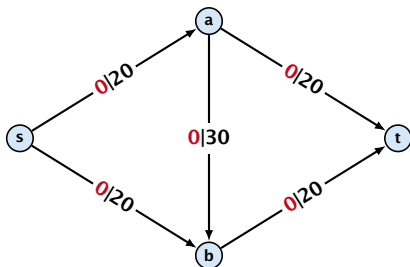


Greedy-algorithm:

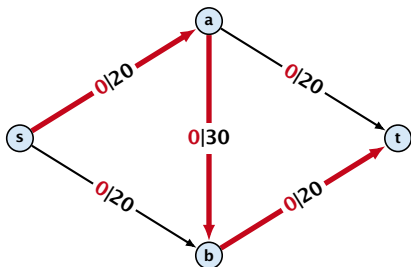
- ▶ start with $f(e) = 0$ everywhere
- ▶ find an s - t path with $f(e) < c(e)$ on every edge
- ▶ augment flow along the path
- ▶ repeat as long as possible



flow value: 0

Greedy-algorithm:

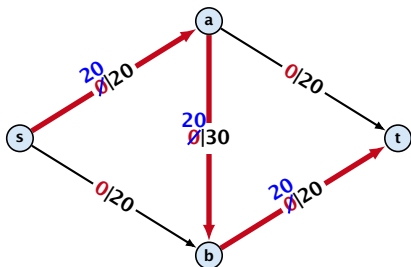
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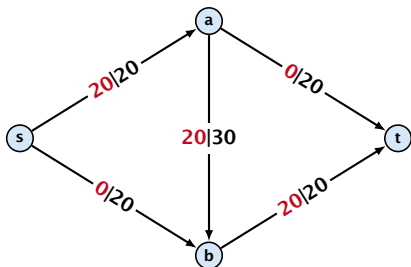
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flow value: 0

Greedy-algorithm:

- ▶ start with $f(e) = 0$ everywhere
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flow value: 20

The Residual Graph

From the graph $G = (V, E, c)$ and the current flow f we construct an auxiliary graph $G_f = (V, E_f, c_f)$ (the residual graph):

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The Residual Graph

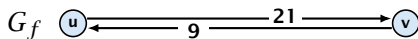
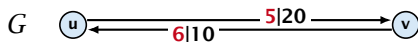
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Augmenting Path Algorithm

Definition 37

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.

Augmenting Path Algorithm

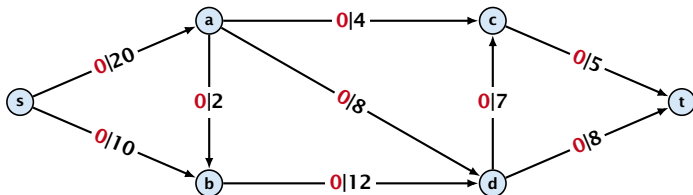
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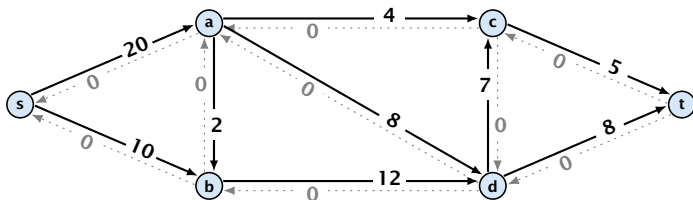
Algorithm 1 FordFulkerson($G = (V, E, c)$)

- 1: Initialize $f(e) \leftarrow 0$ for all edges.
- 2: **while** \exists augmenting path p in G_f **do**
- 3: augment as much flow along p as possible.

