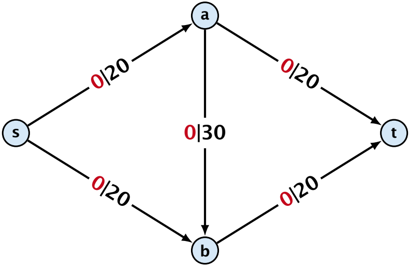
11 Augmenting Path Algorithms

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

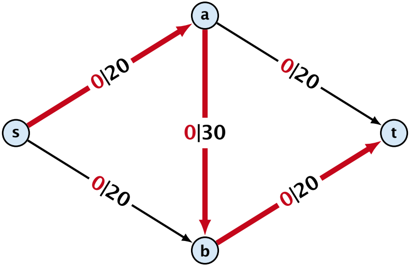


flow value: 0

11 Augmenting Path Algorithms

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

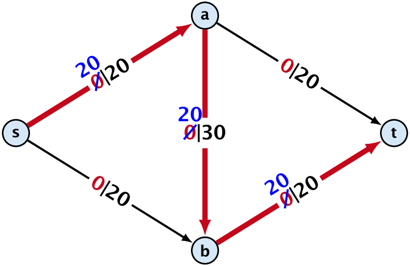


flow value: 0

11 Augmenting Path Algorithms

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

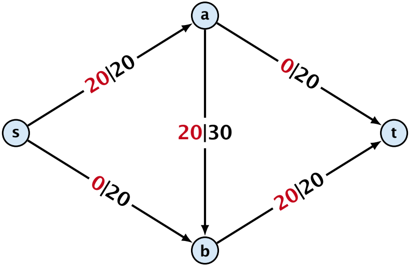


flow value: 0

11 Augmenting Path Algorithms

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: 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):

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):

- Suppose the original graph has edges $e_1 = (u, v)$, and $e_2 = (v, u)$ between u and v.

The Residual Graph

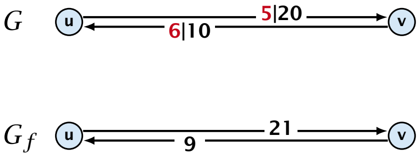
From the graph $G = (V, E, c)$ and the current flow f we construct an auxiliary graph $G_f = (V, E_f, c_f)$ (the residual graph):

- Suppose the original graph has edges $e_1 = (u, v)$, and $e_2 = (v, u)$ between u and v.
- 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 $\max\{0, c(e_2) - f(e_2) + f(e_1)\}$.

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):

- Suppose the original graph has edges $e_1 = (u, v)$, and $e_2 = (v, u)$ between u and v.
- 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 $\max\{0, c(e_2) - f(e_2) + f(e_1)\}$.



Augmenting Path Algorithm

Definition 49

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.

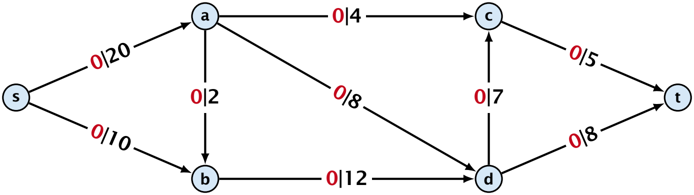
Augmenting Path Algorithm

Definition 49
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.

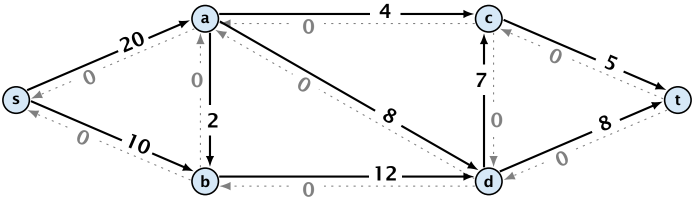
Algorithm 1 FordFulkerson$(G = (V, E, c))$

```
1: Initialize f(e) ← 0 for all edges.
2: while ∃ augmenting path p in G_f do
3:     augment as much flow along p as possible.
```

