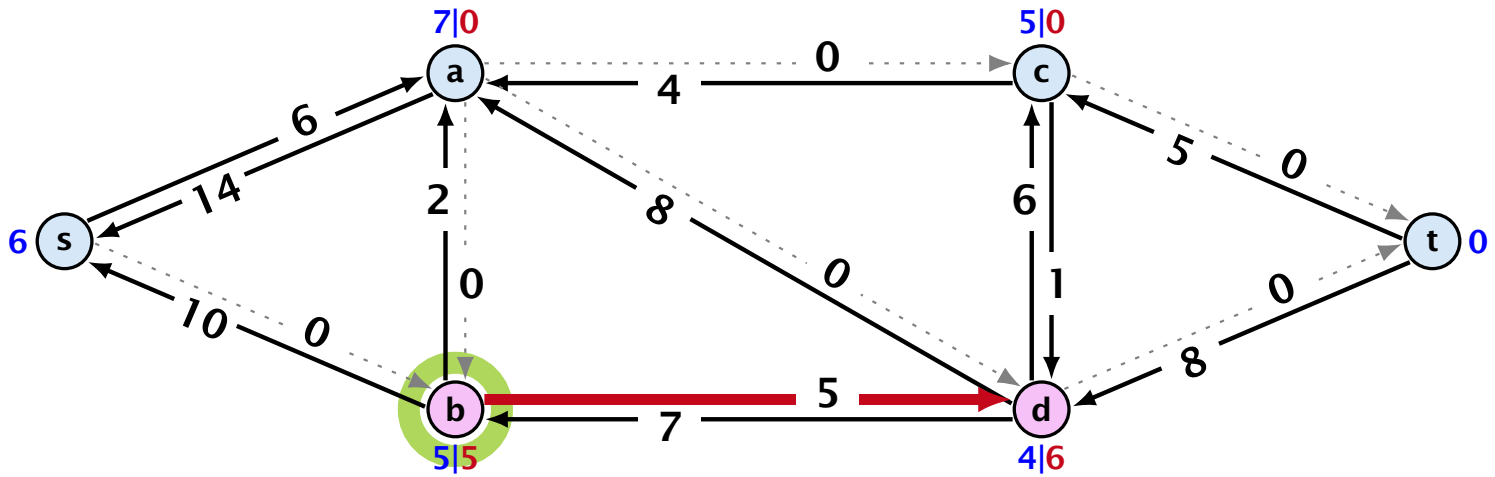


saturating and deactivating push



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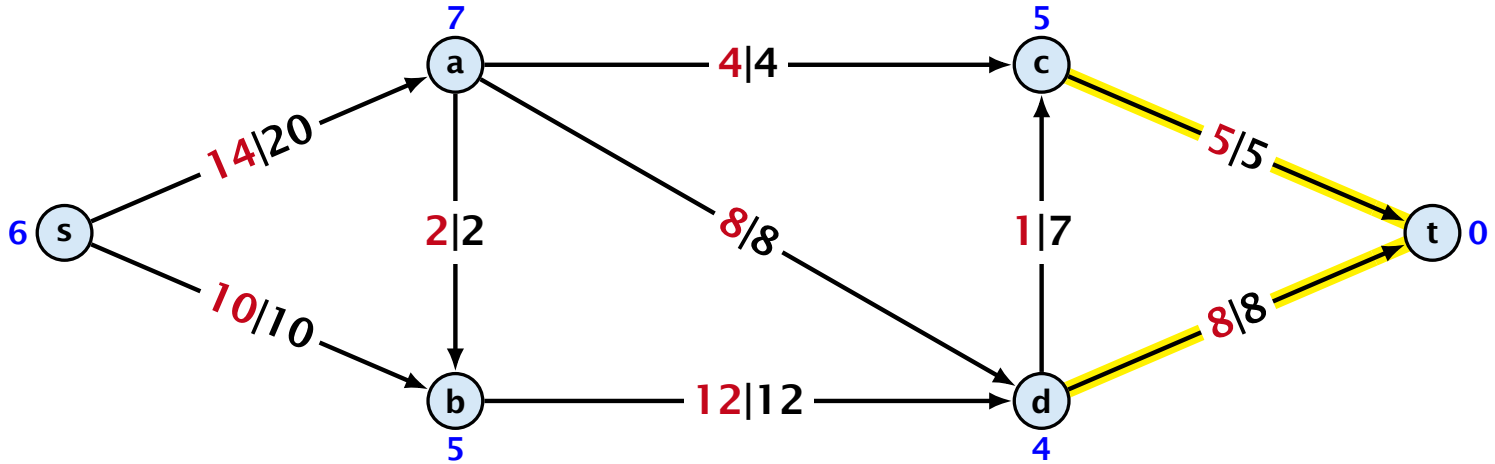

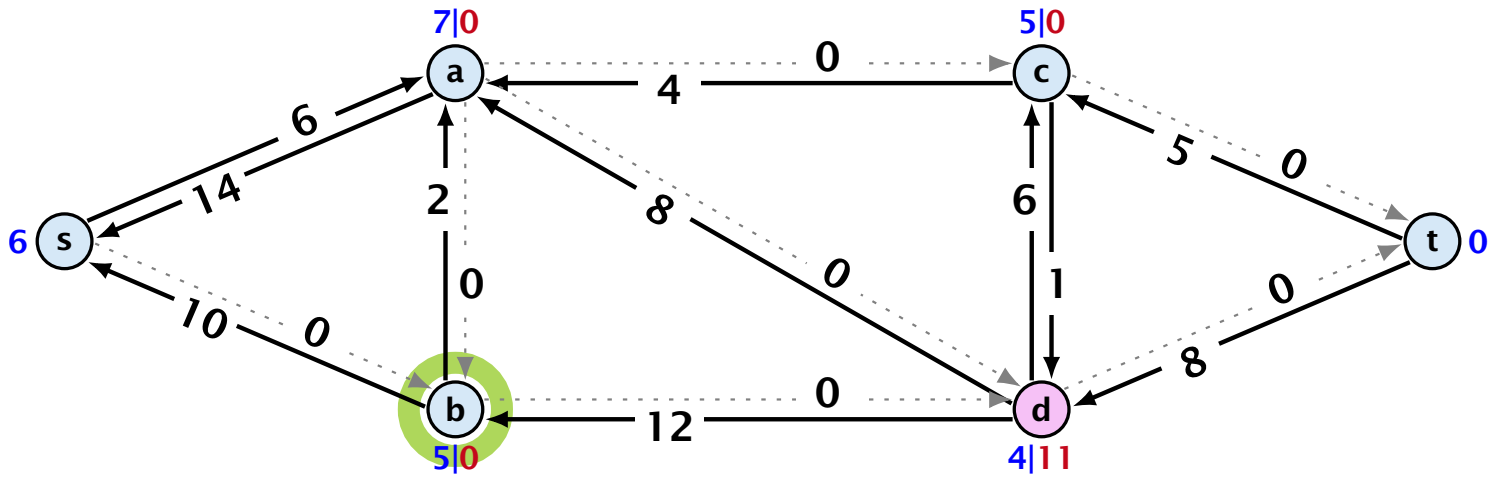

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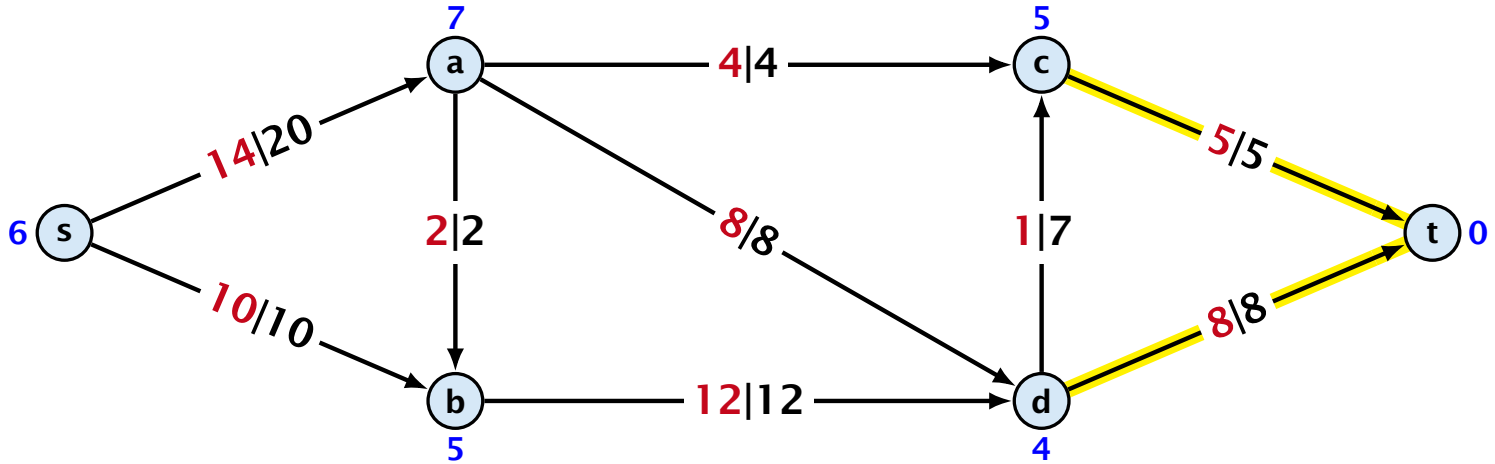

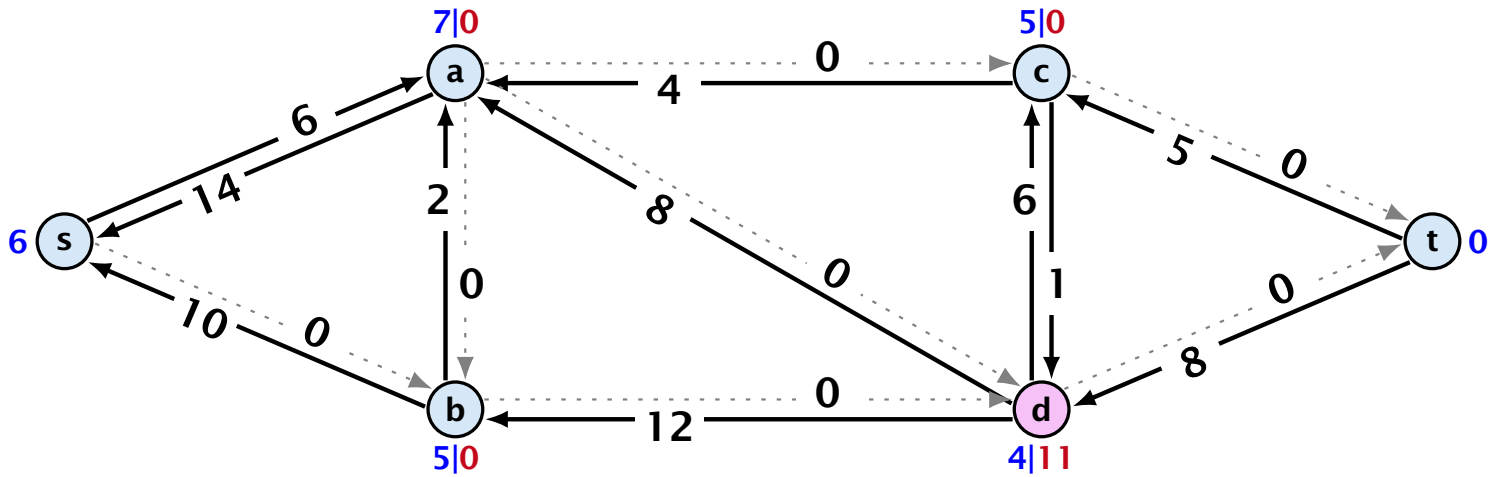

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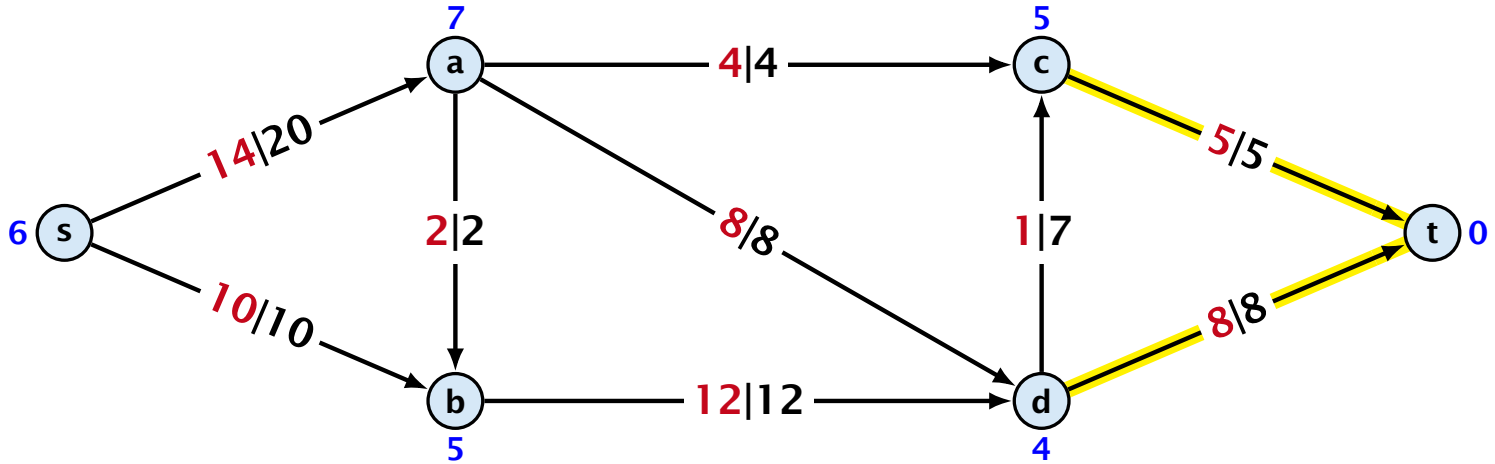

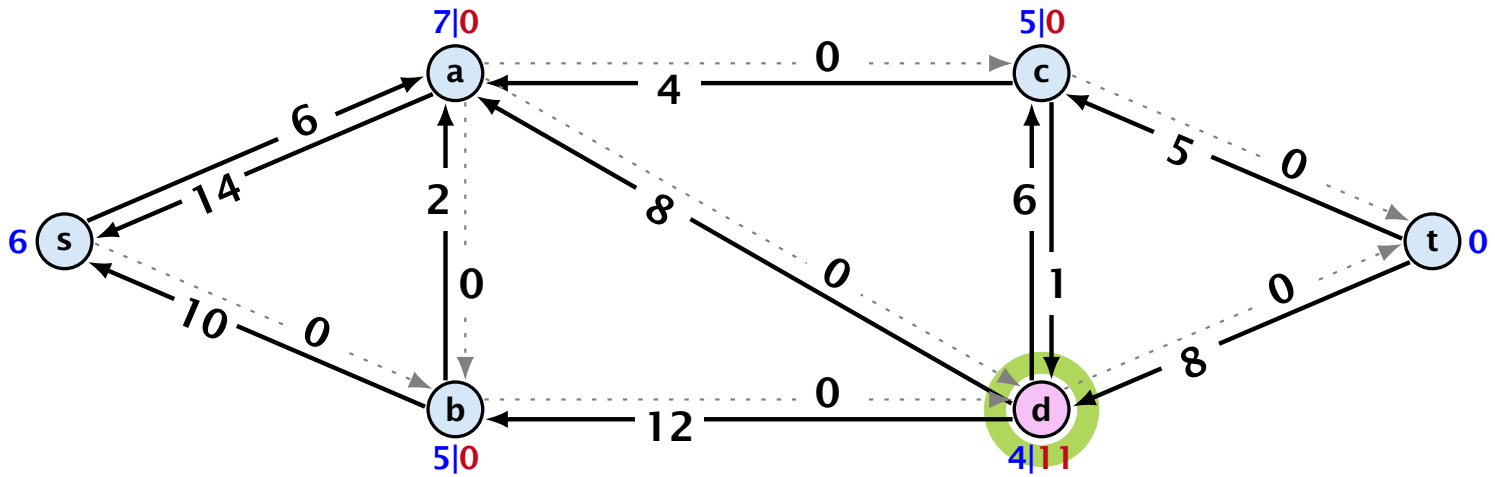

Preflow Push

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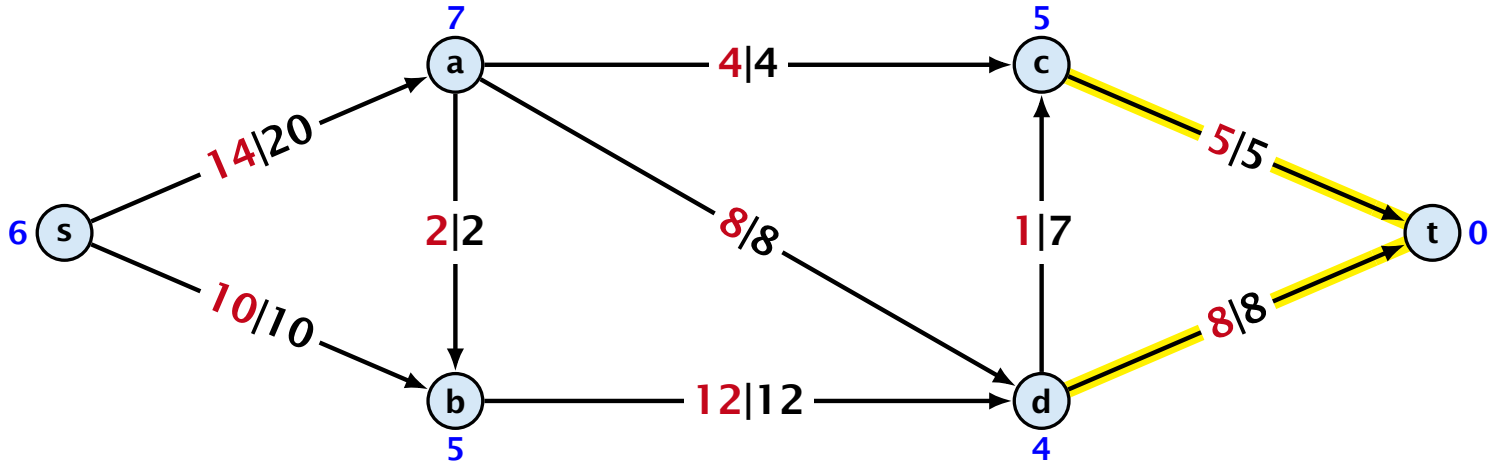
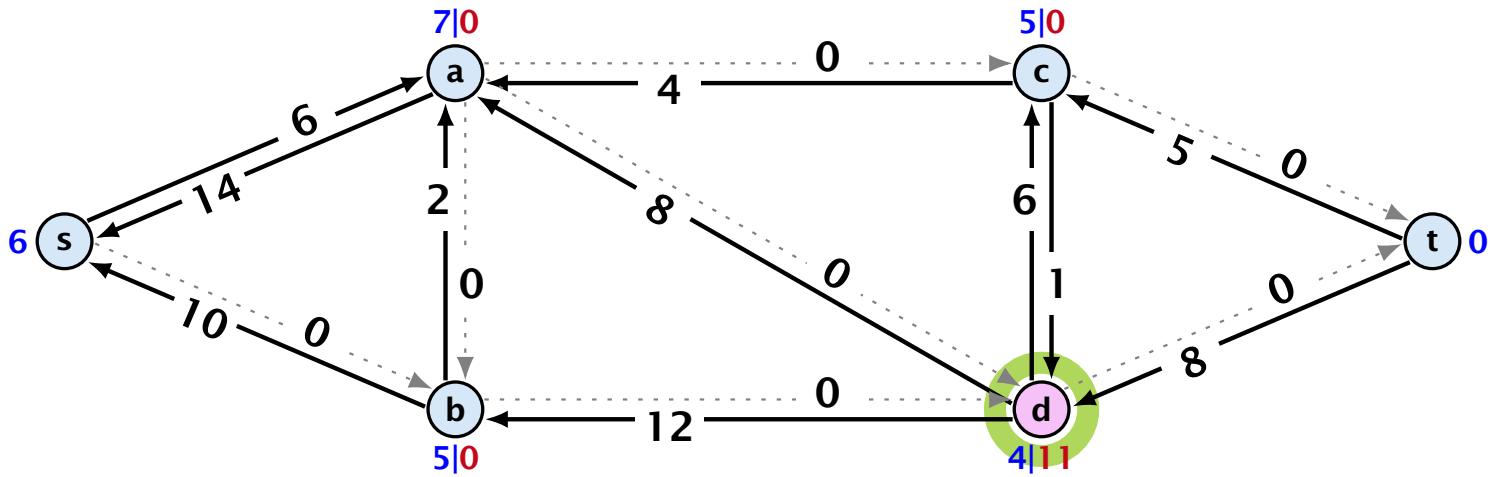


relabel to 6



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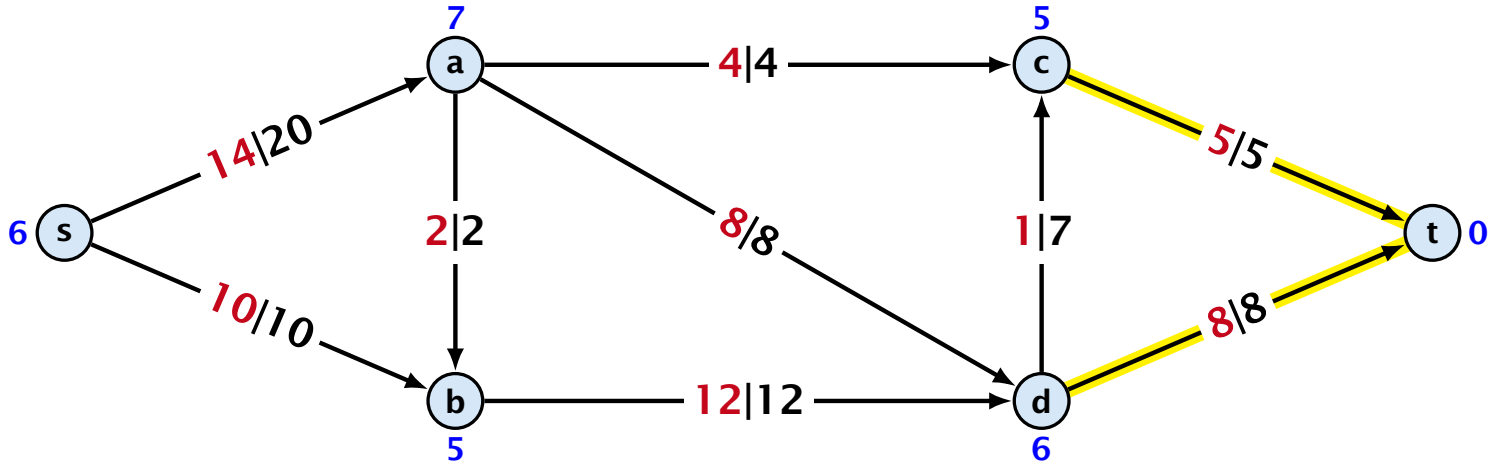

