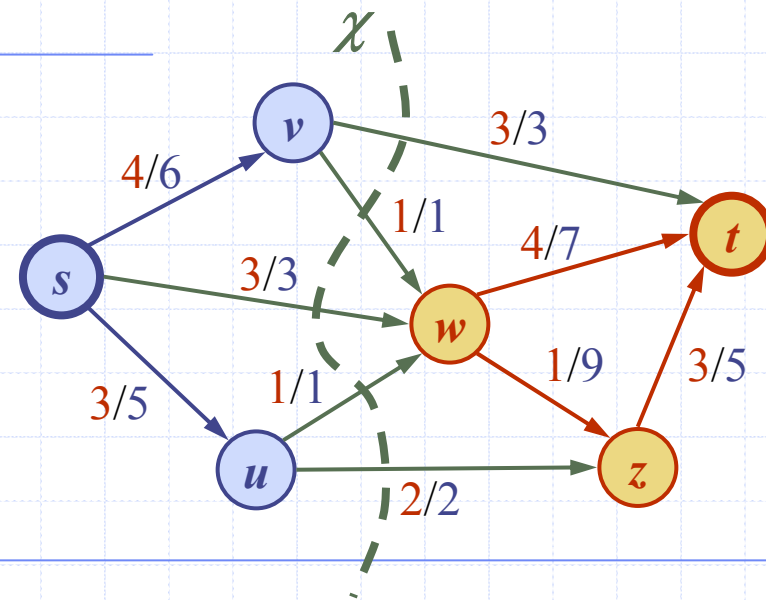


Maximum Flow



Outline and Reading

◆ Flow networks

- Flow
- Cut

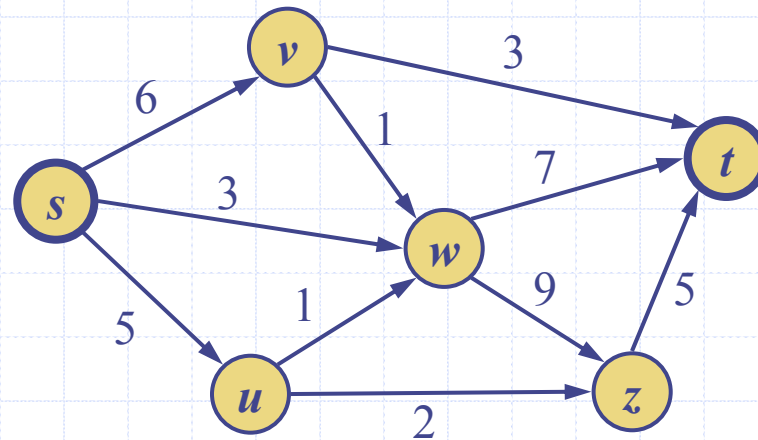
◆ Maximum flow

- Augmenting path
- Maximum flow and minimum cut
- Ford-Fulkerson's algorithm

(see supplement)

Flow Network

- ◆ A flow network (or just network) N consists of
 - A weighted digraph G with nonnegative integer edge weights, where the weight of an edge e is called the capacity $c(e)$ of e
 - Two distinguished vertices, s and t of G , called the source and sink, respectively, such that s has no incoming edges and t has no outgoing edges.
- ◆ Example:



Flow

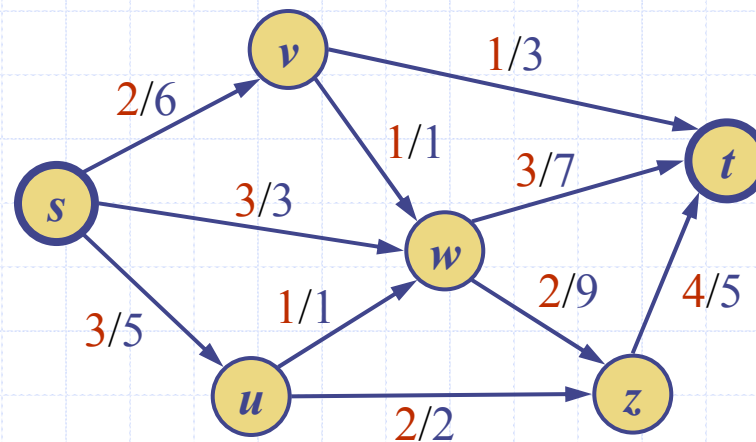
- ◆ A flow f for a network N is an assignment of an integer value $f(e)$ to each edge e that satisfies the following properties:

Capacity Rule: For each edge e , $0 \leq f(e) \leq c(e)$

Conservation Rule: For each vertex $v \neq s, t$
$$\sum_{e \in E^-(v)} f(e) = \sum_{e \in E^+(v)} f(e)$$

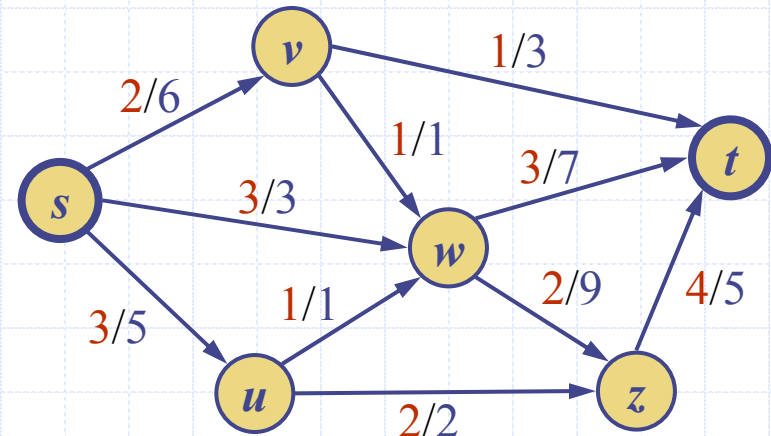
where $E^-(v)$ and $E^+(v)$ are the incoming and outgoing edges of v , resp.

- ◆ The value of a flow f , denoted $|f|$, is the total flow from the source, which is the same as the total flow into the sink
- ◆ Example:

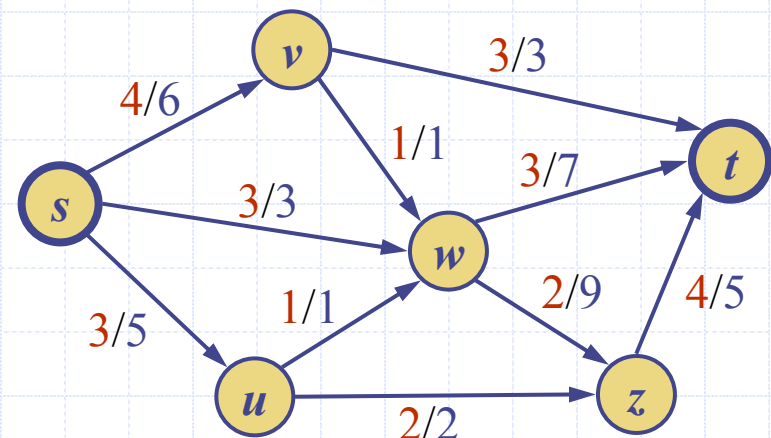


Maximum Flow

- ◆ A flow for a network N is said to be maximum if its value is the largest of all flows for N
- ◆ The maximum flow problem consists of finding a maximum flow for a given network N
- ◆ Applications
 - Hydraulic systems
 - Electrical circuits
 - Traffic movements
 - Freight transportation



