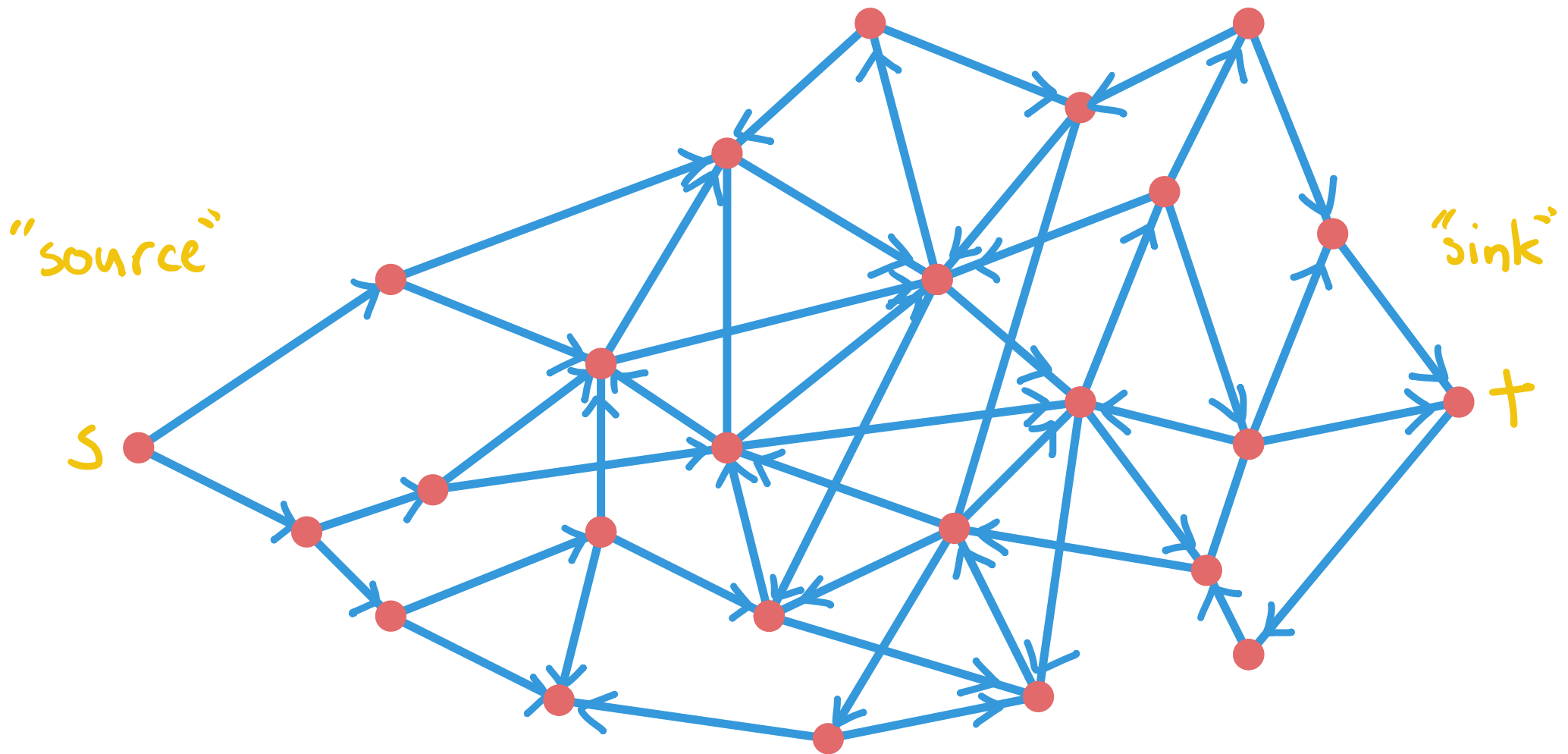


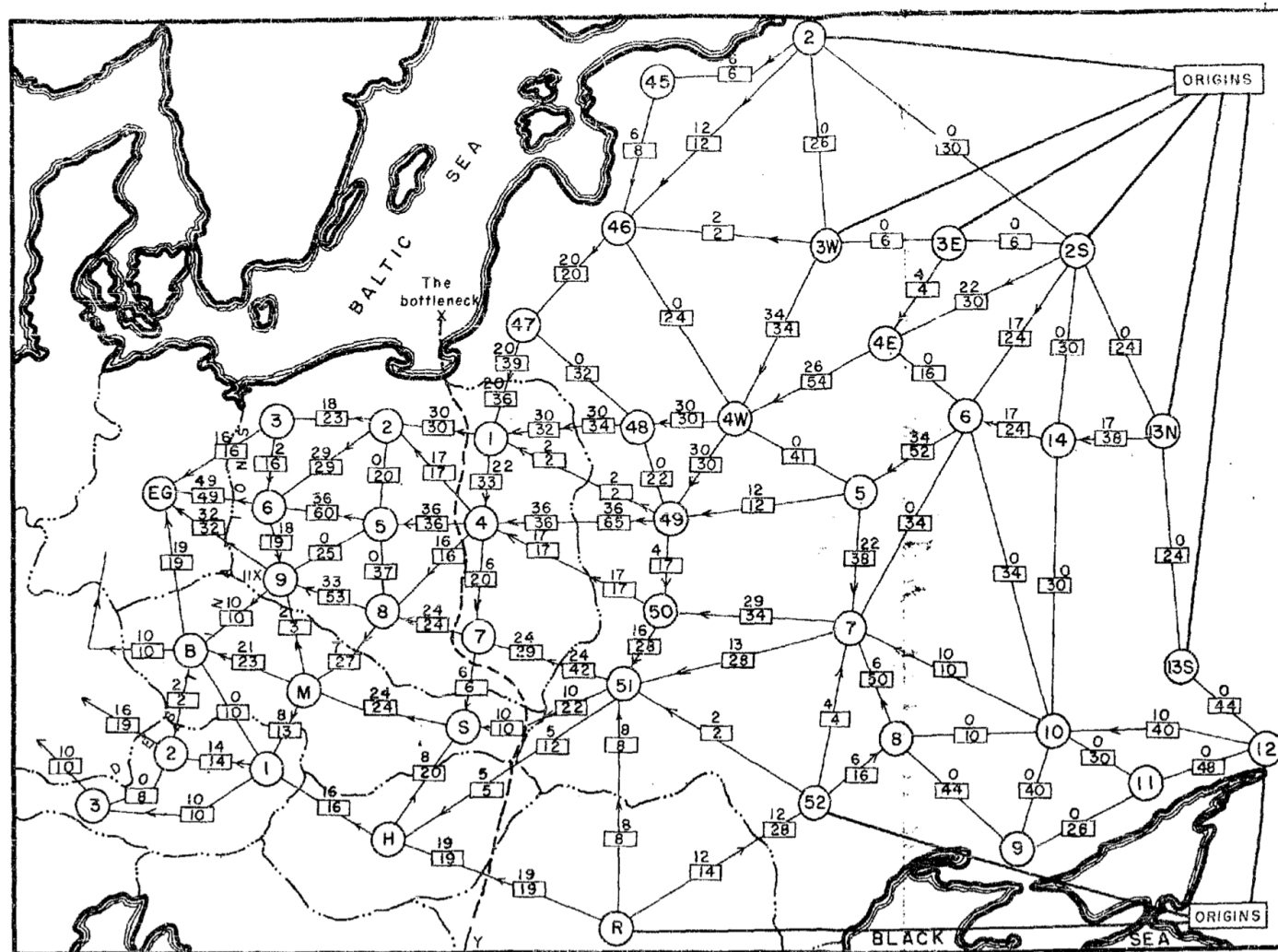
Network Flow

Measuring connectivity



how well connected are s and t?

Physical infrastructure



SECRET
RM-1373
10-24-55
-33-

Fig. 7 — Traffic pattern: entire network available

Legend:

— International boundary

(B) Railway operating division

← 9/12 → Capacity: 12 each way per day. Required flow of 9 per day toward destinations (in direction of arrow) with equivalent number of returning trains in opposite direction

All capacities in $\sqrt{1000}$'s of tons each way per day

Origins: Divisions 2, 3W, 3E, 2S, 13N, 13S, 12, 52 (USSR), and Roumania

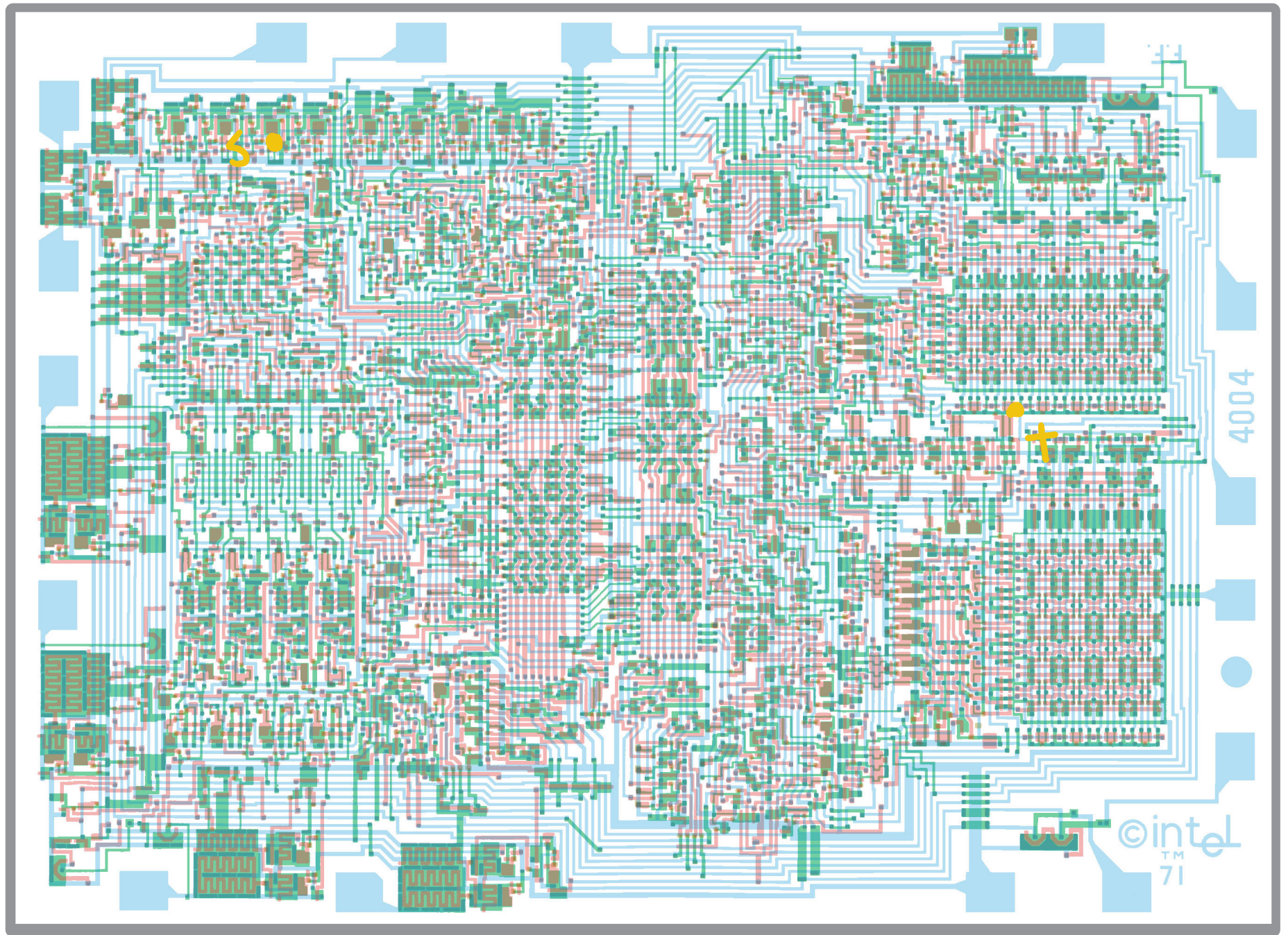
Destinations: Divisions 3, 6, 9 (Poland); B (Czechoslovakia); and 2, 3 (Austria)

Alternative destinations: Germany or East Germany

Note IIX of Division 9, Poland

(from Jeff's notes)

