

# CSC373 Worksheet 5 Solution

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1. *Proof.* Assume that a flow network  $G = (V, E)$  violates the assumption that the network contains a path  $s \rightsquigarrow v \rightsquigarrow t$  for all vertices  $v \in V$ . Let  $u$  be a vertex for which there is no path  $s \rightsquigarrow u \rightsquigarrow t$ .

I must show such that there is no flow at vertex  $u$ . That is, there exists a maximum flow  $f$  in  $G$  such that  $f(u, v) = f(v, u) = 0$  for all vertices  $v \in V$ .

Assume for the sake of contradiction that there is some vertex  $u$  with flow  $f$ . That is, there exists some vertices  $v \in V$  such that  $f(u, v) > 0$  or  $f(v, u) > 0$ .

I see that three cases follows, and I will prove each separately.

1. **Cases 1:**  $f(u, v) = 0$  and  $f(v, u) > 0$

Here, assume that  $f(u, v) = 0$  for all  $v \in V$  and  $f(v, u) > 0$  for some  $v \in V$ .

Then, we can write  $\sum_{v \in V} f(u, v) = 0$  and  $\sum_{v \in V} f(v, u) > 0$

But this violates the flow conservation property (i.e  $\sum_{v \in V} f(u, v) = \sum_{v \in V} f(v, u)$ )

Thus, by proof by contradiction,  $f(u, v) = 0$  and  $f(v, u) = 0$  for all  $v \in V$  and all  $u \in V$  with no path  $s \rightsquigarrow u \rightsquigarrow t$ .

2. **Cases 2:**  $f(u, v) > 0$  and  $f(v, u) = 0$

Here, assume that  $f(u, v) > 0$  for some  $v \in V$  and  $f(v, u) = 0$  for all  $v \in V$ .

Then, by similar work as case 1, the same result follows.

### 3. Cases 3: $f(u, v) > 0$ and $f(v, u) > 0$

Here, assume that  $f(u, v) > 0$  and  $f(v, u) > 0$  for some  $v \in V$ .

Since  $s \rightsquigarrow v \rightsquigarrow t$  and  $u$  is connected by some vertices  $v$ , we can write  $s \rightsquigarrow u \rightsquigarrow t$ .

Then, this violates the fact in header that the vertex  $u$  has no path  $s \rightsquigarrow u \rightsquigarrow t$ .

Thus, by proof by contradiction,  $f(u, v) = 0$  and  $f(v, u) = 0$  for all  $v \in V$  and all  $u \in V$  with no path  $s \rightsquigarrow u \rightsquigarrow t$ .

□

## Notes

### • Maximum Flow:

- Finds a flow of maximum value <sup>[1]</sup>

### Example



Here, the maximum flow is  $10 + 5 + 13 = 28$

### • Flow Network:

- $G = (V, E)$  is a directed graph in which each edge  $(u, v) \in E$  has a nonnegative capacity  $c(u, v) \geq 0$ .
- Two vertices must exist: **source**  $s$  and **sink**  $t$
- **path** from source  $s$  to vertex  $v$  to sink  $t$  is represented by  $s \rightsquigarrow v \rightsquigarrow t$



- **Capacity:**

- Is a non-negative function  $f : V \times V \rightarrow \mathbb{R}_{\geq 0}$
- Has **capacity constraint** where for all  $u, v \in V$   $0 \leq f(u, v) \leq c(u, v)$ 
  - \* Means flow cannot be above capacity constraint

- **Flow:**

- Is a real valued function  $f : V \times V \rightarrow \mathbb{R}$  in  $G$
- Satisfies **capacity constraint** (i.e for all  $u, v \in V$ ,  $0 \leq f(u, v) \leq c(u, v)$ )
- Satisfies **flow conservation**

For all  $u \in V - \{s, t\}$ , we require

$$\sum_{v \in V} f(v, u) = \sum_{v \in V} f(u, v) \quad (1)$$

\* Means flow into vertex  $u$  is the same as flow going out of vertex  $u$ . <sup>[1]</sup>

\*  $\sum_{v \in V} f(u, v)$  means flow out of vertex  $u$

\*  $\sum_{v \in V} f(v, u)$  means flow into vertex  $u$

\*  $v \in V$  in  $\sum_{v \in V} f(u, v)$  means all vertices that are an edge away from vertex  $u$

**Example:**



## References

- 1) Princeton University, Network Flow 1, link
2. I need to formulate the problem of determining whether both of professor Adam's two children can go to the same school as maximum-flow problem.

