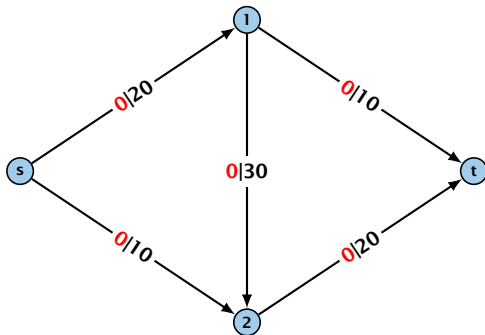


11 Augmenting Path Algorithms

Greedy-algorithm:

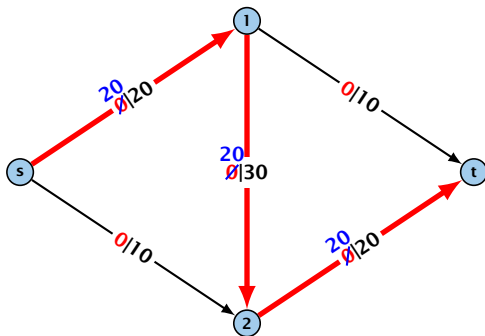
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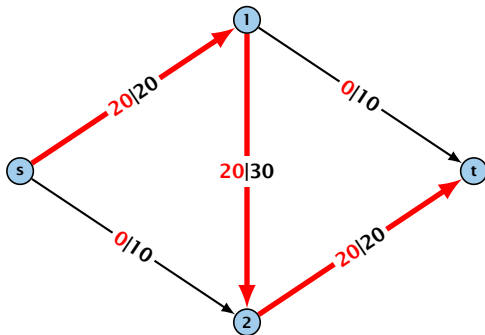
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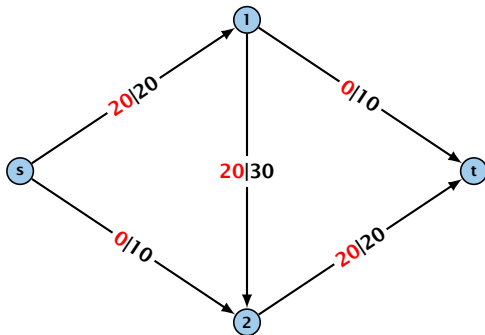
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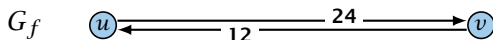
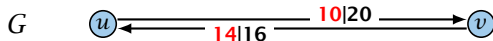
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Augmenting Path Algorithm

Definition 1

An **augmenting path** with respect to flow f , is a path from s to t in the auxiliary graph G_f that contains only edges with non-zero capacity.

Algorithm 1 FordFulkerson($G = (V, E, c)$)

- 1: Initialize $f(e) \leftarrow 0$ for all edges.
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Augmenting Path Algorithm

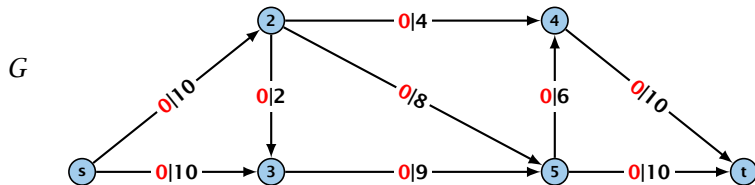
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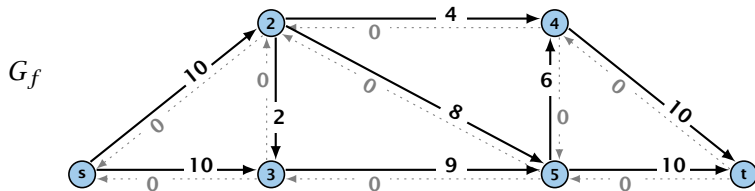
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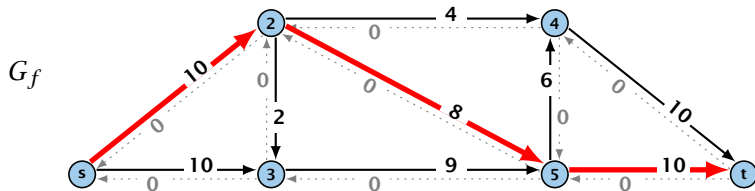
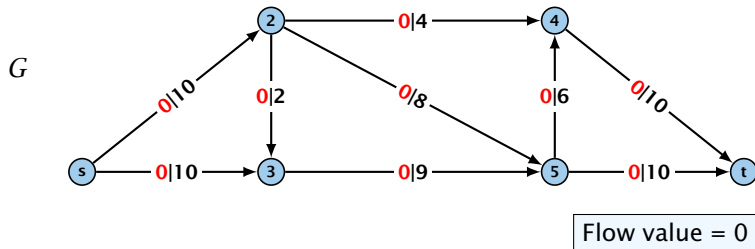
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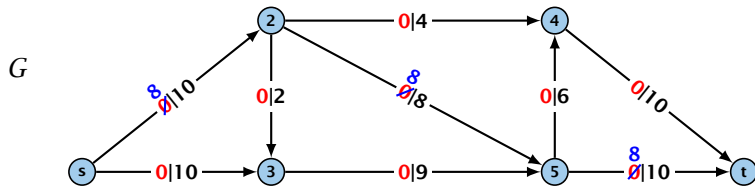
Flow value = 0



