Network Flows and Cuts

Lecture 13

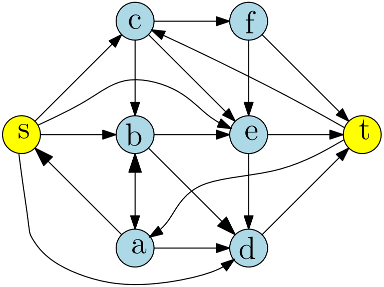
March 16, 2021

Most slides are courtesy Prof. Chekuri

How many edges to cut?

For the graph depicted on the right. How many edges have to be cut before there is no path from s to t?

(A) 1
(B) 2
(C) 3
(D) 4
(E) 5



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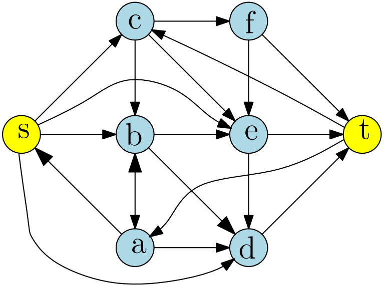
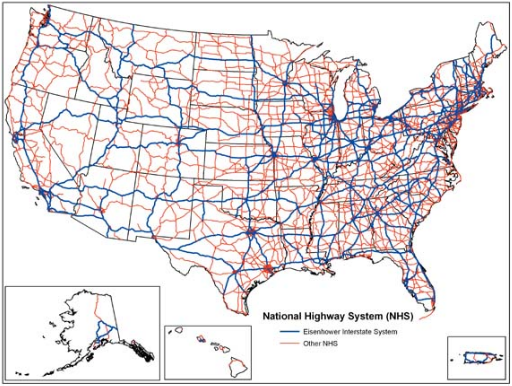


Related Q. At most how many edge disjoint paths from s to t?

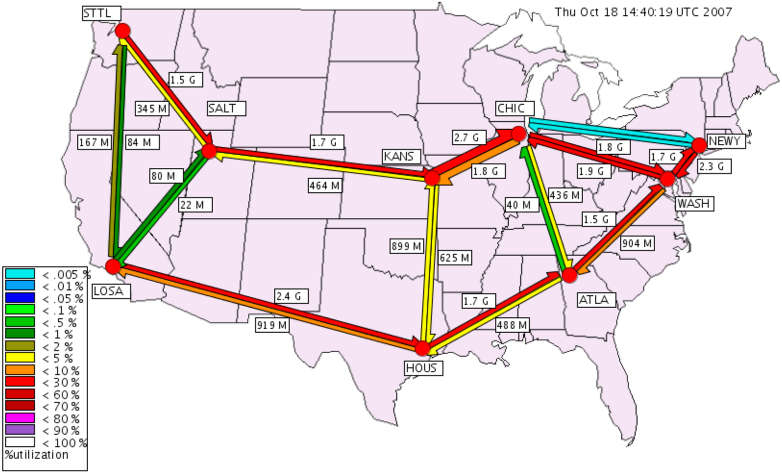
Part I

Network Flows: Introduction and Setup

Transportation/Road Network



Internet Backbone Network



Common Features of Flow Networks

1. **Network** represented by a (directed) *graph* $G = (V, E)$.
2. Each edge e has a **capacity** $c(e) \geq 0$ that limits amount of *traffic* on e.
3. *Source(s)* of traffic/data.
4. *Sink(s)* of traffic/data.
5. Traffic *flows* from sources to sinks.
6. Traffic is *switched/interchanged* at nodes.

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Flow abstract term to indicate stuff (traffic/data/etc) that **flows** from sources to sinks.

Single Source/Single Sink Flows

Simple setting:

- Single source s and single sink t.
- Every other node v is an **internal** node.
- Flow originates at s and terminates at t.

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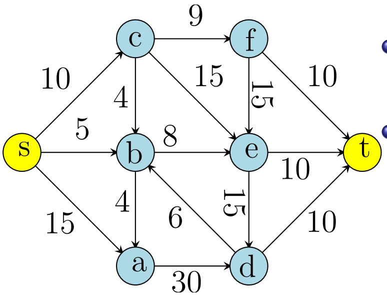

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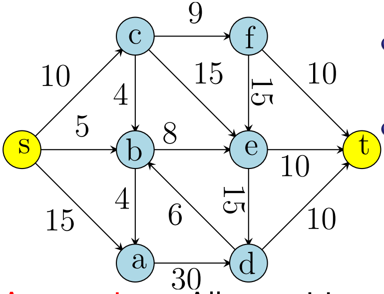

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  Source $s \in V$ has no incoming edges, and sink $t \in V$ has no outgoing edges.

