EECS 336: Introduction to Algorithms	**Lecture 8**
Network Flow	Ford-fulkerson, duality, minimum cut

Reading: 7.0-7.5

Announcements: midterm tuesday

- closed book, closed notes.
- one handwritten cheat sheet.
- dynamic programming.
- focus:
  - writing Parts I-II.
  - writing Parts III-IV
    (given Parts I-II).

Last time:

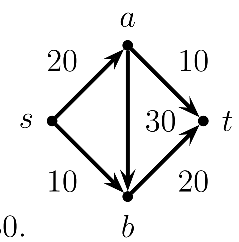
- reductions
- Network flow defn
- Bipartite matching
- reduction: matching $\Rightarrow$ flow.

Today:

- Network flow
- duality: max flow = min cut

Network Flow

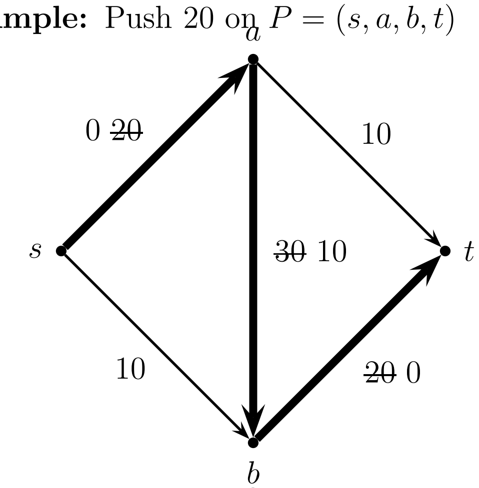
Example:



Max flow = 30.

Idea: repeatedly pus flow on s-t paths until can't push anymore.

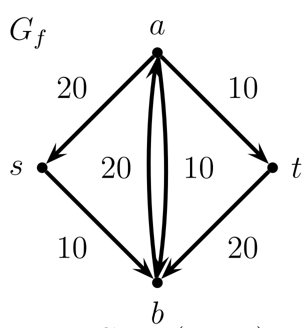
Example: Push 20 on $P = (s, a, b, t)$



Note: when pushing flow, we can undo flow already pushed.

Def: the <u>residual graph</u> G_f for flow f on G is the graph that represents capacity constraints for flows after pushing f

Example: G_f



Construction: $G_f = (V, E_f), c_f(\cdot)$:
For each $e = (u, v) \in E$,

(if $f(e) = c(e)$ discard e)

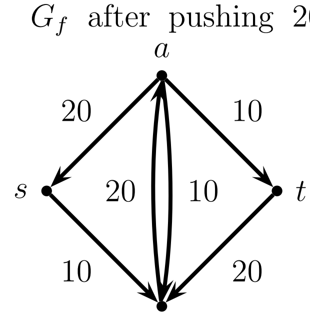
- if $f(e) < c(e)$,
  - add e to E_f
  - $c_f(e) = c(e) - f(e)$
- if $f(e) > 0$
  - let $e' = (v, u)$
  - add e' to E_f
  - $c_f(e') = c(e') + f(e)$

Def: the <u>residual capacity</u> of e in E_f is $c_f(e)$.

Def: the <u>bottleneck</u> capacity of s-t path P in G_f is minimm residual capacity of any edge in P.

Def: an <u>augmenting path</u> P in a residual graph G_f is a path with positive bottleneck capacity.

Example: G_f after pushing 20 on $P = (s, a, b, t)$



Augmenting path $P = (s, b, a, t)$ with bottleneck capacity 10.

Augment f with flow of 10 on P:

- $f(s, b) \leftarrow f(s, b) + 10$
- $f(a, b) \leftarrow f(a, b) - 10$
- $f(a, t) \leftarrow f(a, t) + 10$

Note: can find augmenting paths with BFS.

Algorithm: Augment f with P

- b = bottleneck(P, G_f).

- for e in P:
    - if e a foward edge:

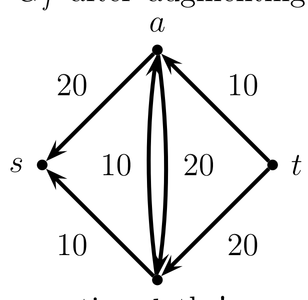
      $$f(e) \leftarrow f(e) + b$$

    - if e a back edge:

      let $e' =$ back edge

      $$f(e') \leftarrow f(e) - b.$$

Example: G_f after augmenting with $P = (s, b, a, t)$



No more augmenting paths!