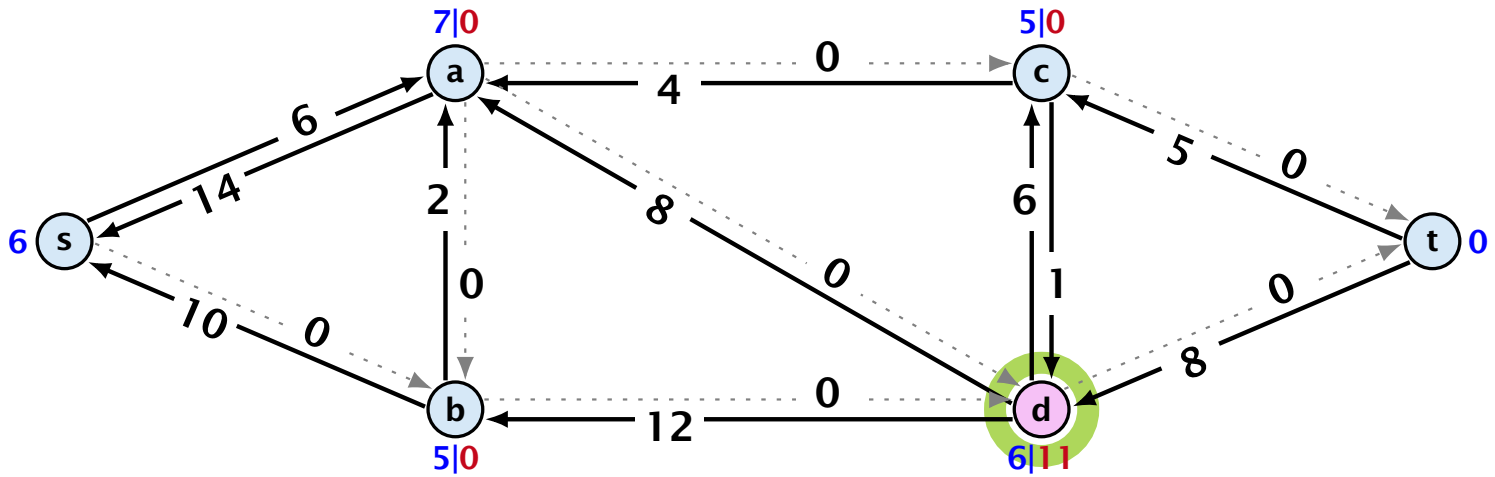

Preflow Push

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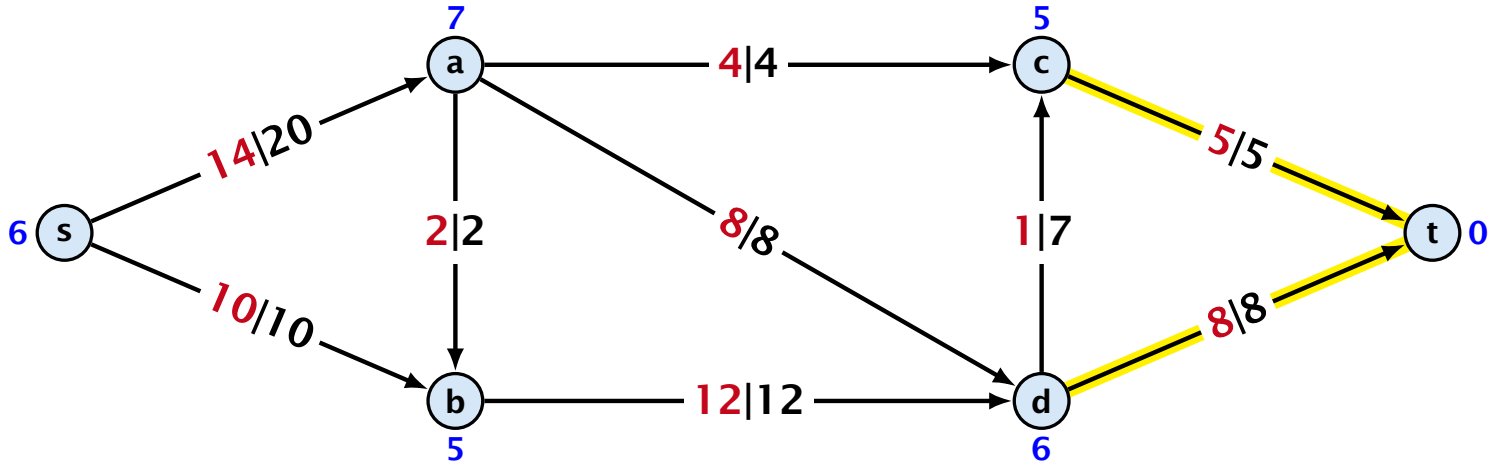
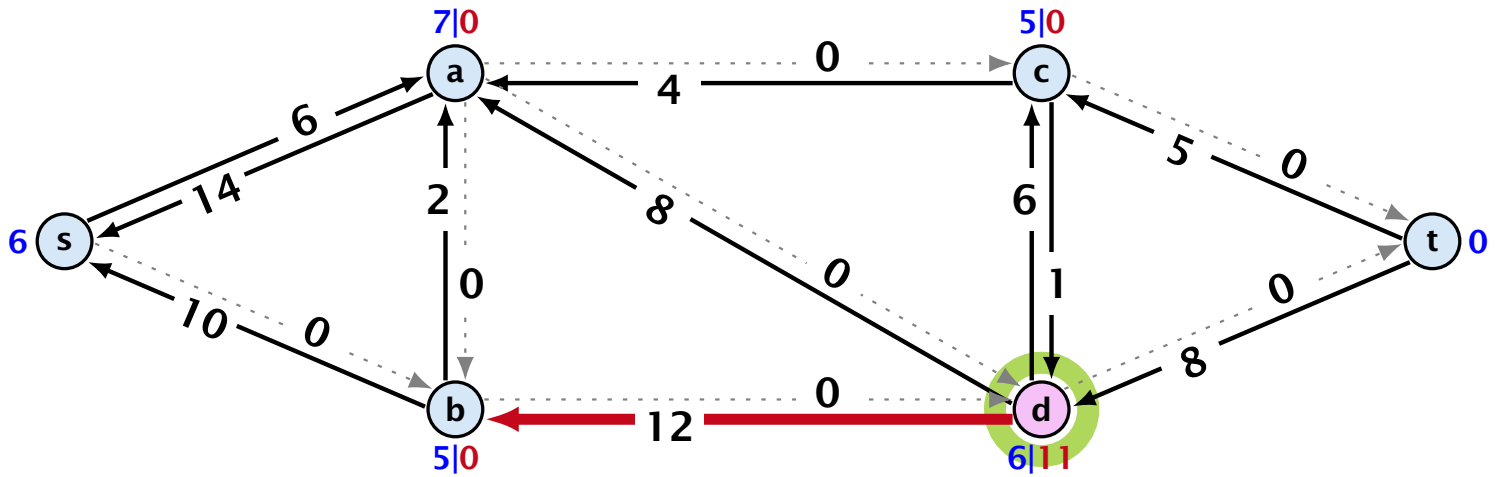


deactivating push



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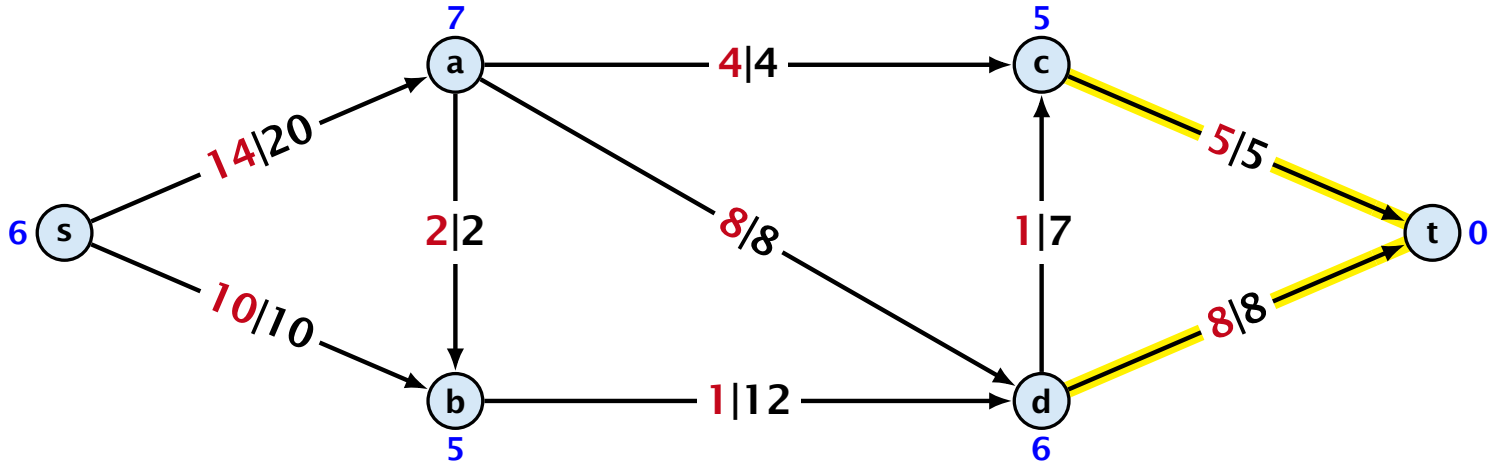

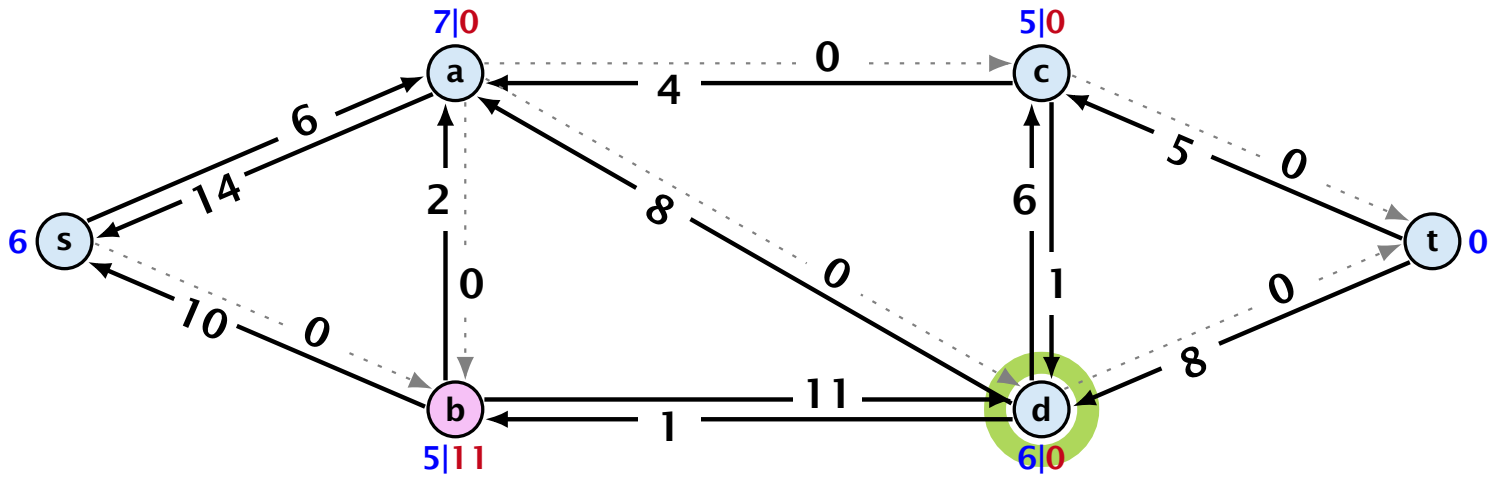

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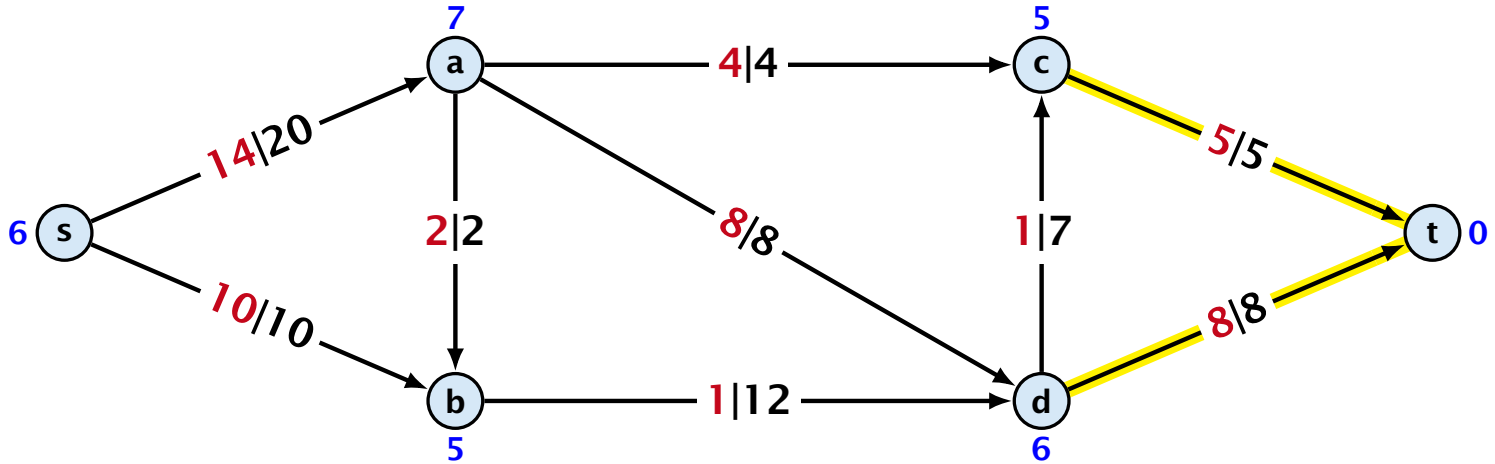

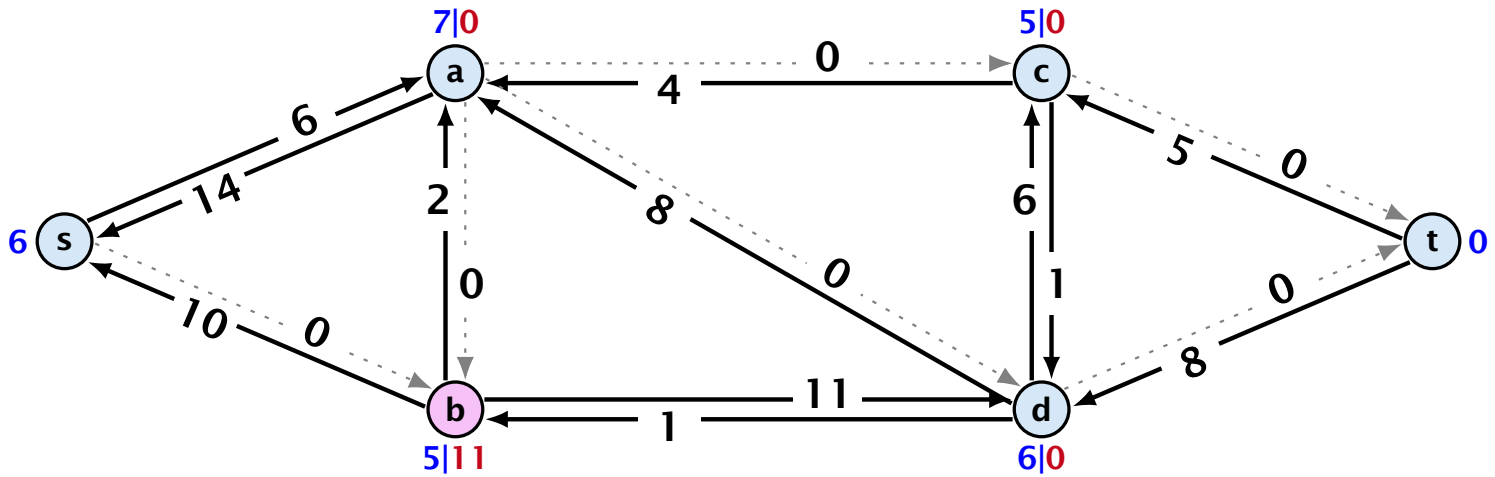

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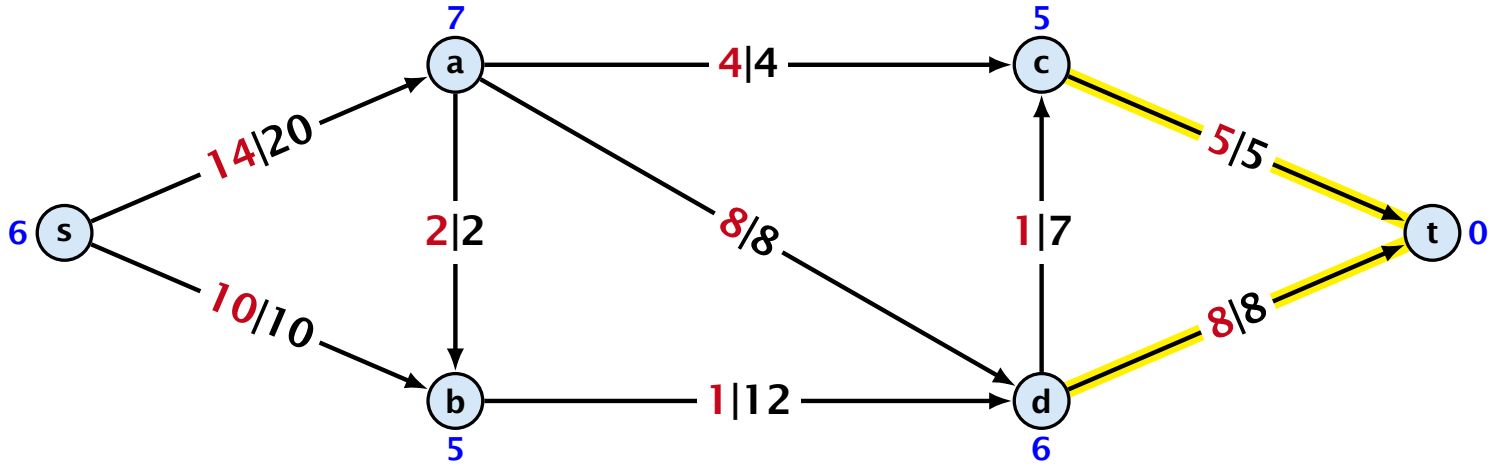

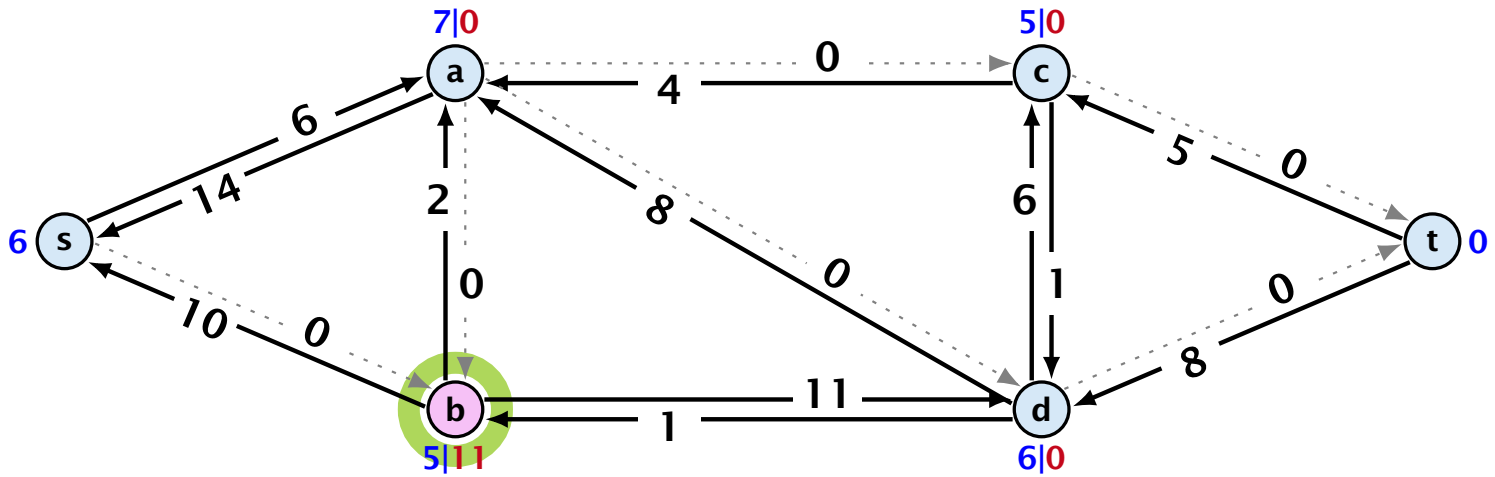

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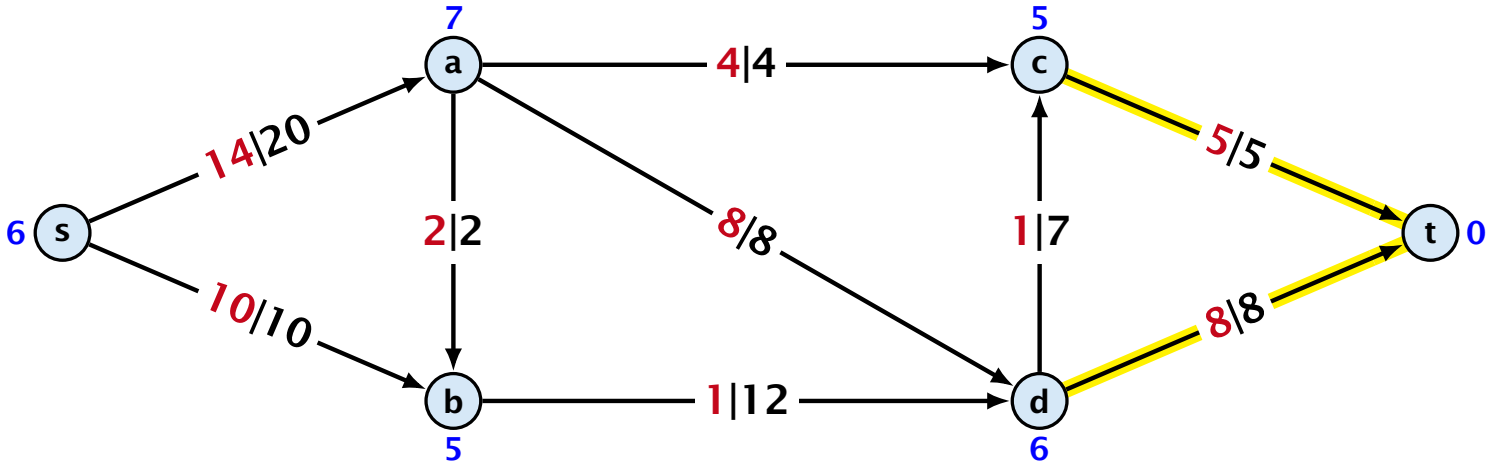
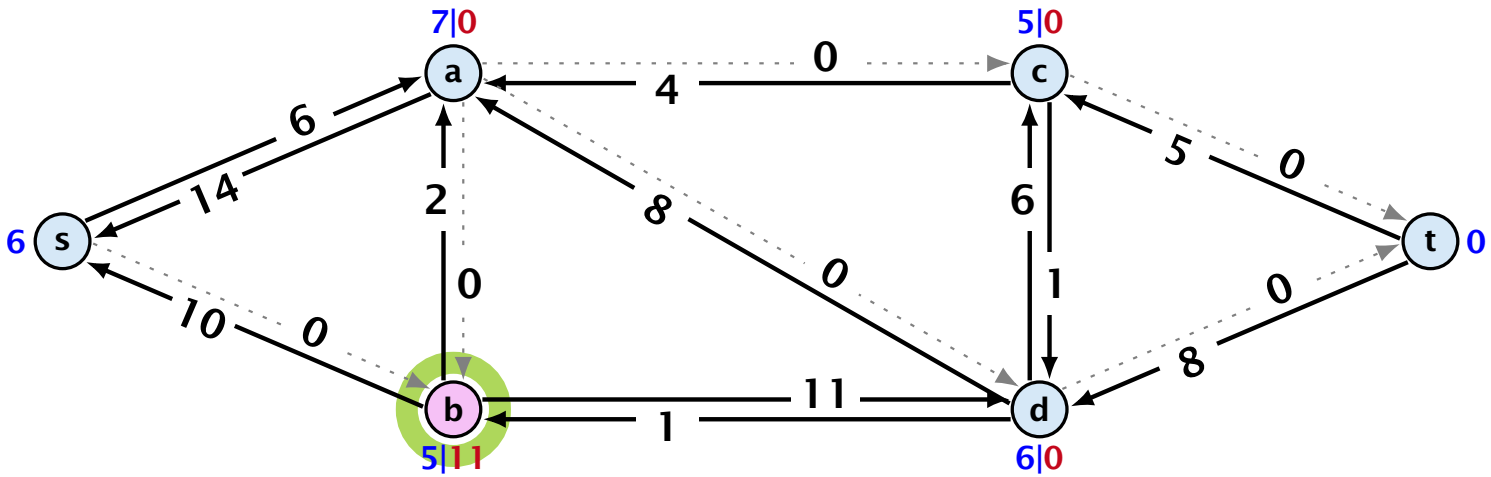


relabel to 7



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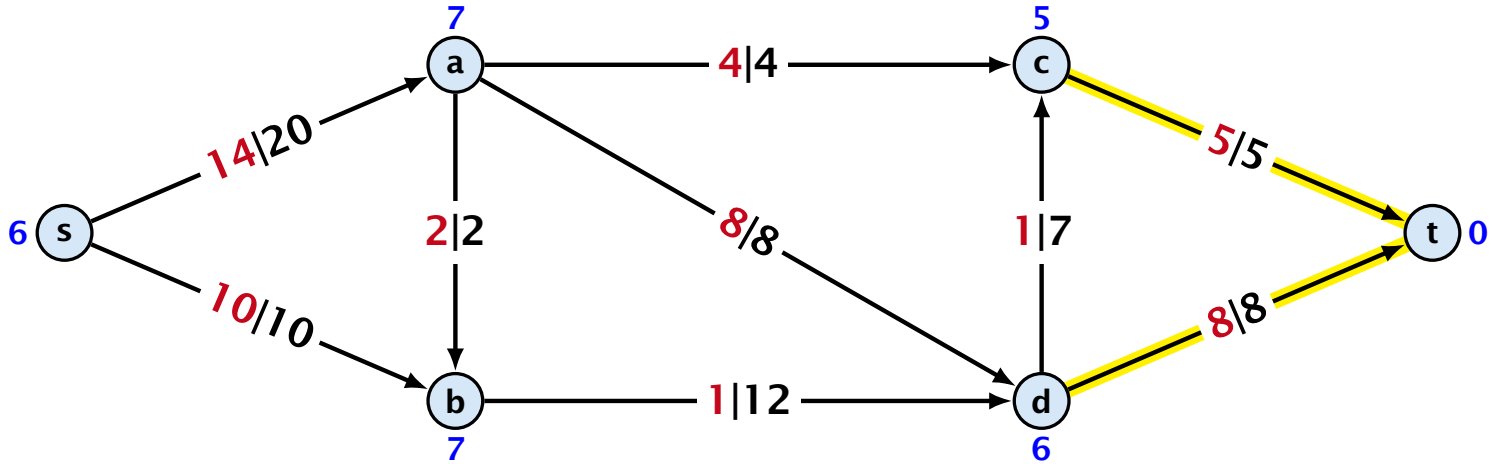