Assumptions: All capacities are integer, and every vertex has at least one edge incident to it.

Definition of Flow

Two ways to define flows:

1. edge based, or
2. path based.

Essentially equivalent but have different uses.

Edge based definition is more compact.

Edge Based Definition of Flow

Definition

Flow in network $G = (V, E)$, is function $f : E \rightarrow \mathbb{R}^{\geq 0}$ s.t.

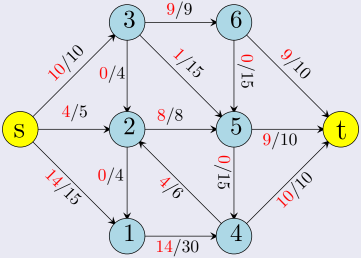

Figure: Flow with value.

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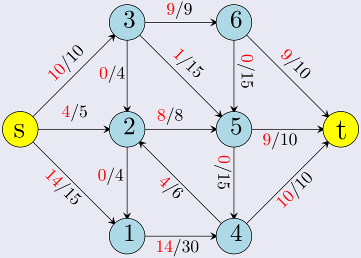

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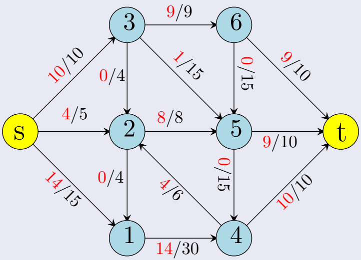

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$$\sum_{e \text{ into } v} f(e) = \sum_{e \text{ out of } v} f(e)$$

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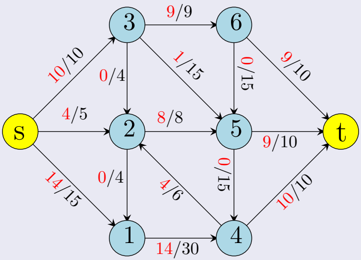

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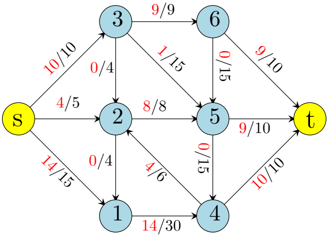
3. Value of flow= (total flow out of source) − (total flow in to source).

More Definitions and Notation

Flow in and out of vertex v

$$f^{\text{in}}(v) = \sum_{e \text{ into } v} f(e) \qquad f^{\text{out}}(v) = \sum_{e \text{ out of } v} f(e)$$



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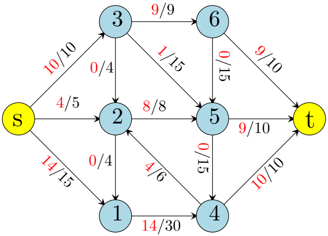

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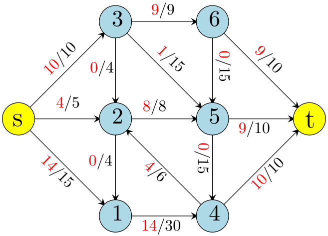


Figure: Flow with value.

Definition. For network G with source s, the **value** of flow f is defined as

$$v(f) = f^{\text{out}}(s) - f^{\text{in}}(s)$$

Value of flow?

In the flow depicted on the right, the value of the flow is.

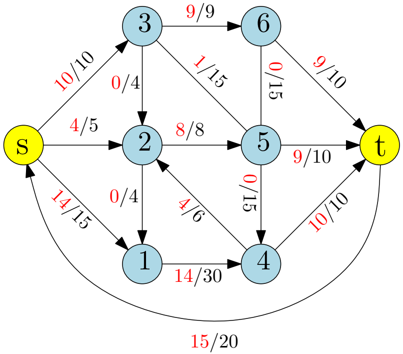
(A) 6.

(B) 13.

(C) 18.

(D) 28.

(E) 43.



A Path Based Definition of Flow

Intuition: Flow goes from source s to sink t along a path.

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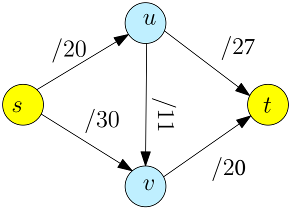
Value of flow: $\sum_{p \in \mathcal{P}} f(p)$.