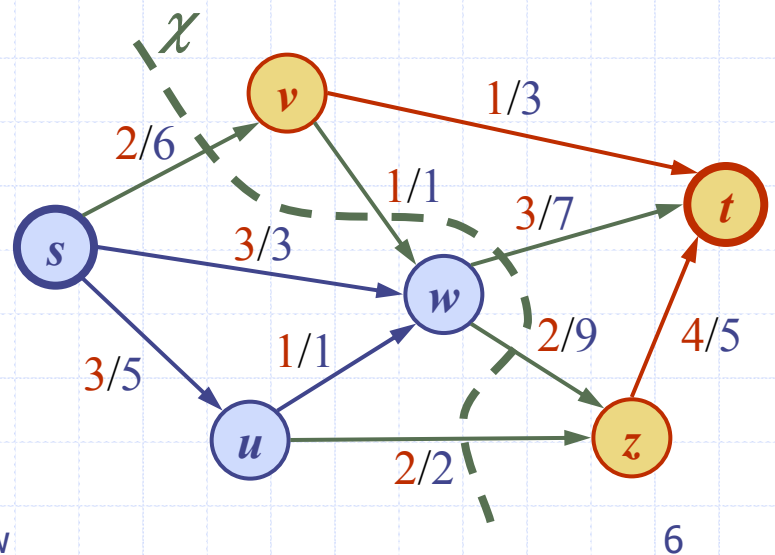
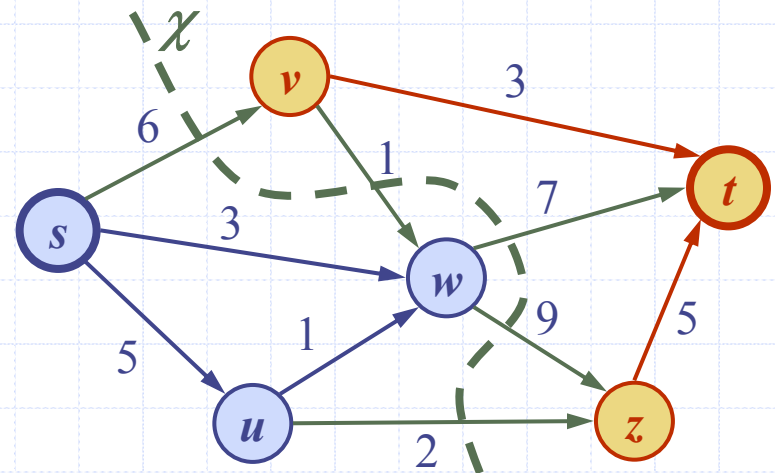
Flow of value $8 = 2 + 3 + 3 = 1 + 3 + 4$



Maximum flow of value $10 = 4 + 3 + 3 = 3 + 3 + 4$

Cut

- ◆ A cut of a network N with source s and sink t is a partition $\chi = (V_s, V_t)$ of the vertices of N such that $s \in V_s$ and $t \in V_t$
 - Forward edge of cut χ : origin in V_s and destination in V_t
 - Backward edge of cut χ : origin in V_t and destination in V_s
- ◆ Flow $f(\chi)$ across a cut χ : total flow of forward edges minus total flow of backward edges
- ◆ Capacity $c(\chi)$ of a cut χ : total capacity of forward edges
- ◆ Example:
 - $c(\chi) = 24$
 - $f(\chi) = 8$



Flow and Cut

Lemma:

The flow $f(\chi)$ across any cut χ is equal to the flow value $|f|$

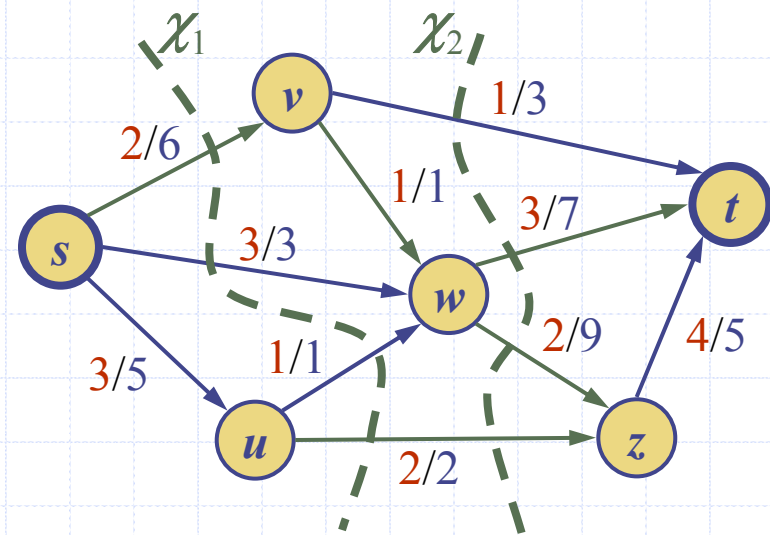
Lemma:

The flow $f(\chi)$ across a cut χ is less than or equal to the capacity $c(\chi)$ of the cut

Theorem:

The value of any flow is less than or equal to the capacity of any cut, i.e., for any flow f and any cut χ , we have

$$|f| \leq c(\chi)$$



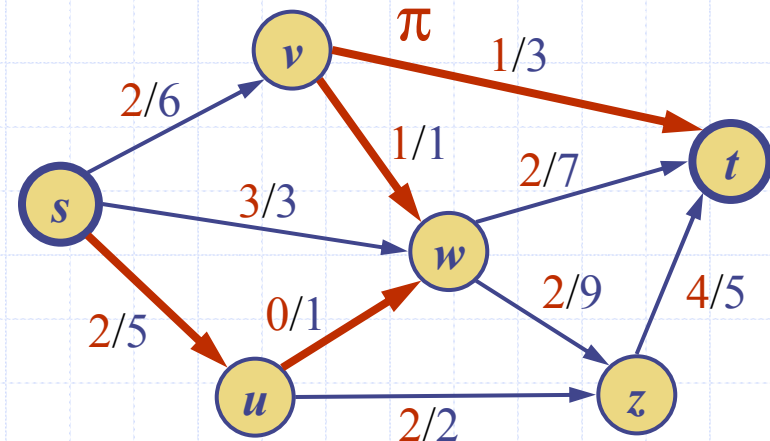
$$c(\chi_1) = 12 = 6 + 3 + 1 + 2$$

$$c(\chi_2) = 21 = 3 + 7 + 9 + 2$$

$$|f| = 8$$

Augmenting Path

- ◆ Consider a flow f for a network N
- ◆ Let e be an edge from u to v :
 - Residual capacity of e from u to v : $\Delta_f(u, v) = c(e) - f(e)$
 - Residual capacity of e from v to u : $\Delta_f(v, u) = f(e)$
- ◆ Let π be a path from s to t
 - The residual capacity $\Delta_f(\pi)$ of π is the smallest of the residual capacities of the edges of π in the direction from s to t
- ◆ A path π from s to t is an augmenting path if $\Delta_f(\pi) > 0$



$$\begin{aligned} \Delta_f(s, u) &= 3 \\ \Delta_f(u, w) &= 1 \\ \Delta_f(w, v) &= 1 \\ \Delta_f(v, t) &= 2 \\ \Delta_f(\pi) &= 1 \\ |f| &= 7 \end{aligned}$$

Flow Augmentation

Lemma:

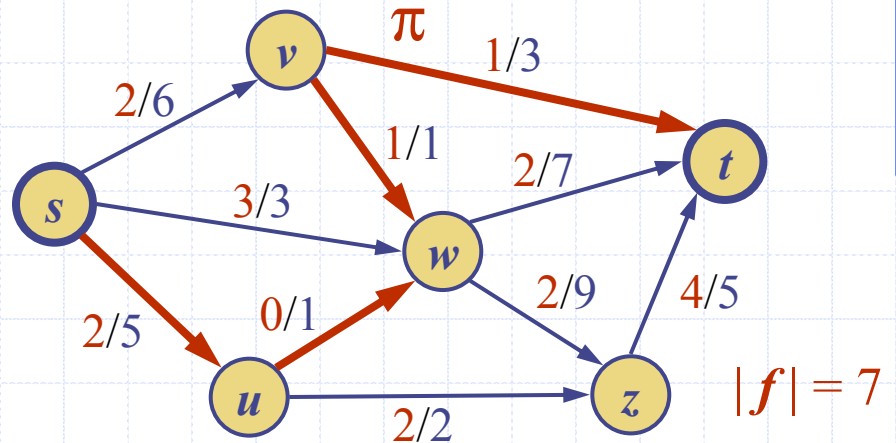
Let π be an augmenting path for flow f in network N . There exists a flow f' for N of value