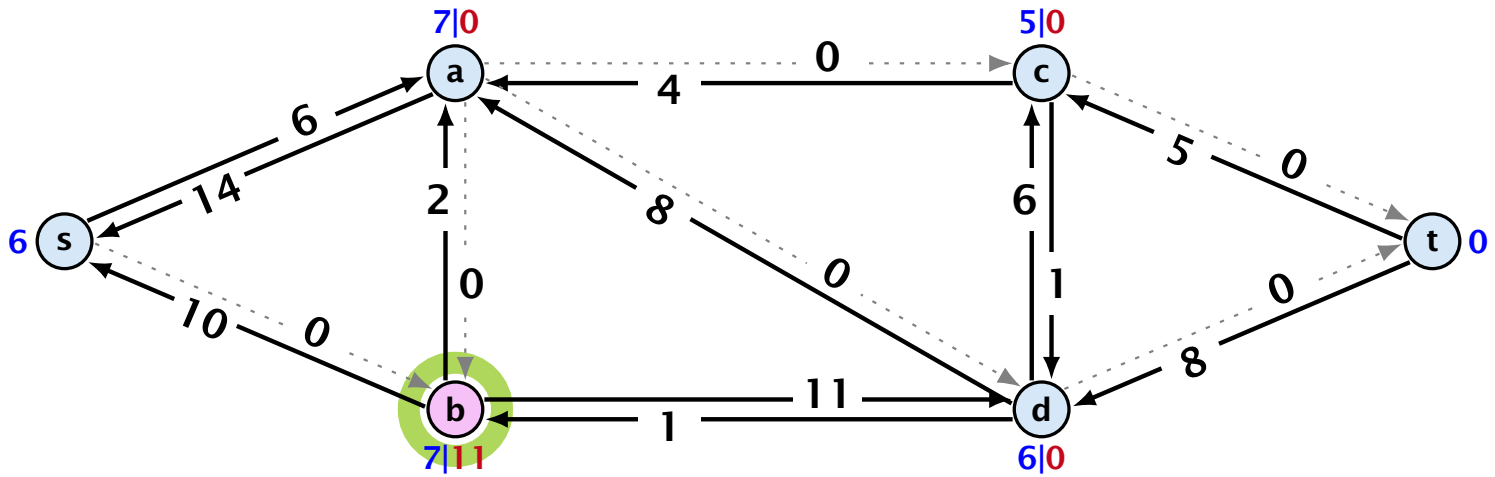

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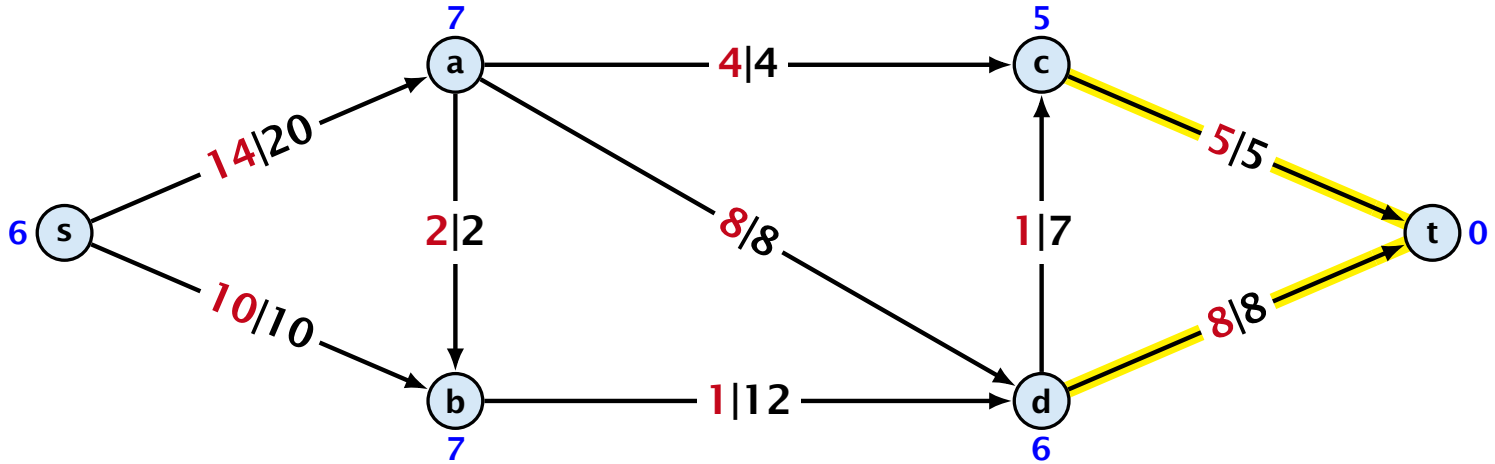
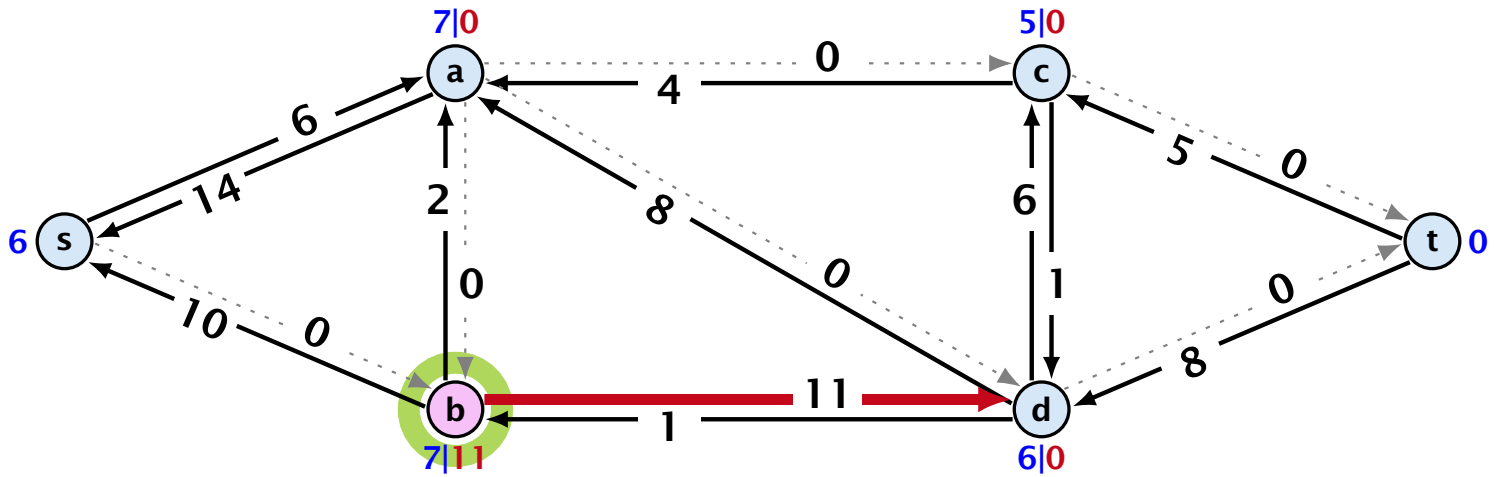


saturating and deactivating push



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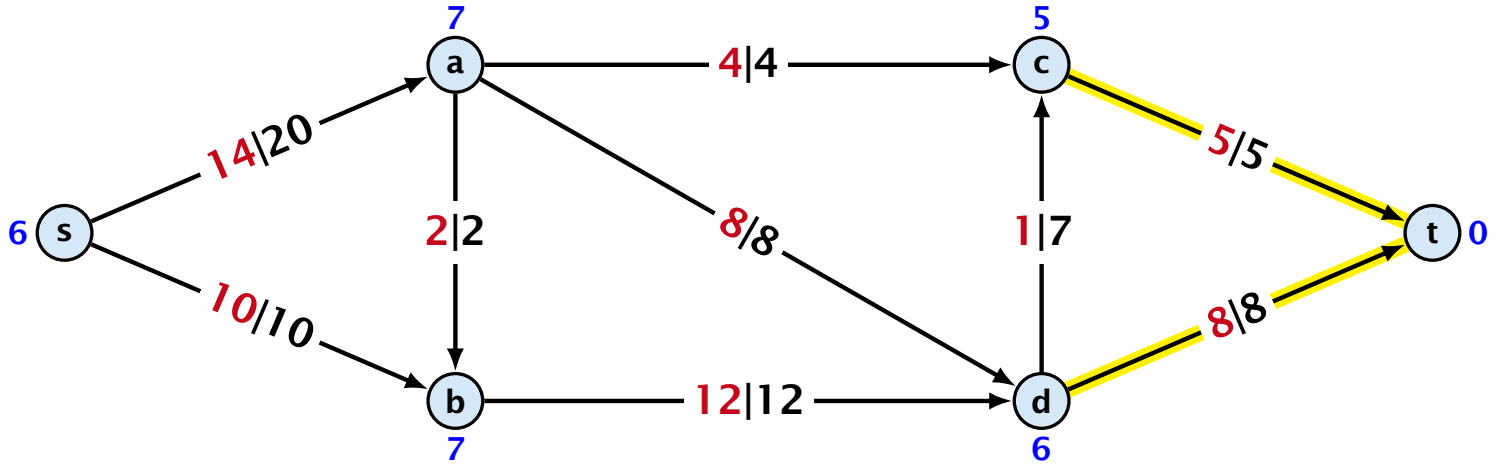

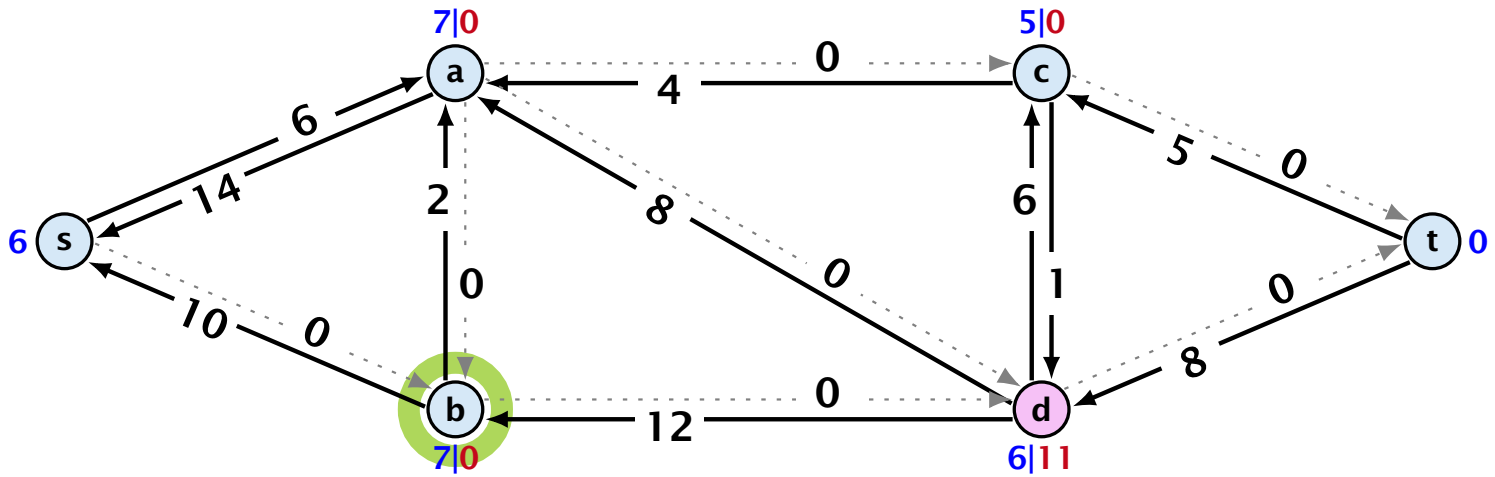

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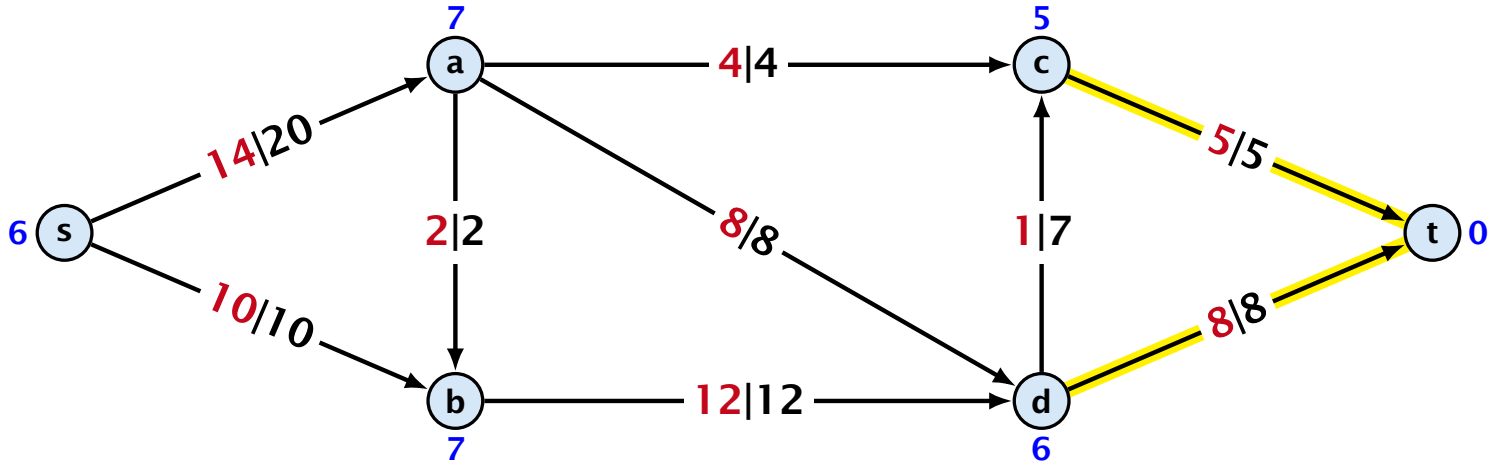

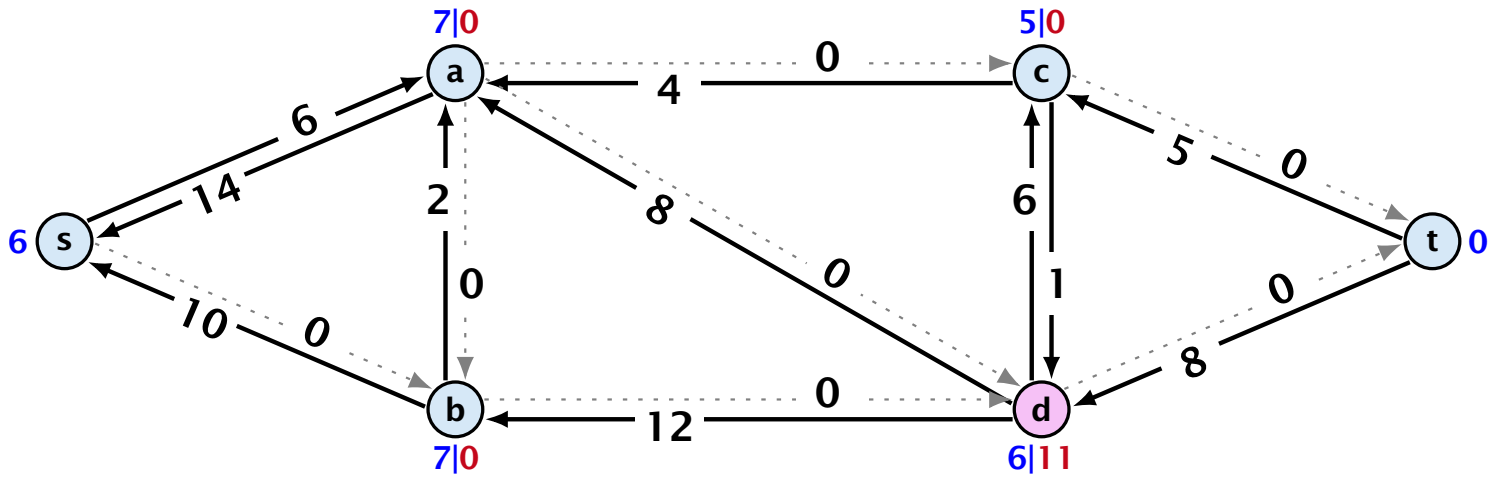

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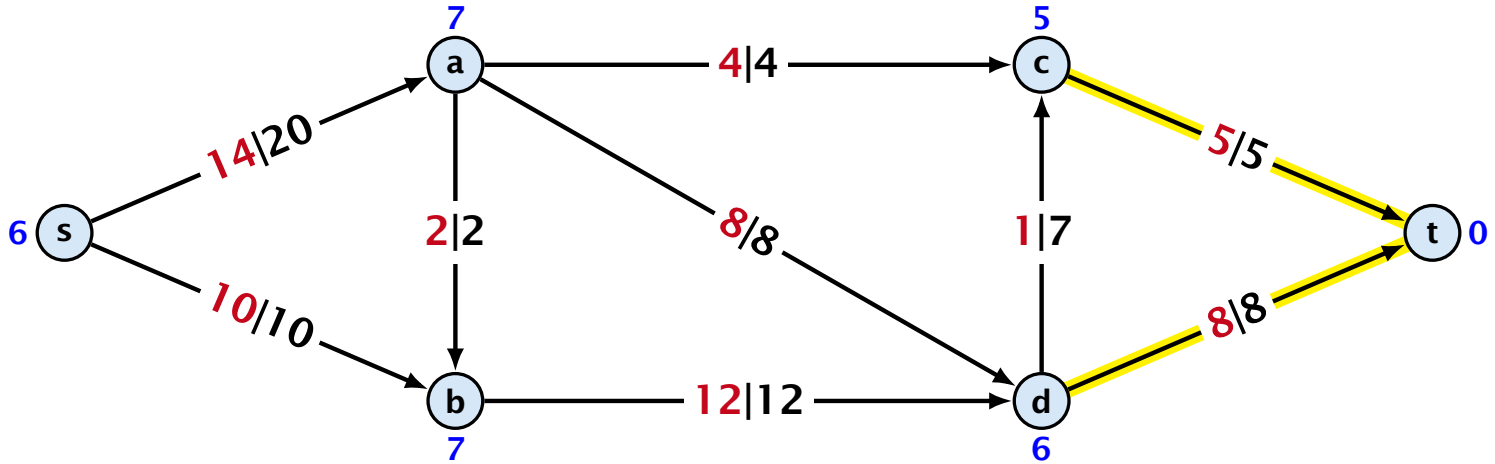

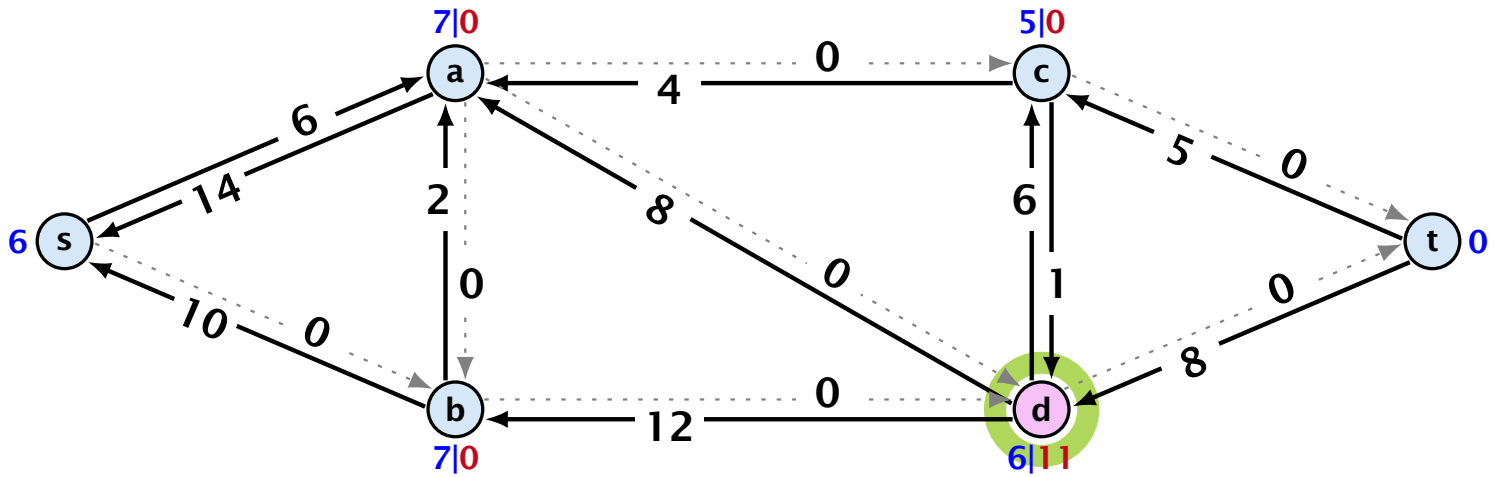

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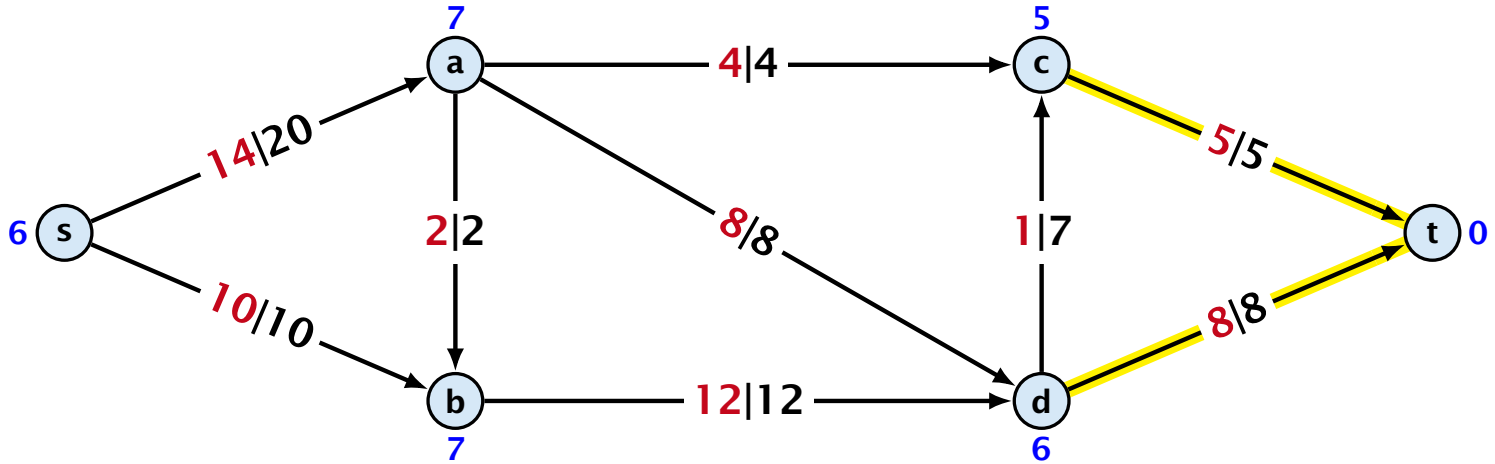
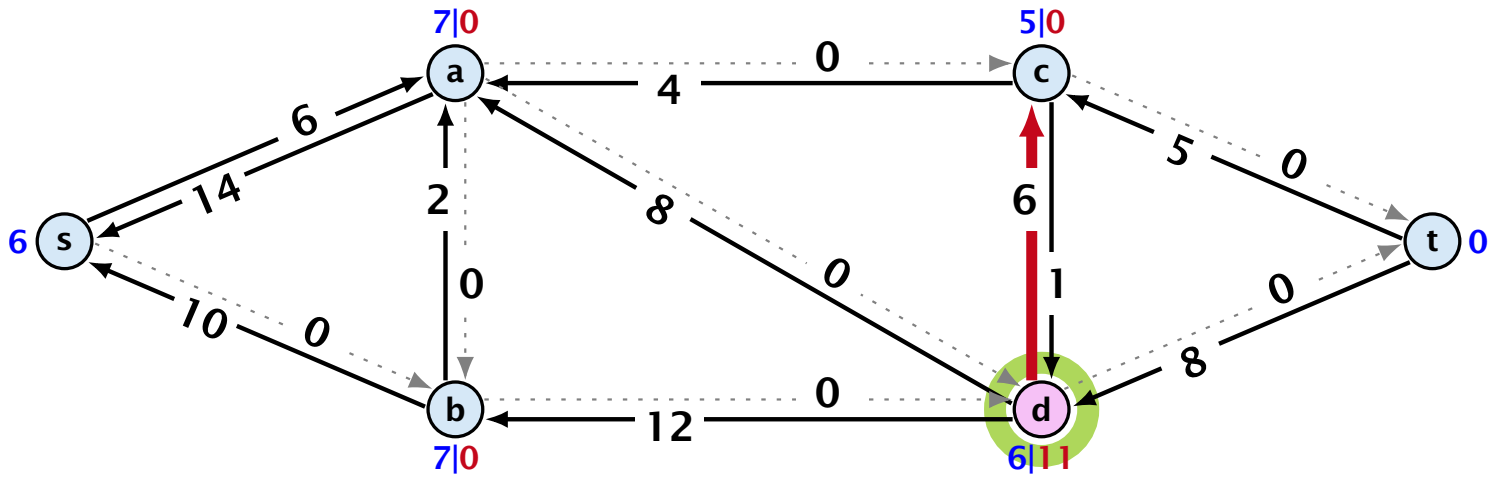


saturating push



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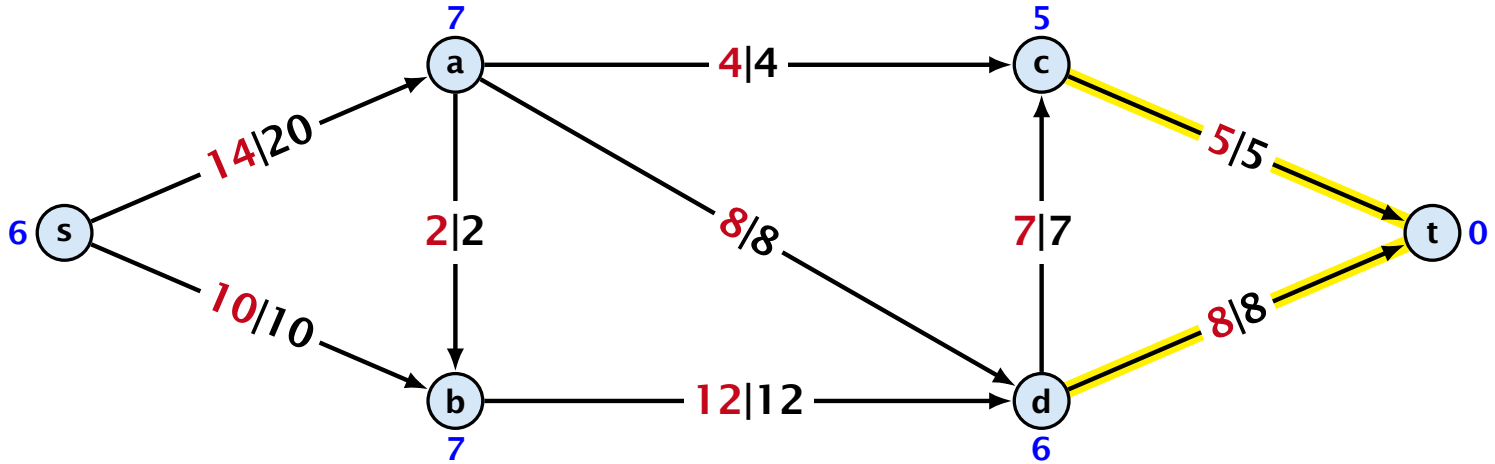