Example



$\mathcal{P} = \{p_1, p_2, p_3\}$

$p_1 : s \to u \to t$

$p_2 : s \to u \to v \to t$

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$f(p_1) = 10, f(p_2) = 4, f(p_3) = 6$

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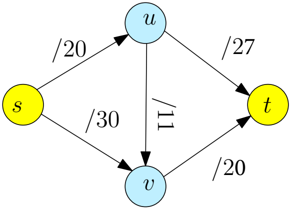

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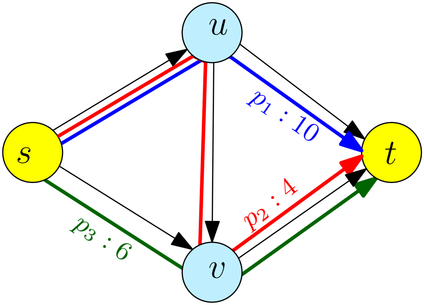

Path based flow implies edge based flow

Lemma

Given a path based flow $f : \mathcal{P} \rightarrow \mathbb{R}^{\geq 0}$ *there is an edge based flow* $f' : E \rightarrow \mathbb{R}^{\geq 0}$ *of the same value.*

Proof.

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Value of f and f' are equal. (**Exercise**) □

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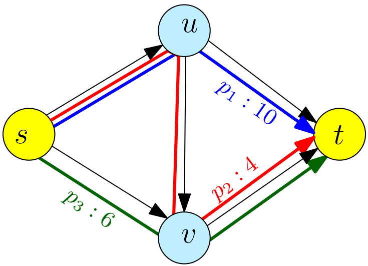

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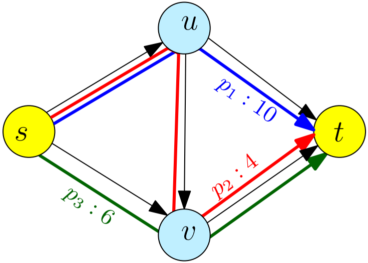

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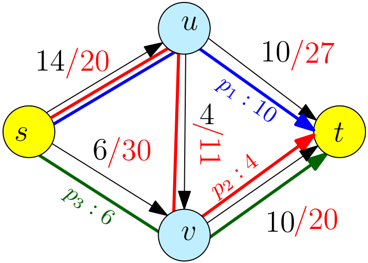

$f'(s \to u) = 14$
$f'(u \to v) = 4$
$f'(s \to v) = 6$
$f'(u \to t) = 10$
$f'(v \to t) = 10$

Flow Decomposition

Edge based flow to Path based Flow

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Given an edge based flow $f' : E \to \mathbb{R}^{\geq 0}$*, there is a path based flow* $f : \mathcal{P} \to \mathbb{R}^{\geq 0}$ *of same value.*

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Given an edge based flow $f' : E \rightarrow \mathbb{R}^{\geq 0}$*, there is a path based flow* $f : \mathcal{P} \rightarrow \mathbb{R}^{\geq 0}$ *of same value. Moreover,* f *assigns non-negative flow to at most* m *paths where* $|E| = m$ *and* $|V| = n$*.*

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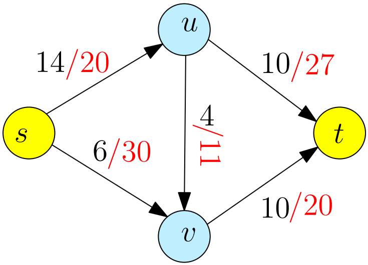
Given f'*, the path based flow can be computed in* $O(mn)$ *time.*

Flow Decomposition

Example

How to decompose the following flow:



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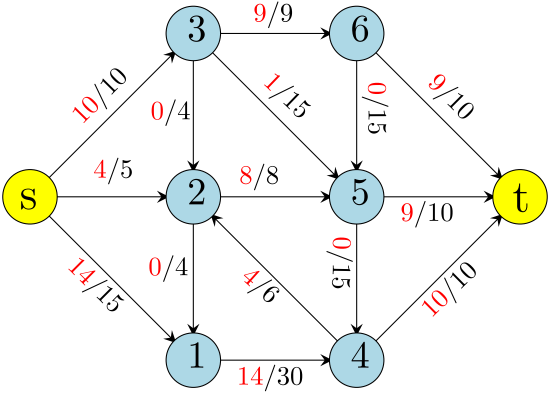
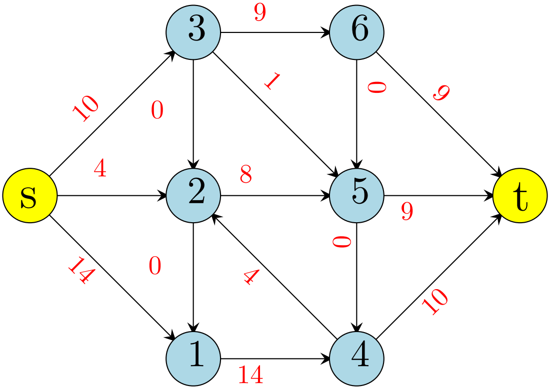
Example

