Preflows

Preflows

Definition 65
An (s,t)-preflow is a function $f : E \mapsto \mathbb{R}^+$ that satisfies

1. For each edge e
$$0 \leq f(e) \leq c(e) \enspace .$$
(capacity constraints)

Preflows

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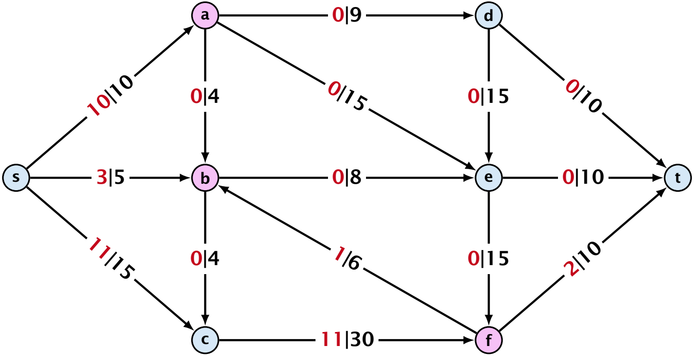
An (s,t)-preflow is a function $f : E \mapsto \mathbb{R}^+$ that satisfies

1. For each edge e
$$0 \leq f(e) \leq c(e) \ .$$
(capacity constraints)

2. For each $v \in V \setminus \{s,t\}$
$$\sum_{e \in \text{out}(v)} f(e) \leq \sum_{e \in \text{into}(v)} f(e) \ .$$

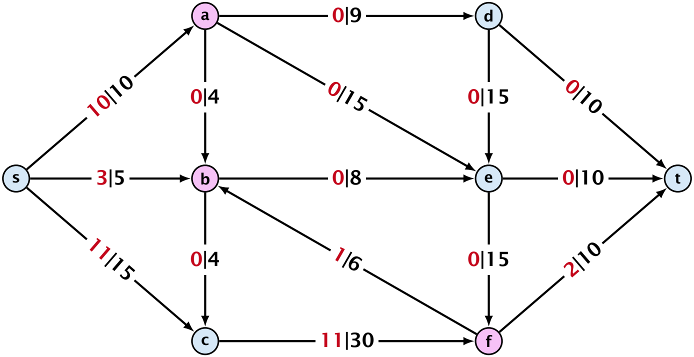
Preflows

Example 66



Preflows

Example 66



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

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

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- $\ell(s) = n$
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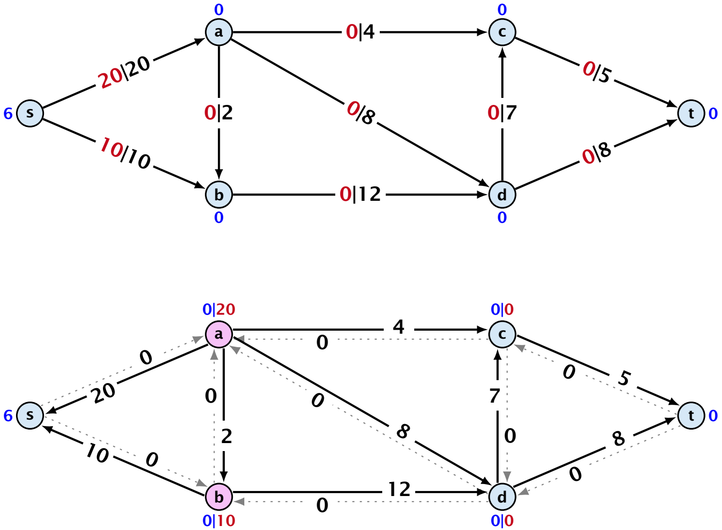
Intuition:

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



0
a
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10|10
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0|20
a
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0
5
20
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0
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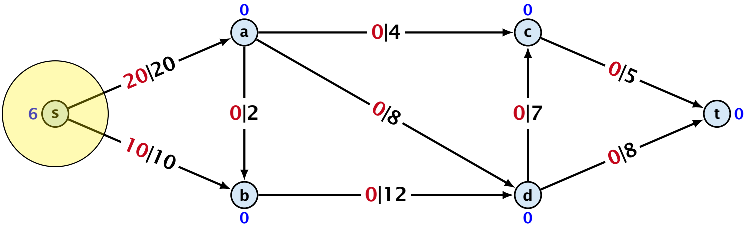
Preflows



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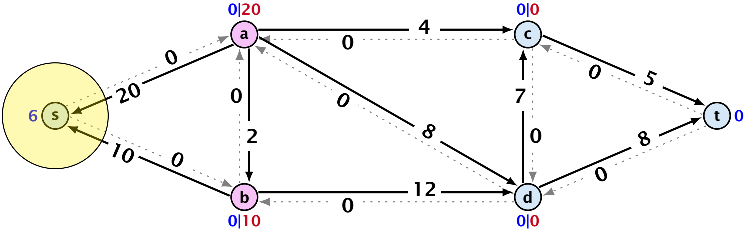

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t
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8
10
0
0
12
b
0
d
0|10
0|0

Preflows

Preflows

Lemma 67
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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Preflows

Lemma 67

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

Proof:

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

Preflows

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- 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

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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 68

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

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

Push Relabel Algorithms

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- 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

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).

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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

