

# Network Flow

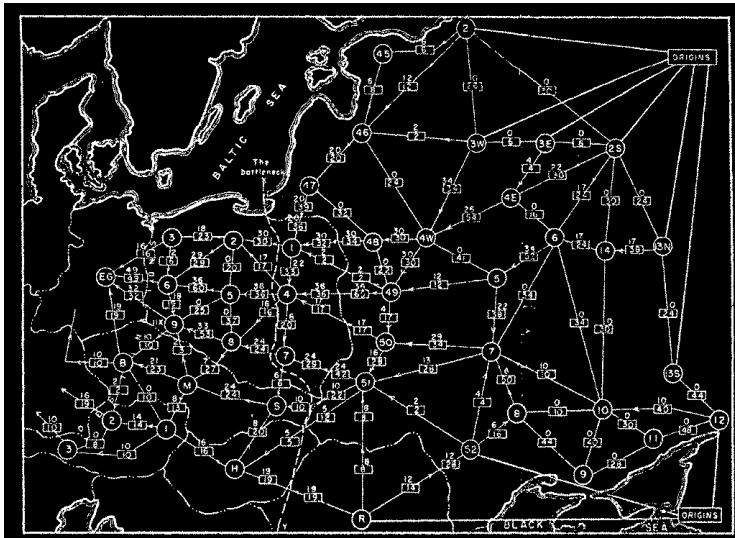
T. M. Murali

April 5, 7, 2021

# Maximum Flow and Minimum Cut

- Two rich algorithmic problems.
- Fundamental problems in combinatorial optimization.
- Beautiful mathematical duality between flows and cuts.
- Numerous non-trivial applications:
  - ▶ Bipartite matching.
  - ▶ Data mining.
  - ▶ Project selection.
  - ▶ Airline scheduling.
  - ▶ Baseball elimination.
  - ▶ Image segmentation.
  - ▶ Network connectivity.
  - ▶ Open-pit mining.
  - ▶ Network reliability.
  - ▶ Distributed computing.
  - ▶ Egalitarian stable matching.
  - ▶ Security of statistical data.
  - ▶ Network intrusion detection.
  - ▶ Multi-camera scene reconstruction.
  - ▶ Gene function prediction.

# History



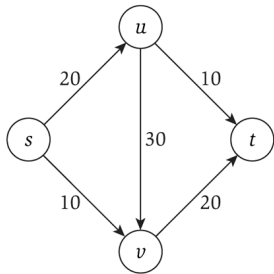
(Soviet Rail Network, Tolstoi, 1930; Harris and Ross, 1955; Alexander Schrijver, *Math Programming*, 91: 3, 2002.)

# Flow Networks

- Use directed graphs to model *transporation networks*:
  - ▶ edges carry traffic and have capacities.
  - ▶ nodes act as switches.
  - ▶ *source* nodes generate traffic, *sink* nodes absorb traffic.

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**Figure 7.2** A flow network, with source  $s$  and sink  $t$ . The numbers next to the edges are the capacities.

- A *flow network* is a directed graph  $G(V, E)$ 
  - ▶ Each edge  $e \in E$  has a capacity  $c(e) > 0$ .
  - ▶ There is a single *source* node  $s \in V$ .
  - ▶ There is a single *sink* node  $t \in V$ .
  - ▶ Nodes other than  $s$  and  $t$  are *internal*.

## Defining Flow

- In a flow network  $G(V, E)$ , an *s-t flow* is a function  $f : E \rightarrow \mathbb{R}^+$  such that
  - ① (*Capacity conditions*) For each  $e \in E$ ,  $0 \leq f(e) \leq c(e)$ .
  - ② (*Conservation conditions*) For each internal node  $v$ ,

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

- The *value* of a flow is  $\nu(f) = \sum_{e \text{ out of } s} f(e)$ .

# Maximum-Flow Problem

## MAXIMUM FLOW

**INSTANCE:** A flow network  $G$

**SOLUTION:** The flow with largest value in  $G$ , where the maximum is taking over all possible flows on  $G$ .

- Output should assign a flow value to each edge in the graph.
- The flow on each edge should satisfy the capacity condition.
- The flow into and out of each internal node should satisfy the conservation conditions.
- The value of the output flow, i.e., the total flow out of the source node in the output flow, must be the largest over all possible flows on  $G$ .

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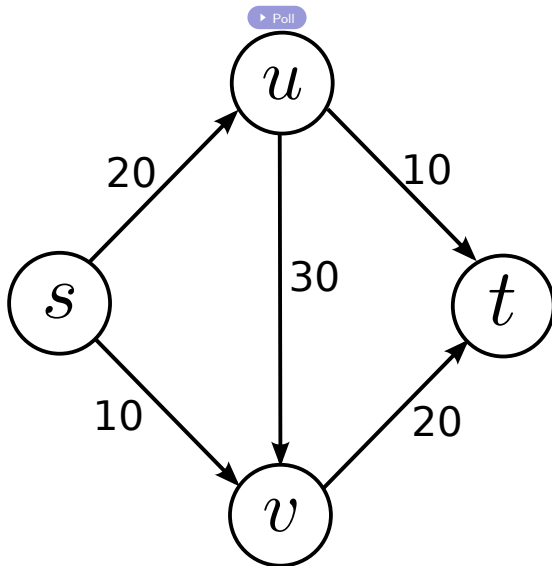
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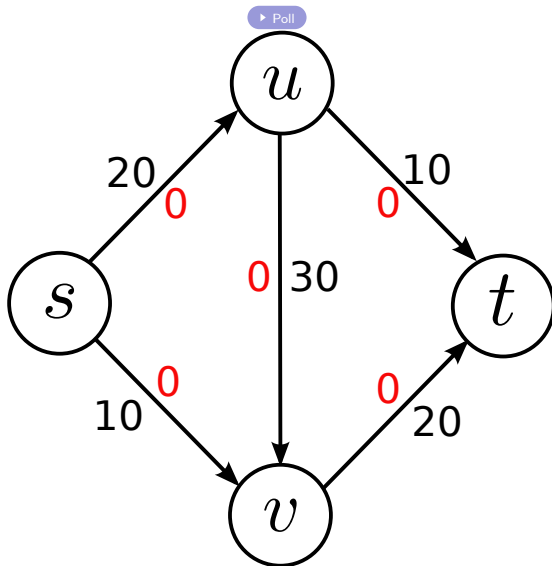
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- The value of the output flow, i.e., the total flow out of the source node in the output flow, must be the largest over all possible flows on  $G$ .
- Assumptions:
  - 1 No edges enter  $s$ , no edges leave  $t$ .
  - 2 There is at least one edge incident on each node.
  - 3 All edge capacities are integers.



