

## Motivation

## 26. Flow in Networks

Flow Network, Maximal Flow, Cut, Res Network, Max-flow Min-cut Theorem, Ford-Fulkerson Method, Edmonds-Karp Algorithm, Maximal Bipartite Matching [Ottman/Widmayer, Kap. 9.7, 9.8.1], [Cormen et al, Kap. 26.1-26.3]

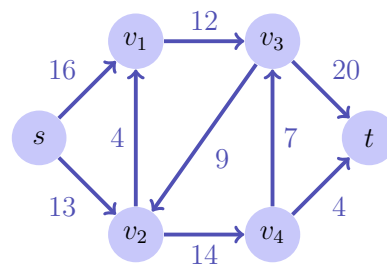
- Modelling flow of fluents, components on conveyors, current in electrical networks or information flow in communication networks.
- Connectivity of Communication Networks, Bipartite Matching, Circulation, Scheduling, Image Segmentation, Baseball Elimination...

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## Flow Network

- **Flow network**  $G = (V, E, c)$ : directed graph with **capacities**
- Antiparallel edges forbidden:  $(u, v) \in E \Rightarrow (v, u) \notin E$ .
- Model a missing edge  $(u, v)$  by  $c(u, v) = 0$ .
- **Source**  $s$  and **sink**  $t$ : special nodes. Every node  $v$  is on a path between  $s$  and  $t$ :  $s \rightsquigarrow v \rightsquigarrow t$



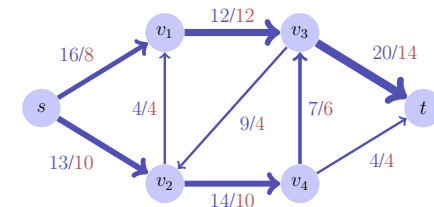
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## Flow

A **Flow**  $f : V \times V \rightarrow \mathbb{R}$  fulfills the following conditions:

- **Bounded Capacity:** For all  $u, v \in V$ :  $f(u, v) \leq c(u, v)$ .
- **Skew Symmetry:** For all  $u, v \in V$ :  $f(u, v) = -f(v, u)$ .
- **Conservation of flow:** For all  $u \in V \setminus \{s, t\}$ :

$$\sum_{v \in V} f(u, v) = 0.$$



**Value** of the flow:  
 $|f| = \sum_{v \in V} f(s, v)$ .  
 Here  $|f| = 18$ .

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## How large can a flow possibly be?

Limiting factors: cuts

- **cut separating  $s$  from  $t$** : Partition of  $V$  into  $S$  and  $T$  with  $s \in S$ ,  $t \in T$ .
- **Capacity** of a cut:  $c(S, T) = \sum_{v \in S, v' \in T} c(v, v')$
- **Minimal cut**: cut with minimal capacity.
- **Flow over the cut**:  $f(S, T) = \sum_{v \in S, v' \in T} f(v, v')$

## Implicit Summation

Notation: Let  $U, U' \subseteq V$

$$f(U, U') := \sum_{\substack{u \in U \\ u' \in U'}} f(u, u'), \quad f(u, U') := f(\{u\}, U')$$

Thus

- $|f| = f(s, V)$
- $f(U, U) = 0$
- $f(U, U') = -f(U', U)$
- $f(X \cup Y, Z) = f(X, Z) + f(Y, Z)$ , if  $X \cap Y = \emptyset$ .
- $f(R, V) = 0$  if  $R \cap \{s, t\} = \emptyset$ . [flow conversation!]

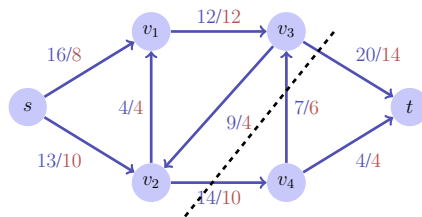
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## How large can a flow possibly be?

