Maximum Flows

- **A flow network $G = (V, E)$ is a directed graph in which each edge $(u, v) \in E$ has a nonnegative capacity .**
- **If $(u, v) \notin E$, we assume that $c(u, v) = 0$.**
- **We distinguish two vertices in a flow network: a source s and a sink t.**

A flow in G is a real-valued function $f : V \times V \to R$ that satisfies the following three properties:

Capacity constraint: For all $u, v \in V$, we require $f(u, v) \leq c(u, v)$.

Skew symmetry: For all $u, v \in V$, we require $f(u, v) = -f(v, u)$.

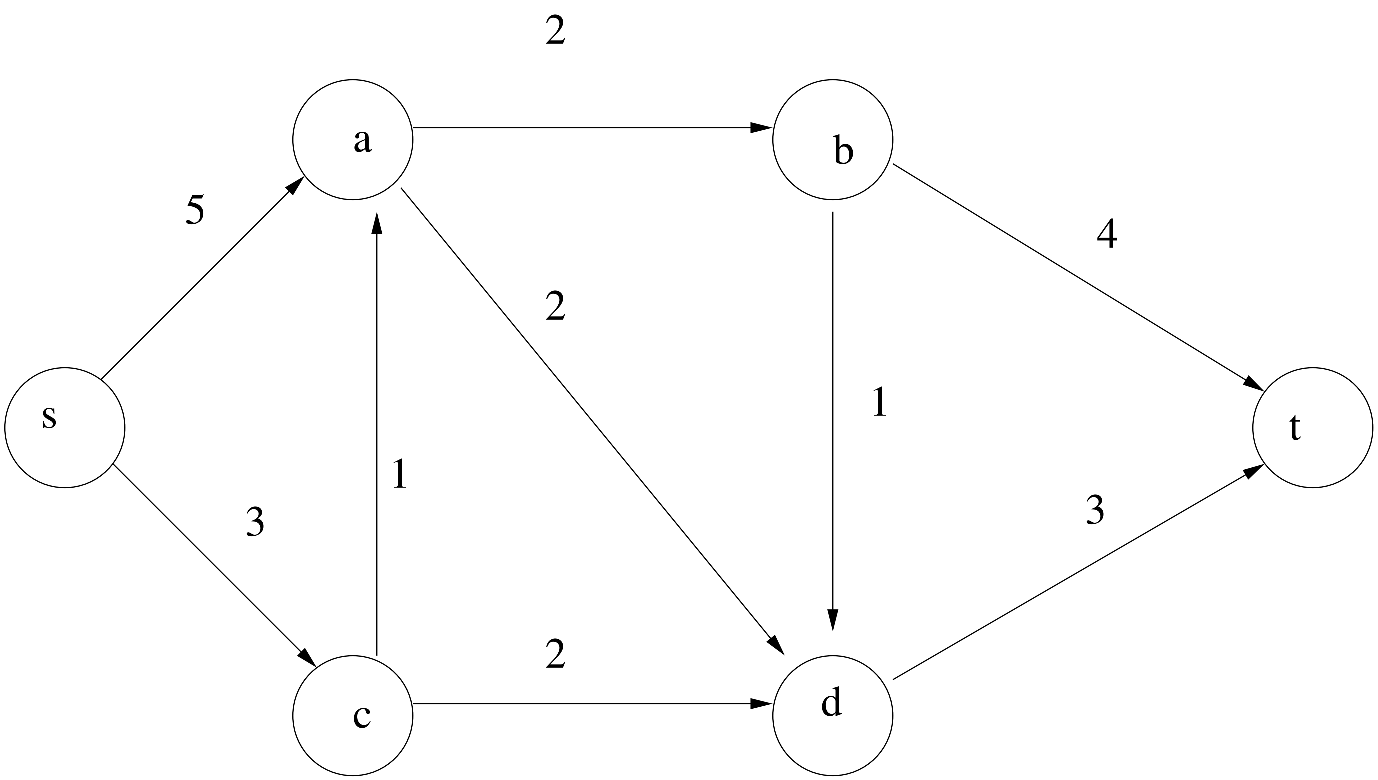
Flow conservation: For all $u \in V - \{s, t\}$, we require

