CSE 421
Introduction to Algorithms

Lecture 17: Polynomial-Time MaxFlow/MinCut Algorithms

Announcements

Midterm next **Wednesday, November 8, 6:00 – 7:30 pm in this room**

- See post on Important Midterm Information

- Links to sample midterm, practice problems, and reference sheet posted yesterday

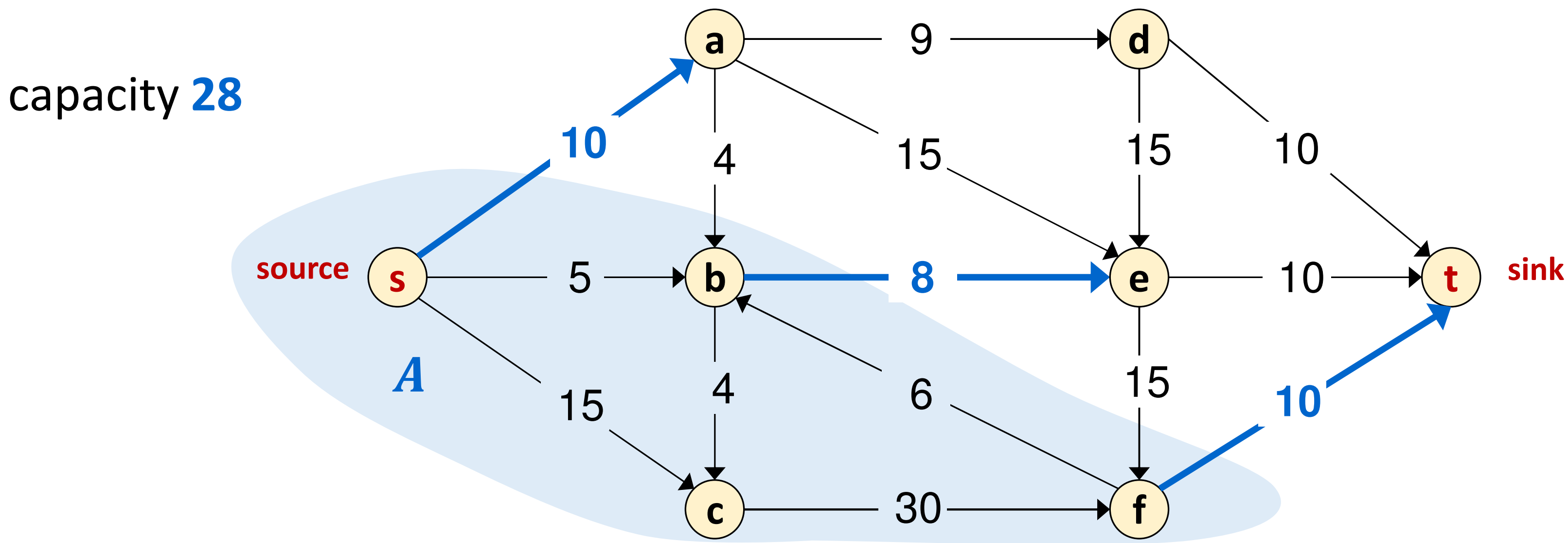
- Zoom review session for Q&A on Tuesday Nov 7 at 4:30 pm.

Minimum Cut Problem

Minimum s-t cut problem:

Given: a flow network

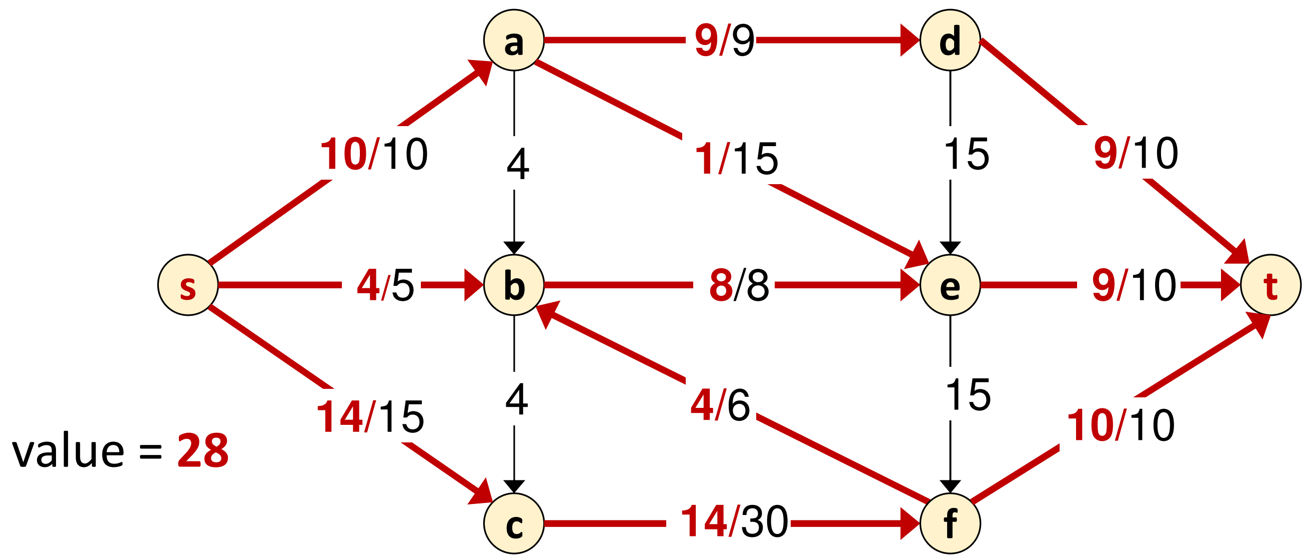
Find: an s-t cut (A, B) of minimum capacity $c(A,B) = \sum_{e \text{ out of } A} c(e)$