$$|f'| = |f| + \Delta_f(\pi)$$

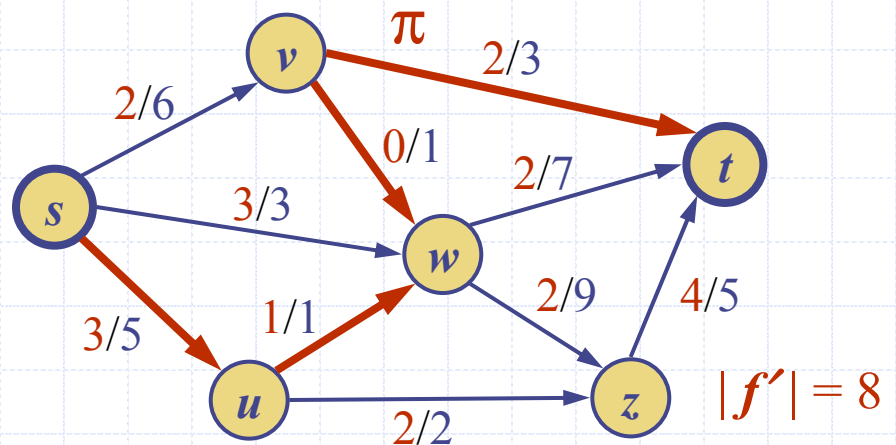
Proof:

We compute flow f' by modifying the flow on the edges of π

- Forward edge:
 $f'(e) = f(e) + \Delta_f(\pi)$
- Backward edge:
 $f'(e) = f(e) - \Delta_f(\pi)$



$$\Downarrow \Delta_f(\pi) = 1$$



Ford-Fulkerson's Algorithm

- ◆ Initially, $f(e) = 0$ for each edge e
- ◆ Repeatedly
 - Search for an augmenting path π
 - Augment by $\Delta_f(\pi)$ the flow along the edges of π
- ◆ A specialization of DFS (or BFS) searches for an augmenting path
 - An edge e is traversed from u to v provided $\Delta_f(u, v) > 0$

