Network Flow

Lecture 11

September 30, 2014

Part I

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1. Transfer as much "merchandise" as possible from one point to another.
2. Wireless network, transfer a large file from s to t.
3. Limited capacities.

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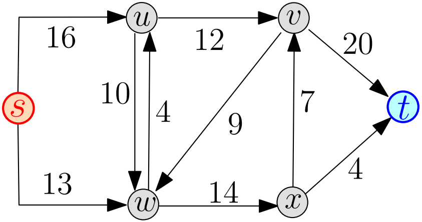

Network: Definition

1. Given a network with capacities on each connection.
2. Q: How much "flow" can transfer from source s to a sink t?
3. The flow is ***splitable***.
4. Network examples: water pipes moving water. Electricity network.
5. Internet is packet base, so not quite splitable.

Definition

- ⋆ $\mathbf{G} = (\mathbf{V}, \mathbf{E})$: a ***directed*** graph.
- ⋆ $\forall\,(u \to v) \in \mathbf{E}(\mathbf{G})$: ***capacity*** $c(u, v) \geq 0$,
- ⋆ $(u \to v) \notin G \implies c(u, v) = 0$.
- ⋆ s: ***source*** vertex, t: target ***sink*** vertex.
- ⋆ $\mathbf{G}$, s, t and $c(\cdot)$: form ***flow network*** or ***network***.

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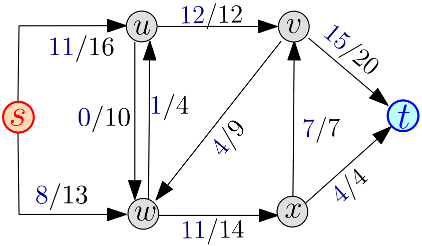

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2. Flow on edge: non-negative quantity $\leq$ capacity of edge.

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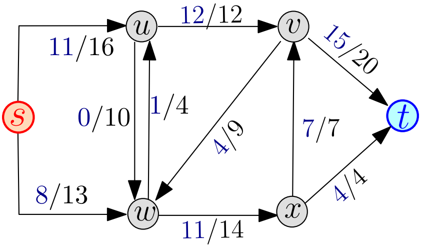

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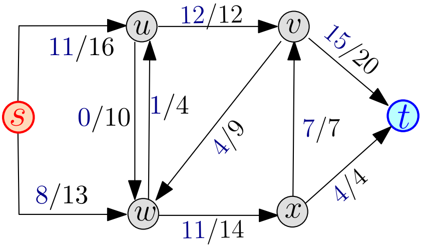

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Flow definition

Definition (flow)

flow in network is a function $f(\cdot,\cdot) : \mathbf{E}(\mathbf{G}) \rightarrow \mathbb{R}$:

(A) ***Bounded by capacity***:
$\forall (u \rightarrow v) \in \mathbf{E} \qquad f(u,v) \leq c(u,v)$.

(B) ***Anti symmetry***:
$\forall u, v \qquad f(u,v) = -f(v,u)$.

(C) Two special vertices: (i) the ***source*** s and the ***sink*** t.

(D) ***Conservation of flow*** (Kirchhoff's Current Law):
$\forall u \in \mathbf{V} \setminus \{s,t\} \qquad \sum_{v} f(u,v) = 0$.

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Problem: Max Flow

1. Flow on edge can be negative (i.e., positive flow on edge in other direction).

Problem (Maximum flow)

Given a network $\mathbf{G}$ *find the* ***maximum flow*** *in* $\mathbf{G}$. *Namely, compute a legal flow* f *such that* $|f|$ *is maximized.*

Part II

Some properties of flows and residual networks

Flow across sets of vertices

1. $\forall X, Y \subseteq \mathbf{V}$, let $f(X, Y) = \sum_{x \in X, y \in Y} f(x, y)$.
   $f(v, S) = f\Big(\{v\}, S\Big)$, where $v \in \mathbf{V}(\mathbf{G})$.

Observation

$|f| = f(s, \mathbf{V})$.

Basic properties of flows: (i)

Lemma

For a flow f, the following properties holds:

(i) $\forall u \in \mathbf{V}(\mathbf{G})$ *we have* $f(u, u) = 0$,

Proof.

Holds since $(u \rightarrow u)$ it not an edge in $\mathbf{G}$.

$(u \rightarrow u)$ capacity is zero,

Flow on $(u \rightarrow u)$ is zero. □

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Basic properties of flows: (ii)

Lemma

For a flow f*, the following properties holds:*
(ii) $\forall X \subseteq \mathbf{V}$ *we have* $f(X, X) = 0$,

Proof.

$$f(X, X) = \sum_{\{u,v\} \subseteq X, u \neq v} \left(f(u, v) + f(v, u) \right) + \sum_{u \in X} f(u, u)$$
$$= \sum_{\{u,v\} \subseteq X, u \neq v} \left(f(u, v) - f(u, v) \right) + \sum_{u \in X} 0 = 0,$$

by the anti-symmetry property of flow. □

Basic properties of flows: (iii)

Lemma

For a flow f, the following properties holds:
(iii) $\forall X, Y \subseteq \mathbf{V}$ *we have* $f(X, Y) = -f(Y, X)$,

Proof.