The problem statement tells us the following:

1. There is 1 supersource (location of home)
2. There is 1 sink (location of school)
3. There are two sources ( $s_1$  as child 1,  $s_2$  as child 2)
4. Edge  $(u, v)$  has capacity of 0 or more (0 representing unavailable sidewalk, 1 for sidewalk with capacity of 1, 2 for street with capacity of 2 and so on)
5. Each vertex represents corner of intersection, and two children can have their paths crossing here.
6. Has flow of 2, 1 or 0 (1 is where one of the two children walking on the road. 0 is none.)

Here we are to find whether children must go on to a vertex and out to the same edge with the flow of 2, or determine whether there is only edge to school with capacity of 1 or less.

If none, then both children can safely go to school.



### Notes:

- **Cross at a Corner**

- Means to walk across the street at a corner of the intersection.



- **Multiple Sources and Sinks**

- Has edges  $(s, s_i)$  where  $i = 1 \dots n$  and  $(t_j, t)$  where  $j = 1 \dots n$  with capacity of  $\infty$

### Example:

Lucky Puck Company having a set of  $m$  factories  $\{s_1, s_2, \dots, s_m\}$ , and a set of  $n$  warehouses and  $n$  warehouses  $\{t_1, t_2, \dots, t_n\}$



3. I need to show how to transform a flow network  $G = (V, E)$  with vertex capacities into an equivalent flow network  $G' = (V', E')$  without vertex capacities.

For each vertex capacities, change as follows.



After transformation, there will be  $m$  more edges and vertices, where  $m$  represents the number of vertex capacities in  $G$ .

Notes:

- **Vertex Capacities**

- Each vertex  $v$  has limit  $l(v)$  on how much flow can pass through  $v$

4. I need to show how to convert the problem of finding a flow  $f$  that obeys the constraints into the problem of finding a maximum flow in a single source, single-sink flow network

The steps are as follows:

- Combine all sources  $s_i$  into a single source  $s$
- Combine all sinks  $t_j$  into a single sink  $t$
- Connect source  $s$  to each adjacent vertex  $v$  with edge weight  $\sum_i f(s_i, v) = p_i$ 
  - The total edge weight from  $s$  should be  $\sum_i p_i$
- Connect each adjacent vertex  $v$  of  $t$  to  $t$  with edge weight  $\sum_j f(v, t_j) = q_j$ 
  - The total edge weight to  $t$  should be  $\sum_j q_j$
- Find a simple path from  $s$  to  $t$  with the maximum amount of total flow



**Correct Solution:**

I need to show how to convert the problem of finding a flow  $f$  that obeys the constraints into the problem of finding a maximum flow in a single source, single-sink flow network

The steps are as follows:

- Combine all sources  $s_i$  into a single source  $s$
- Combine all sinks  $t_j$  into a single sink  $t$
- Connect source  $s$  to each adjacent vertex  $v$  with edge weight  $\sum_i f(s_i, v) = p_i$ 
  - The total edge weight from  $s$  should be  $\sum_i p_i$
- Connect each adjacent vertex  $v$  of  $t$  to  $t$  with edge weight  $\sum_j f(v, t_j) = q_j$ 
  - The total edge weight to  $t$  should be  $\sum_j q_j$
- Find a simple path from  $s$  to  $t$  with the maximum amount of total flow

### Example



### Notes:

- **Ford-Fulkerson Method**
  - Is a greedy algorithm that solves the maximum-flow problem
    - \* Determines maximum flow from start vertex to sink vertex in a graph
  - Called method (not algorithm) because several different implementations with different running time is used



### FORD-FULKERSON-METHOD( $G, s, t$ )

- 1 initialize flow  $f$  to 0
- 2 **while** there exists an augmenting path  $p$  in the residual network  $G_f$
- 3     augment flow  $f$  along  $p$
- 4 **return**  $f$

#### • Residual Network

- Indicates how much more flow is allowed in each edge in the network graph <sup>[1]</sup>
- Consists of edges with capacities that represents how we can change the flow on edges of  $G$ .
- Provides roadmap for adding flow to the original flow network



### Steps

- 1)  $Flow = Capacity$ : Opposite arrow



- 2)  $Flow < Capacity$ :

- $Flow$ : Opposite Arrow
- $Capacity - Flow$ : Current Arrow



### • Augmenting Path

- Is a path from source  $S$  to sink  $T$  where you can increase the amount of flow
- Is a path that doesn't contain cycle (simple path) [2]