For each flow and each cut it holds that  $f(S, T) = |f|$ :

$$\begin{aligned} f(S, T) &= f(S, V) - \underbrace{f(S, S)}_0 = f(S, V) \\ &= f(s, V) + \underbrace{f(S - \{s\}, V)}_{\neq t, \neq s} = |f|. \end{aligned}$$

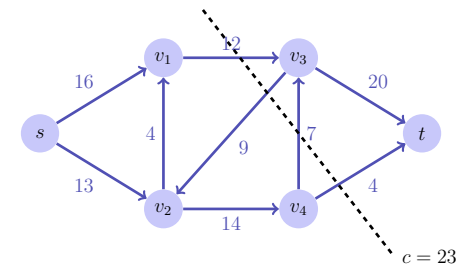


## Maximal Flow ?

In particular, for each cut  $(S, T)$  of  $V$ .

$$|f| \leq \sum_{v \in S, v' \in T} c(v, v') = c(S, T)$$

Will discover that equality holds for  $\min_{S, T} c(S, T)$ .

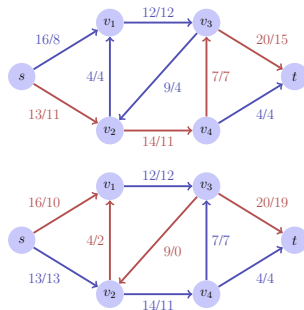
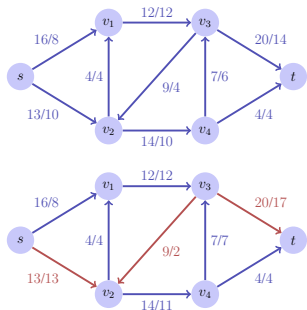


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## Maximal Flow ?

### Naive Procedure



Conclusion: greedy increase of flow does not solve the problem.

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## The Method of Ford-Fulkerson

- Start with  $f(u, v) = 0$  for all  $u, v \in V$
- Determine rest network\*  $G_f$  and expansion path in  $G_f$
- Increase flow via expansion path\*
- Repeat until no expansion path available.

$$G_f := (V, E_f, c_f)$$

$$c_f(u, v) := c(u, v) - f(u, v) \quad \forall u, v \in V$$

$$E_f := \{(u, v) \in V \times V \mid c_f(u, v) > 0\}$$

\*Will now be explained

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## Increase of flow, negative!

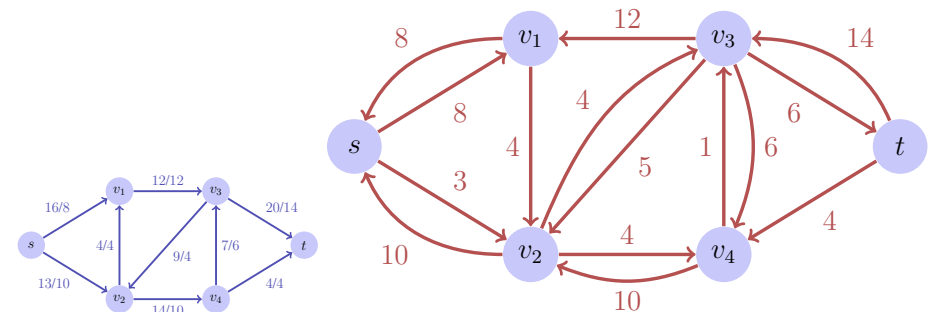
Let some flow  $f$  in the network be given.

Finding:

- Increase of the flow along some edge possible, when flow can be increased along the edge, i.e. if  $f(u, v) < c(u, v)$ .  
Rest capacity  $c_f(u, v) = c(u, v) - f(u, v) > 0$ .
- Increase of flow **against the direction** of the edge possible, if flow can be reduced along the edge, i.e. if  $f(u, v) > 0$ .  
Rest capacity  $c_f(v, u) = f(u, v) > 0$ .

## Rest Network

Rest network  $G_f$  provided by the edges with positive rest capacity:



Rest networks provide the same kind of properties as flow networks with the exception of permitting antiparallel capacity-edges

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## Observation

### Theorem

Let  $G = (V, E, c)$  be a flow network with source  $s$  and sink  $t$  and  $f$  a flow in  $G$ . Let  $G_f$  be the corresponding rest networks and let  $f'$  be a flow in  $G_f$ . Then  $f \oplus f'$  with

$$(f \oplus f')(u, v) = f(u, v) + f'(u, v)$$

defines a flow in  $G$  with value  $|f| + |f'|$ .