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

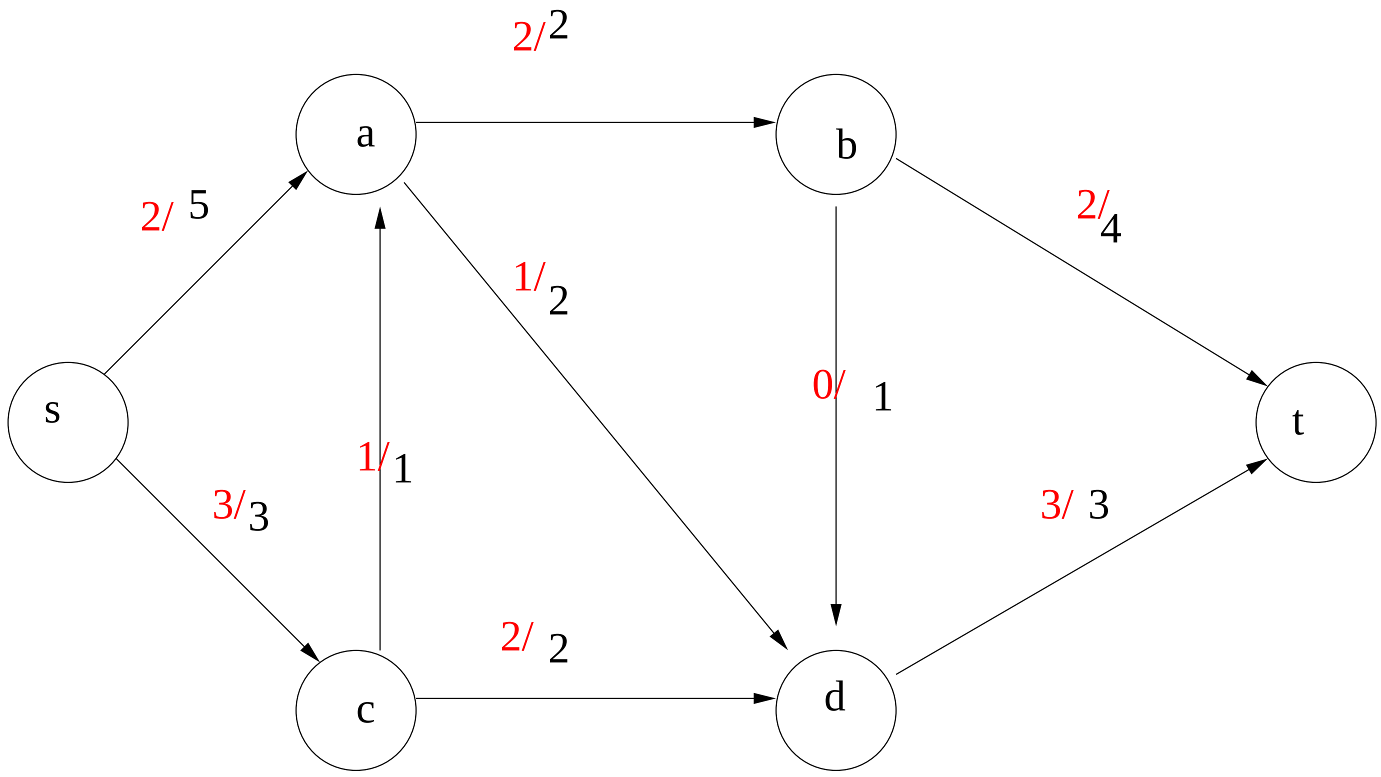
The value of a flow f is defined as

$$|f| = \sum_{v \in V} f(s, v) \ , \tag{1}$$

Example



Solutions



Ford Fulkerson

Ford-Fulkerson-Method(G, s, t)

initialize flow f **to** 0
while there exists an augmenting path p
  do augment flow f **along** p
return f