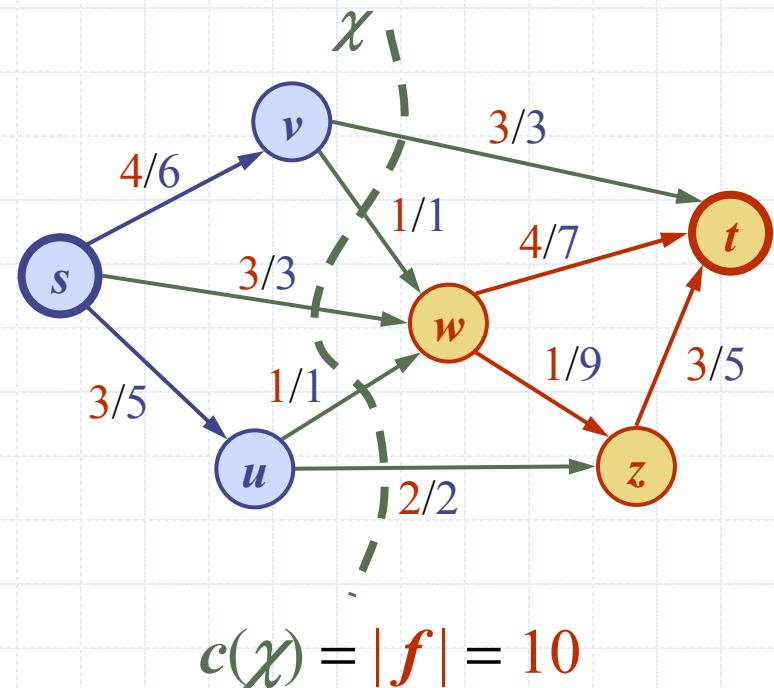
```
Algorithm FordFulkersonMaxFlow(N)
for all  $e \in G.edges()$ 
    setFlow( $e, 0$ )
while  $G$  has an augmenting path  $\pi$ 
    { compute residual capacity  $\Delta$  of  $\pi$  }
     $\Delta \leftarrow \infty$ 
    for all edges  $e \in \pi$ 
        { compute residual capacity  $\delta$  of  $e$  }
        if  $e$  is a forward edge of  $\pi$ 
             $\delta \leftarrow \text{getCapacity}(e) - \text{getFlow}(e)$ 
        else {  $e$  is a backward edge }
             $\delta \leftarrow \text{getFlow}(e)$ 
        if  $\delta < \Delta$ 
             $\Delta \leftarrow \delta$ 
    { augment flow along  $\pi$  }
    for all edges  $e \in \pi$ 
        if  $e$  is a forward edge of  $\pi$ 
            setFlow( $e, \text{getFlow}(e) + \Delta$ )
        else {  $e$  is a backward edge }
            setFlow( $e, \text{getFlow}(e) - \Delta$ )
```