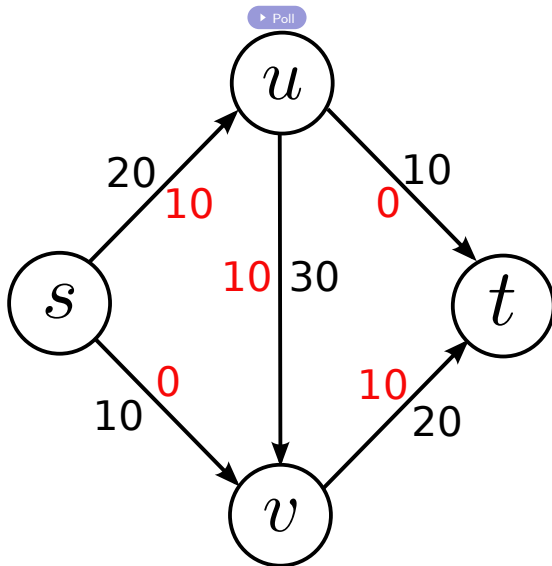
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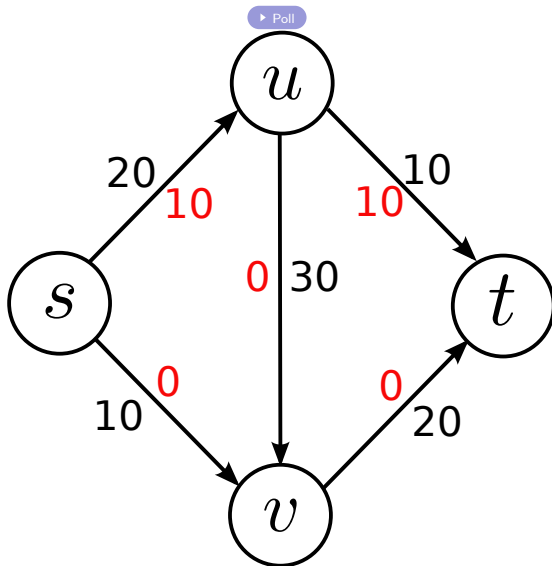
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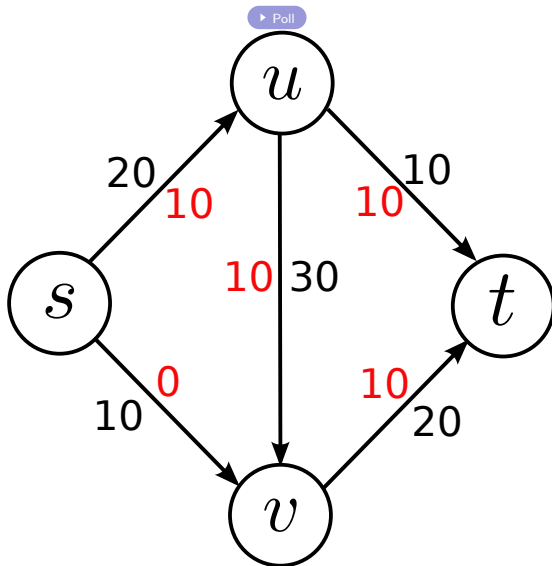
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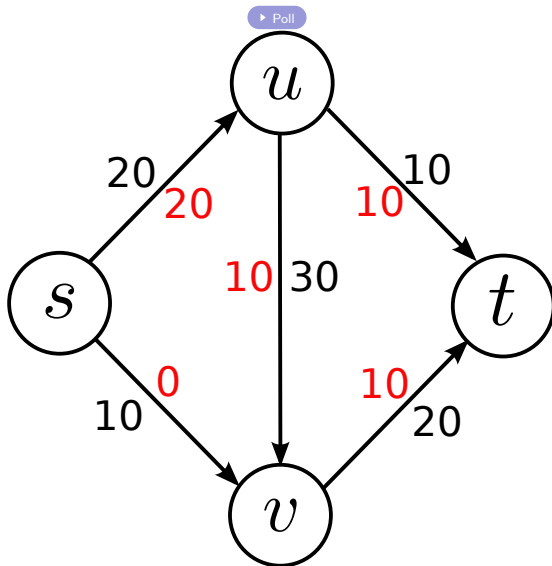
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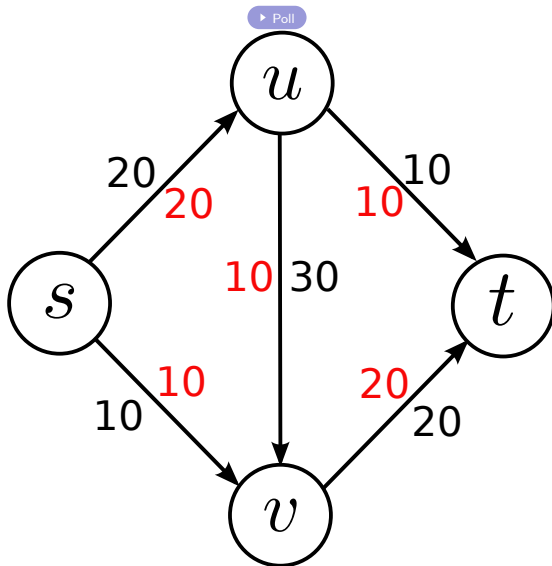
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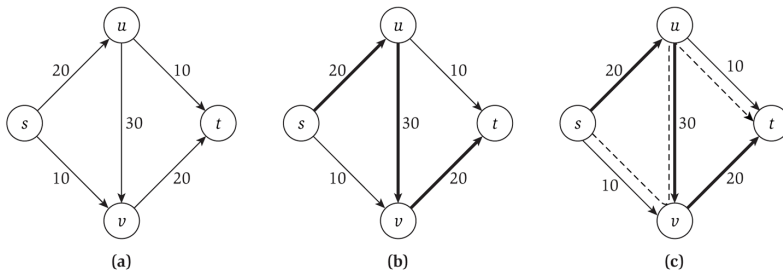
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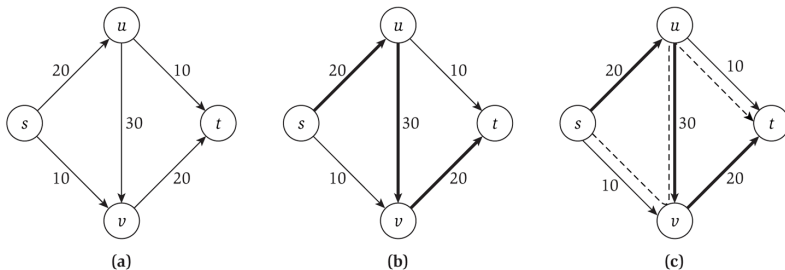
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**Figure 7.3** (a) The network of Figure 7.2. (b) Pushing 20 units of flow along the path  $s, u, v, t$ . (c) The new kind of augmenting path using the edge  $(u, v)$  backward.

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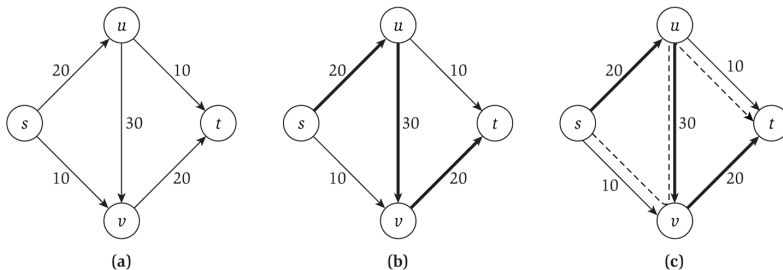
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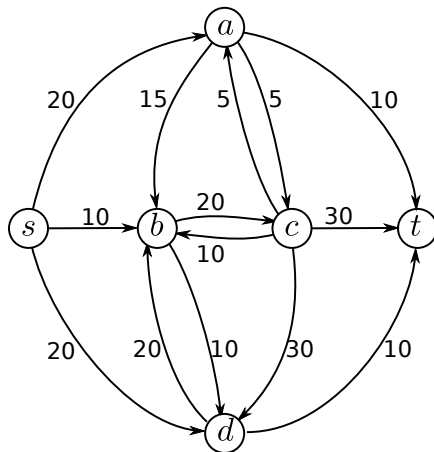
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  - 3 Idea to increase flow: Push flow along edges with leftover capacity and undo flow on edges already carrying flow.