## Proof

$f \oplus f'$  defines a flow in  $G$ :

- capacity limit

$$(f \oplus f')(u, v) = f(u, v) + \underbrace{f'(u, v)}_{\leq c(u, v) - f(u, v)} \leq c(u, v)$$

- skew symmetry

$$(f \oplus f')(u, v) = -f(v, u) + -f'(v, u) = -(f \oplus f')(v, u)$$

- flow conservation  $u \in V - \{s, t\}$ :

$$\sum_{v \in V} (f \oplus f')(u, v) = \sum_{v \in V} f(u, v) + \sum_{v \in V} f'(u, v) = 0$$

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## Proof

Value of  $f \oplus f'$

$$\begin{aligned} |f \oplus f'| &= (f \oplus f')(s, V) \\ &= \sum_{u \in V} f(s, u) + f'(s, u) \\ &= f(s, V) + f'(s, V) \\ &= |f| + |f'| \end{aligned}$$

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## Augmenting Paths

**expansion path**  $p$ : simple path from  $s$  to  $t$  in the rest network  $G_f$ .

**Rest capacity**  $c_f(p) = \min\{c_f(u, v) : (u, v) \text{ edge in } p\}$

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## Flow in $G_f$

### Theorem

The mapping  $f_p : V \times V \rightarrow \mathbb{R}$ ,

$$f_p(u, v) = \begin{cases} c_f(p) & \text{if } (u, v) \text{ edge in } p \\ -c_f(p) & \text{if } (v, u) \text{ edge in } p \\ 0 & \text{otherwise} \end{cases}$$

provides a flow in  $G_f$  with value  $|f_p| = c_f(p) > 0$ .

$f_p$  is a flow (easy to show). there is one and only one  $u \in V$  with  $(s, u) \in p$ . Thus  $|f_p| = \sum_{v \in V} f_p(s, v) = f_p(s, u) = c_f(p)$ .

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## Consequence

Strategy for an algorithm:

With an expansion path  $p$  in  $G_f$  the flow  $f \oplus f_p$  defines a new flow with value  $|f \oplus f_p| = |f| + |f_p| > |f|$ .

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## Max-Flow Min-Cut Theorem

### Theorem

Let  $f$  be a flow in a flow network  $G = (V, E, c)$  with source  $s$  and sink  $t$ . The following statements are equivalent:

- 1  $f$  is a maximal flow in  $G$
- 2 The rest network  $G_f$  does not provide any expansion paths
- 3 It holds that  $|f| = c(S, T)$  for a cut  $(S, T)$  of  $G$ .

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## Proof

- (3)  $\Rightarrow$  (1):  
It holds that  $|f| \leq c(S, T)$  for all cuts  $S, T$ . From  $|f| = c(S, T)$  it follows that  $|f|$  is maximal.
- (1)  $\Rightarrow$  (2):  
 $f$  maximal Flow in  $G$ . Assumption:  $G_f$  has some expansion path  $|f \oplus f_p| = |f| + |f_p| > |f|$ . Contradiction.

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## Proof (2) $\Rightarrow$ (3)

Assumption:  $G_f$  has no expansion path

Define  $S = \{v \in V : \text{there is a path } s \rightsquigarrow v \text{ in } G_f\}$ .

$(S, T) := (S, V \setminus S)$  is a cut:  $s \in S, t \in T$ .

Let  $u \in S$  and  $v \in T$ . Then  $c_f(u, v) = 0$ , also  $c_f(u, v) = c(u, v) - f(u, v) = 0$ . Somit  $f(u, v) = c(u, v)$ .