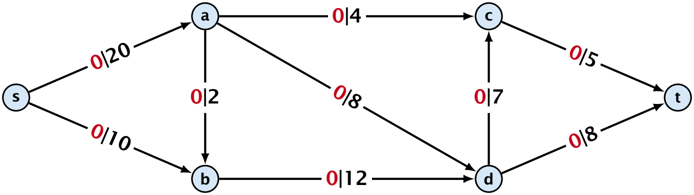
Augmenting Paths



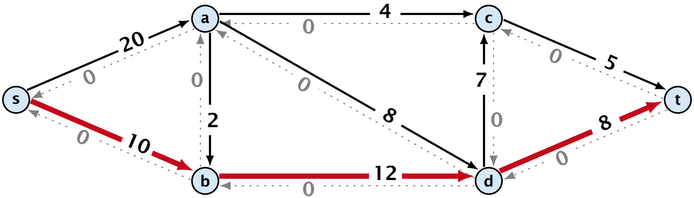
flow value: 0



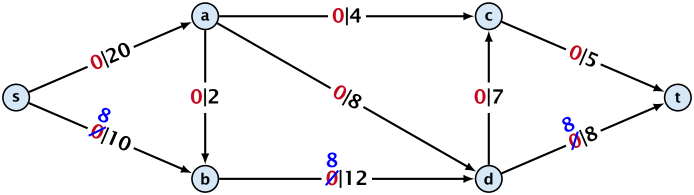
Augmenting Paths



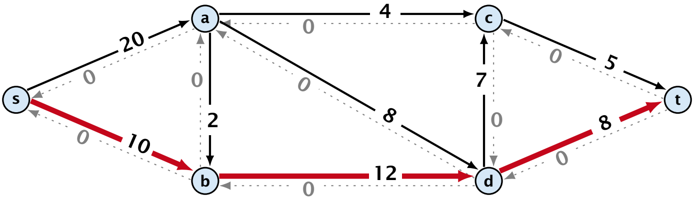
flow value: 0



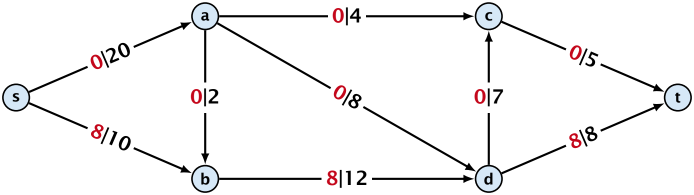
Augmenting Paths



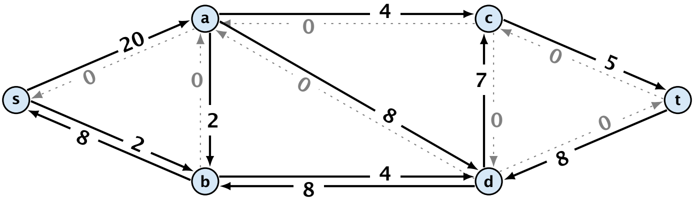
flow value: 0



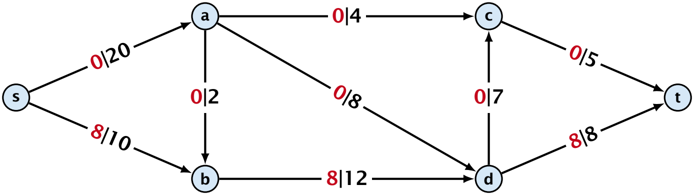
Augmenting Paths



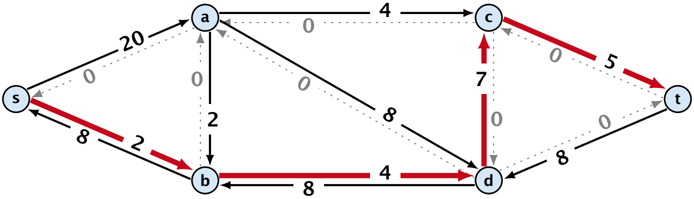
flow value: 8



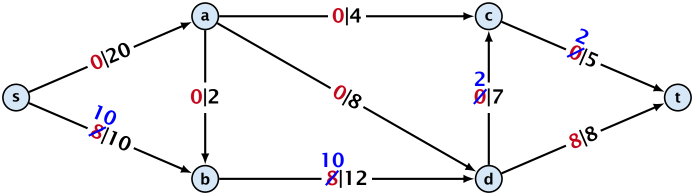
Augmenting Paths



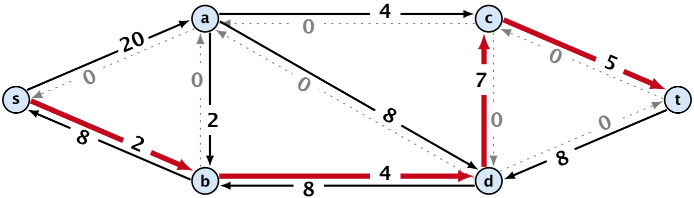
flow value: 8



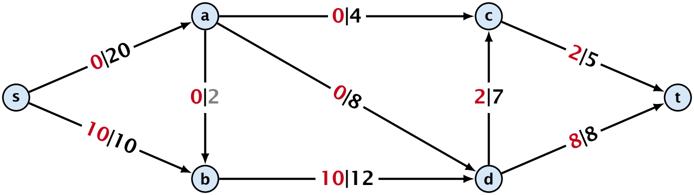
Augmenting Paths



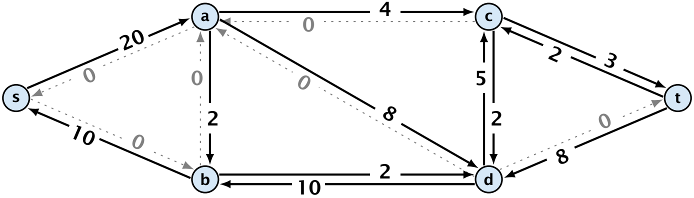
flow value: 8



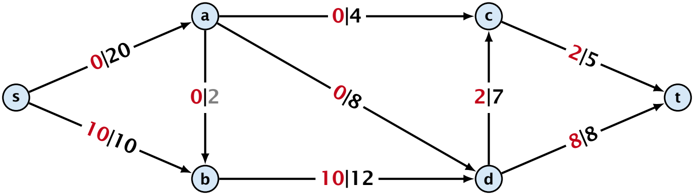
Augmenting Paths



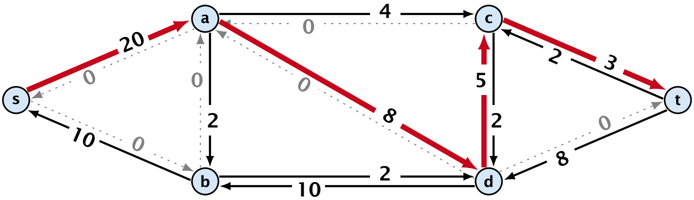
flow value: 10



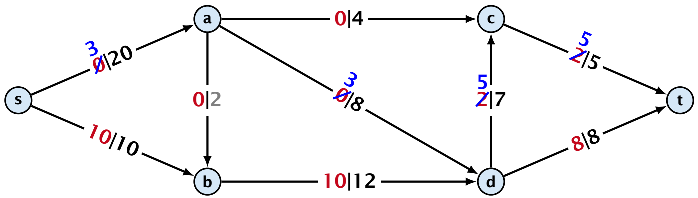
Augmenting Paths



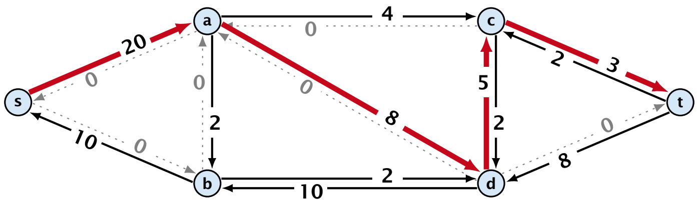
flow value: 10



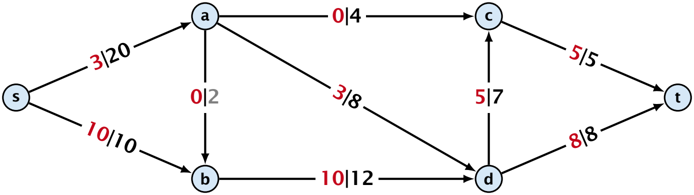
Augmenting Paths



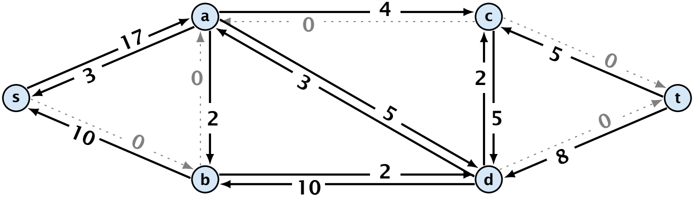
flow value: 10



Augmenting Paths



flow value: 13



Augmenting Path Algorithm

Augmenting Path Algorithm

Theorem 50

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

Augmenting Path Algorithm

Theorem 50

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

Theorem 51

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

Augmenting Path Algorithm

Theorem 50

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

Theorem 51

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

□

Augmenting Path Algorithm

Theorem 50

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

Theorem 51

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 $\mathrm{val}(f) = \mathrm{cap}(A, V \setminus A)$.
2. Flow f is a maximum flow.

□

Augmenting Path Algorithm

Theorem 50

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

Theorem 51

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

□

Augmenting Path Algorithm

Augmenting Path Algorithm

1. $\Longrightarrow$ 2.

This we already showed.

Augmenting Path Algorithm

$1. \implies 2.$

This we already showed.

$2. \implies 3.$

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

Augmenting Path Algorithm

$1. \Longrightarrow 2.$

This we already showed.

$2. \Longrightarrow 3.$

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

$3. \Longrightarrow 1.$

- Let f be a flow with no augmenting paths.

Augmenting Path Algorithm

1. $\Longrightarrow$ 2.

This we already showed.

2. $\Longrightarrow$ 3.

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.

Augmenting Path Algorithm

1. $\Longrightarrow$ 2.

This we already showed.

2. $\Longrightarrow$ 3.

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

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

Augmenting Path Algorithm

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

Augmenting Path Algorithm

$$\begin{aligned}\mathrm{val}(f) &= \sum_{e\in\mathrm{out}(A)} f(e) - \sum_{e\in\mathrm{into}(A)} f(e)\\ &= \sum_{e\in\mathrm{out}(A)} c(e)\end{aligned}$$

Augmenting Path Algorithm

$$\begin{aligned}\mathrm{val}(f) &= \sum_{e\in\mathrm{out}(A)} f(e) - \sum_{e\in\mathrm{into}(A)} f(e)\\ &= \sum_{e\in\mathrm{out}(A)} c(e)\\ &= \mathrm{cap}(A, V\setminus A)\end{aligned}$$

Augmenting Path Algorithm

$$
\begin{aligned}
\mathrm{val}(f) &= \sum_{e\in\mathrm{out}(A)} f(e) - \sum_{e\in\mathrm{into}(A)} f(e) \\
&= \sum_{e\in\mathrm{out}(A)} c(e) \\
&= \mathrm{cap}(A, V\setminus A)
\end{aligned}
$$

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.

Analysis

Assumption:
All capacities are integers between 1 and C.

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

Lemma 52

The algorithm terminates in at most $\mathrm{val}(f^*) \le nC$ *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 52

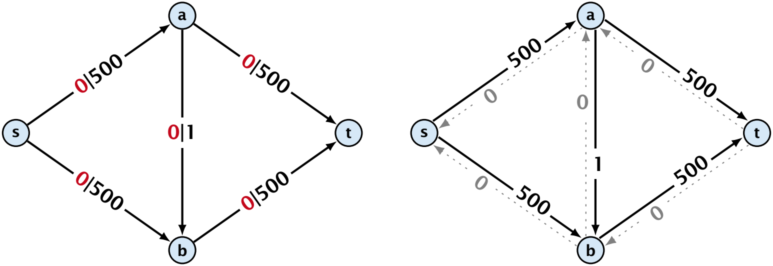
The algorithm terminates in at most $\mathrm{val}(f^*) \le nC$ iterations, where f^* denotes the maximum flow. Each iteration can be implemented in time $\mathcal{O}(m)$. This gives a total running time of $\mathcal{O}(nmC)$.