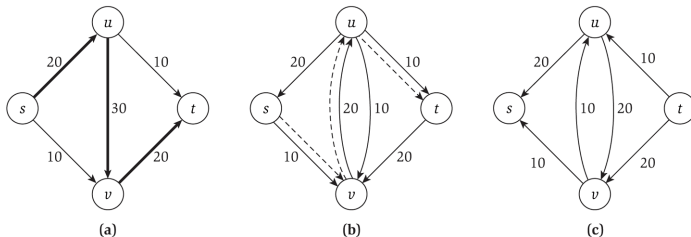
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# Running Example for Ford-Fulkerson Algorithm



# Residual Graph

- Given a flow network  $G(V, E)$  and a flow  $f$  on  $G$ , the *residual graph*  $G_f$  of  $G$  with respect to  $f$  is a directed graph such that
  - (Nodes)  $G_f$  has the same nodes as  $G$ .
  - (Forward edges) For each edge  $e = (u, v) \in E$  such that  $f(e) < c(e)$ ,  $G_f$  contains the edge  $(u, v)$  with a *residual capacity*  $c(e) - f(e)$ .
  - (Backward edges) For each edge  $e \in E$  such that  $f(e) > 0$ ,  $G_f$  contains the edge  $e' = (v, u)$  with a *residual capacity*  $f(e)$ .



**Figure 7.4** (a) The graph  $G$  with the path  $s, u, v, t$  used to push the first 20 units of flow. (b) The residual graph of the resulting flow  $f$ , with the residual capacity next to each edge. The dotted line is the new augmenting path. (c) The residual graph after pushing an additional 10 units of flow along the new augmenting path  $s, v, u, t$ .

# Augmenting Paths in a Residual Graph

- Let  $P$  be a simple  $s$ - $t$  path in  $G_f$ .
- $b = \text{bottleneck}(P, f)$  is the minimum residual capacity of any edge in  $P$ .

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- $b = \text{bottleneck}(P, f)$  is the minimum residual capacity of any edge in  $P$ .
- The following operation  $\text{augment}(f, P)$  yields a new flow  $f'$  in  $G$ :

---

$\text{augment}(f, P)$

Let  $b = \text{bottleneck}(P, f)$

For each edge  $(u, v) \in P$

  If  $e = (u, v)$  is a forward edge then

    increase  $f(e)$  in  $G$  by  $b$

  Else  $((u, v)$  is a backward edge, and let  $e = (v, u)$ )

    decrease  $f(e)$  in  $G$  by  $b$

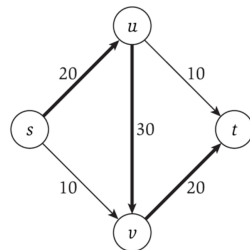
  Endif

Endfor

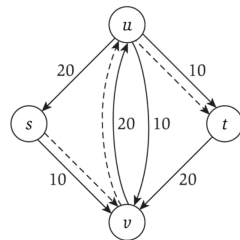
Return( $f$ )

---

- $e$  is forward edge in  $G_f \Rightarrow$  flow *increases* along  $e$  in  $G$ .
- $e = (u, v)$  is backward edge in  $G_f \Rightarrow$  flow *decreases* along  $(v, u)$  in  $G$ . ▶ Work out example.



(a)



(b)

## Correctness of $\text{augment}(f, P)$

We skipped the proofs in class. Work them out on your own.

- A simple  $s$ - $t$  path in the residual graph is an *augmenting path*.
- Let  $f'$  be the flow returned by  $\text{augment}(f, P)$ .
- Claim:  $f'$  is a flow. Verify capacity and conservation conditions.



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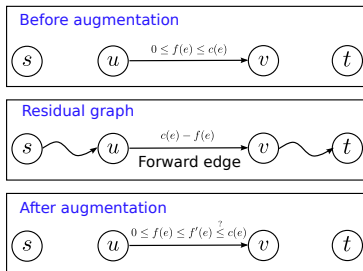
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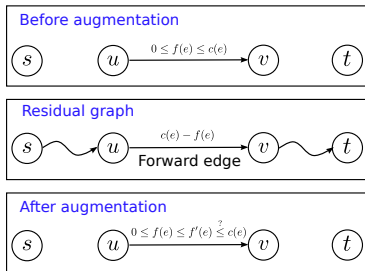
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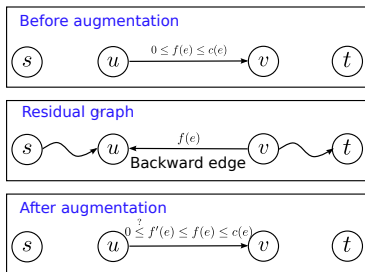
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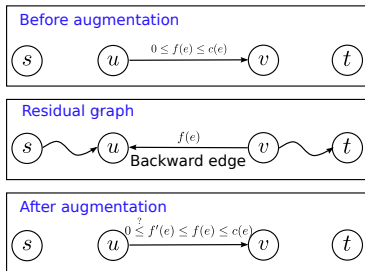
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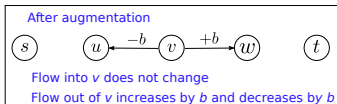
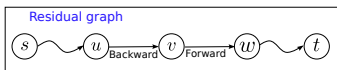
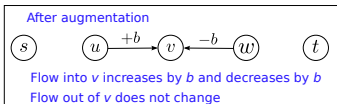
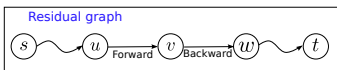
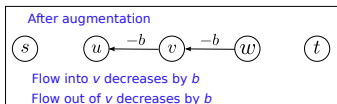
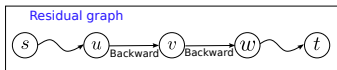
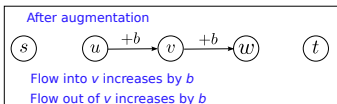
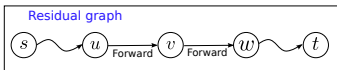
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  - ▶ Conservation condition on internal node  $v \in P$ . Four cases to work out.





# Ford-Fulkerson Algorithm

---

Max-Flow

Initially  $f(e) = 0$  for all  $e$  in  $G$

While there is an  $s$ - $t$  path in the residual graph  $G_f$

    Let  $P$  be a simple  $s$ - $t$  path in  $G_f$

$f' = \text{augment}(f, P)$

    Update  $f$  to be  $f'$

    Update the residual graph  $G_f$  to be  $G_{f'}$

Endwhile

Return  $f$

---

▶ [Work out running example.](#)

# Analysis of the Ford-Fulkerson Algorithm

- Running time
  - ▶ Does the algorithm terminate?
  - ▶ If so, how many loops does the algorithm take?
- Correctness: if the algorithm terminates, why does it output a maximum flow?

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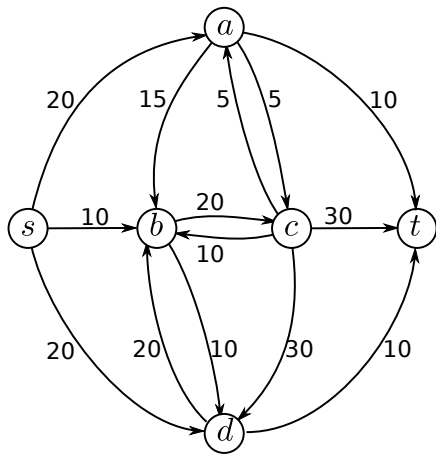
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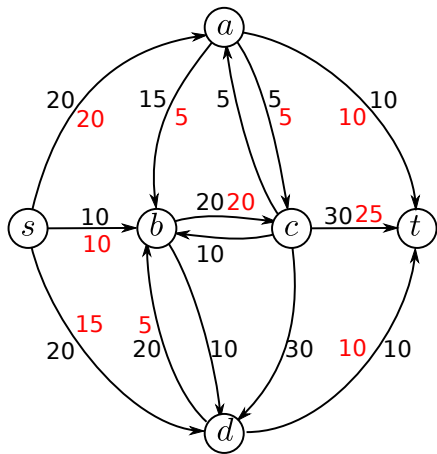
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- Claim: Algorithm runs in  $O(mC)$  time.