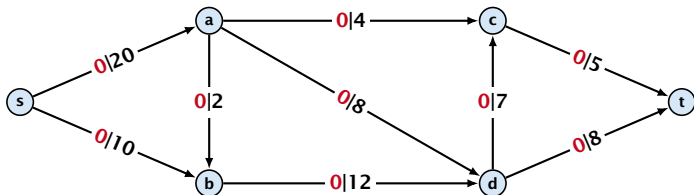
Augmenting Paths



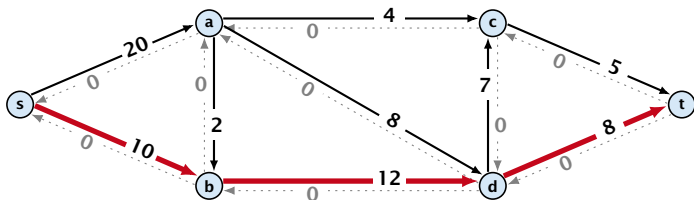
flow value: 0



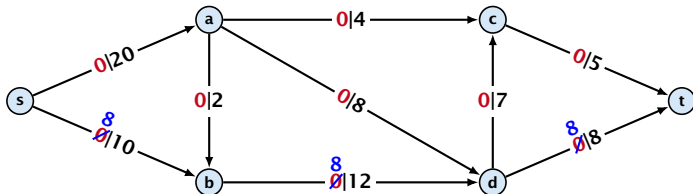
Augmenting Paths



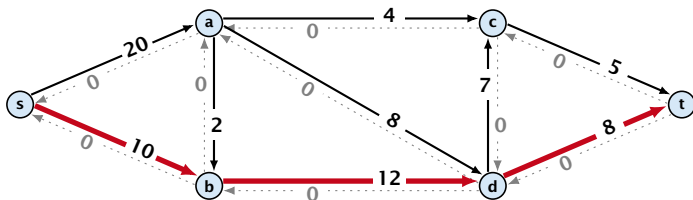
flow value: 0



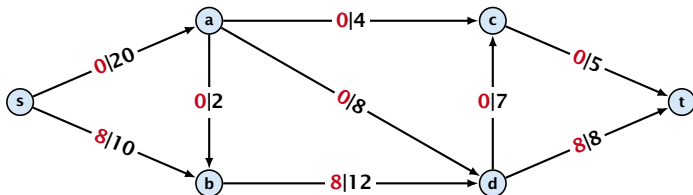
Augmenting Paths



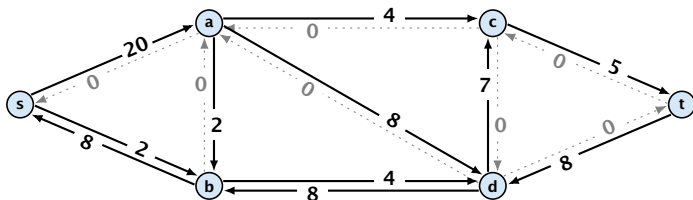
flow value: 0



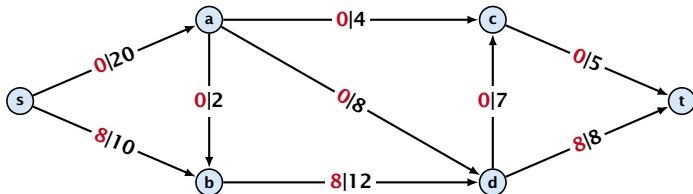
Augmenting Paths



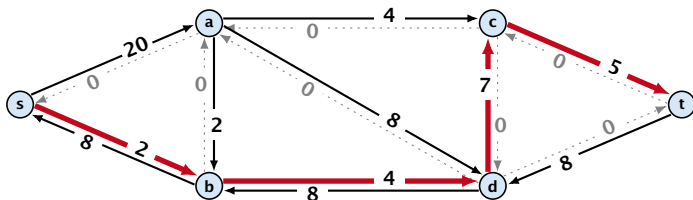
flow value: 8



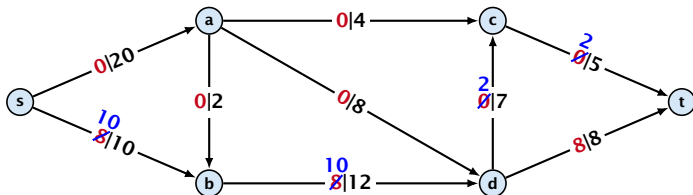
Augmenting Paths



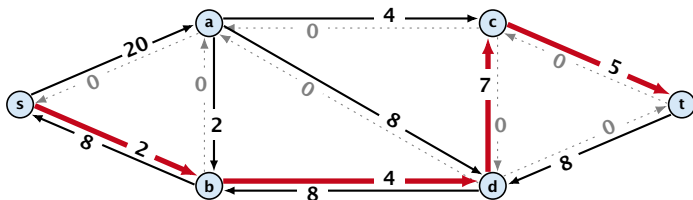
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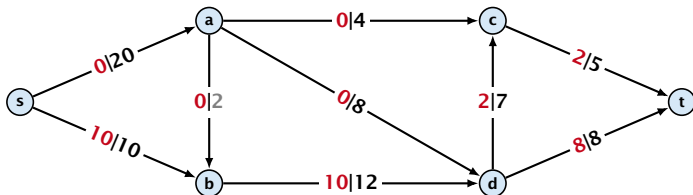
Augmenting Paths