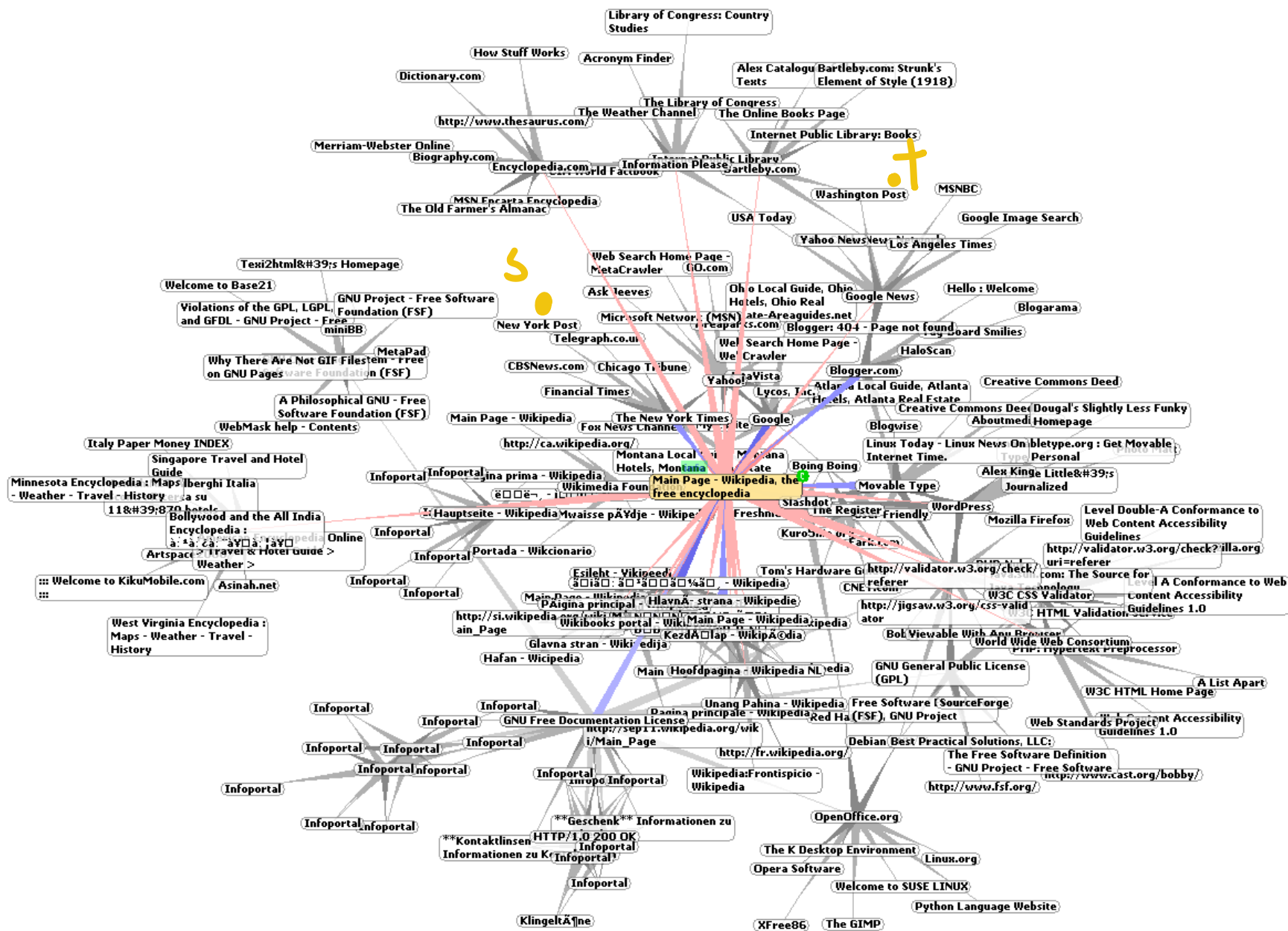
CPU's

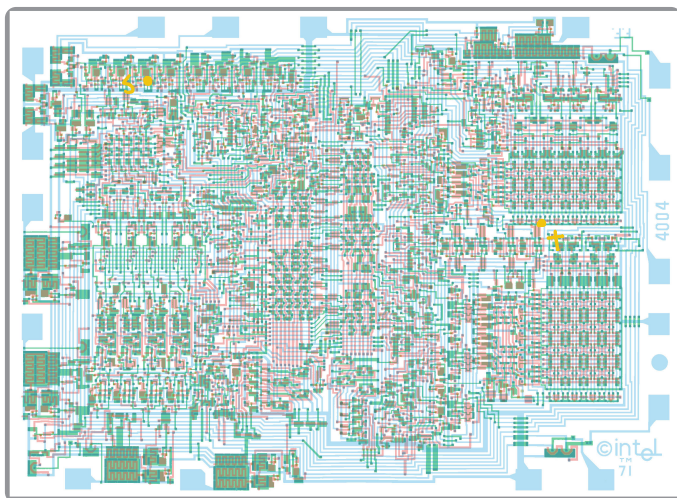
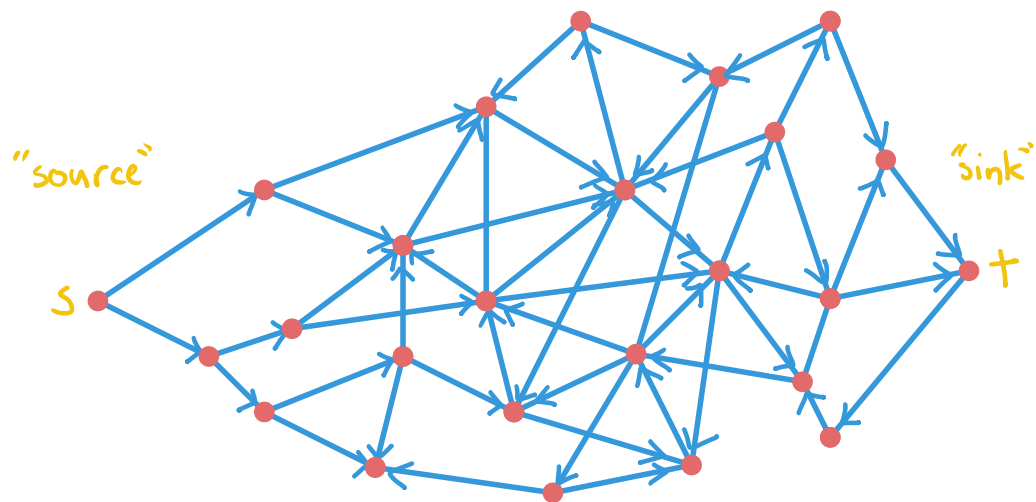


social network



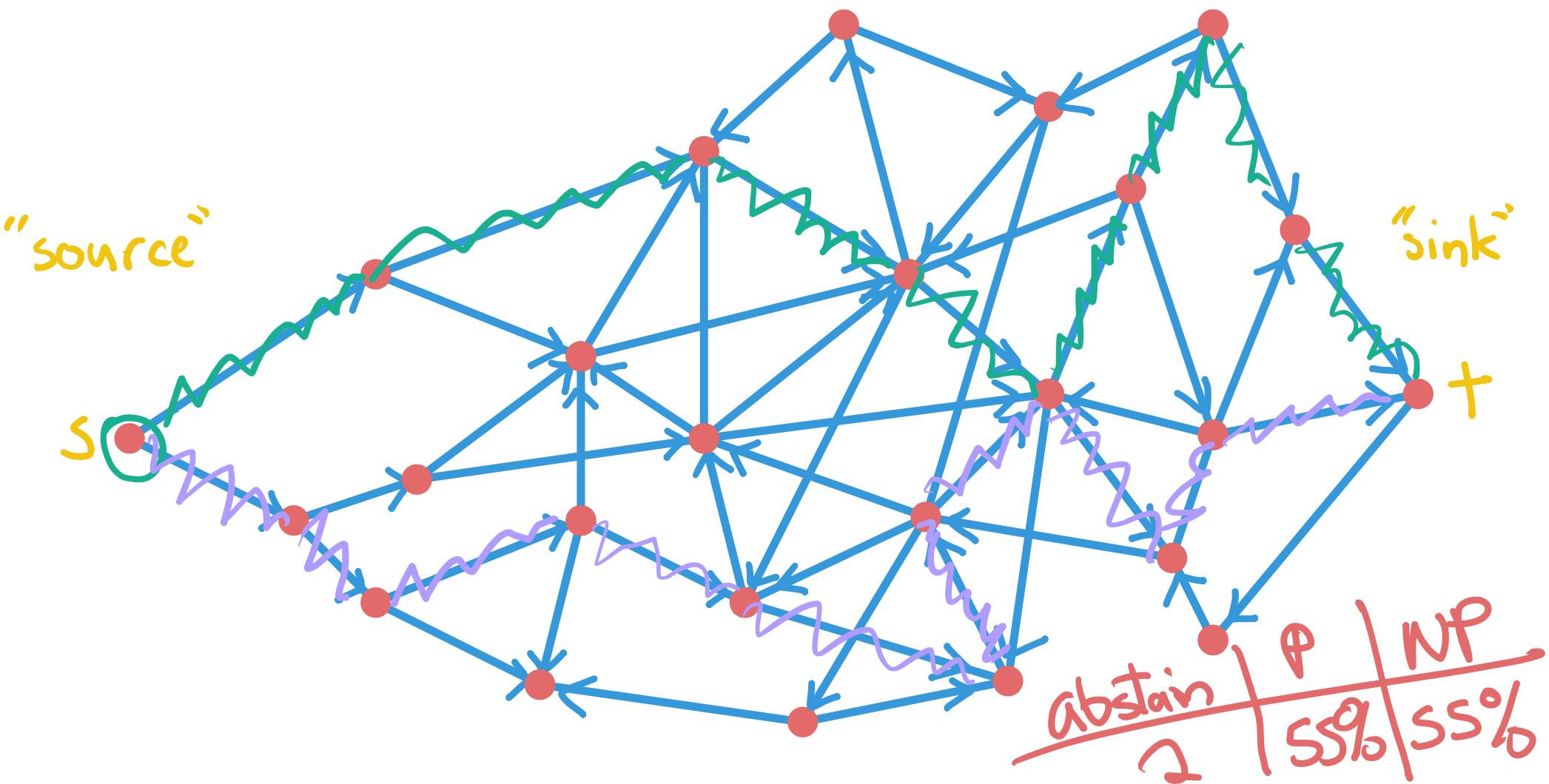
www





- ① Is there an $s \rightsquigarrow t$ path?
- ② How many distinct $s \rightsquigarrow t$ paths?
- ③ how many k -edge $s \rightsquigarrow t$ walks?
(k fixed)
- ④ length of shortest $s \rightsquigarrow t$ path?
- ⑤ how many shortest $s \rightsquigarrow t$ paths?
- ⑥ In a random walk starting from s , what is the expected # of steps until we reach t ?
- ⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?
- ⑧ min # of edge deletions to disconnect $s \rightsquigarrow t$?

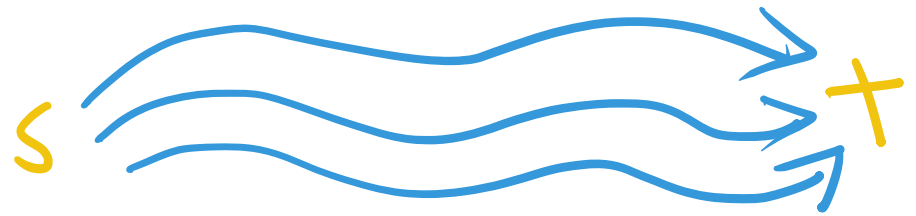
Measuring connectivity



⑦ max # of edge-disjoint $s \leadsto t$ paths?

⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?