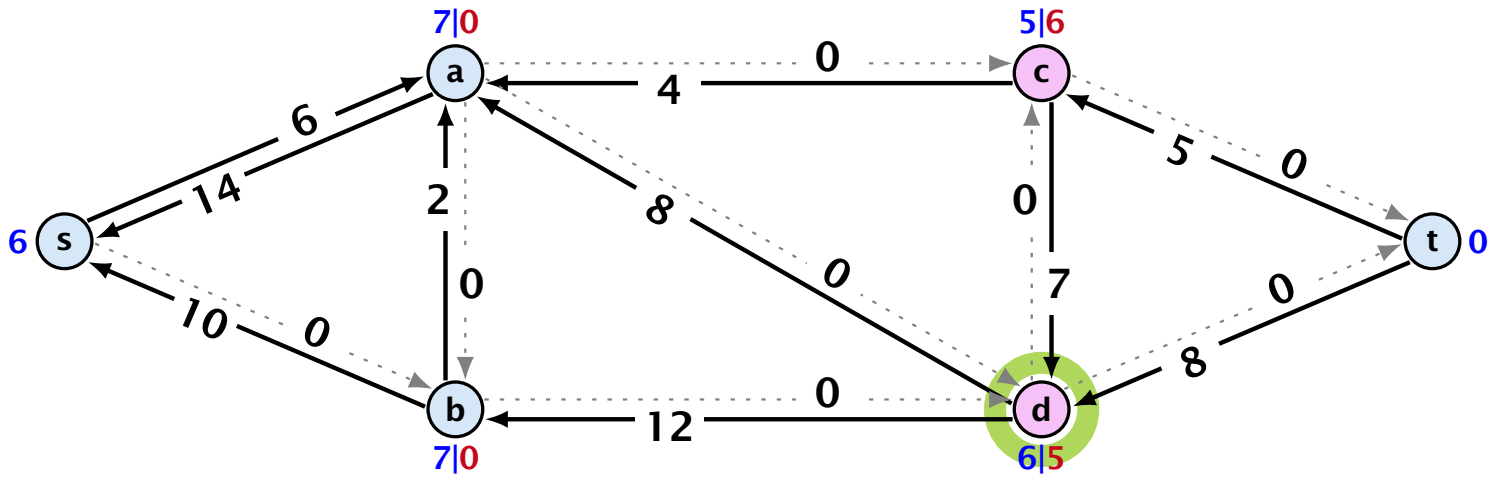

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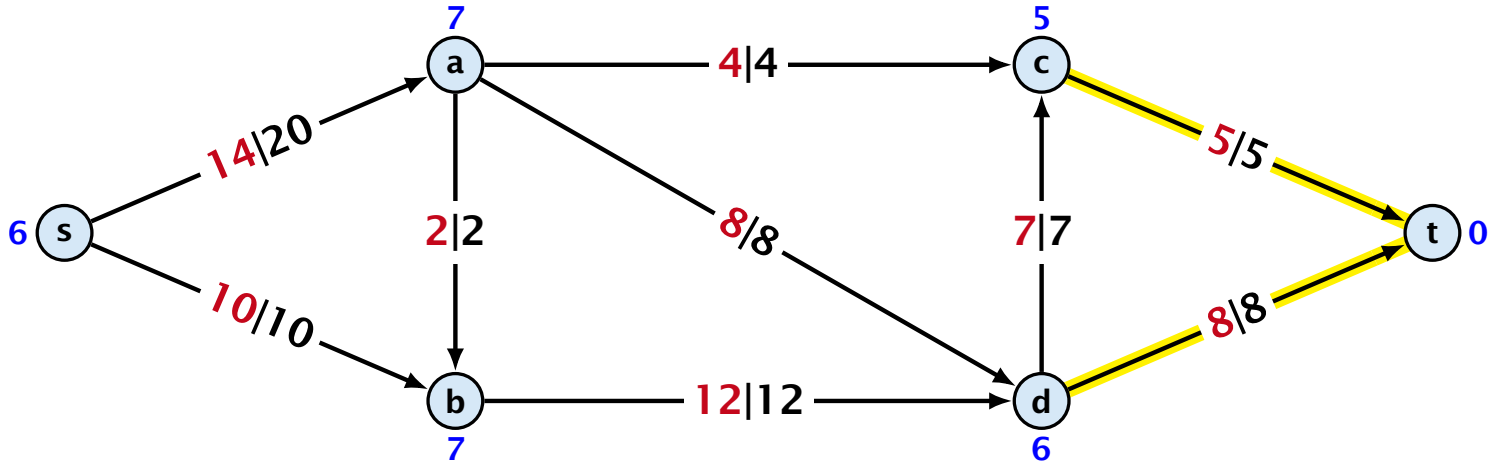
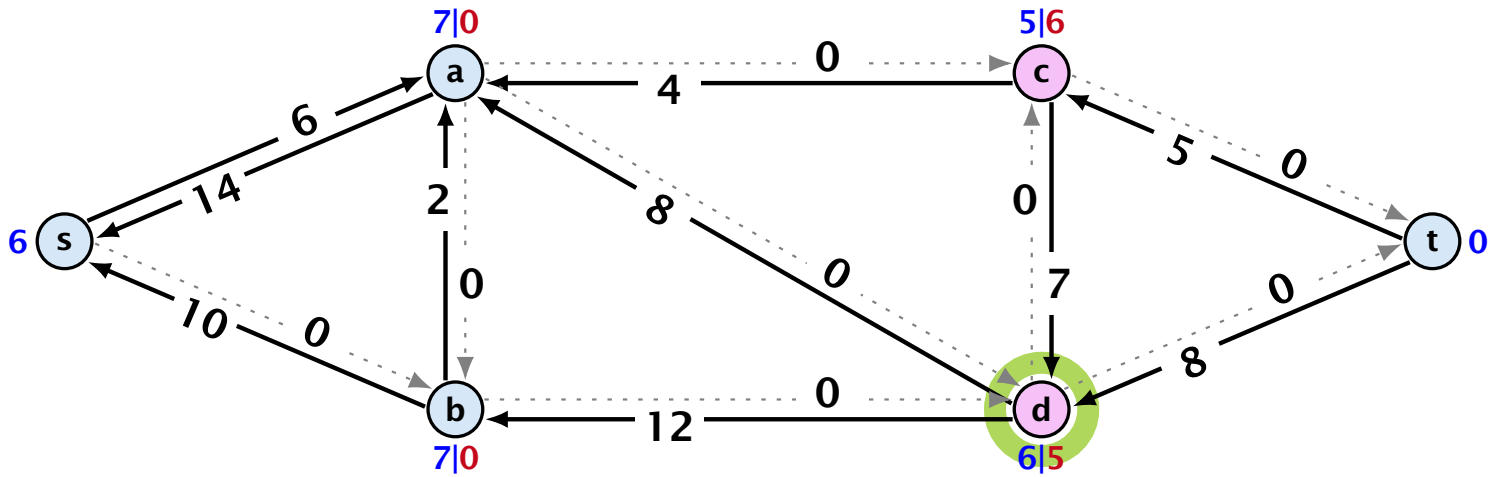


relabel to 8



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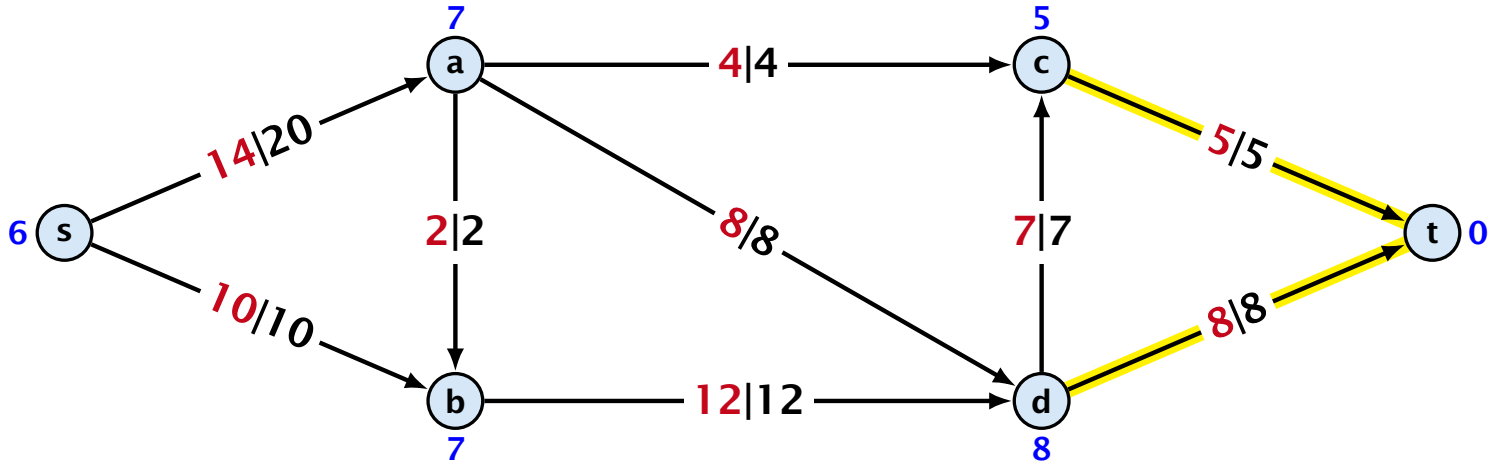

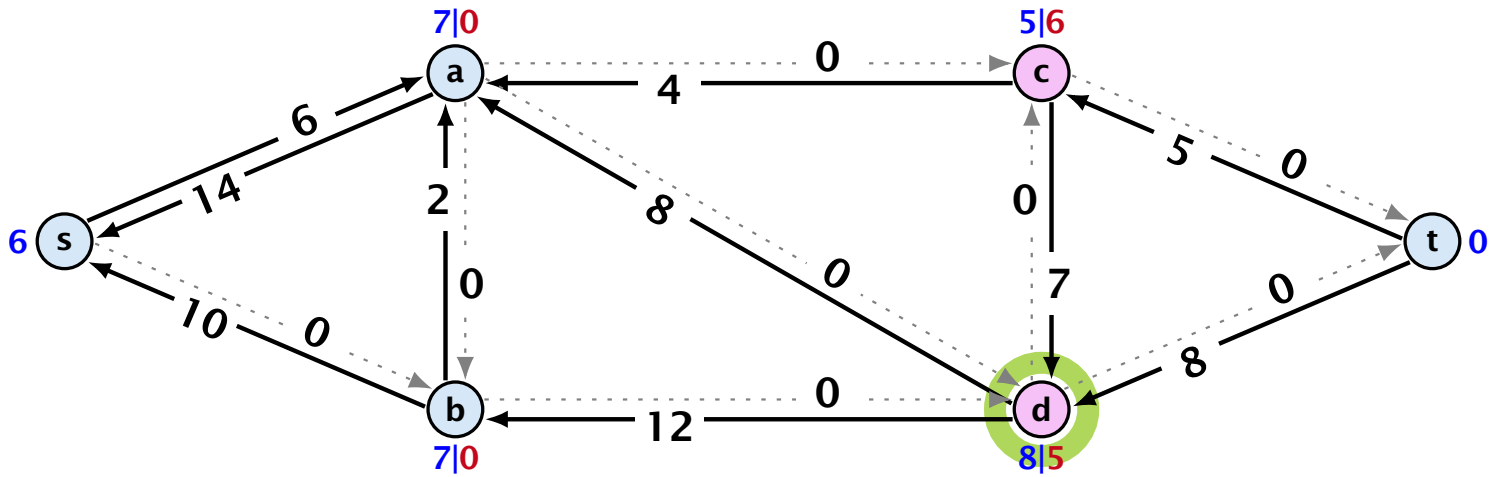

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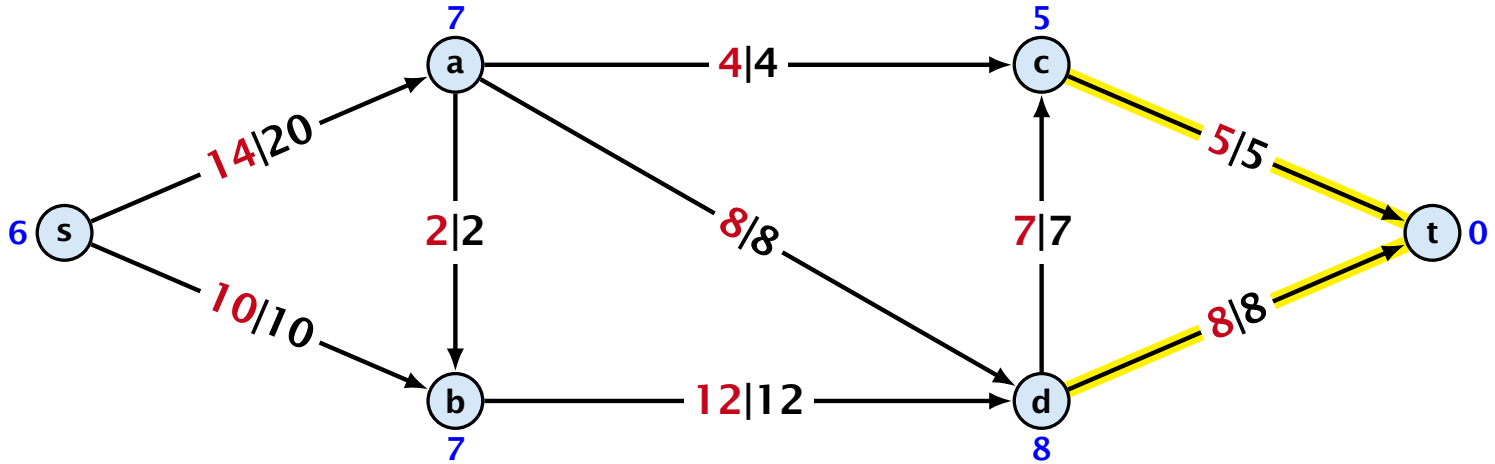
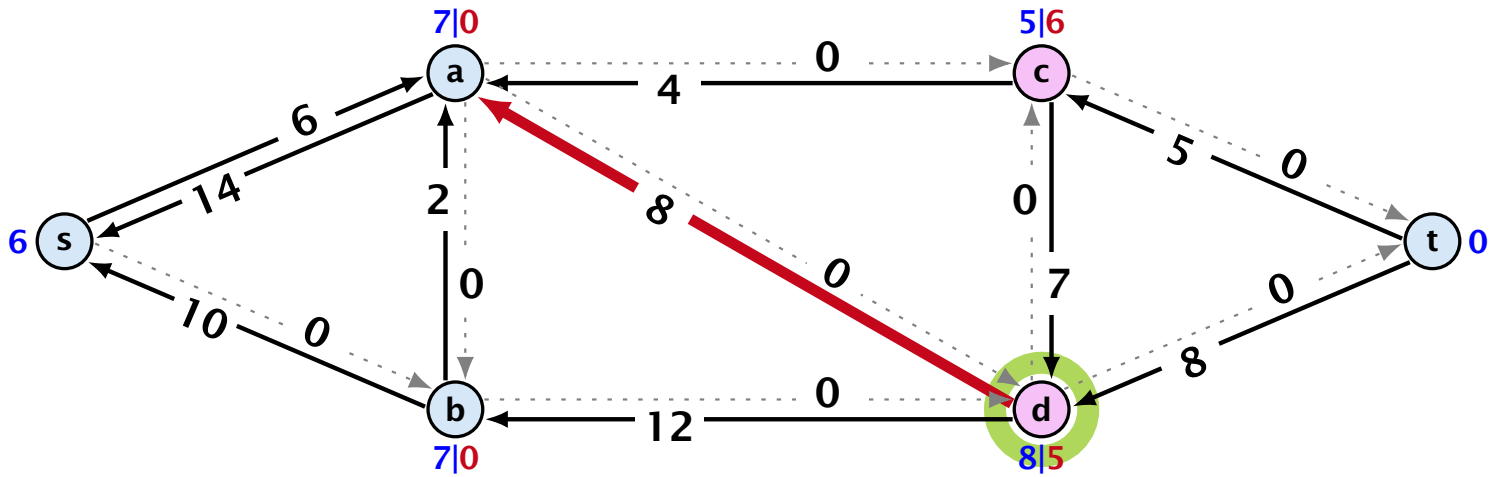


deactivating push



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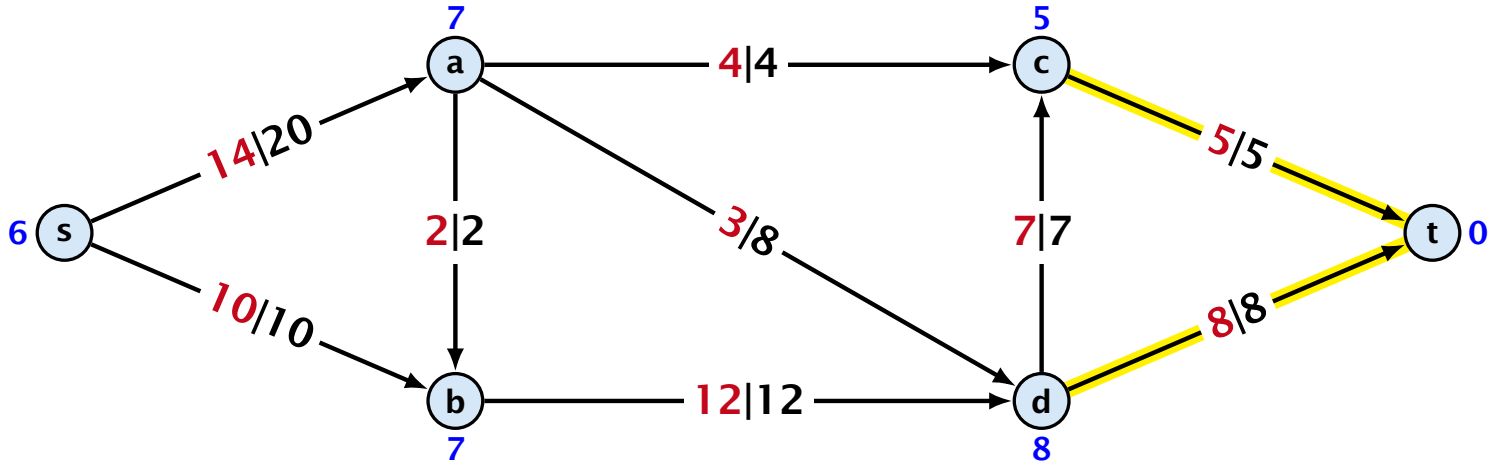

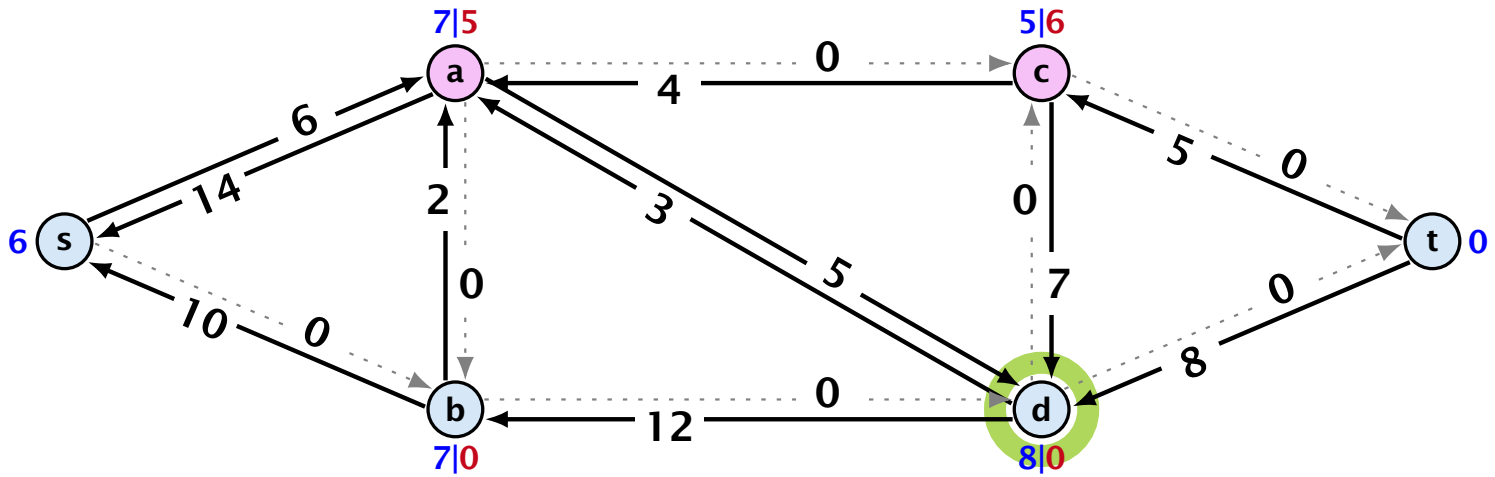

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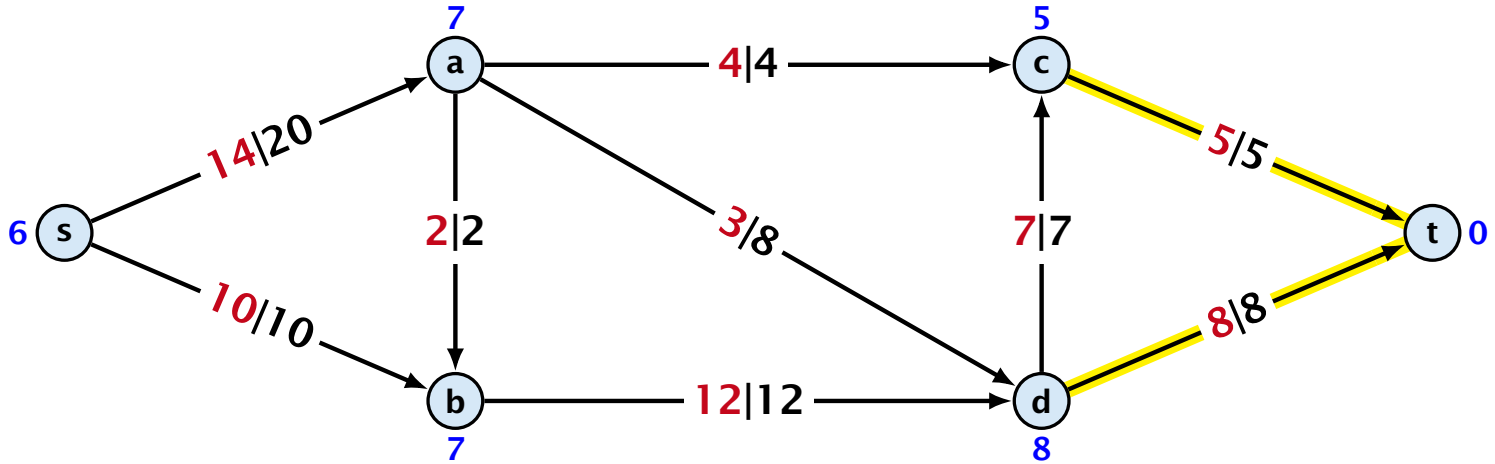

