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- start with $f(e) = 0$ everywhere
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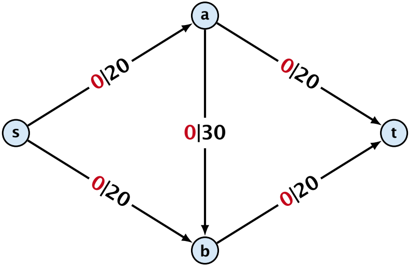
- repeat as long as possible



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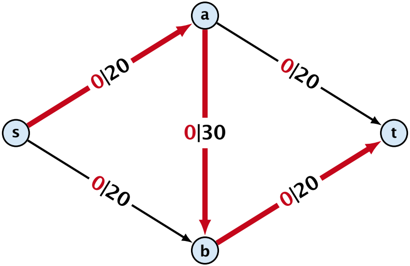

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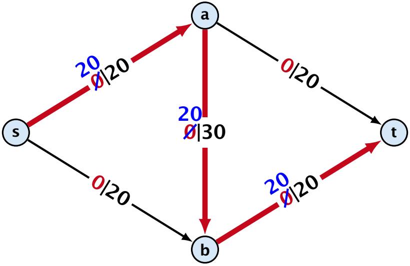

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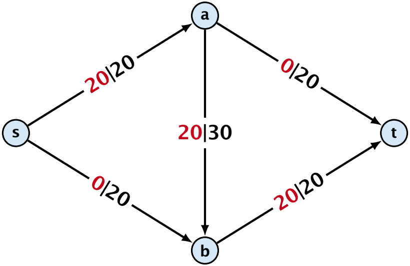

flow value: 20

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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- G_f has edge e_1' with capacity $\max\{0, c(e_1) - f(e_1) + f(e_2)\}$ and e_2' with with capacity $\max\{0, c(e_2) - f(e_2) + f(e_1)\}$.

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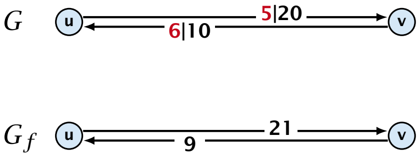

Augmenting Path Algorithm

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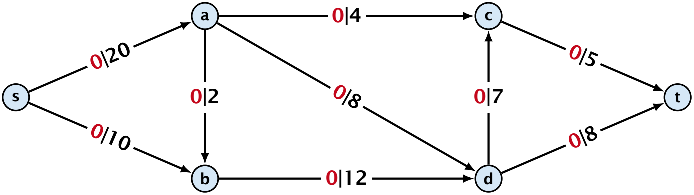
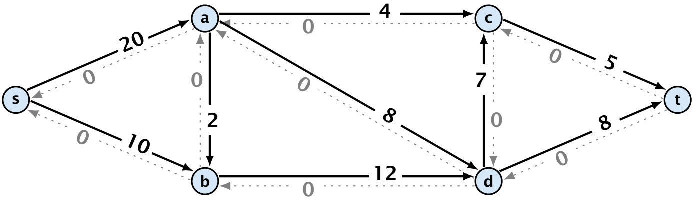
Algorithm 1 FordFulkerson($G = (V, E, c)$)

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

Augmenting Paths



flow value: 0



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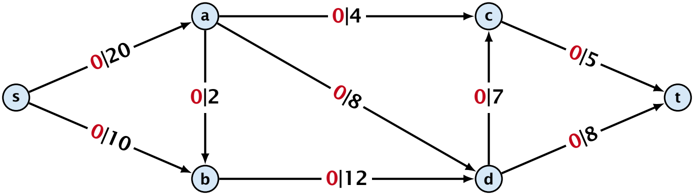
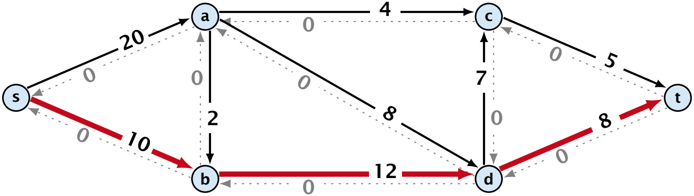