"path packing"



collection of edge-disjoint paths

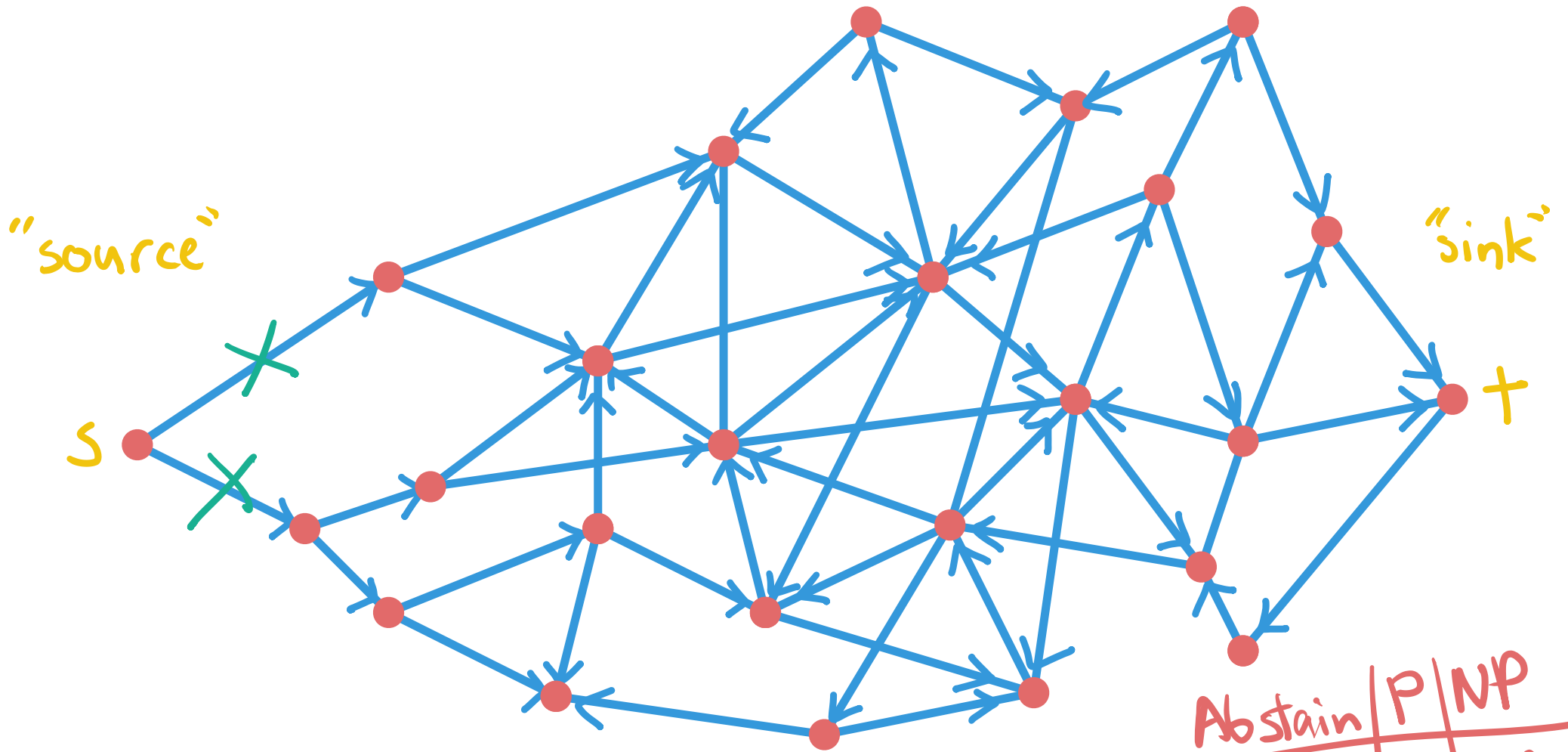
"packing paths into edges"

Question ⑦ = max cardinality path packing

1st example of "packing problem"

path p "packs into" each edge $e \in p$

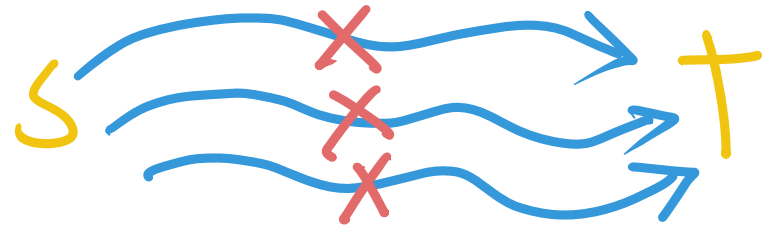
Measuring connectivity



Abstain	P	NP
2	45%	55%

⑧ min # of edge deletions to disconnect $s \rightsquigarrow t$?

⑧ min # of edge deletions to
disconnect $s \rightarrow t$?



" $s \rightarrow t$ cut"

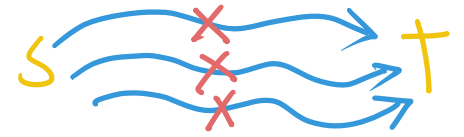
set of edges whose removal
disconnects t from s

Question ⑧ = min s - t cut

⑧ min # of edge deletions to disconnect $s \rightsquigarrow t$?

Question ⑧ = min s - t cut

" $s \rightarrow t$ cut"



set of edges whose removal disconnects t from s

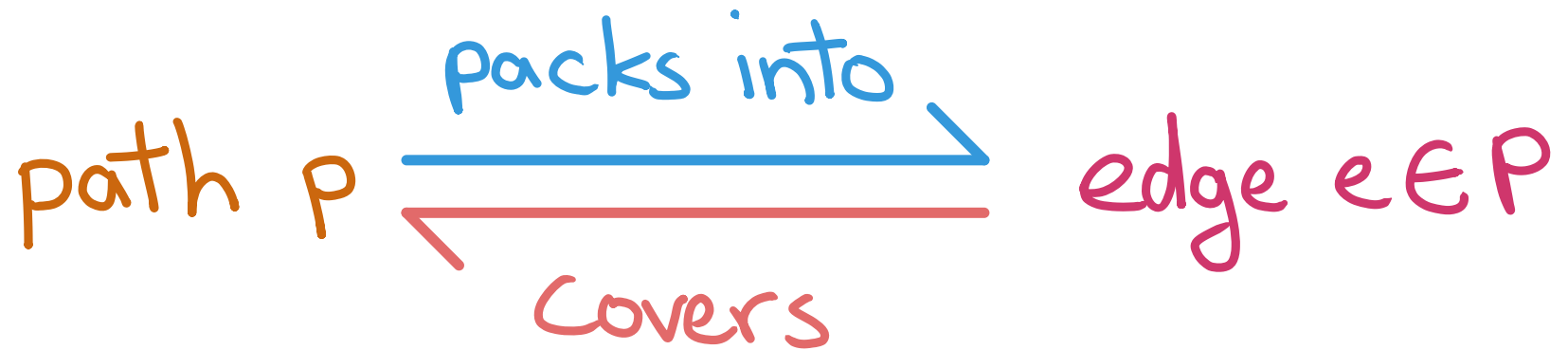
example of "covering problem"

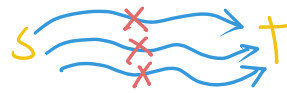
edge e "covers" path p containing e

goal:

min edge set covering all $s \rightsquigarrow t$ paths

Duality





Duality
 path p $\xrightarrow{\text{packs into}}$ edge $e \in P$
~~covers~~

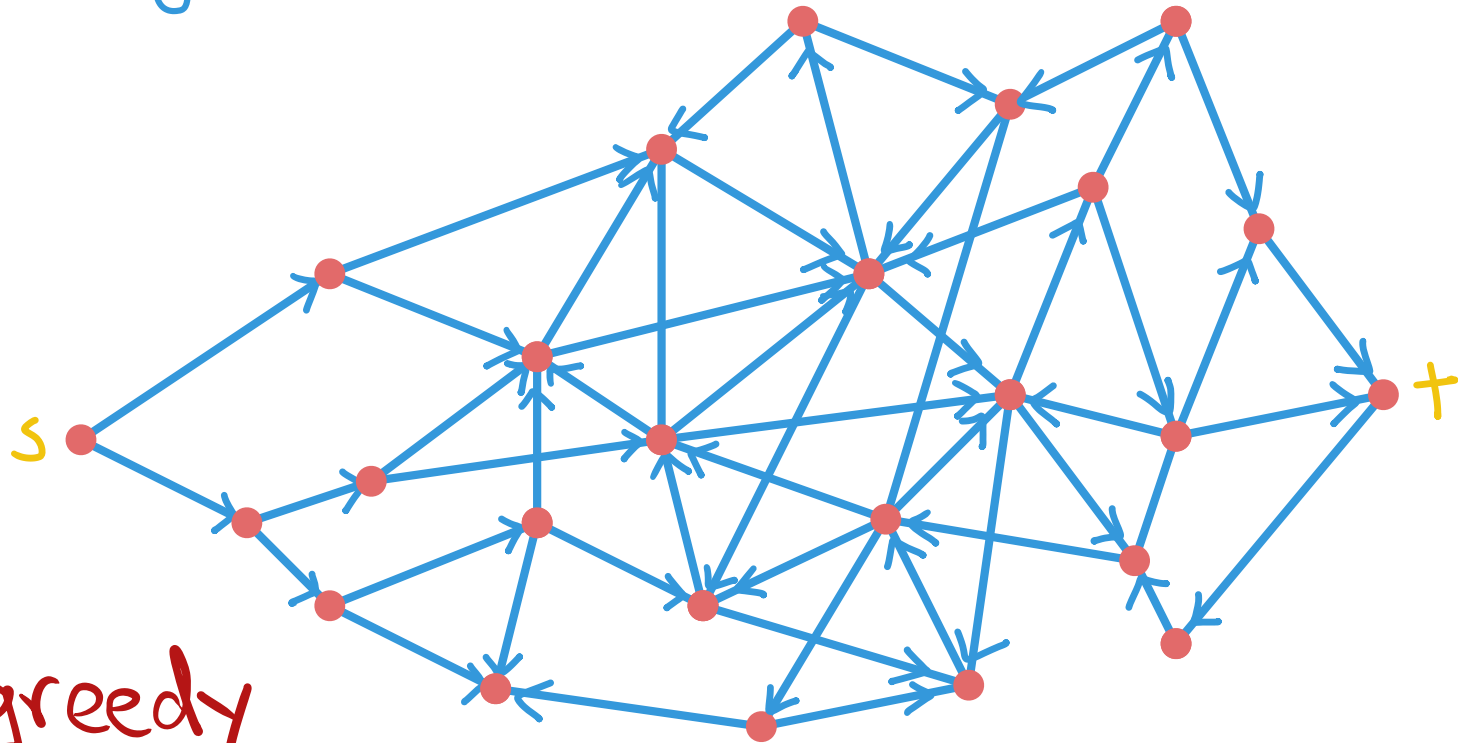
Lemma

$$\left(\begin{array}{c} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{array} \right) \leq \left(\begin{array}{c} \text{min \# edges} \\ \text{in any } s \rightsquigarrow t \text{ cut} \end{array} \right)$$

* 2nd example of
 packing $\leq$ covering

How to compute

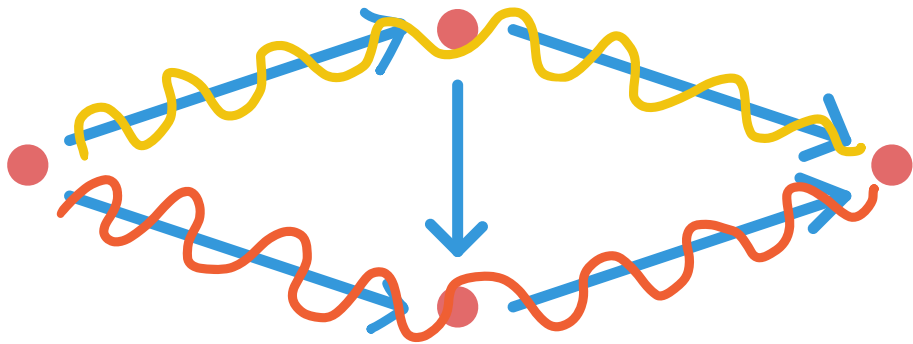
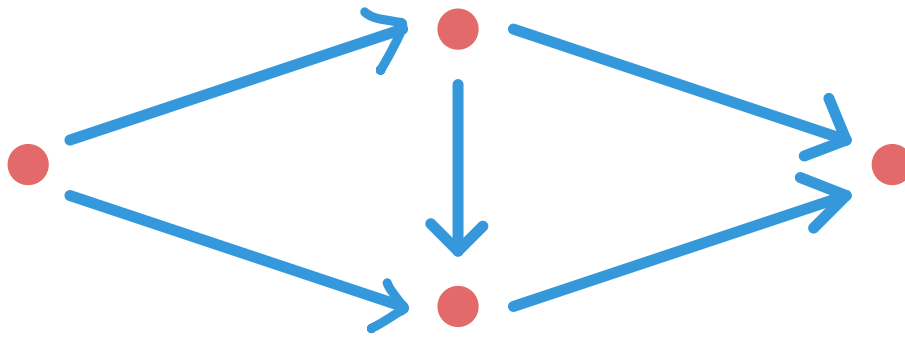
⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