Theorem 53

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

A Bad Input

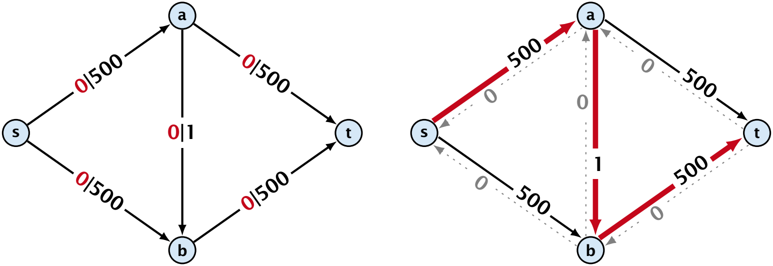
Problem: The running time may not be polynomial



flow value: 0

A Bad Input

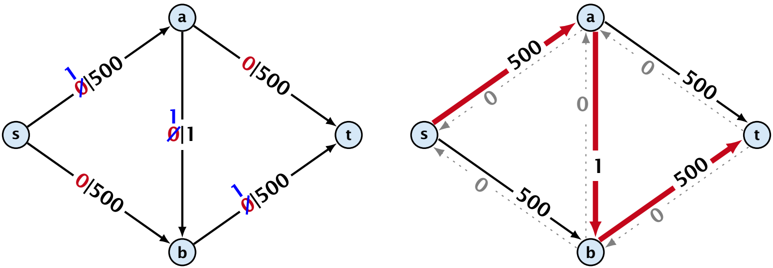
Problem: The running time may not be polynomial



flow value: 0

A Bad Input

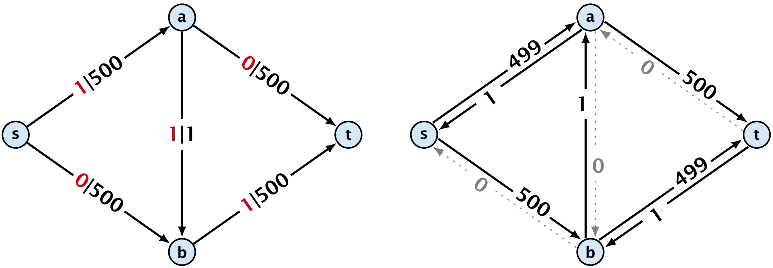
Problem: The running time may not be polynomial



flow value: 0

A Bad Input

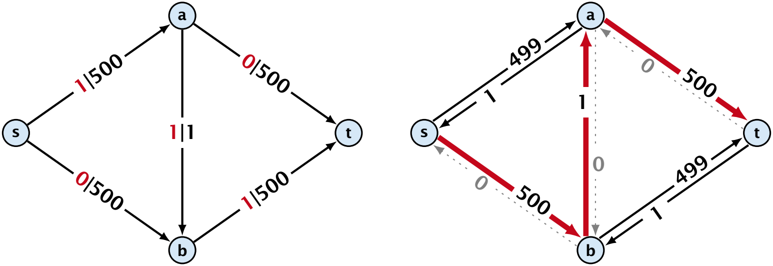
Problem: The running time may not be polynomial



flow value: 1

A Bad Input

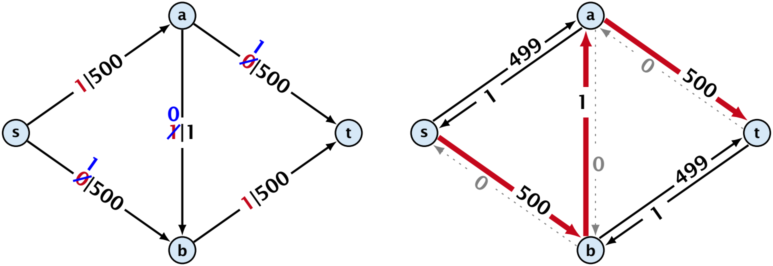
Problem: The running time may not be polynomial



flow value: 1

A Bad Input

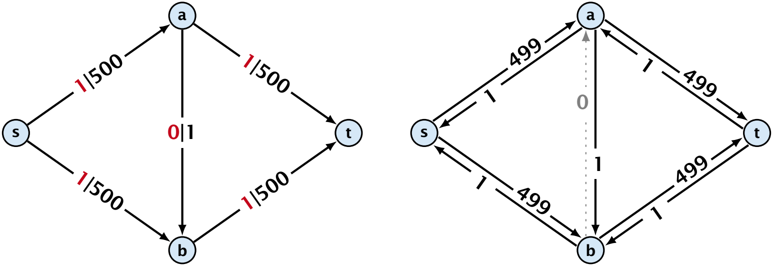
Problem: The running time may not be polynomial



flow value: 1

A Bad Input

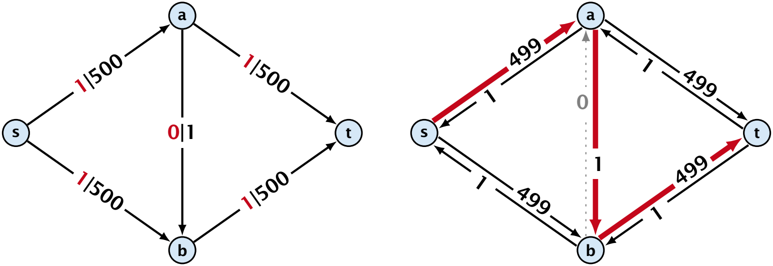
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

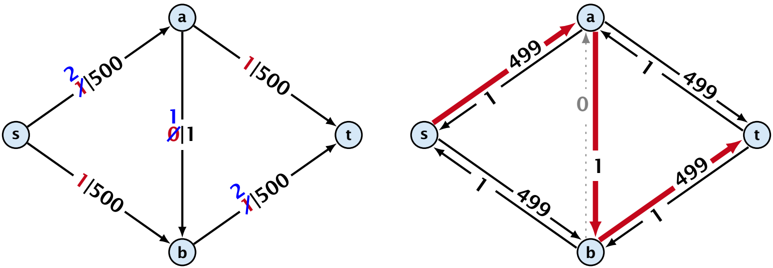
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

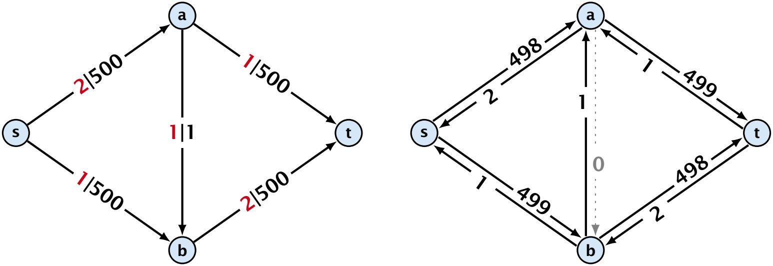
Problem: The running time may not be polynomial



flow value: 2

A Bad Input

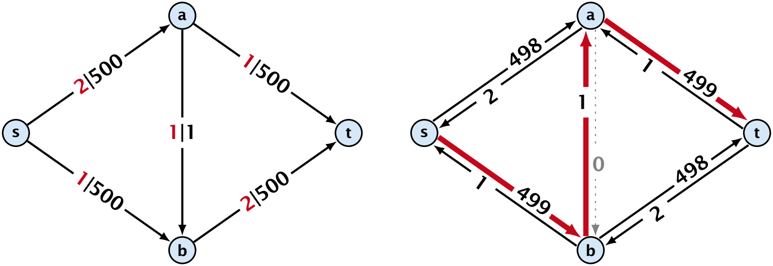
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

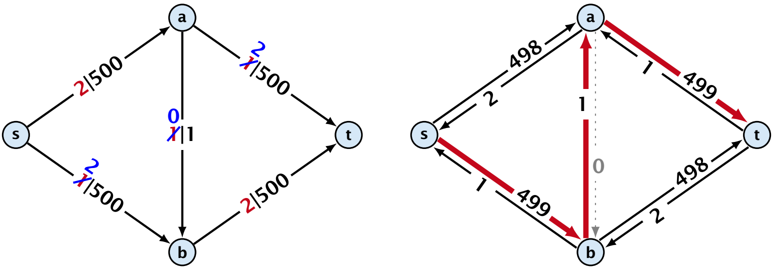
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