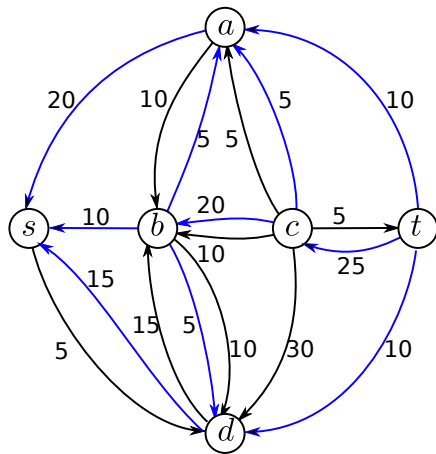
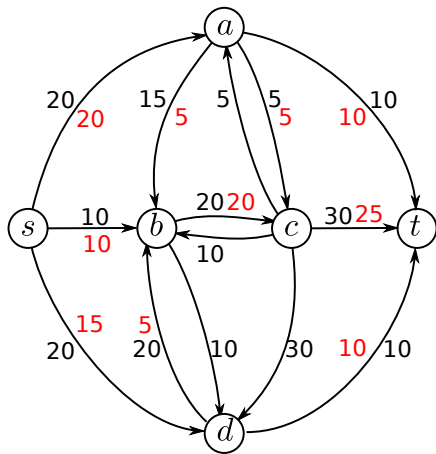
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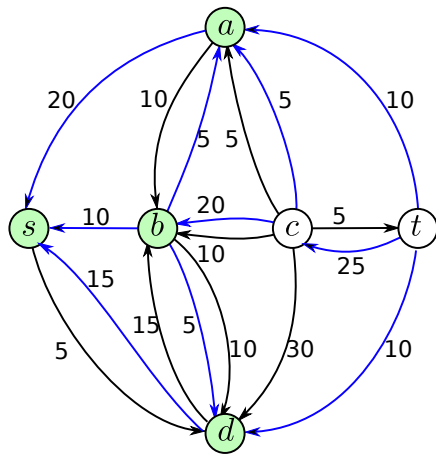
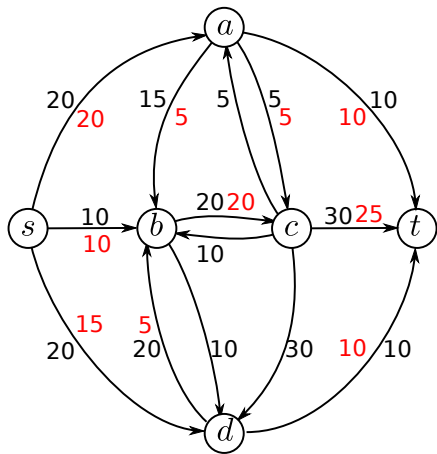


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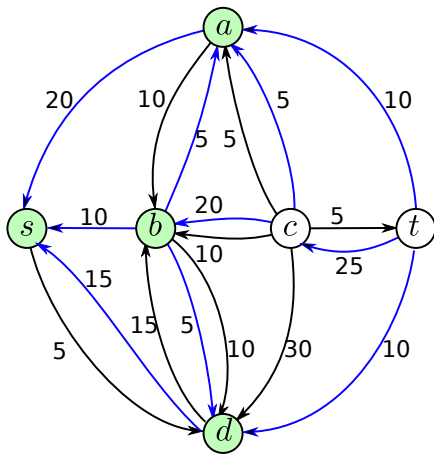
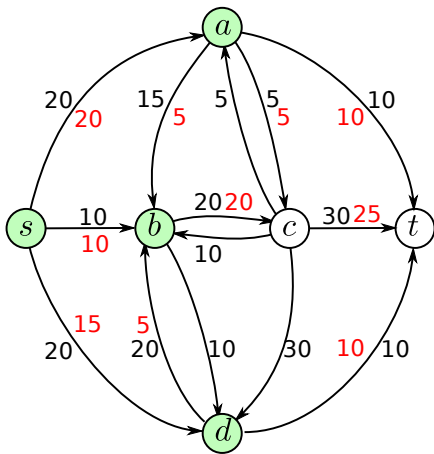


► Poll

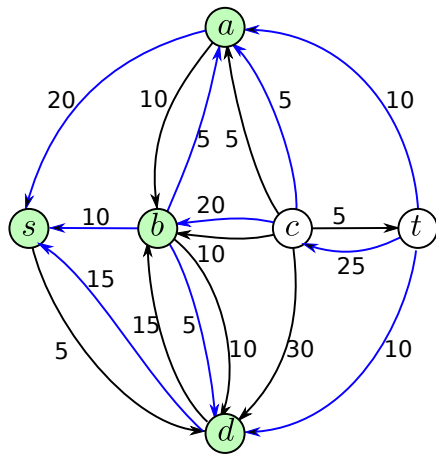
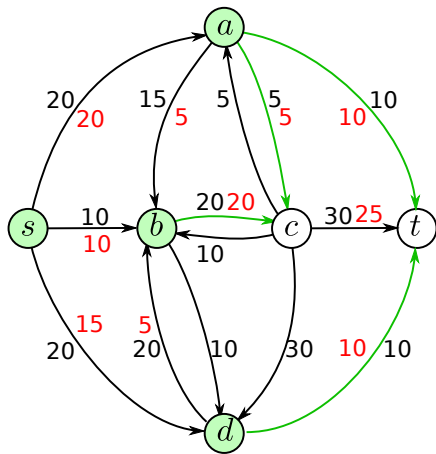
## Example for Ford-Fulkerson Algorithm



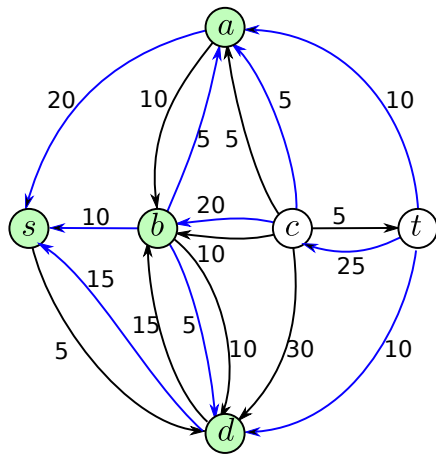
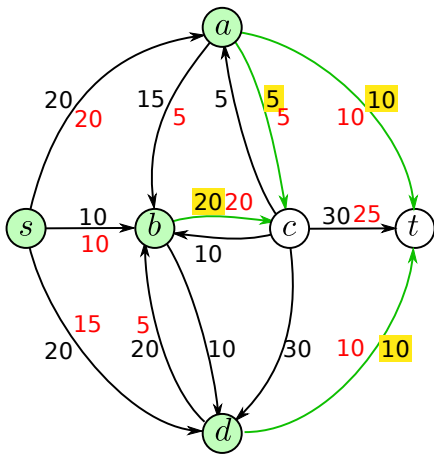
# Example for Ford-Fulkerson Algorithm



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# Example for Ford-Fulkerson Algorithm



# Correctness of the Ford-Fulkerson Algorithm

- How large can the flow be?