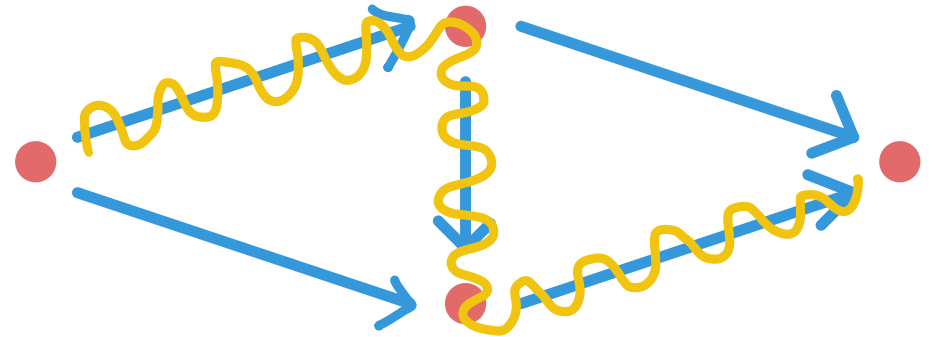
Iterative/greedy

① while there is a path $p: s \rightsquigarrow t$

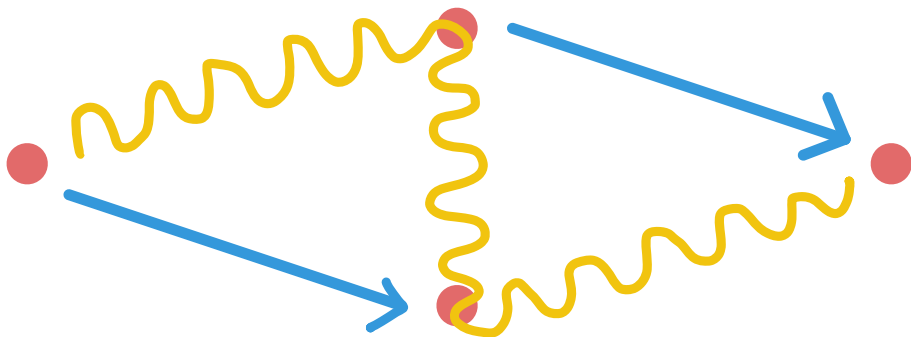
② take p and remove all its edges from the graph



(good)

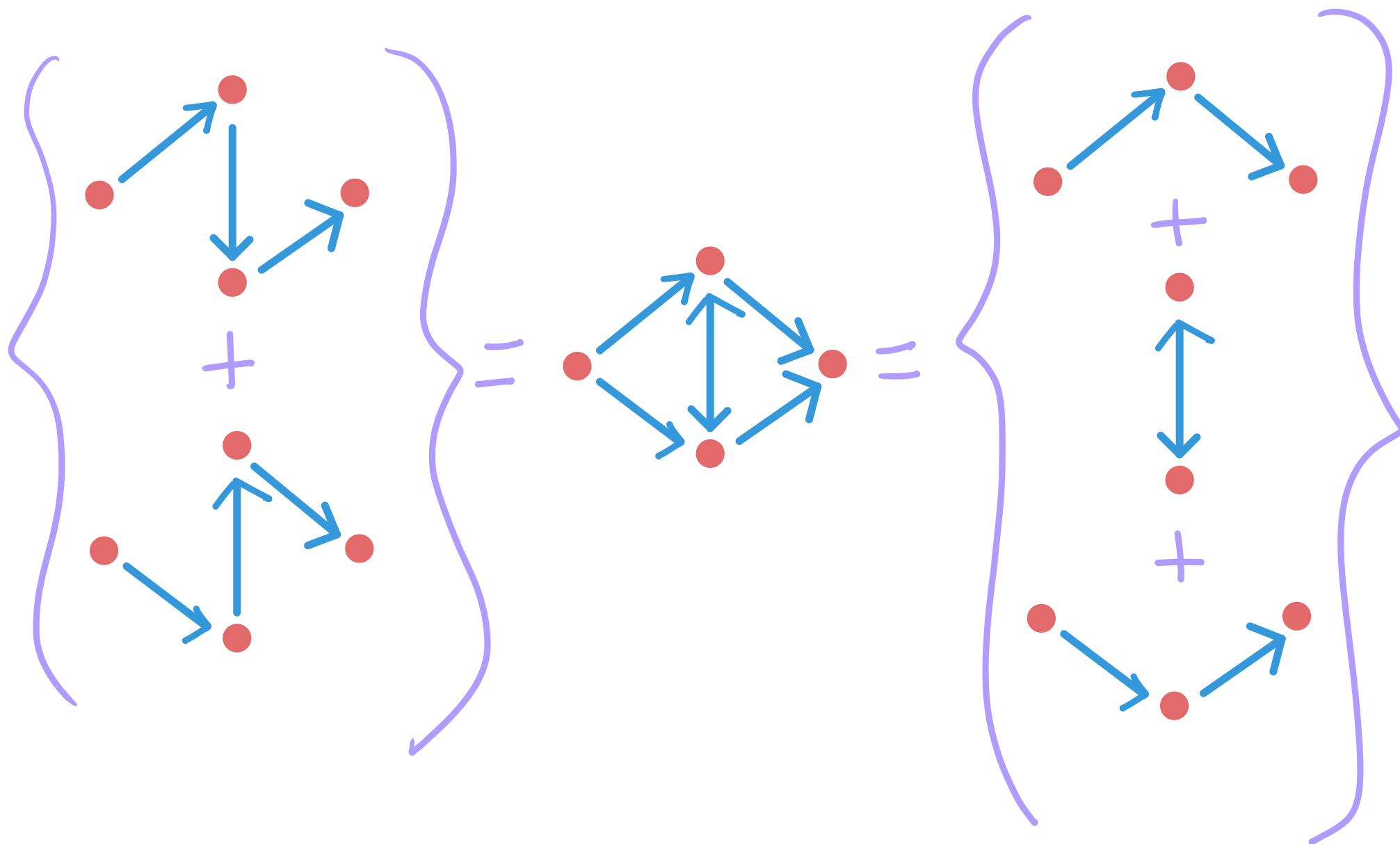


(bad)

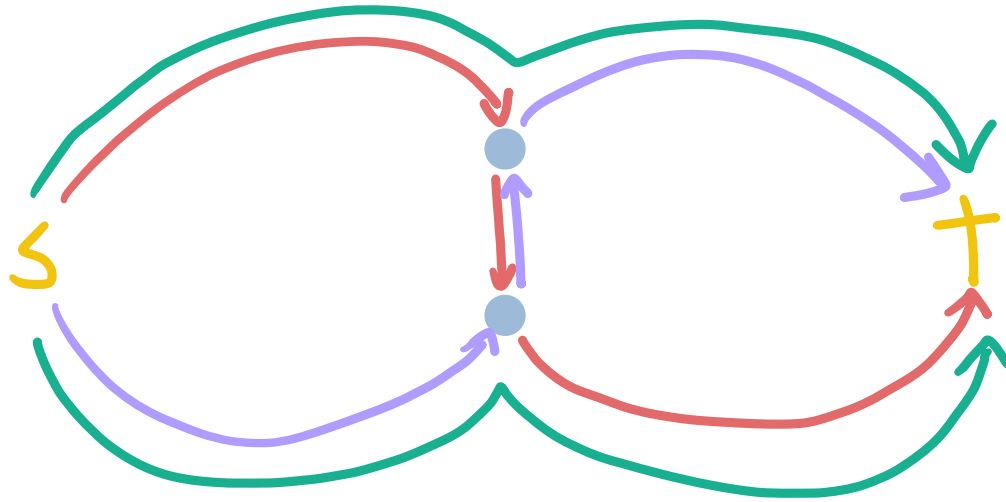


① while there is a path $p: s \rightsquigarrow t$
 @ take p and remove all its
 edges from the graph

Consider:



Lemma let p, q be edge-disjoint $s \rightsquigarrow t$ paths



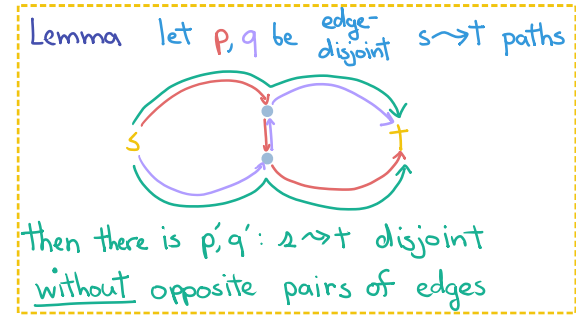
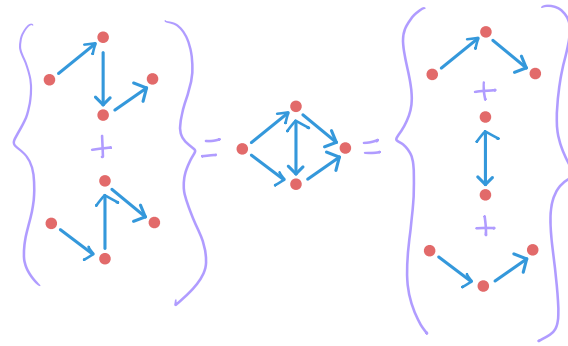
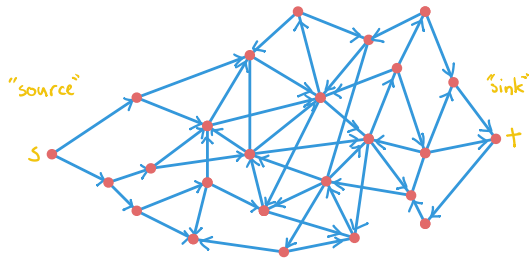
then there is p', q' : $s \rightsquigarrow t$ disjoint
without opposite pairs of edges

Proof: try it!

hint: by induction on # of opposite pairs

How to compute

⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



augmenting-paths($G = (V, E), s, t$)

/ Ford and Fulkerson [FF56]*

1. $P \leftarrow \emptyset$

2. While there is an (s, t) -path $p : s \rightsquigarrow t$:

A. Remove all of p 's edges from the graph.

B. Add the reverse of all of p 's edges to the graph.

C. Uncross p with previously selected paths, and add p to P .

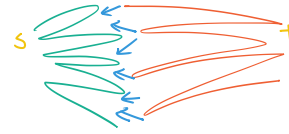
"residual graph"

④ let

S = vertices reachable from s in residual graph

T = all other vertices (incl. t)

C = edges from S to T



⑤ each path decrease $|C|$ by 1.