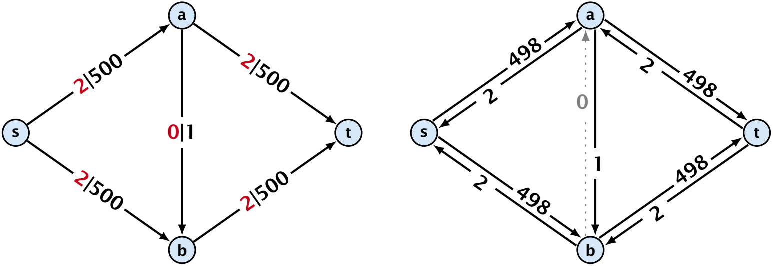
Problem: The running time may not be polynomial



flow value: 3

A Bad Input

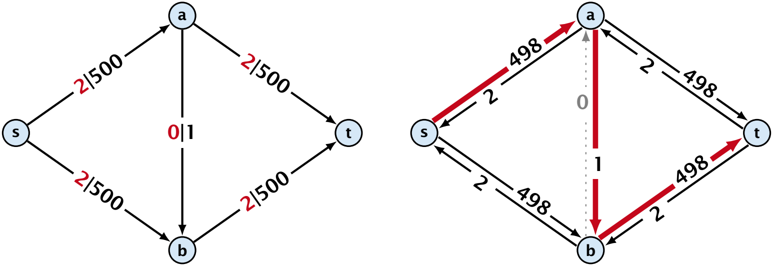
Problem: The running time may not be polynomial



flow value: 4

A Bad Input

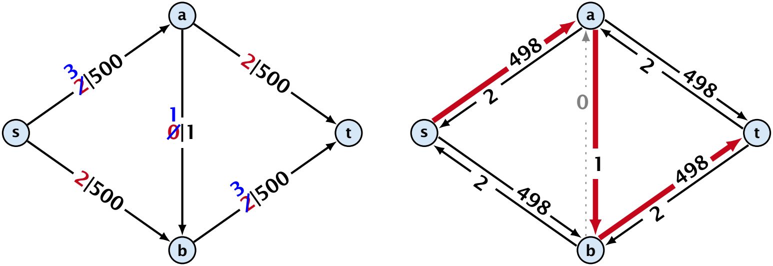
Problem: The running time may not be polynomial



flow value: 4

A Bad Input

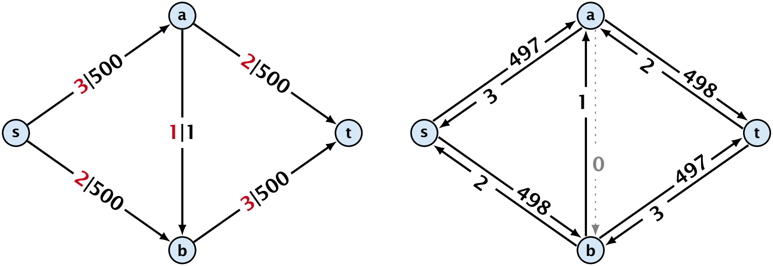
Problem: The running time may not be polynomial



flow value: 4

A Bad Input

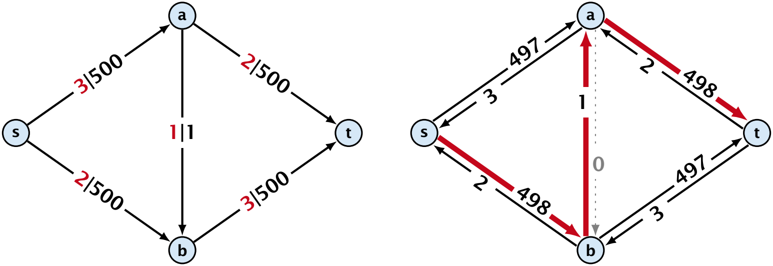
Problem: The running time may not be polynomial



flow value: 5

A Bad Input

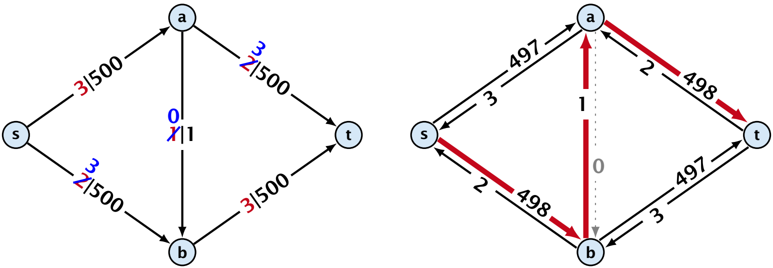
Problem: The running time may not be polynomial



flow value: 5

A Bad Input

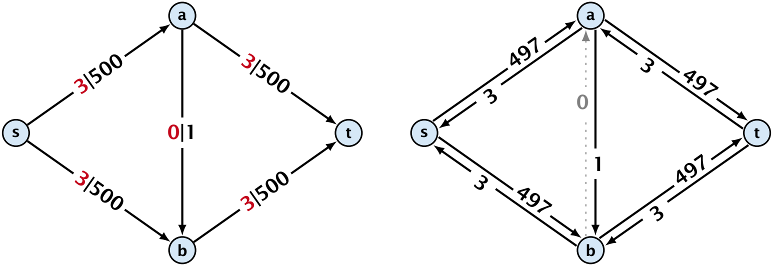
Problem: The running time may not be polynomial



flow value: 5

A Bad Input

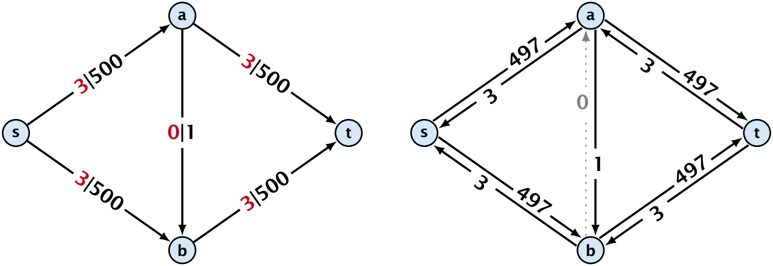
Problem: The running time may not be polynomial



flow value: 6

A Bad Input

Problem: The running time may not be polynomial



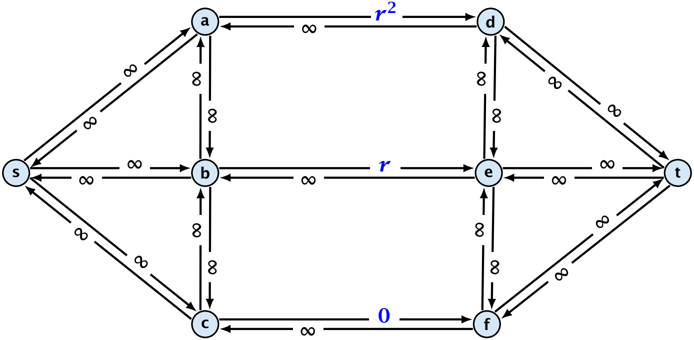
flow value: 6

Question:

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

A Pathological Input

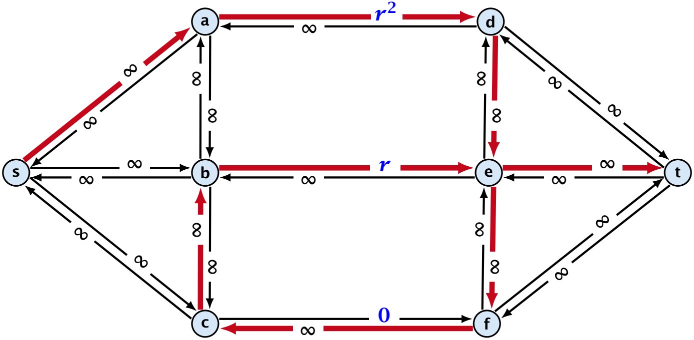
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: 0

A Pathological Input

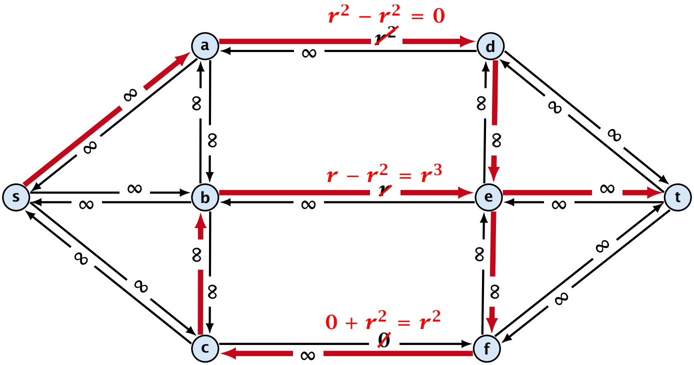
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: 0

A Pathological Input

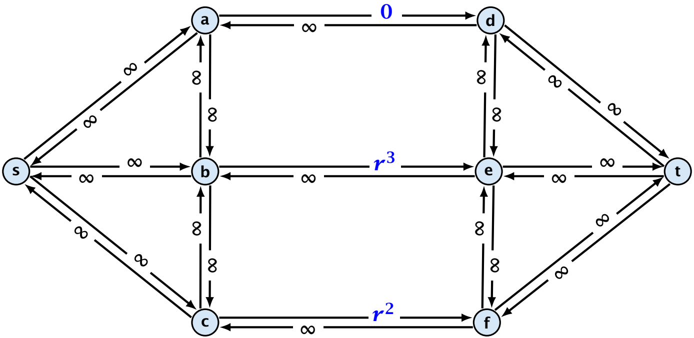
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: 0