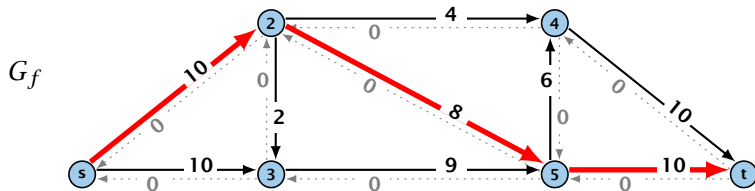
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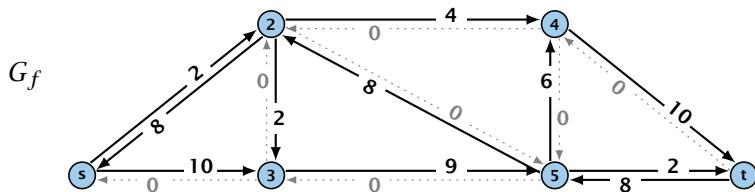
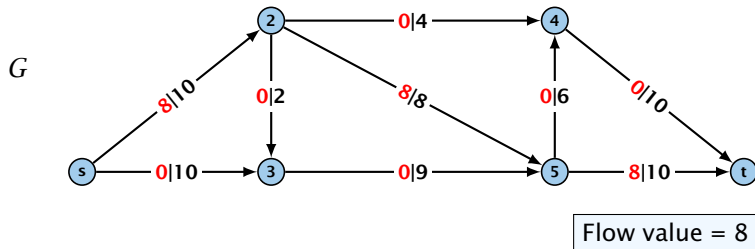
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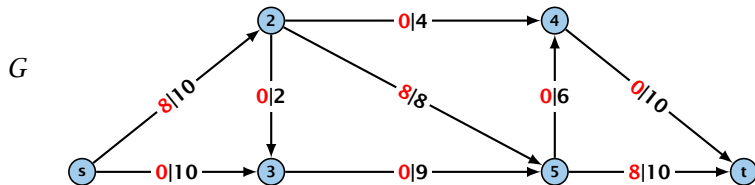
Flow value = 8