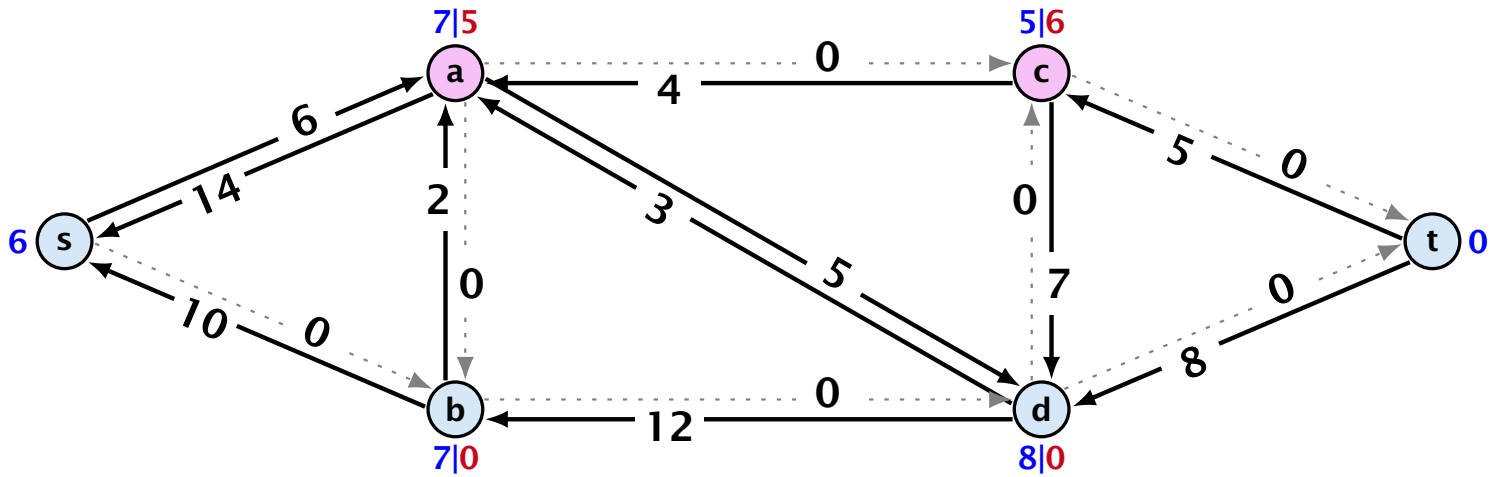

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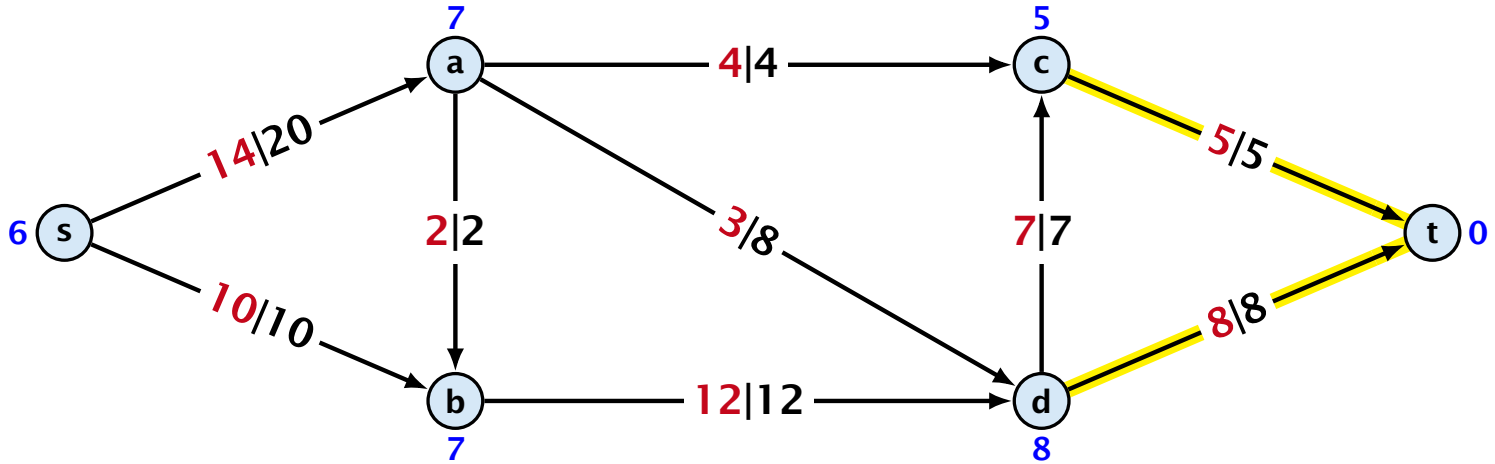

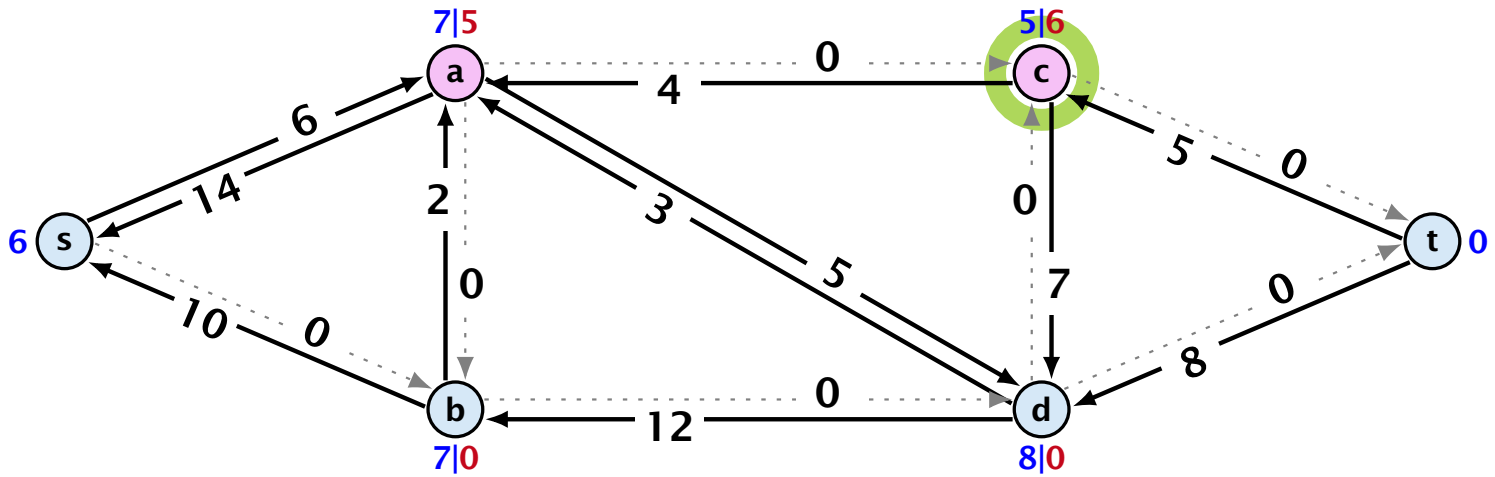

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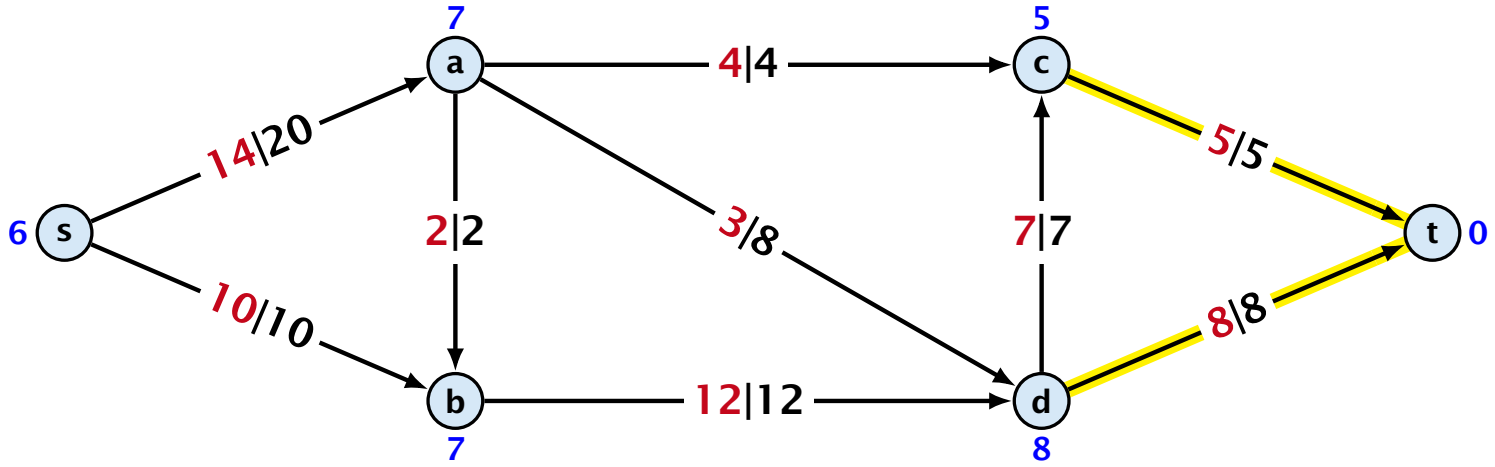

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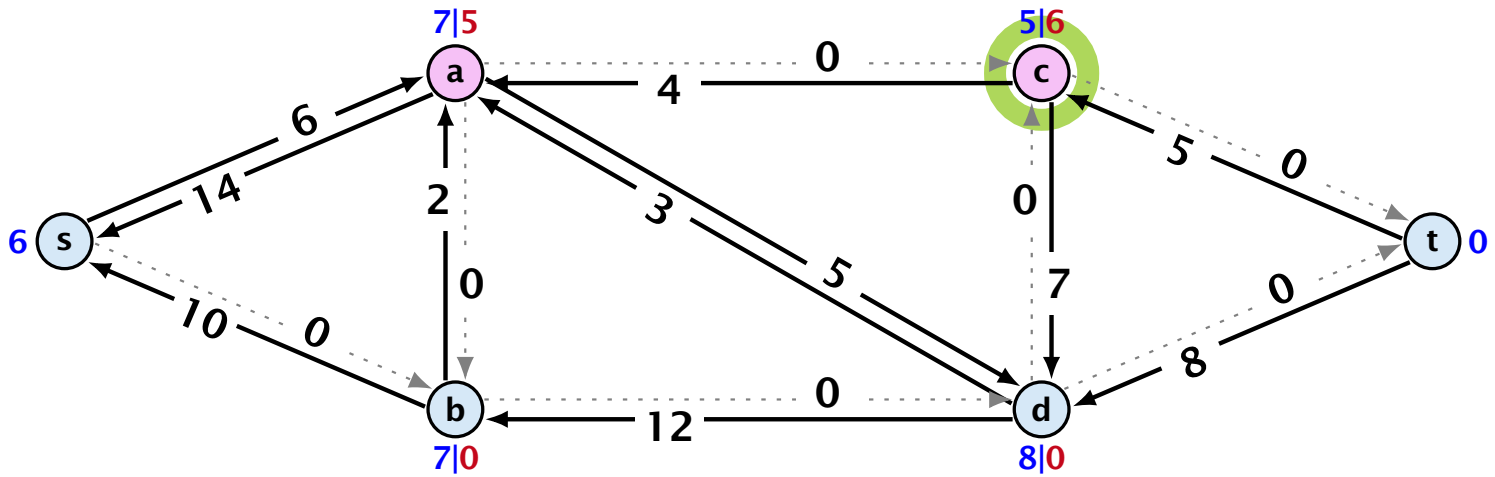

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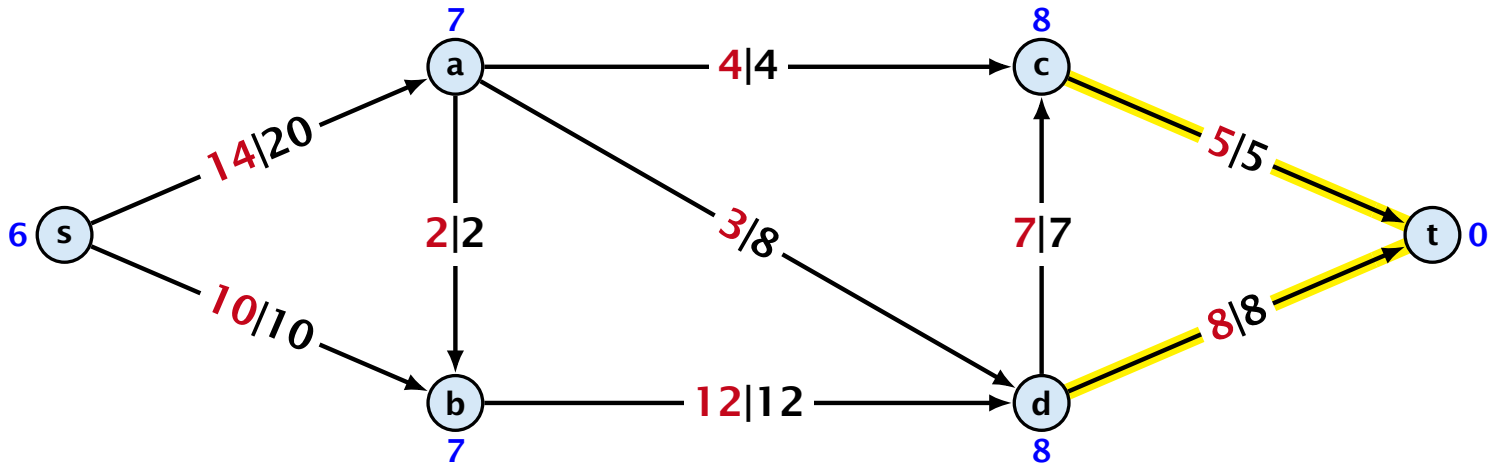

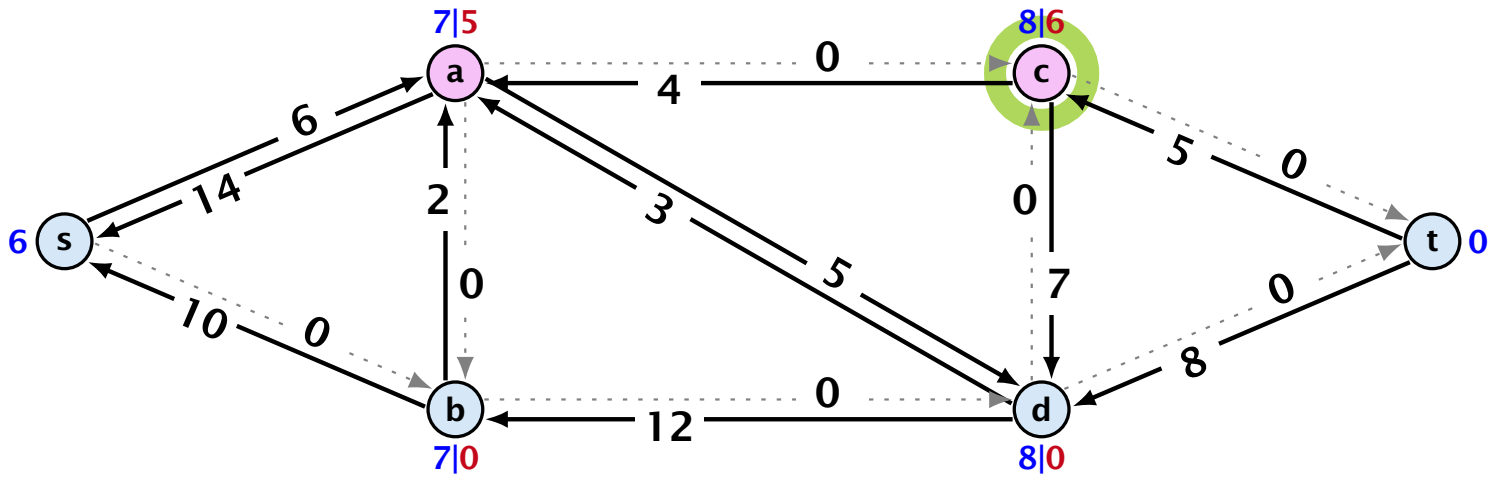

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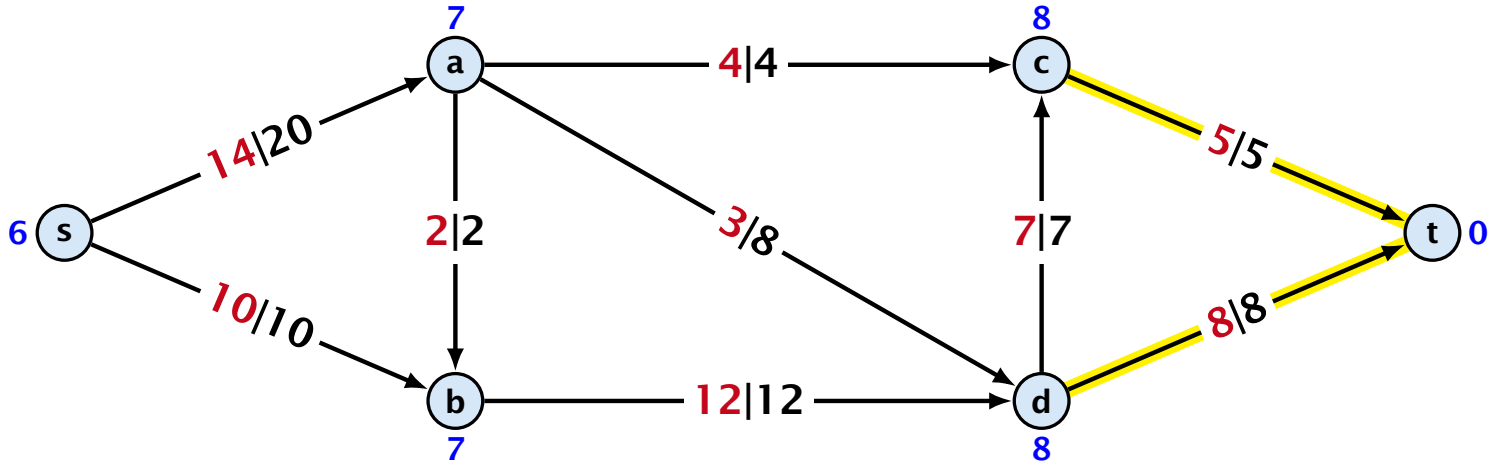
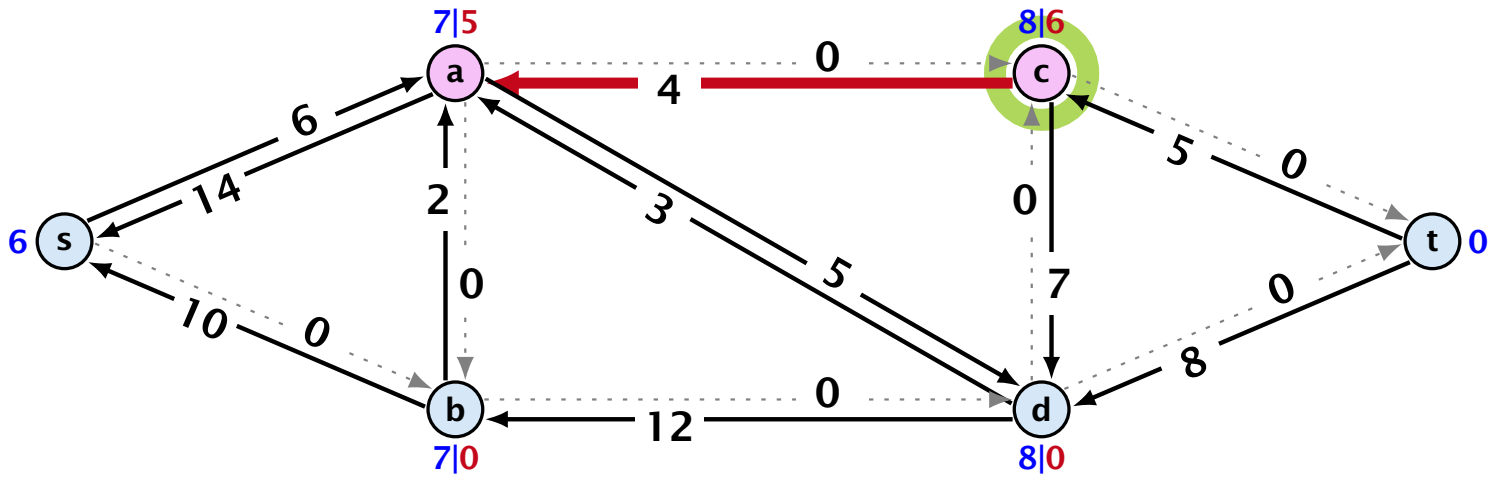


saturating push



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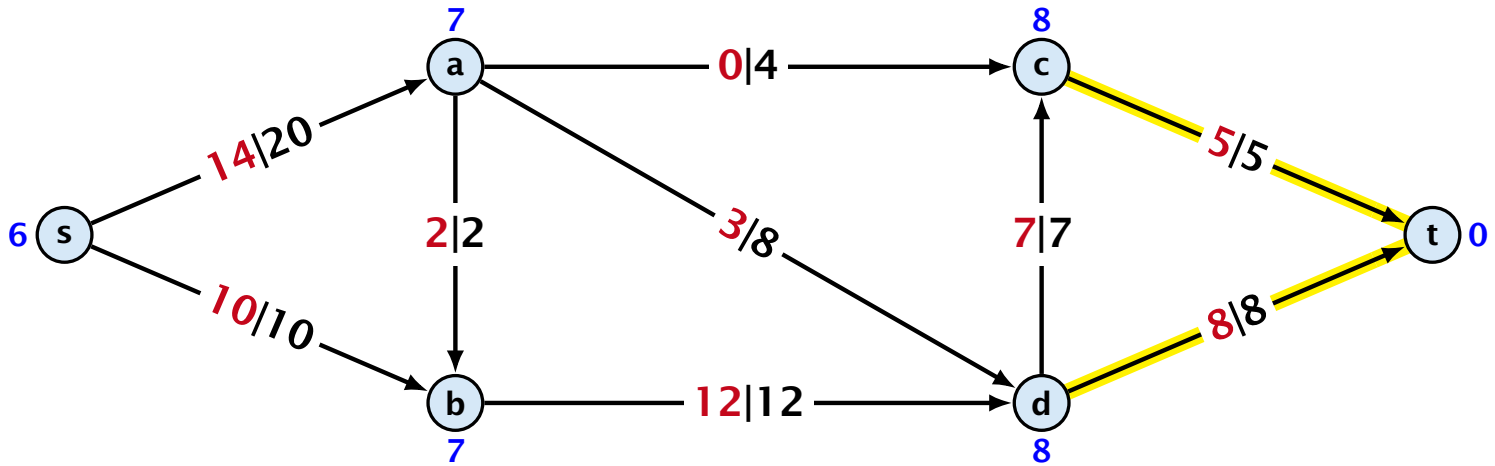

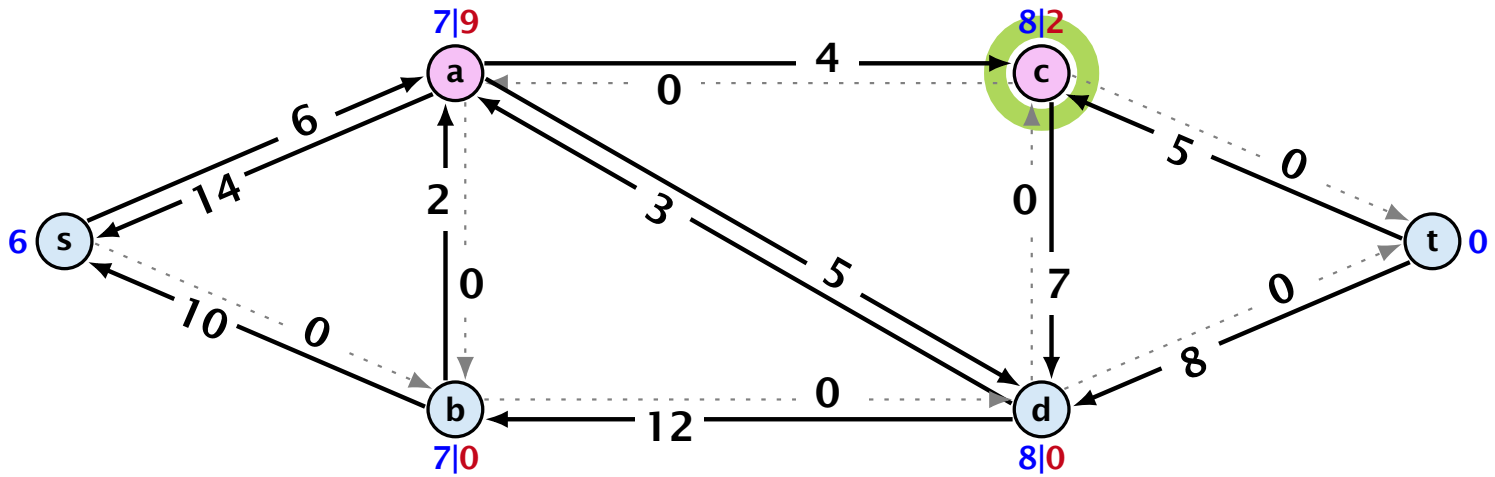

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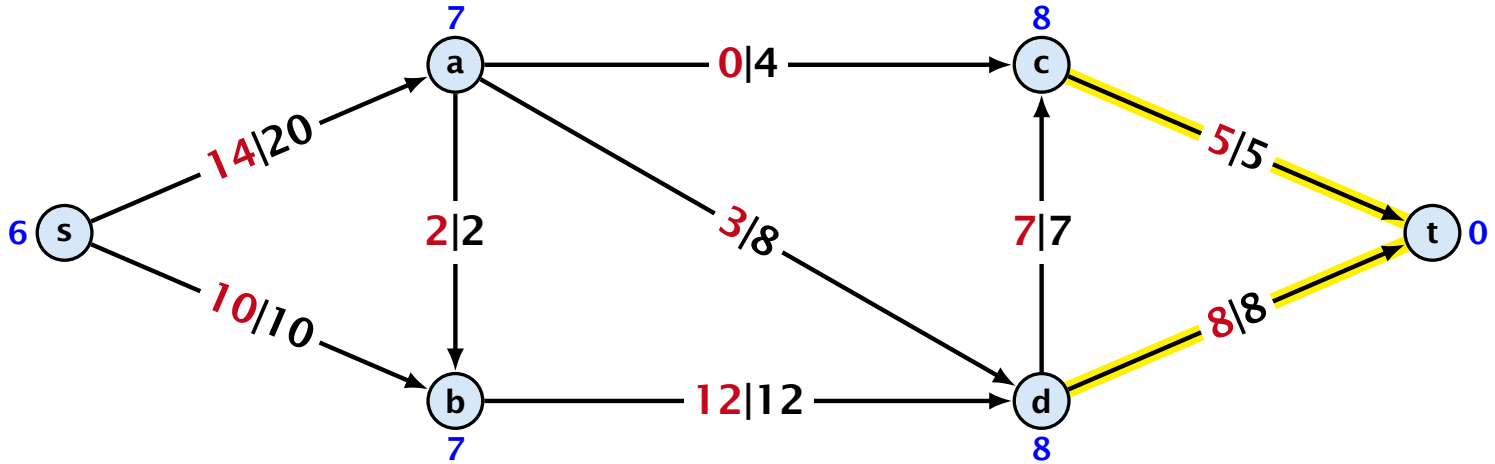
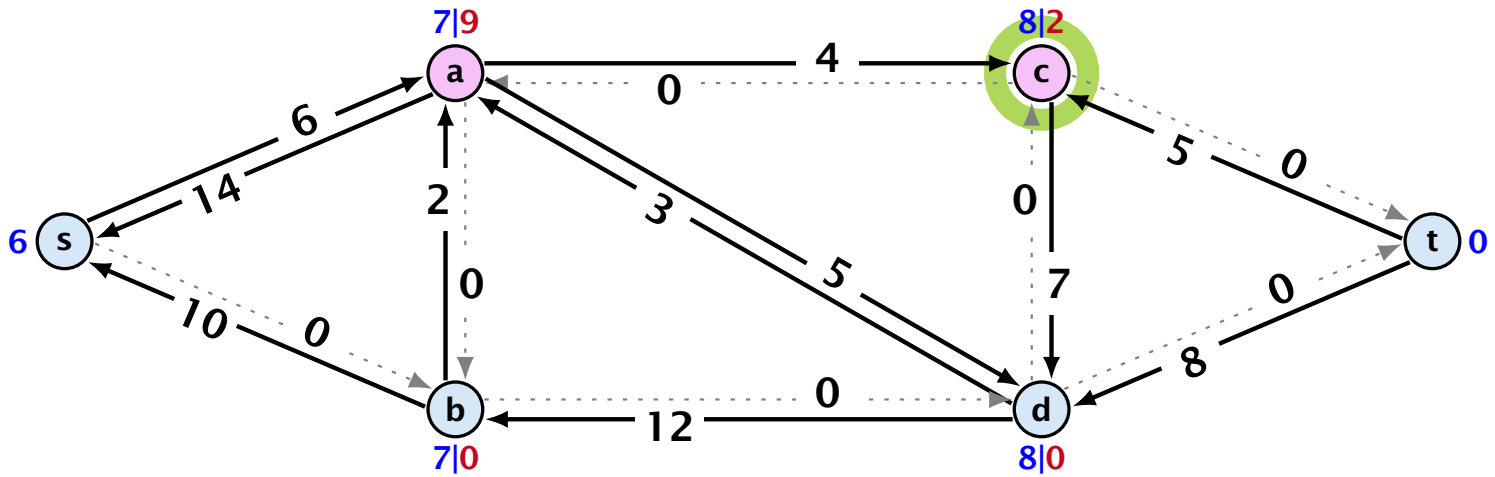