A Pathological Input

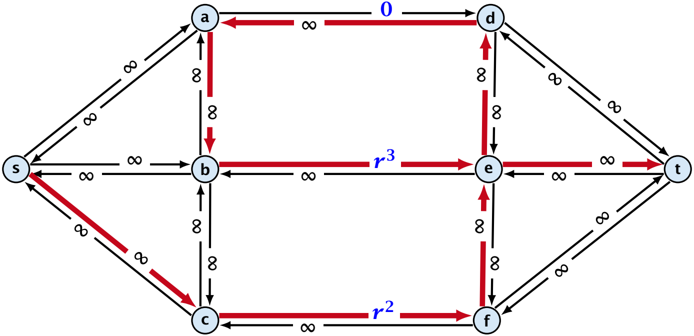
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: r^2

A Pathological Input

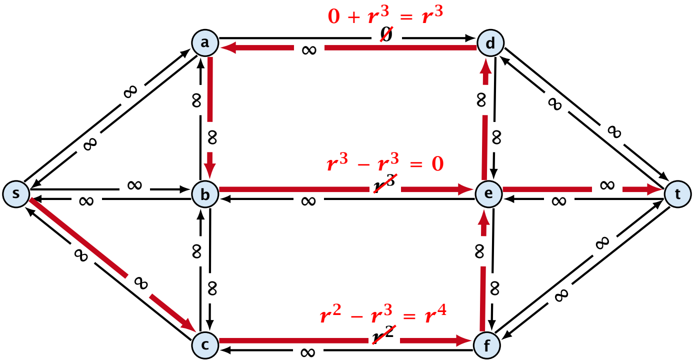
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: r^2

A Pathological Input

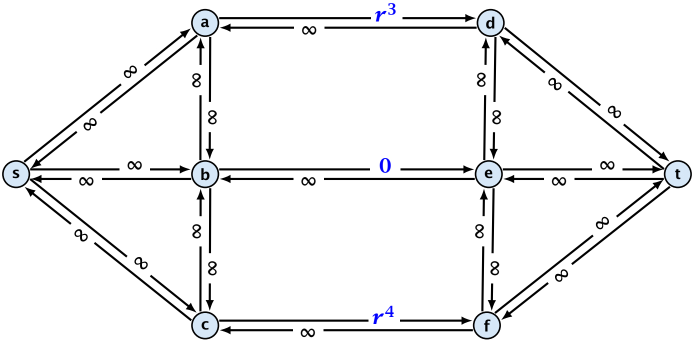
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



flow value: r^2

A Pathological Input

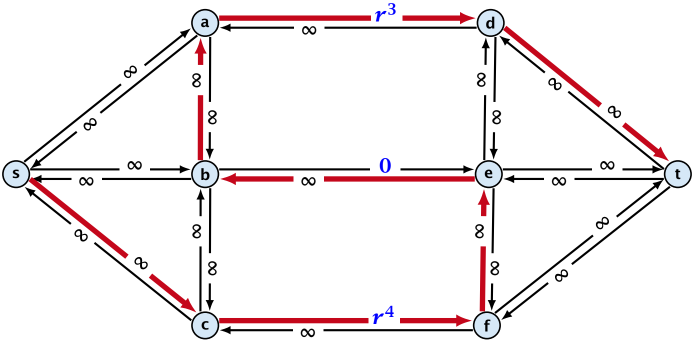
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



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

A Pathological Input

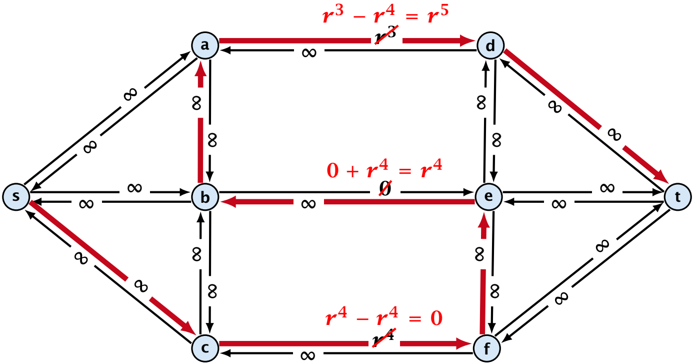
Let $r = \frac{1}{2}(\sqrt{5}-1)$. Then $r^{n+2} = r^n - r^{n+1}$.



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

A Pathological Input

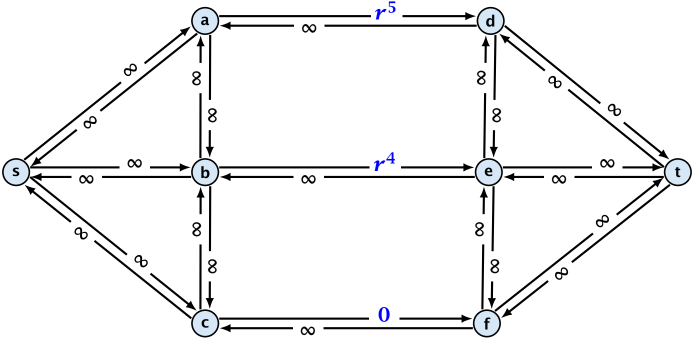
Let $r = \frac{1}{2}(\sqrt{5} - 1)$. Then $r^{n+2} = r^n - r^{n+1}$.



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!!!

How to choose augmenting paths?

How to choose augmenting paths?

- We need to find paths efficiently.

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

Several possibilities:

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

Several possibilities:

- Choose path with maximum bottleneck capacity.

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

Several possibilities:

- Choose path with maximum bottleneck capacity.
- Choose path with sufficiently large bottleneck capacity.

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

Several possibilities:

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

Overview: Shortest Augmenting Paths

Overview: Shortest Augmenting Paths

Lemma 54

The length of the shortest augmenting path never decreases.

Overview: Shortest Augmenting Paths

Lemma 54
The length of the shortest augmenting path never decreases.

Lemma 55
After at most $\mathcal{O}(m)$ augmentations, the length of the shortest augmenting path strictly increases.

Overview: Shortest Augmenting Paths

These two lemmas give the following theorem:

Overview: Shortest Augmenting Paths

These two lemmas give the following theorem:

Theorem 56

The shortest augmenting path algorithm performs at most $\mathcal{O}(mn)$ augmentations. This gives a running time of $\mathcal{O}(m^2n)$.

Overview: Shortest Augmenting Paths

These two lemmas give the following theorem:

Theorem 56

The shortest augmenting path algorithm performs at most $\mathcal{O}(mn)$ augmentations. This gives a running time of $\mathcal{O}(m^2n)$.

Proof.

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

$\square$

Overview: Shortest Augmenting Paths

These two lemmas give the following theorem:

Theorem 56

The shortest augmenting path algorithm performs at most $\mathcal{O}(mn)$ augmentations. This gives a running time of $\mathcal{O}(m^2n)$.

Proof.

- We can find the shortest augmenting paths in time $\mathcal{O}(m)$ via BFS.
- $\mathcal{O}(m)$ augmentations for paths of exactly $k < n$ edges.

□

Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

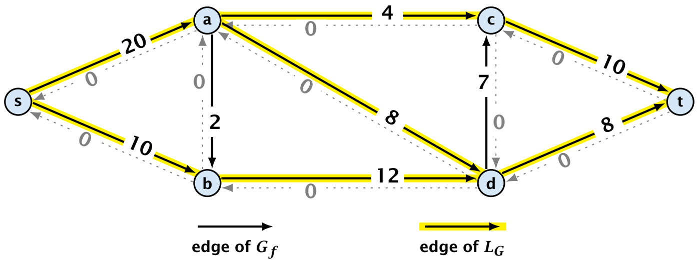
Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u, v) with $\ell(v) = \ell(u) + 1$.

Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u, v) with $\ell(v) = \ell(u) + 1$.

A path P is a shortest s-u path in G_f **iff** it is an s-u path in L_G.

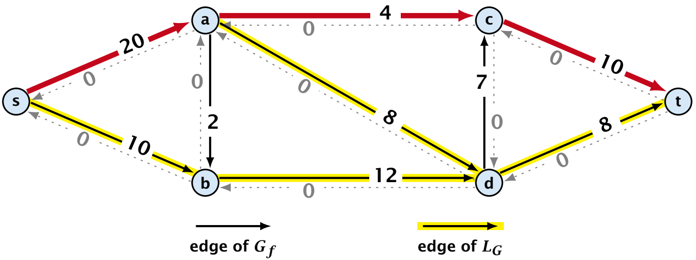


Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u, v) with $\ell(v) = \ell(u) + 1$.