# Correctness of the Ford-Fulkerson Algorithm

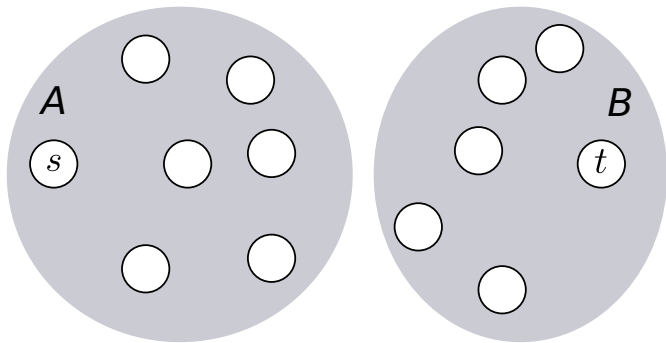
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# Correctness of the Ford-Fulkerson Algorithm

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- Is there a better bound?
- Proof strategy:
  - 1 Define  $s$ - $t$  cut, its capacity, and flow in and out of the cut.
  - 2 For *any*  $s$ - $t$  cut, prove *any* flow  $\leq$  its capacity.
  - 3 Define a specific  $s$ - $t$  cut at the end of the Ford-Fulkerson algorithm.
  - 4 Prove that the flow across this cut *equals* its capacity.

## $s$ - $t$ Cuts and Capacities

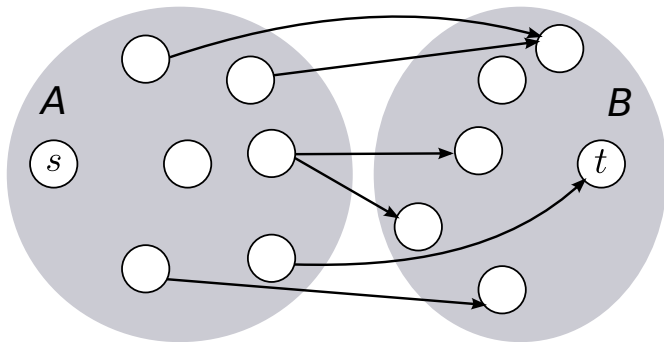
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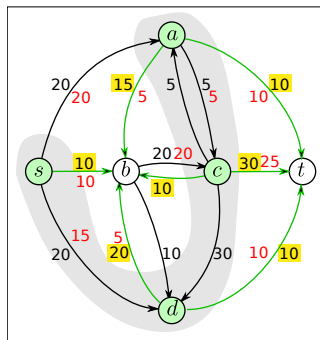
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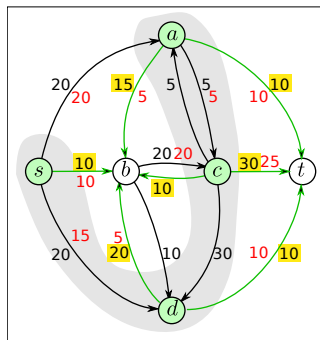


Flow = 45, Capacity of cut =

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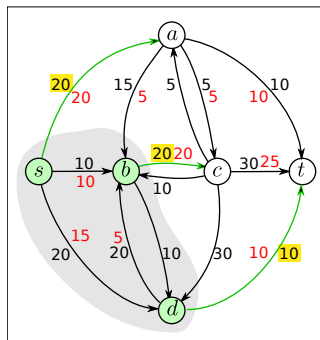


Flow = 45, Capacity of cut = 105

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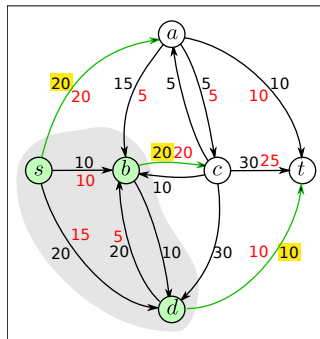


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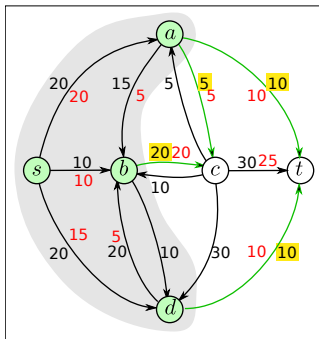
Flow = 45, Capacity of cut = 50



## $s$ - $t$ Cuts and Capacities

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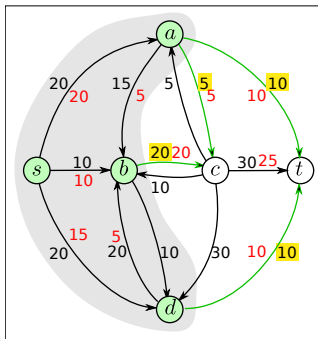


Flow = 45, Capacity of cut =

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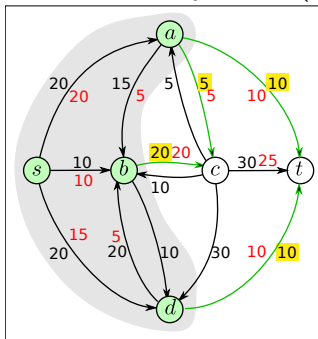
Flow = 45, Capacity of cut = 45

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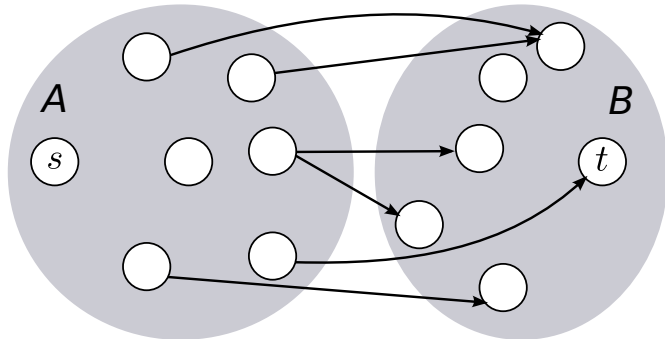
$$c(A, B) = \sum_{e \text{ out of } A} c(e) = \sum_{e=(u,v), u \in A, v \in B} c(e).$$

- Intuition: For every flow  $f$  and for every  $s$ - $t$  cut  $(A, B)$ ,  $\nu(f) \leq c(A, B)$ .



Flow = 45, Capacity of cut = 45

## Some Useful Notation



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

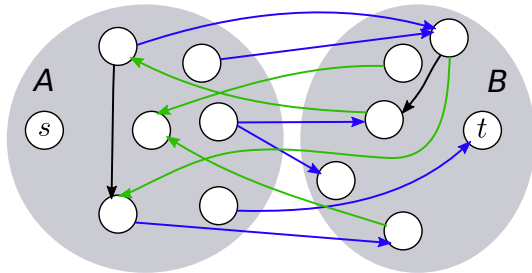
$$f^{\text{in}}(v) = \sum_{e \text{ into } v} f(e)$$

For  $S \subseteq V$ ,

$$f^{\text{out}}(S) = \sum_{e \text{ out of } S} f(e)$$

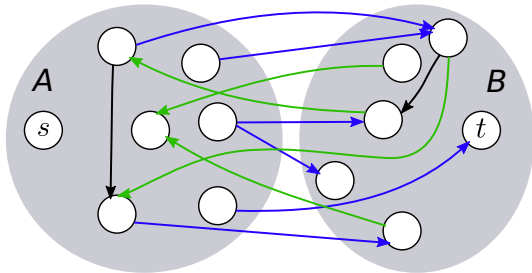
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## Fun Facts about Cuts