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

Push Relabel Algorithms

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The relabel operation

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

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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)

```
find initial preflow f
while there is active node u do
    if there is admiss. arc e out of u then
        push(G, e, f, c)
    else
        relabel(u)
return f
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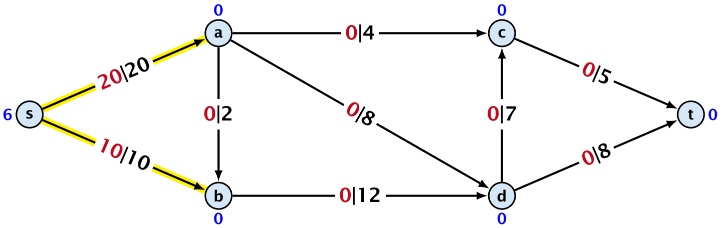
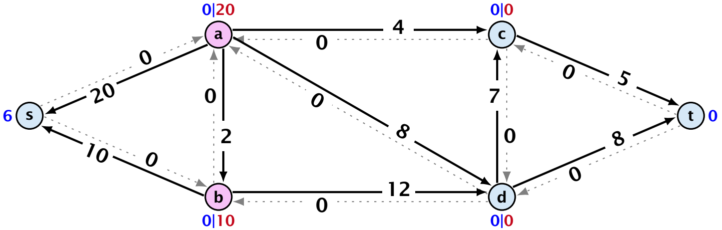
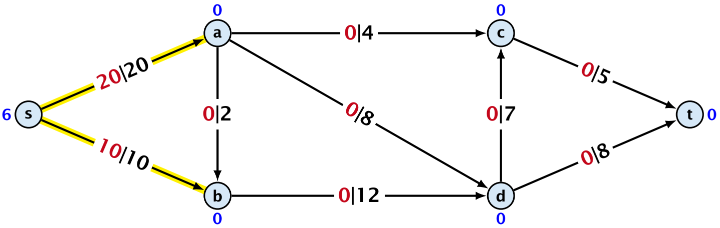
In the following example we always stick to the same active node u until it becomes inactive but this is not required.

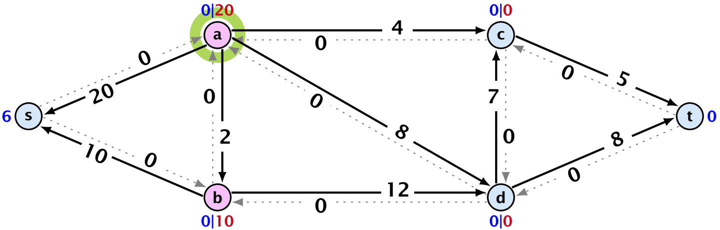
Preflow Push



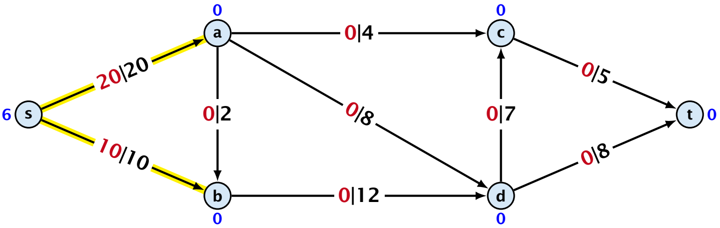


Preflow Push

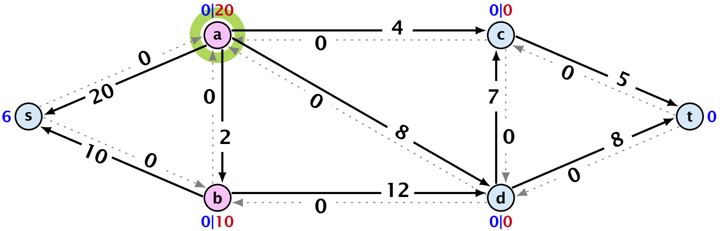




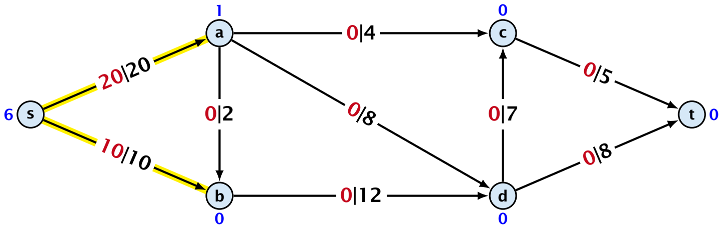
Preflow Push

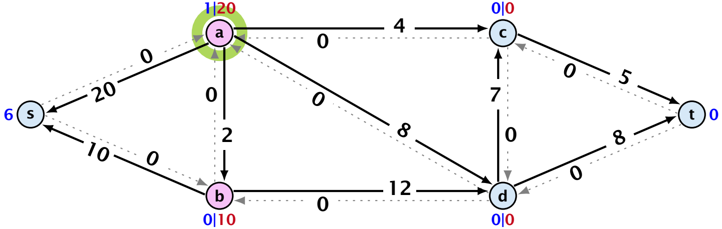


relabel to 1

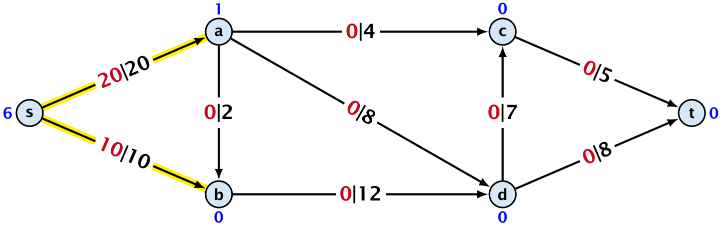


Preflow Push

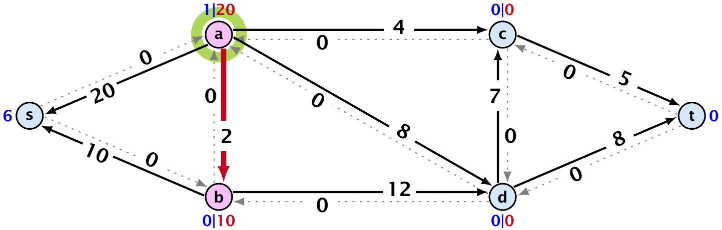




Preflow Push



saturating push



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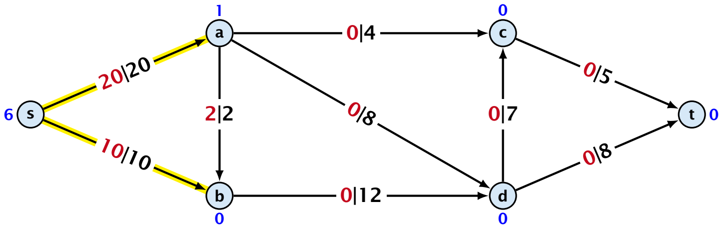

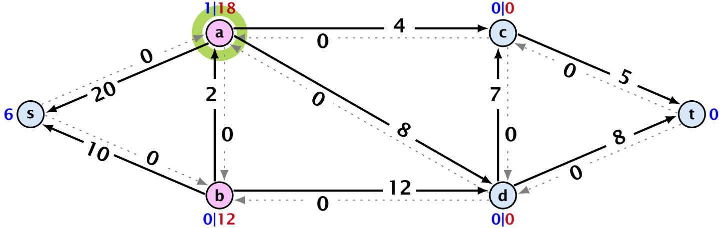

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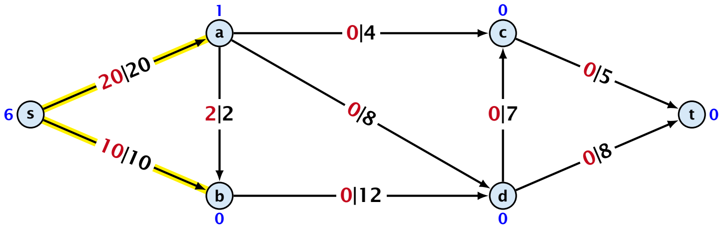
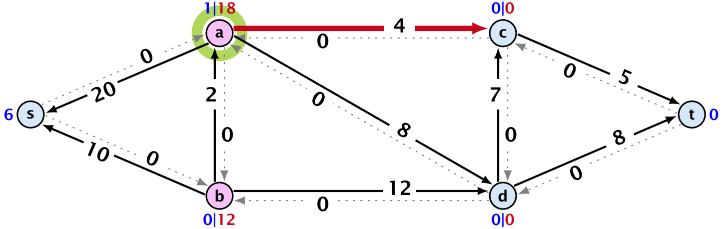


saturating push



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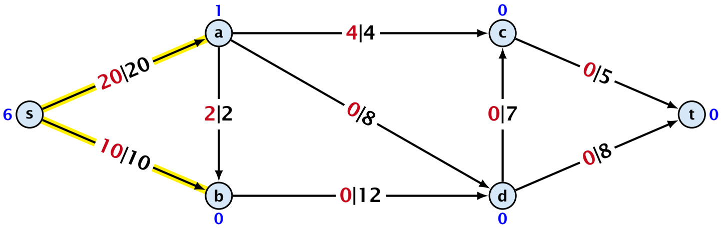

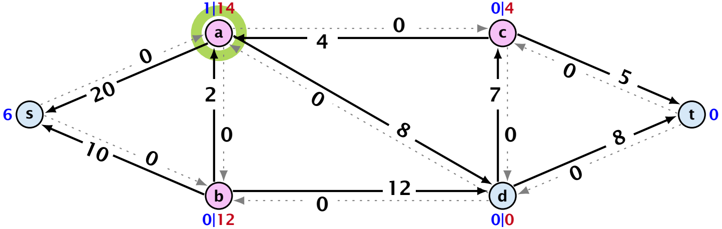

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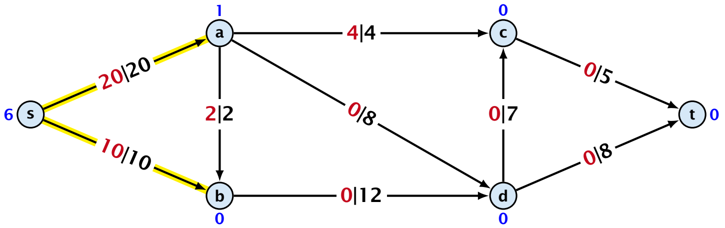
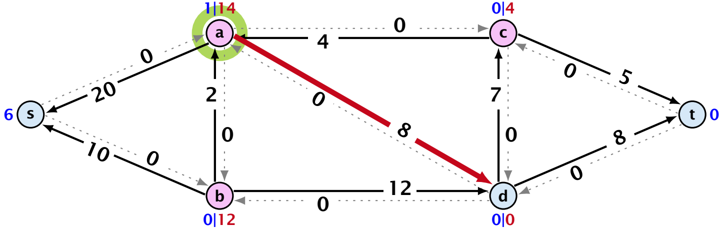


saturating push



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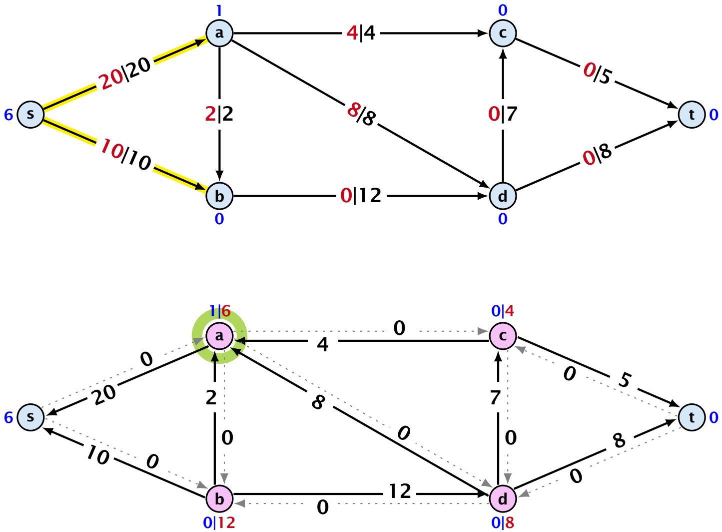

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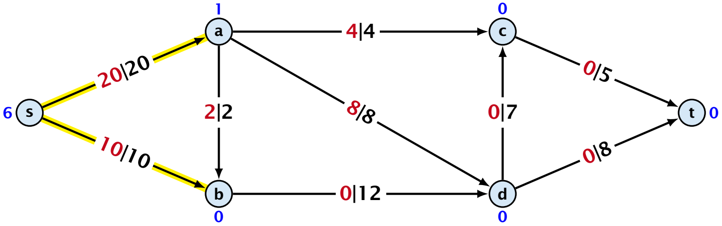
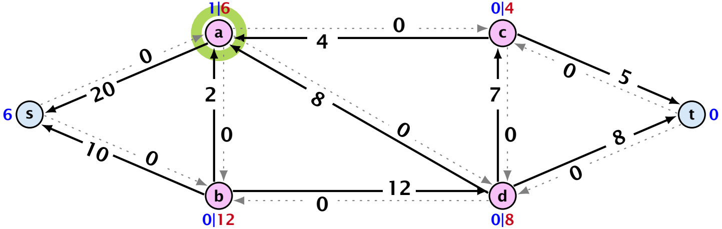


relabel to 7



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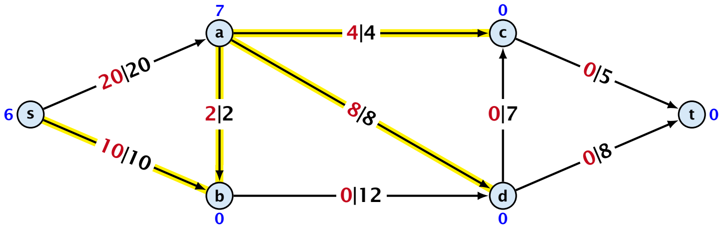

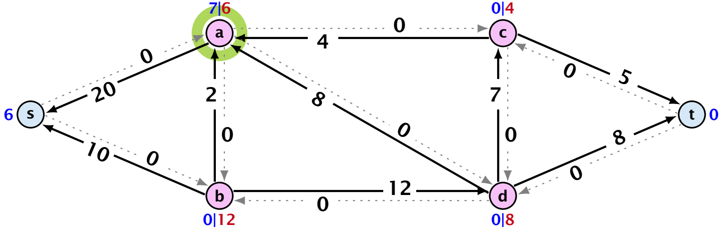

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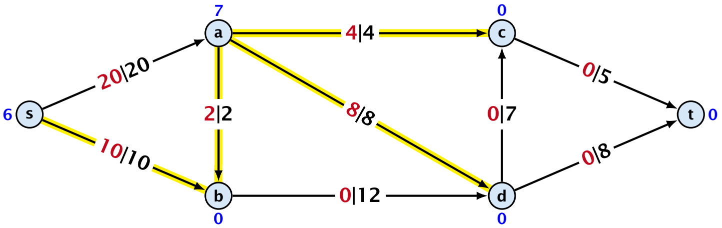
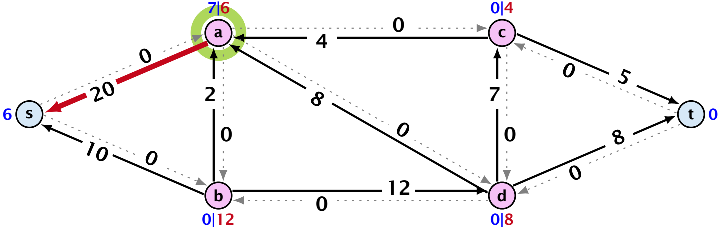


deactivating push



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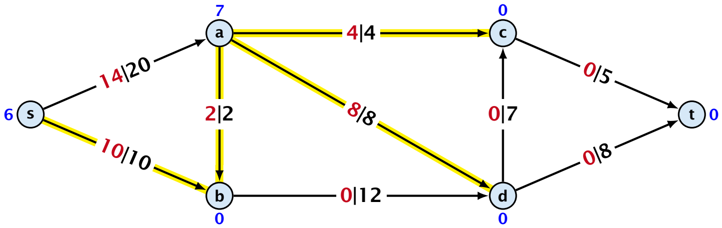

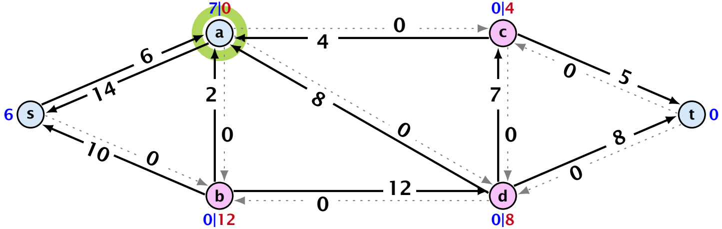

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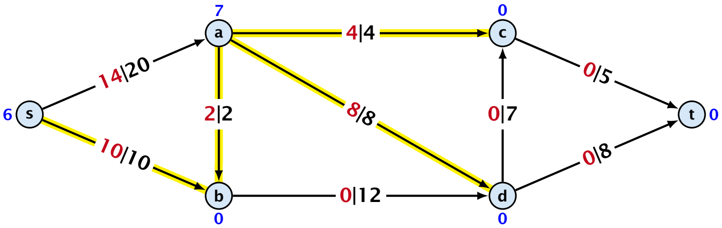