flow value: 0



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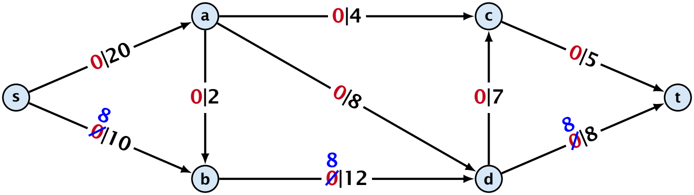
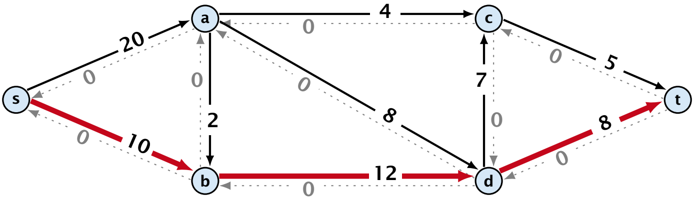


flow value: 0



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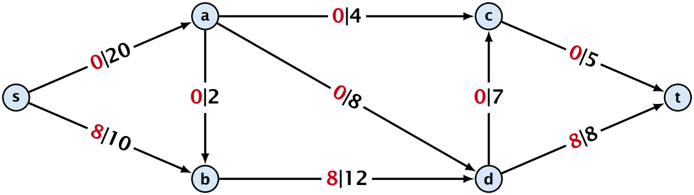
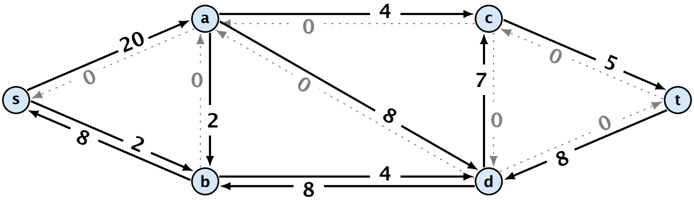


flow value: 8



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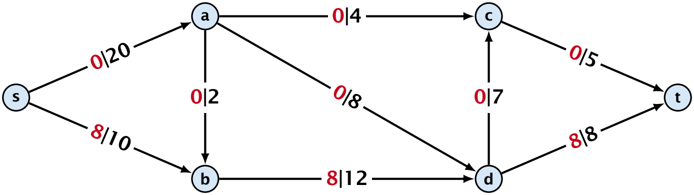

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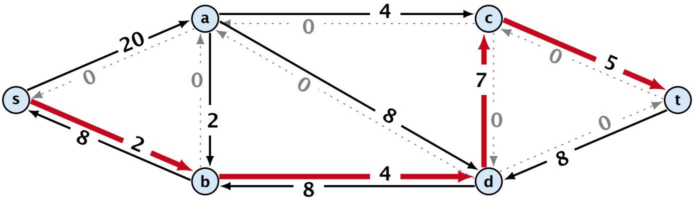

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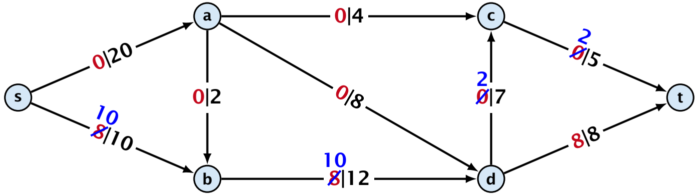

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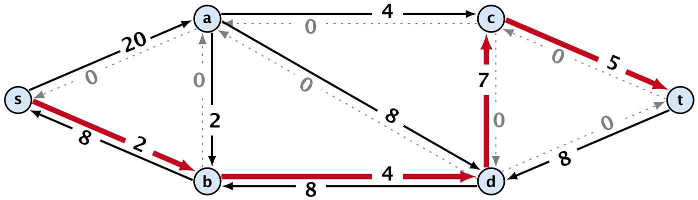

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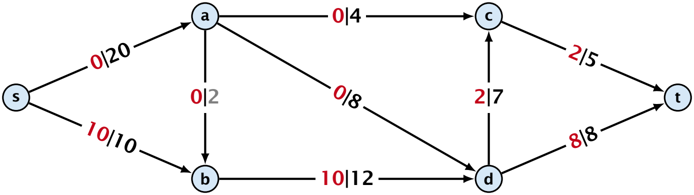
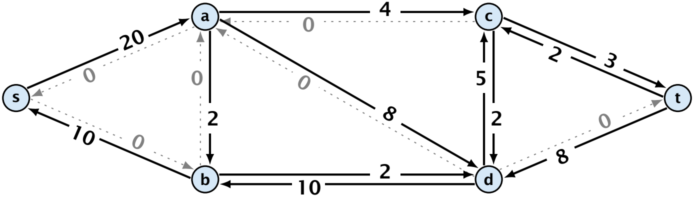


flow value: 10



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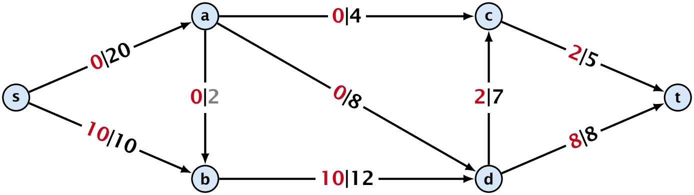