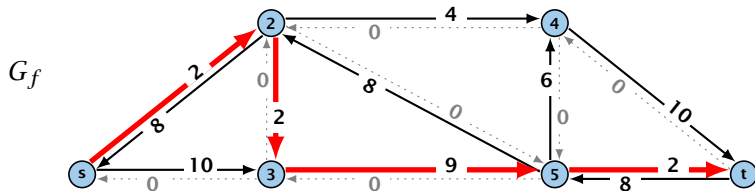
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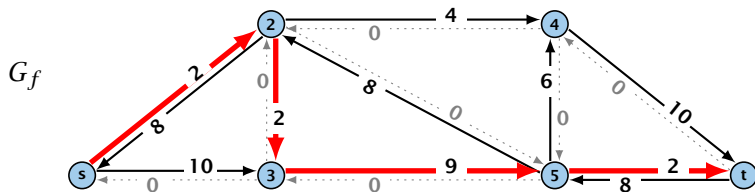
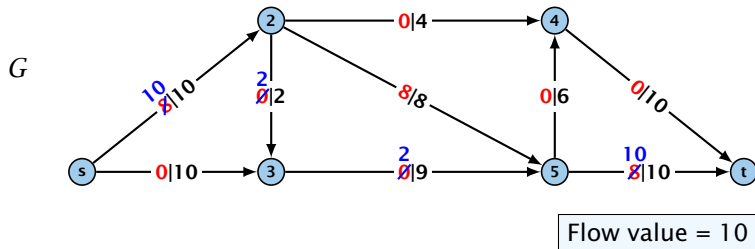
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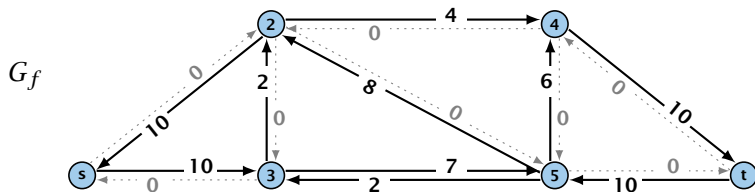
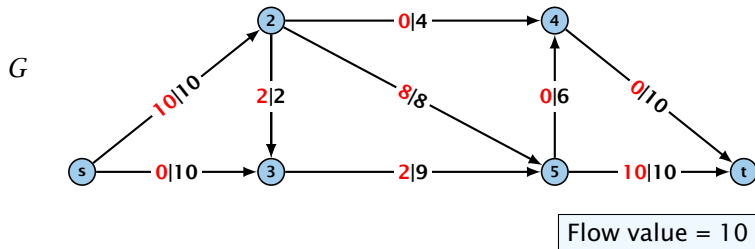
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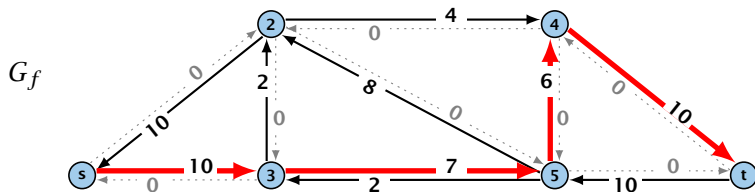
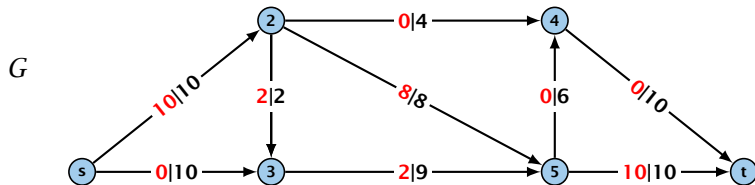
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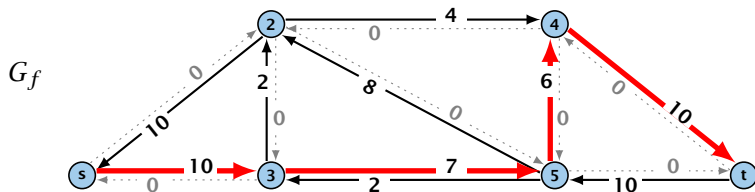
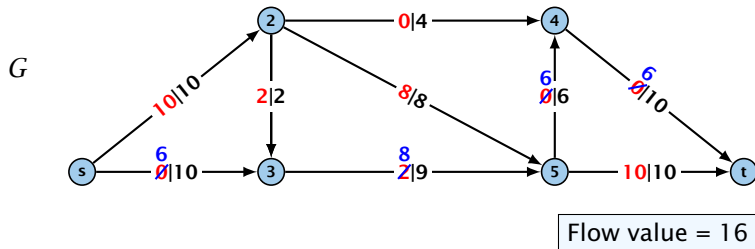
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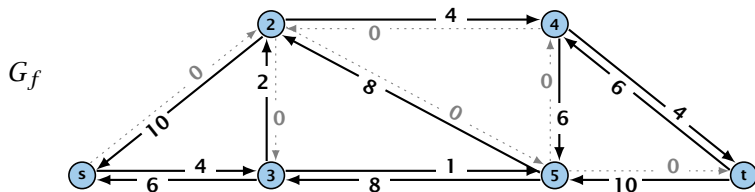
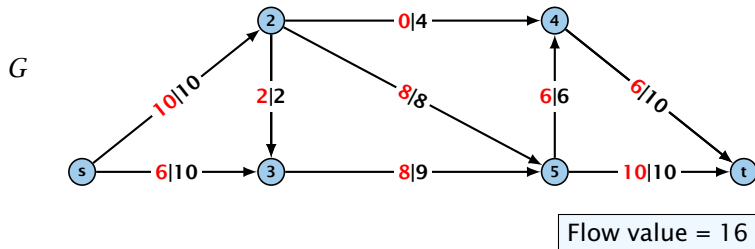
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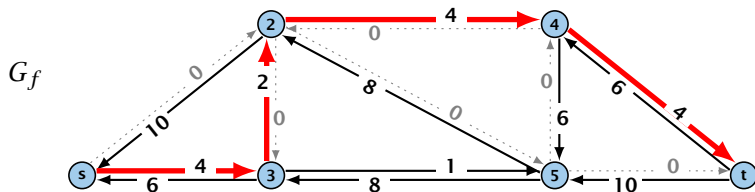
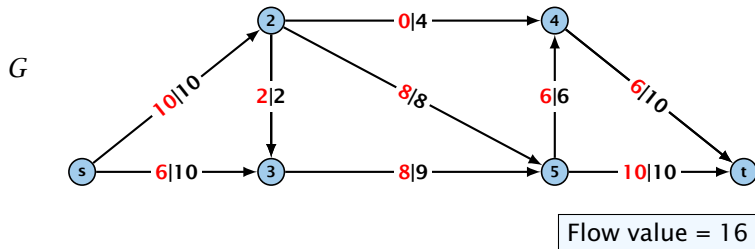