⑥ at end, $|C| = 0$.

$$\Rightarrow \left(\begin{array}{c} \# \text{ paths} \\ \text{packed} \end{array} \right) = \left(\begin{array}{c} \# \text{ edges} \\ \text{initially in } C \end{array} \right)$$

Recall Lemma

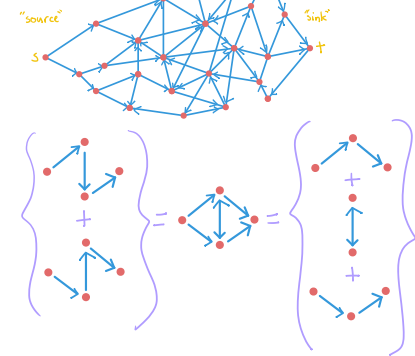
$$\left(\begin{array}{c} \max \# \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{array} \right) \leq \left(\begin{array}{c} \min \# \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{array} \right)$$

$$\left(\begin{array}{c} \# \text{ paths} \\ \text{packed} \end{array} \right) \leq \left(\begin{array}{c} \max \# \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{array} \right) \leq \left(\begin{array}{c} \min \# \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{array} \right) \leq \left(\begin{array}{c} \# \text{ edges} \\ \text{initially in } C \end{array} \right)$$

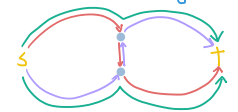
equal

How to compute

⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



Lemma let p, q be edge-disjoint $s \rightsquigarrow t$ paths



then there is p', q' $s \rightsquigarrow t$ disjoint without opposite pairs of edges

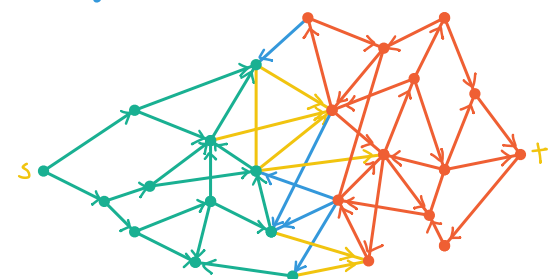
augmenting-paths($G = (V, E), s, t$)

/* Ford and Fulkerson [FF56]

1. $P \leftarrow \emptyset$
2. While there is an (s, t) -path $p : s \rightsquigarrow t$:
 - A. Remove all of p 's edges from the graph.
 - B. Add the reverse of all of p 's edges to the graph.
 - C. Uncross p with previously selected paths, and add p to P .

let (S, I) partition V st. $s \in S, t \in I$

C = edges from S to I (is an (s, t) -cut)



$$(\# \text{ paths packed}) \stackrel{!}{=} (\max \# \text{ disjoint } s \rightarrow t \text{ paths}) \stackrel{!}{=} (\min \# \text{ edges in any } s \rightarrow t \text{ cut}) \stackrel{!}{=} (\# \text{ edges initially in } C)$$

Theorems

$$\textcircled{1} \left(\max \# \text{ disjoint } s \rightarrow t \text{ paths} \right) = \left(\min \# \text{ edges in any } s \rightarrow t \text{ cut} \right)$$

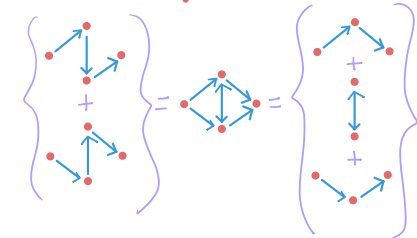
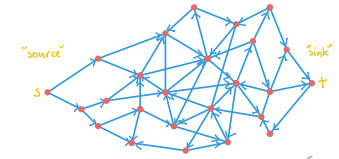
$$\textcircled{2} \left(\# \text{ paths packed} \right) = \left(\max \# \text{ disjoint } s \rightarrow t \text{ paths} \right)$$

$$\textcircled{3} \left(\min \# \text{ edges in any } s \rightarrow t \text{ cut} \right) = \left(\# \text{ edges initially in } C \right)$$

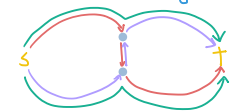
(where $(\# \text{ paths packed})$ and $(\# \text{ edges initially in } C)$ refers to the outcome of iterative finding paths in the residual graph)

How to compute

⑦ max # of edge-disjoint $s \rightarrow t$ paths?



Lemma let p, q be edge-disjoint $s \rightarrow t$ paths



then there is p', q' : $s \rightarrow t$ disjoint without opposite pairs of edges

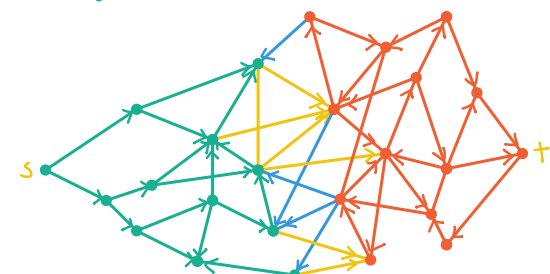
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augmenting-paths($G = (V, E), s, t$)

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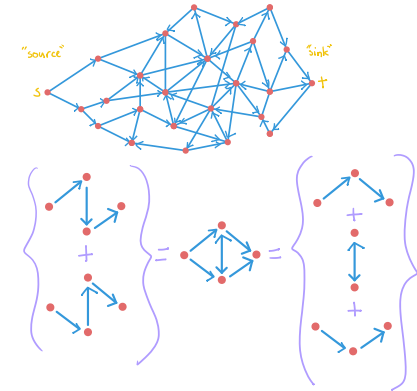
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3. $S \leftarrow \{\text{vertices still reachable from } s\}$.
4. Return the (s, t) -path packing P and the (s, t) -cut $\partial^+(S)$.

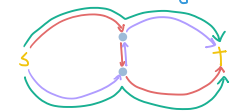
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How to compute

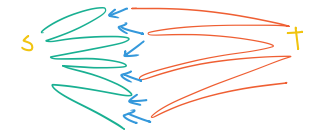
⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



Lemma let p, q be edge-disjoint $s \rightsquigarrow t$ paths



then there is $p', q' : s \rightsquigarrow t$ disjoint without opposite pairs of edges



$$\textcircled{1} \left(\begin{array}{c} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{array} \right) = \left(\begin{array}{c} \text{min \#} \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{array} \right)$$

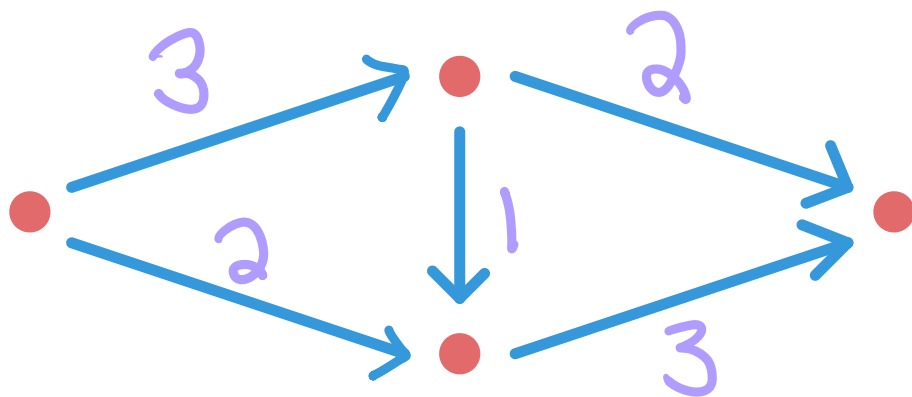
$$\textcircled{2} \left(\begin{array}{c} \# \text{ paths} \\ \text{packed} \end{array} \right) = \left(\begin{array}{c} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{array} \right)$$

$$\textcircled{3} \left(\begin{array}{c} \text{min \#} \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{array} \right) = \left(\begin{array}{c} \# \text{ edges} \\ \text{initially in } C \end{array} \right)$$

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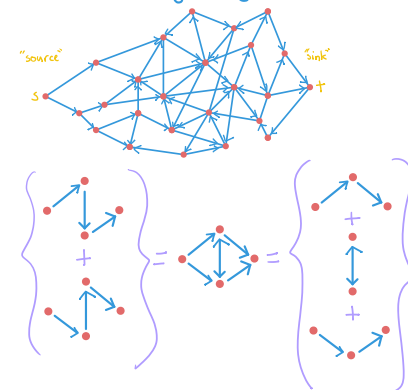
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Next time: edge capacities,
fractional packings, & network flow

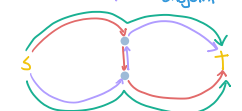


How to compute

⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



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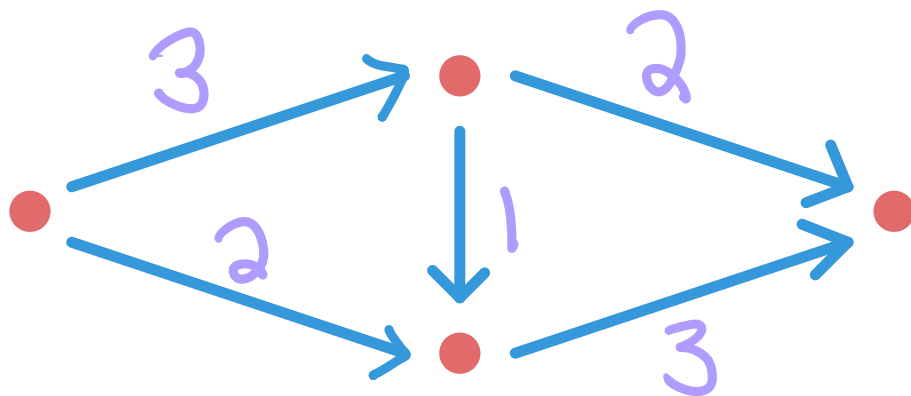
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capacity $c(e) > 0$: we can reuse
edge e up to $c(e)$ times

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capacity $c(e) > 0$: reuse edge e up to $c(e)$ times

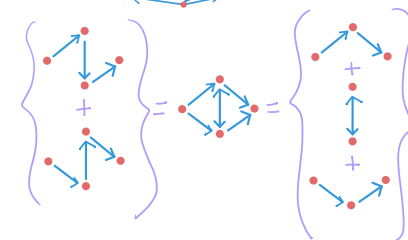
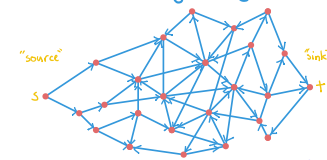
• if $c(e)$ large, Augmenting-Paths not polynomial time

• if $c(e)$ not integral (and just real-valued)

what about max fractional path packing

How to compute

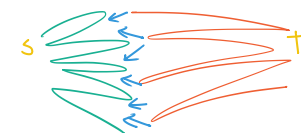
⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



Lemma let p, q be edge-disjoint $s \rightsquigarrow t$ paths



then there is p', q' : $s \rightsquigarrow t$ disjoint without opposite pairs of edges



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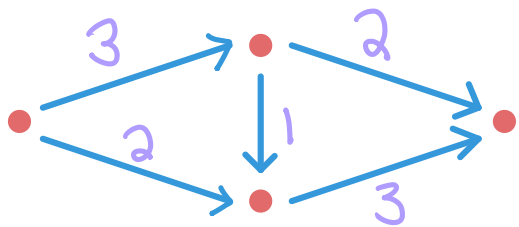
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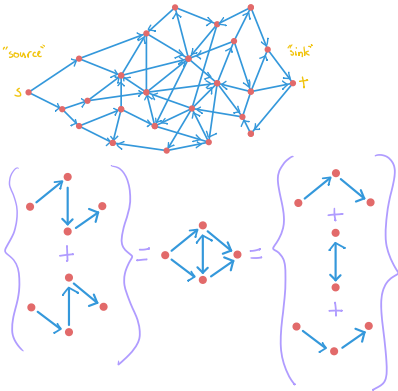


capacity $c(e) > 0$:
reuse edge e up to $c(e)$ times

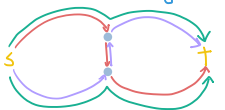
(Weighted) path packings

How to compute

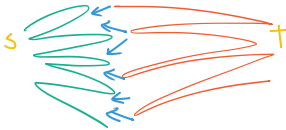
⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



Lemma let p, q be edge-disjoint $s \rightsquigarrow t$ paths



then there is $p', q' : s \rightsquigarrow t$ disjoint without opposite pairs of edges



① $\left(\begin{smallmatrix} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{smallmatrix} \right) = \left(\begin{smallmatrix} \text{min \#} \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{smallmatrix} \right)$

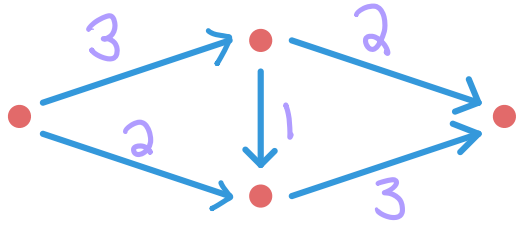
② $\left(\begin{smallmatrix} \# \text{ paths} \\ \text{packed} \end{smallmatrix} \right) = \left(\begin{smallmatrix} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{smallmatrix} \right)$

③ $\left(\begin{smallmatrix} \text{min \#} \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{smallmatrix} \right) = \left(\begin{smallmatrix} \# \text{ edges} \\ \text{initially in } C \end{smallmatrix} \right)$

1. $P \leftarrow \emptyset$
2. While there is an (s, t) -path $p : s \rightsquigarrow t$:
 - A. Remove all of p 's edges from the graph.
 - B. Add the reverse of all of p 's edges to the graph.
 - C. Uncross p with previously selected paths, and add p to P .³
3. $S \leftarrow \{\text{vertices still reachable from } s\}$.
4. Return the (s, t) -path packing P and the (s, t) -cut $\partial^+(S)$.