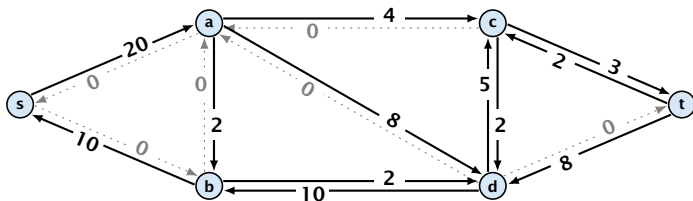
flow value: 8



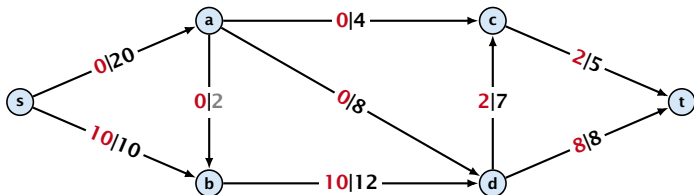
Augmenting Paths



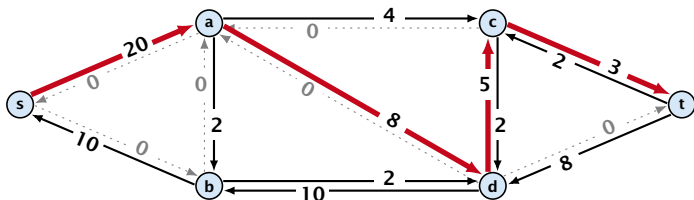
flow value: 10



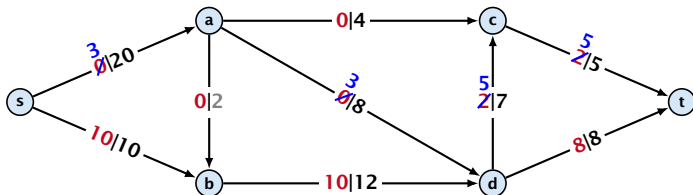
Augmenting Paths



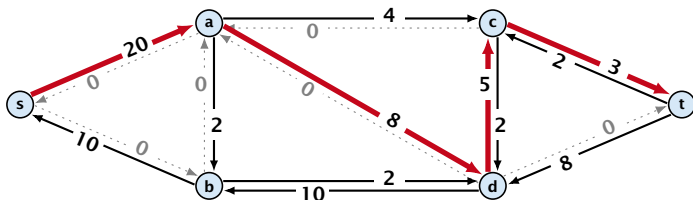
flow value: 10



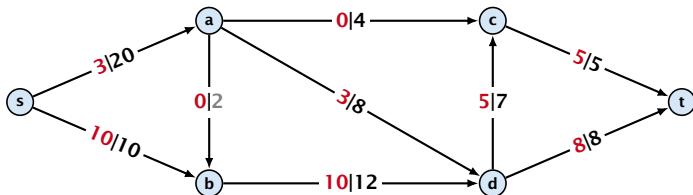
Augmenting Paths



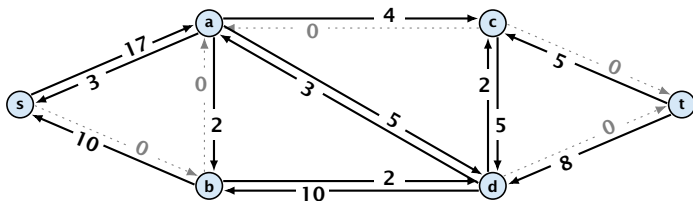
flow value: 10



Augmenting Paths



flow value: 13



Augmenting Path Algorithm

Augmenting Path Algorithm

Theorem 38

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

Augmenting Path Algorithm

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

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Proof.

Let f be a flow. The following are equivalent:

1. There exists a cut A such that $\text{val}(f) = \text{cap}(A, V \setminus A)$.



Augmenting Path Algorithm

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Augmenting Path Algorithm

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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 A such that $\text{val}(f) = \text{cap}(A, V \setminus A)$.
2. Flow f is a maximum flow.
3. There is no augmenting path w.r.t. f .



Augmenting Path Algorithm

Augmenting Path Algorithm

1. \Rightarrow 2.

This we already showed.

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- ▶ Let f be a flow with no augmenting paths.

Augmenting Path Algorithm

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- ▶ Let f be a flow with no augmenting paths.
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Augmenting Path Algorithm

1. \Rightarrow 2.

This we already showed.

2. \Rightarrow 3.

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

Contradiction.

3. \Rightarrow 1.

- ▶ Let f be a flow with no augmenting paths.
- ▶ Let A be the set of vertices reachable from s in the residual graph along non-zero capacity edges.
- ▶ Since there is no augmenting path we have $s \in A$ and $t \notin A$.

Augmenting Path Algorithm

$\text{val}(f)$

Augmenting Path Algorithm

$$\text{val}(f) = \sum_{e \in \text{out}(A)} f(e) - \sum_{e \in \text{into}(A)} f(e)$$

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 .

Assumption:

All capacities are integers between 1 and C .

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Invariant:

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

Lemma 40

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 $\mathcal{O}(nmC)$.