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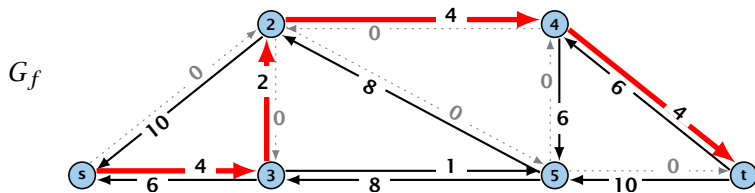
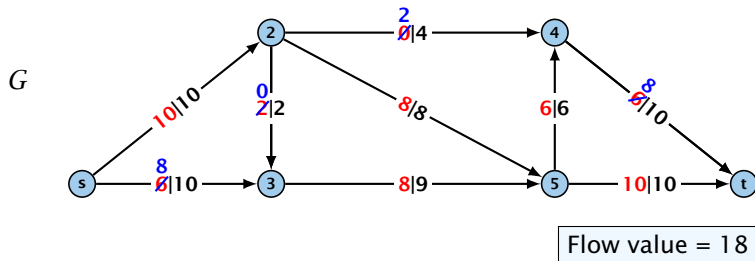
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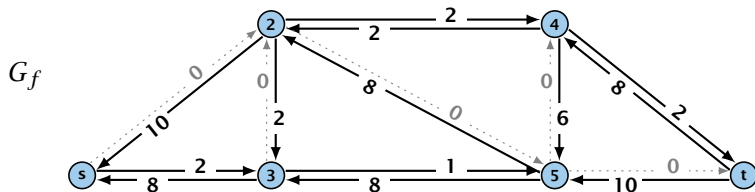
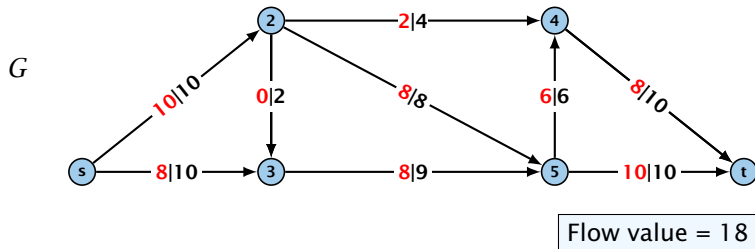
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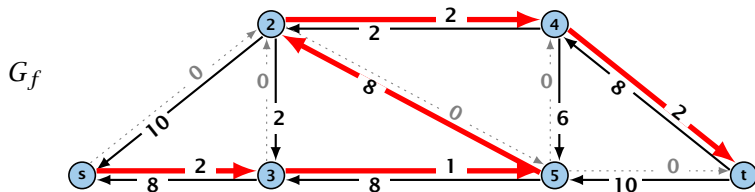
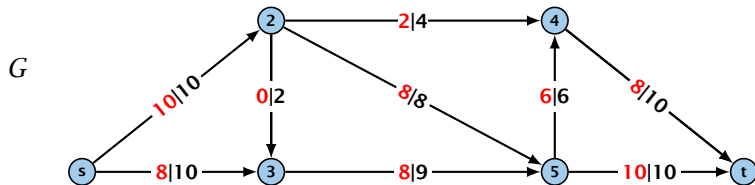
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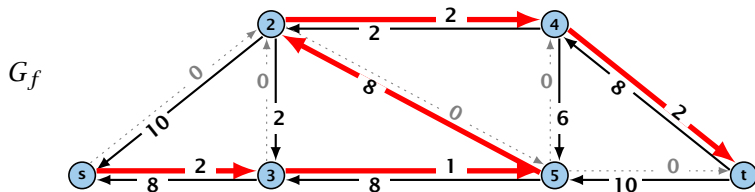
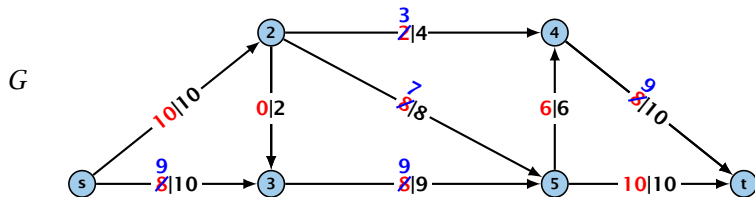
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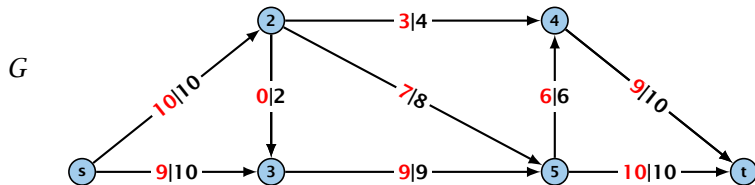
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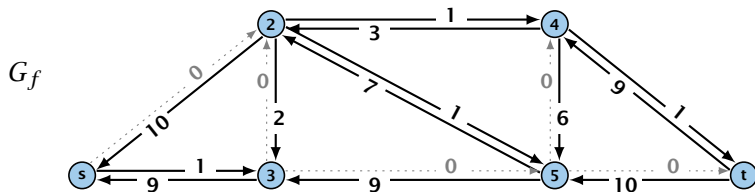
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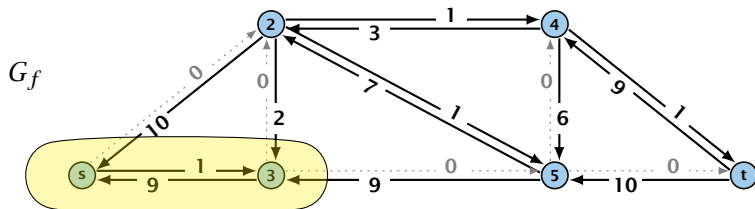
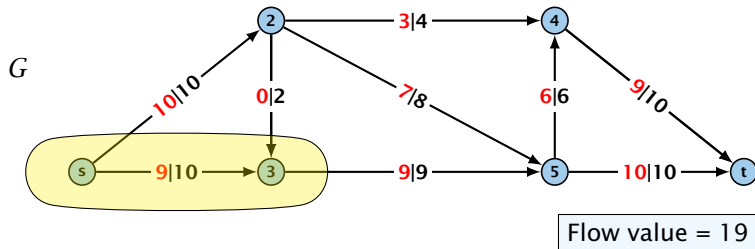
Augmenting Path Algorithm