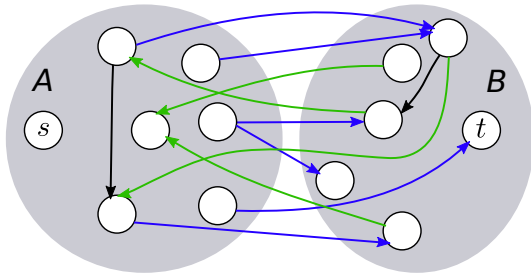
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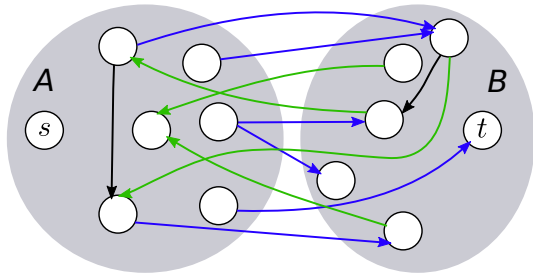
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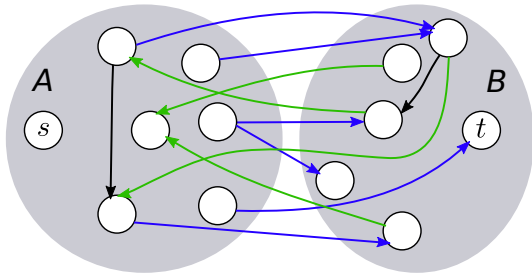
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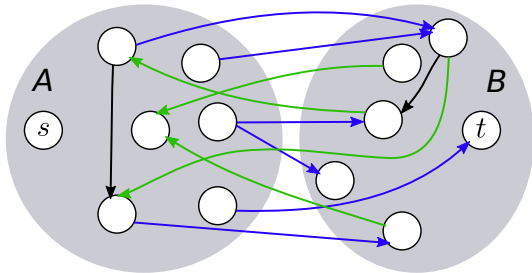


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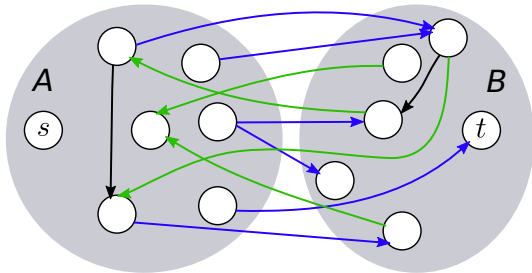
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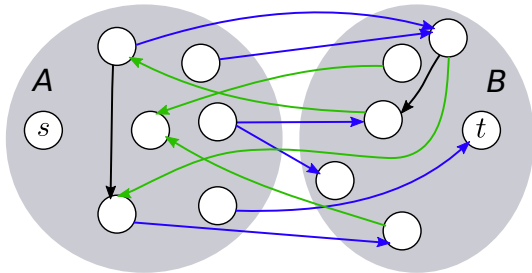
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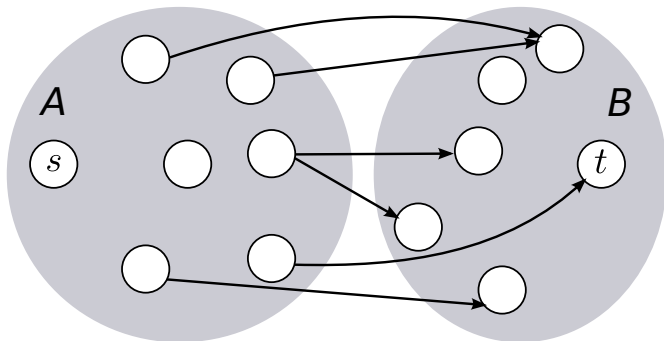
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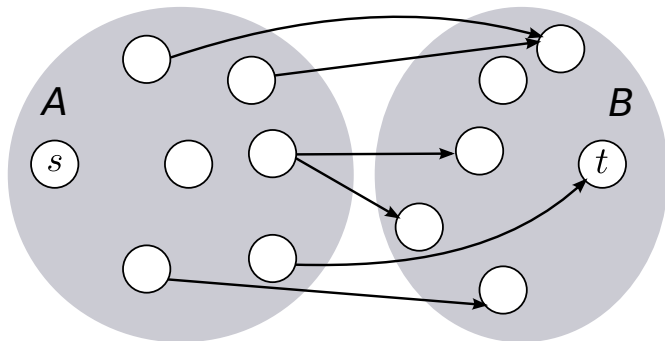
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- Corollary:  $\nu(f) = f^{\text{in}}(B) - f^{\text{out}}(B)$ .

## Important Fact about Cuts



- For any flow  $f$  and any  $s$ - $t$  cut  $(A, B)$ ,  $\nu(f) \leq c(A, B)$ .

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$$\begin{aligned}
 \nu(f) &= f^{\text{out}}(A) - f^{\text{in}}(A) \\
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# Max-Flows and Min-Cuts

- Let  $f$  be any  $s$ - $t$  flow and  $(A, B)$  any  $s$ - $t$  cut. We proved  $\nu(f) \leq c(A, B)$ .

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- Very strong statement: The value of **every** flow is  $\leq$  capacity of **any** cut.
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- Question: Is the reverse true? Is the smallest capacity of a cut at most the maximum flow?
- Answer: Yes, and the Ford-Fulkerson algorithm computes this cut!

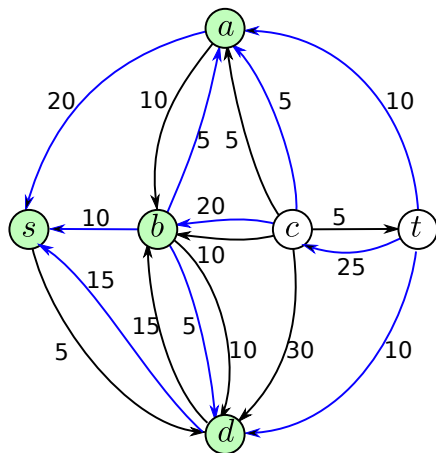
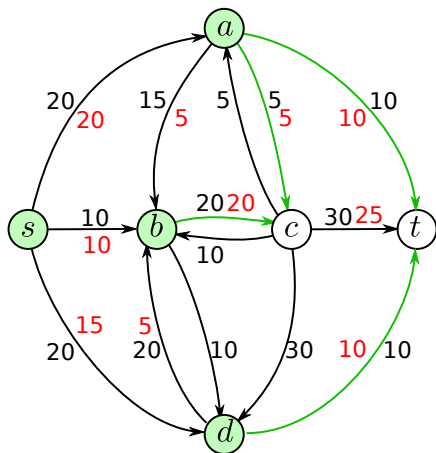
## Flows and Cuts

- Let  $\bar{f}$  denote the flow computed by the Ford-Fulkerson algorithm.
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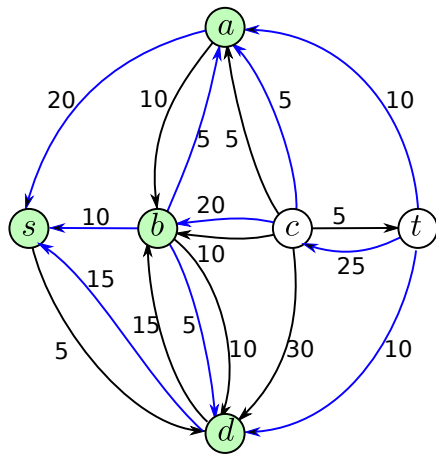
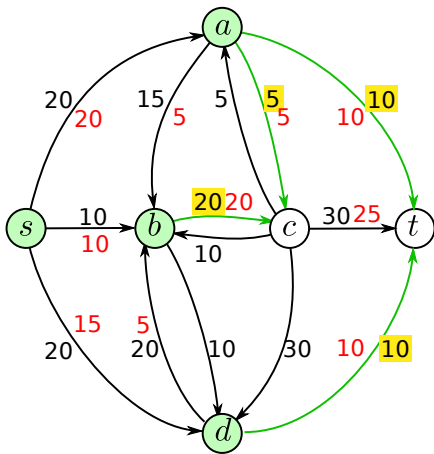
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- Claim: If  $f$  is an  $s-t$  flow such that  $G_f$  has no  $s-t$  path, then there is an  $s-t$  cut  $(A^*, B^*)$  such that  $\nu(f) = c(A^*, B^*)$ .
  - ▶ Claim applies to *any* flow  $f$  such that  $G_f$  has no  $s-t$  path, and not just to the flow  $\bar{f}$  computed by the Ford-Fulkerson algorithm.