- **The residual capacity of** (u, v)**, is**

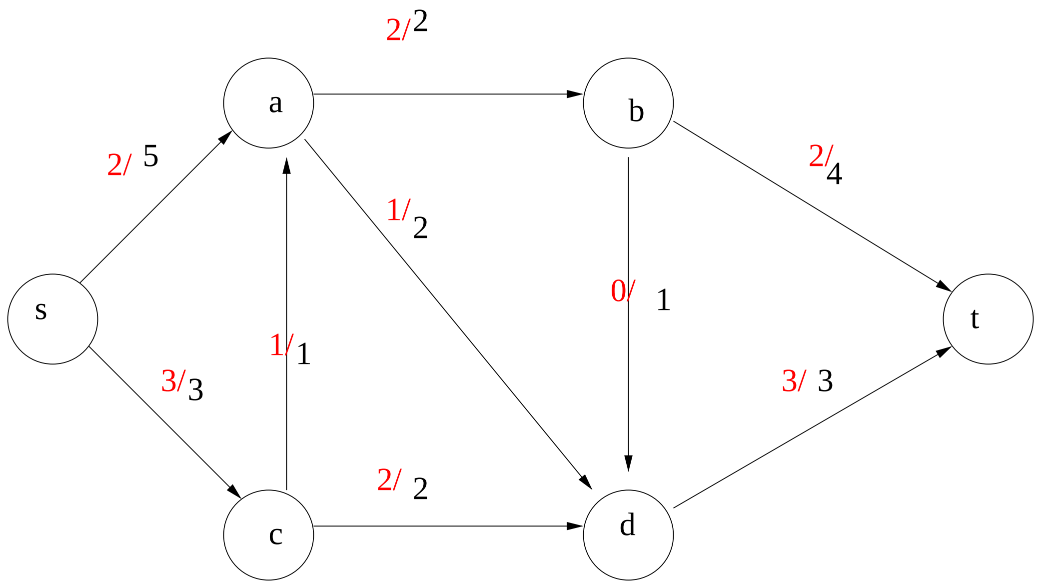
$$c_f(u, v) = c(u, v) - f(u, v) \ . \qquad (2)$$

- **The residual graph** G_f **is the graph consisting of edges with positive residual capacity**
- **Flows add**

s-t Cuts

An s-t cut satsfies

- $s \in S$, $t \in T$
- $S \cup T = V$, $S \cap T = \emptyset$



$$c(S,T) = \sum_{u \in S, v \in T} c(u,v)$$

$$f(S,T) = \sum_{u \in S, v \in T} f(u,v)$$

- **For all cuts (S,T) and all feasible flows f, $f(S,T) \le c(S,T)$**
- **For all pairs of cuts (S_1,T_1) and (S_2,T_2), and all feasible flows f, $f(S_1,T_1) = f(S_2,T_2)$.**

Max-flow min-cut theorem

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

1. **f is a maximum flow in G.**
2. **The residual network G_f contains no augmenting paths.**
3. **$|f| = c(S, T)$ for some cut (S, T) of G.**

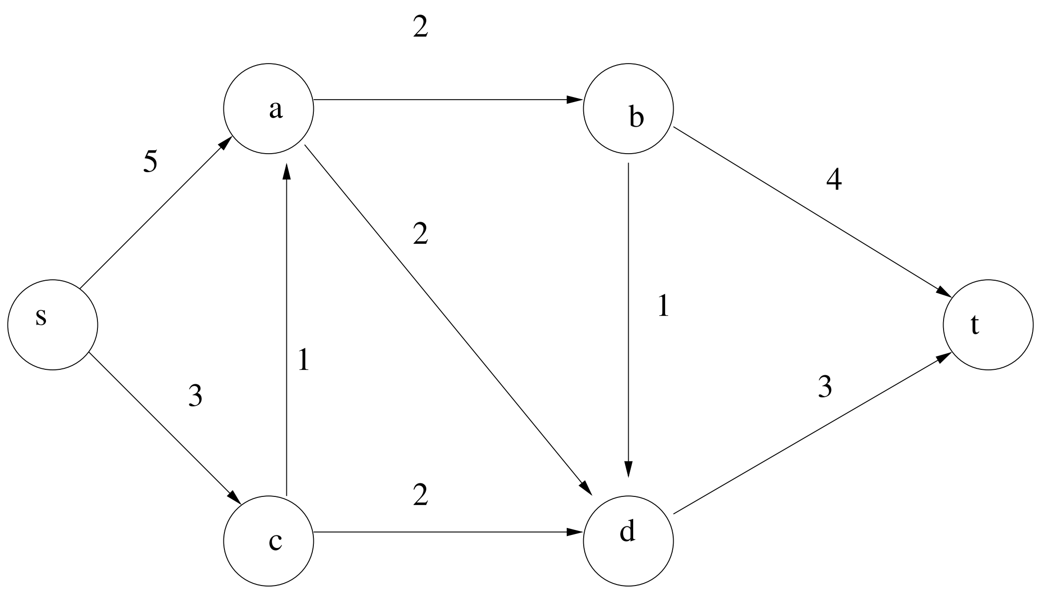
Ford Fulkerson expanded

Ford-Fulkerson(G, s, t)