- Edge  $(u, v)$  of an augmented path can be increased by upto  $c_f(u, v)$  without violating the capacity constraint

### • Augmentation

- 한국어로 '불필요한 수압 decrease 해서 앞으로 가는 수압 더 쉐게 만들기'
- Is symbolized by  $f \uparrow f'$

- \*  $f$  is a flow in  $G$
- \*  $f'$  is a flow in the residual network  $G_f$

### References

- 1) Hacker Earth, Maximum Flow, link
- 2) Stack Overflow, What Exactly Is Augmentation Path, link

### 5. Rough Works:

I need to show if the augmented flow of  $f$  and  $f' \in G$  and satisfy the flow conservation property and capacity constraint.

- Proving that  $f \uparrow f'$  satisfies the flow conservation property

Let  $G = (V, E)$  be a flow network with sources  $s$  and sink  $t$ . Let  $f, f'$  be a flow in  $G$ . Let  $(u, v)$  be an edge in  $E$  where  $u \in V - \{s, t\}$  and  $v \in V$ . We note that if  $(u, v) \in E$ , then  $(v, u) \notin E$  and  $f(v, u) = 0$ . Thus, we can re-write the definition of flow augmentation (equation (26.4)) as

$$(f \uparrow f')(u, v) = \begin{cases} f(u, v) + f'(u, v) & [\text{If } (u, v) \in E] \\ 0 & [\text{Otherwise}] \end{cases} \quad (2)$$

which implies that the value of the augmentation of flow  $f \uparrow f'$  on edge  $(u, v)$  is the sum of flow  $f(u, v)$  and  $f'(u, v)$  in  $G$ . We now prove that the

- Disproving that  $f \uparrow f'$  satisfies the capacity constraint

### Notes:

- I need clarification from professor about the meaning of  $f' \in G$ . Is  $f'$  a flow from flow network or residual network?
- I feel I am struggling because I am jumping to solution without understanding the problem
- I feel constructing a predicate logic would have helped to better understand this problem

- Noticed that a solution in University of Texas really elaborated on  $f \uparrow f'(u, v)$  before moving onto strategizing and constructing a solution

capacity constraint property.

First, we prove that  $f \uparrow f'$  satisfies the flow conservation property. We note that if edge  $(u, v) \in E$ , then  $(v, u) \notin E$  and  $f(v, u) = 0$ . Thus, we can rewrite the definition of flow augmentation (equation (26.4)), when applied to two flows, as

$$f \uparrow f'(u, v) = \begin{cases} f(u, v) + f'(u, v), & \text{if } (u, v) \in E \\ 0, & \text{otherwise.} \end{cases}$$

The definition implies that the new flow on each edge is simply the sum of the two flows on that edge. We now prove that in  $f \uparrow f'$ , the net incoming flow for each vertex equals the net outgoing flow. Let  $u \notin \{s, t\}$  be any vertex of  $G$ . We have

- **Flow Network (cont'd)** [Important!]

– Flow network requires that

- 1)  $G = (V, E)$  is a directed graph
- 2) each edge  $(u, v) \in E$  has a non-negative capacity  $c(u, v) \geq 0$
- 3) If  $E$  contains an edge  $(u, v)$ , then there is no edge  $(v, u)$  in the reverse direction (no anti-parallel edge)

- **Augmentation (cont'd)**

– Augmentation of flow  $f$  by  $f'$  or  $f \uparrow f'$  is a function  $V \times V \rightarrow \mathbb{R}$  is defined by

$$(f \uparrow f')(u, v) = \begin{cases} f(u, v) + f'(u, v) - f'(v, u) & [\text{If } (u, v) \in E] \\ 0 & [\text{Otherwise}] \end{cases} \quad (3)$$

– Augmentation of flow  $f \uparrow f'$  is the sum of flow on edge  $(u, v)$  in both flow network  $G$  and residual network  $G'$

- **Proof of flow conservation for  $f \uparrow f'$  when  $f \in G$  and  $f' \in G_f$**

Let  $G = (V, E)$  be a flow network with sources  $s$  and sink  $t$ . Let  $f$  be a flow in  $G$ . Let  $G_f$  be a residual network of  $G$  induced by  $f$  and let  $f'$  be a flow in  $G_f$ . Let  $(u, v)$  be an edge in  $E$  where  $u \in V - \{s, t\}$  and  $v \in V$ . We note that if  $(u, v) \in E$ , then  $(v, u) \notin E$  and  $f(v, u) = 0$ . Thus, the definition

$$(f \uparrow f')(u, v) = \begin{cases} f(u, v) + f'(u, v) - f'(v, u) & [\text{If } (u, v) \in E] \\ 0 & [\text{Otherwise}] \end{cases} \quad (1)$$

implies that the augmented flow  $f \uparrow f'(u, v)$  on edge  $(u, v)$  is the sum of flow  $f(u, v)$  in flow network  $G$  and flow  $f'(u, v)$  minus its antiparallel flow  $-f'(v, u)$  in residual flow network  $G'$ .