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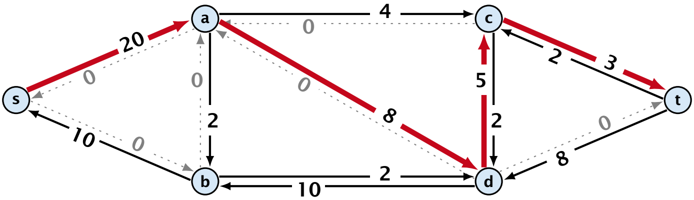

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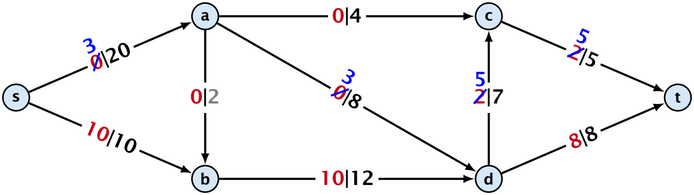

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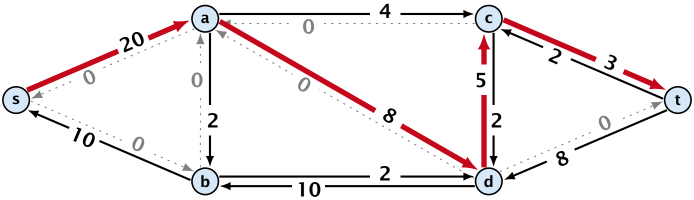

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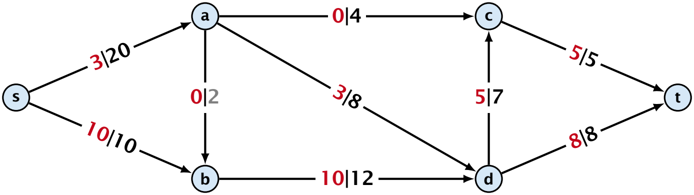
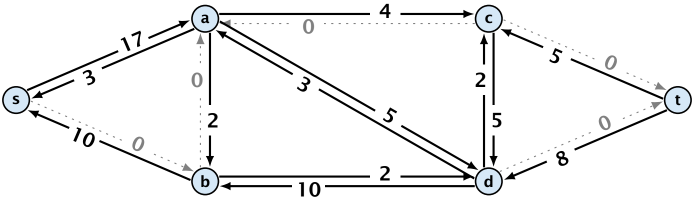


flow value: 13



Augmenting Path Algorithm

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Theorem 38
A flow f is a maximum flow ***iff*** *there are no augmenting paths.*

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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 $\mathrm{val}(f) = \mathrm{cap}(A, V \setminus A)$.

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Proof.
Let f be a flow. The following are equivalent:

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

□

Augmenting Path Algorithm

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$1. \Longrightarrow 2.$

This we already showed.

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

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This we already showed.

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

3\. $\Longrightarrow$ 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

$$\mathrm{val}(f)$$

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

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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

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 troughout the algorithm.

Lemma 40

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

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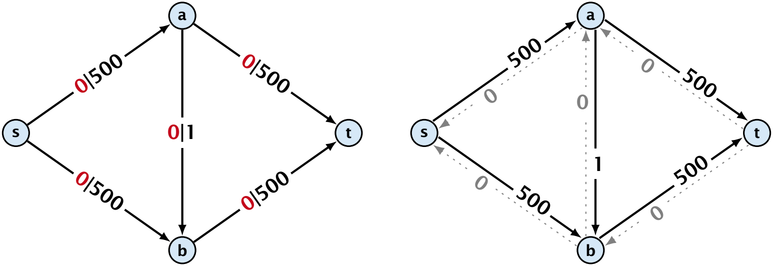
Theorem 41