relabel to 9



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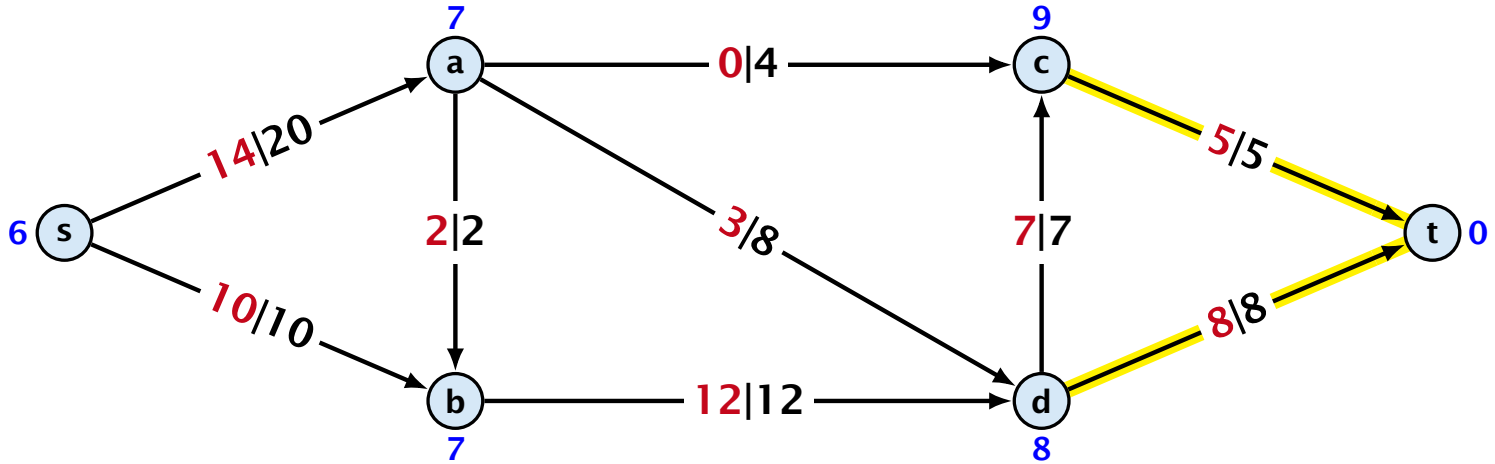

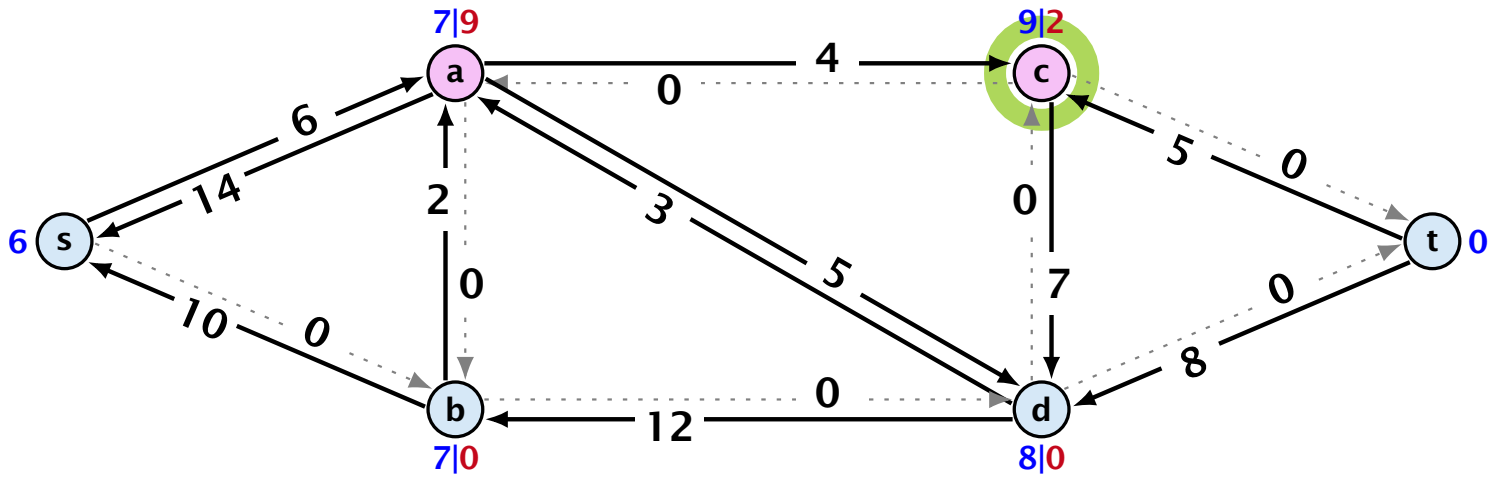

Preflow Push

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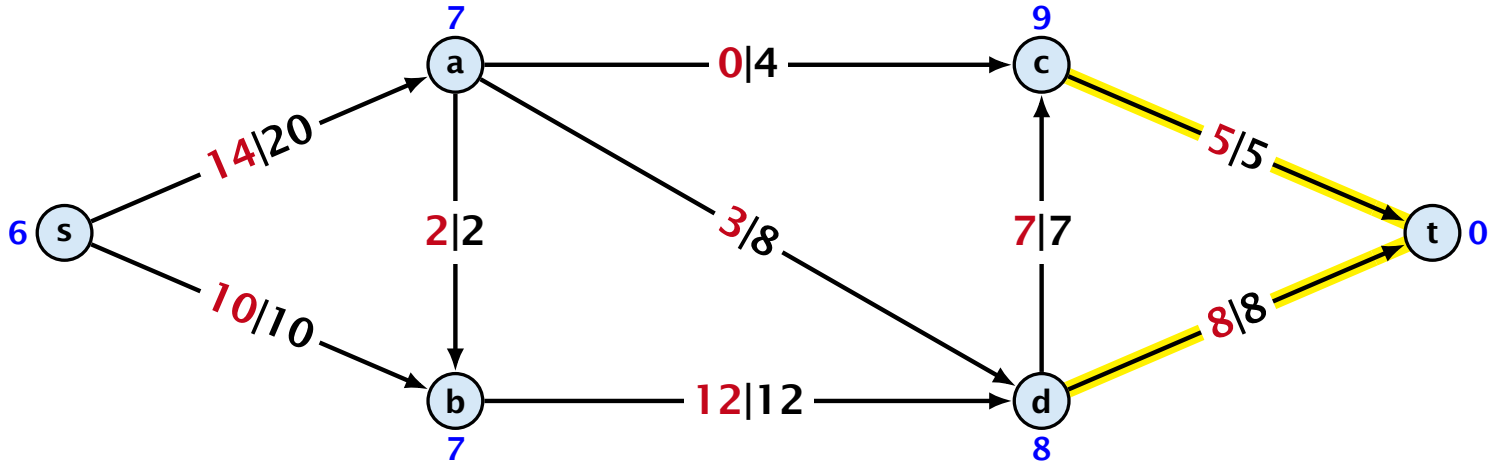
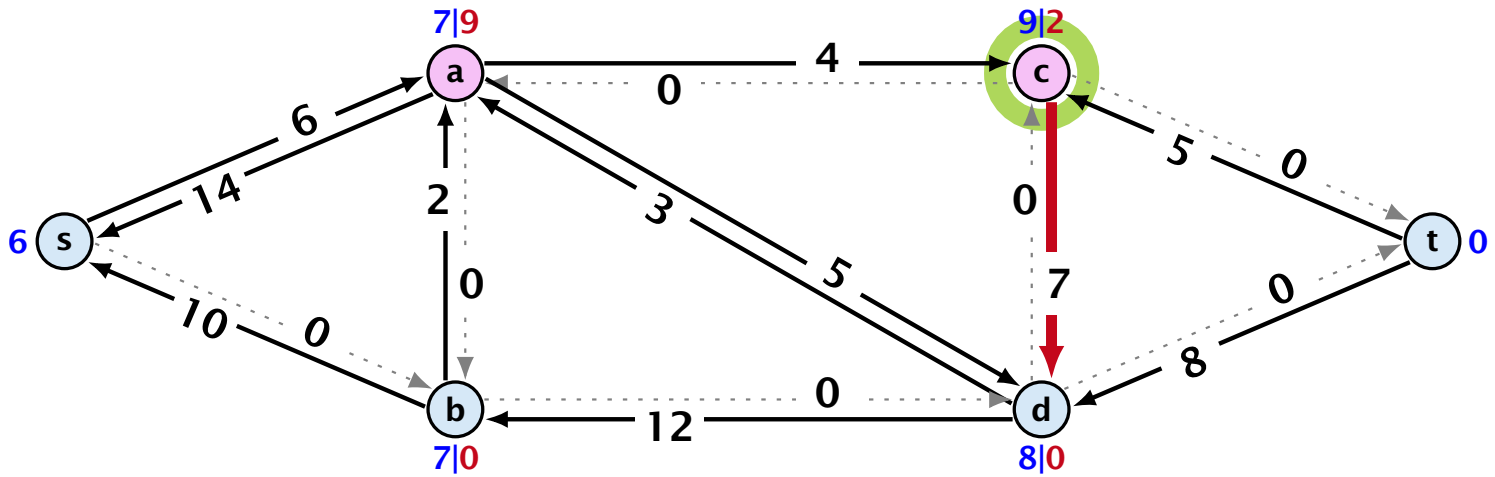


deactivating push



Preflow Push

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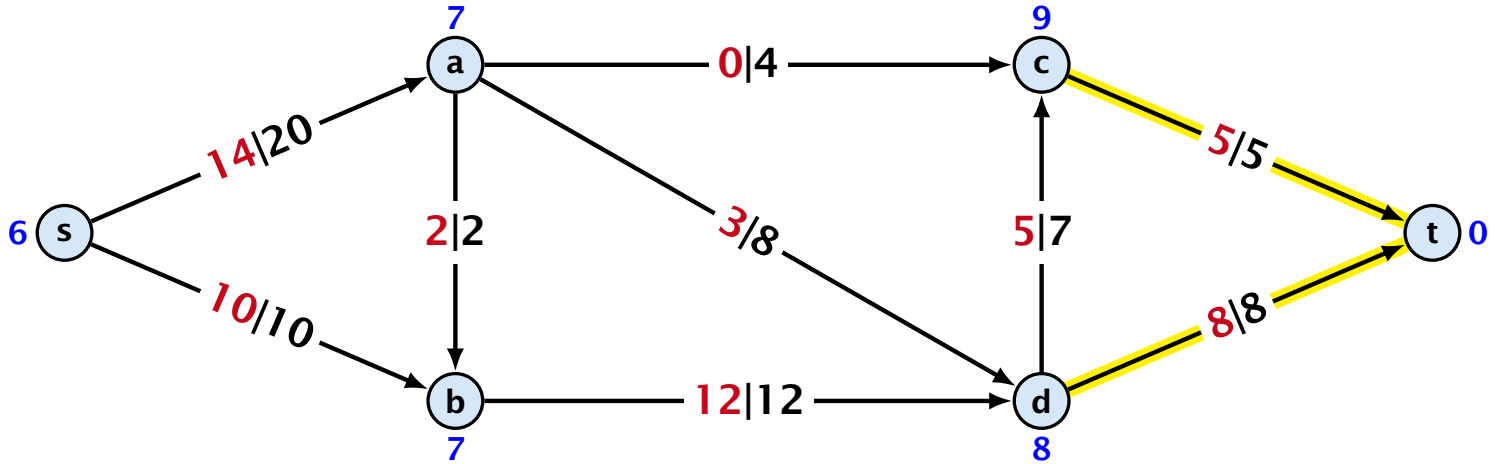

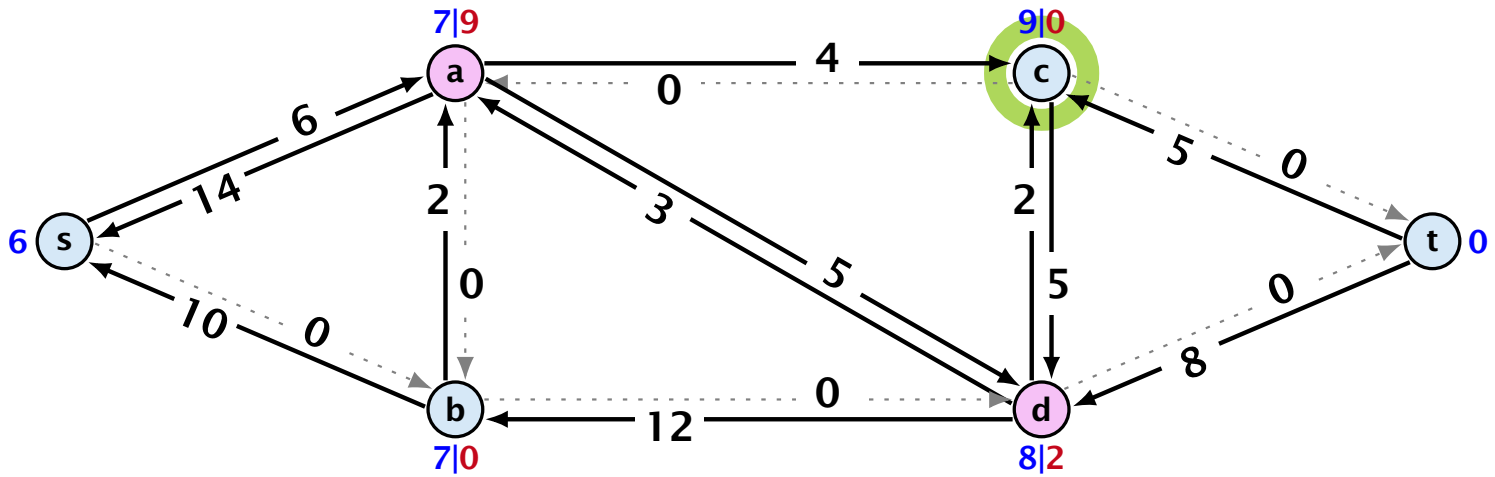

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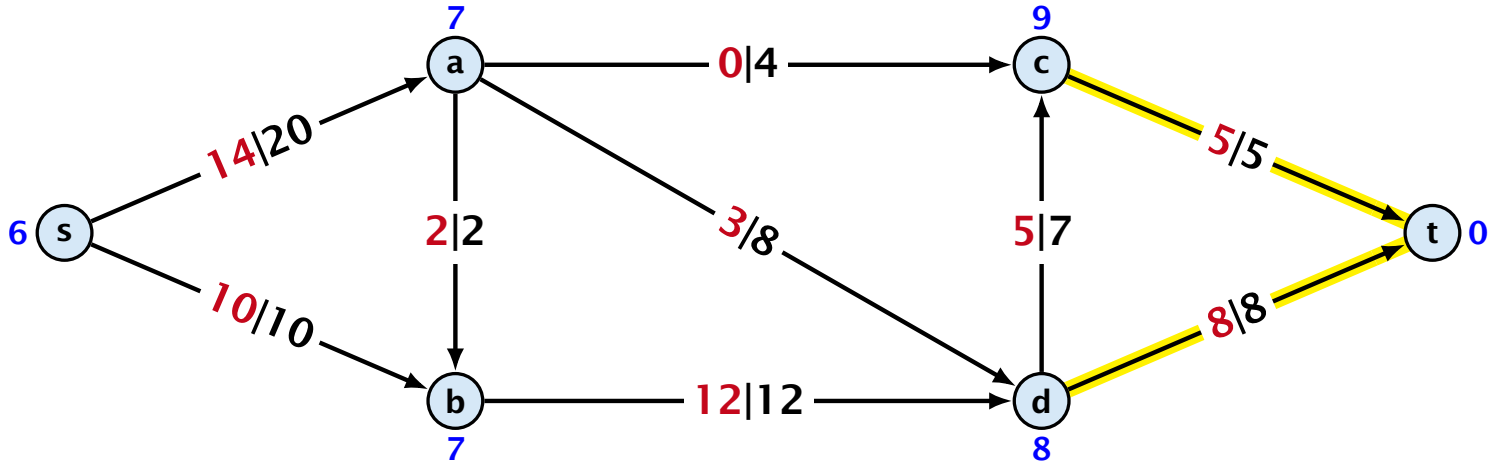

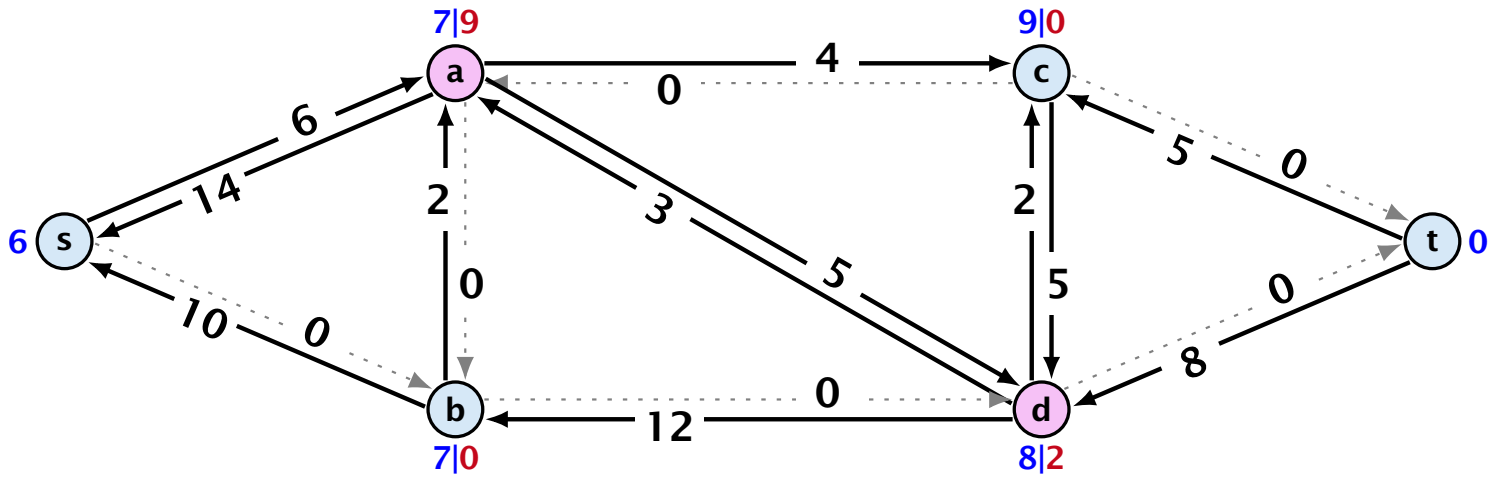

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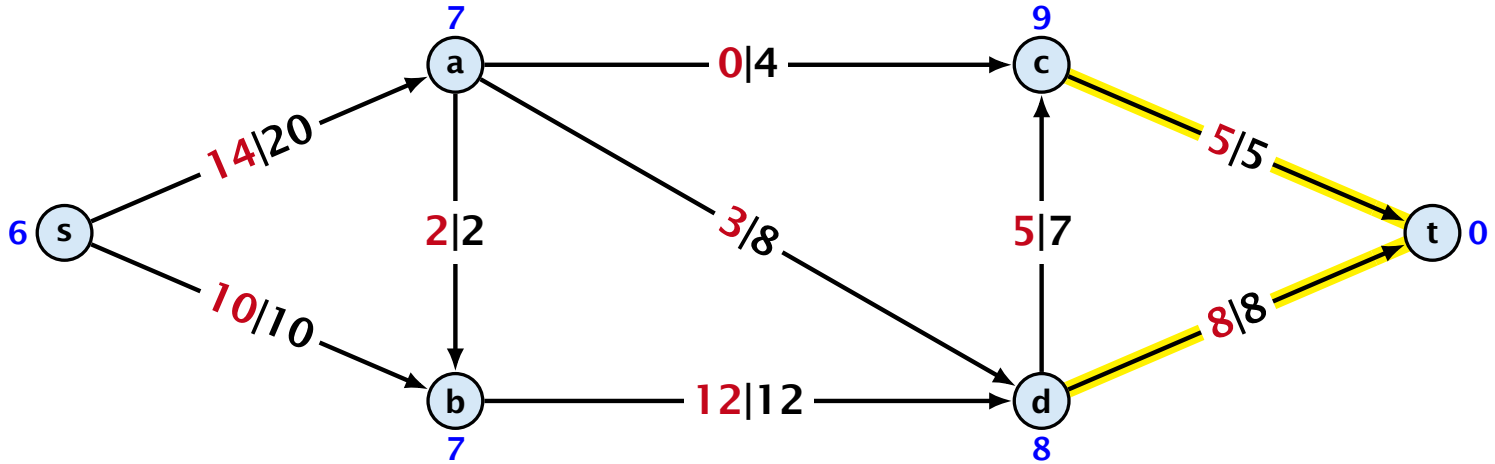
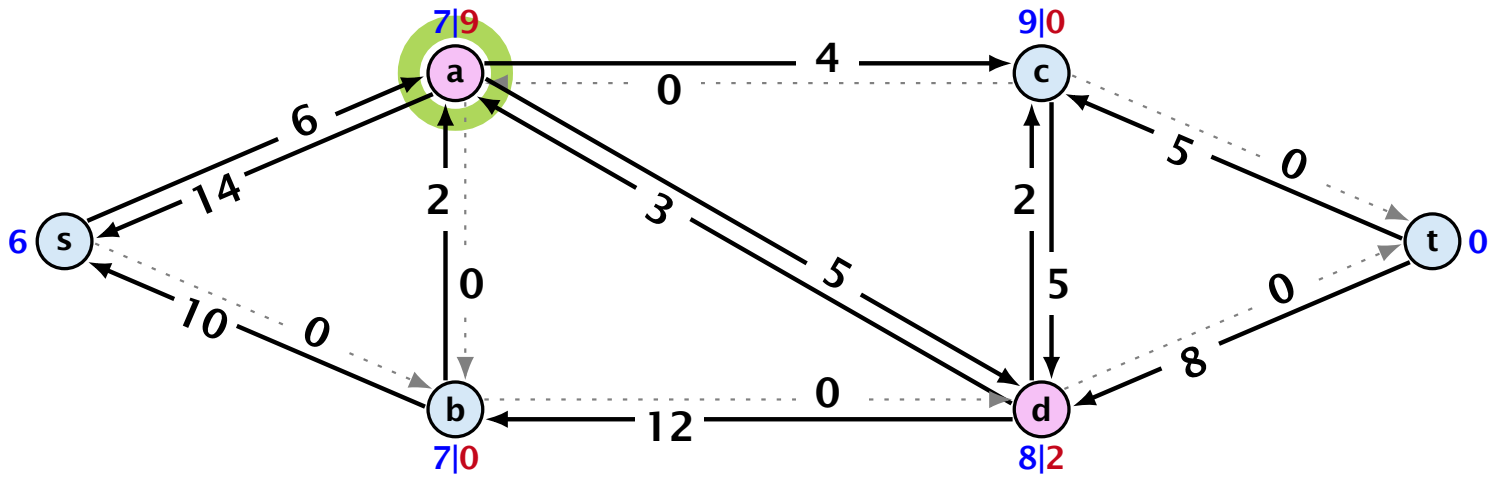
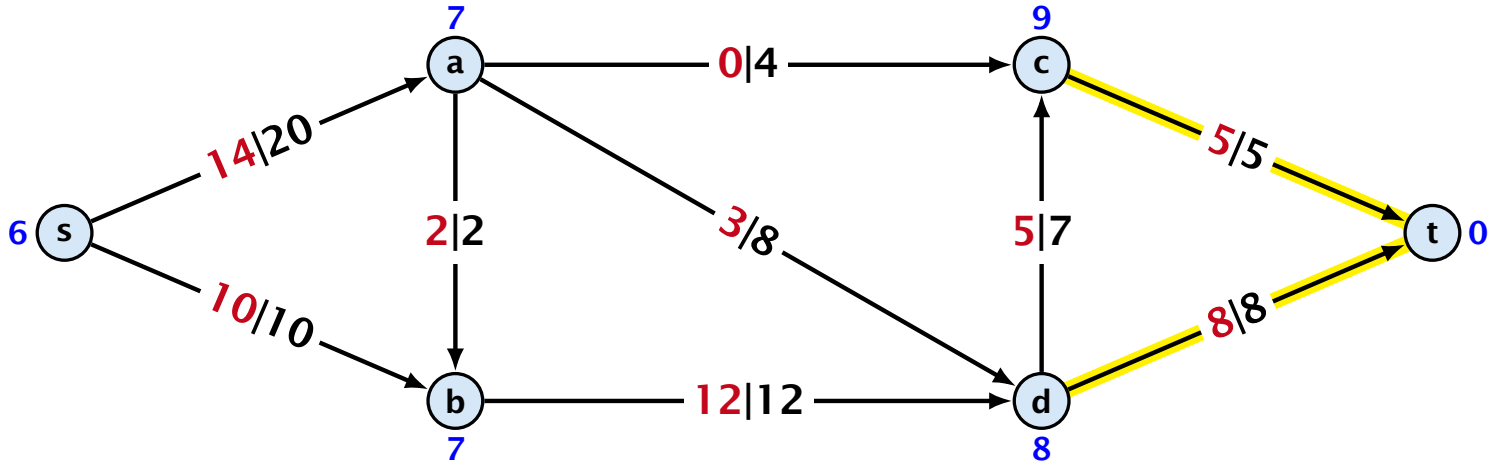