Maximum Flow Problem

Given: a flow network

Find: an s-t flow of maximum value



Ford-Fulkerson Augmenting Path Algorithm

```
Ford-Fulkerson(G, s, t, c) {
   foreach e ∈ E  f(e) ← 0
   Gf ← residual graph

   while (Gf has an s-t path P) {
      f ← Augment(f, c, P)
      update Gf
   }
   return f
}
```

```
Augment(f, c, P) {
   b ← bottleneck(P)
   foreach e ∈ P {
      if  (e ∈ E) f(e) ← f(e) + b
      else        f(eR)← f(eR) - b
   }
   return f
}
```

MaxFlow/MinCut & Ford-Fulkerson Algorithm

Augmenting Path Theorem: Flow $\boldsymbol{f}$ is a max flow $\Leftrightarrow$ there are no augmenting paths wrt $\boldsymbol{f}$

Max-Flow Min-Cut Theorem: The value of the max flow equals the value of the min cut.
[Elias-Feinstein-Shannon 1956, Ford-Fulkerson 1956] **"MaxFlow = MinCut"**

Flow Integrality Theorem: If all capacities are integers then there is a maximum flow with all-integer flow values.

Ford-Fulkerson Algorithm: $O(\boldsymbol{m})$ per iteration. With integer capacities each at most $\boldsymbol{C}$ need at most **MaxFlow** $< \boldsymbol{nC}$ iterations for a total of $O(\boldsymbol{mnC})$ time.

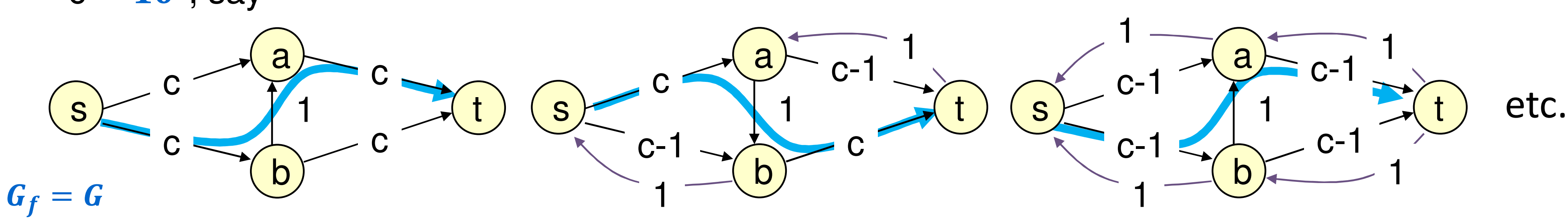
Ford-Fulkerson Efficiency

Worst case runtime $O(mnC)$ with integer capacities $\leq C$.

- $O(m)$ time per iteration.
- At most nC iterations.
- This is “pseudo-polynomial” running time.

- May take exponential time, even with integer capacities:

c $= 10^9$, say



Choosing Good Augmenting Paths

Polynomial-Time Variants of Ford-Fulkerson

Use care when selecting augmenting paths.

- Some choices lead to exponential algorithms.
- Clever choices lead to polynomial algorithms.
- If capacities are irrational, algorithm not guaranteed to terminate!

Goal: Choose augmenting paths so that:

- Can find augmenting paths efficiently.
- Few iterations.

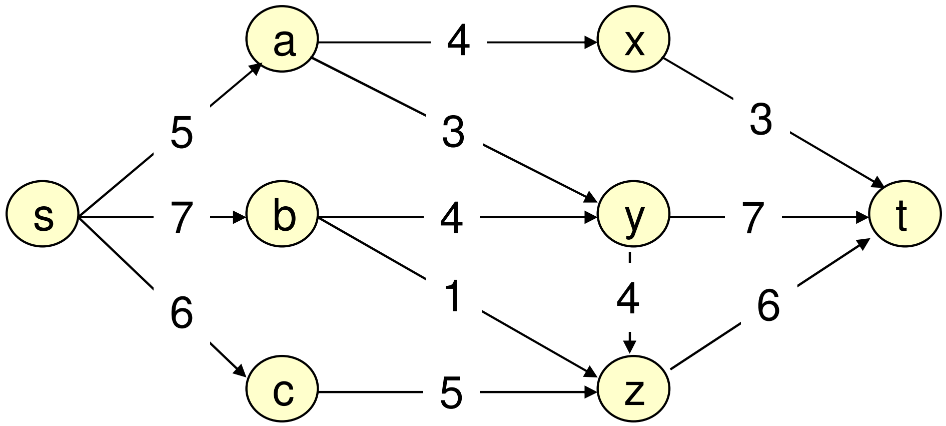
- Choose augmenting paths with: [Edmonds-Karp 1972, Dinitz 1970]
  - Max bottleneck capacity.
  - Sufficiently large bottleneck capacity.
  - Fewest number of edges.