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

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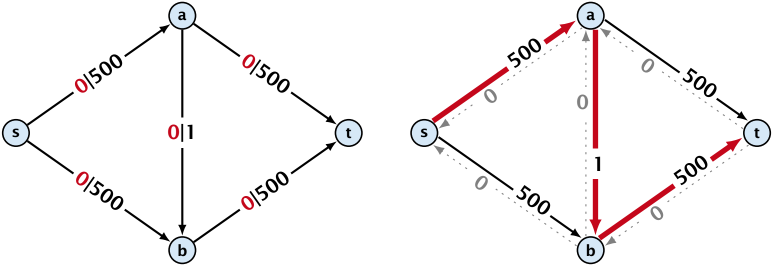

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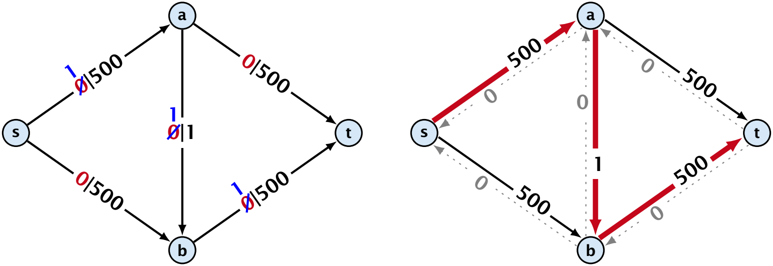

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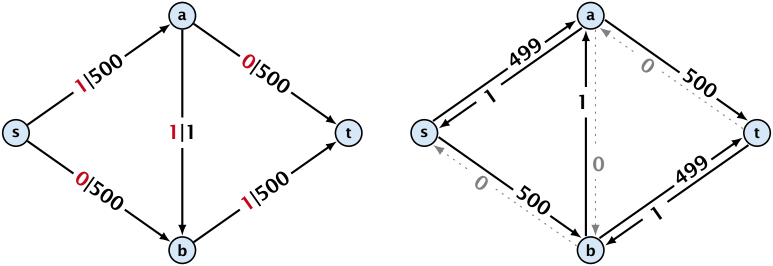

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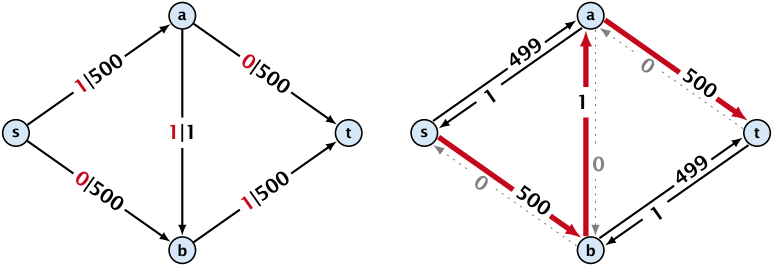

flow value: 1

A Bad Input

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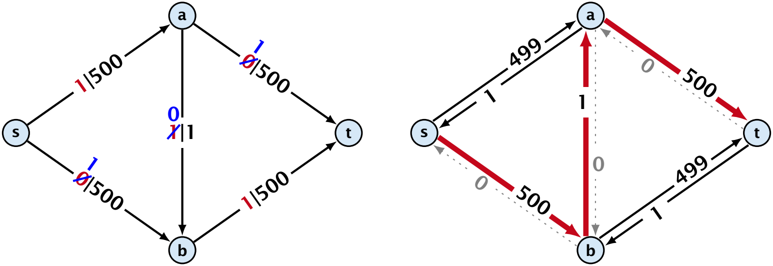

flow value: 1

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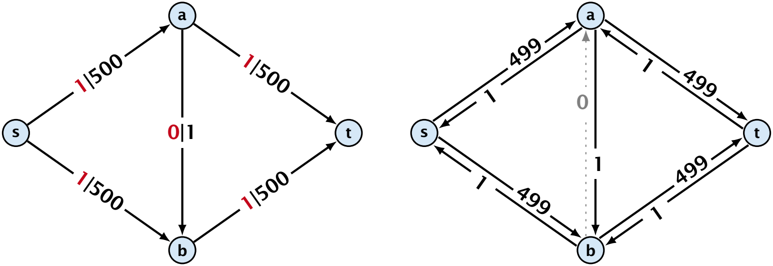
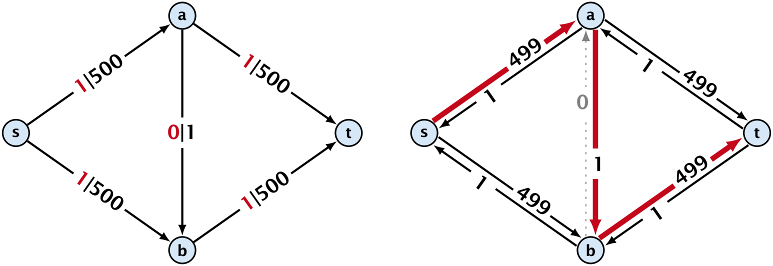