Lemma 40

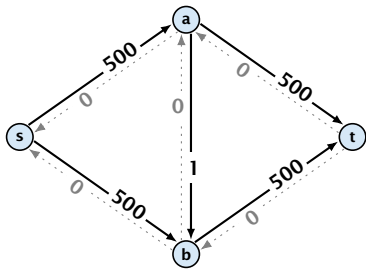
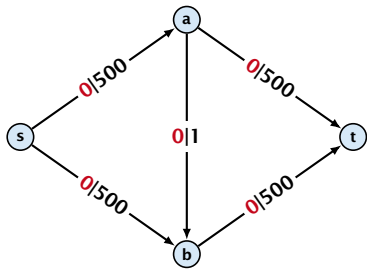
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Theorem 41

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

A Bad Input

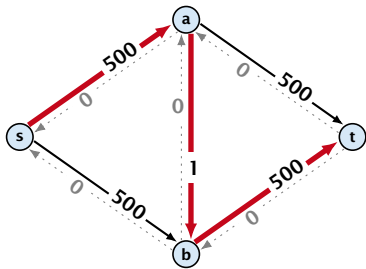
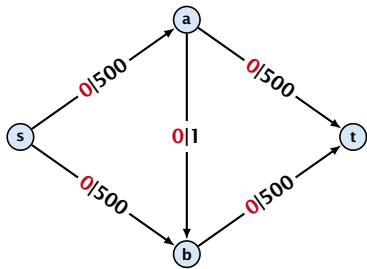
Problem: The running time may not be polynomial



flow value: 0

A Bad Input

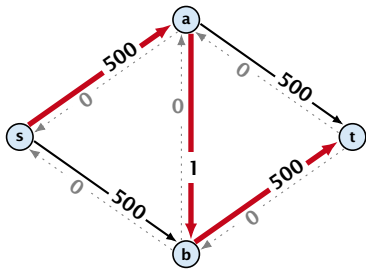
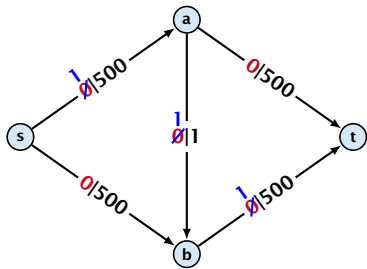
Problem: The running time may not be polynomial



flow value: 0

A Bad Input

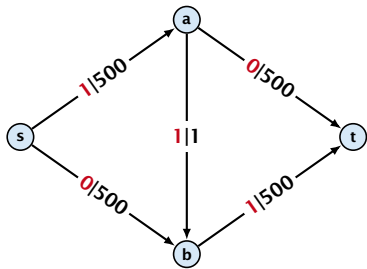
Problem: The running time may not be polynomial



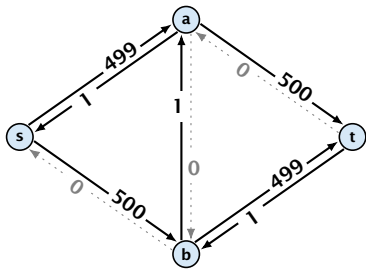
flow value: 0

A Bad Input

Problem: The running time may not be polynomial

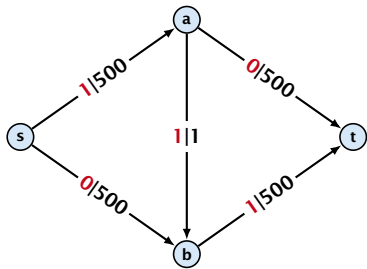


flow value: 1

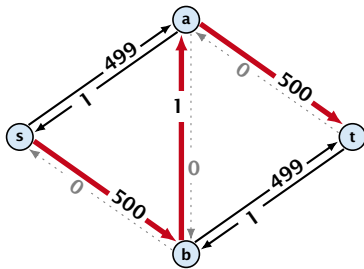


A Bad Input

Problem: The running time may not be polynomial

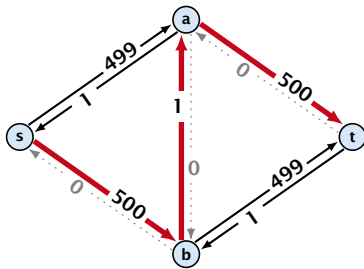
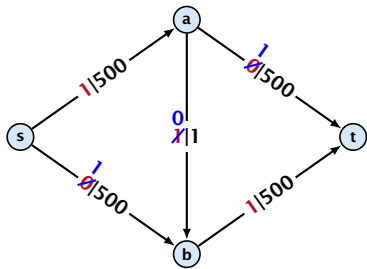