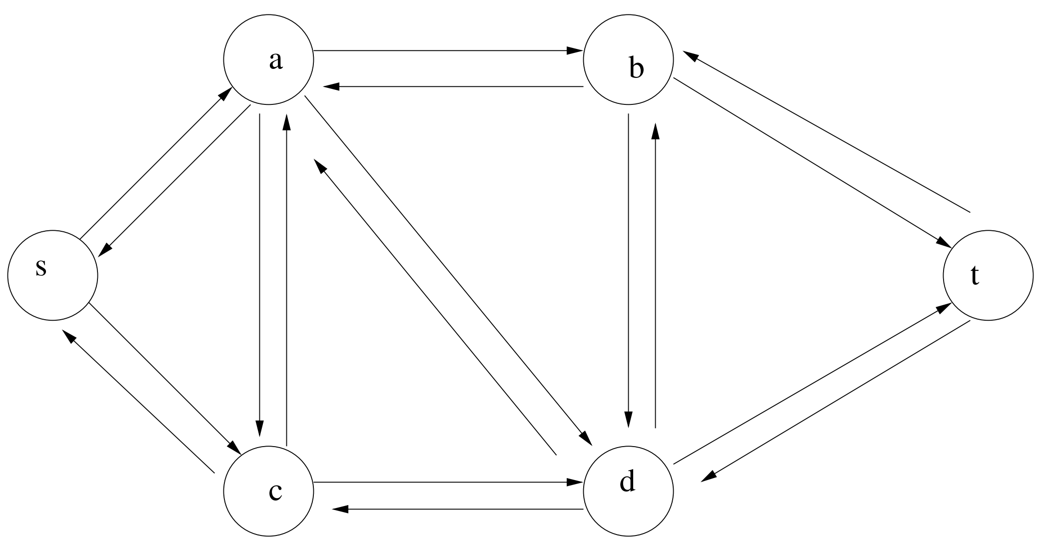
for each edge $(u, v) \in E[G]$
  do $f[u, v] \leftarrow 0$
    $f[v, u] \leftarrow 0$
while there exists a path p **from** s **to** t **in the residual network** G_f
  do $c_f(p) \leftarrow \min\{c_f(u, v) : (u, v)$ **is in** $p\}$
    for each edge (u, v) **in** p
      do $f[u, v] \leftarrow f[u, v] + c_f(p)$
        $f[v, u] \leftarrow -f[u, v]$