flow value: 2

A Bad Input

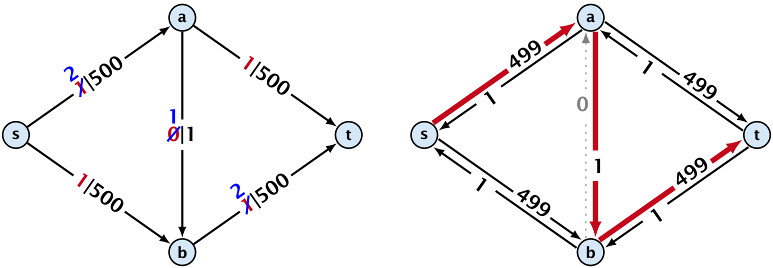
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

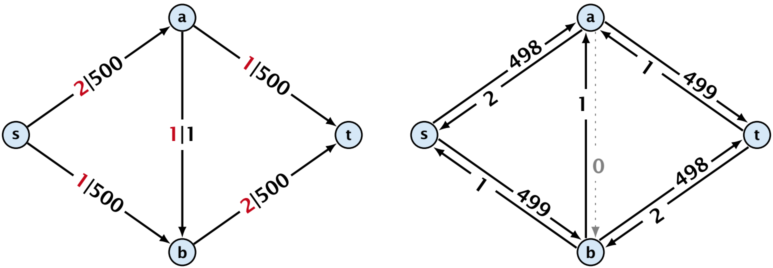
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

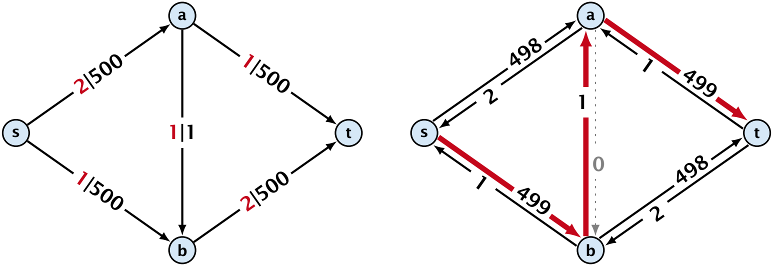
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

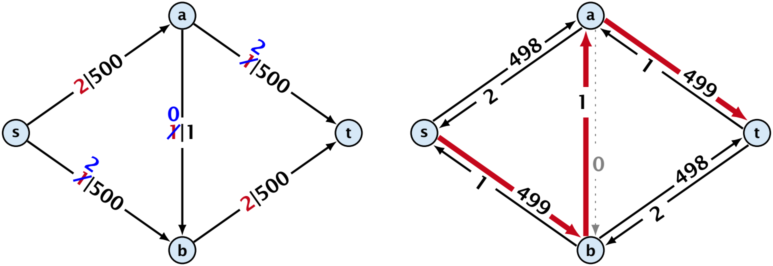
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

Problem: The running time may not be polynomial



flow value: 3

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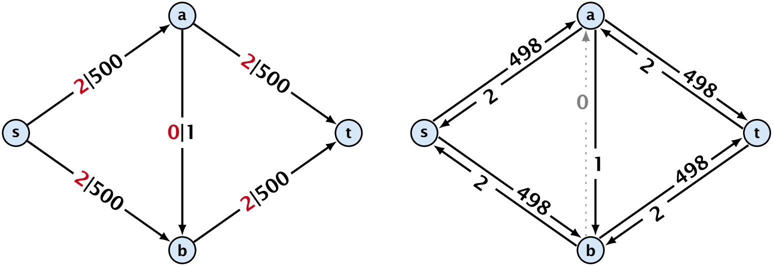
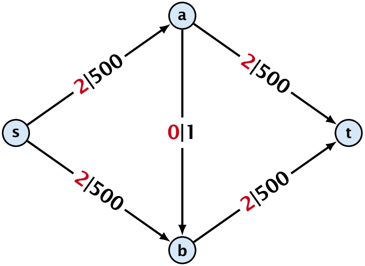
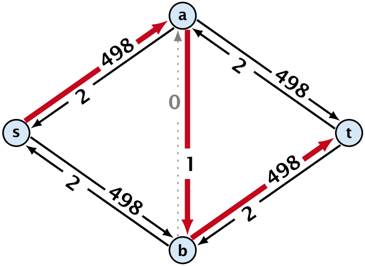