Polynomial-Time MaxFlow: Capacity Scaling

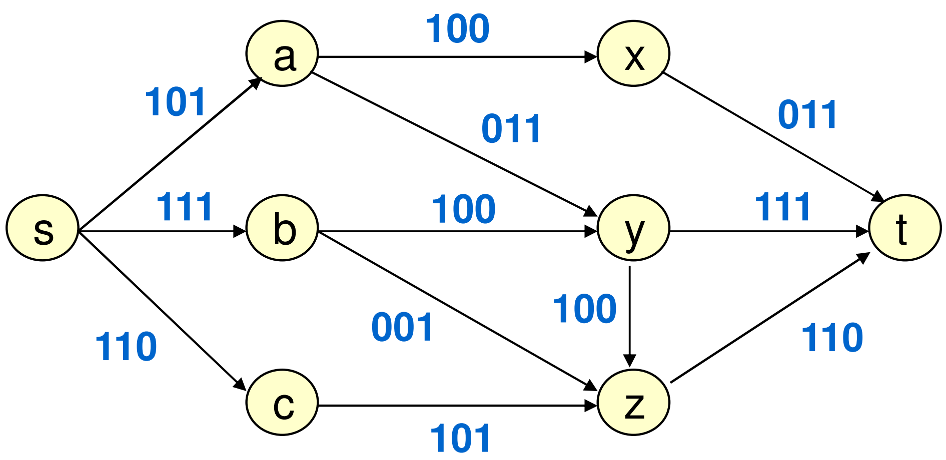
General idea:

- Choose augmenting paths **P** with ‘large’ capacity.
- Can augment flows along a path **P** by any amount $\leq$ **bottleneck**$(\boldsymbol{P})$
  - Ford-Fulkerson still works
- Choose that amount to be “nice round number” (i.e. a big power of 2.)
- Get a flow that is maximum for the high-order bits first and then add more bits later