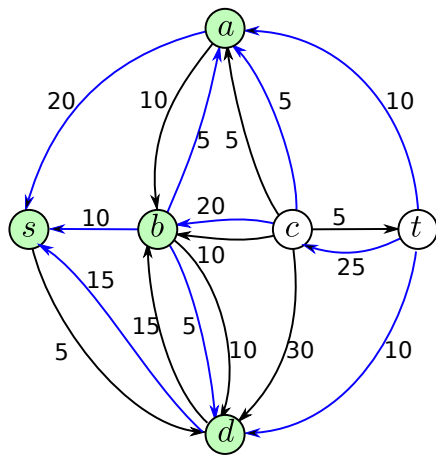
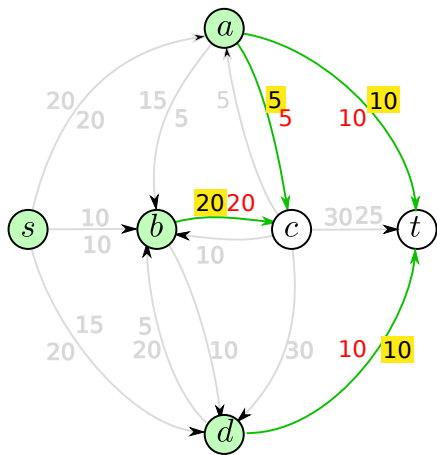
# Termination of Ford-Fulkerson Algorithm



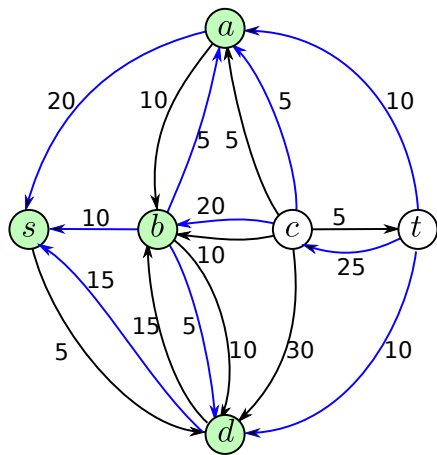
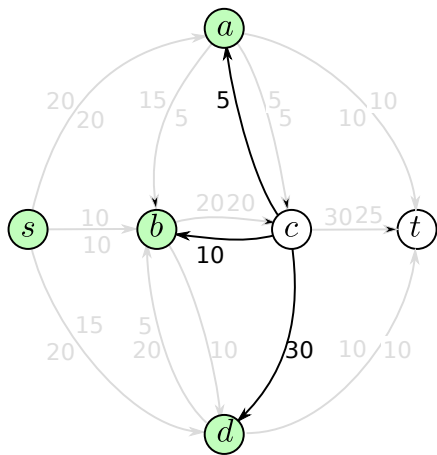
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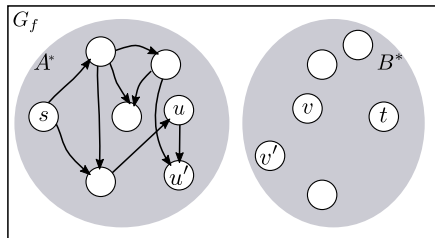
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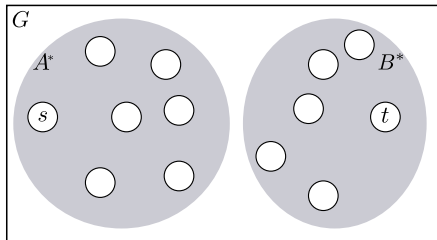
# Proof of Claim Relating Flows to Cuts

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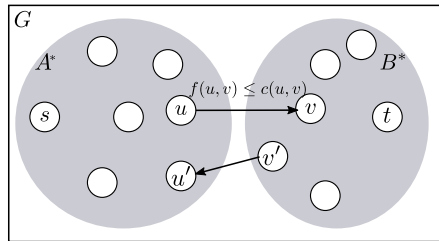
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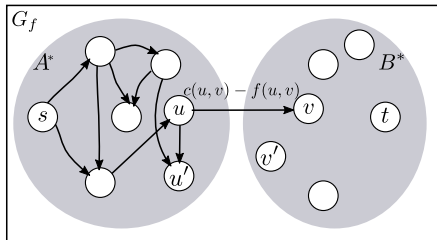
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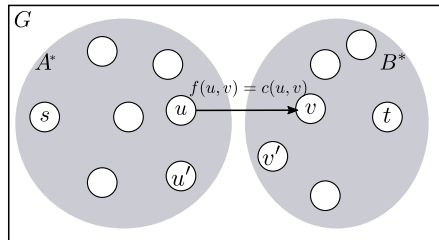
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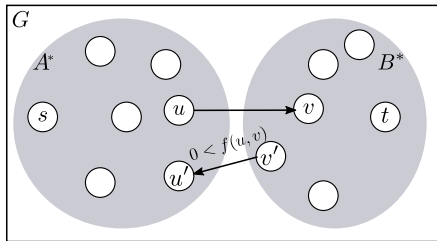
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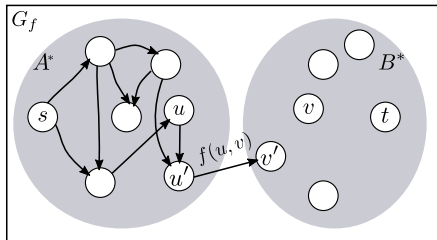
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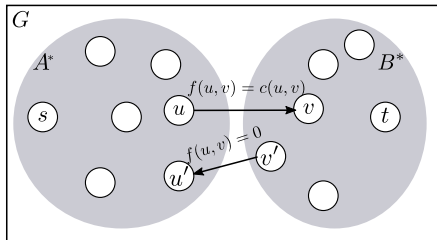
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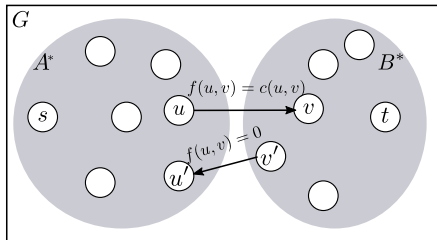
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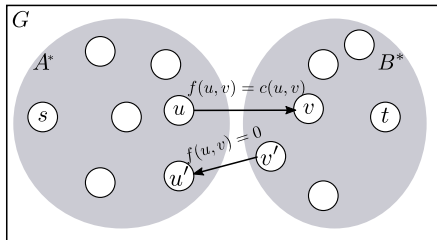
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$$\begin{aligned}
 \nu(f) &= f^{\text{out}}(A^*) - f^{\text{in}}(A^*) \\
 &= \sum_{e \text{ out of } A^*} f(e) - \sum_{e \text{ into } A^*} f(e) \\
 &= \sum_{e \text{ out of } A^*} c(e) - \sum_{e \text{ into } A^*} 0 = c(A^*, B^*).
 \end{aligned}$$

# Max-Flow Min-Cut Theorem

- The flow  $\bar{f}$  computed by the Ford-Fulkerson algorithm is a maximum flow.
- Given a flow of maximum value, we can compute a minimum  $s$ - $t$  cut in  $O(m)$  time.
- In every flow network, there is a flow  $f$  and a cut  $(A, B)$  such that  $\nu(f) = c(A, B)$ .