Max-Flow and Min-Cut

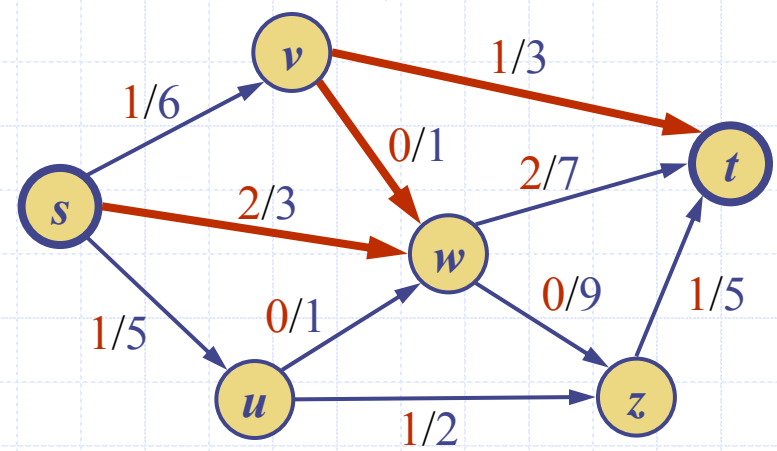
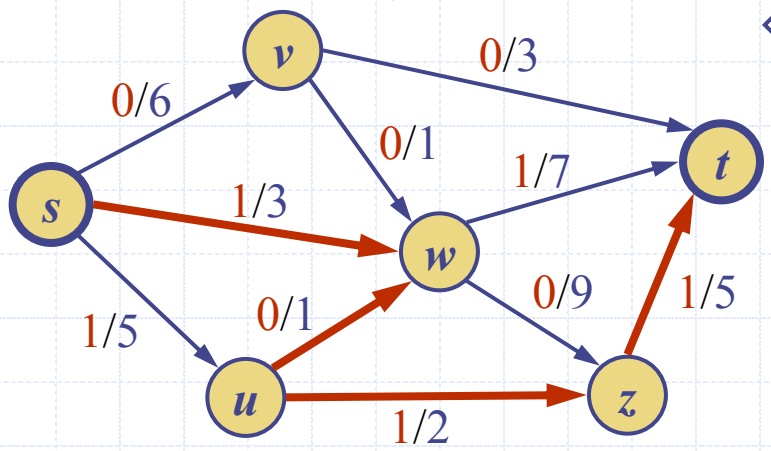
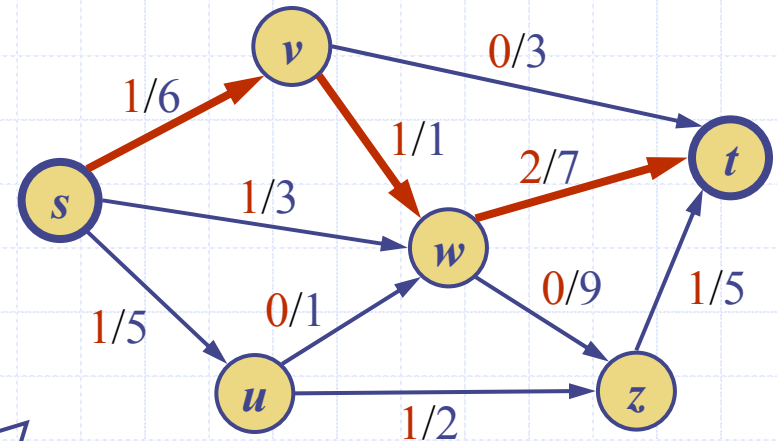
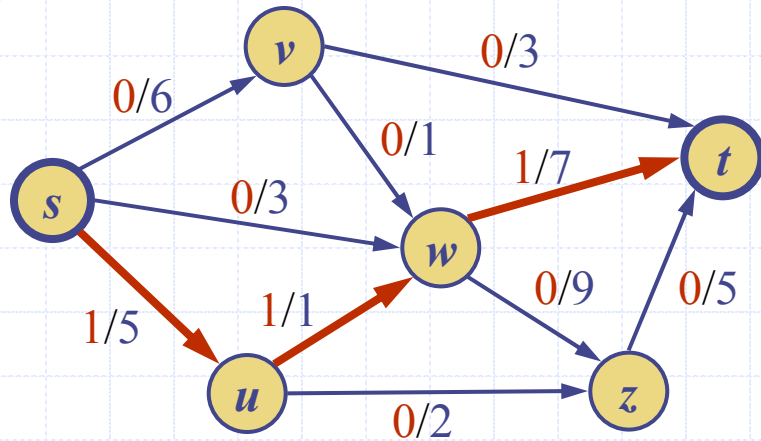
- ◆ Termination of Ford-Fulkerson's algorithm
 - There is no augmenting path from s to t with respect to the current flow f
- ◆ Define
 - V_s set of vertices reachable from s by augmenting paths
 - V_t set of remaining vertices
- ◆ Cut $\chi = (V_s, V_t)$ has capacity
 - $c(\chi) = |f|$
 - Forward edge: $f(e) = c(e)$
 - Backward edge: $f(e) = 0$
- ◆ Thus, flow f has maximum value and cut χ has minimum capacity

Theorem:

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



Example (1)