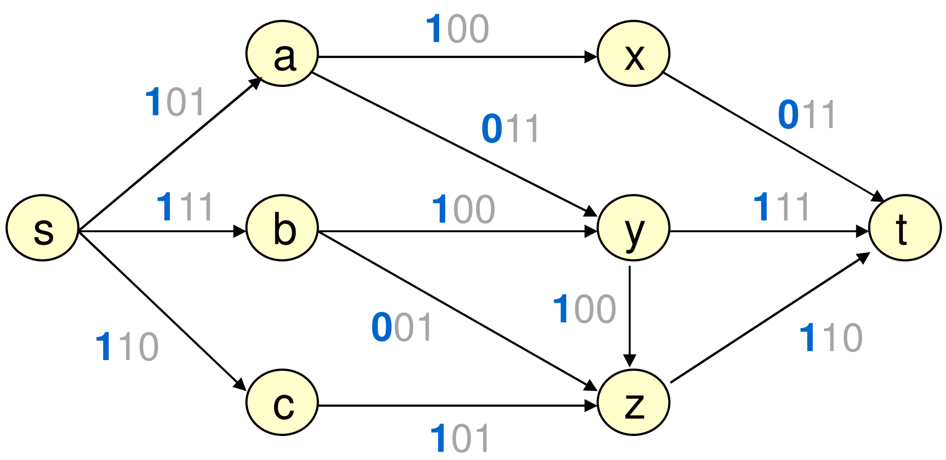
Capacity Scaling



Write Capacities in Binary

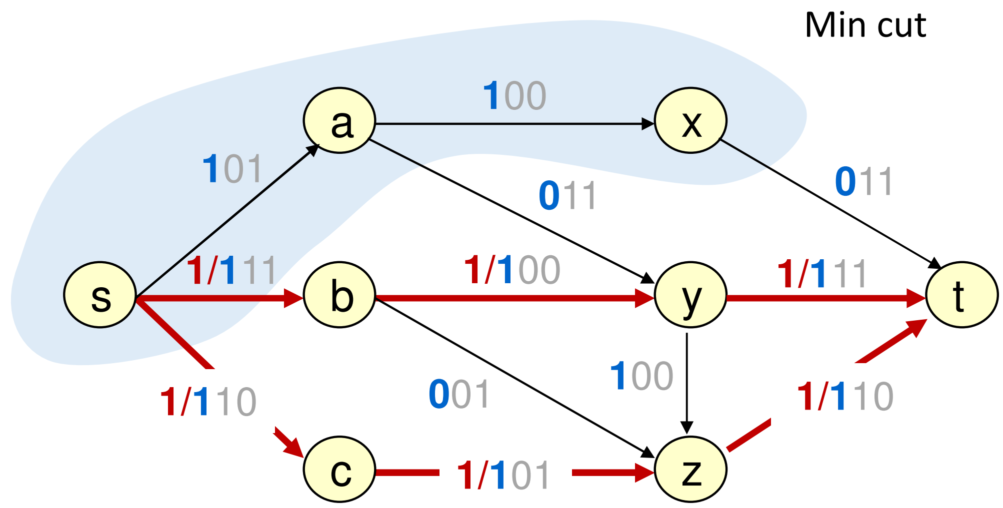


Capacity Scaling Bit 1



Solve flow problem with capacities with just the high-order bit:

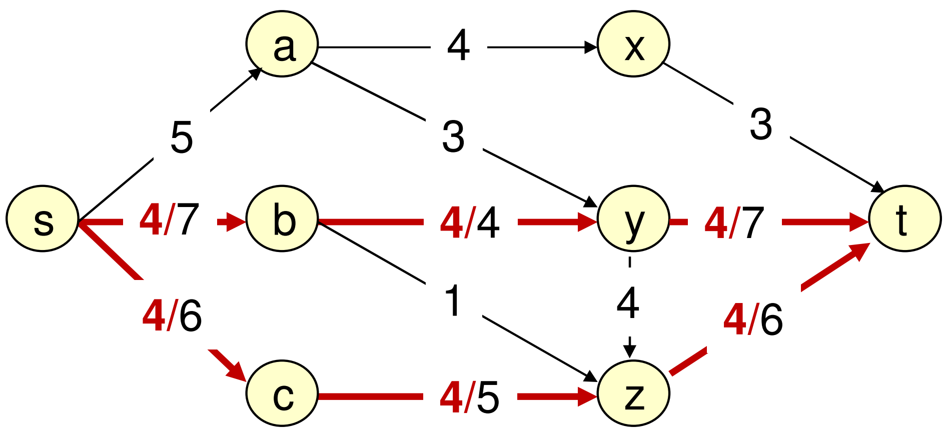
Capacity Scaling Bit 1



Solve flow problem with capacities with just the high-order bit:

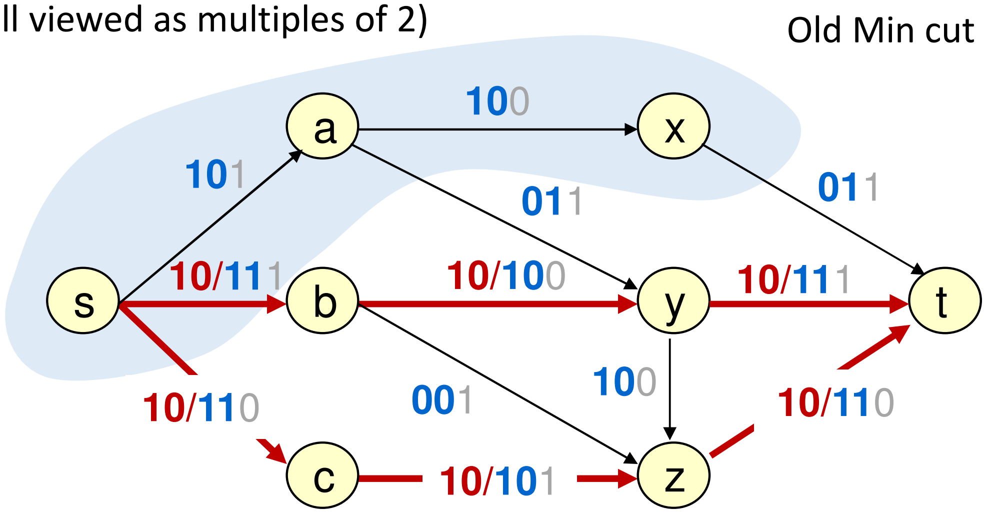
- Each edge has "capacity" ≤ 1 (equivalent to 4 here)
- Time $O(mn)$