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# Max-Flow Min-Cut Theorem

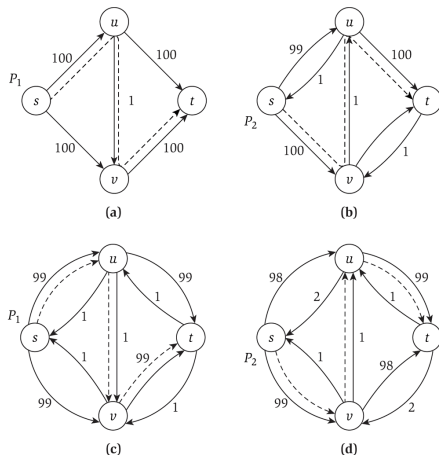
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- In every flow network, there is a flow  $f$  and a cut  $(A, B)$  such that  $\nu(f) = c(A, B)$ .
- **Max-Flow Min-Cut Theorem:** in every flow network, the maximum value of an  $s$ - $t$  flow is equal to the minimum capacity of an  $s$ - $t$  cut.
- Corollary: If all capacities in a flow network are integers, then there is a maximum flow  $f$  where  $f(e)$ , the value of the flow on edge  $e$ , is an integer for every edge  $e$  in  $G$ .

# Real-Valued Capacities

- If capacities are real-valued, Ford-Fulkerson algorithm may not terminate!
- But Max-Flow Min-Cut theorem is still true. Why?

▶ Skip scaling algorithm

# Bad Augmenting Paths



**Figure 7.6** Parts (a) through (d) depict four iterations of the Ford-Fulkerson Algorithm using a bad choice of augmenting paths: The augmentations alternate between the path  $P_1$  through the nodes  $s, u, v, t$  in order and the path  $P_2$  through the nodes  $s, v, u, t$  in order.

# Improving Ford-Fulkerson Algorithm

- Bad case for Ford-Fulkerson algorithm is when the bottleneck edge is the augmenting path has a low capacity.
- Idea: decrease number of iterations by picking  $s$ - $t$  path with bottleneck edge of largest capacity.



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- Modified idea: Maintain a *scaling parameter*  $\Delta$  and choose only augmenting paths with bottleneck capacity at least  $\Delta$ .
- $G_f(\Delta)$ : residual network restricted to edges with residual capacities  $\geq \Delta$ .

# Scaling Max-Flow Algorithm

---

Scaling Max-Flow

Initially  $f(e) = 0$  for all  $e$  in  $G$

Initially set  $\Delta$  to be the largest power of 2 that is no larger than the maximum capacity out of  $s$ :  $\Delta \leq \max_{e \text{ out of } s} c_e$

While  $\Delta \geq 1$

While there is an  $s$ - $t$  path in the graph  $G_f(\Delta)$

Let  $P$  be a simple  $s$ - $t$  path in  $G_f(\Delta)$

$f' = \text{augment}(f, P)$

Update  $f$  to be  $f'$  and update  $G_f(\Delta)$

Endwhile

$\Delta = \Delta/2$

Endwhile

Return  $f$

---

# Correctness of the Scaling Max-Flow Algorithm

- Flow and residual capacities are integer valued throughout.
- When  $\Delta = 1$ ,  $G_f(\Delta)$  and  $G_f$  are identical.
- Therefore, when the scaling algorithm terminates, the flow is a maximum flow.

# Running time of the Scaling Max-Flow Algorithm I

---

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$\Delta$ -scaling phase

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- $\Delta$ -scaling phase: one iteration of the algorithm's outer loop, with  $\Delta$  fixed.
- Claim: the number of  $\Delta$ -scaling phases is at most

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- Claim: During a  $\Delta$ -scaling phase, each iteration increases the flow by  $\geq \Delta$ .

## Value of Flow at the End of a $\Delta$ -Scaling Phase

- Let  $f$  be the flow at the end of a  $\Delta$ -scaling phase and  $\bar{f}$  be the max flow.
- Claim: Then there is an  $s$ - $t$  cut in  $(A, B)$  in  $G$  such that

$$\nu(f) \leq \nu(\bar{f}) \leq c(A, B) \leq \nu(f) + m\Delta$$

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# Running time of the Scaling Max-Flow Algorithm II

---

```

Scaling Max-Flow
Initially  $f(e)=0$  for all  $e$  in  $G$ 
Initially set  $\Delta$  to be the largest power of 2 that is no larger
than the maximum capacity out of  $s$ :  $\Delta \leq \max_{e \text{ out of } s} c_e$ 
While  $\Delta \geq 1$ 
  While there is an  $s$ - $t$  path in the graph  $G_f(\Delta)$ 
    Let  $P$  be a simple  $s$ - $t$  path in  $G_f(\Delta)$ 
     $f' = \text{augment}(f, P)$ 
    Update  $f$  to be  $f'$  and update  $G_f(\Delta)$ 
  Endwhile
   $\Delta = \Delta/2$ 
Endwhile
Return  $f$ 
  
```

---

 $\Delta$ -scaling phase $\leq 2m$  iterations

- Claim: the number of augmentations in a  $\Delta$ -scaling phase is  $\leq 2m$ .
  - ▶ Base case: In the first  $\Delta$ -scaling phase, each edge incident on  $s$  can be used in at most one augmenting path.
  - ▶ Induction: At the end of the some  $\Delta$ -scaling phase, let value of  $\Delta$  be  $\Gamma$  and let  $f'$  be the flow:  $\nu(f') \geq \nu(\bar{f}) - m\Gamma$ .

# Running time of the Scaling Max-Flow Algorithm II

---

```

Scaling Max-Flow
Initially  $f(e)=0$  for all  $e$  in  $G$ 
Initially set  $\Delta$  to be the largest power of 2 that is no larger
than the maximum capacity out of  $s$ :  $\Delta \leq \max_{e \text{ out of } s} c_e$ 
While  $\Delta \geq 1$ 
  While there is an  $s$ - $t$  path in the graph  $G_f(\Delta)$ 
    Let  $P$  be a simple  $s$ - $t$  path in  $G_f(\Delta)$ 
     $f' = \text{augment}(f, P)$ 
    Update  $f$  to be  $f'$  and update  $G_f(\Delta)$ 
  Endwhile
   $\Delta = \Delta/2$ 
Endwhile
Return  $f$ 

```

---

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- Claim: the number of augmentations in a  $\Delta$ -scaling phase is  $\leq 2m$ .
  - ▶ Base case: In the first  $\Delta$ -scaling phase, each edge incident on  $s$  can be used in at most one augmenting path.
  - ▶ Induction: At the end of the some  $\Delta$ -scaling phase, let value of  $\Delta$  be  $\Gamma$  and let  $f'$  be the flow:  $\nu(f') \geq \nu(\bar{f}) - m\Gamma$ .
  - ▶ In the next  $\Delta$ -scaling phase, the value of  $\Delta$  is  $\Gamma/2$ . Let  $f$  be the flow at the end of this phase.
  - ▶ Since each iteration increases the flow by  $\geq \Gamma/2$ , if the current  $\Delta$ -scaling phase continues for more than  $2m$  iterations, then  $\nu(f) \geq \nu(f') + 2m\Gamma/2 \geq \nu(\bar{f})$ .
- Claim: the running time of the scaling max-flow algorithm is  $O(m^2 \log C)$ .

## Other Maximum Flow Algorithms

- Running time of the Ford-Fulkerson algorithm is  $O(mC)$ , which is *pseudo-polynomial*: polynomial in the magnitudes of the numbers in the input.
- Scaling algorithm runs in time polynomial in the size of the input (the graph and the number of bits needed to represent the capacities).

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- Edmonds-Karp, Dinitz: choose augmenting path to be the shortest path in  $G_f$  (use breadth-first search). Algorithm runs in  $O(mn)$  iterations.
- Improved algorithms take time  $O(mn \log n)$ ,  $O(n^3)$ , etc.
- Chapter 7.4: Preflow-push max-flow algorithm that is not based on augmenting paths. Runs in  $O(n^2m)$  or  $O(n^3)$  time.