*/

Theorem 14.5 ([FF56]). *Let $G = (V, E)$ be a directed graph with m edges, and let $s, t \in V$ be distinct vertices. Let λ be the size of the max-flow/min-cut from s to t . Then augmenting-paths(G, s, t) produces both a maximum packing and a minimum cut in $O(m\lambda)$ time.*

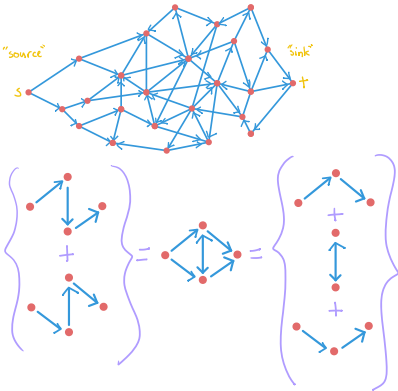


capacity $c(e) > 0$:
reuse edge e up to $c(e)$ times

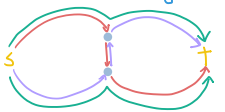
Integer capacities

How to compute

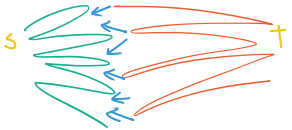
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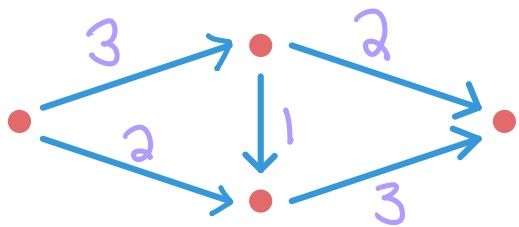
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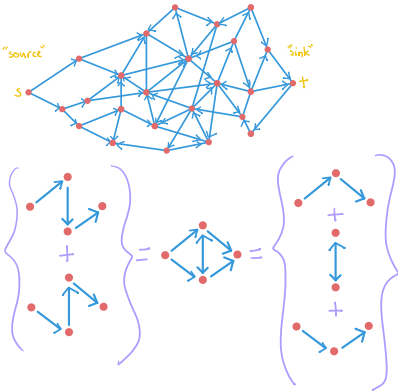


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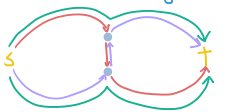
Rational capacities

How to compute

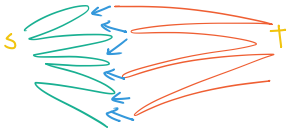
⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



Lemma let p, q be edge-disjoint $s \rightsquigarrow t$ paths



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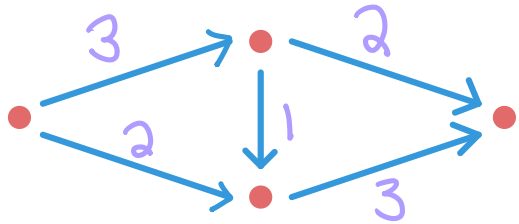
② $\left(\begin{smallmatrix} \# \text{ paths} \\ \text{packed} \end{smallmatrix} \right) = \left(\begin{smallmatrix} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{smallmatrix} \right)$

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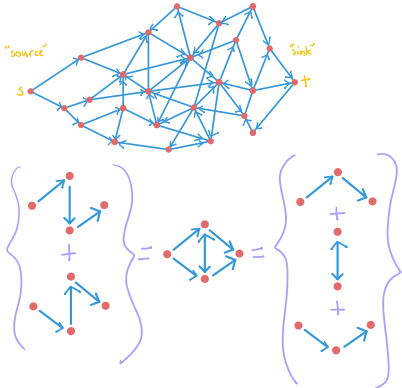


capacity $c(e) > 0$:
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Real capacities

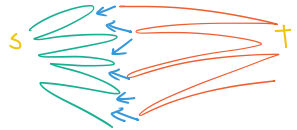
How to compute

⑦ max # of edge-disjoint $s \rightsquigarrow t$ paths?



Lemma let p, q be edge-disjoint $s \rightsquigarrow t$ paths

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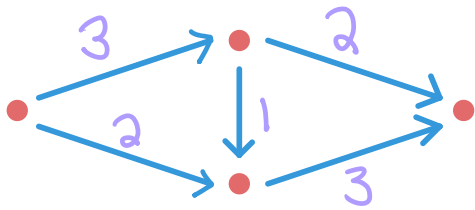
augmenting-paths($G = (V, E), s, t$)

/* Ford and Fulkerson [FF56]

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capacity $c(e) > 0$: reuse edge e
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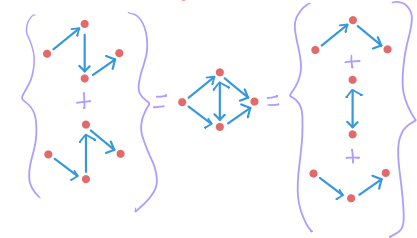
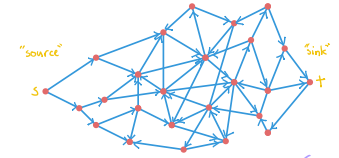
- if $c(e)$ large, Augmenting-Paths not polynomial time
- if $c(e)$ not integral (and just real-valued) what about max fractional path packing

Good news:

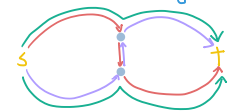
our duality theorems still hold

How to compute

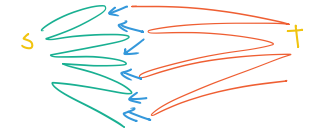
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$$\textcircled{1} \left(\begin{array}{c} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{array} \right) = \left(\begin{array}{c} \text{min \#} \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{array} \right)$$

$$\textcircled{2} \left(\begin{array}{c} \# \text{ paths} \\ \text{packed} \end{array} \right) = \left(\begin{array}{c} \text{max \#} \\ \text{disjoint} \\ s \rightsquigarrow t \text{ paths} \end{array} \right)$$

$$\textcircled{3} \left(\begin{array}{c} \text{min \#} \\ \text{edges in any} \\ s \rightsquigarrow t \text{ cut} \end{array} \right) = \left(\begin{array}{c} \# \text{ edges} \\ \text{initially in } C \end{array} \right)$$

remaining issues algorithmic

Max Flow "liquid" version of path packing

Input $G=(V,E)$ directed capacities $c:E \rightarrow \mathbb{R}_{>0}$

source $s \in V$, sink $t \in V$

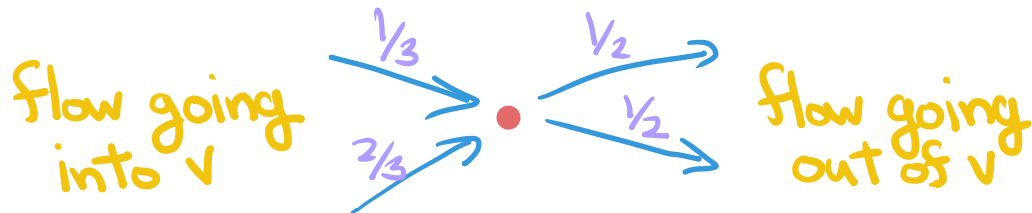
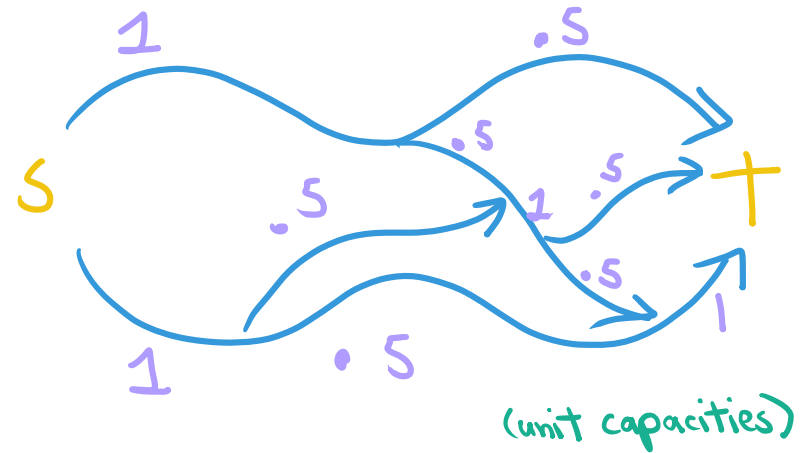
"s-t Flow" $f:E \rightarrow \mathbb{R}_{\geq 0}$ s.t.

(a) "capacity constraints"

$$0 \leq f(e) \leq c(e) \quad \forall e \in E$$

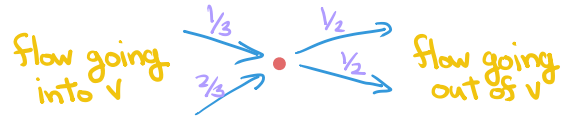
(b) "conservation of flow"

$$\sum_{(u,v) \in E} f(u,v) = \sum_{(v,w) \in E} f(v,w) \quad \forall v \notin \{s,t\}$$

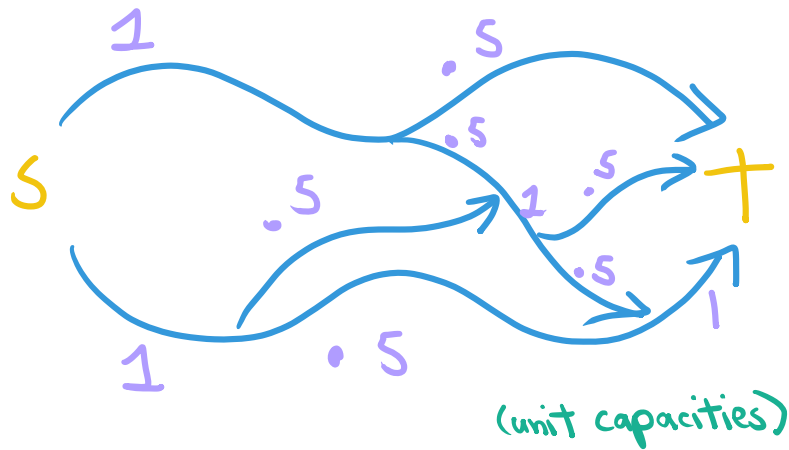


(b) "Conservation of flow"

$$\sum_{(u,v) \in E} f(u,v) = \sum_{(v,w) \in E} f(v,w) \quad \forall v \notin \{s, t\}$$



net flow out of s = net flow into t



"net flow from s to t",
"size of flow"

Max flow problem

find $s \rightarrow t$ flow of maximum size

"linear program"

size of flow

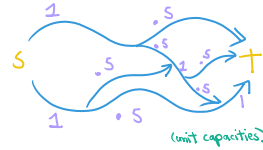
$$\max \sum_{(s \rightarrow w) \in E} f(s, w) - \sum_{(u \rightarrow s) \in E} f(u, s) \quad \text{over } f \in \mathbb{R}^E$$

"capacity constraints" s.t. $0 \leq f(e) \leq c(e) \quad \forall e \in E$

"conservation of flow" $\sum_{(u, v) \in E} f(u, v) = \sum_{(v, w) \in E} f(v, w) \quad \forall v \notin \{s, t\}$

"linear program" because objective, constraints, all linear functions of f

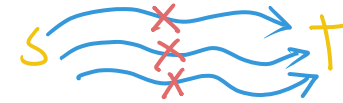
How does Max Flow



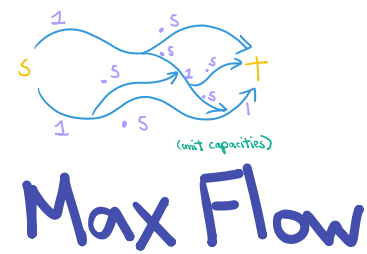
relate to

max path packings,

min cut?




 max path packings vs



let $x: P_{s,t} \rightarrow \mathbb{R}_{\geq 0}$ encode a path packing

define $f: E \rightarrow \mathbb{R}_{\geq 0}$ as:

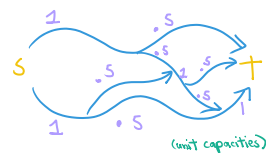
$$f(e) = \sum_{p: e \in p} x_p.$$

then f is feasible flow of same size

(PSO discusses converse)