Capacity Scaling Bit 1



Capacity Scaling Bit 2

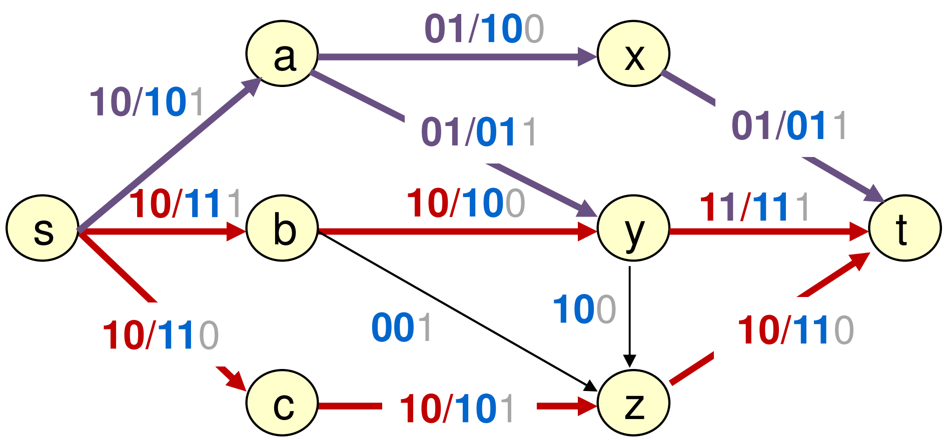
Add 0 bit to the end of the flows
Add bit 2 to capacities (all viewed as multiples of 2)



Solve flow problem with capacities with the **2** high-order bits:

- Capacity of old min cut goes up by ≤ 1 per edge (equivalent to 2 here) for a total residual capacity $\leq m$.

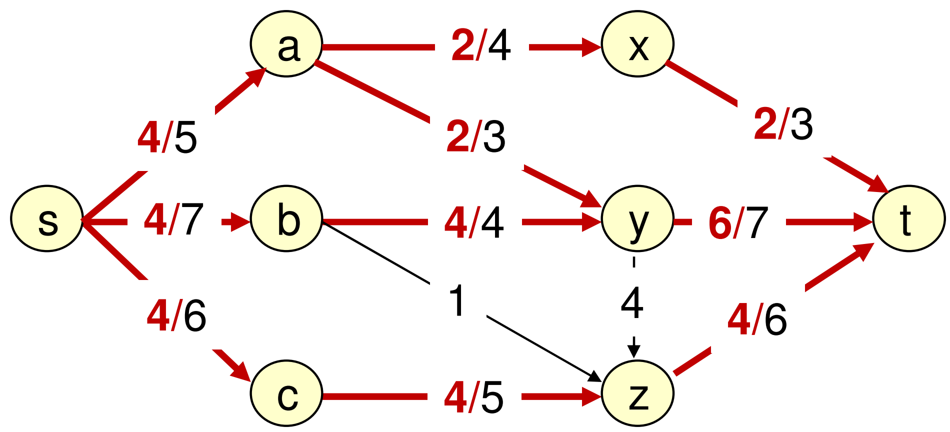
Capacity Scaling Bit 2



Solve flow problem with capacities with the **2** high-order bits:

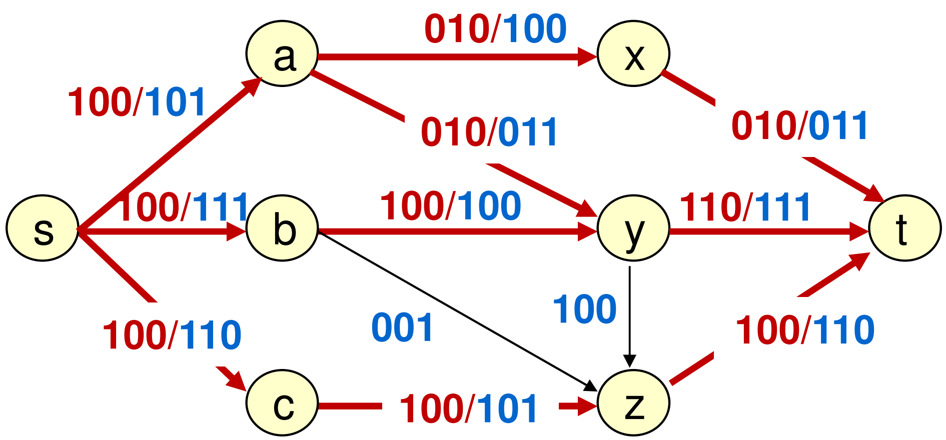
- Capacity of old min cut goes up by ≤ 1 per edge (equivalent to 2 here) for a total residual capacity $\leq m$.
- Time $O(m^2)$ for $\leq m$ iterations.

Capacity Scaling Bits 1 and 2



Capacity Scaling Bit 3

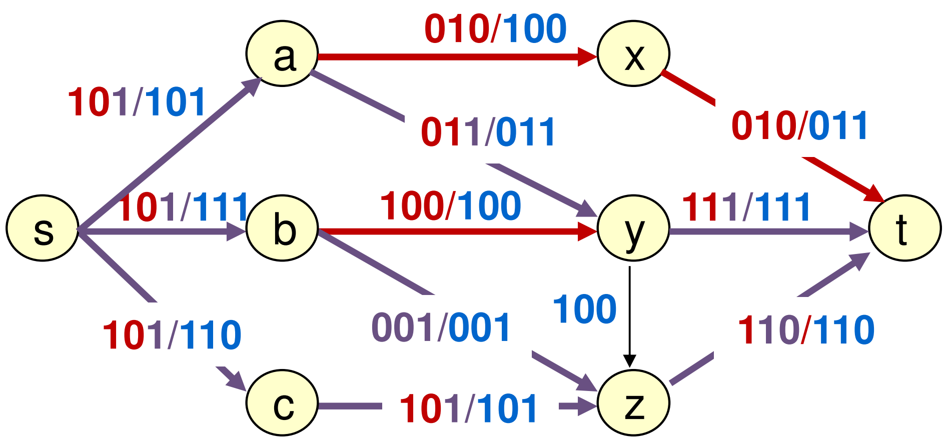
Add 0 bit to the end of the flows
Add bit 3 to capacities (all now multiples of 1)



Solve flow problem with capacities with all 3 bits:

- Capacity of old min cut goes up by ≤ 1 per edge for a total residual capacity $\leq m$.