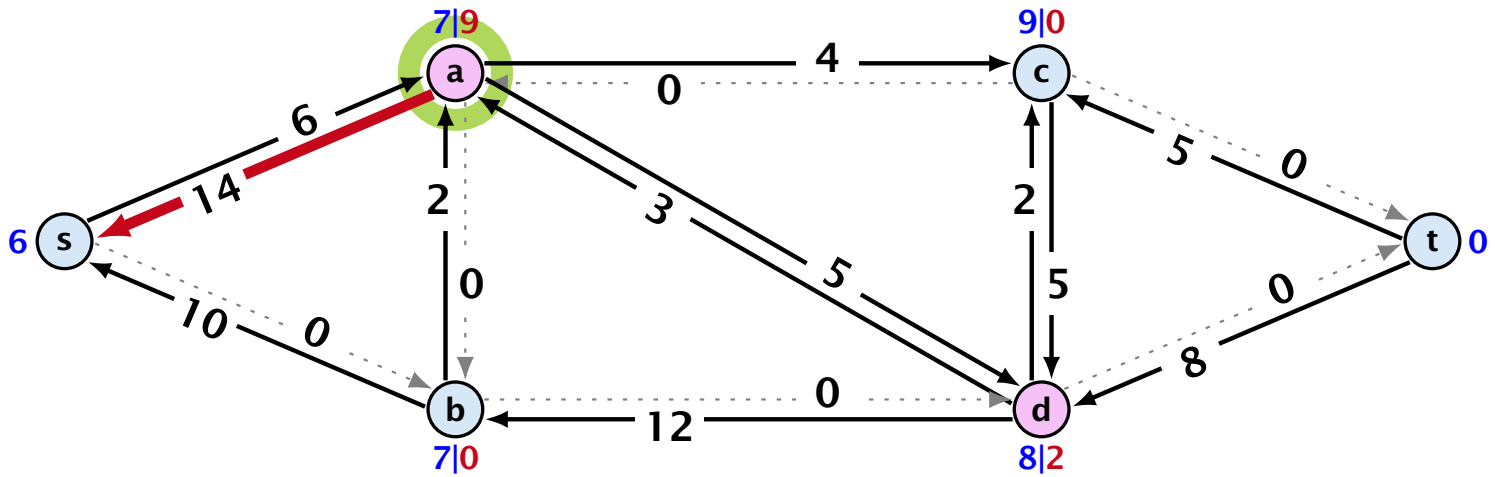


Preflow Push

The yellow edges indicate the cut that is introduced by the smallest missing label.



deactivating push



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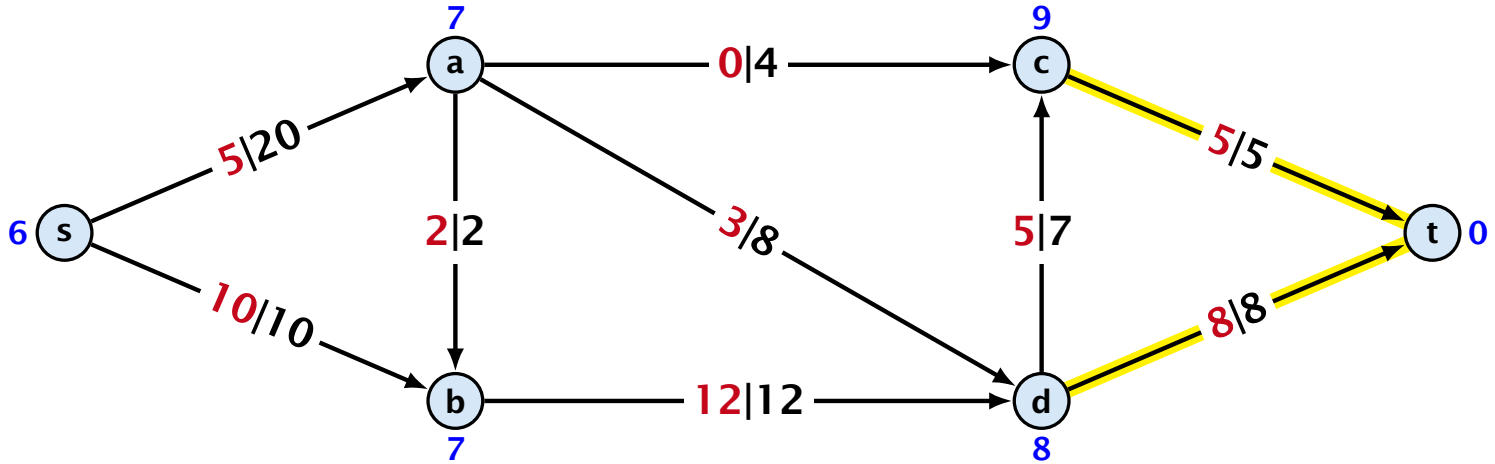

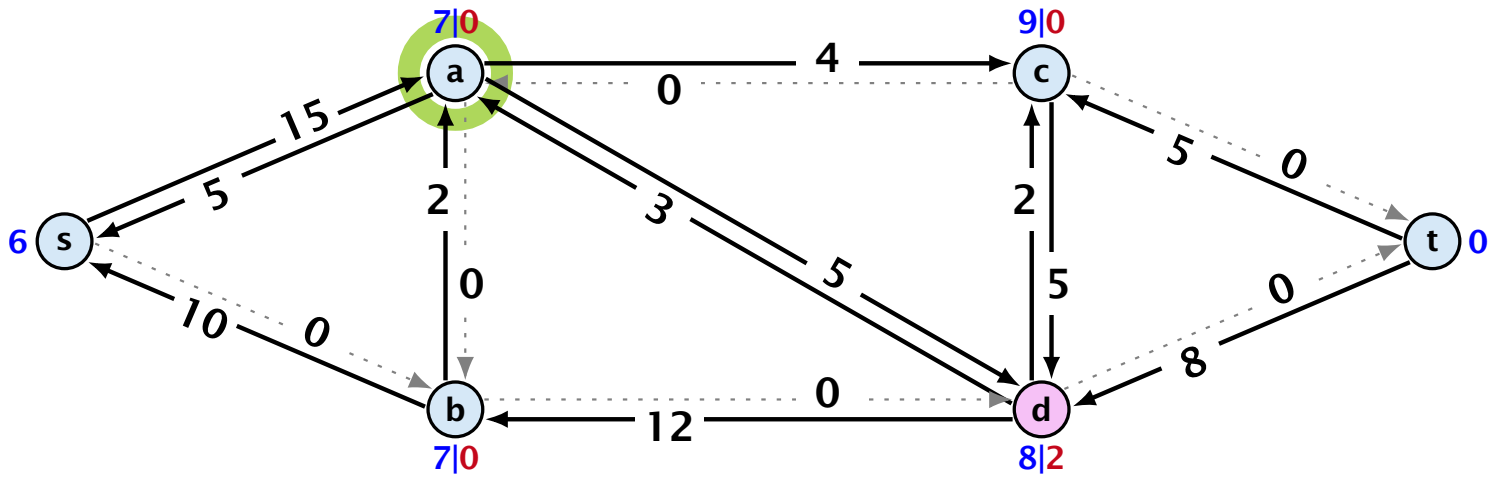

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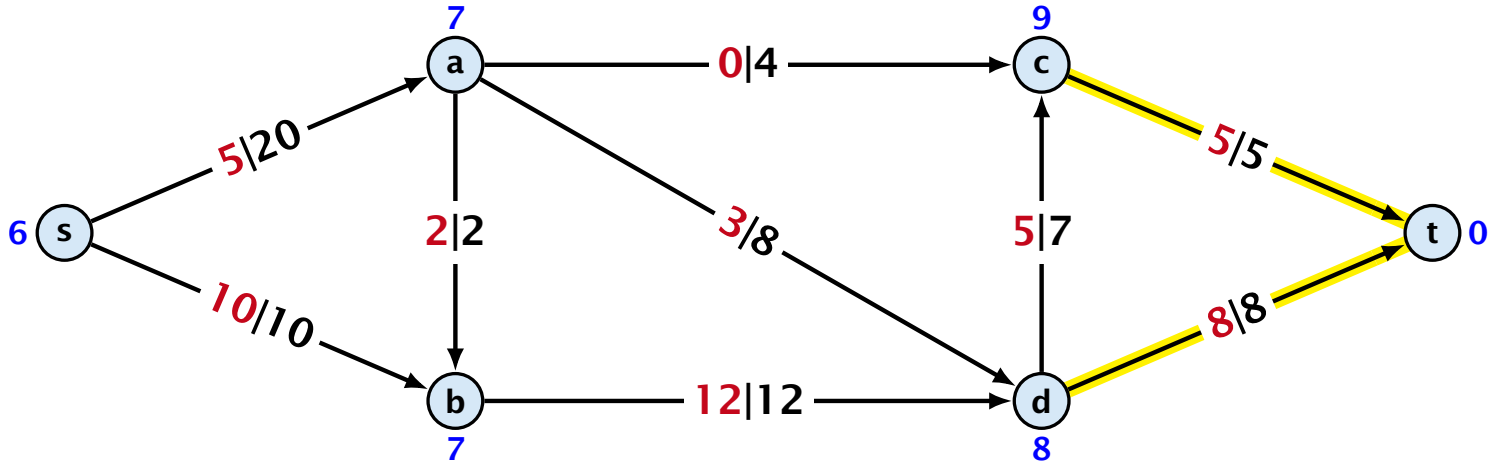

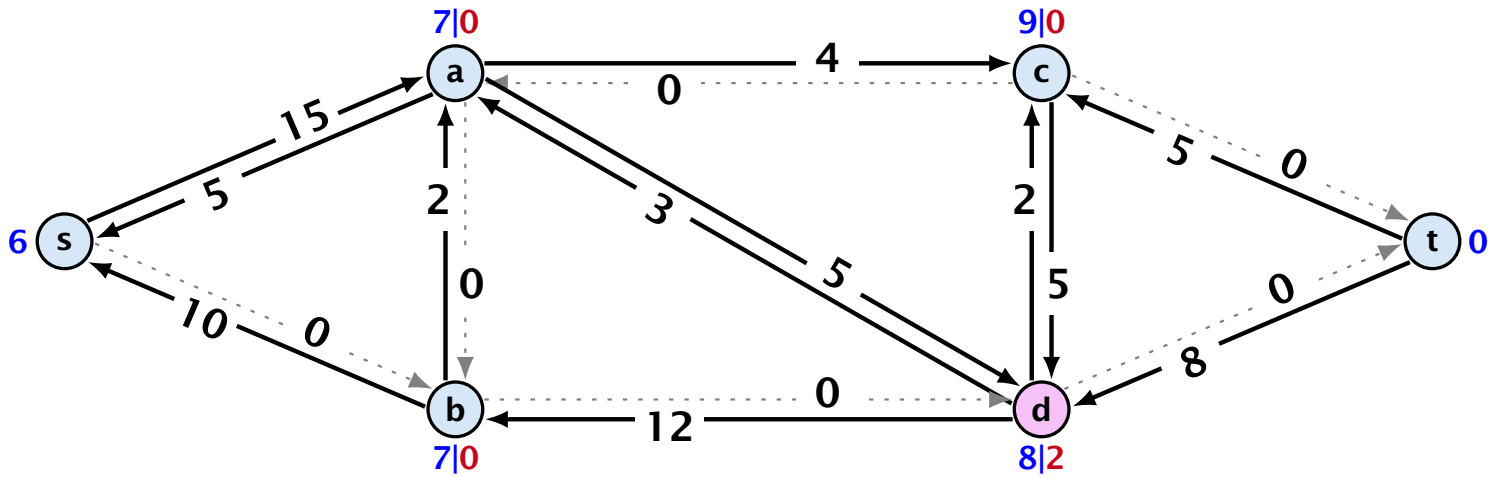

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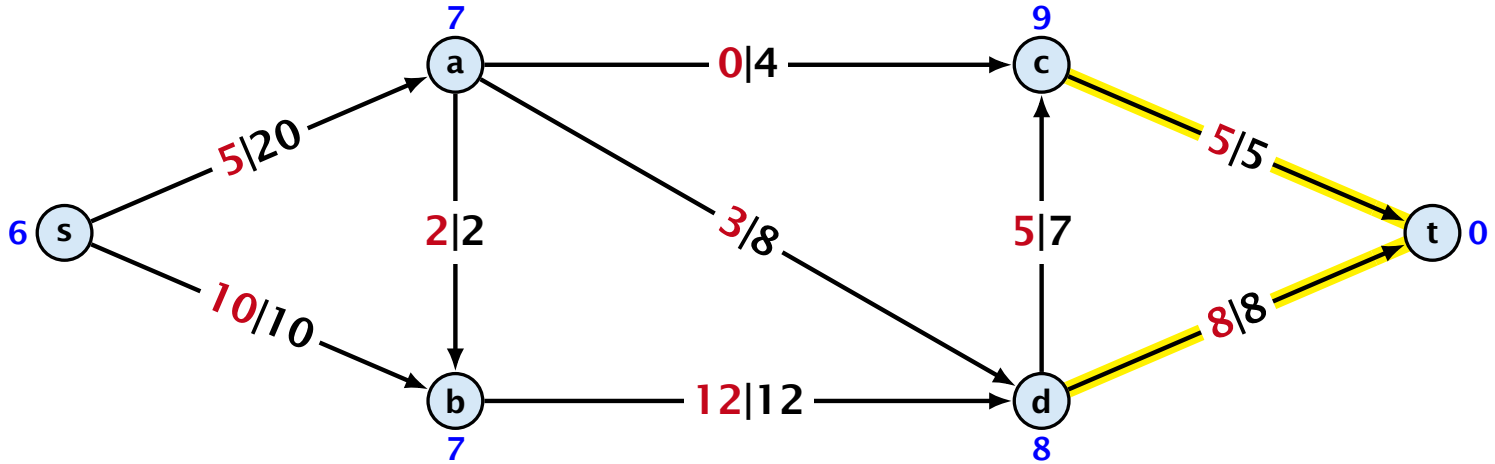

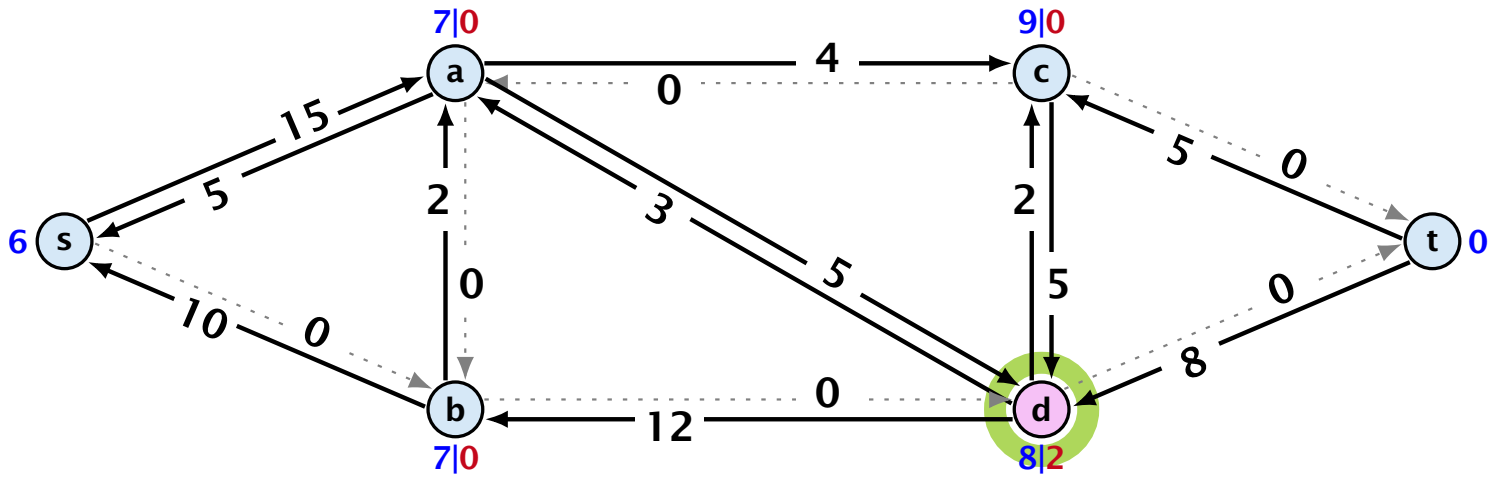

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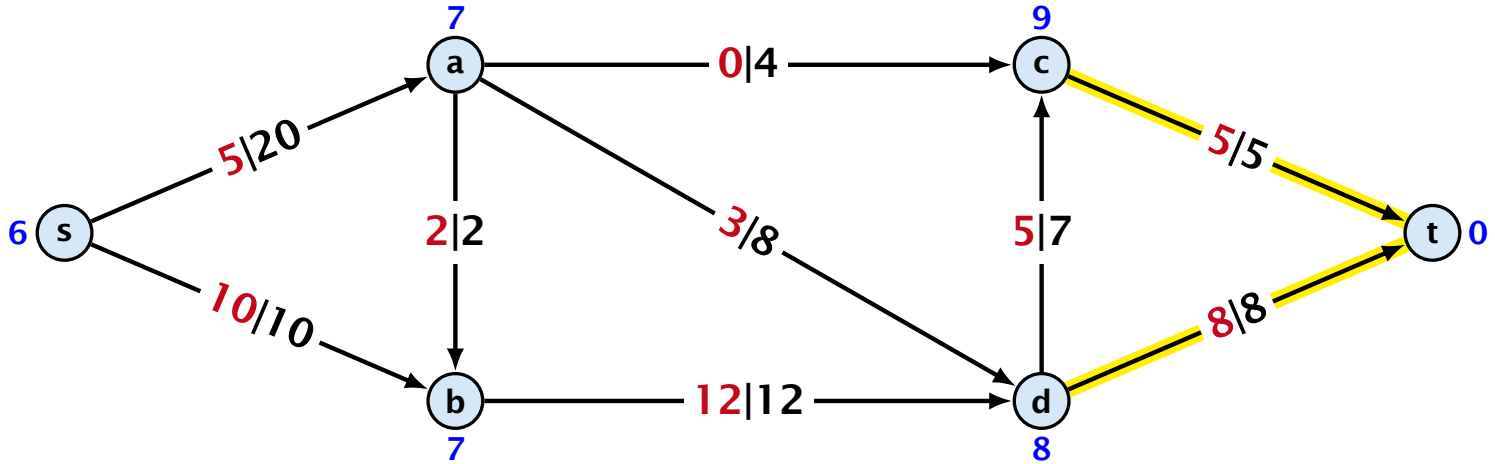
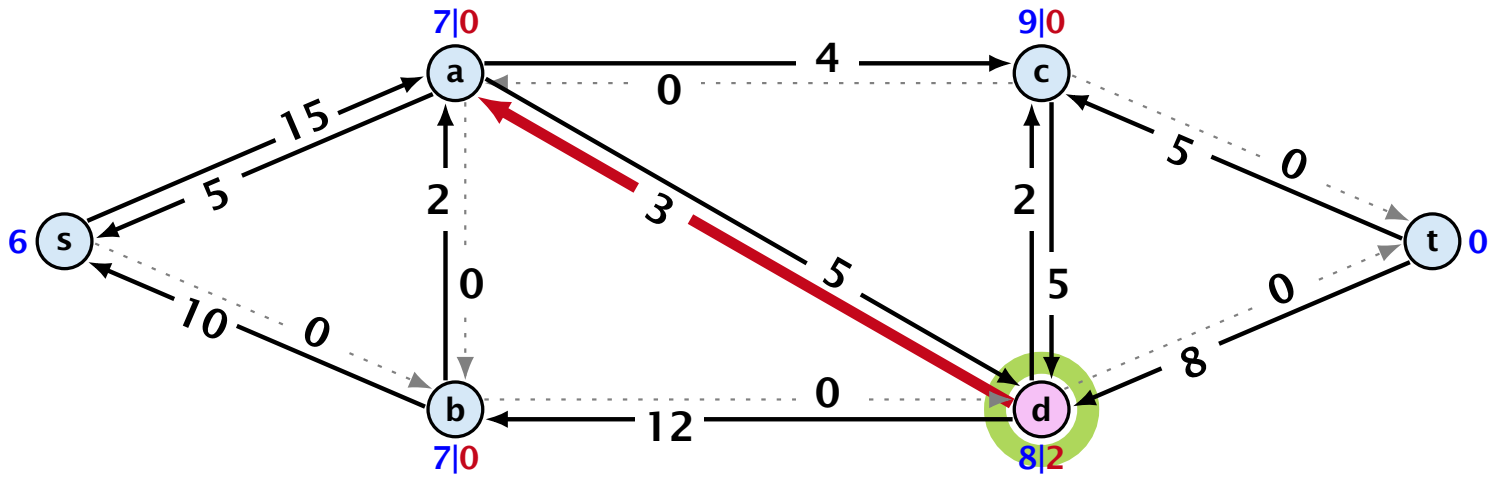


deactivating push



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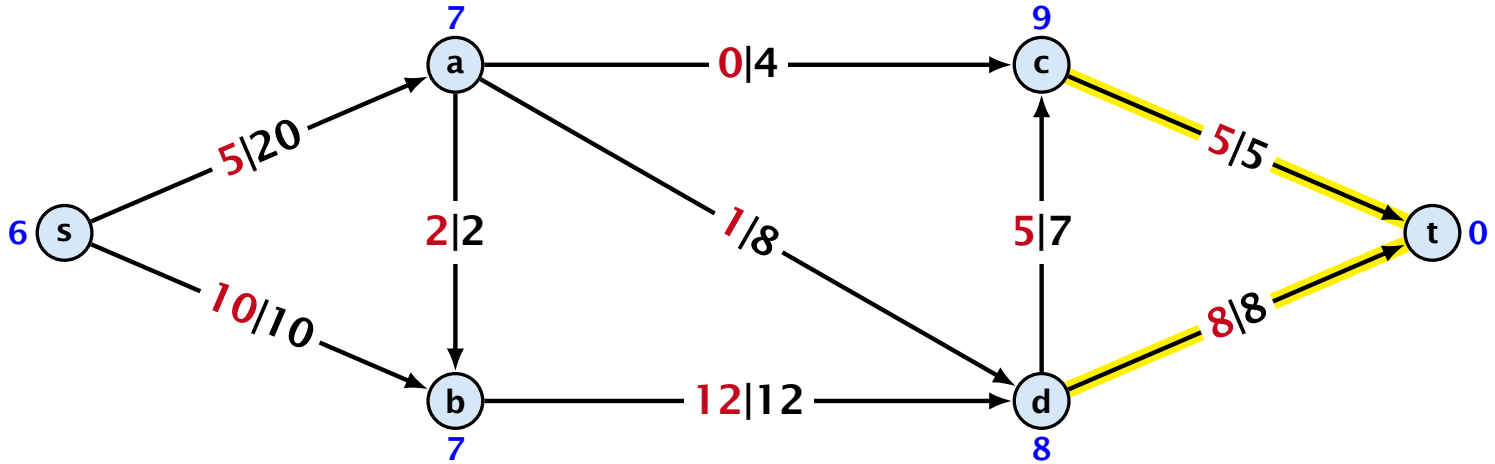