A path P is a shortest s-u path in G_f **iff** it is an s-u path in L_G.

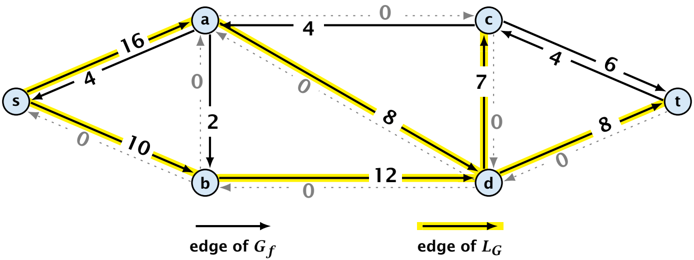


Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u,v) with $\ell(v) = \ell(u) + 1$.

A path P is a shortest s-u path in G_f **iff** it is an s-u path in L_G.

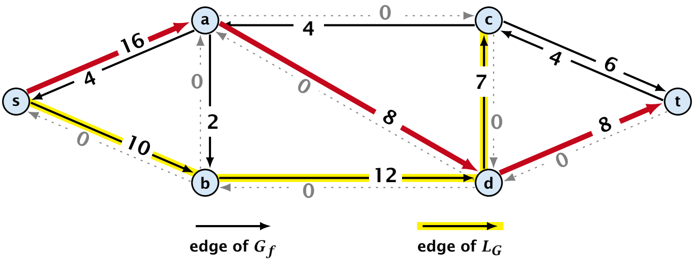


Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u,v) with $\ell(v) = \ell(u) + 1$.

A path P is a shortest s-u path in G_f **iff** it is an s-u path in L_G.

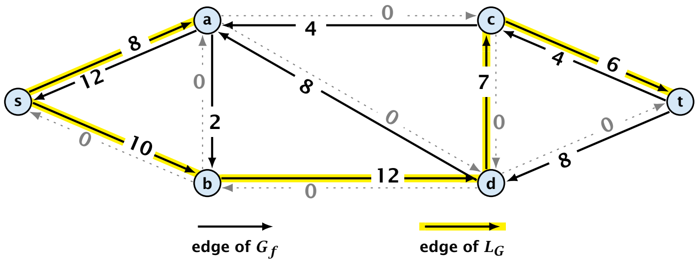


Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u,v) with $\ell(v) = \ell(u) + 1$.

A path P is a shortest s-u path in G_f **iff** it is an s-u path in L_G.

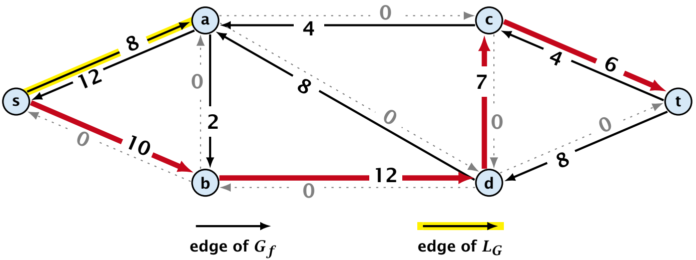


Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u,v) with $\ell(v) = \ell(u) + 1$.

A path P is a shortest s-u path in G_f **iff** it is an s-u path in L_G.

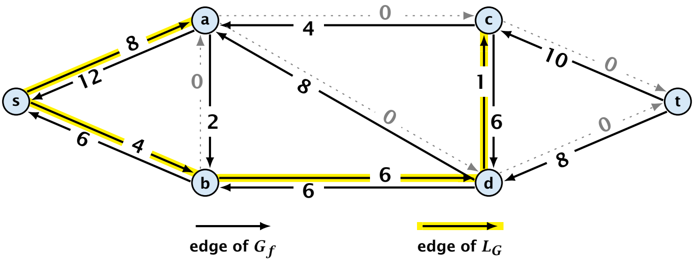


Shortest Augmenting Paths

Define the level $\ell(v)$ of a node as the length of the shortest s-v path in G_f (along non-zero edges).

Let L_G denote the subgraph of the residual graph G_f that contains only those edges (u,v) with $\ell(v) = \ell(u) + 1$.

A path P is a shortest s-u path in G_f **iff** it is an s-u path in L_G.



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.

Shortest Augmenting Path

First Lemma:

The length of the shortest augmenting path never decreases.

Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.

Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.

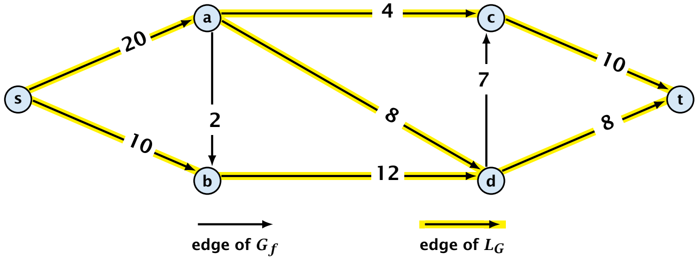
Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.



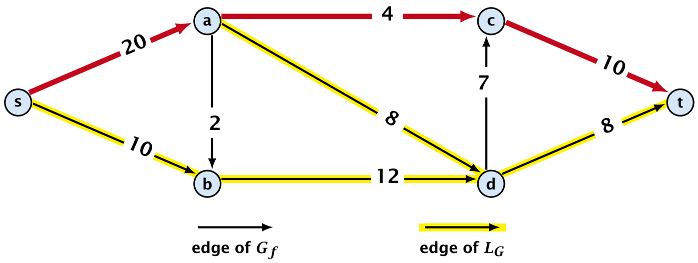
Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.



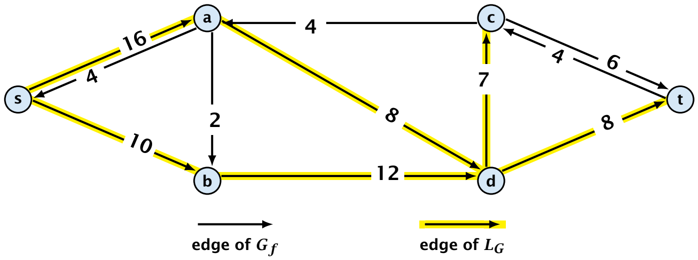
Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.



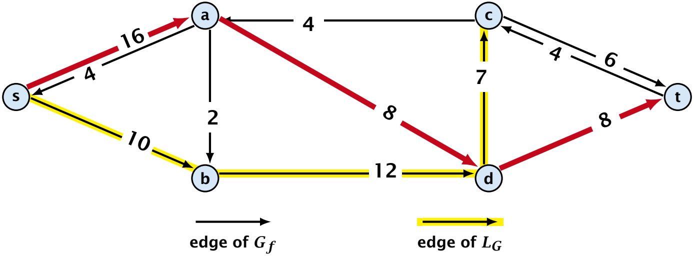
Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.



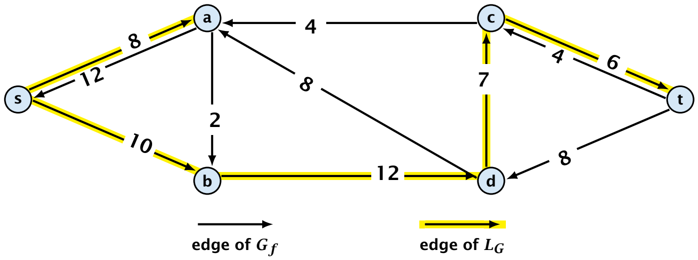
Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.



Shortest Augmenting Path

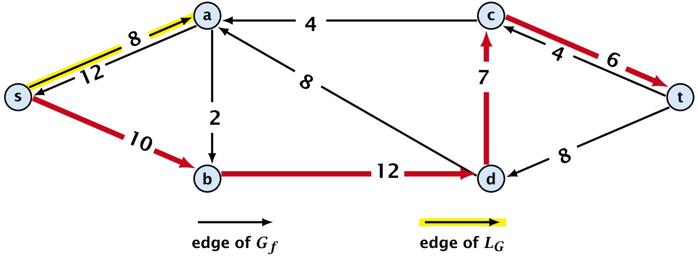
First Lemma:

The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.