Algorithm: Ford-Fulkerson

- $f \leftarrow$ null flow.
- $G_f \leftarrow G$.
- while exists s-t path P in G_f (by BFS)
    - augment f with P.
    - $G_f \leftarrow$ residual graph for G and f.
- return f.

Runtime

Each iteration:

- construct G_f: $O(m)$.
- find P: $O(m)$.
- augmentation: $O(n)$.
- (Total: $O(m)$)

Fact: the value of flow increases by bottleneck capacity in each iteration.

Theorem: if C is upper bound on max flow and all capacities are integral then algorithm terminates in $O(C)$ iterations with runtime $O(mC)$

Proof: (by "measure of progress")

1. bottleneck capacities integral:
    - current residual capacities integral

      $\Rightarrow$ integral bottleneck capacity

      $\Rightarrow$ next residual capacities integral
    - induction!
2. bottleneck capacities ≥ 1
3. flow increases by 1 each iteration
4. terminates in $\leq C$ iterations.

QED

Note: $C \leq \sum_{e \text{ out of } s} c(e)$.

Note: Clever choice of augmenting paths gives runtime $O(m^2 \log C)$.

Correctness

1. f is feasible.
2. f is optimal.

Lemma: f is feasible.

Proof: induction!

Max flow = min cut

"duality: for maximization problem there is corresponding minimization problem"

Recall: an s-t cut (A, B) is partition of V into A and B with $s \in A$ and $t \in B$.

Def: the capacity of cut (A, B) is
$$c(A, B) = \sum_{e \text{ from } A \text{ to } B} c(e)$$

Goal: flow algorithm is optimal

Proof Approach: primal = dual.

Claim 1: any flow f and any cut (A, B) then $\underbrace{|f|}_{\text{value of flow}} \leq c(A, B)$.

Claim 2: for flow f^* with no augmenting path in G_{f^*} then exists cut (A^*, B^*) with $|f^*| = c(A^*, B^*)$

Picture:

```
*      cuts     **
 ****         **
     *** *****
        *
   ***** **
 **        ***
*    flows    ***
```

Proof: (of theorem)

- all flows $|f| \underbrace{\leq}_{\text{by Claim 1}} c(A^*, B^*) \underbrace{=}_{\text{by Claim 2}} |f^*|$.

Corollary: value of max flow = capacity of min cut

Lemma: for any flow f, cut (A, B) then,
$$|f| = \sum_{e \text{ out of } A} f(e) - \sum_{e \text{ in to } A} f(e)$$

Proof: (by picture, see text for formal proof)

Proof: (of Claim 1)

From Lemma:
$$\begin{aligned} |f| &= \sum_{e \text{ out of } A} f(e) - \sum_{e \text{ in to } A} f(e) \\ &\leq \sum_{e \text{ out of } A} f(e) \\ &\leq \sum_{e \text{ out of } A} c(e) \\ &= c(A, B) \end{aligned}$$

Proof: (of Claim 2) no s-t path in G_f:

- let A^* be vertices connected to s.

  $(B^* = V \setminus A^*)$
- (A^*, B^*) is cut:
  - $s \in S^*$
  - $t \in B^*$
- for all $e = (u, v)$ out of A^* in G:
  - $e \notin G_f$

    $\Rightarrow f^*(e) = c(e)$
- for all $e = (u, v)$ in to A^* in G:
  - $e' = (v, u) \notin G_f$

    $\Rightarrow f^*(e) = 0$
- Lemma
$$\begin{aligned} \Rightarrow |f| &= \sum_{e \text{ out of } A^*} f(e) - \sum_{e \text{ in to } A^*} f(e) \\ &= \sum_{e \text{ out of } A^*} c(e) - 0 \\ &= c(A^*, B^*) \end{aligned}$$

Summary

- algorithm: augmenting paths in residual graph.
- correctness: max-flow min-cut theorem.
- many problems can be reduced to network flows.
- entire courses on network flows.