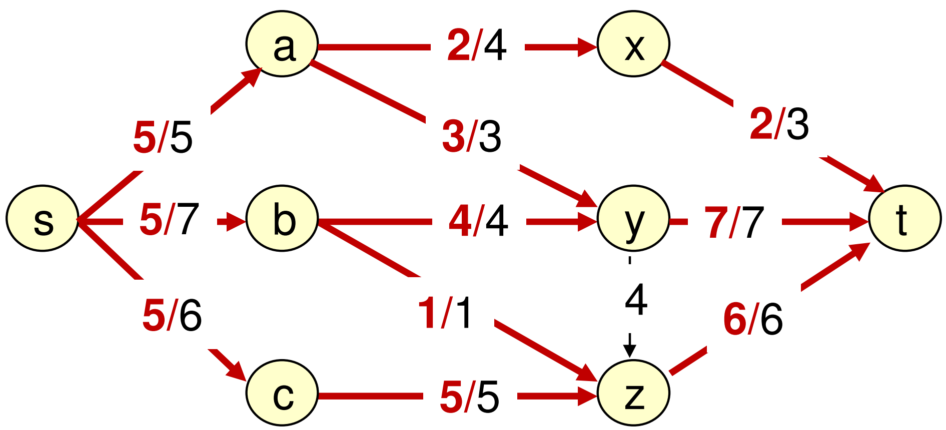
Capacity Scaling Bit 3



Solve flow problem with capacities with all 3 bits:

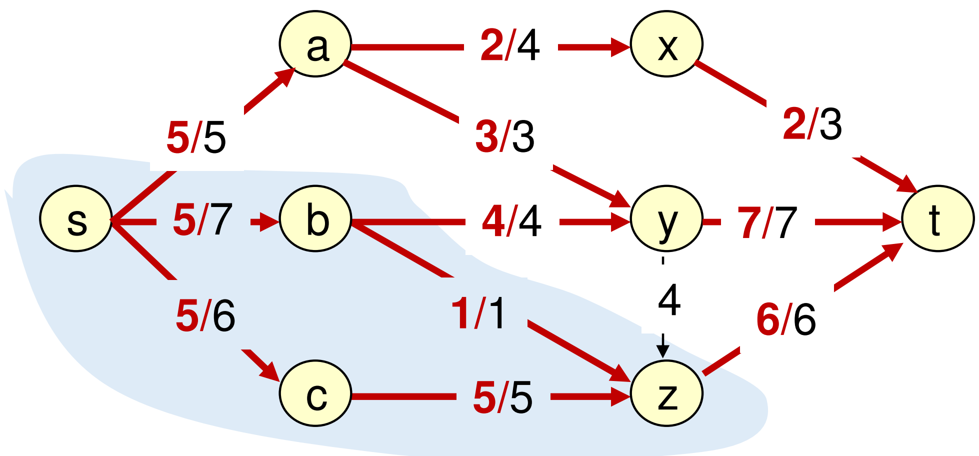
- Capacity of old min cut goes up by $\leq \mathbf{1}$ per edge for a total residual capacity $\leq \boldsymbol{m}$.
- Time $O(\boldsymbol{m}^2)$ for $\leq \boldsymbol{m}$ iterations.

Capacity Scaling All Bits



Flow = **15**

Capacity Scaling All Bits



Flow = **15**

Cut Value = **15**

Flow is a MaxFlow

Total time for capacity scaling

- Number of rounds = $\lceil \log_2 \boldsymbol{C} \rceil$ where $\boldsymbol{C}$ is the largest capacity
- Time per round $O(\boldsymbol{m}^2)$
  - At most $\boldsymbol{m}$ augmentations per round
  - $O(\boldsymbol{m})$ time per augmentation

Total time $O(\boldsymbol{m}^2 \log \boldsymbol{C})$

Great!   This is now polynomial time in the input size.

Can we get more?

- What about an algorithm with a number of arithmetic operations that doesn’t depend on the size of the numbers?

Polynomial-Time Variants of Ford-Fulkerson

Use care when selecting augmenting paths.

- Some choices lead to exponential algorithms.
- Clever choices lead to polynomial algorithms.
- If capacities are irrational, algorithm not guaranteed to terminate!