Flow value = 19



Augmenting Path Algorithm



Augmenting Path Algorithm

Theorem 2

A flow f is a maximum flow iff there are no augmenting paths.

Theorem 3

The value of a maximum flow is equal to the value of a minimum cut.

Proof.

Let f be a flow. The following are equivalent:

1. There exists a cut C such that $|f| = \text{val}(C)$.
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Augmenting Path Algorithm

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This we already showed.

2. \Rightarrow 3.

If there were an augmenting path, we could improve the flow.
Contradiction.

3. \Rightarrow 1.

Let G_f be a flow with no augmenting paths.

Let S be the set of vertices reachable from s in the residual graph along non-saturated capacity edges.

Since there is no augmenting path, there is no edge from S to T .

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Let G_f be a flow with no augmenting paths.

Let S be the set of vertices reachable from s in the residual graph.

Let T be the set of vertices not in S .

Let E_f be the set of edges with positive residual capacity.

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Augmenting Path Algorithm

$\text{val}(f)$

Augmenting Path Algorithm

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This finishes the proof.

Here the first equality uses the flow value lemma, and the second exploits the fact that the flow along incoming edges must be 0 as the residual graph does not have edges leaving A .

Analysis

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All capacities are integers between 1 and C .

Invariant:

Every flow value $f(e)$ and every residual capacity $c_f(e)$ remains integral throughout the algorithm.

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Lemma 4

The algorithm terminates in at most $\text{val}(f^*) \leq nC$ iterations, where f^* denotes the maximum flow. Each iteration can be implemented in time $\mathcal{O}(m)$. This gives a total running time of $\mathcal{O}(nmC)$.

Theorem 5

If all capacities are integers, then there exists a maximum flow for which every flow value $f(e)$ is integral.

Lemma 4

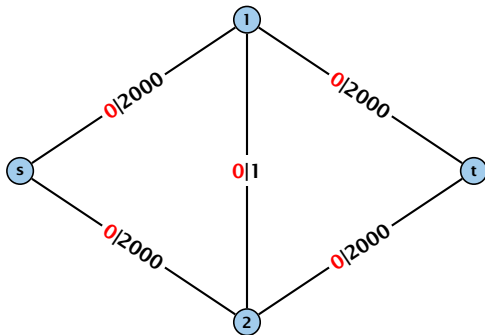
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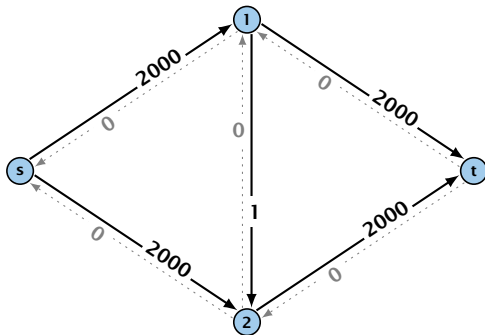
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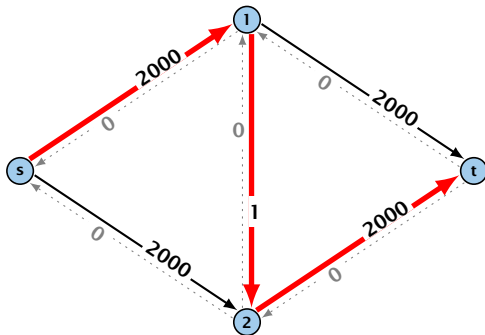


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Can we tweak the algorithm so that the running time is polynomial in the input length?

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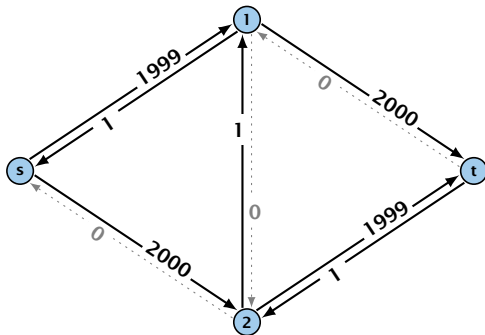


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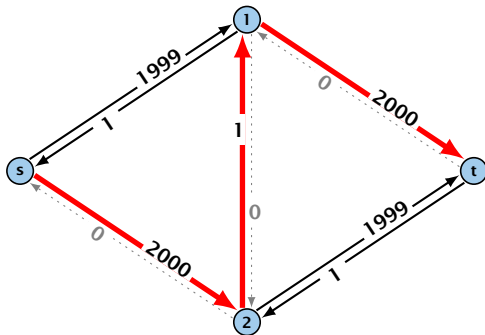


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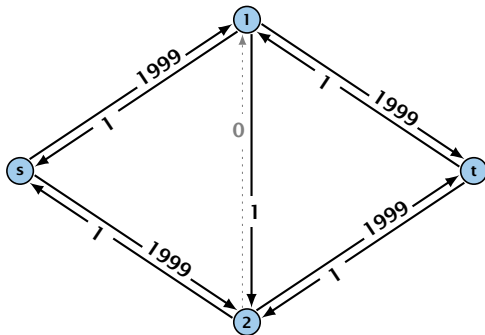


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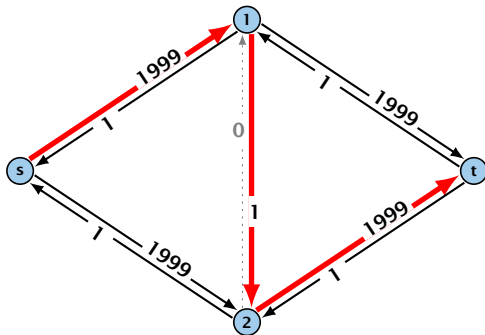