flow value: 1



A Bad Input

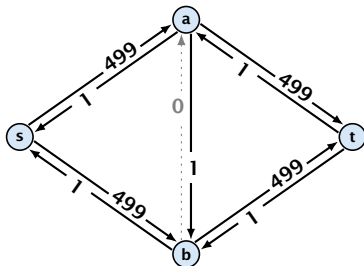
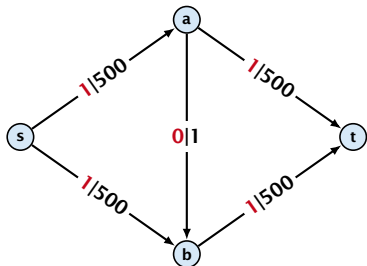
Problem: The running time may not be polynomial



flow value: 1

A Bad Input

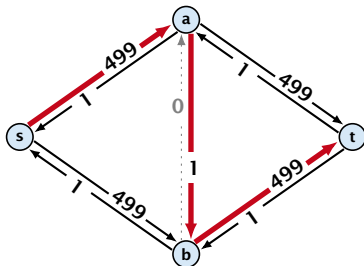
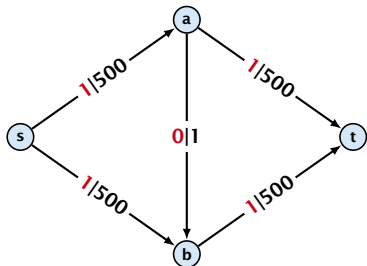
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

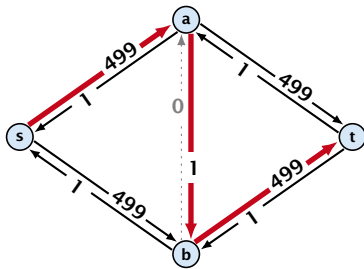
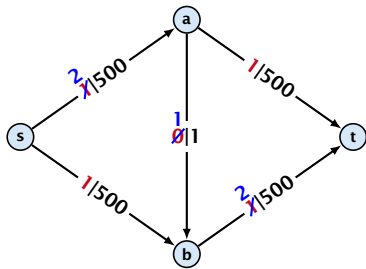
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

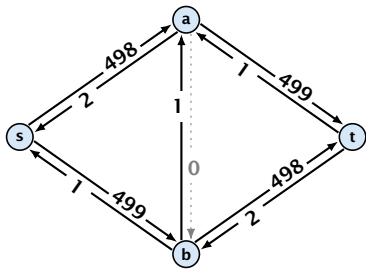
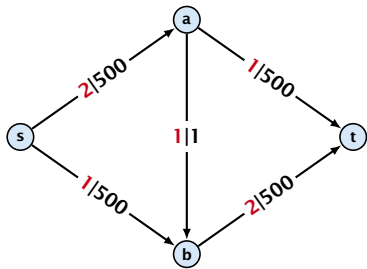
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

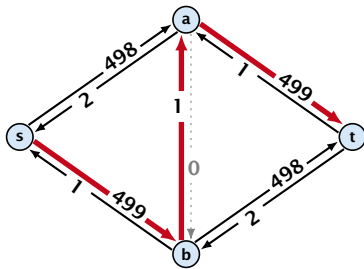
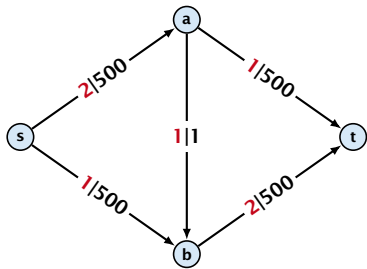
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

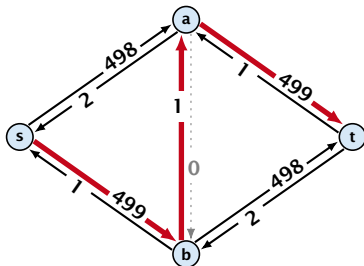
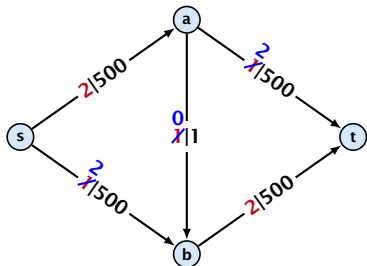
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

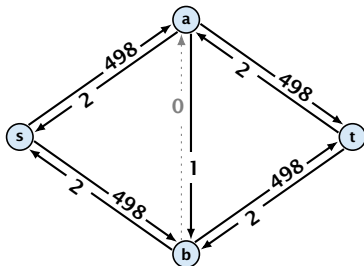
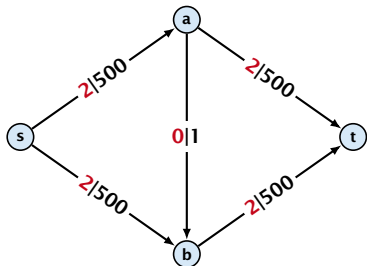
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