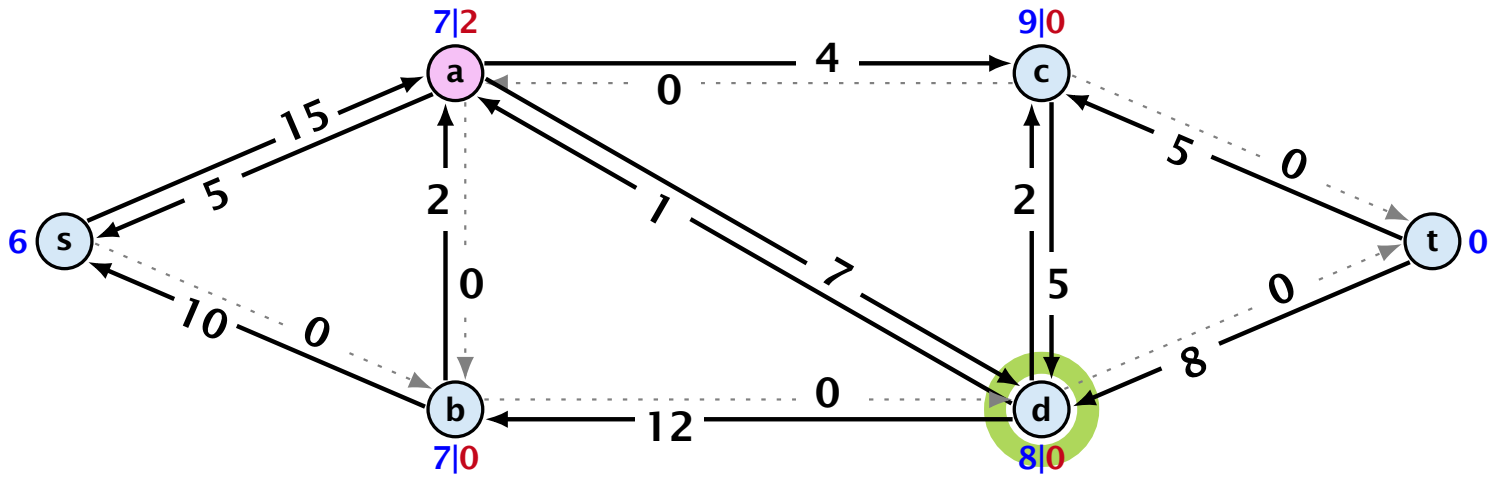

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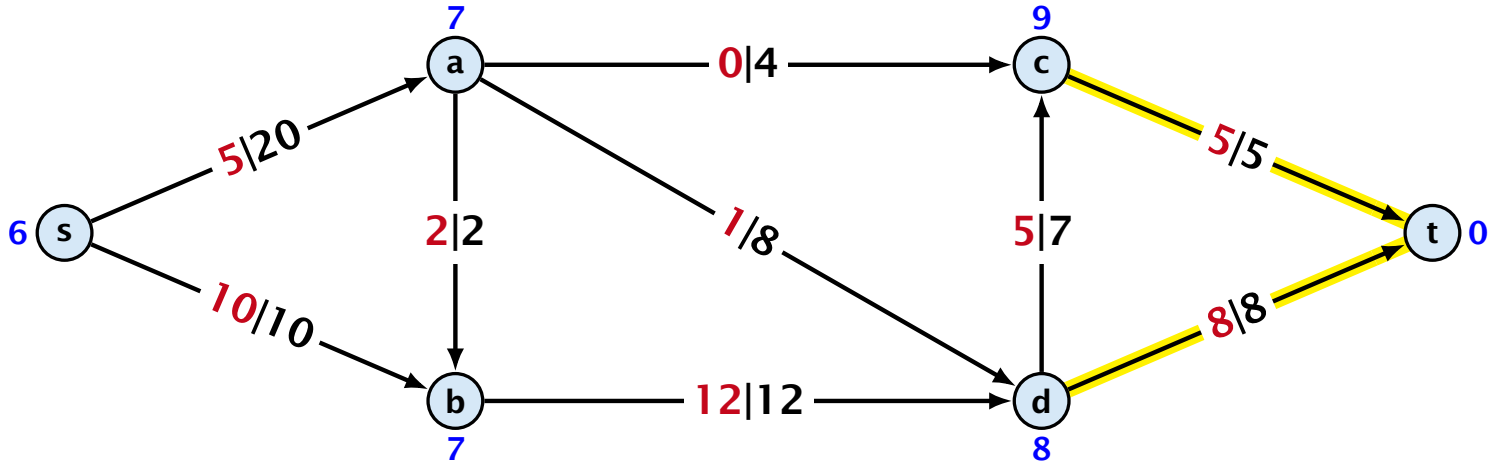

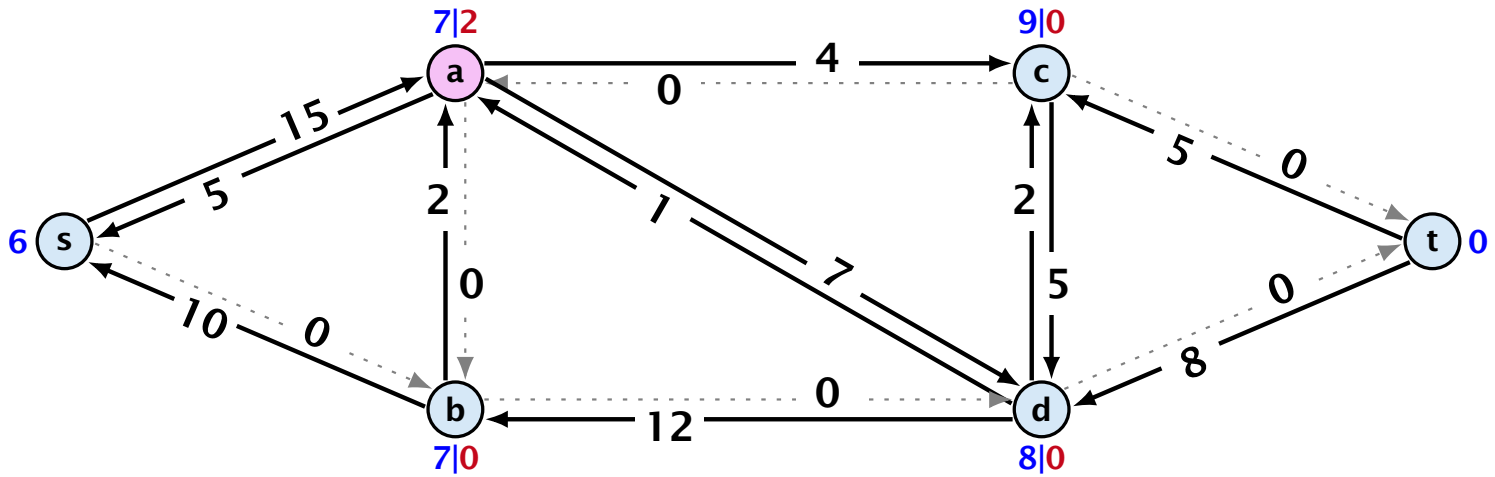

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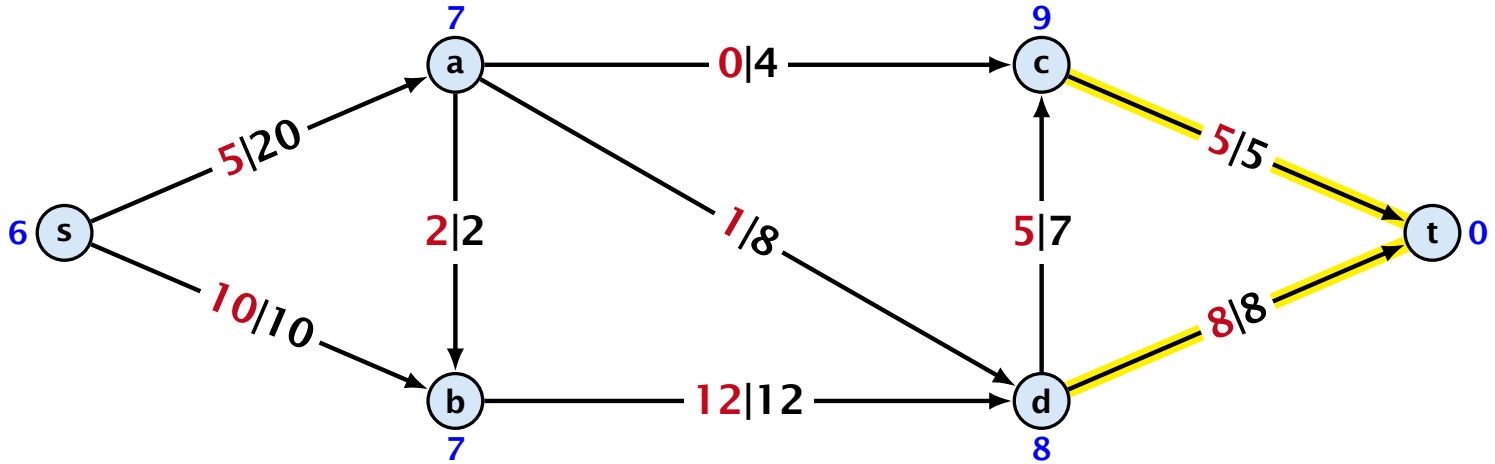

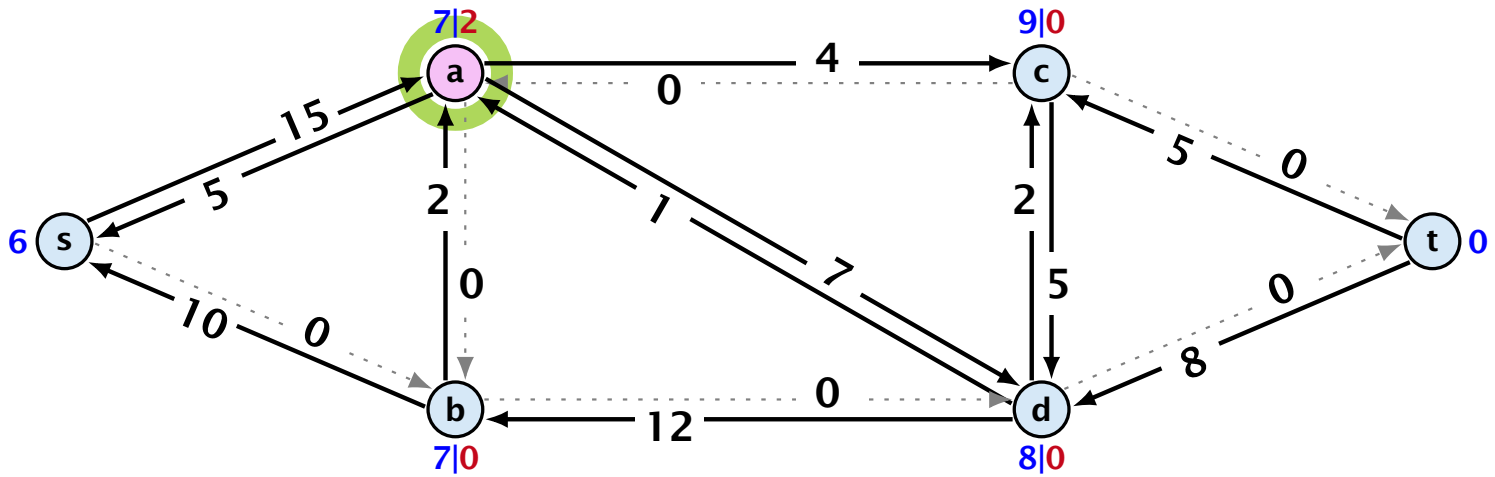

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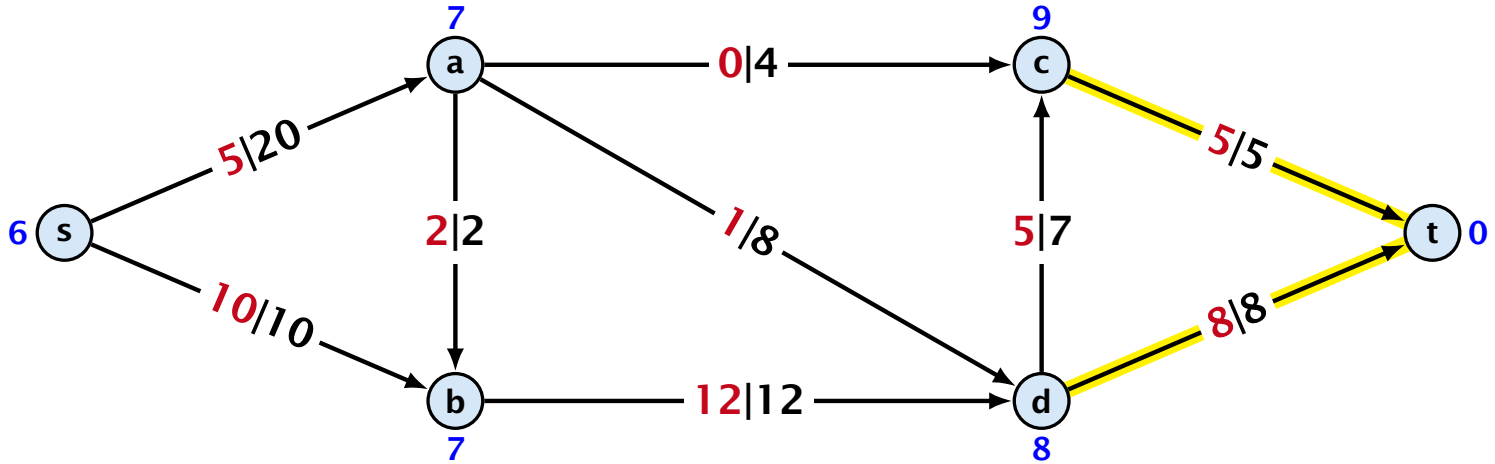

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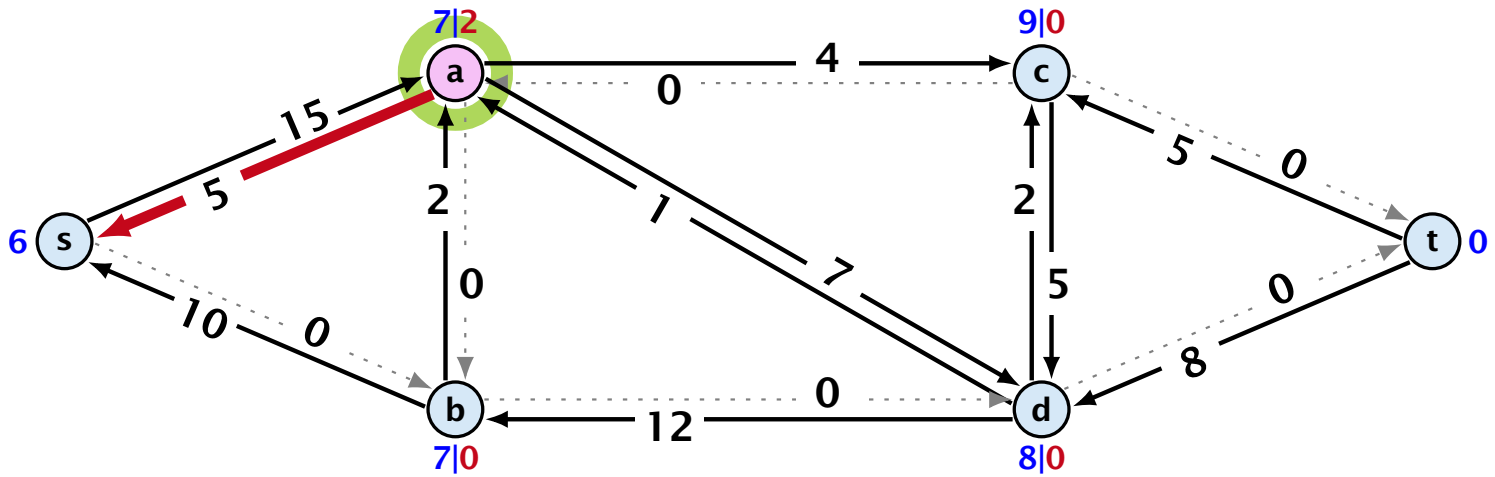

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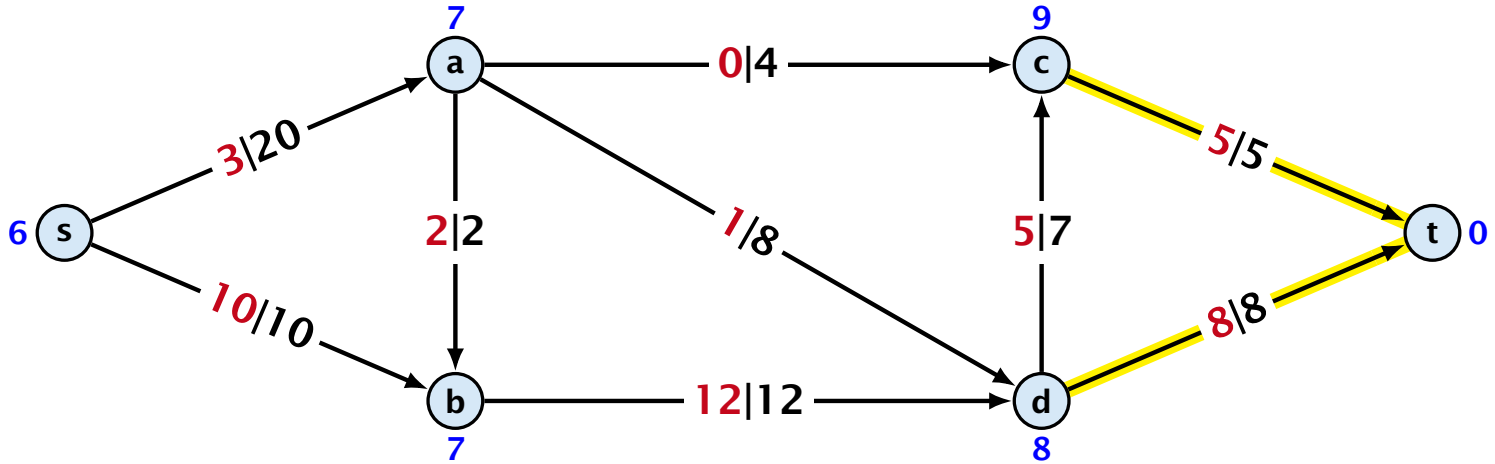

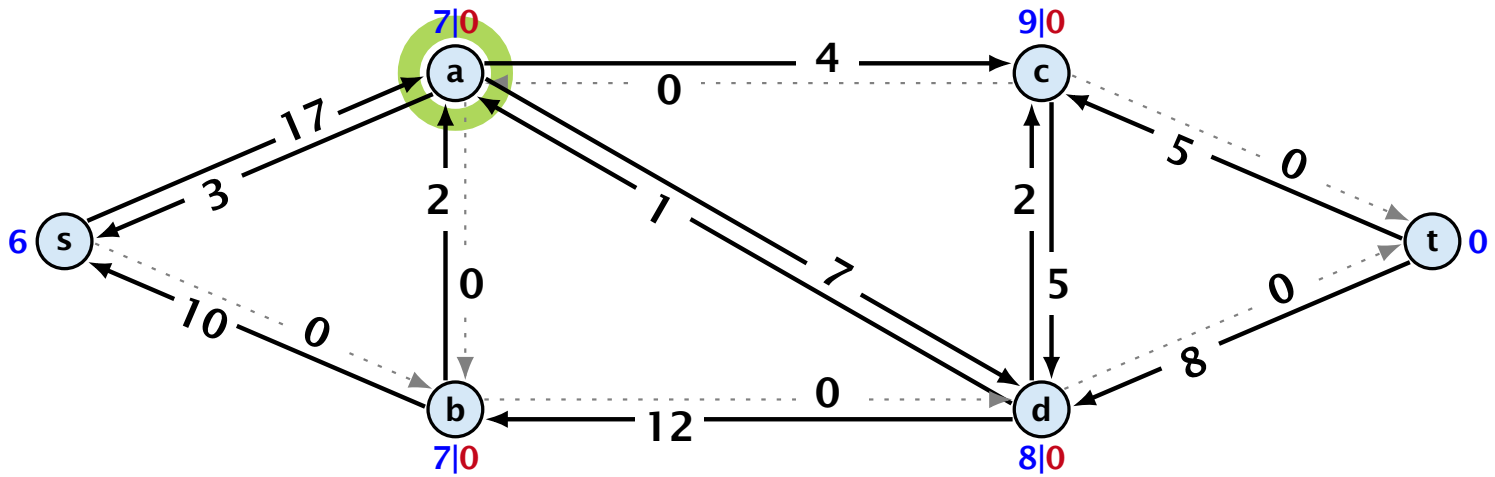

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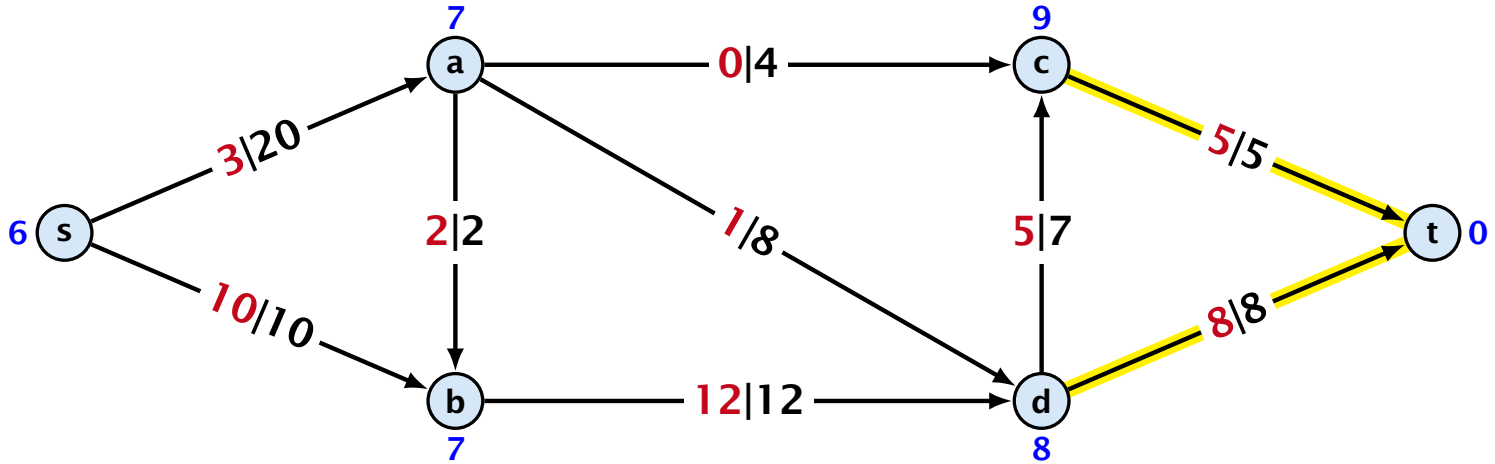

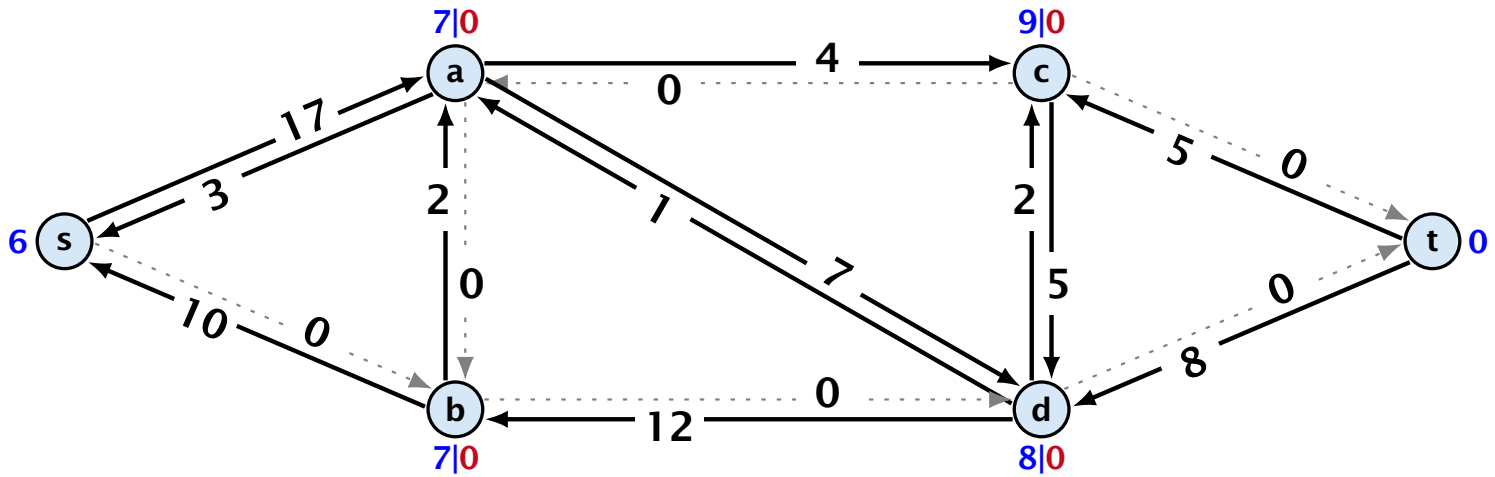

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Note that the lemma is almost trivial. A node v having excess flow means that the current preflow ships something to v. The residual graph allows to *undo* flow. Therefore, there must exist a path that can undo the shipment and move it back to s. However, a formal proof is required.

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- Let $f(B) = \sum_{v \in B} f(v)$ be the excess flow of all nodes in B.

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

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

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

Analysis

Lemma 58

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

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Proof.

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

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- Since the label of v is at most $2n - 1$, there are at most n pushes along (u, v).

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- A relabel increases Φ by at most 1.

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

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 deactivating 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 61

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

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 deactivating 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,

$$\begin{aligned}\#\text{deactivating\_pushes} &\leq \#\text{relabels} + 2n \cdot \#\text{saturating\_pushes} \\ &\leq \mathcal{O}(n^2 m) \ .\end{aligned}$$

Analysis

Theorem 62

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

Analysis

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

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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

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)

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

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

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- 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

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 2 discharge(u)

```
1: while u is active do
2:     v ← u.current-neighbour
3:     if v = null then
4:         relabel(u)
5:         u.current-neighbour ← u.neighbour-list-head
6:     else
7:         if (u, v) admissible then push(u, v)
8:         else u.current-neighbour ← v.next-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 63

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

In order for e to become admissible the other end-point say v has to push flow to u (so that the edge (u,v) re-appears in the residual graph). For this the label of v needs to be larger than the label of u. Then in order to make (u,v) admissible the label of u has to increase.

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 discharge(u) is correct, and that we can perform a relabel in Line 4.