flow/capacity



Example

flow



Summary: Edge vs Path based Flow

Edge based flows:

1. **compact** representation, only m values to be specified, and
2. need to check flow conservation explicitly at each internal node.

Path flows:

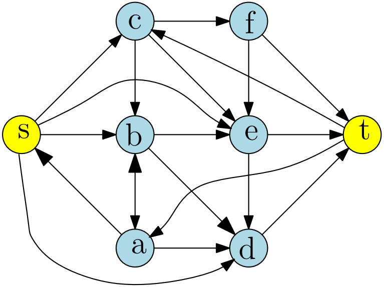
1. in some applications, paths more natural,
2. not compact,
3. no need to check flow conservation constraints.

Equivalence shows that we can go back and forth easily.

Back to the begining

If $f : \mathcal{P} \to \mathbb{R}^+$ is a path based flow on this network, then can paths p, p' with $f(p), f(p') = 1$ share edges?

- **(A)** Yes
- **(B)** No
- **(C)** May be



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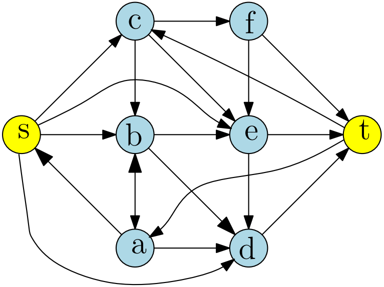

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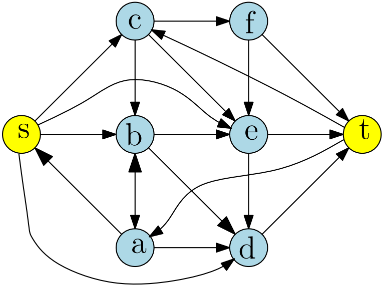

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Value of the flow $\leq$ # edge disjoint paths. (**Exercise**)

The Maximum-Flow Problem

Problem

Input A network G with capacity c and source s and sink t.

Goal Find flow of **maximum** value.

The Maximum-Flow Problem

Problem

Input: A network G with capacity c and source s and sink t.

Goal: Find flow of **maximum** value.

Question: Given a flow network, what is an *upper bound* on the maximum flow between source and sink?

Part II

Cuts

Cuts

Definition (s-t cut)

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The **capacity** of a cut E' is $c(E') = \sum_{e \in E'} c(e)$.

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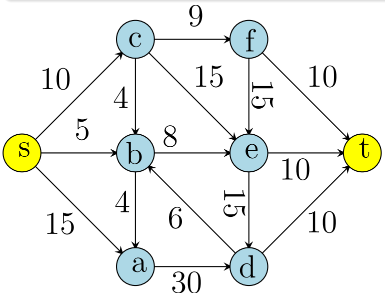
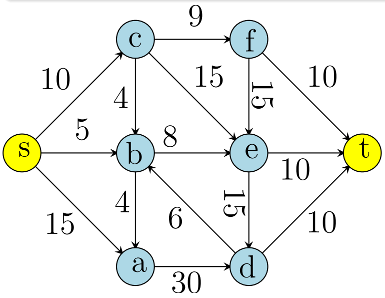


Cuts

Definition (s-t cut)

Given a flow network an **s-t cut** is a set of edges $E' \subset E$ such that removing E' *disconnects* s from t: in other words there is no directed $s \rightarrow t$ path in $E - E'$.

The **capacity** of a cut E' is $c(E') = \sum_{e \in E'} c(e)$.