By the anti-symmetry of flow, as

$$f(X, Y) = \sum_{x \in X, y \in Y} f(x, y) = - \sum_{x \in X, y \in Y} f(y, x) = -f(Y, X).$$

□

Basic properties of flows: (iv)

Lemma

For a flow f, the following properties holds:

(iv) $\forall X, Y, Z \subseteq \mathbf{V}$ *such that* $X \cap Y = \emptyset$ *we have that*

$f(X \cup Y, Z) = f(X, Z) + f(Y, Z)$ *and*

$f(Z, X \cup Y) = f(Z, X) + f(Z, Y)$.

Proof.

Follows from definition. (Check!) □

Basic properties of flows: (v)

Lemma

For a flow f, the following properties holds:

(v) $\forall u \in \mathbf{V} \setminus \{s, t\}$, *we have* $f(u, \mathbf{V}) = f(\mathbf{V}, u) = 0$.

Proof.

This is a restatement of the conservation of flow property. □

Basic properties of flows: summary

Lemma

For a flow f, the following properties holds:

(i) $\forall u \in \mathsf{V}(\mathsf{G})$ *we have* $f(u, u) = 0$,

(ii) $\forall X \subseteq \mathsf{V}$ *we have* $f(X, X) = 0$,

(iii) $\forall X, Y \subseteq \mathsf{V}$ *we have* $f(X, Y) = -f(Y, X)$,

(iv) $\forall X, Y, Z \subseteq \mathsf{V}$ *such that* $X \cap Y = \emptyset$ *we have that* $f(X \cup Y, Z) = f(X, Z) + f(Y, Z)$ *and* $f(Z, X \cup Y) = f(Z, X) + f(Z, Y)$.

(v) For all $u \in \mathsf{V} \setminus \{s, t\}$, *we have* $f(u, \mathsf{V}) = f(\mathsf{V}, u) = 0$.

All flow gets to the sink

Claim

$|f| = f(\mathbf{V}, t)$.

Proof.

$$|f| =$$

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$$|f| = f(s, \mathsf{V}) = f\Big(\mathsf{V} \setminus (\mathsf{V} \setminus \{s\}),\, V\Big)$$

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$$|f| = f\Big(\mathbf{V} \setminus (\mathbf{V} \setminus \{s\})\,,\, V\Big)$$
$$= f(\mathbf{V}, V) - f(V \setminus \{s\}\,, \mathbf{V})$$

$\square$

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Since $f(\mathbf{V}, V) = 0$ by (i) □

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|f| &= f(\mathbf{V}, V) - f(V \setminus \{s\}, \mathbf{V}) \\
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&= f(\mathbf{V}, \mathbf{V} \setminus \{s\}) \\
&= f(\mathbf{V}, t) + f(\mathbf{V}, \mathbf{V} \setminus \{s, t\})
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Since $f(\mathbf{V}, V) = 0$ by (i) and $f(\mathbf{V}, u) = 0$ by (iv). □

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Since $f(\mathbf{V}, V) = 0$ by (i) and $f(\mathbf{V}, u) = 0$ by (iv). □

Residual capacity

Definition

c: capacity, f: flow.
The ***residual capacity*** of an edge $(u \rightarrow v)$ is

$$c_f(u, v) = c(u, v) - f(u, v).$$

1. residual capacity $c_f(u, v)$ on $(u \rightarrow v)$ = amount of unused capacity on $(u \rightarrow v)$.
2. ... next construct graph with all edges not being fully used by f.

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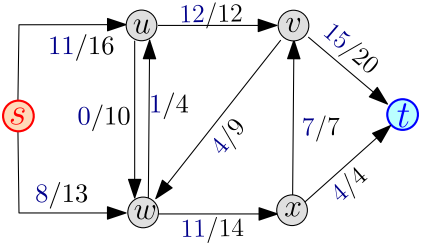
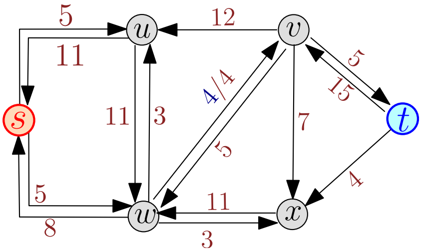