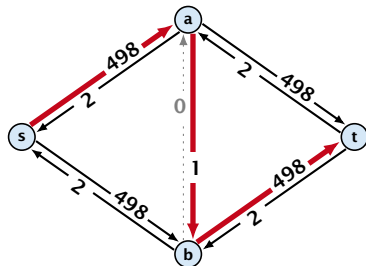
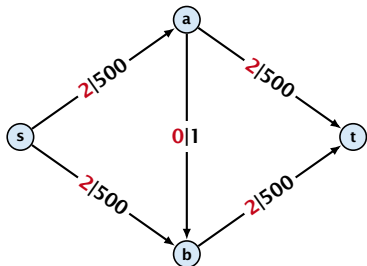
Problem: The running time may not be polynomial



flow value: 4

A Bad Input

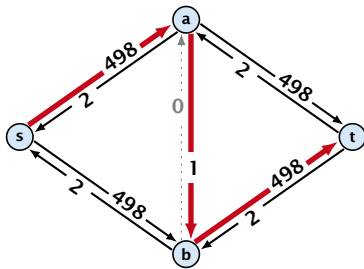
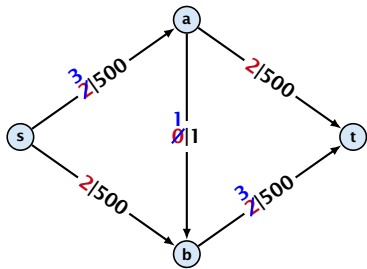
Problem: The running time may not be polynomial



flow value: 4

A Bad Input

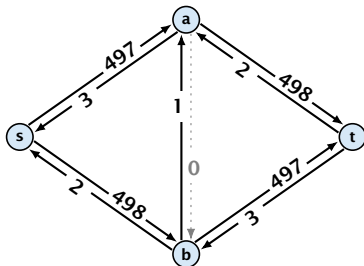
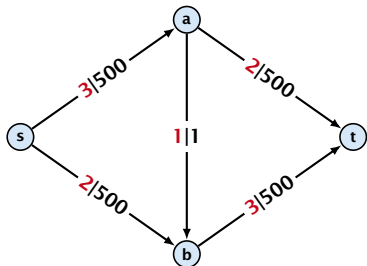
Problem: The running time may not be polynomial



flow value: 4

A Bad Input

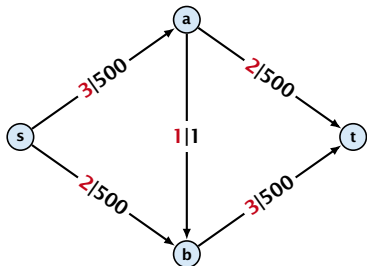
Problem: The running time may not be polynomial



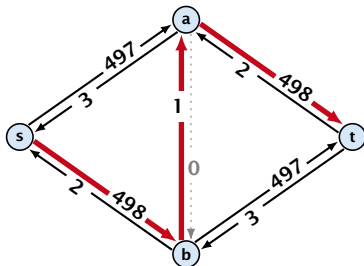
flow value: 5

A Bad Input

Problem: The running time may not be polynomial

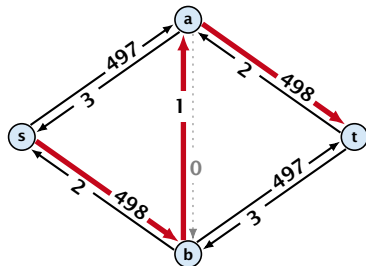
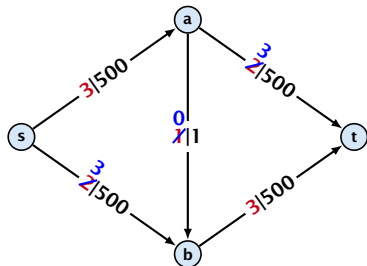


flow value: 5



A Bad Input

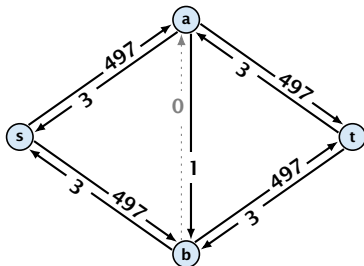
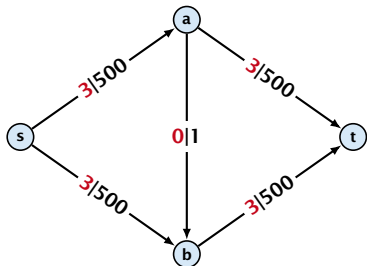
Problem: The running time may not be polynomial



flow value: 5

A Bad Input

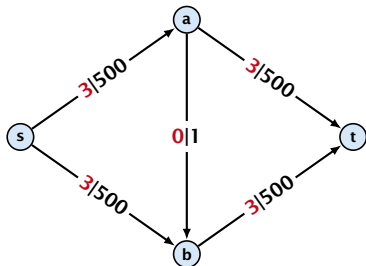
Problem: The running time may not be polynomial