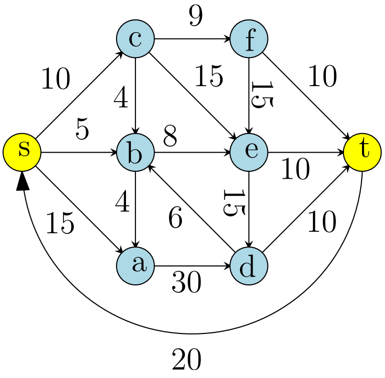


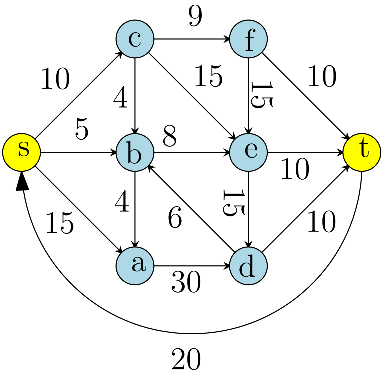
Caution:

1. Cut may leave $t \rightarrow s$ paths!
2. There might be many s-t cuts.

s — t cuts

A death by a thousand cuts

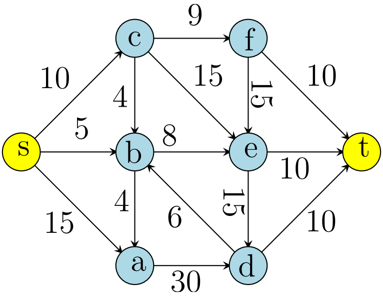




Minimal Cut

Definition (Minimal s-t cut.)

Given a s-t flow network $G = (V, E)$, $E' \subseteq E$ is a **minimal cut** if for all $e \in E'$, if $E' \setminus \{e\}$ is not a cut.



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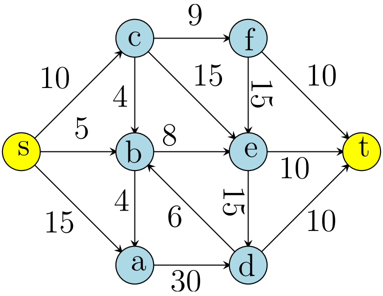


Observation: given a cut E', can check efficiently whether E' is a minimal cut or not. How?

Is this a minimal cut?

Definition (Minimal s-t cut.)

Given a s-t flow network $G = (V, E)$ with n vertices and m edges, $E' \subseteq E$ is a **minimal cut** if for all $e \in E'$, $E' \setminus \{e\}$ is not a cut.

Checking if a set E' forms a minimal s-t cut can be done in

(A) $O(n + m)$.

(B) $O(n \log n + m)$.

(C) $O((n + m) \log n)$.

(D) $O(nm)$.

(E) $O(nm \log n)$.

(F) You flow, me cut.

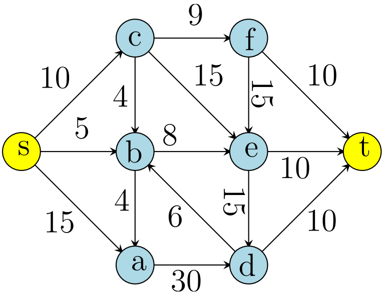
Cuts as Vertex Partitions

Let $A \subset V$ such that

1. $s \in A$, $t \notin A$, and
2. $B = V \setminus A$ (hence $t \in B$).

The **cut** (A, B) is the set of edges

$$c(A, B) = \{(u, v) \in E \mid u \in A, v \in B\}.$$



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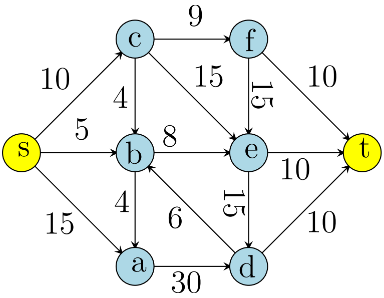

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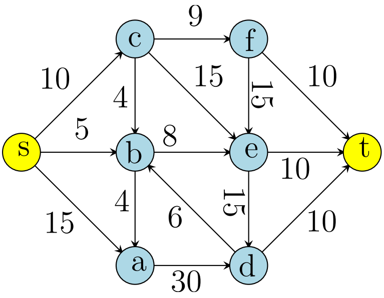

Claim

$c(A, B)$ *is an* s-t *cut.*

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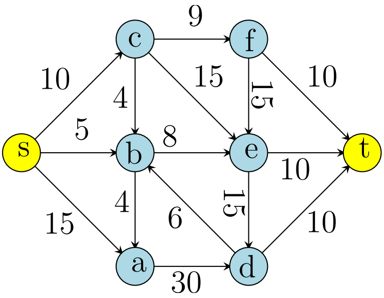

Claim

$c(A, B)$ is an s-t cut.