Graph



Residual graph

$$f(u, w) = -f(w, u) = -1 \implies c_f(u, w) = 10 - (-1) = 11.$$

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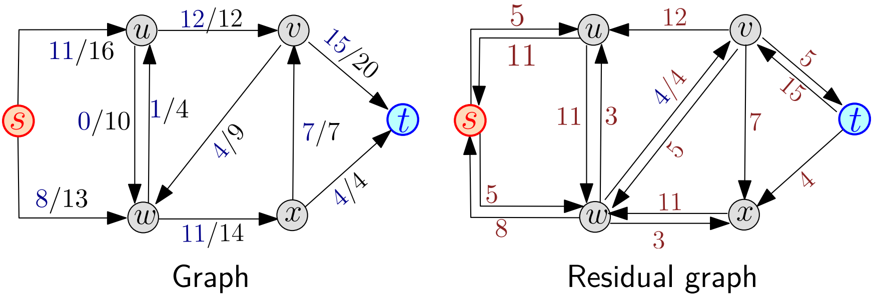

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Residual graph: Definition

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Given f, $\mathbf{G} = (\mathbf{V}, E)$ and c, as above, the ***residual graph*** (or ***residual network***) of $\mathbf{G}$ and f is the graph $\mathbf{G}_f = (\mathbf{V}, \mathbf{E}_f)$ where

$$\mathbf{E}_f = \left\{ (u, v) \in V \times \mathbf{V} \;\middle|\; c_f(u, v) > 0 \right\}.$$

1. $(u \to v) \in \mathbf{E}$: might induce two edges in $\mathbf{E}_f$
2. If $(u \to v) \in \mathbf{E}$, $f(u, v) < c(u, v)$ and $(v \to u) \notin \mathbf{E}(\mathbf{G})$
3. $\implies c_f(u, v) = c(u, v) - f(u, v) > 0$
4. ... and $(u \to v) \in \mathbf{E}_f$. Also,

   $$c_f(v, u) = c(v, u) - f(v, u) = 0 - (-f(u, v)) = f(u, v),$$

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1. $(u \to v) \in \mathbf{E}$: might induce two edges in $\mathbf{E}_f$
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3. $\implies c_f(u, v) = c(u, v) - f(u, v) > 0$
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   $$c_f(v, u) = c(v, u) - f(v, u) = 0 - (-f(u, v)) = f(u, v),$$

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Residual graph: Definition

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Residual network properties

Since every edge of $\mathbf{G}$ induces at most two edges in $\mathbf{G}_f$, it follows that $\mathbf{G}_f$ has at most twice the number of edges of $\mathbf{G}$; formally, $|\mathbf{E}_f| \leq 2\,|\mathbf{E}|$.

Lemma

Given a flow f defined over a network $\mathbf{G}$, then the residual network $\mathbf{G}_f$ together with c_f form a flow network.

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Increasing the flow

Lemma

$\mathbf{G}(\mathbf{V}, E)$, *a flow* f, *and* h *a flow in* $\mathbf{G}_f$. $\mathbf{G}_f$: *residual network of* f. *Then* $f + h$ *is a flow in* $\mathbf{G}$ *and its capacity is* $|f + h| = |f| + |h|$.

proof

By definition: $(f + h)(u, v) = f(u, v) + h(u, v)$ and thus $(f + h)(X, Y) = f(X, Y) + h(X, Y)$. Verify legal...

1. Anti symmetry: $(f + h)(u, v) = f(u, v) + h(u, v) = -f(v, u) - h(v, u) = -(f + h)(v, u)$.
2. Bounded by capacity:

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Increasing the flow – proof continued

proof continued

1. For $u \in V - s - t$ we have $(f+h)(u, \mathsf{V}) = f(u, \mathsf{V}) + h(u, \mathsf{V}) = 0 + 0 = 0$ and as such $f + h$ comply with the conservation of flow requirement.
2. Total flow is

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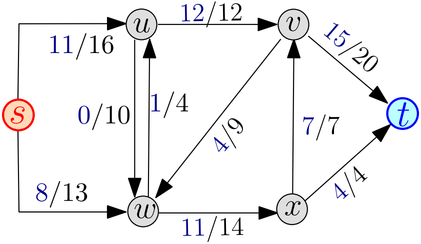
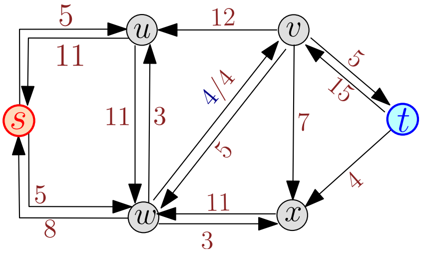
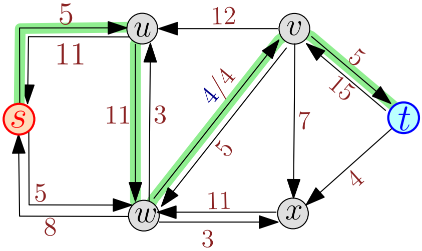
Augmenting path



Graph



Residual graph



Definition

For $\mathbf{G}$ and a flow f, a path π in $\mathbf{G}_f$ between s and t is an ***augmenting path***.