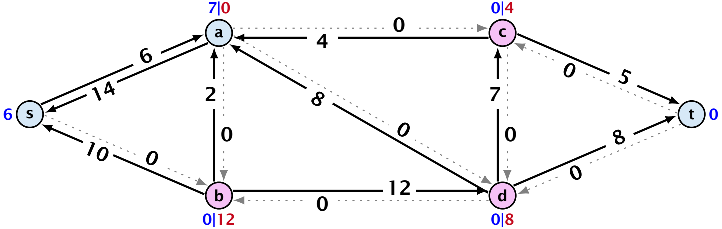

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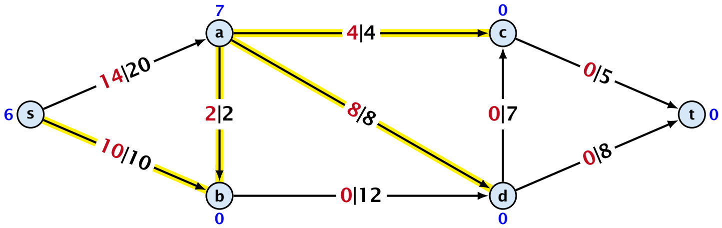

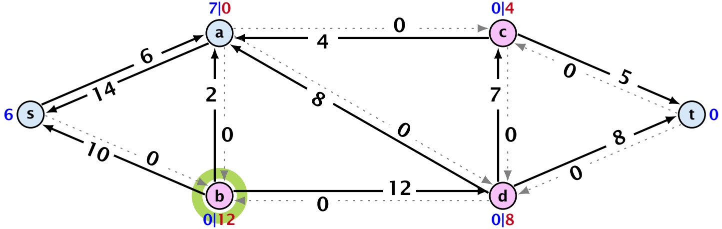

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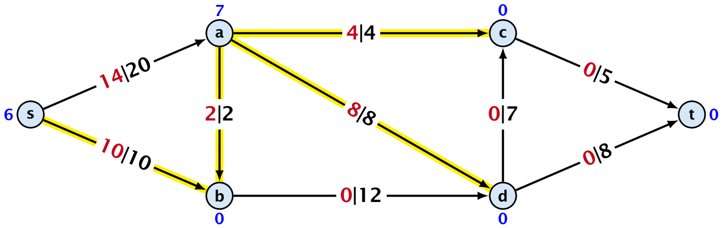
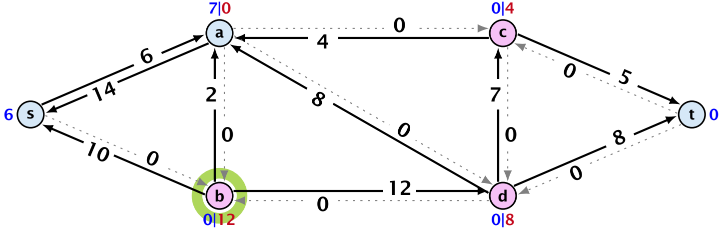


relabel to 1



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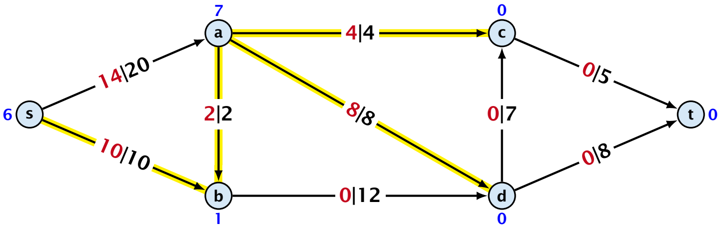

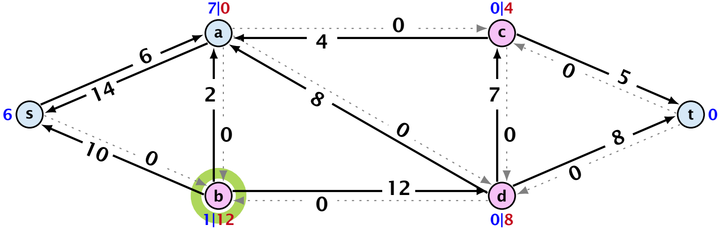

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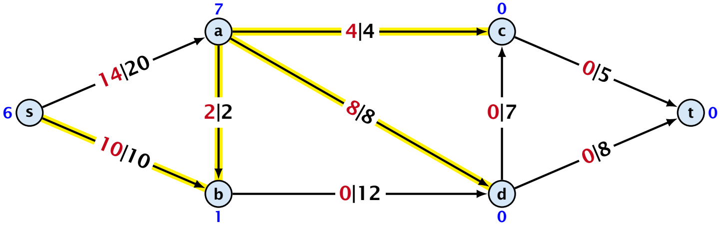
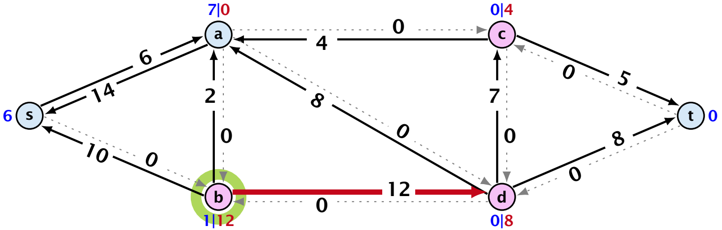


saturating and deactivating push



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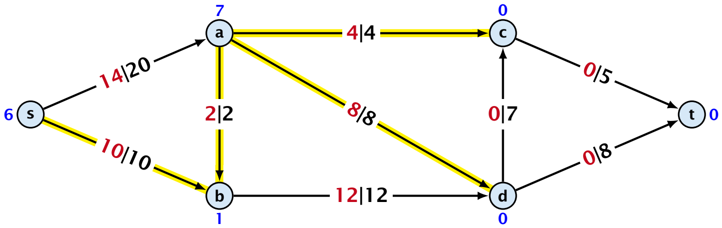

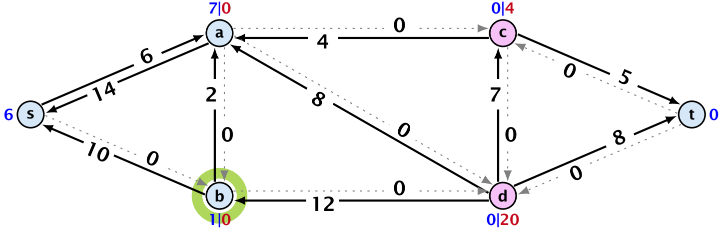

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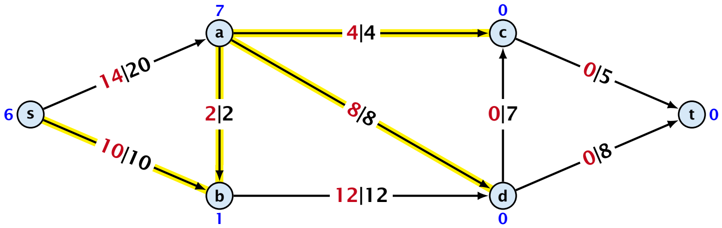

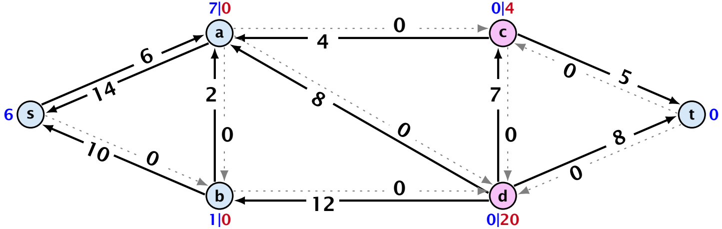

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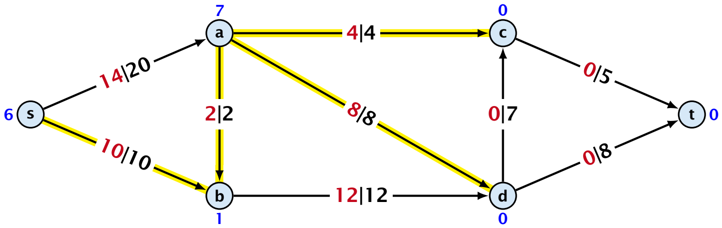

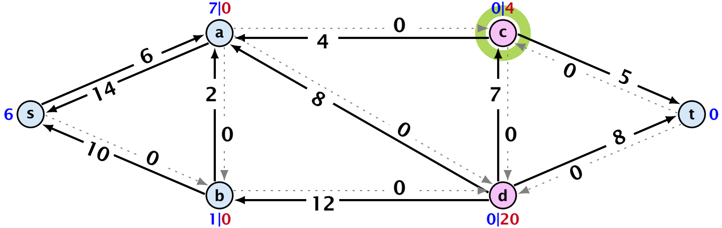

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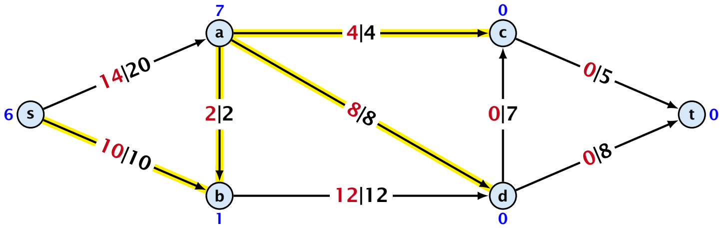
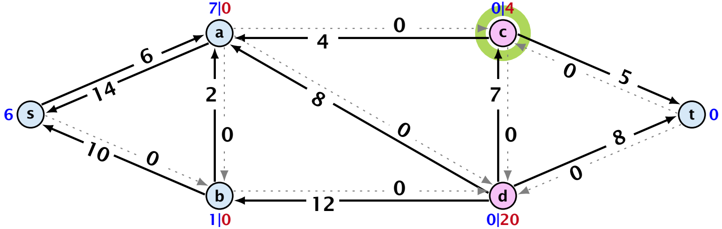


relabel to 1



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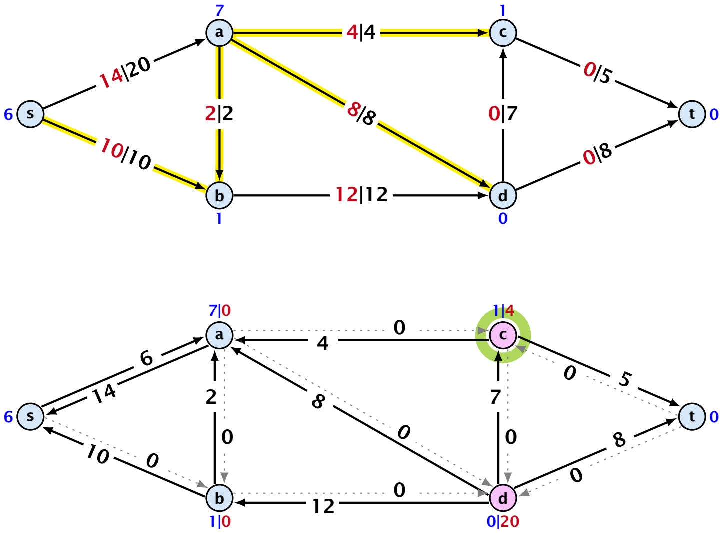

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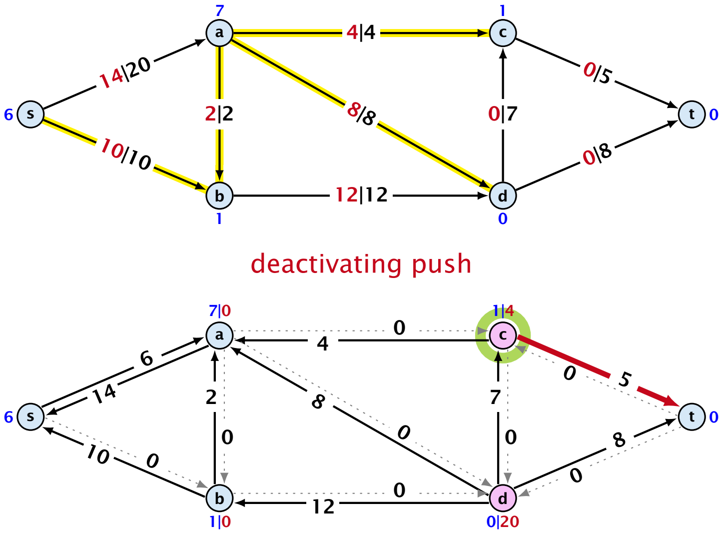

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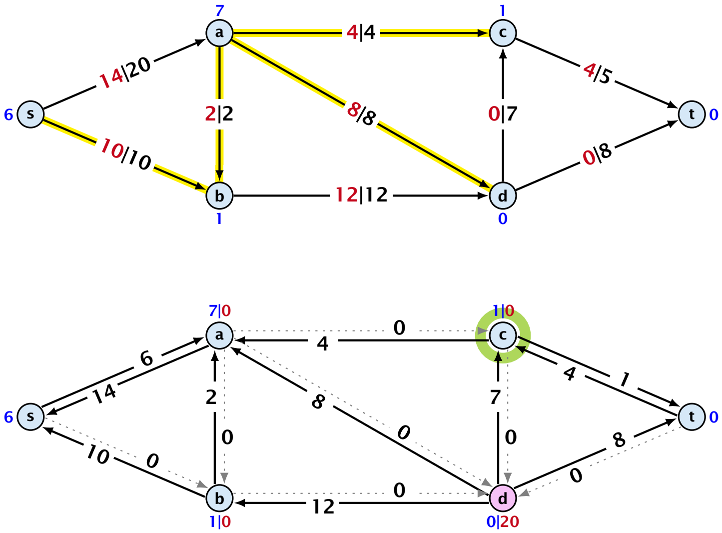

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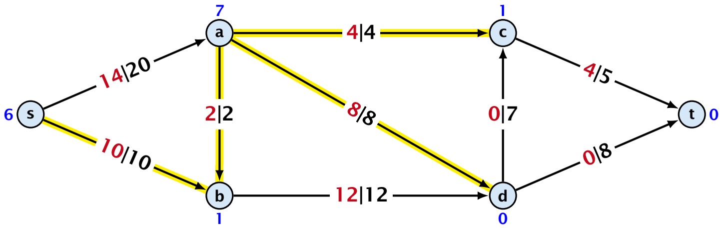

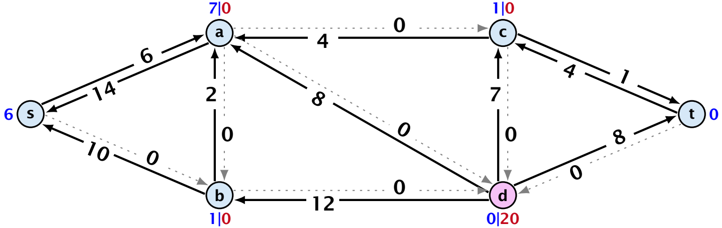

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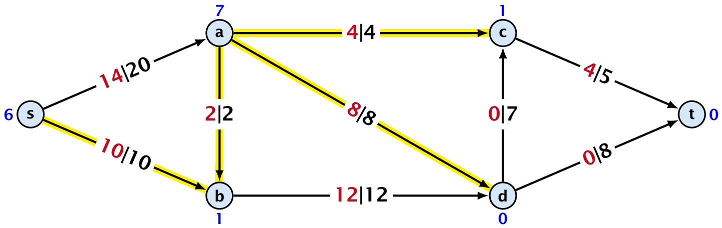

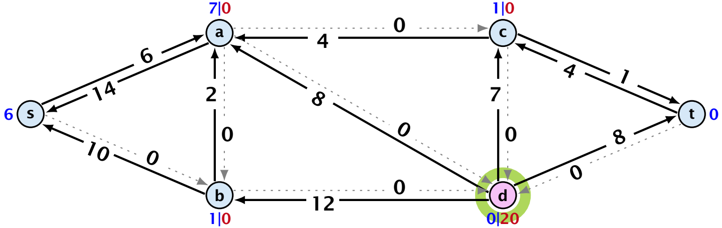

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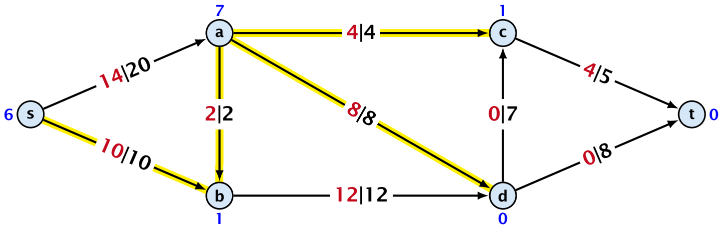

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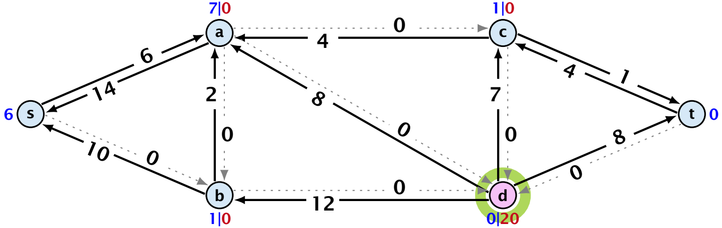

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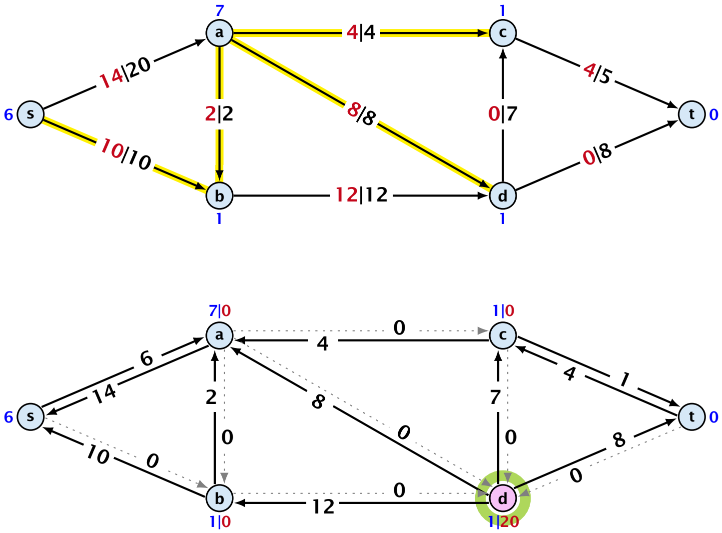

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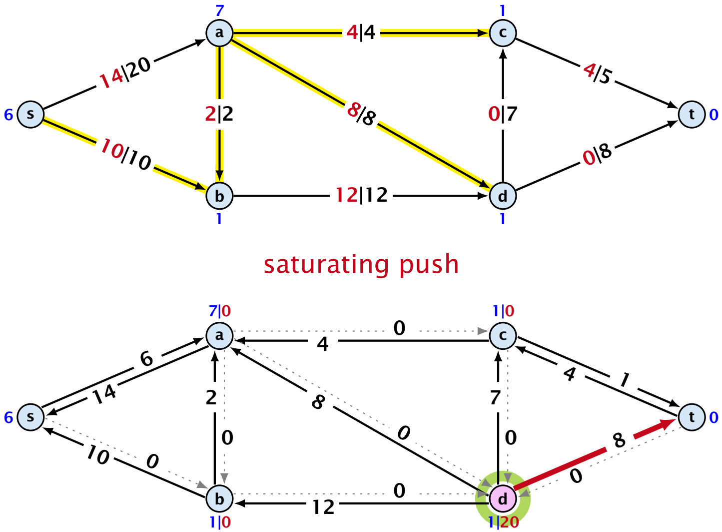

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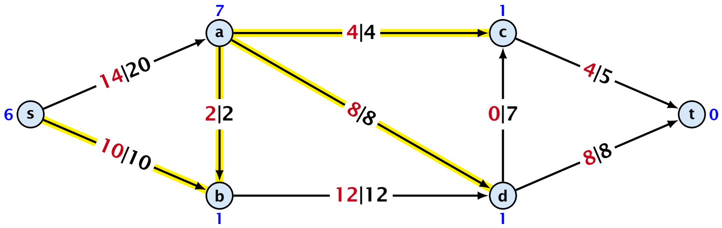

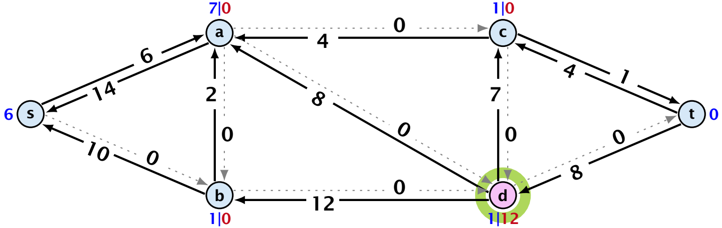

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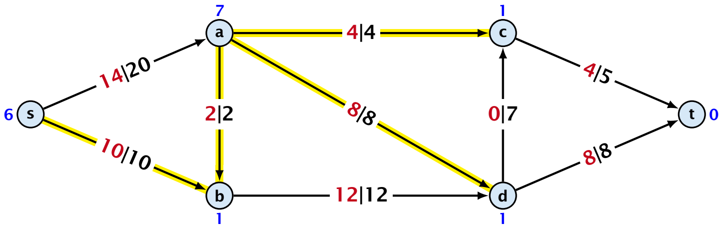

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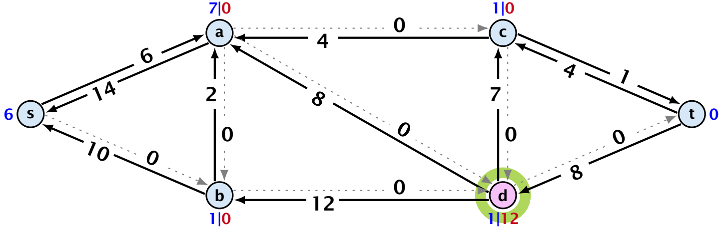