Proof.

Let P be any $s \to t$ path in G. Since t is not in A, P has to leave A via some edge (u, v) in $c(A, B)$. □

Cuts as Vertex Partitions

Lemma

Suppose E' *is an* s-t *cut. Then there is a cut* $c(A, B)$ *such that* $c(A, B) \subseteq E'$.

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Corollary

Every minimal *s-t cut E' is a cut of the form $c(A, B)$.*

Alternate notation for cuts

Other common notation for cuts:

Undirected graphs: $G = (V, E)$ and $A \subset V$. $\delta_G(A)$ or $\delta(A)$ is set of edges with one end point in A and the other end point in $V \setminus A$.

Directed graphs: $G = (V, E)$ and $A \subset V$.
Edges going out of A

$$\delta_G^+(A) = \{(u, v) \in E \mid u \in A, v \in V \setminus A\}$$

Edges coming into A

$$\delta_G^-(A) = \{(u, v) \in E \mid u \in V \setminus A, v \in A\}$$

Minimum Cut

Definition

Given a flow network an s-t **minimum** cut is a cut E' of smallest capacity amongst all s-t cuts.

The minimum cut in the network flow depicted is:

(A) 10

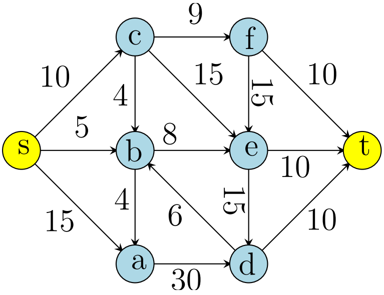
(B) 18

(C) 28

(D) 30

(E) 48.

(F) No minimum cut, no cry.



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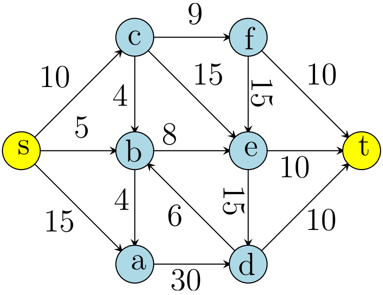

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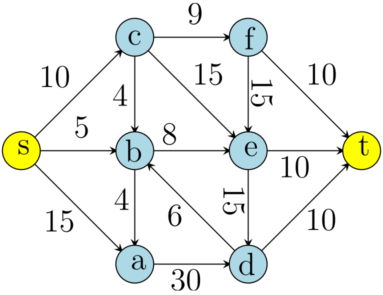

Observation: exponential number of ***s*-*t*** cuts and no "easy" algorithm to find a minimum cut.

The Minimum-Cut Problem

Problem

Input A flow network G

Goal Find the capacity of a *minimum* s-t cut

Flows and Cuts

Lemma

For any s-t cut E', **maximum** *s-t flow $\leq$ capacity of E'.*

Proof.

Formal proof easier with path based definition of flow.
Suppose $f : \mathcal{P} \rightarrow \mathbb{R}^{\geq 0}$ is a max-flow.

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Assign each path $p \in \mathcal{P}$ to exactly one edge $e \in E'$.
Let $\mathcal{P}_e$ be paths assigned to $e \in E'$.

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$$v(f) = \sum_{p \in \mathcal{P}} f(p) = \sum_{e \in E'} \sum_{p \in \mathcal{P}_e} f(p) \leq \sum_{e \in E'} c(e).$$

□

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Corollary

Maximum s-t flow $\leq$ minimum s-t cut.

Flows and Cuts

Lemma

∃ an s-t cut E', such that **maximum** *flow $=$ capacity of E'.*

Proof.

Flows and Cuts

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$\exists$ *an* s-t *cut* E'*, such that* **maximum** *flow* $=$ *capacity of* E'.

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Intuition: Let f be a maximum *edge* flow. Construct graph G' with edge capacities to $c'(e) = c(e) - f(e)$. Remove edges with $c'(e) = 0$.

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Exercise. □

Max-Flow Min-Cut Theorem

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In any flow network the maximum s-t flow is equal to the minimum s-t cut.

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Can compute minimum-cut from maximum flow and vice-versa!

Proof coming shortly.

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Many applications:

1. optimization
2. graph theory
3. combinatorics

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Input A network G with capacity c and source s and sink t.

Goal Find flow of **maximum** value from s to t.

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Exercise: Given G, s, t as above, show that one can remove all edges into s and all edges out of t without affecting the flow value between s and t.