flow value: 4

A Bad Input

Problem: The running time may not be polynomial





flow value: 4

A Bad Input

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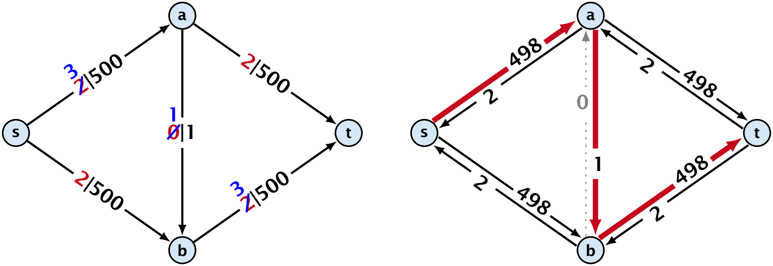

flow value: 4

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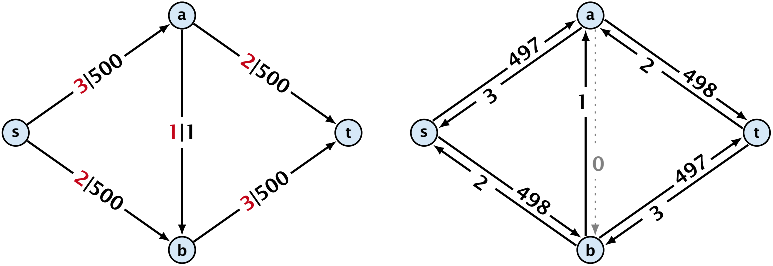
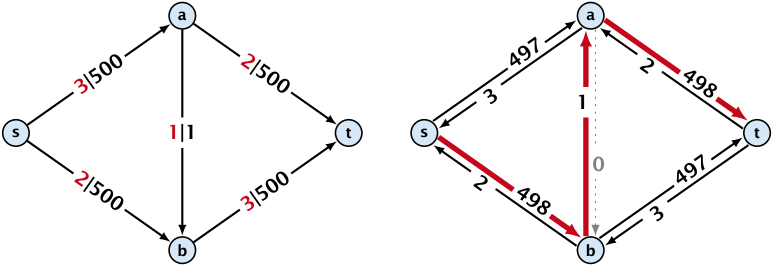
Problem: The running time may not be polynomial



flow value: 5

A Bad Input

Problem: The running time may not be polynomial



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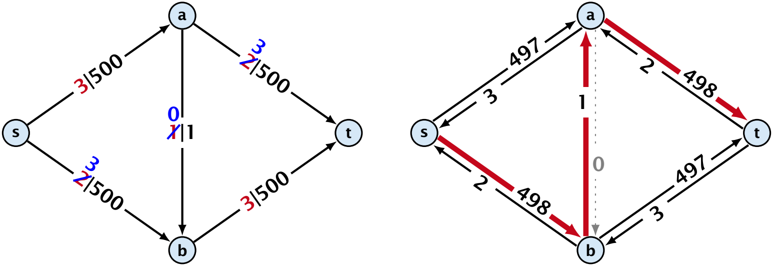

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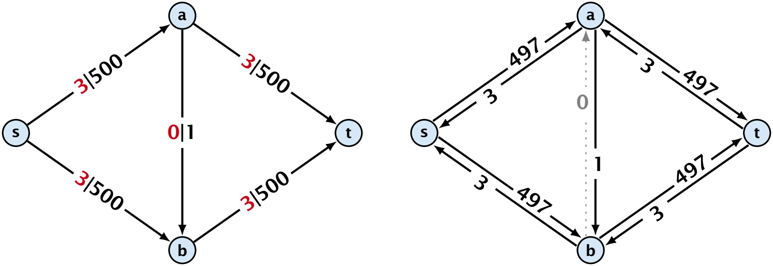
A Bad Input