More on augmenting paths

1. π: augmenting path.
2. All edges of π have positive capacity in $\mathbf{G}_f$.
3. ... otherwise not in $\mathbf{E}_f$.
4. f, π: can improve f by pushing positive flow along π.

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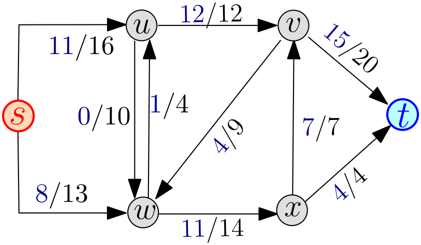
Residual capacity

Definition

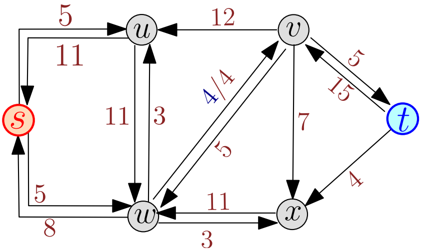
π: augmenting path of f.
$c_f(\pi)$: maximum amount of flow can push on π.
$c_f(\pi)$ is ***residual capacity*** of π.
Formally,

$$c_f(\pi) = \min_{(u \to v) \in \pi} c_f(u, v).$$

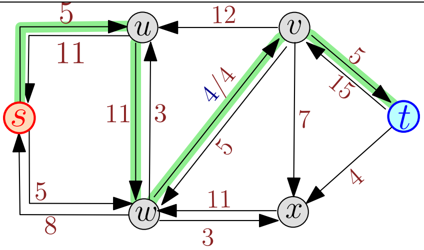
An example of an augmenting path



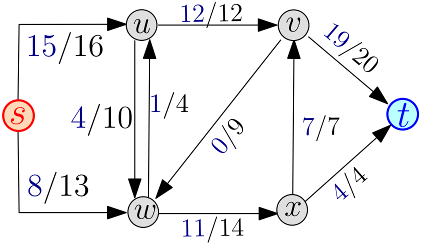
(A) Flow



(B) Residual network



(C) Augmenting path



(D) New flow

Flow along augmenting path

$$f_\pi(u,v) = \begin{cases} c_f(\pi) & \text{if } (u \to v) \text{ is in } \pi \\ -c_f(\pi) & \text{if } (v \to u) \text{ is in } \pi \\ 0 & \text{otherwise.} \end{cases}$$

Increase flow by augmenting flow

Lemma

π: *augmenting path.* f_π *is flow in* $\mathbf{G}_f$ *and* $|f_\pi| = c_f(\pi) > 0$.

Get bigger flow...

Lemma

Let f *be a flow, and let* π *be an augmenting path for* f. *Then* $f + f_\pi$ *is a "better" flow. Namely,* $|f + f_\pi| = |f| + |f_\pi| > |f|$.

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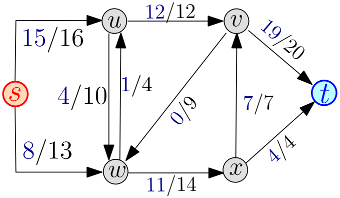
Flowing into the wall

1. Namely, $f + f_\pi$ is flow with larger value than f.
2. Can this flow be improved?



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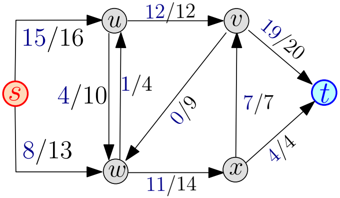

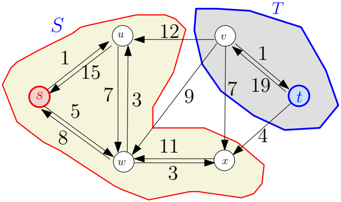

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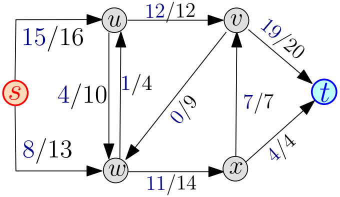