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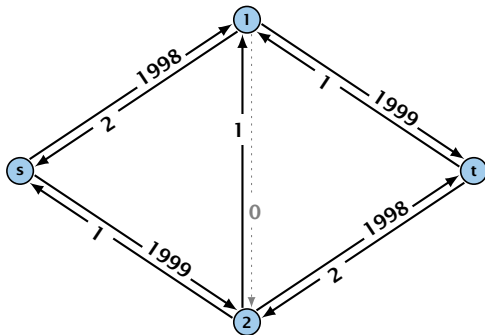


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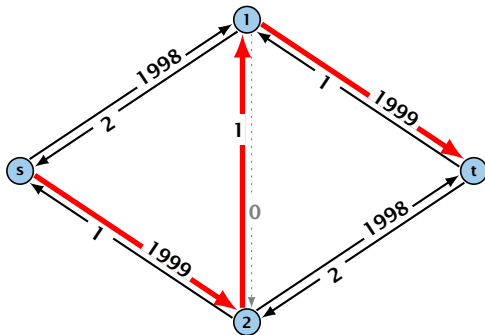


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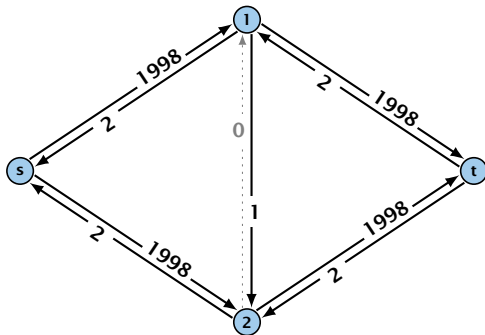


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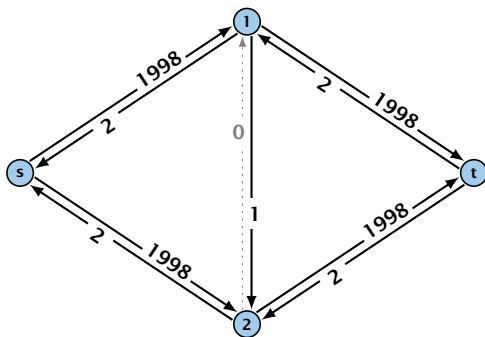


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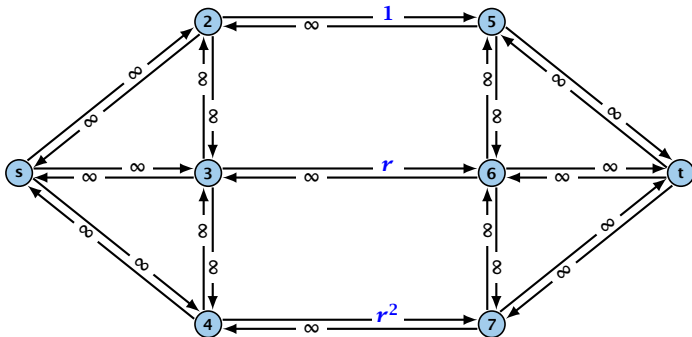


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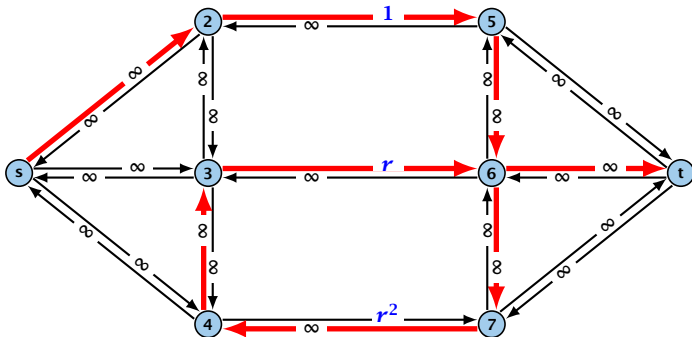
A Pathological Input