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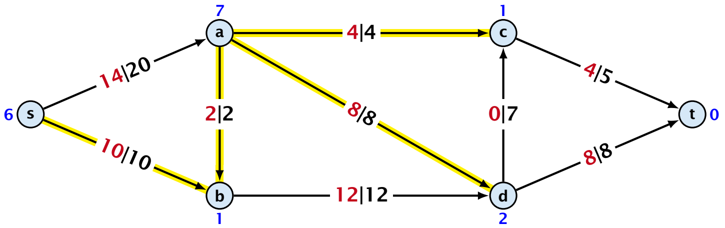

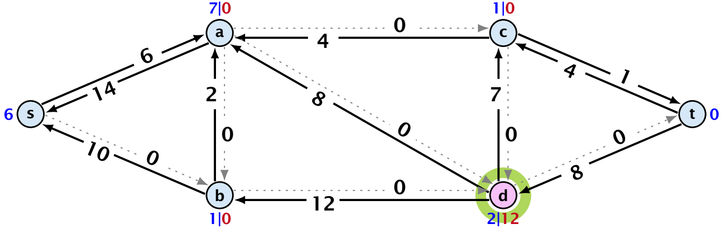

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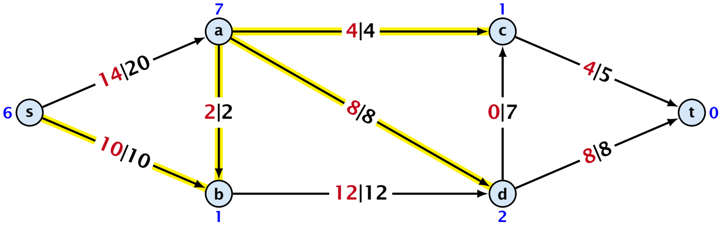
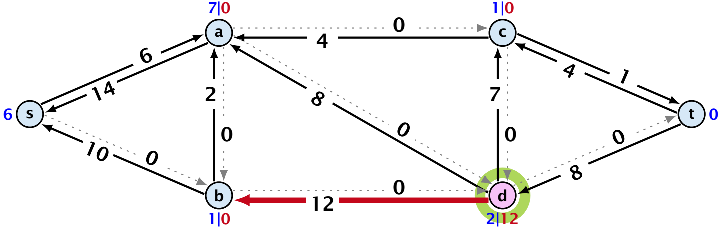


saturating and deactivating push



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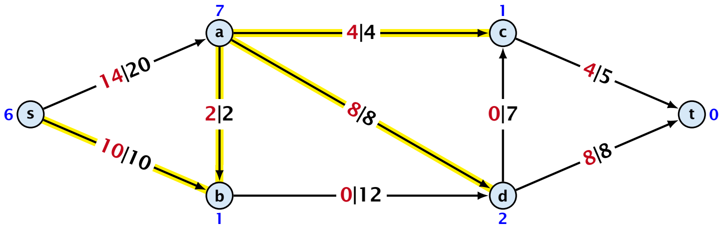

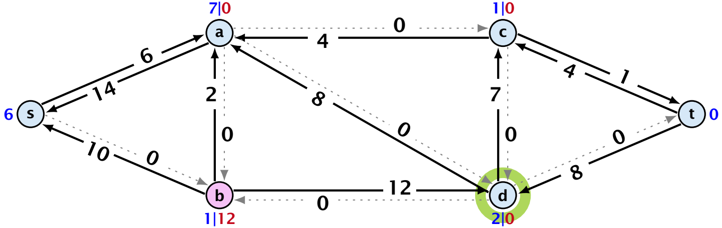

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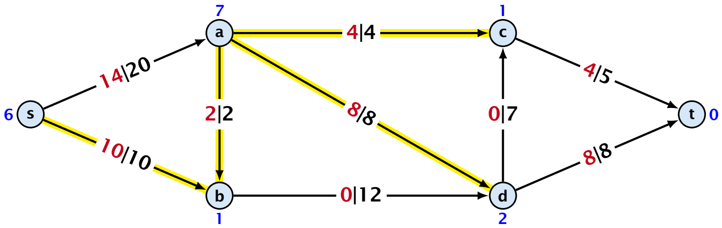

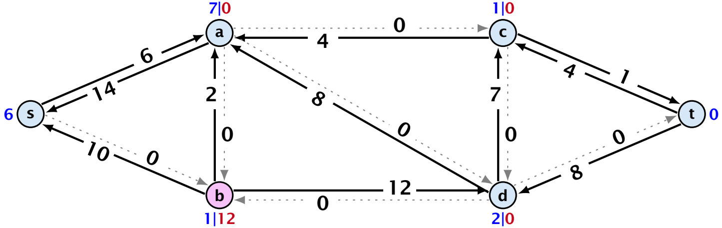

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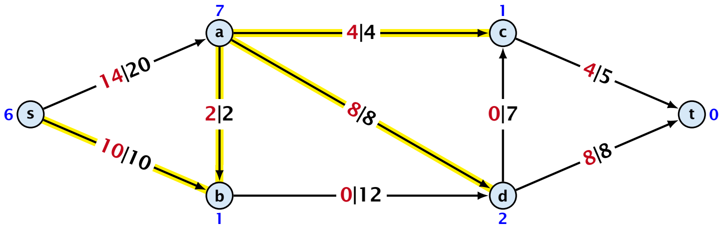

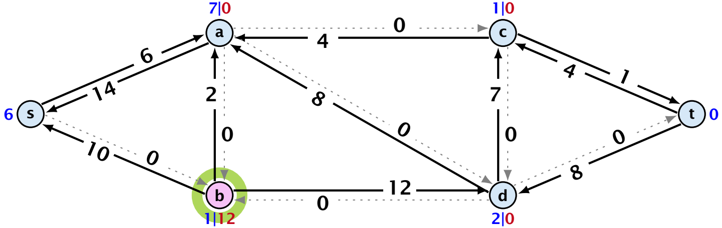

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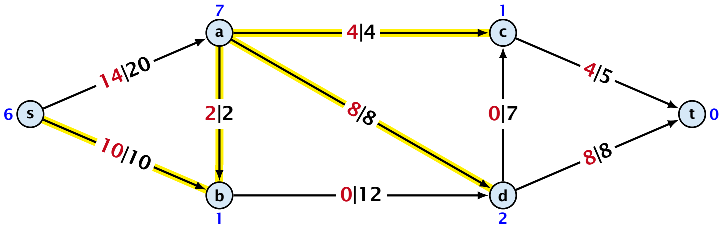
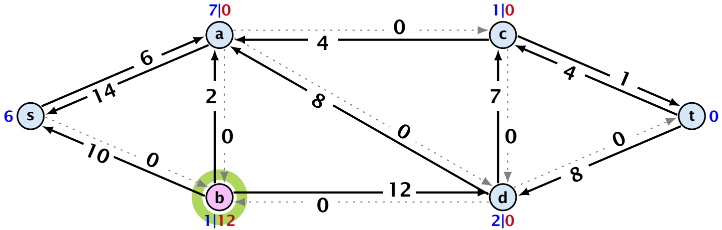


relabel to 3



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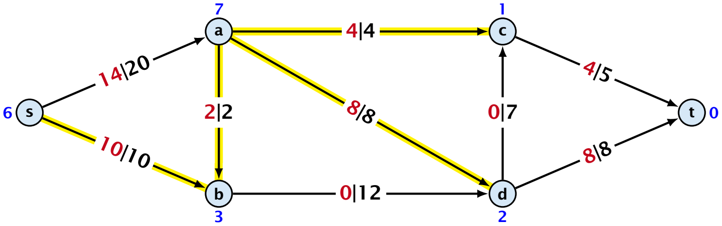

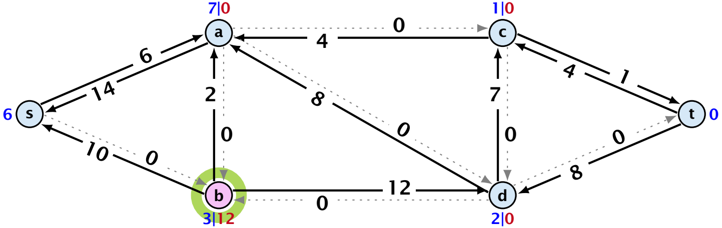

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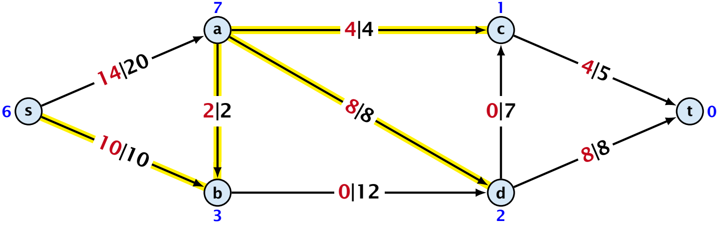
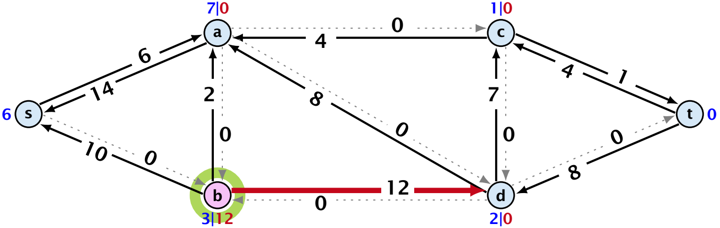


saturating and deactivating push



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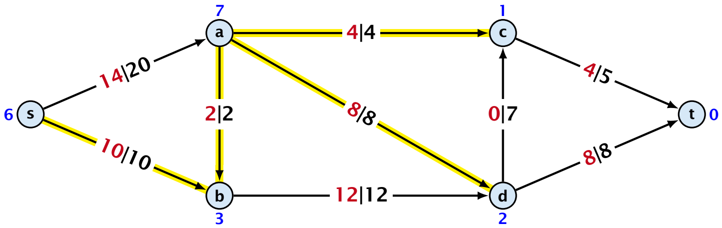

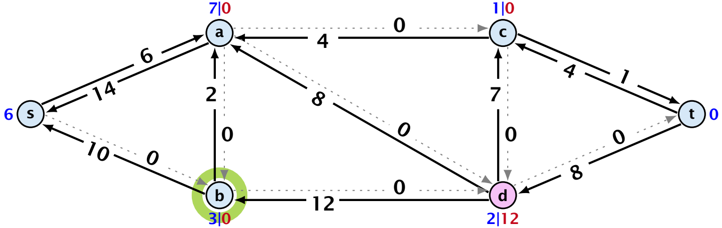

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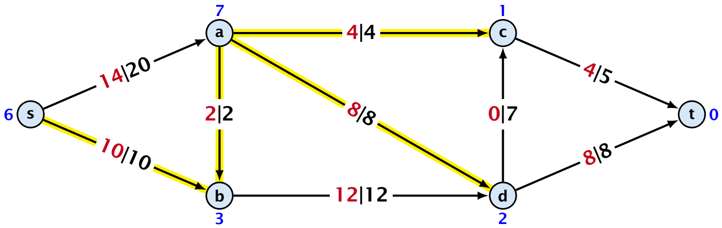

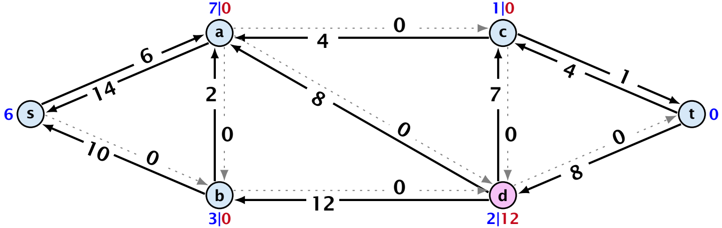

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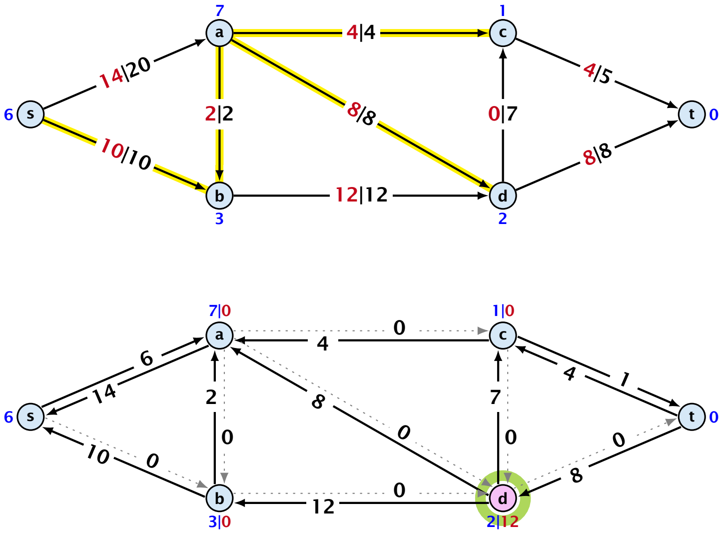

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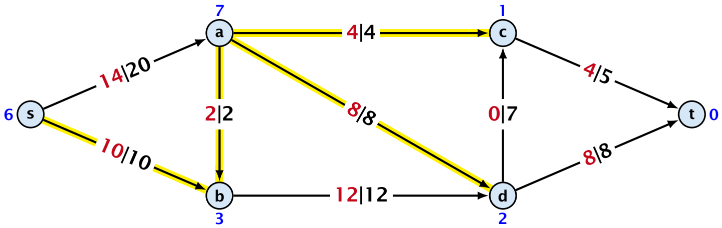
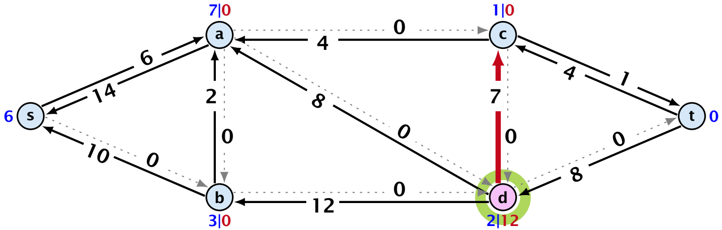


saturating push



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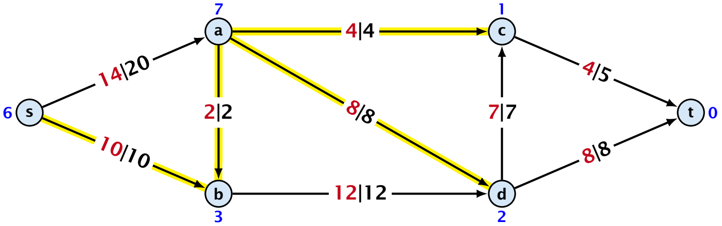

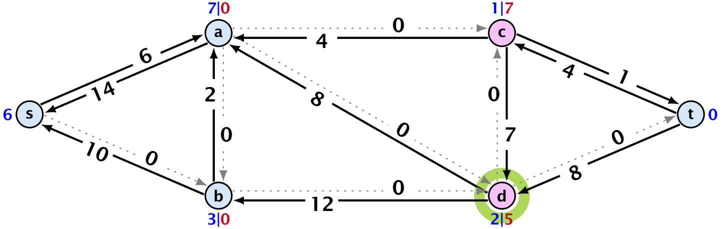

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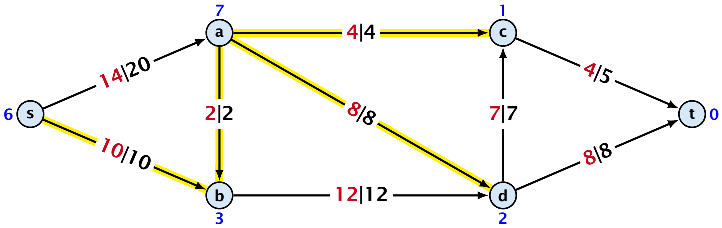
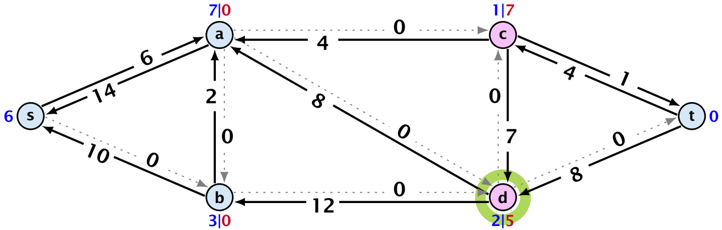


relabel to 4



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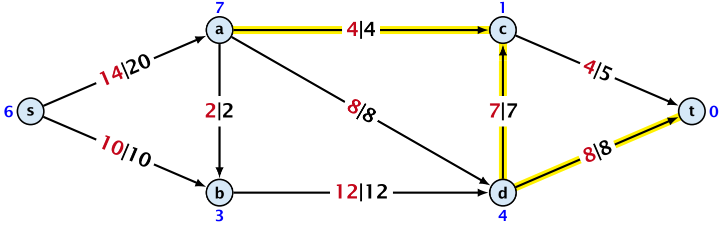

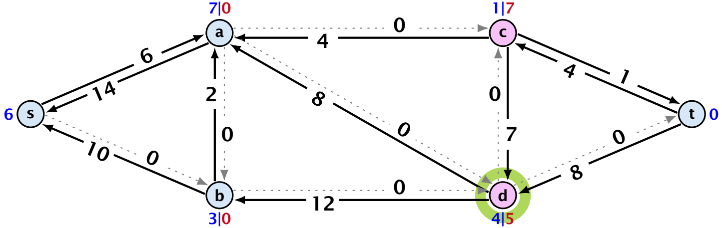

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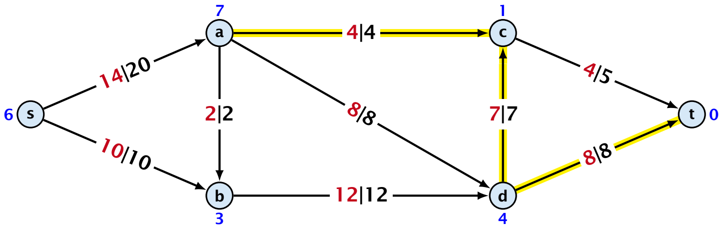
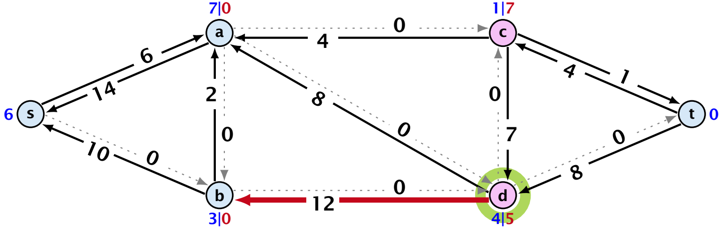


deactivating push



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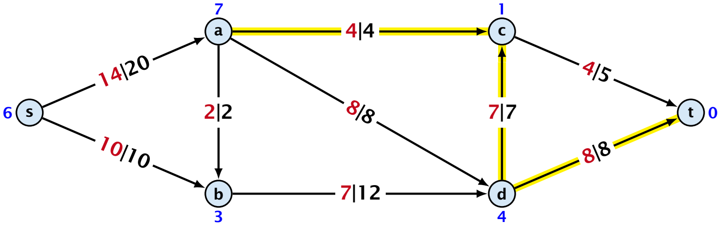

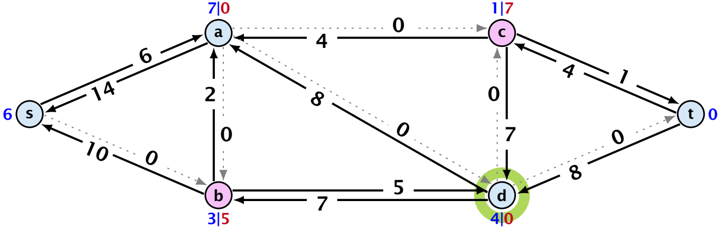

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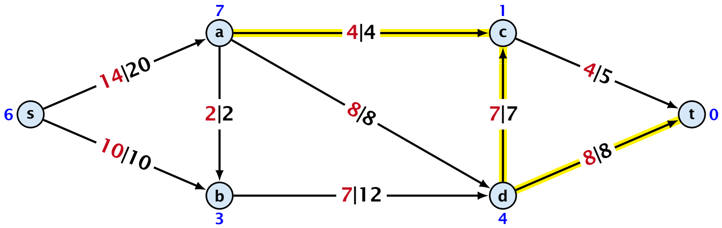