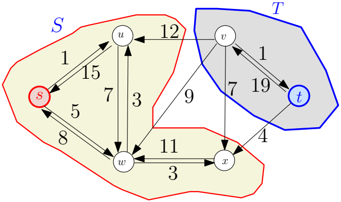

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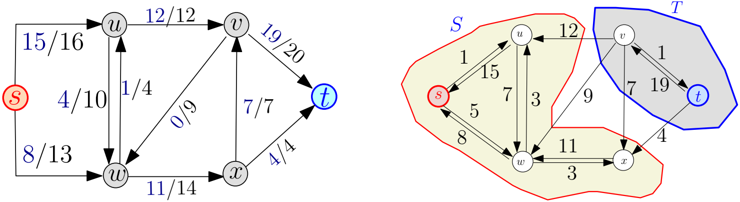

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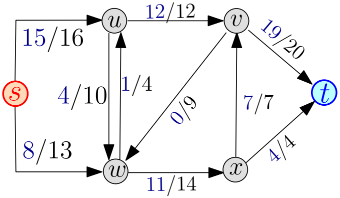

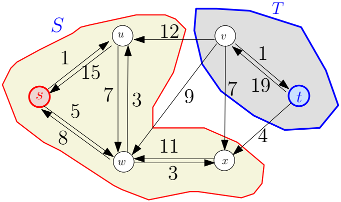

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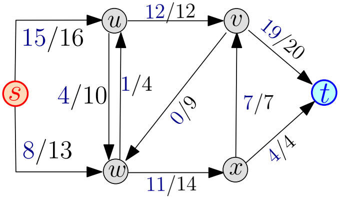

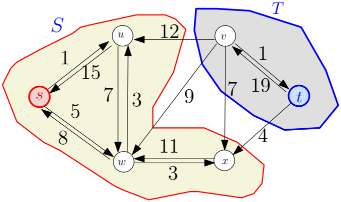

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The Ford-Fulkerson method

```
algFordFulkerson(G, c)
    begin
        f ← Zero flow on G
        while (G_f has augmenting
                           path p) do
            (* Recompute G_f for
               this check *)
            f ← f + f_p
        return f
    end
```

Part III

On maximum flows

Some definitions

Definition

(S, T): ***directed cut*** in flow network $\mathbf{G} = (\mathbf{V}, E)$.
A partition of $\mathbf{V}$ into S and $T = V \setminus S$, such that $s \in S$ and $t \in T$.

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Definition

The ***minimum cut*** is the cut in $\mathbf{G}$ with the minimum capacity.

Flow across cut is the whole flow

Lemma

$\mathbf{G}$,f,s,t. (S, T): cut of $\mathbf{G}$.
Then $f(S, T) = |f|$.

Proof.

$$
\begin{aligned}
f(S, T) &= f(S, \mathbf{V}) - f(S, S) = f(S, \mathbf{V}) \\
&= f(s, \mathbf{V}) + f(S - s, \mathbf{V}) = f(s, \mathbf{V}) \\
&= |f|,
\end{aligned}
$$

since $T = \mathbf{V} \setminus S$, and $f(S - s, \mathbf{V}) = \sum_{u \in S - s} f(u, \mathbf{V}) = 0$ (note that u can not be t as $t \in T$). □

Flow bounded by cut capacity

Claim

The flow in a network is upper bounded by the capacity of any cut (S, T) *in* **G**.

Proof.

Consider a cut (S, T). We have $|f| = f(S, T) = \sum_{u \in S, v \in T} f(u, v) \leq \sum_{u \in S, v \in T} c(u, v) = c(S, T)$. □

THE POINT

Key observation

Maximum flow is bounded by the capacity of the minimum cut.

Surprisingly...

Maximum flow is exactly the value of the minimum cut.

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The Min-Cut Max-Flow Theorem

Theorem (Max-flow min-cut theorem)

If f is a flow in a flow network $\mathbf{G} = (\mathbf{V}, E)$ with source s and sink t, then the following conditions are equivalent:

- *(A) f is a maximum flow in $\mathbf{G}$.*
- *(B) The residual network $\mathbf{G}_f$ contains no augmenting paths.*
- *(C) $|f| = c(S, T)$ for some cut (S, T) of $\mathbf{G}$. And (S, T) is a minimum cut in $\mathbf{G}$.*

Proof: (A) $\Rightarrow$ (B):

Proof.

(A) $\Rightarrow$ (B): By contradiction. If there was an augmenting path p then $c_f(p) > 0$, and we can generate a new flow $f + f_p$, such that $|f + f_p| = |f| + c_f(p) > |f|$. A contradiction as f is a maximum flow. □

Proof: (B) $\Rightarrow$ (C):

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s and t are disconnected in $\mathbf{G}_f$.

Set

$S = \left\{ v \;\middle|\; \text{Exists a path between } s \text{ and } v \text{ in } \mathbf{G}_f \right\}$ $\qquad T = \mathbf{V} \setminus S.$

Have: $s \in S$, $t \in T$, $\forall u \in S$ and $\forall v \in T$: $f(u, v) = c(u, v)$.