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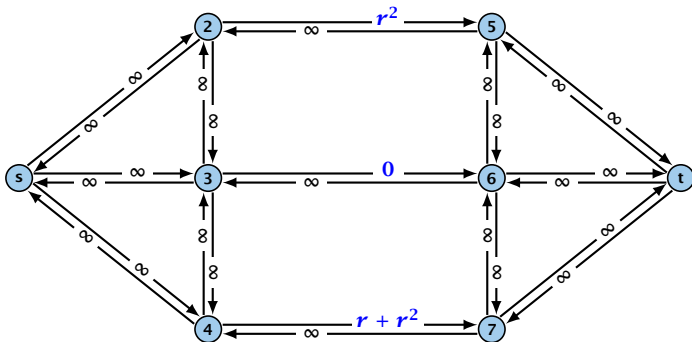
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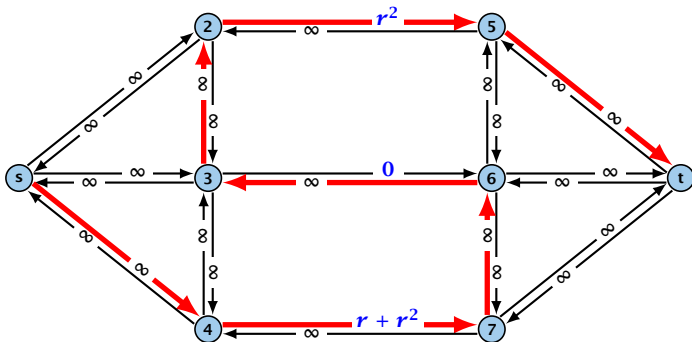
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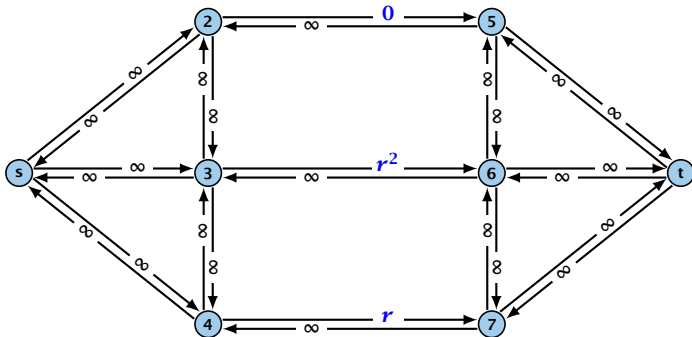
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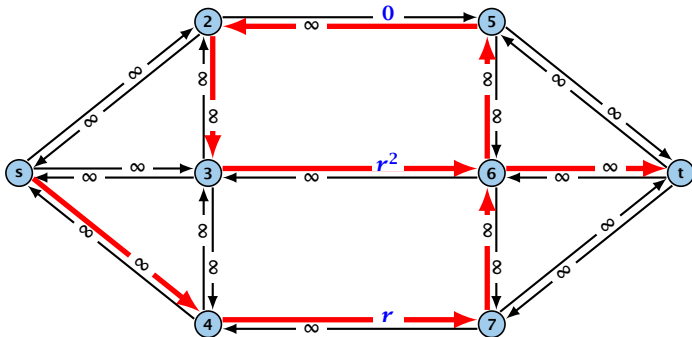
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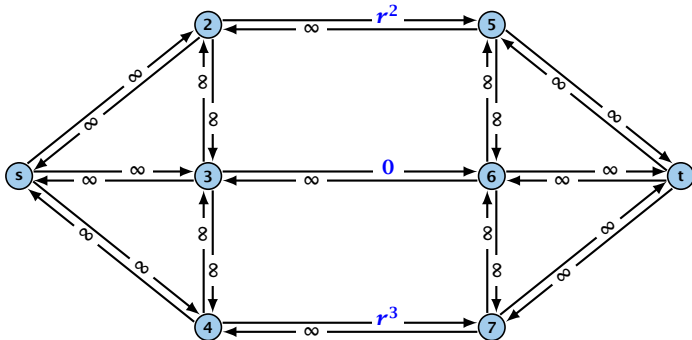
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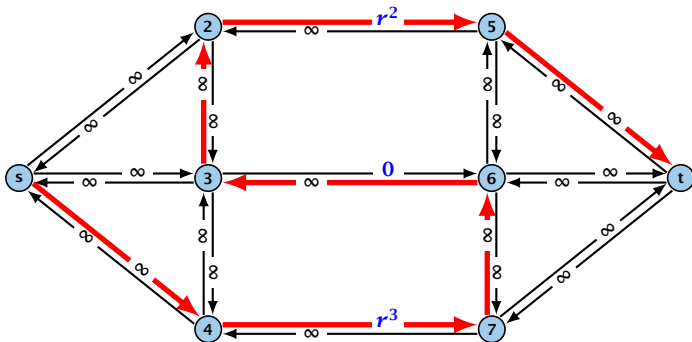
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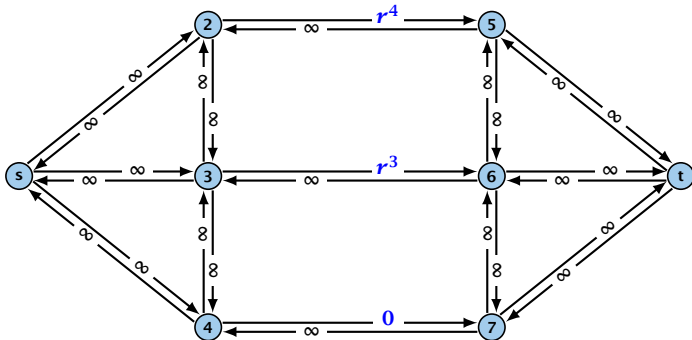
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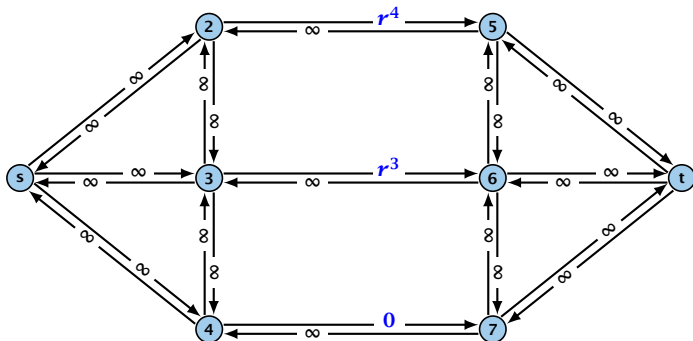
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Running time may be infinite!!!



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Lemma 6

The length of the shortest augmenting path never decreases.

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After at most $\mathcal{O}(m)$ augmentations, the length of the shortest augmenting path strictly increases.

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Proof.

We can find the shortest augmenting paths in time $\mathcal{O}(m)$.