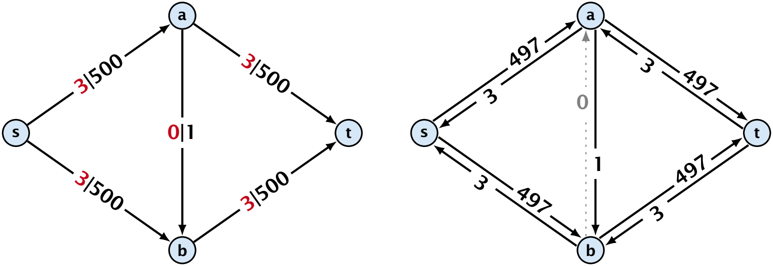
Problem: The running time may not be polynomial



flow value: 6

A Bad Input

Problem: The running time may not be polynomial



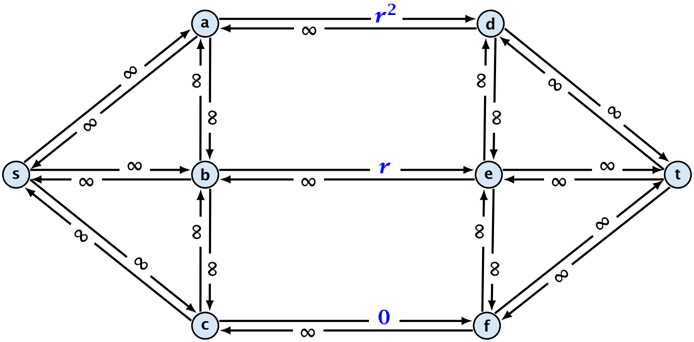
flow value: 6

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

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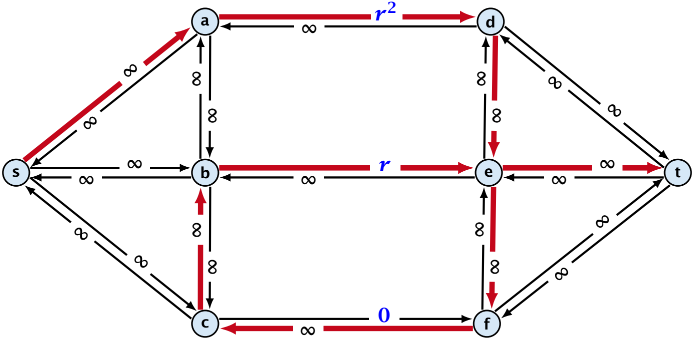

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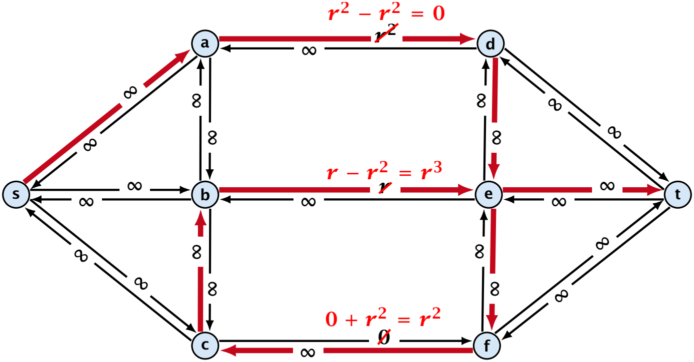
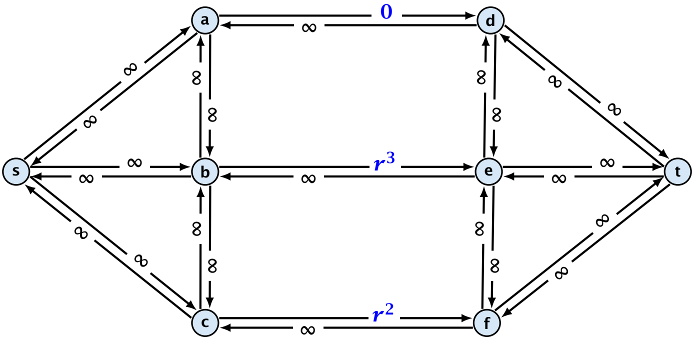


flow value: 0

A Pathological Input

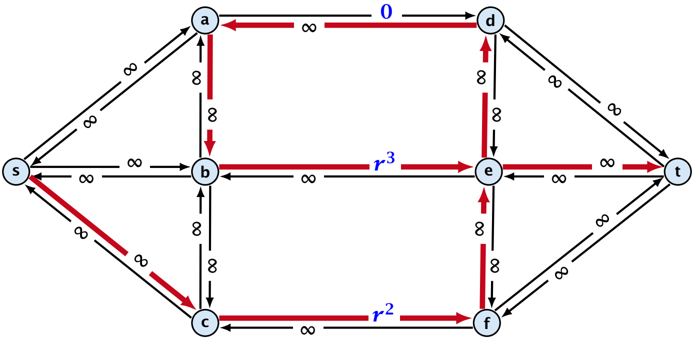
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: r^2