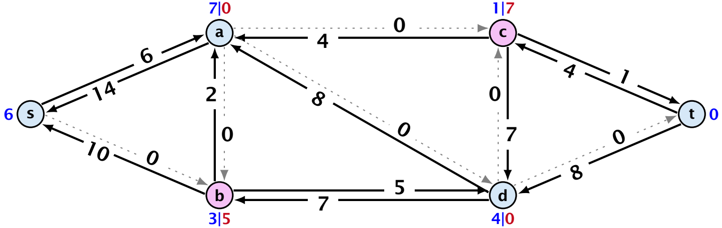

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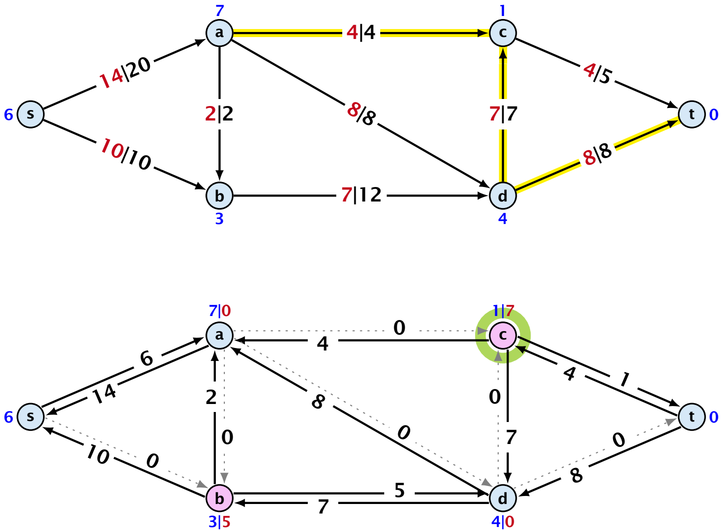

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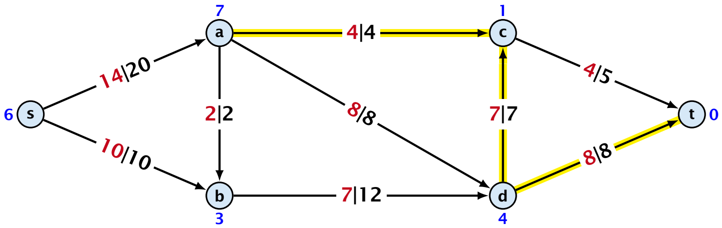
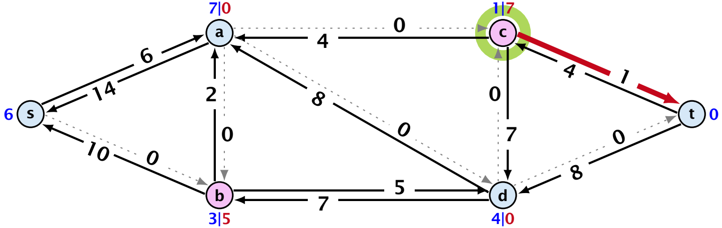


saturating push



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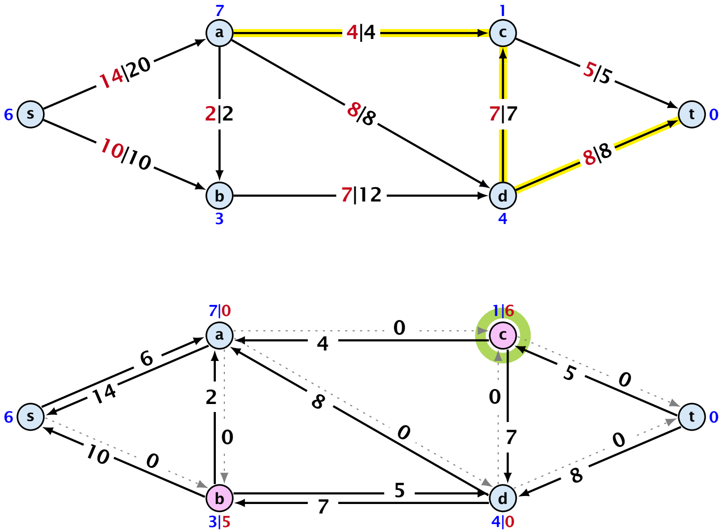

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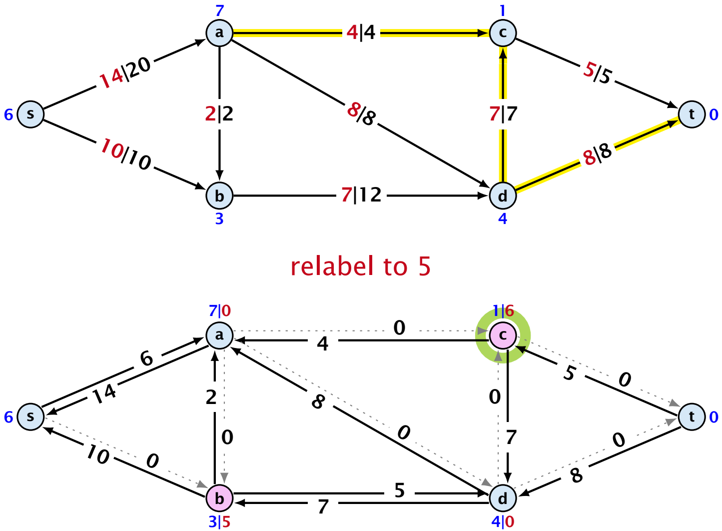

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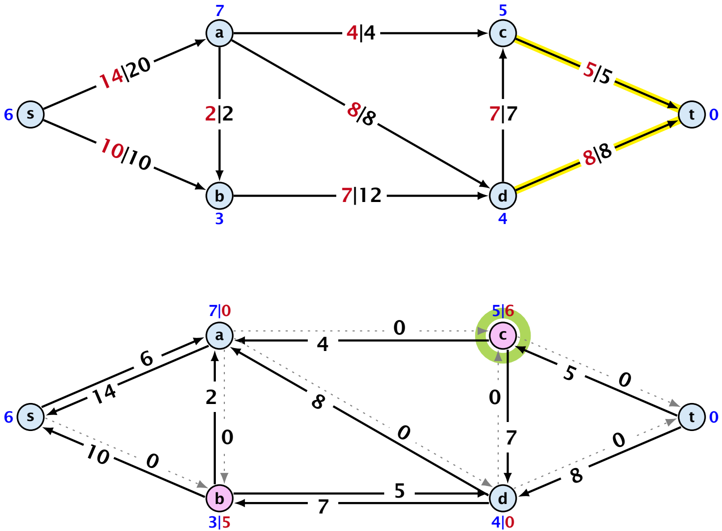

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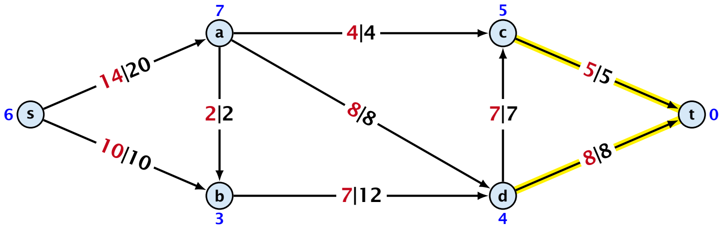
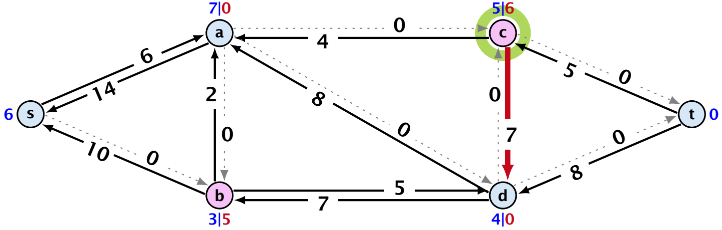


deactivating push



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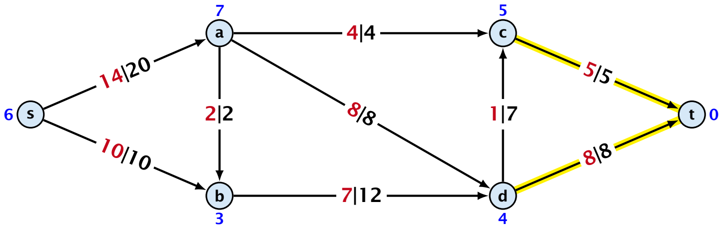

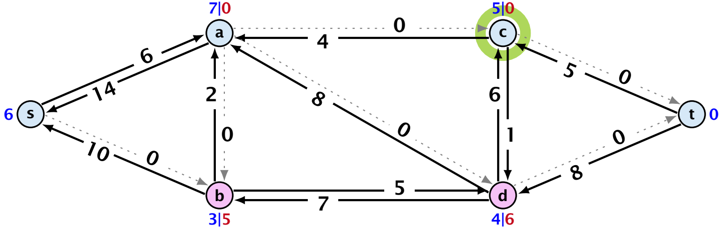

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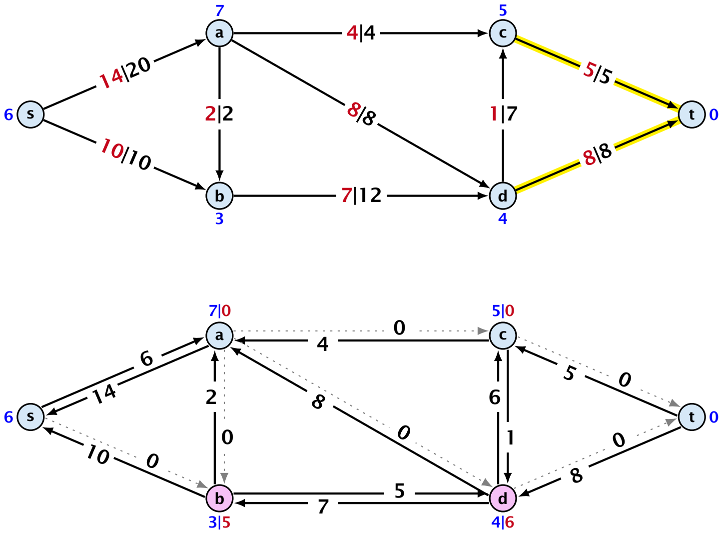

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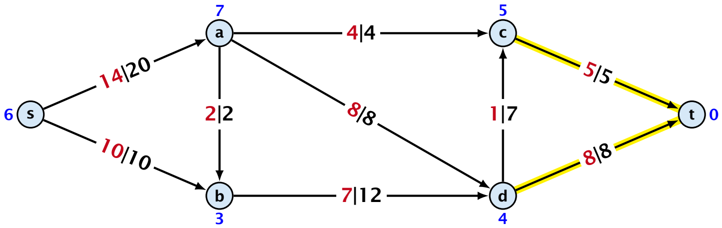

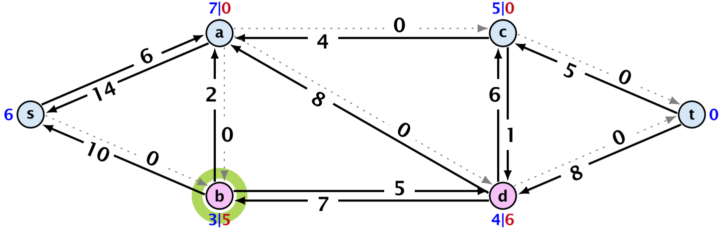

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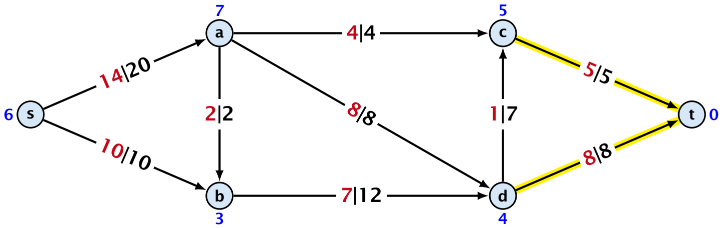
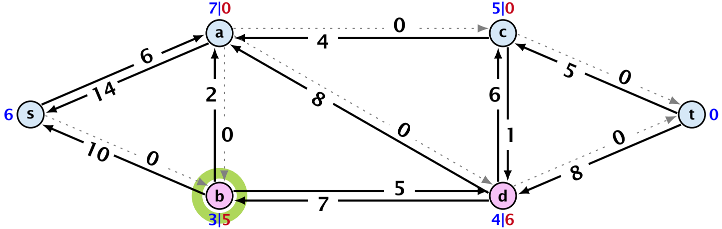


relabel to 5



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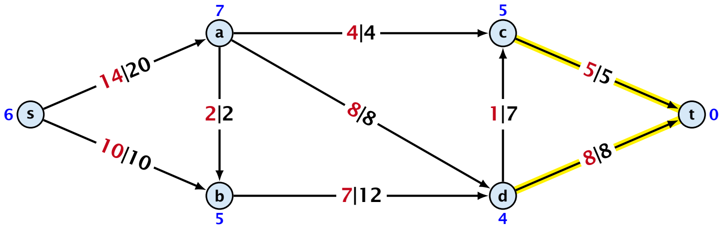

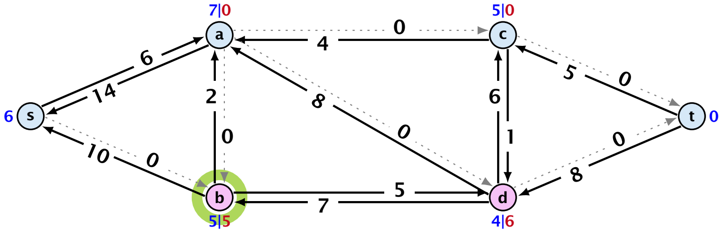

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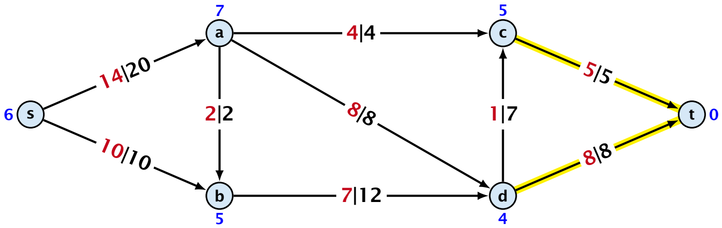
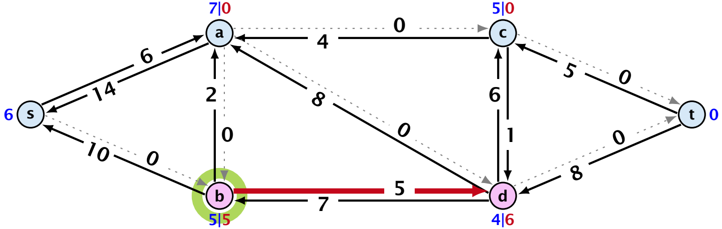


saturating and deactivating push



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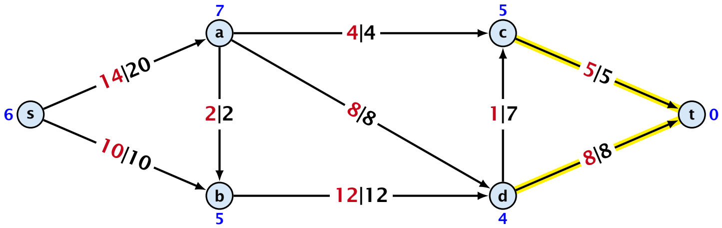

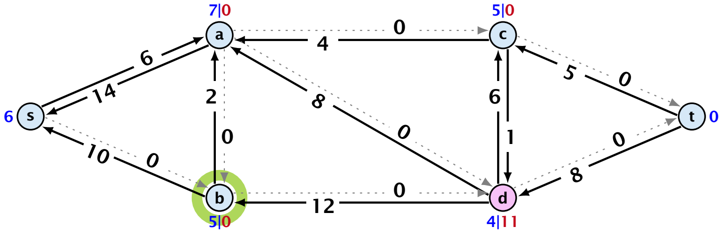

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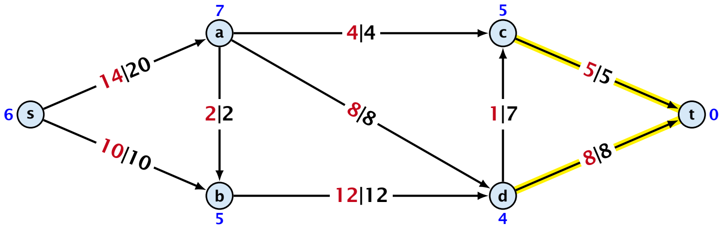

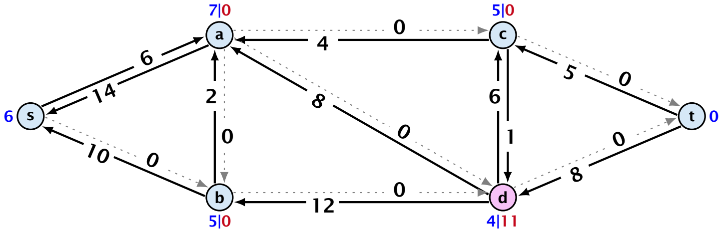

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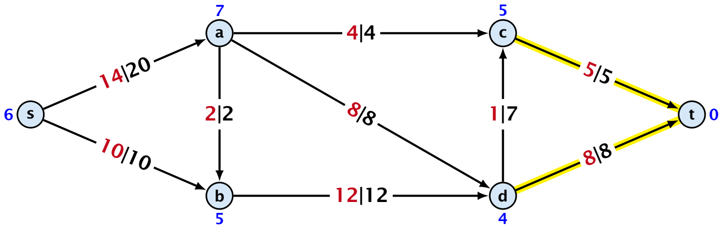

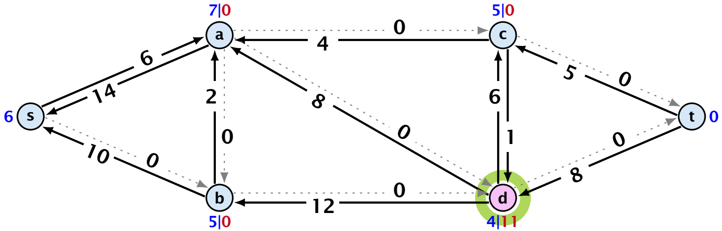

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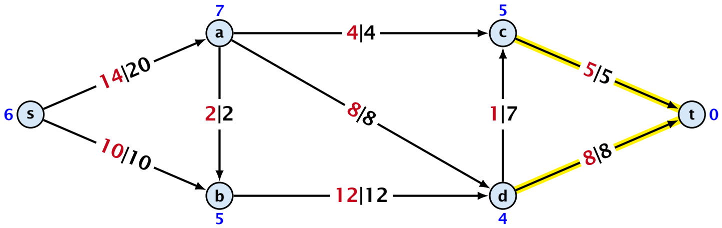

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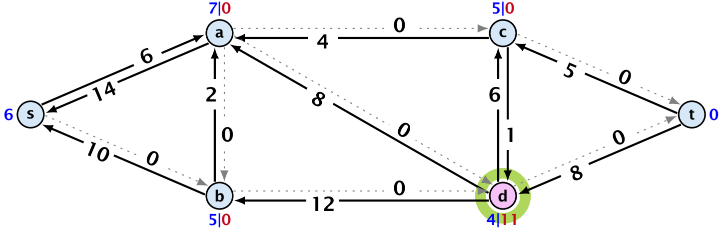

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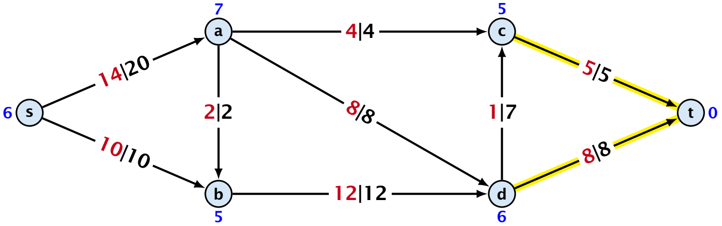

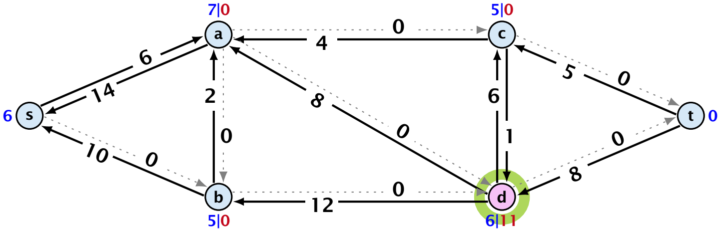

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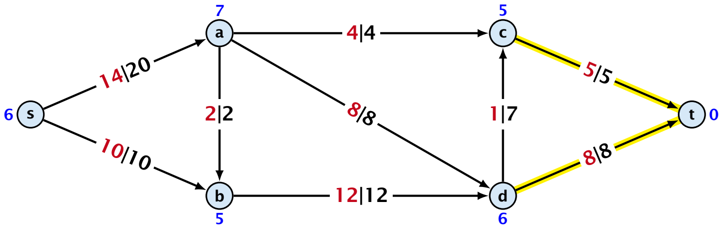

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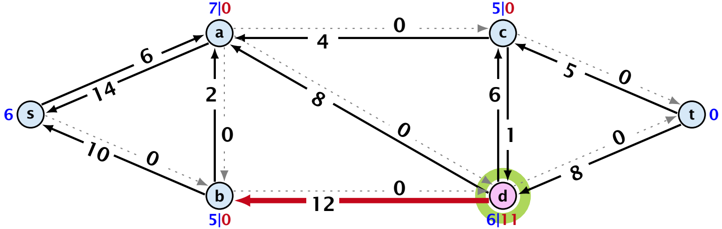