Thus,

the total number of augmentations for paths of strictly increasing edges

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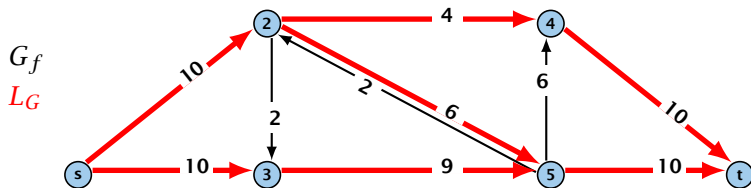
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In the following we assume that the residual graph G_f does not contain zero capacity edges.

This means, we construct it in the usual sense and then delete edges of zero capacity.

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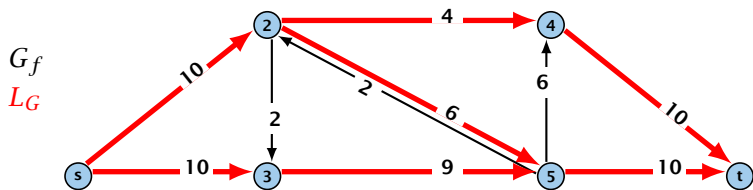
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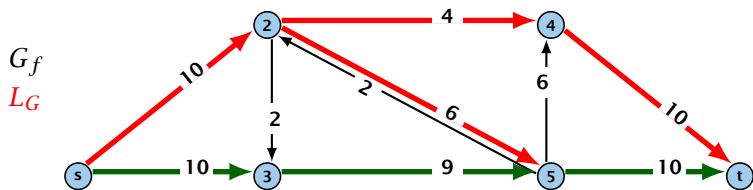
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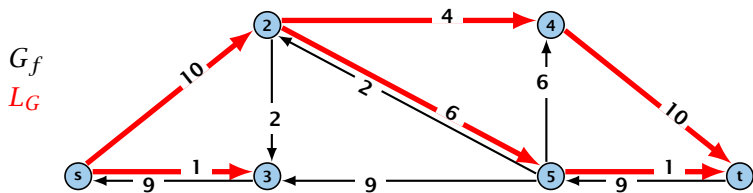
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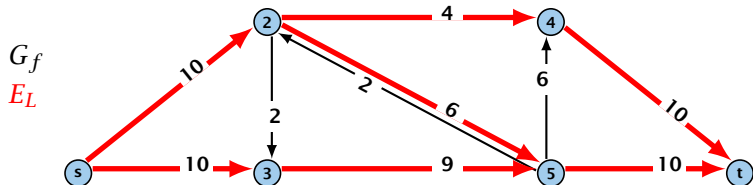
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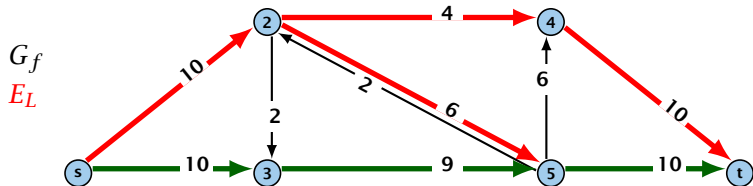
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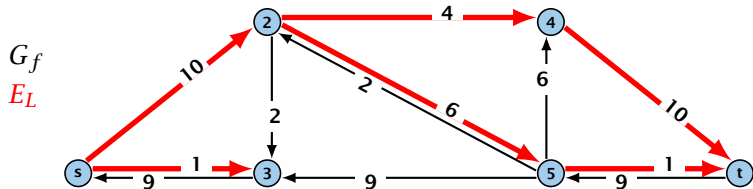
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There exist networks with $m = \Theta(n^2)$ that require $\mathcal{O}(mn)$ augmentations, when we restrict ourselves to only augment along shortest augmenting paths.

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The total cost for performing an augmentation **during** a phase is only $\mathcal{O}(n)$. For every edge in the augmenting path one has to update the residual graph G_f and has to check whether the edge is still in E_L for the next search.

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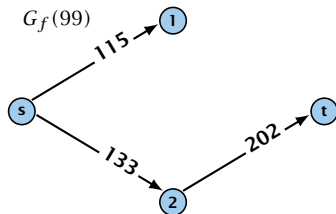
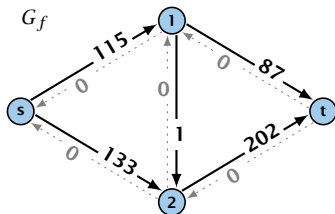
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Algorithm 2 maxflow(G, s, t, c)

```
1: foreach  $e \in E$  do  $f_e \leftarrow 0$ ;  
2:  $\Delta \leftarrow 2^{\lceil \log_2 C \rceil}$   
3: while  $\Delta \geq 1$  do  
4:    $G_f(\Delta) \leftarrow \Delta$ -residual graph  
5:   while there is augmenting path  $P$  in  $G_f(\Delta)$  do  
6:      $f \leftarrow \text{augment}(f, c, P)$   
7:      $\text{update}(G_f(\Delta))$   
8:    $\Delta \leftarrow \Delta/2$   
9: return  $f$ 
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- ▶ This gives me an upper bound on the flow that I can still add.

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Theorem 14

We need $\mathcal{O}(m \log C)$ augmentations. The algorithm can be implemented in time $\mathcal{O}(m^2 \log C)$.