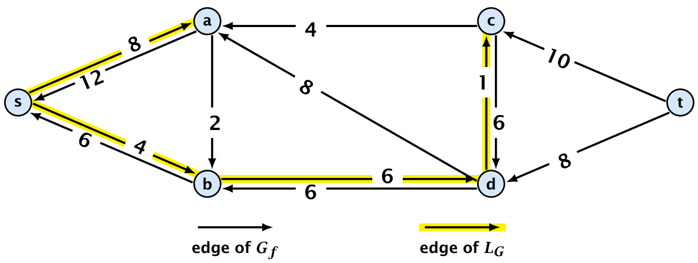
Shortest Augmenting Path

First Lemma:
The length of the shortest augmenting path never decreases.

After an augmentation G_f changes as follows:

- Bottleneck edges on the chosen path are deleted.
- Back edges are added to all edges that don't have back edges so far.

These changes cannot decrease the distance between s and t.



Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Let M denote the set of edges in graph L_G at the beginning of a round when the distance between s and t is k.

Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Let M denote the set of edges in graph L_G at the beginning of a round when the distance between s and t is k.

An s-t path in G_f that uses edges not in M has length larger than k, even when using edges added to G_f during the round.

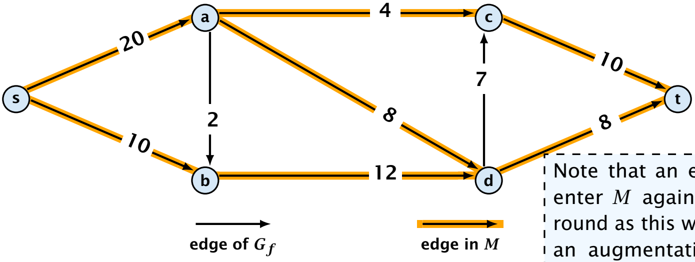
Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Let M denote the set of edges in graph L_G at the beginning of a round when the distance between s and t is k.

An s-t path in G_f that uses edges not in M has length larger than k, even when using edges added to G_f during the round.

In each augmentation an edge is deleted from M.



Note that an edge cannot enter M again during the round as this would require an augmentation along a non-shortest path.

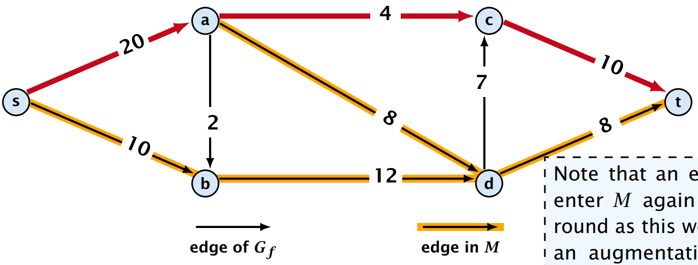
Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Let M denote the set of edges in graph L_G at the beginning of a round when the distance between s and t is k.

An s-t path in G_f that uses edges not in M has length larger than k, even when using edges added to G_f during the round.

In each augmentation an edge is deleted from M.



Note that an edge cannot enter M again during the round as this would require an augmentation along a non-shortest path.

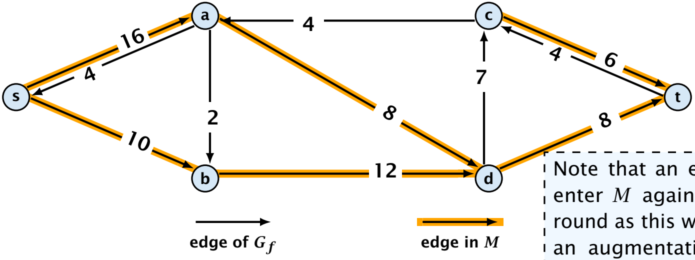
Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Let M denote the set of edges in graph L_G at the beginning of a round when the distance between s and t is k.

An s-t path in G_f that uses edges not in M has length larger than k, even when using edges added to G_f during the round.

In each augmentation an edge is deleted from M.



Note that an edge cannot enter M again during the round as this would require an augmentation along a non-shortest path.

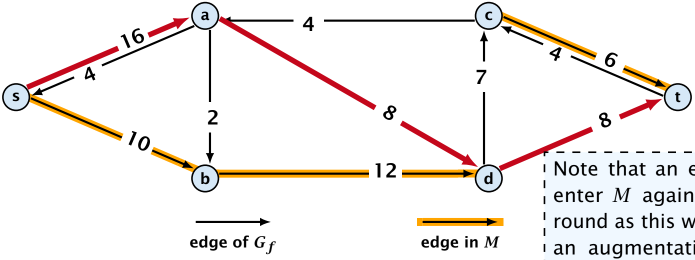
Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Let M denote the set of edges in graph L_G at the beginning of a round when the distance between s and t is k.

An s-t path in G_f that uses edges not in M has length larger than k, even when using edges added to G_f during the round.

In each augmentation an edge is deleted from M.



Note that an edge cannot enter M again during the round as this would require an augmentation along a non-shortest path.

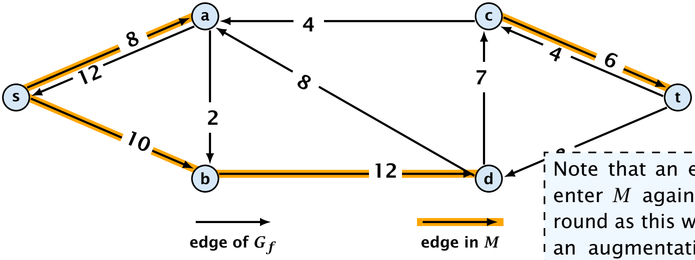
Shortest Augmenting Path

Second Lemma: After at most m augmentations the length of the shortest augmenting path strictly increases.

Let M denote the set of edges in graph L_G at the beginning of a round when the distance between s and t is k.

An s-t path in G_f that uses edges not in M has length larger than k, even when using edges added to G_f during the round.

In each augmentation an edge is deleted from M.



Note that an edge cannot enter M again during the round as this would require an augmentation along a non-shortest path.

Shortest Augmenting Paths

Shortest Augmenting Paths

Theorem 57

The shortest augmenting path algorithm performs at most $\mathcal{O}(mn)$ augmentations. Each augmentation can be performed in time $\mathcal{O}(m)$.

Shortest Augmenting Paths

Theorem 57

The shortest augmenting path algorithm performs at most $\mathcal{O}(mn)$ augmentations. Each augmentation can be performed in time $\mathcal{O}(m)$.

Theorem 58 (without proof)

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

Shortest Augmenting Paths

Theorem 57
The shortest augmenting path algorithm performs at most $\mathcal{O}(mn)$ augmentations. Each augmentation can be performed in time $\mathcal{O}(m)$.

Theorem 58 (without proof)
There exist networks with $m = \Theta(n^2)$ that require $\Omega(mn)$ augmentations, when we restrict ourselves to only augment along shortest augmenting paths.

Note:
There always exists a set of m augmentations that gives a maximum flow (why?).

Shortest Augmenting Paths

When sticking to shortest augmenting paths we cannot improve (asymptotically) on the number of augmentations.

Shortest Augmenting Paths

When sticking to shortest augmenting paths we cannot improve (asymptotically) on the number of augmentations.

However, we can improve the running time to $\mathcal{O}(mn^2)$ by improving the running time for finding an augmenting path (currently we assume $\mathcal{O}(m)$ per augmentation for this).

Shortest Augmenting Paths

We maintain a subset M of the edges of G_f with the guarantee that a shortest s-t path using only edges from M is a shortest augmenting path.

Shortest Augmenting Paths

We maintain a subset M of the edges of G_f with the guarantee that a shortest s-t path using only edges from M is a shortest augmenting path.

With each augmentation some edges are deleted from M.

Shortest Augmenting Paths

We maintain a subset M of the edges of G_f with the guarantee that a shortest s-t path using only edges from M is a shortest augmenting path.

With each augmentation some edges are deleted from M.

When M does not contain an s-t path anymore the distance between s and t strictly increases.

Shortest Augmenting Paths

We maintain a subset M of the edges of G_f with the guarantee that a shortest s-t path using only edges from M is a shortest augmenting path.

With each augmentation some edges are deleted from M.

When M does not contain an s-t path anymore the distance between s and t strictly increases.

Note that M is not the set of edges of the level graph but a subset of level-graph edges.

Suppose that the initial distance between s and t in G_f is k.

Suppose that the initial distance between s and t in G_f is k.

M is initialized as the level graph L_G.

Suppose that the initial distance between s and t in G_f is k.

M is initialized as the level graph L_G.

Perform a DFS search to find a path from s to t using edges from M.

Suppose that the initial distance between s and t in G_f is k.

M is initialized as the level graph L_G.

Perform a DFS search to find a path from s to t using edges from M.

Either you find t after at most n steps, or you end at a node v that does not have any outgoing edges.