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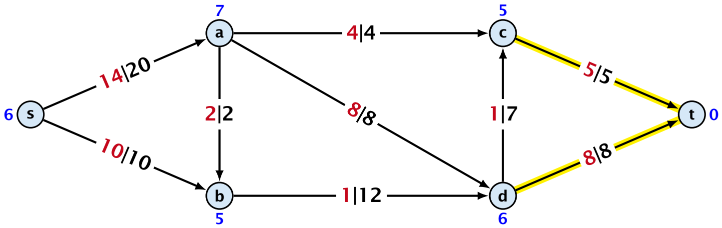

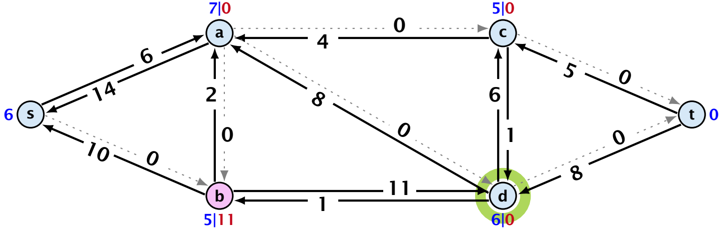

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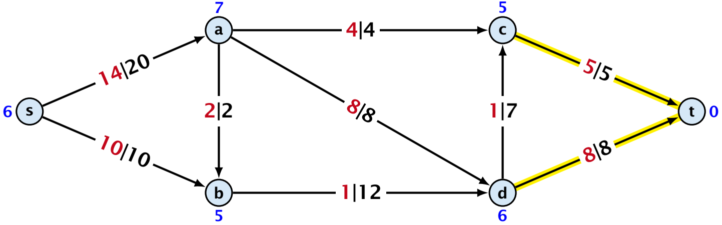

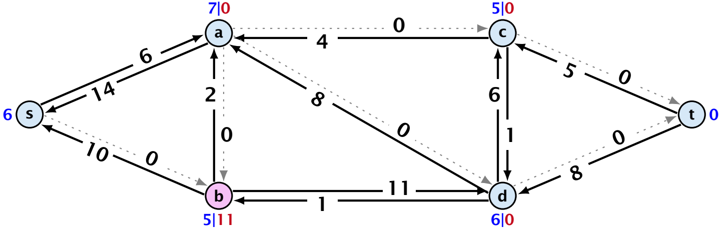

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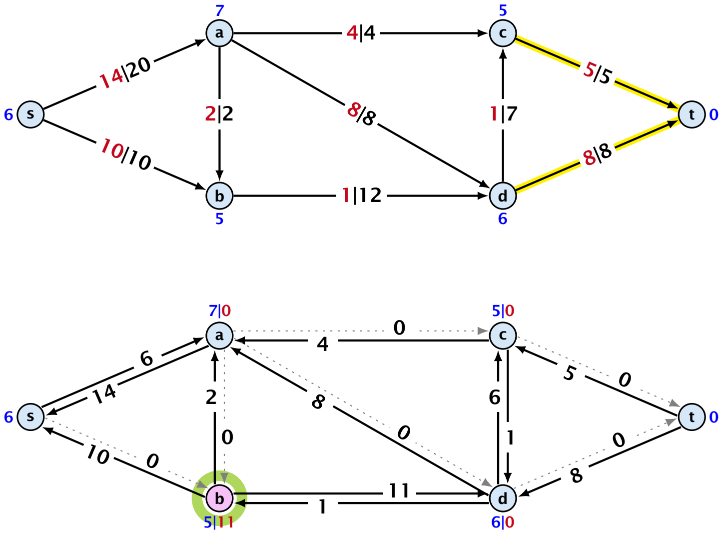

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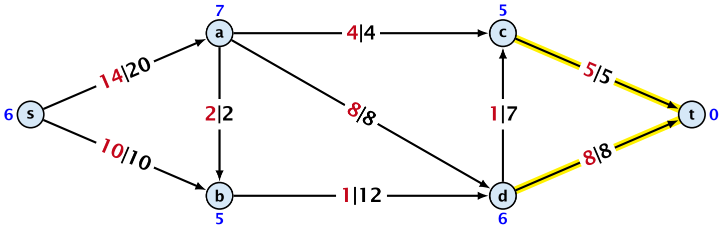

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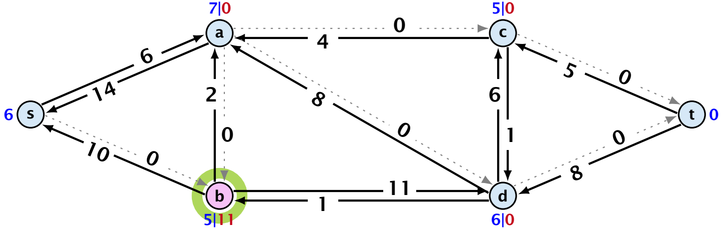

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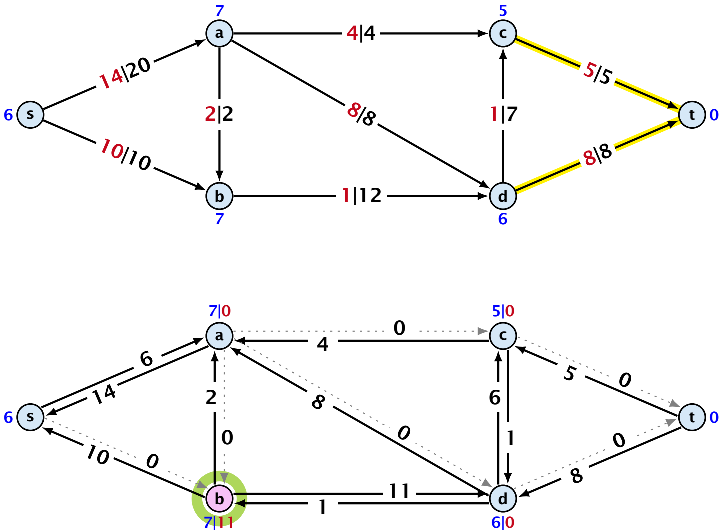

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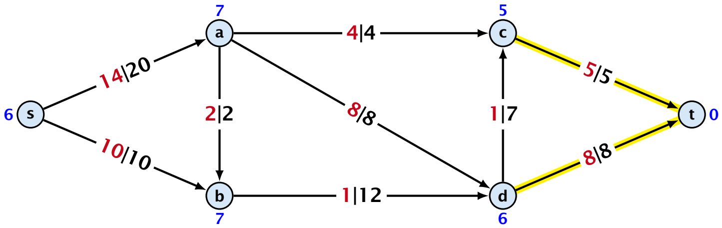

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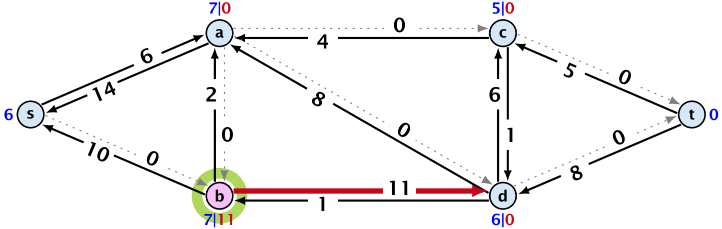

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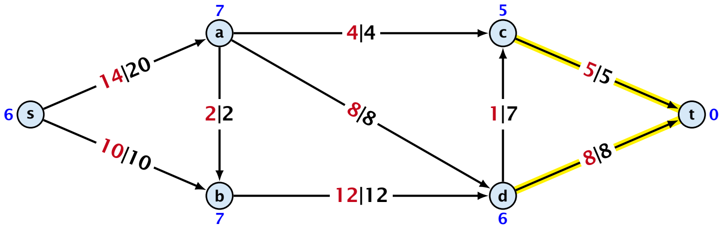

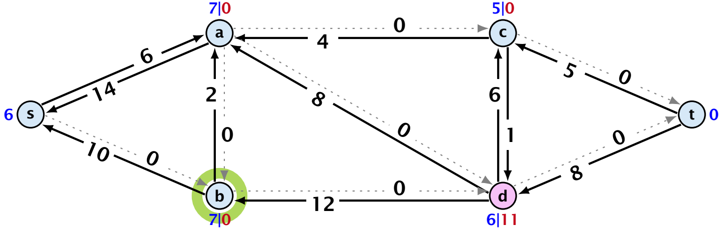

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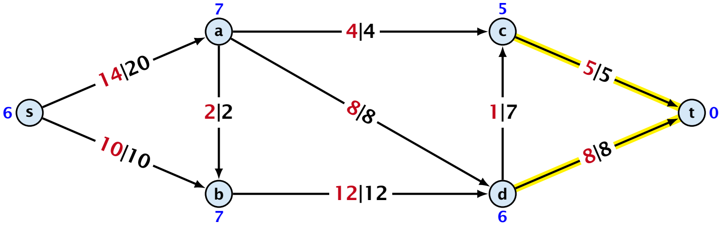

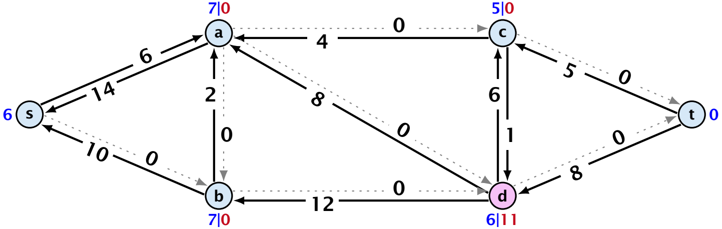

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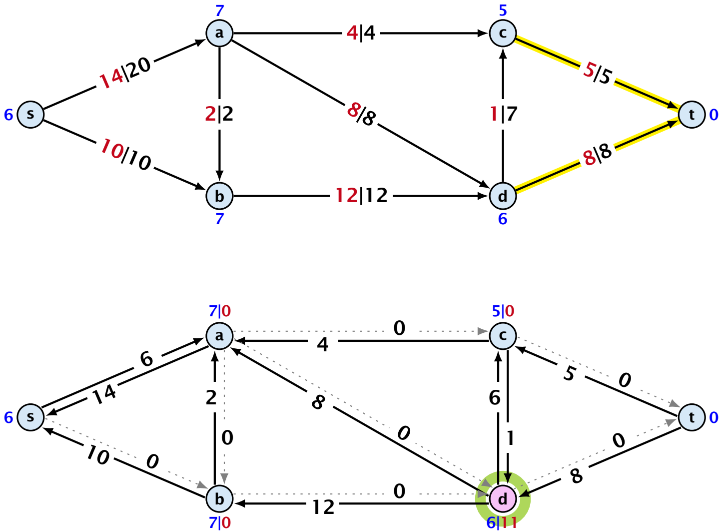

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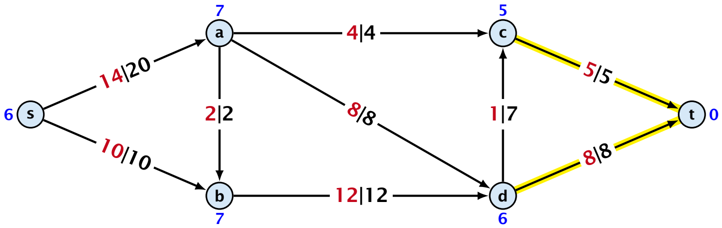

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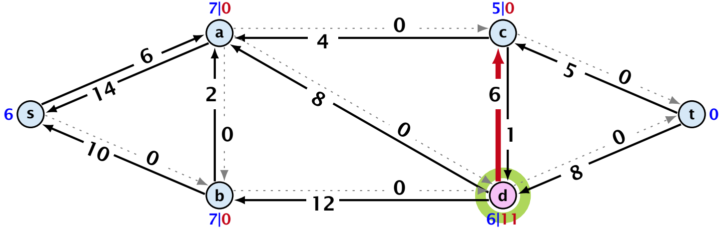

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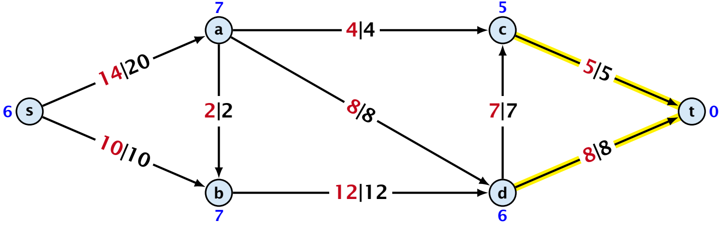

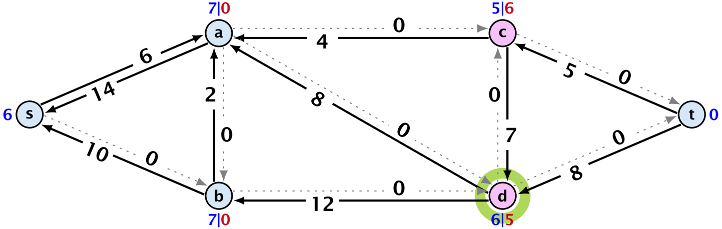

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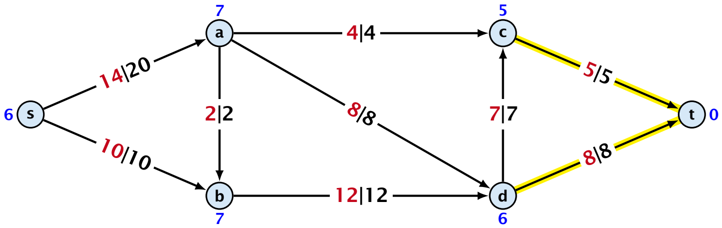

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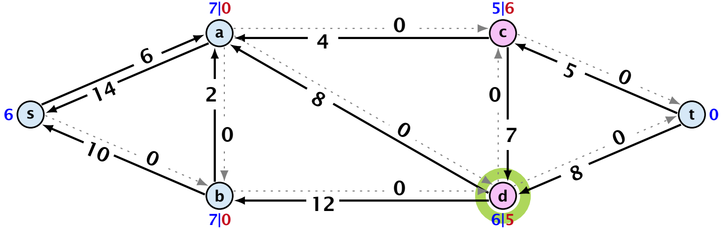

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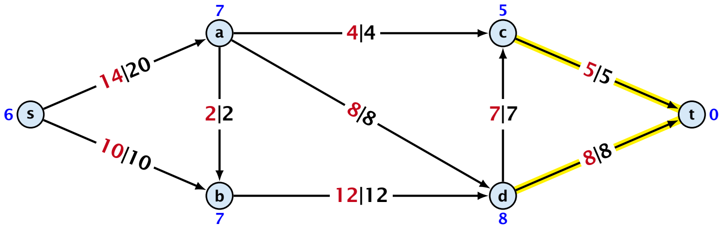

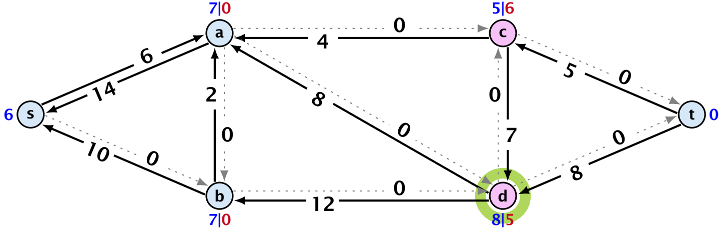

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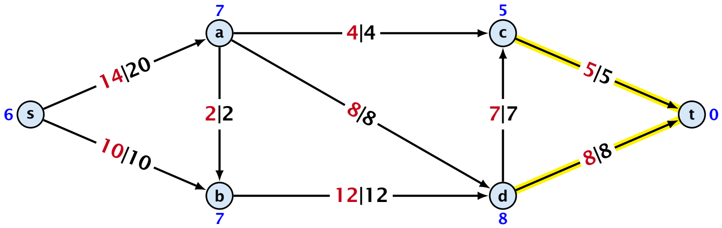

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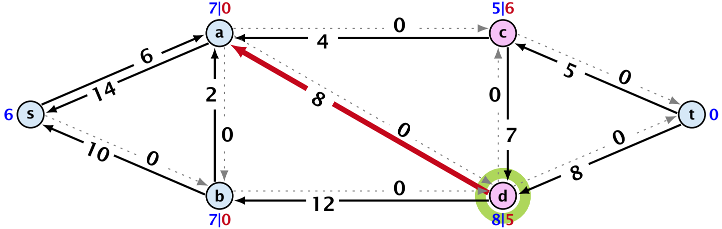

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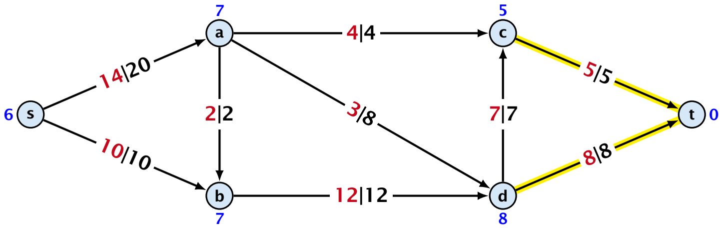

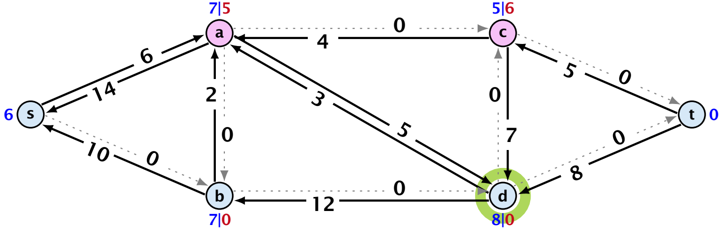

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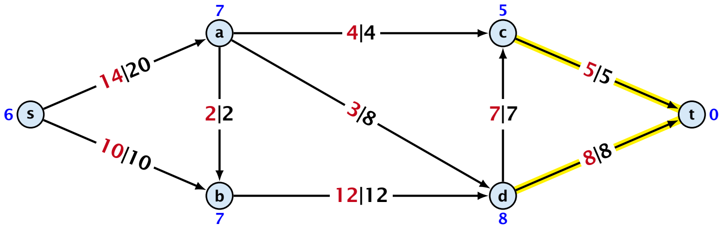

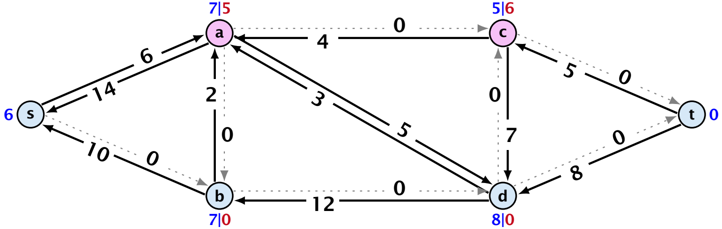

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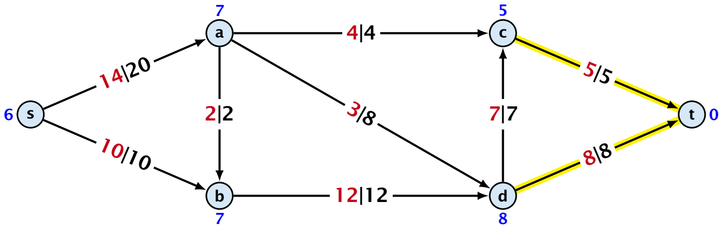

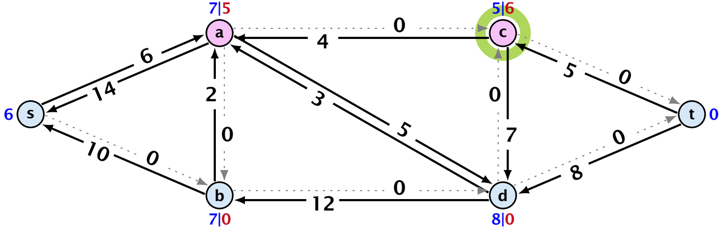

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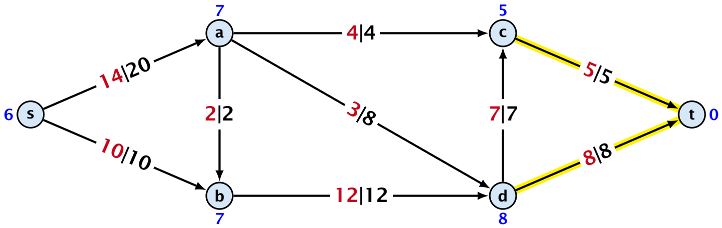