Thus

$$|f| = f(S, T) = \sum_{u \in S} \sum_{v \in T} f(u, v) = \sum_{u \in S} \sum_{v \in T} c(u, v) = C(S, T).$$



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## Algorithm Ford-Fulkerson( $G, s, t$ )

**Input:** Flow network  $G = (V, E, c)$

**Output:** Maximal flow  $f$ .

**for**  $(u, v) \in E$  **do**

$f(u, v) \leftarrow 0$

**while** Exists path  $p : s \rightsquigarrow t$  in rest network  $G_f$  **do**

$c_f(p) \leftarrow \min\{c_f(u, v) : (u, v) \in p\}$

**foreach**  $(u, v) \in p$  **do**

$f(u, v) \leftarrow f(u, v) + c_f(p)$

$f(v, u) \leftarrow f(v, u) - c_f(p)$

## Practical Consideration

In an implementation of the Ford-Fulkerson algorithm the negative flow edges are usually not stored because their value always equals the negated value of the antiparallel edge.

$f(u, v) \leftarrow f(u, v) + c_f(p)$

$f(v, u) \leftarrow f(v, u) - c_f(p)$

is then transformed to

**if**  $(u, v) \in E$  **then**

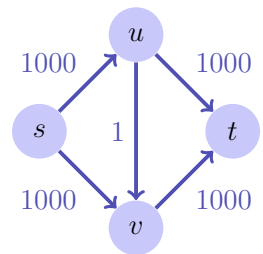
$f(u, v) \leftarrow f(u, v) + c_f(p)$

**else**

$f(v, u) \leftarrow f(v, u) - c_f(p)$

## Analysis

- The Ford-Fulkerson algorithm does not necessarily have to converge for irrational capacities. For integers or rational numbers it terminates.
- For an integer flow, the algorithm requires maximally  $|f_{\max}|$  iterations of the while loop (because the flow increases minimally by 1). Search a single increasing path (e.g. with DFS or BFS)  $\mathcal{O}(|E|)$  Therefore  $\mathcal{O}(f_{\max}|E|)$ .



With an unlucky choice the algorithm may require up to 2000 iterations here.

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## Edmonds-Karp Algorithm

Choose in the Ford-Fulkerson-Method for finding a path in  $G_f$  the expansion path of shortest possible length (e.g. with BFS)

## Edmonds-Karp Algorithm

### Theorem

When the Edmonds-Karp algorithm is applied to some integer valued flow network  $G = (V, E)$  with source  $s$  and sink  $t$  then the number of flow increases applied by the algorithm is in  $\mathcal{O}(|V| \cdot |E|)$ .  
 $\Rightarrow$  Overall asymptotic runtime:  $\mathcal{O}(|V| \cdot |E|^2)$

[Without proof]

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## Application: maximal bipartite matching

Given: bipartite undirected graph  $G = (V, E)$ .

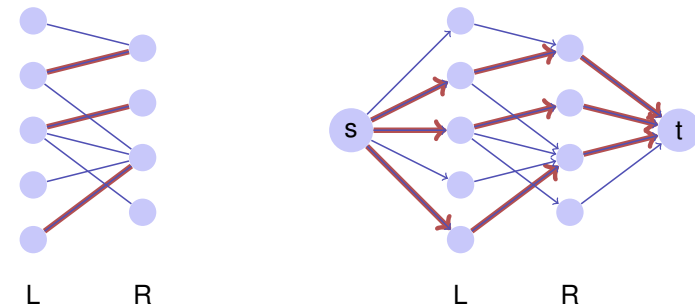
**Matching**  $M$ :  $M \subseteq E$  such that  $|\{m \in M : v \in m\}| \leq 1$  for all  $v \in V$ .

**Maximal Matching**  $M$ : Matching  $M$ , such that  $|M| \geq |M'|$  for each matching  $M'$ .



## Corresponding flow network

Construct a flow network that corresponds to the partition  $L, R$  of a bipartite graph with source  $s$  and sink  $t$ , with directed edges from  $s$  to  $L$ , from  $L$  to  $R$  and from  $R$  to  $t$ . Each edge has capacity 1.



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## Integer number theorem

### Theorem

*If the capacities of a flow network are integers, then the maximal flow generated by the Ford-Fulkerson method provides integer numbers for each  $f(u, v)$ ,  $u, v \in V$ .*

[without proof]

Consequence: Ford-Fulkerson generates for a flow network that corresponds to a bipartite graph a maximal matching

$$M = \{(u, v) : f(u, v) = 1\}.$$