We now prove that the augmented flow satisfies flow conservation. That is,

$$\sum_{v \in V} f \uparrow f'(u, v) = \sum_{v \in V} f \uparrow f'(v, u) \quad (2)$$

.

And indeed we have

$$\sum_{v \in V} f \uparrow f'(u, v) = \sum_{v \in V} f(u, v) + f'(u, v) - f'(v, u) \quad [\text{By augmentation def.}] \quad (3)$$

$$= \sum_{v \in V} f(u, v) + \sum_{v \in V} f'(u, v) - \sum_{v \in V} f'(v, u) \quad (4)$$

$$= \sum_{v \in V} f(v, u) + \sum_{v \in V} f'(v, u) - \sum_{v \in V} f'(u, v) \quad [\text{By flow conserv. of } f \text{ and } f'] \quad (5)$$

$$= \sum_{v \in V} f(v, u) + f'(v, u) - f'(u, v) \quad (6)$$

$$= \sum_{v \in V} f \uparrow f'(v, u) \quad (7)$$

– Flow in residual network also obey flow conservation

- **Proof of capacity constraint for  $f \uparrow f'$  when  $f \in G$  and  $f' \in G_f$**

**Predicate Logic:**  $\forall f \in G, \forall f' \in G_f, \forall (u, v) \in E$  where  $u, v \in V, 0 \leq (f \uparrow f')(u, v) \wedge (f \uparrow f')(u, v) \leq c(u, v)$

Let  $G = (V, E)$  be a flow network with sources  $s$  and sink  $t$ . Let  $f$  be a flow in  $G$ . Let  $G_f$  be a residual network of  $G$  induced by  $f$  and let  $f'$  be a flow in  $G_f$ . Let  $(u, v)$  be an edge in  $E$  where  $u, v \in V$ .

I need to prove that  $f \uparrow f'$  satisfies capacity constraint. That is,  $0 \leq (f \uparrow f')(u, v) \wedge (f \uparrow f')(u, v) \leq c(u, v)$ .

I see there are two parts. I will prove each parts separately.

1. **Part 1** ( $0 \leq (f \uparrow f')(u, v)$ )

Here, I need to show  $0 \leq (f \uparrow f')(u, v)$ . That is,  $0 \leq f(u, v) + f'(u, v) - f'(v, u)$ .

And indeed we have,

$$(f \uparrow f')(u, v) = f(u, v) + f'(u, v) - f'(v, u) \quad (8)$$

$$\geq f(u, v) + f'(u, v) - c_f(v, u) \quad [\text{Since } f'(v, u) \leq c_f(v, u)] \quad (9)$$

$$= f(u, v) + f'(u, v) - f(u, v) \quad [\text{By def. of residual capacity}] \quad (10)$$

$$= f'(u, v) \quad (11)$$

$$\geq 0 \quad [\text{By cap. const. of } f' \text{ in } G_f] \quad (12)$$

$$(13)$$

–  $c_f(v, u) = f(u, v)$  is allowed

2. **Part 2**  $((f \uparrow f')(u, v) \leq c(u, v))$

Here, I need to show  $(f \uparrow f')(u, v) \leq c(u, v)$ . That is,  $f(u, v) + f'(u, v) - f'(v, u) \leq c(u, v)$ .

And indeed we have,

$$(f \uparrow f')(u, v) = f(u, v) + f'(u, v) - f'(v, u) \quad (14)$$

$$\leq f(u, v) + f'(u, v) \quad [\text{Since } f'(v, u) \geq 0 \text{ by cap. cons. of } f'] \quad (15)$$

$$= f(u, v) + c_f(u, v) \quad [\text{Since } f'(u, v) \leq c_f(u, v)] \quad (16)$$

$$= f(u, v) + (c(u, v) - f(u, v)) \quad [\text{By def of res. capacity}] \quad (17)$$

$$= c(u, v) \quad (18)$$

$$(19)$$