Algorithm

Graph

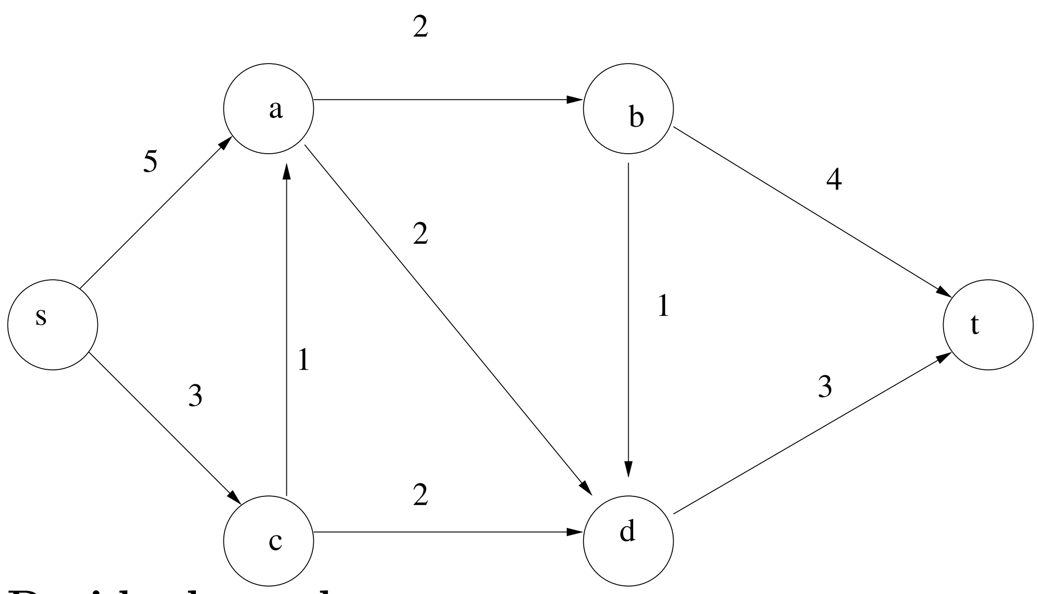


Residual graph

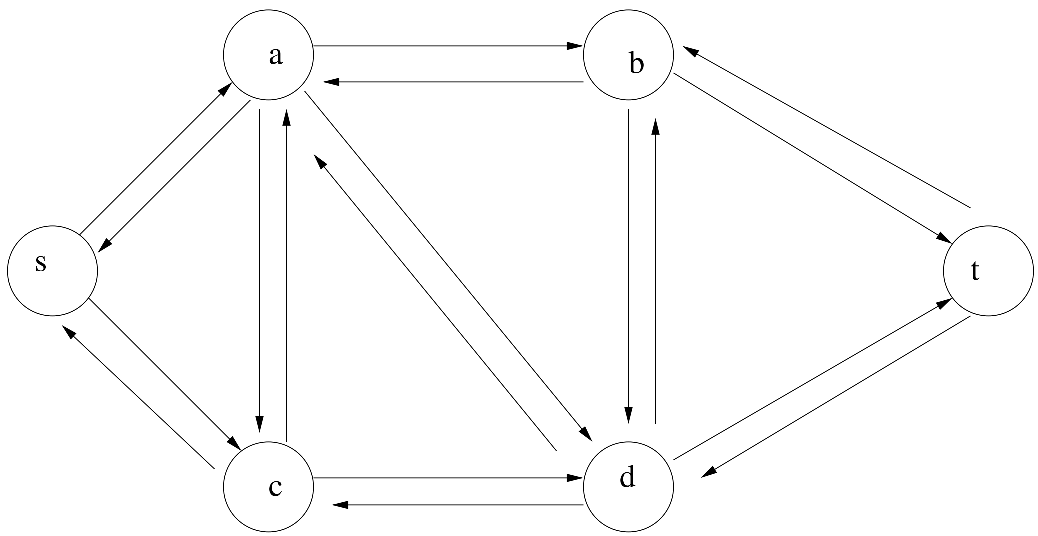


Algorithm

Graph

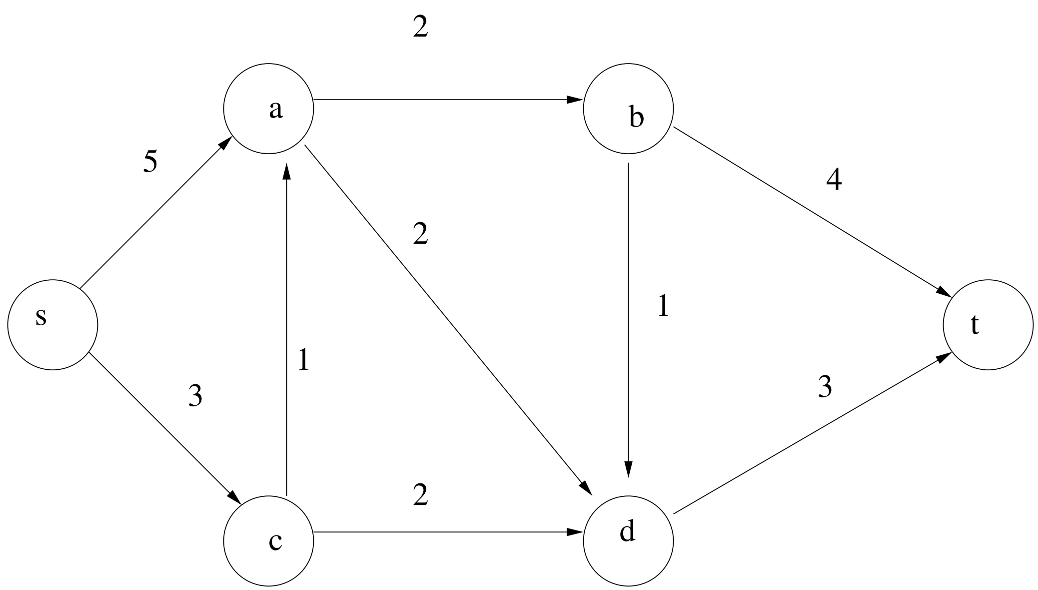


Residual graph



Algorithm

Graph



Residual graph