By contradiction: $\exists u \in S$, $v \in T$ s.t. $f(u, v) < c(u, v) \implies$ $(u \to v) \in \mathbf{E}_f \implies v$ would be reachable from s in $\mathbf{G}_f$.

Contradiction.

$\implies |f| = f(S, T) = c(S, T)$.

(S, T) must be mincut. Otherwise $\exists (S', T')$:

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But... $|f| = f(S', T') \leq c(S', T')$. A contradiction. □

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(S, T) must be mincut. Otherwise $\exists (S', T')$:
$c(S', T') < c(S, T) = f(S, T) = |f|$,
But... $|f| = f(S', T') \leq c(S', T')$. A contradiction. □

Proof: (B) $\Rightarrow$ (C):

Proof.

s and t are disconnected in $\mathbf{G}_f$.
Set
$S = \left\{ v \;\middle|\; \text{Exists a path between } s \text{ and } v \text{ in } \mathbf{G}_f \right\}$ $\quad T = \mathbf{V} \setminus S.$
Have: $s \in S$, $t \in T$, $\forall u \in S$ and $\forall v \in T$: $f(u, v) = c(u, v)$.
By contradiction: $\exists u \in S$, $v \in T$ s.t. $f(u, v) < c(u, v) \implies (u \to v) \in \mathbf{E}_f \implies v$ would be reachable from s in $\mathbf{G}_f$.
Contradiction.
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But... $|f| = f(S', T') \leq c(S', T')$. A contradiction. $\square$

Proof: (C) $\Rightarrow$ (A):

Proof.

Well, for any cut (U, V), we know that $|f| \leq c(U, \mathsf{V})$. This implies that if $|f| = c(S, T)$ then the flow can not be any larger, and it is thus a maximum flow. □

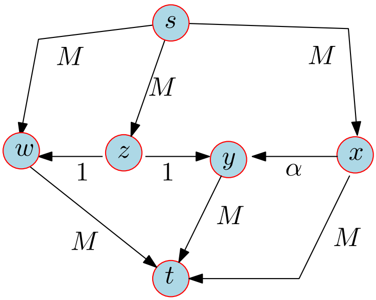
Implications

1. The max-flow min-cut theorem $\implies$ if **algFordFulkerson** terminates, then computed max flow.
2. Does not imply **algFordFulkerson** always terminates.
3. **algFordFulkerson** might not terminate.

Part IV

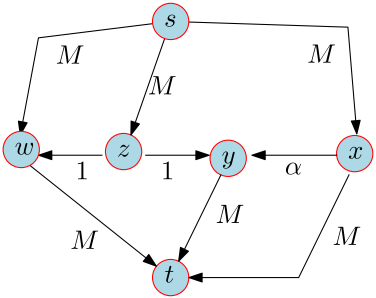
Non-termination of Ford-Fulkerson

Ford-Fulkerson runs in vain



1. M: large positive integer.
2. $\alpha = (\sqrt{5} - 1)/2 \approx 0.618$.
3. $\alpha < 1$,
4. $1 - \alpha < \alpha$.
5. Maximum flow in this network is: $2M + 1$.

Ford-Fulkerson runs in vain



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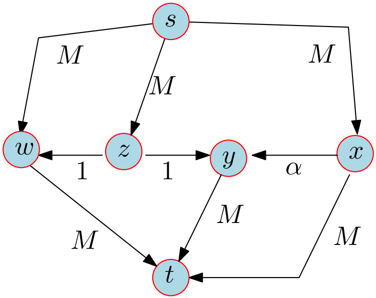

1. M: large positive integer.
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Some algebra...

For $\alpha = \dfrac{\sqrt{5}-1}{2}$:

$$\alpha^2$$

Some algebra...

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$$\alpha^2 = \left(\frac{\sqrt{5}-1}{2}\right)^2$$

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For $\alpha = \frac{\sqrt{5}-1}{2}$:

$$\alpha^2 = \left(\frac{\sqrt{5}-1}{2}\right)^2 = \frac{1}{4}\left(\sqrt{5}-1\right)^2$$

Some algebra...

For $\alpha = \dfrac{\sqrt{5}-1}{2}$:

$$\alpha^2 = \left(\frac{\sqrt{5}-1}{2}\right)^2 = \frac{1}{4}\left(\sqrt{5}-1\right)^2 = \frac{1}{4}\left(5 - 2\sqrt{5} + 1\right)$$

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For $\alpha = \dfrac{\sqrt{5}-1}{2}$:

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$$= 1 + \frac{1}{4}\left(2-2\sqrt{5}\right)$$

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For $\alpha = \dfrac{\sqrt{5}-1}{2}$:

$$\alpha^2 = \left(\frac{\sqrt{5}-1}{2}\right)^2 = \frac{1}{4}\left(\sqrt{5}-1\right)^2 = \frac{1}{4}\left(5 - 2\sqrt{5} + 1\right)$$
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$$= 1 - \frac{\sqrt{5}-1}{2}$$

Some algebra...