Suppose that the initial distance between s and t in G_f is k.

M is initialized as the level graph L_G.

Perform a DFS search to find a path from s to t using edges from M.

Either you find t after at most n steps, or you end at a node v that does not have any outgoing edges.

You can delete incoming edges of v from M.

Analysis

Analysis

Let a phase of the algorithm be defined by the time between two augmentations during which the distance between s and t strictly increases.

Analysis

Let a phase of the algorithm be defined by the time between two augmentations during which the distance between s and t strictly increases.

Initializing M for the phase takes time $\mathcal{O}(m)$.

Analysis

Let a phase of the algorithm be defined by the time between two augmentations during which the distance between s and t strictly increases.

Initializing M for the phase takes time $\mathcal{O}(m)$.

The total cost for searching for augmenting paths during a phase is at most $\mathcal{O}(mn)$, since every search (successful (i.e., reaching t) or unsuccessful) decreases the number of edges in M and takes time $\mathcal{O}(n)$.

Analysis

Let a phase of the algorithm be defined by the time between two augmentations during which the distance between s and t strictly increases.

Initializing M for the phase takes time $\mathcal{O}(m)$.

The total cost for searching for augmenting paths during a phase is at most $\mathcal{O}(mn)$, since every search (successful (i.e., reaching t) or unsuccessful) decreases the number of edges in M and takes time $\mathcal{O}(n)$.

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 M for the next search.

Analysis

Let a phase of the algorithm be defined by the time between two augmentations during which the distance between s and t strictly increases.

Initializing M for the phase takes time $\mathcal{O}(m)$.

The total cost for searching for augmenting paths during a phase is at most $\mathcal{O}(mn)$, since every search (successful (i.e., reaching t) or unsuccessful) decreases the number of edges in M and takes time $\mathcal{O}(n)$.

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 M for the next search.

There are at most n phases. Hence, total cost is $\mathcal{O}(mn^2)$.

How to choose augmenting paths?

- We need to find paths efficiently.

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

Several possibilities:

How to choose augmenting paths?

- We need to find paths efficiently.
- We want to guarantee a small number of iterations.

Several possibilities:

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

Capacity Scaling

Capacity Scaling

Intuition:

- Choosing a path with the highest bottleneck increases the flow as much as possible in a single step.

Capacity Scaling

Intuition:

- Choosing a path with the highest bottleneck increases the flow as much as possible in a single step.
- Don't worry about finding the exact bottleneck.

Capacity Scaling

Intuition:

- Choosing a path with the highest bottleneck increases the flow as much as possible in a single step.
- Don't worry about finding the exact bottleneck.
- Maintain scaling parameter Δ.

Capacity Scaling

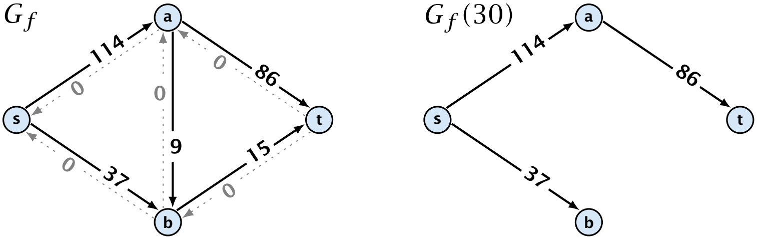
Intuition:

- Choosing a path with the highest bottleneck increases the flow as much as possible in a single step.
- Don't worry about finding the exact bottleneck.
- Maintain scaling parameter Δ.
- $G_f(\Delta)$ is a sub-graph of the residual graph G_f that contains only edges with capacity at least Δ.

Capacity Scaling

Intuition:

- Choosing a path with the highest bottleneck increases the flow as much as possible in a single step.
- Don't worry about finding the exact bottleneck.
- Maintain scaling parameter Δ.
- $G_f(\Delta)$ is a sub-graph of the residual graph G_f that contains only edges with capacity at least Δ.



Capacity Scaling

Algorithm 1 maxflow(G, s, t, c)

foreach $e \in E$ **do** $f_e \leftarrow 0$;
$\Delta \leftarrow 2^{\lceil \log_2 C \rceil}$
while $\Delta \geq 1$ **do**
    $G_f(\Delta) \leftarrow \Delta$-residual graph
    while there is augmenting path P in $G_f(\Delta)$ **do**
        $f \leftarrow$ augment(f, c, P)
        update$(G_f(\Delta))$
    $\Delta \leftarrow \Delta/2$
return f

Capacity Scaling

Capacity Scaling

Assumption:

All capacities are integers between 1 and C.

Capacity Scaling

Assumption:
All capacities are integers between 1 and C.

Invariant:
All flows and capacities are/remain integral throughout the algorithm.

Capacity Scaling

Assumption:
All capacities are integers between 1 and C.

Invariant:
All flows and capacities are/remain integral throughout the algorithm.

Correctness:
The algorithm computes a maxflow:

- because of integrality we have $G_f(1) = G_f$

Capacity Scaling

Assumption:
All capacities are integers between 1 and C.

Invariant:
All flows and capacities are/remain integral throughout the algorithm.

Correctness:
The algorithm computes a maxflow:

- because of integrality we have $G_f(1) = G_f$
- therefore after the last phase there are no augmenting paths anymore

Capacity Scaling

Assumption:
All capacities are integers between 1 and C.

Invariant:
All flows and capacities are/remain integral throughout the algorithm.

Correctness:
The algorithm computes a maxflow:

- because of integrality we have $G_f(1) = G_f$
- therefore after the last phase there are no augmenting paths anymore
- this means we have a maximum flow.

Capacity Scaling

Capacity Scaling

Lemma 59

There are $\lceil \log C \rceil + 1$ *iterations over* Δ.

Proof: obvious.

Capacity Scaling

Lemma 59

There are $\lceil \log C \rceil + 1$ iterations over Δ.

Proof: obvious.

Lemma 60

Let f be the flow at the end of a Δ-phase. Then the maximum flow is smaller than $\mathrm{val}(f) + m\Delta$.

Proof: less obvious, but simple:

Capacity Scaling

Lemma 59

There are $\lceil \log C \rceil + 1$ *iterations over* Δ*.*

Proof: obvious.

Lemma 60

Let f *be the flow at the end of a* Δ*-phase. Then the maximum flow is smaller than* $\mathrm{val}(f) + m\Delta$*.*

Proof: less obvious, but simple:

- There must exist an s-t cut in $G_f(\Delta)$ of zero capacity.

Capacity Scaling

Lemma 59

There are $\lceil \log C \rceil + 1$ iterations over Δ.

Proof: obvious.

Lemma 60

Let f be the flow at the end of a Δ-phase. Then the maximum flow is smaller than $\mathrm{val}(f) + m\Delta$.

Proof: less obvious, but simple:

- There must exist an s-t cut in $G_f(\Delta)$ of zero capacity.
- In G_f this cut can have capacity at most $m\Delta$.

Capacity Scaling

Lemma 59

There are $\lceil \log C \rceil + 1$ *iterations over* Δ.

Proof: obvious.

Lemma 60

Let f *be the flow at the end of a* Δ*-phase. Then the maximum flow is smaller than* $\mathrm{val}(f) + m\Delta$.

Proof: less obvious, but simple:

- There must exist an s-t cut in $G_f(\Delta)$ of zero capacity.
- In G_f this cut can have capacity at most $m\Delta$.
- This gives me an upper bound on the flow that I can still add.

Capacity Scaling

Capacity Scaling

Lemma 61

There are at most $2m$ augmentations per scaling-phase.

Capacity Scaling

Lemma 61

There are at most $2m$ augmentations per scaling-phase.

Proof:

- Let f be the flow at the end of the previous phase.

Capacity Scaling

Lemma 61
There are at most $2m$ augmentations per scaling-phase.

Proof:

- Let f be the flow at the end of the previous phase.
- $\mathrm{val}(f^*) \le \mathrm{val}(f) + 2m\Delta$

Capacity Scaling

Lemma 61

There are at most $2m$ augmentations per scaling-phase.

Proof:

- Let f be the flow at the end of the previous phase.
- $\text{val}(f^*) \leq \text{val}(f) + 2m\Delta$
- Each augmentation increases flow by Δ.

Capacity Scaling

Lemma 61

There are at most $2m$ augmentations per scaling-phase.

Proof:

- Let f be the flow at the end of the previous phase.
- $\mathrm{val}(f^*) \le \mathrm{val}(f) + 2m\Delta$
- Each augmentation increases flow by Δ.

Theorem 62

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