Goal: Choose augmenting paths so that:

- Can find augmenting paths efficiently.
- Few iterations.

- Choose augmenting paths with: [Edmonds-Karp 1972, Dinitz 1970]
  - Max bottleneck capacity.
  - Sufficiently large bottleneck capacity.
  - Fewest number of edges. (i.e. just run BFS to find an augmenting path.)

Edmonds-Karp Algorithm (Ford-Fulkerson with BFS)

Use Breadth First Search as the search algorithm to find an s-t path in G_f.

- Using any shortest augmenting path

Theorem: Ford-Fulkerson using BFS terminates in $O(m^2 n)$ time. [Edmonds-Karp, Dinitz]

"One of the most obvious ways to implement Ford-Fulkerson is always polynomial time"

Why might this be good intuitively?

- Longer augmenting paths involve more edges so may be more likely to hit a low residual capacity one which would limit the amount of flow improvement.

The proof uses a completely different idea…

Edmonds-Karp Algorithm (Ford-Fulkerson with BFS)

Analysis Focus:

For any edge e that could be in the residual graph G_f, (either an edge in G or its reverse)

count # of iterations that e is the first bottleneck edge on the augmenting path chosen by the algorithm.

Claim: This can't happen in more than $n/2$ iterations.

Proof: Write $e = (u, v)$.

Show that each time it happens, the distance from s to u in the residual graph G_f is at least 2 more than it was the last time.

This would be enough since the distance is either $< n$ (or infinite and hence u isn't reachable) so this can happen at most $n/2$ times.

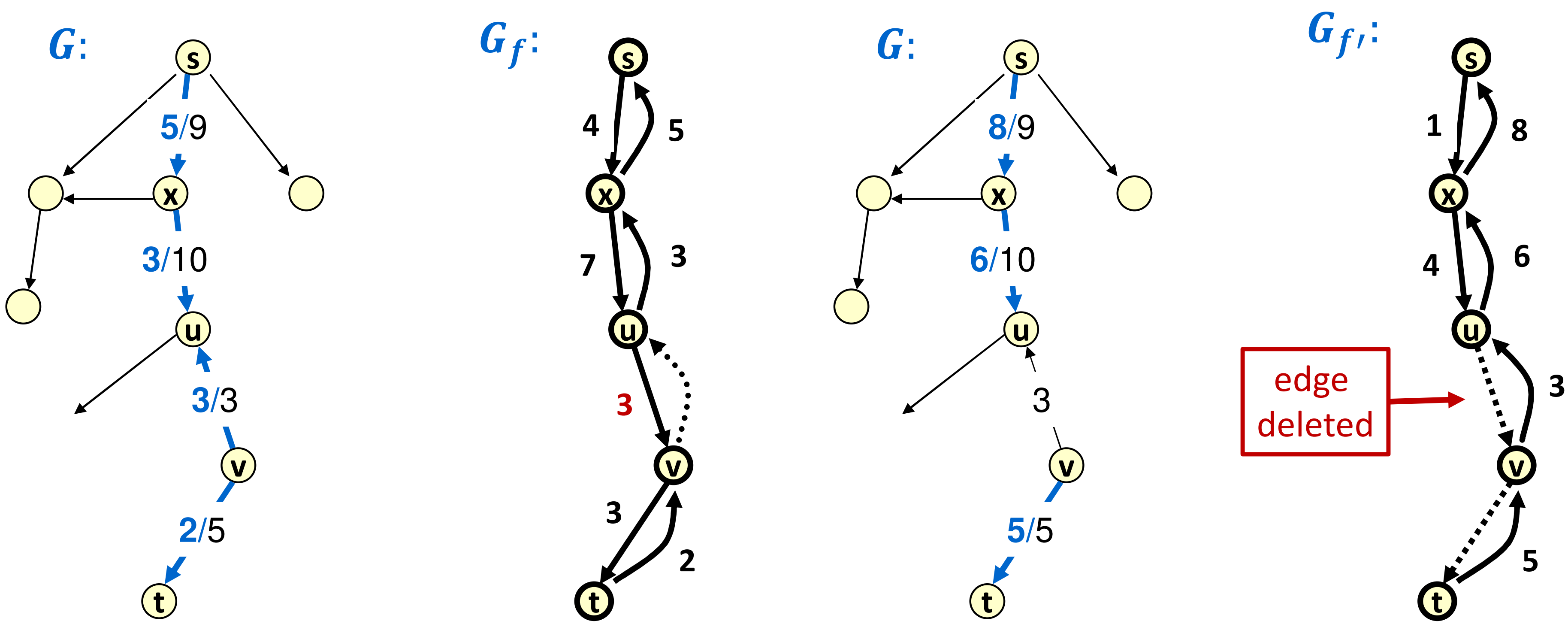
Distances in the Residual Graph

Key Lemma: Let f be a flow, G_f the residual graph, and P be a shortest augmenting path. No vertex is closer to s in the residual graph after augmenting along P.

