

Introduction to network flows

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1 Notations and definitions

- Graph is denoted as $G = (V, E)$. We consider $n = |V|$, $m = |E|$.
- Maximum flow problem is introduced for a tuple (G, c, s, t) , where G is some directed graph such that if arc vu belongs to E , arc uv also belongs to E . c is a capacity function. s is a starting node, called *source*, while t is the target node called *sink*.
- Capacity constraint means $f(u, v) \leq c(u, v)$ for any pair (u, v) . If there is no edge uv in E , $c(u, v)$ is considered to be zero.
- Skew symmetry constraint means $f(u, v) = -f(v, u)$ for any pair (u, v) .
- Flow conservation means $\sum_{v \in V} f(v, u) = \sum_{v \in V} f(u, v)$ for any node u except s and t . In other words no flow is “stuck” in any intermediate node.
- $\sum_{v \in V} f(s, v) = \sum_{v \in V} f(v, t) = |f|$ is called the value of the flow f .
- Residual capacity of an arc is defined as $c'(v, u) = c(v, u) - f(v, u)$. It indicates how much the flow function can be increased on this edge.
- Residual network is a tuple (G, c', s, t) , where c' stands for residual capacity.
- Augmenting path is a path $v_0, v_1, v_2, \dots, v_k$ such that $v_0 = s$, $v_k = t$ and all residual capacities $c(v_i, v_{i+1}) > 0$.
- Level graph G_L is a graph constructed from a given graph G by running breadth-first search in a residual network (i.e. BFS uses only edges that have positive residual capacity) and removing all edges except those which go from some level to the next level.

2 Lecture plan (optimistic)

1. Introduction to maximum flow problem.
2. Ford-Fulkerson theorem: maximum flow equals minimum cut.
3. Ford-Fulkerson algorithm: find any augmenting path while it exists.
4. Finding some partition that yields the minimum cut.
5. Application: closure problem.
6. Application: maximum matching.
7. Scaling technique. An $O(m^2 \log C)$ time bound for combination of DFS and scaling.
8. Flow decomposition.
9. Blocking flow. Dinic's algorithm. $O(n^2 m)$ time bound.

3 Algorithm details

- To find an augmenting path, run a DFS from s to t using only edges with positive residual capacity (that is, $f_{uv} < c_{uv}$). Note that the edge can be present in the residual network even it was not in the original graph: it is the case of reverse edges, for them $c_{uv} = 0$ and $f_{uv} < 0$ because flow was pushed in the opposite direction.
- When an augmenting path was found, find minimal residual capacity among its edges. Let the path be $s = v_0, v_1, \dots, v_{k-1}, v_k = t$. Then you should take the value $v = \min(c_{v_0 v_1} - f_{v_0 v_1}, c_{v_1 v_2} - f_{v_1 v_2}, \dots)$. Push the flow through the path, adding v to flow on the edges in the same direction ($v_0 v_1, v_1 v_2, \dots$) and subtracting it from the flow on edges in the opposite ($v_1 v_0, v_2 v_1, \dots$).
- To find some minimal cut, find a maximum flow and run the DFS from s over residual network (the graph with edges with positive residual capacity). The visited vertices will form exactly one part of a minimum cut.
- Tricky point: in directed graphs only edges from the s -part of the cut to the t -part of the cut are counted. Edges in the opposite direction do not contribute to the capacity of the cut.
- To find the flow decomposition, you should first find the maximum flow. After that repeatedly run a DFS from s along the edges with positive flow (and not residual capacity, as before). Each DFS over those edges would terminate at t without backtracking and yield a path for the decomposition. When the path is found, take the minimum flow along it and subtract it from the values of the flow on edges along the path.

4 Theoretical problems to think about

1. If capacities may be non-integer, construct the testcase on which Ford-Fulkerson algorithm does not terminate in finite time.
2. Prove that any maximum flow function f produces the same canonical cut.
3. Given a flow network and some maximum flow function f , find in linear time all edges, such that increasing capacity function of these edges will increase the minimum cut. In other words, find all edges that belong to each minimum s-t cut.
4. For a graph with n vertices and m edges, consider the maximum flow decomposition into minimum number of paths. How many paths will there be in worst case? Find a bound and show that it is tight (to show tightness, for each (n, m) present a graph and show that the decomposition in it must have at least certain number of paths).
5. Prove that if $c(v, u) = 1$ (unit network) for any $vu \in E$ the worktime of Dinic's algorithm is bound by $O(m\sqrt{m})$.