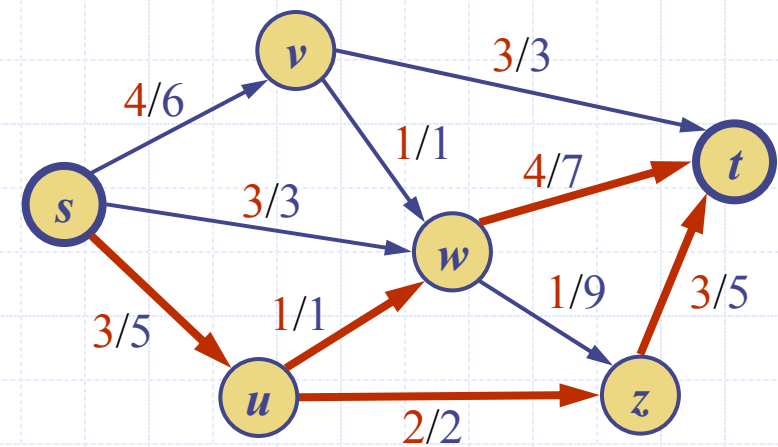
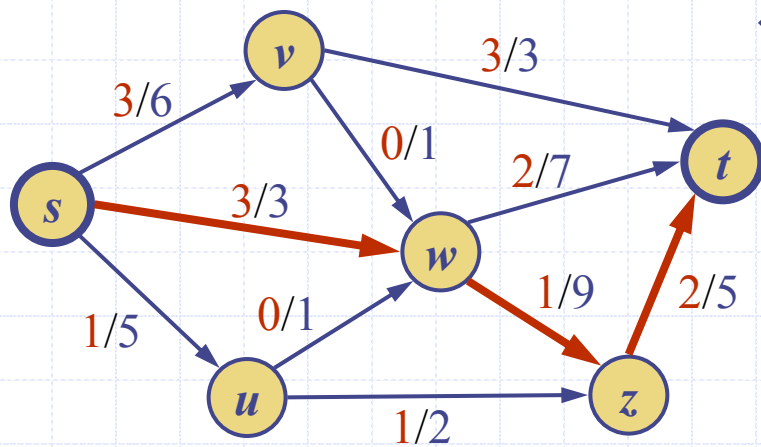
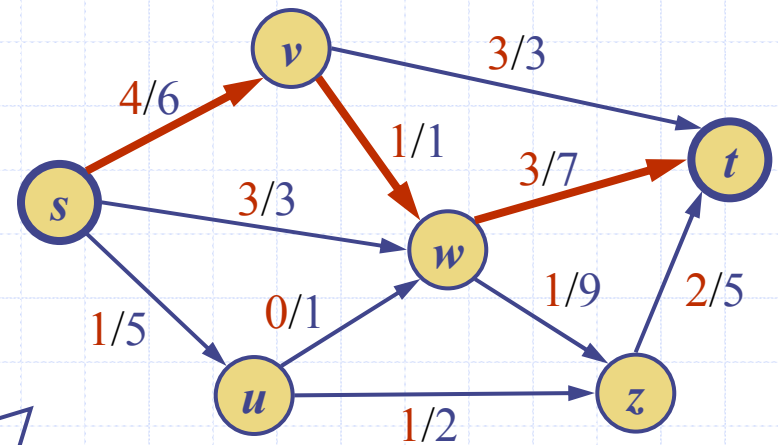
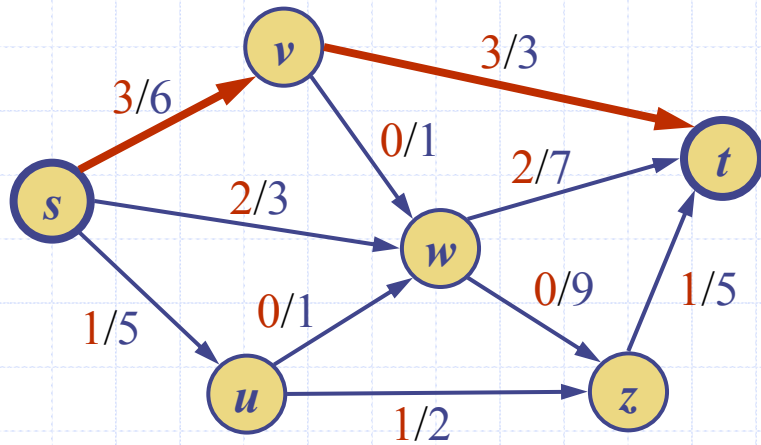


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Maximum Flow

12

Example (2)



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Maximum Flow

13

Analysis

- ◆ In the worst case, Ford-Fulkerson's algorithm performs $|f^*|$ flow augmentations, where f^* is a maximum flow
- ◆ Example
 - The augmenting paths found alternate between π_1 and π_2
 - The algorithm performs 100 augmentations
- ◆ Finding an augmenting path and augmenting the flow takes $O(n + m)$ time
- ◆ The running time of Ford-Fulkerson's algorithm is $O(|f^*|(n + m))$