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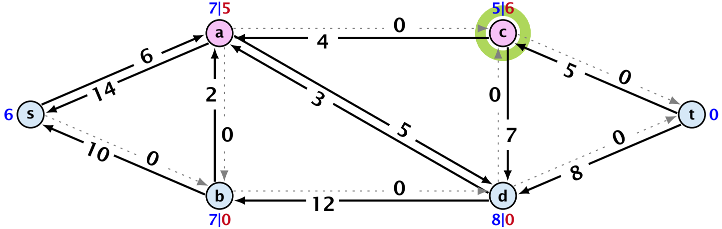

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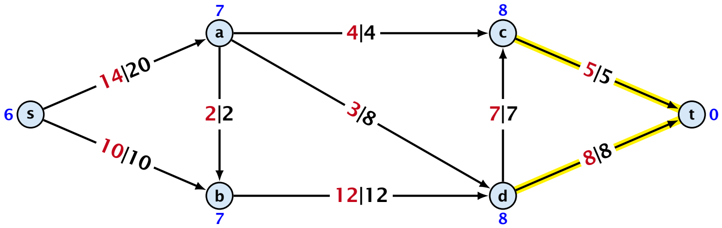

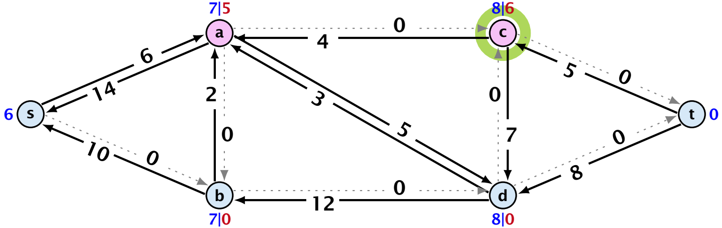

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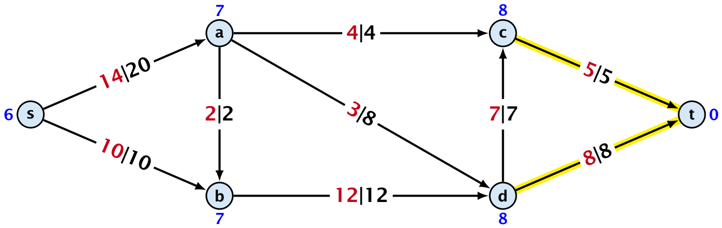

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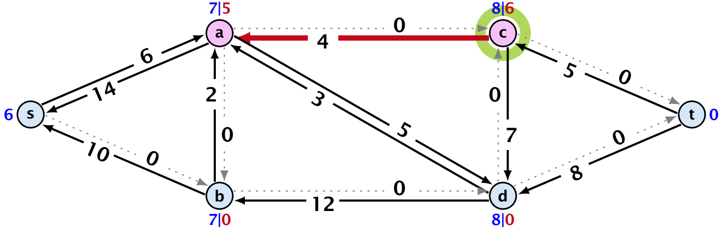

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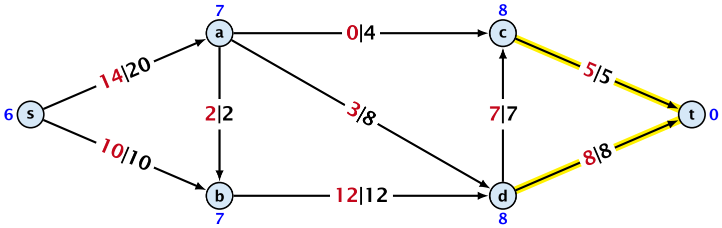

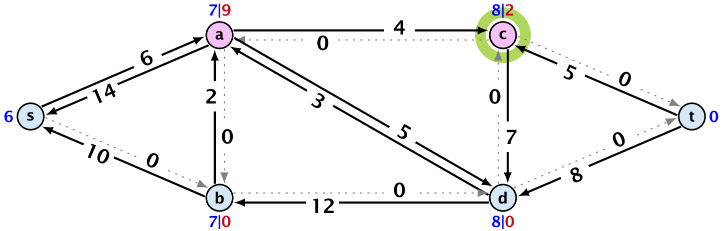

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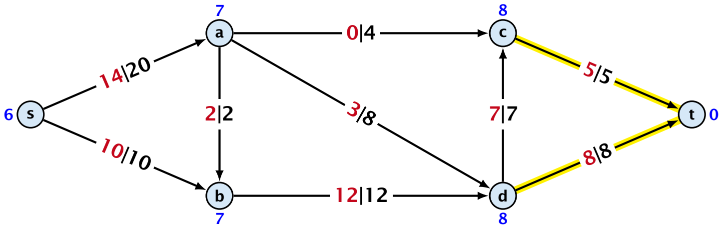

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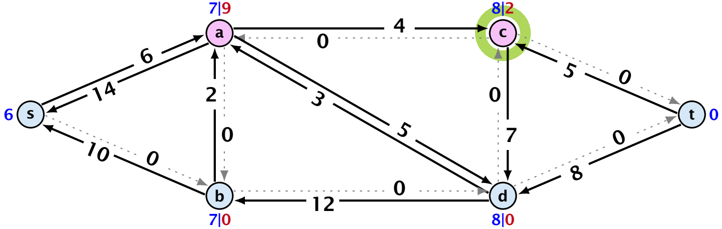

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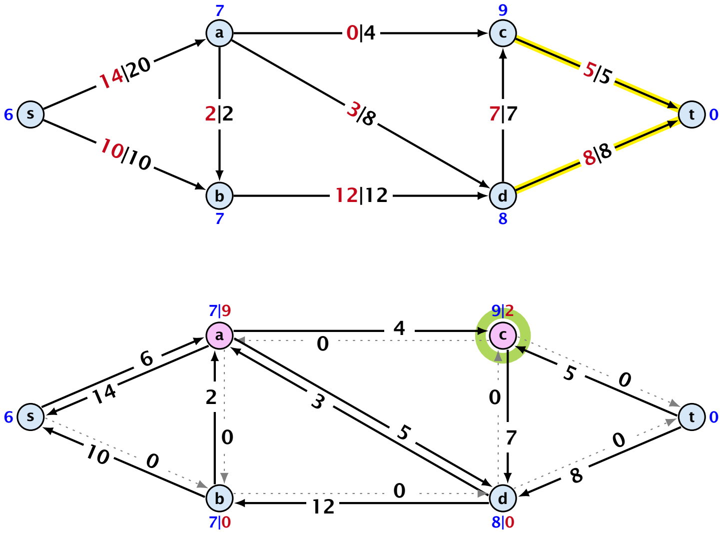

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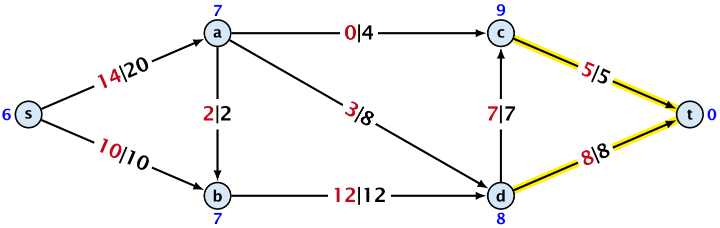

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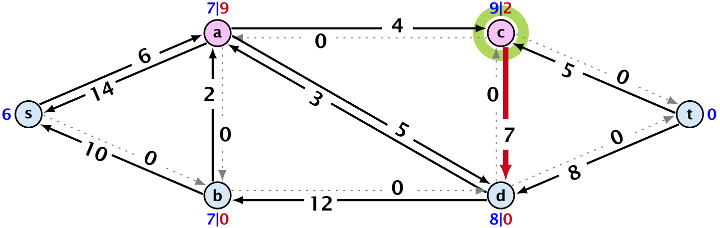

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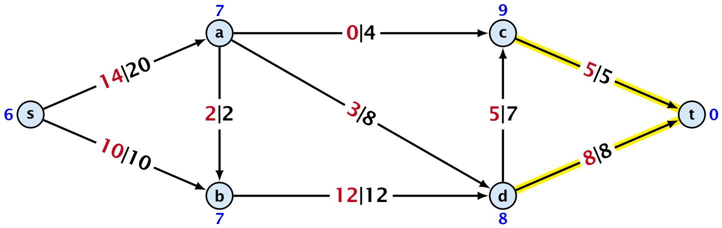

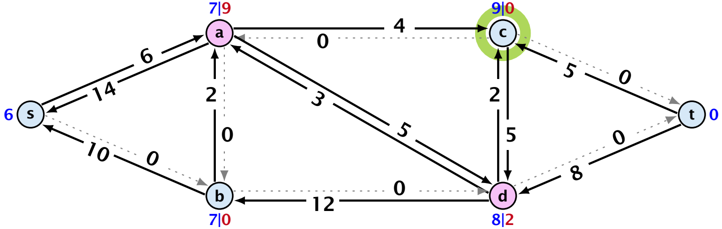

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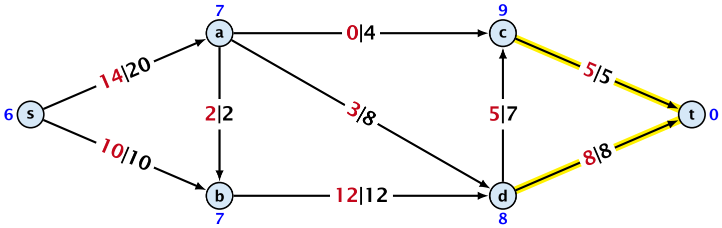

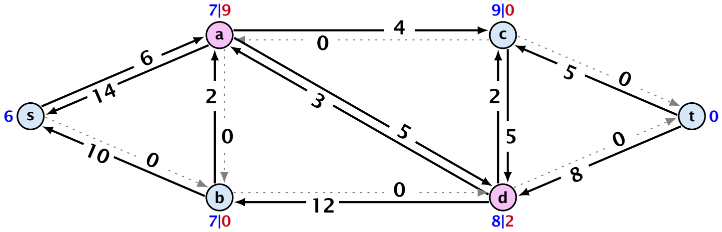

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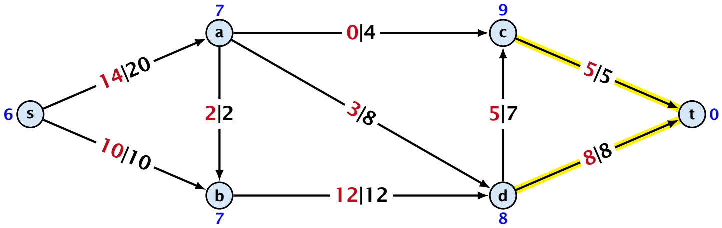

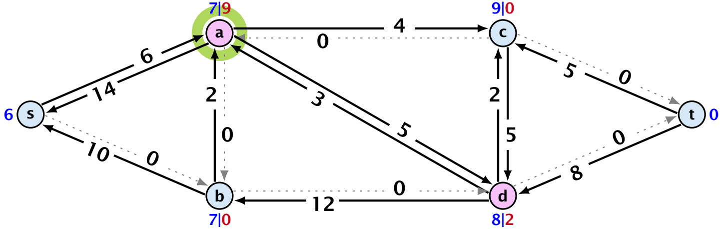

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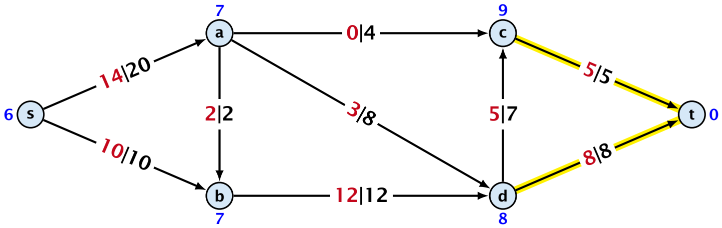

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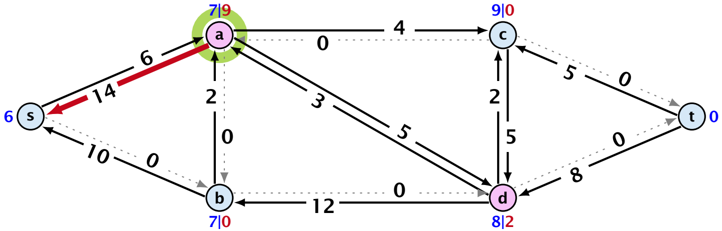

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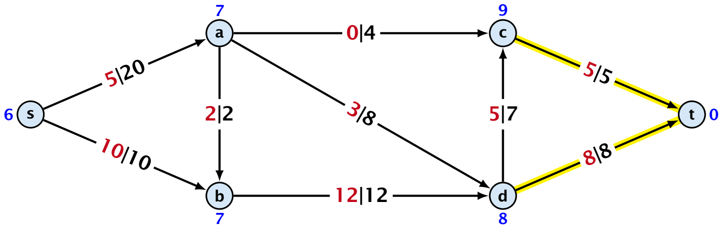

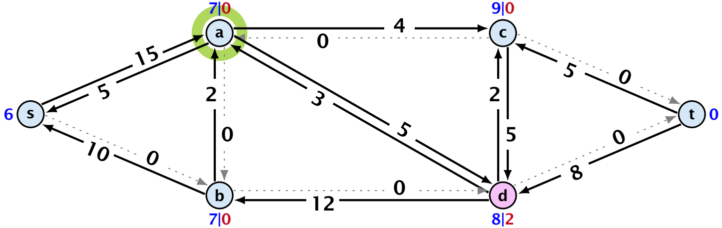

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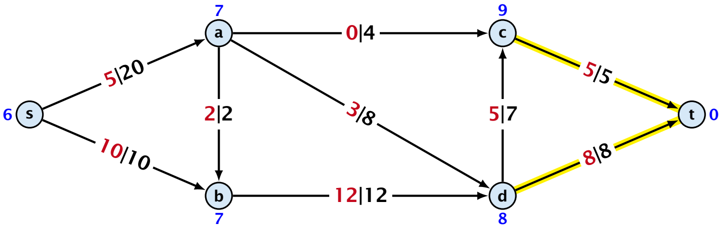

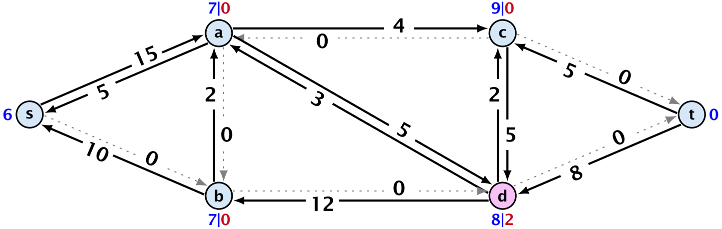

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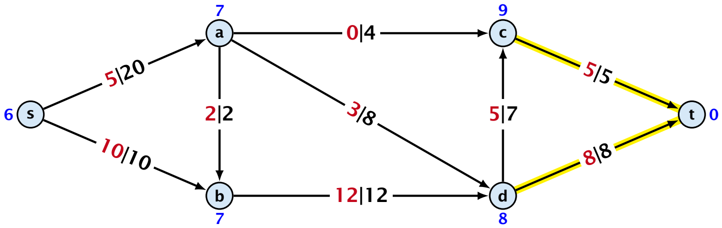

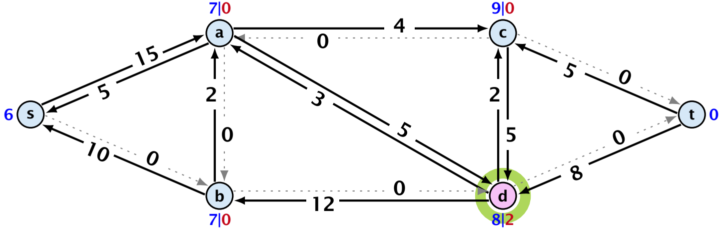

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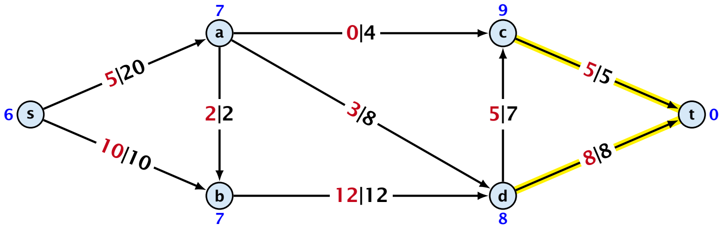

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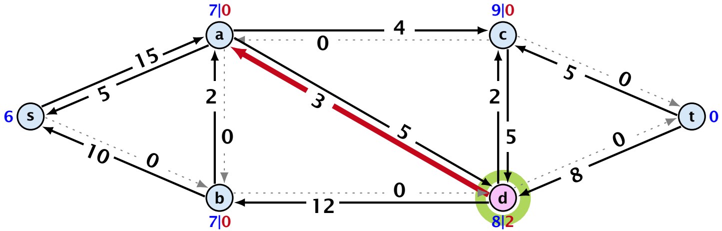

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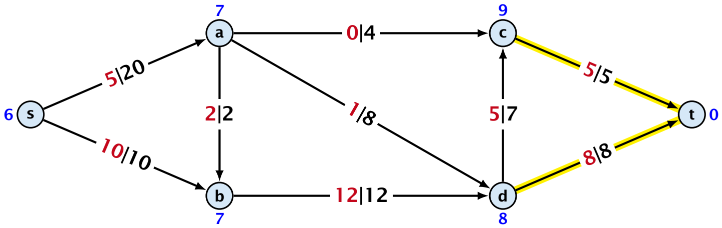
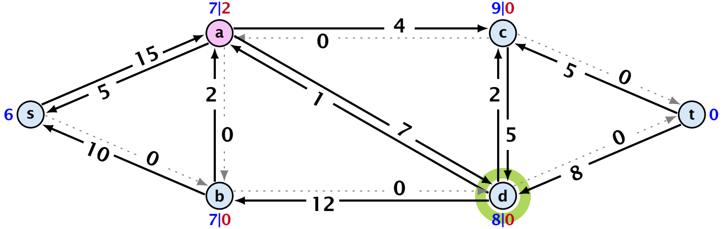
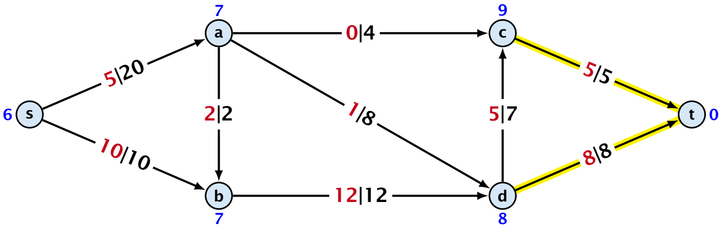
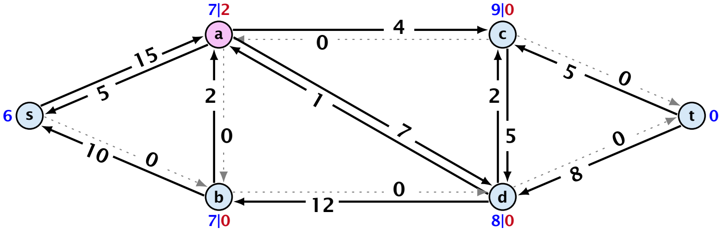




Preflow Push