Proof: Augmenting along P can only change the edges in G_f by either:

1. Deleting a forward edge
   - Deleting any edge can never reduce distances
2. Add a backward edge (v, u) that is the reverse of an edge (u, v) of P
   - Since P was a shortest path in G_f, the distance from s to v in G_f is already more than the distance from s to u. Using the new backward edge (v, u) to get to u would be an even longer path to u so it is never on a shortest path to any node in the new residual graph. ■

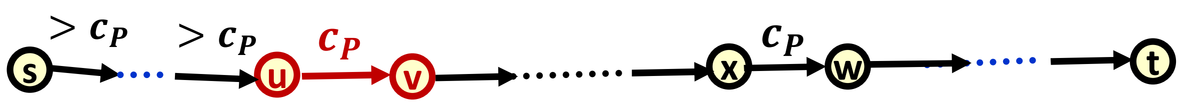
Augmentation vs BFS



First Bottleneck Edges in G_f

Shortest s-t path P in G_f

Write $c_P = \textbf{bottleneck}(P)$



$d_f(s,v) = d_f(s,u) + 1$ since P is a shortest path.

After augmenting along P, edge (u,v) disappears; but will have edge (v,u)

distance is ≥ 2 larger than before

For (u,v) to be a first bottleneck edge later, it must get added back to the residual graph by augmenting along a shortest path P' containing (v,u) in $G_{f'}$ for some flow f'

Since P' is shortest $d_{f'}(s,u) = d_{f'}(s,v) + 1 \geq d_f(s,v) + 1 = d_f(s,u) + 2$

The next time that (u,v) is first bottleneck edge is even later so distance is at least as large! ■

Edmonds-Karp Algorithm (Ford-Fulkerson with BFS)

Analysis Focus:

For any edge e that could be in the residual graph G_f, (either an edge in G or its reverse)

count # of iterations that e is the first bottleneck edge on the augmenting path chosen by the algorithm.

Claim: This can't happen in more than $n/2$ iterations

Claim ⇒ Theorem:

Only $2m$ edges and $O(m)$ time per iteration so $O(m^2 n)$ time overall. ■

Which is better in practice $O(m^2 n)$ vs. $O(m^2 \log C)$?

History & State of the Art for MaxFlow Algorithms

#	year	discoverer(s)	bound
1	1951	Dantzig	$O(n^2mU)$
2	1955	Ford & Fulkerson	$O(nmU)$
3	1970	Dinitz Edmonds & Karp	$O(nm^2)$
4	1970	Dinitz	$O(n^2m)$
5	1972	Edmonds & Karp Dinitz	$O(m^2 \log U)$
6	1973	Dinitz Gabow	$O(nm \log U)$
7	1974	Karzanov	$O(n^3)$
8	1977	Cherkassky	$O(n^2\sqrt{m})$
9	1980	Galil & Naamad	$O(nm \log^2 n)$
10	1983	Sleator & Tarjan	$O(nm \log n)$
11	1986	Goldberg & Tarjan	$O(nm \log(n^2/m))$
12	1987	Ahuja & Orlin	$O(nm + n^2 \log U)$
13	1987	Ahuja et al.	$O(nm \log(n\sqrt{\log U}/(m+2)))$
14	1989	Cheriyan & Hagerup	$E(nm + n^2 \log^2 n)$
15	1990	Cheriyan et al.	$O(n^3/\log n)$
16	1990	Alon	$O(nm + n^{8/3} \log n)$
17	1992	King et al.	$O(nm + n^{2+\epsilon})$
18	1993	Phillips & Westbrook	$O(nm(\log_{m/n} n + \log^{2+\epsilon} n))$
19	1994	King et al.	$O(nm \log_{m/(n \log n)} n)$
20	1997	Goldberg & Rao	$O(m^{3/2} \log(n^2/m) \log U)$ $O(n^{2/3} m \log(n^2/m) \log U)$

Source: Goldberg & Rao, FOCS '97

21	**2013**	**Orlin**	$O(\boldsymbol{mn})$
22	**2014**	**Lee & Sidford**	$\boldsymbol{m\sqrt{n}} \log^{O(1)} \boldsymbol{n} \log \boldsymbol{U}$
23	**2016**	**Madry**	$\boldsymbol{m^{10/7} U^{1/7}} \log^{O(1)} \boldsymbol{n}$
24	**2021**	**Gao, Liu, & Peng**	$\boldsymbol{m^{3/2-1/328}} \log^{O(1)} \boldsymbol{n} \log \boldsymbol{U}$
25	**2022**	**van den Brand et al.**	$\boldsymbol{m^{3/2-1/58}} \log^{O(1)} \boldsymbol{n} \log \boldsymbol{U}$
26	**2022**	**Chen et al.**	$\boldsymbol{m^{1+o(1)}} \log \boldsymbol{U}$

Tables use ***U*** instead of ***C*** for the upper bound on capacities

Methods: Augmenting Paths – increase flow to capacity
Preflow-Push – decrease flow to get flow conservation
Linear Programming – randomized high probability