For $\alpha = \dfrac{\sqrt{5}-1}{2}$:

$$
\begin{aligned}
\alpha^2 &= \left(\frac{\sqrt{5}-1}{2}\right)^2 = \frac{1}{4}\left(\sqrt{5}-1\right)^2 = \frac{1}{4}\left(5-2\sqrt{5}+1\right)\\
&= 1 + \frac{1}{4}\left(2-2\sqrt{5}\right)\\
&= 1 + \frac{1}{2}\left(1-\sqrt{5}\right)\\
&= 1 - \frac{\sqrt{5}-1}{2}\\
&= 1 - \alpha.
\end{aligned}
$$

Some algebra...

Claim

Given: $\alpha = (\sqrt{5} - 1)/2$ *and* $\alpha^2 = 1 - \alpha$.

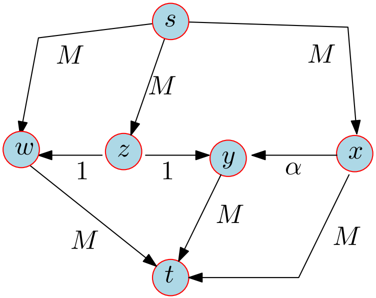
$$\implies \forall i \qquad \alpha^i - \alpha^{i+1} = \alpha^{i+2}$$

Proof.

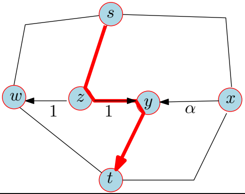
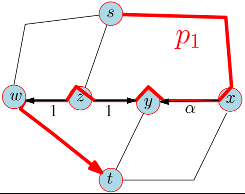
$$\alpha^i - \alpha^{i+1} = \alpha^i(1 - \alpha) = \alpha^i \alpha^2 = \alpha^{i+2}.$$

□

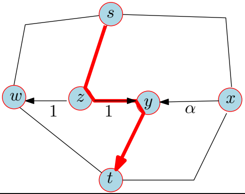
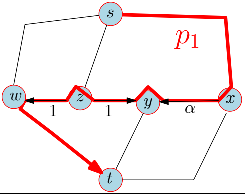
The network



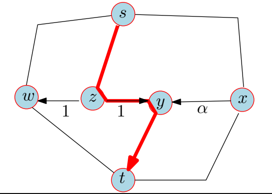
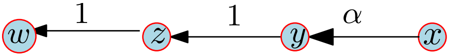
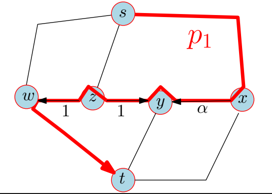
Let it flow...

#	Augment. path π	c_π	New residual network
0.			
1.			

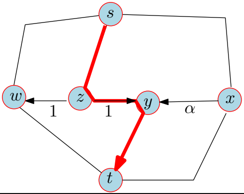
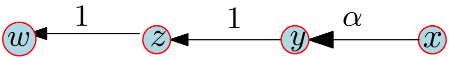
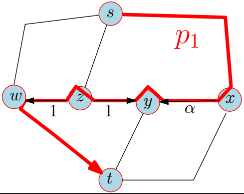
Let it flow...

#	Augment. path π	c_π	New residual network
0.		**1**	
1.			

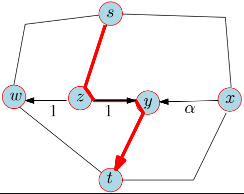
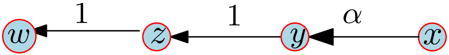
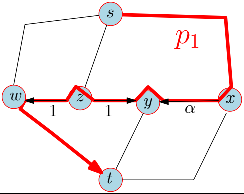
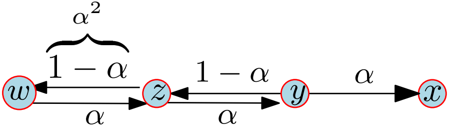
Let it flow...

#	Augment. path π	c_π	New residual network
0.		1	
1.			

Let it flow...

#	Augment. path π	c_π	New residual network
0.		$\mathbf{1}$	
1.		$\boldsymbol{\alpha}$	

Let it flow...