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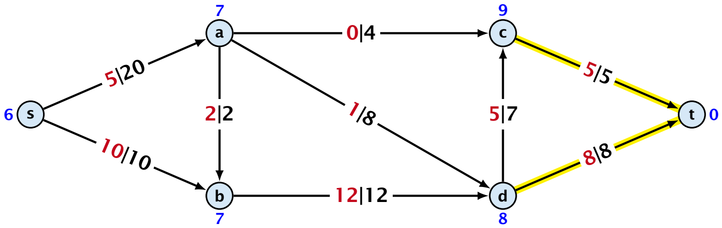

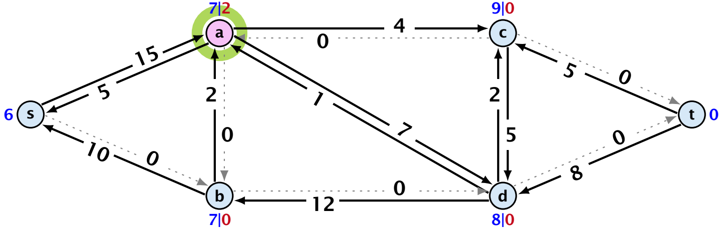

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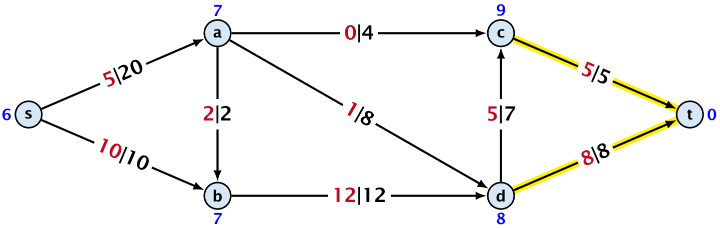
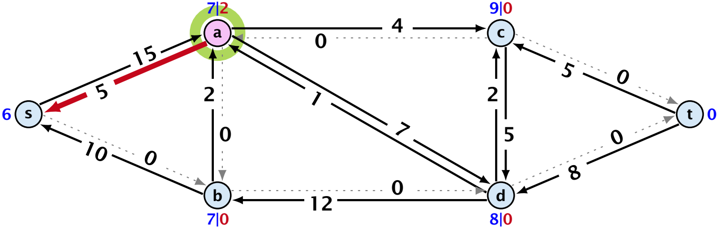


deactivating push



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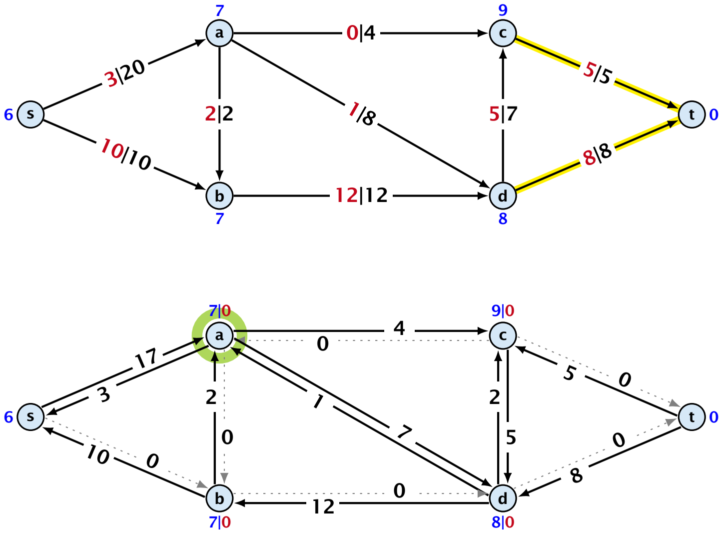

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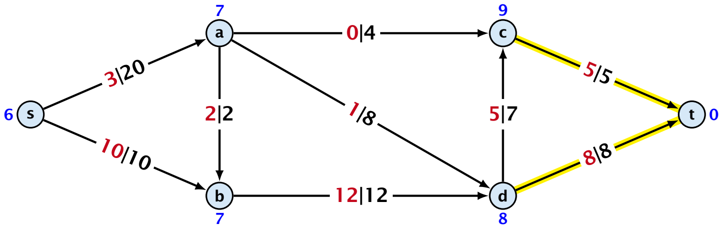

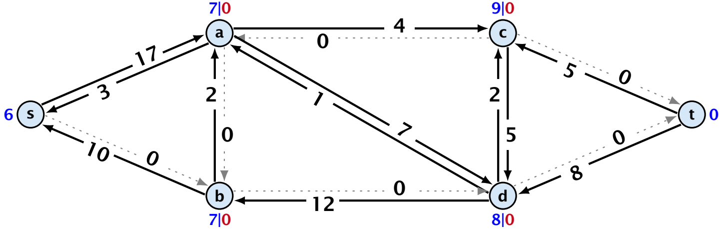

Analysis

Lemma 69

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

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- In the residual graph there are no edges into A, and, hence, no edges leaving A/entering B can carry any flow.

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- 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

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

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

Analysis

Lemma 70
The label of a node cannot become larger than $2n-1$.

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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.

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

Analysis

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

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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 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,

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

Analysis

Theorem 74
There is an implementation of the generic push relabel algorithm with running time $\mathcal{O}(n^2m)$.

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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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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

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

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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)

```
while u is active do
    v ← u.current-neighbour
    if v = null then
        relabel(u)
        u.current-neighbour ← u.neighbour-list-head
    else
        if (u, v) admissible then push(u, v)
        else u.current-neighbour ← v.next-in-list
```

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

Lemma 75

If $v = \mathrm{null}$ 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 ($v = \mathrm{null}$) all edges are not admissible. □

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