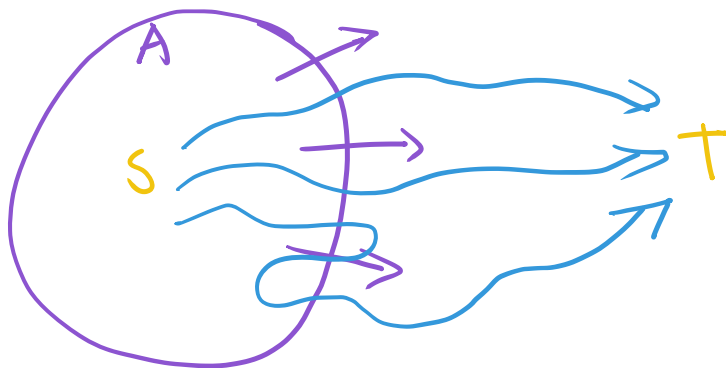


vs



Max Flow

let $C = 2^+(A)$ min-cut, $f: E \rightarrow \mathbb{R}_{\geq 0}$ max flow
 (ACV w/ $s \in A$, $t \notin A$)



$$(\text{size of } f) = (\text{net flow out of } A) \leq (\text{capacity of } 2^+(A))$$

max path packings vs Max Flow

let $x: P_{s,t} \rightarrow \mathbb{R}_{\geq 0}$ encode a path packing

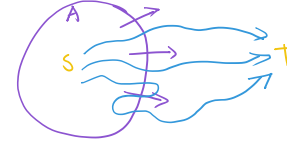
define $f: E \rightarrow \mathbb{R}_{\geq 0}$ as:

$$f(e) = \sum_{p: e \in p} x_p$$

then f is feasible flow of same size

min cut vs Max Flow

let $C = \partial^+(A)$ min-cut, $f: E \rightarrow \mathbb{R}_{\geq 0}$ max flow
($A \subset V$ w/ $s \in A, t \notin A$)

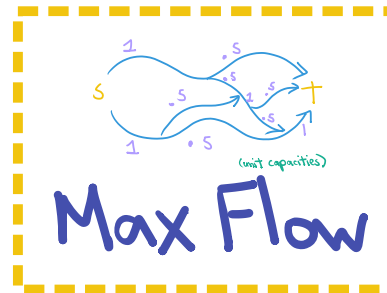


$$(\text{size of } f) = (\text{net flow out of } A) \leq (\text{capacity of } \partial^+(A))$$

we showed



$\leq$



$\leq$



But

equal

 max path packings vs  Max Flow
 let $x: P_{st} \rightarrow \mathbb{R}_{\geq 0}$ encode a path packing
 define $f: E \rightarrow \mathbb{R}_{\geq 0}$ as:

$$f(e) = \sum_{p \ni e} x_p$$

 then f is feasible flow of same size

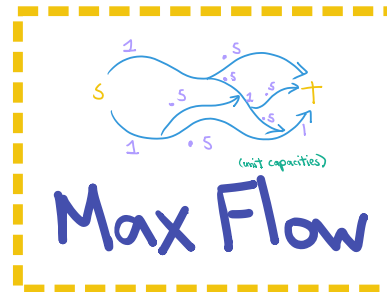
 min cut vs  Max Flow
 let $C = \mathcal{J}(A)$ min-cut, $f: E \rightarrow \mathbb{R}_{\geq 0}$ max flow
 (not at unit flow)

 $(\text{size of } f) = (\text{net flow out of } A) \leq (\text{capacity of } \mathcal{J}(A))$

Theorem



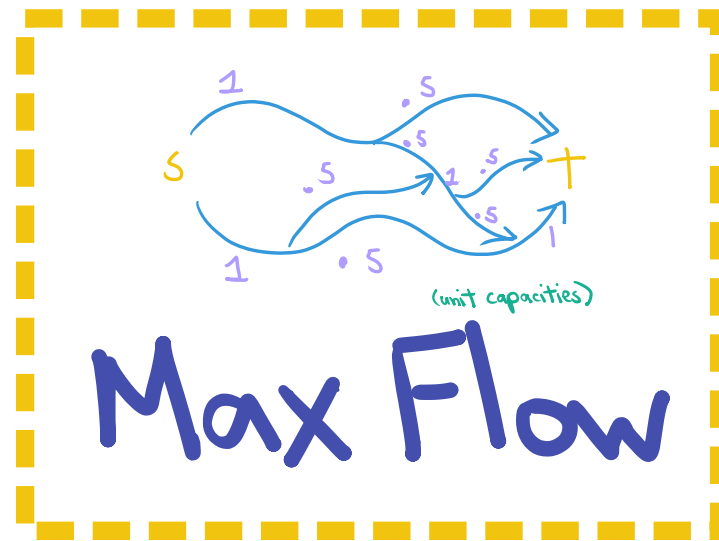
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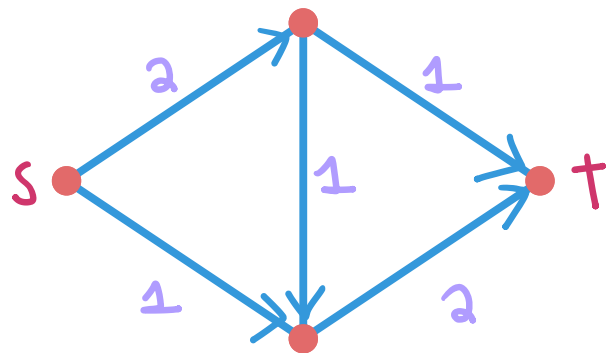
Next: strongly polynomial times



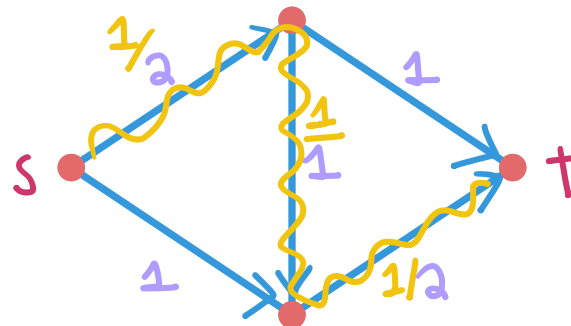
Residual graphs w/r/t flows

(exactly what you would expect)

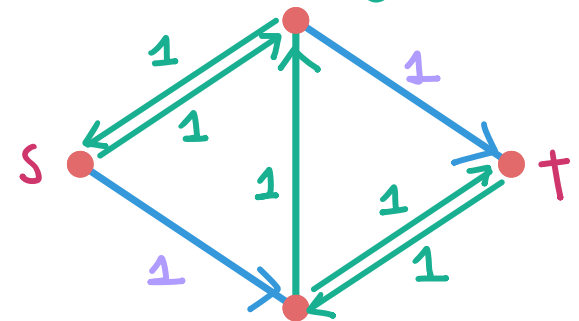
(capacities)



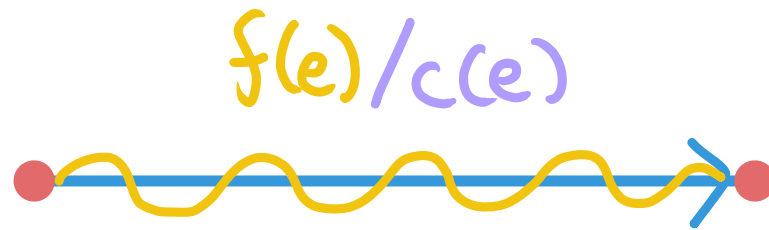
(1 unit flow)



(residual edges)



let $f: E \rightarrow \mathbb{R}_{\geq 0}$ be s-t flow
 $e \in E$ w/ capacity $c(e)$

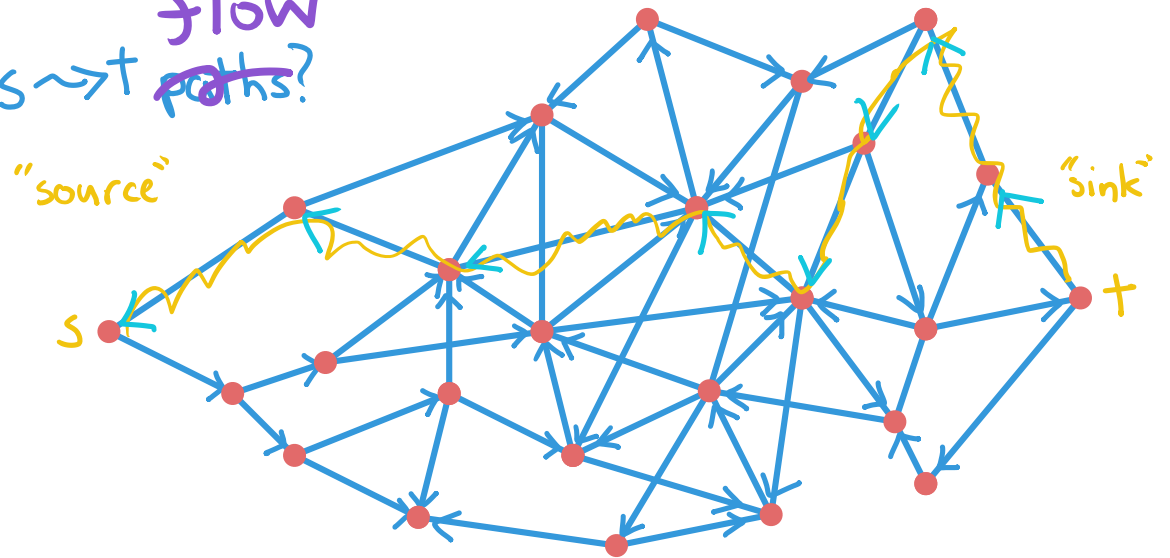


this leaves $f(e) - c(e)$ capacity in forwards direction
and $f(e)$ capacity backwards



How to compute

⑦ max # of ~~edge-disjoint~~ $s \rightsquigarrow t$ ~~paths?~~ ^{flow}



① while there is a path $p: s \rightsquigarrow t$

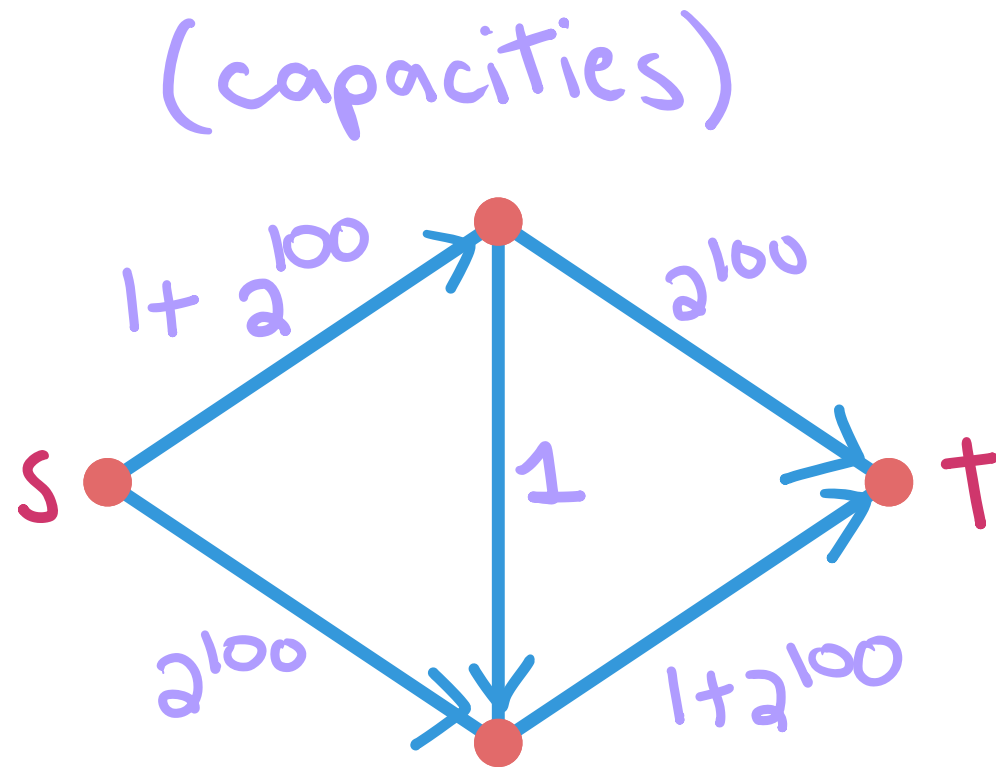
Ⓐ take p and ~~remove all its~~ route as much
~~edges from the graph~~ flow as possible