flow value: 6

A Bad Input

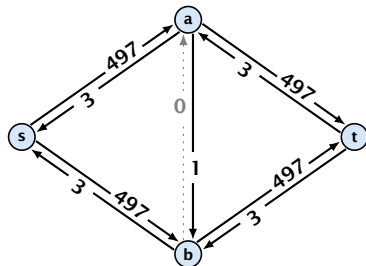
Problem: The running time may not be polynomial



flow value: 6

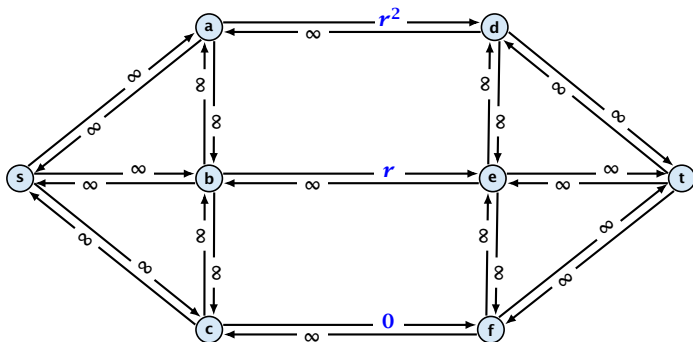
Question:

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



A Pathological Input

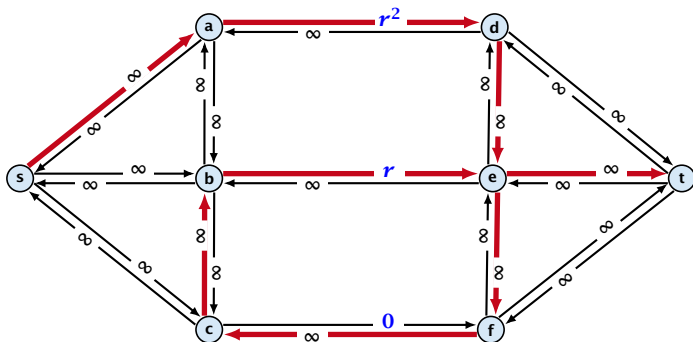
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: 0

A Pathological Input

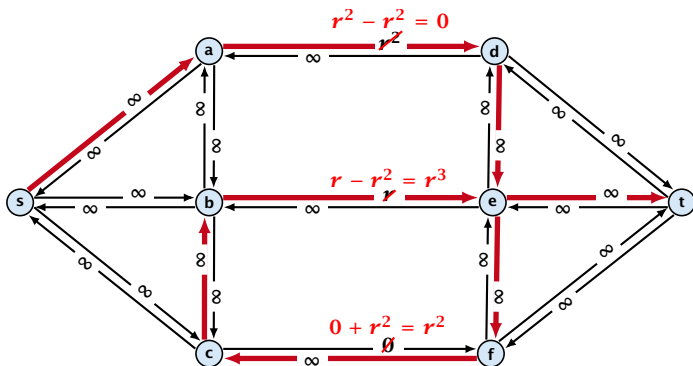
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: 0

A Pathological Input

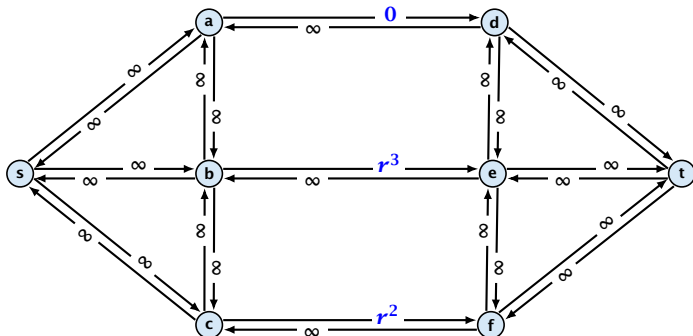
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: 0

A Pathological Input

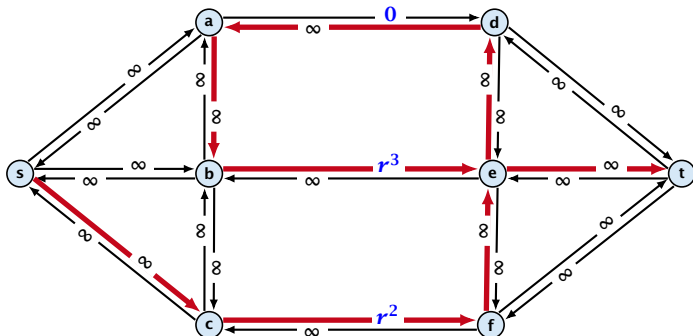
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: r^2