A Pathological Input

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



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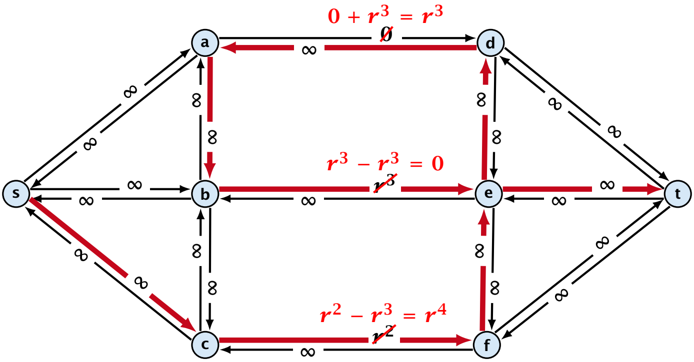

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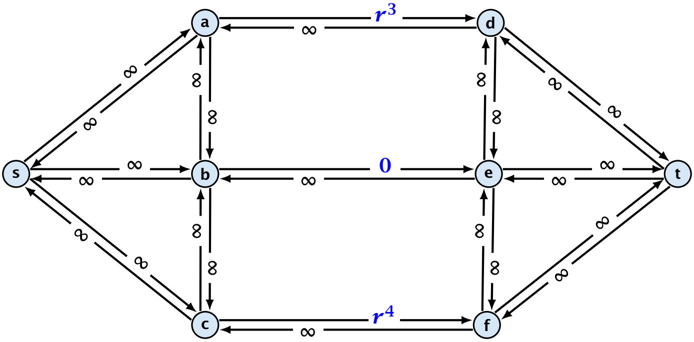
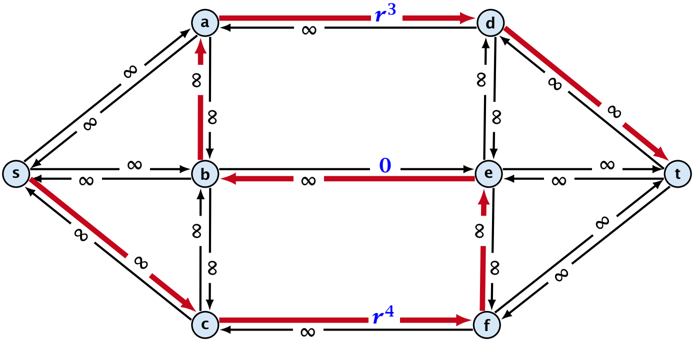


flow value: $r^2 + r^3$

A Pathological Input

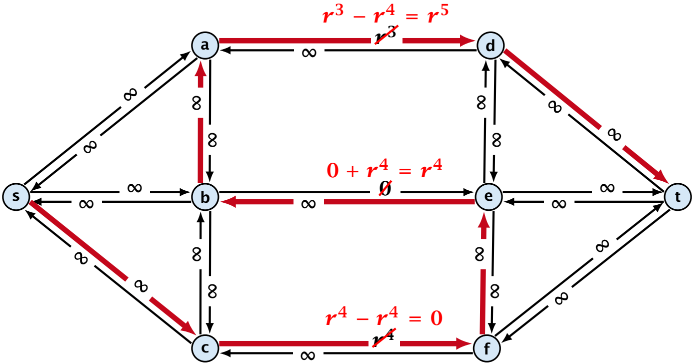
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



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

A Pathological Input

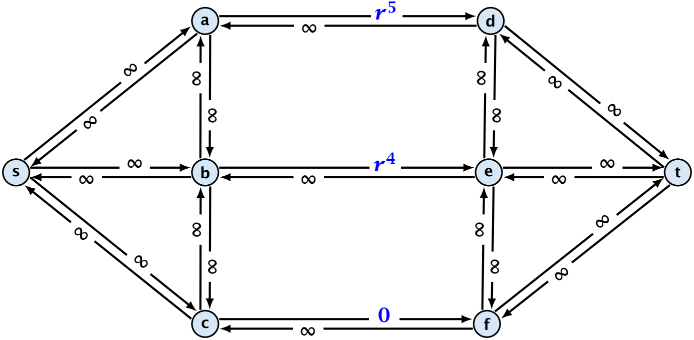
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



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

Running time may be infinite!!!

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- We need to find paths efficiently.
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Several possibilities:

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