#	Augment. path π	c_π	New residual network
0.		$\mathbf{1}$	
1.		$\boldsymbol{\alpha}$	

Let it flow II

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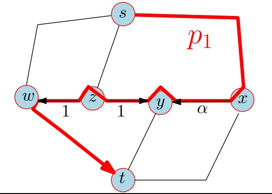
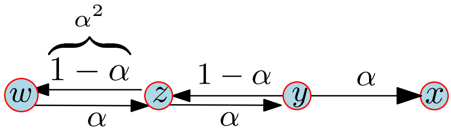
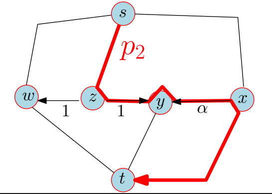
<tr><td>1.</td><td></td><td>α</td><td></td></tr>
<tr><td>2.</td><td></td><td></td><td></td></tr>
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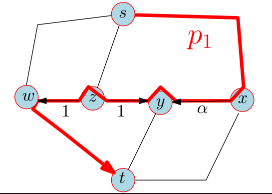
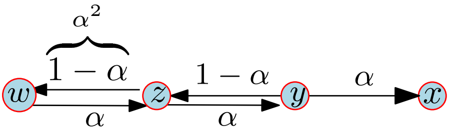
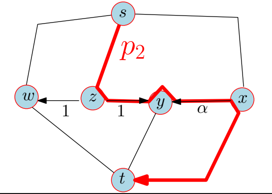
Let it flow II

#	Augment. path π	c_π	New residual network
1.		α	
2.		α	

Let it flow II

<table>
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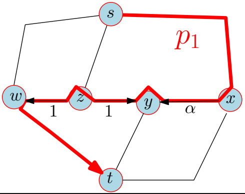
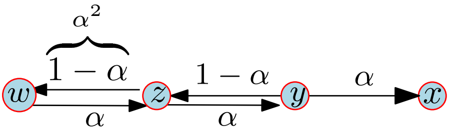
<tr><td>1.</td><td>
</td><td>α</td><td>
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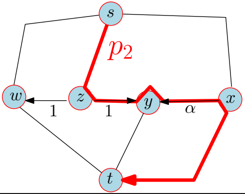
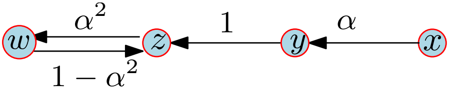
<tr><td>2.</td><td>
</td><td>α</td><td>
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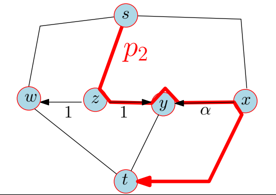
<td>
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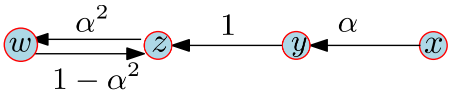
<td>$\boldsymbol{\alpha^2}$</td>
<td>
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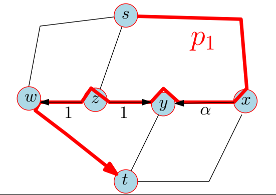
<td>
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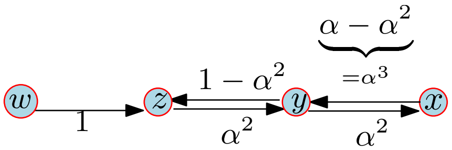
<td>
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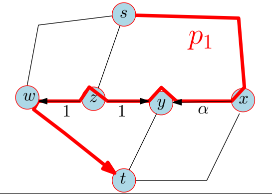
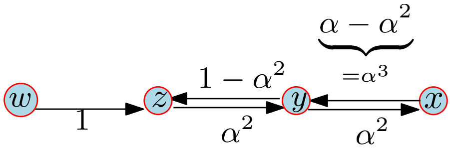
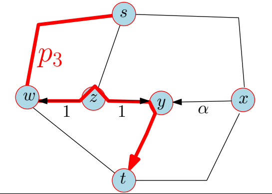
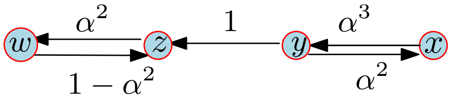
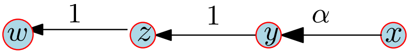
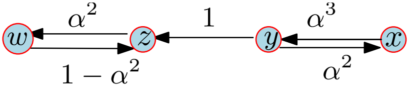
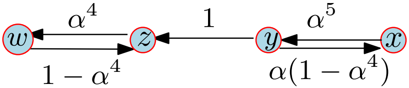
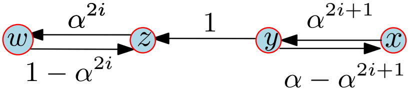
Let it flow III

3.		$\boldsymbol{\alpha^2}$	
4.		$\boldsymbol{\alpha^2}$	

Let it flow III

moves	Residual network after
0	
moves $\mathbf{0, (1, 2, 3, 4)}$	
moves $\mathbf{0, (1, 2, 3, 4)^2}$	
$\mathbf{0.(1, 2, 3, 4)^i}$	

Namely, the algorithm never terminates.

Notes

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