A Pathological Input

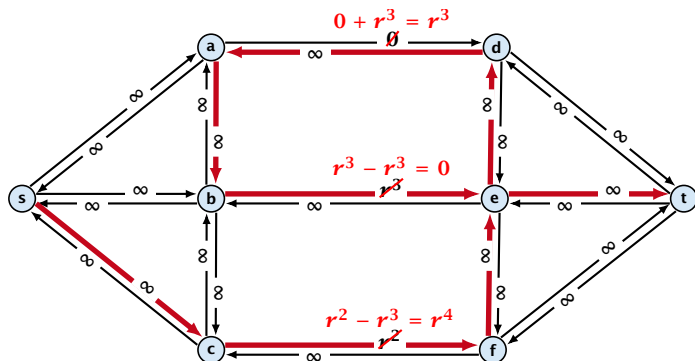
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: r^2

A Pathological Input

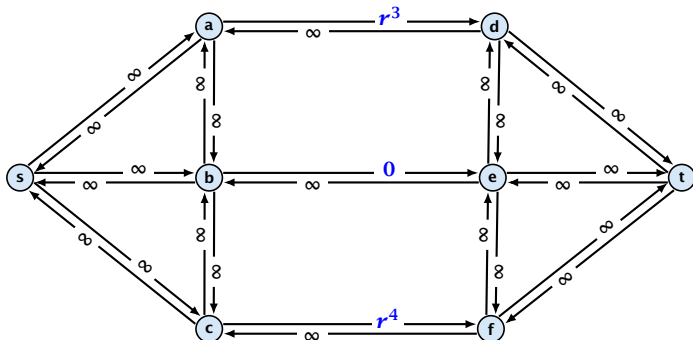
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: r^2

A Pathological Input

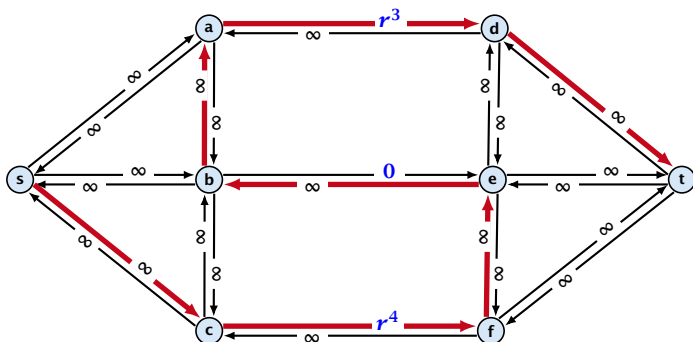
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: $r^2 + r^3$

A Pathological Input

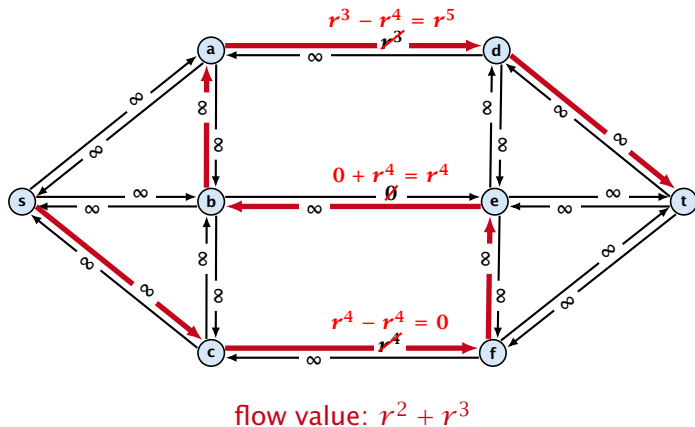
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: $r^2 + r^3$

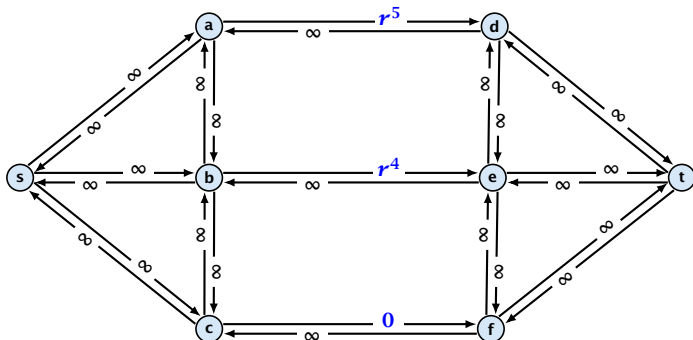
A Pathological Input

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A Pathological Input

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flow value: $r^2 + r^3 + r^4$

Running time may be infinite!!!

How to choose augmenting paths?

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Several possibilities:

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- ▶ Choose path with sufficiently large bottleneck capacity.
- ▶ Choose the shortest augmenting path.