Ⓑ add the reverse of all of p 's
edges in the graph

Ⓒ uncross p w/ previously selected
paths

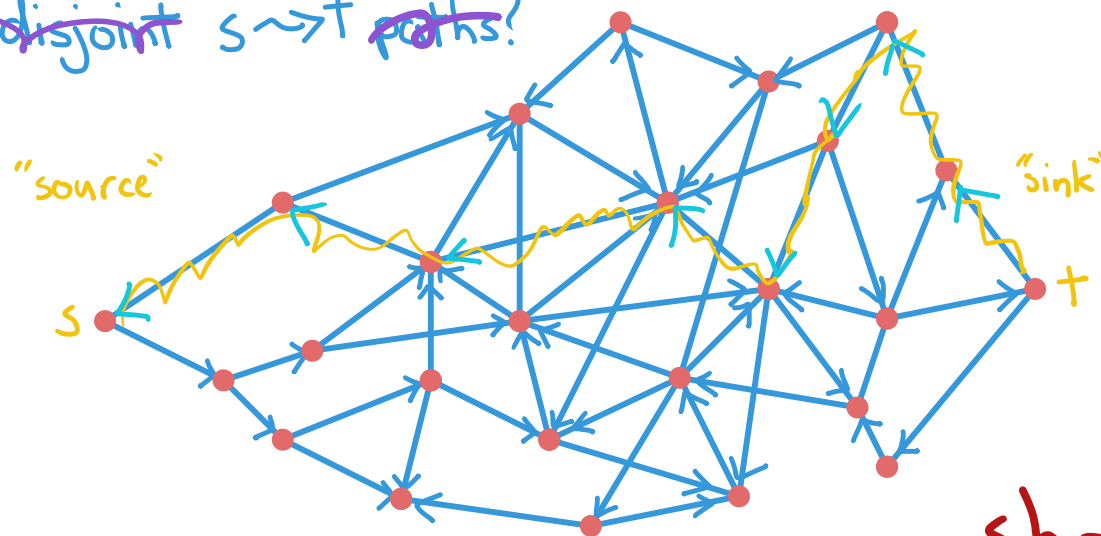
update residual
graph

↑
reasonable, but not quite polynomial time



How to compute

⑦ max ~~# of edge-disjoint~~ $s \rightsquigarrow t$ ~~paths?~~ ^{flow}



shortest path
(Edmonds, Karp)

① while there is a path $p: s \rightsquigarrow t$

Ⓐ take p and ~~remove all its~~ route as much flow as possible
~~edges from the graph~~

Ⓑ add the reverse of all of p 's edges in the graph

Ⓒ ~~uncross p w/ previously selected~~ paths

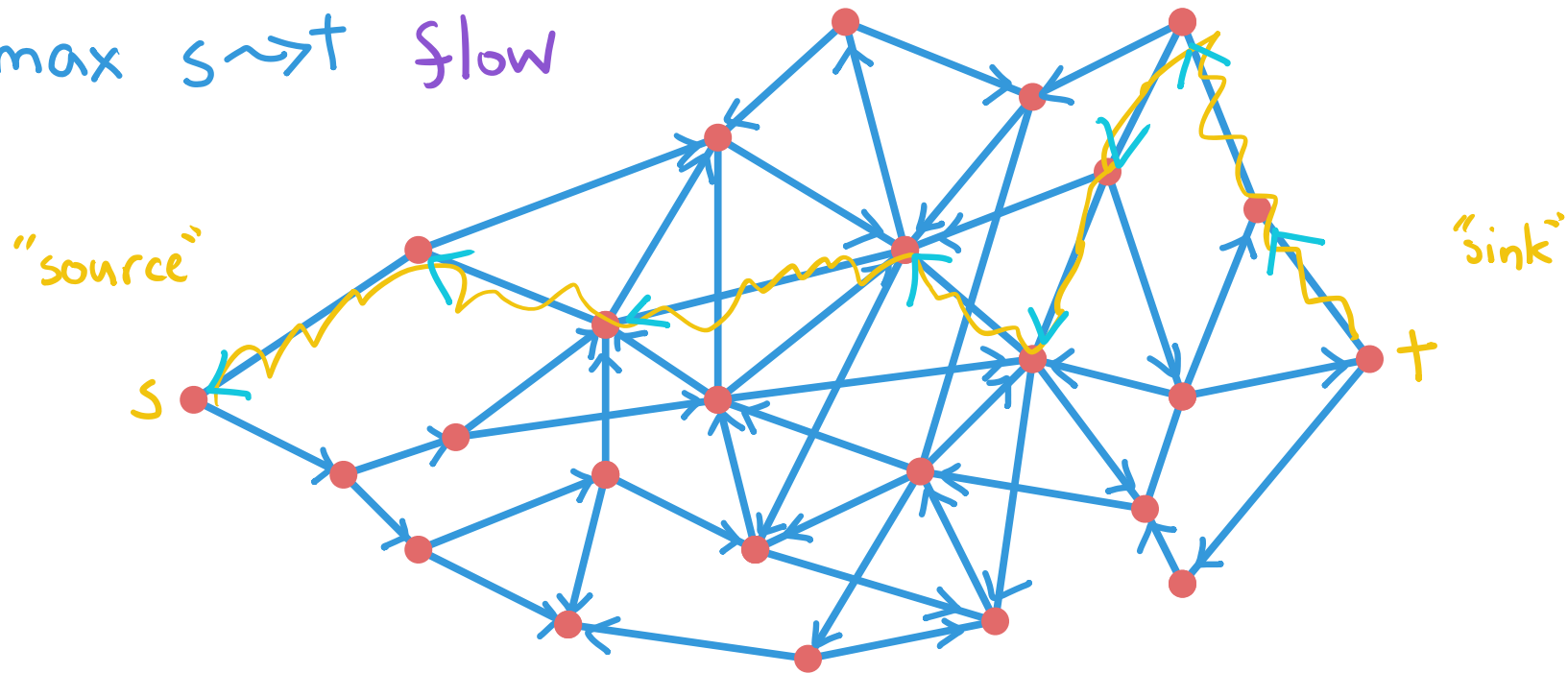
update residual graph

(cleaned up)

(Edmonds, Karp)

How to compute

⑦ max $s \rightsquigarrow t$ flow



① while there is a path $p: s \rightsquigarrow t$

② take shortest path p and
route as much flow as possible

③ update residual graph

Analysis

① while there is a path $p: s \rightsquigarrow t$

Ⓐ take shortest path p and
route as much flow as possible

Ⓑ update residual graph

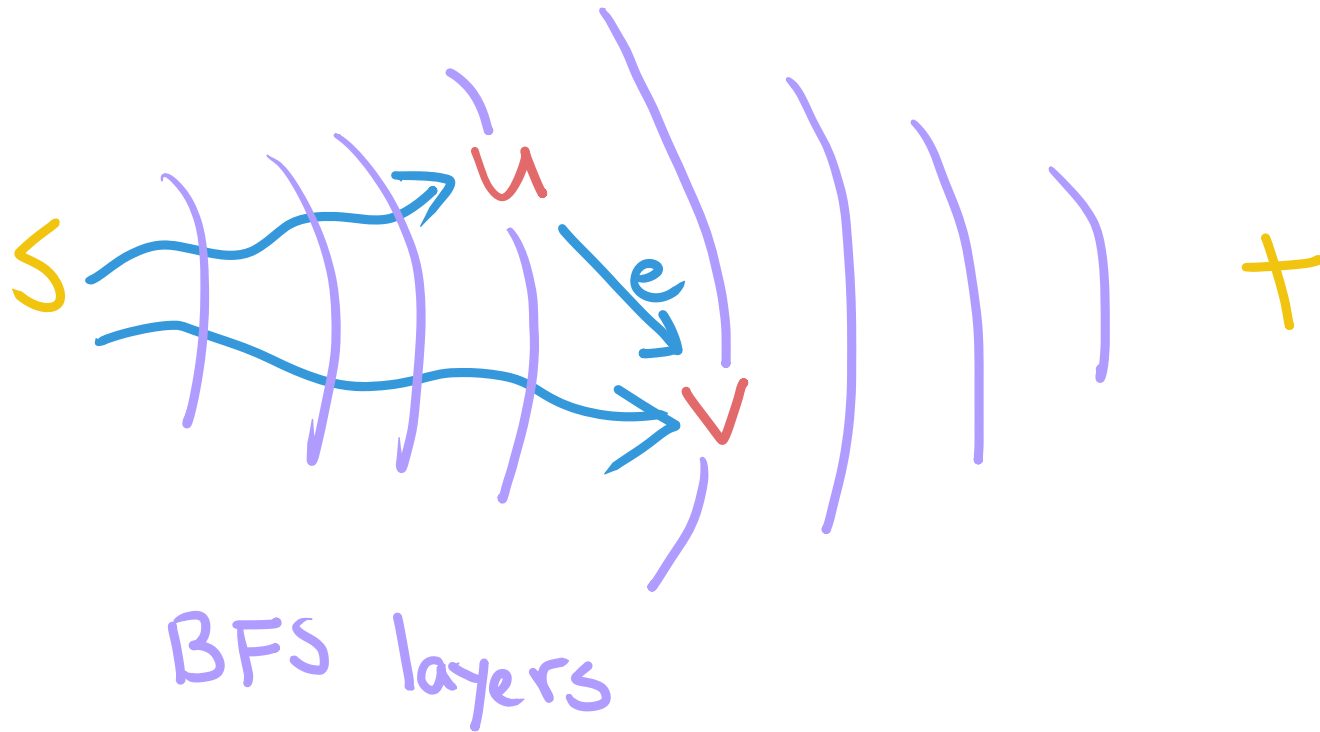
Key
Lemma $\forall v \in V$, distance from s to v
in residual graph never decreases



let us first assume true.

fix $e = (u \rightarrow v) \in E$,

consider distances to u and v



① while there is a path $p: s \rightsquigarrow t$

② take **shortest path** p and
route as much flow as possible
③ update residual graph

Key
Lemma $\forall v \in V$, distance from s to v
in residual graph never decreases

① e removed from RG ,
 $\Rightarrow e$ in shortest $s \rightsquigarrow t$ path



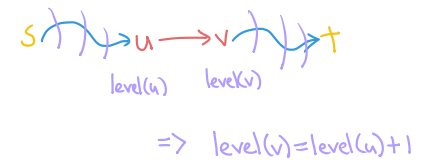
$$\Rightarrow level(v) = level(u) + 1$$

① while there is a path $p: s \rightsquigarrow t$

- ② take **shortest path** p and route as much flow as possible
- ③ update residual graph

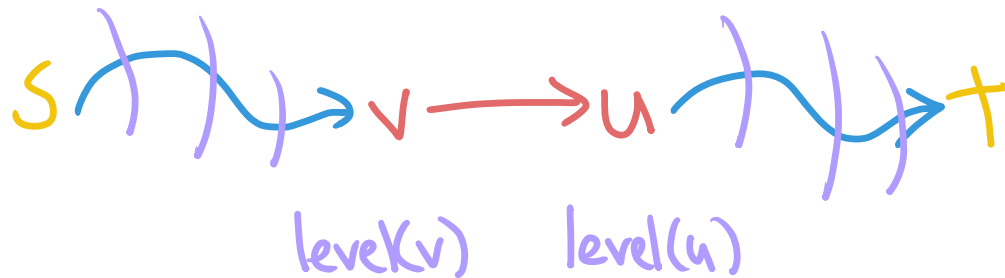
Key Lemma $\forall v \in V$, distance from s to v in residual graph never decreases

- ① e removed from ^(residual graph) RG ,
 $\Rightarrow e$ in shortest $s \rightsquigarrow t$ path



② $e = (u \rightarrow v)$ added back in to RG

$\Rightarrow (v \rightarrow u)$ was in shortest $s \rightsquigarrow t$ path



$$\Rightarrow \text{level}(u) = \text{level}(v) + 1$$

④ while there is a path $p: s \rightsquigarrow t$

⑥ take shortest path p and
route as much flow as possible

⑦ update residual graph

Key
Lemma $\forall v \in V$, distance from s to v
in residual graph never decreases

① e removed from ^(residual graph) RG ,
 $\Rightarrow e$ in shortest $s \rightsquigarrow t$ path



$\Rightarrow level(v) = level(u) + 1$

② $e = (u \rightarrow v)$ added back in to RG
 $\Rightarrow (v \rightarrow u)$ was in shortest $s \rightsquigarrow t$ path



$\Rightarrow level(u) = level(v) + 1$

each event ①/② $\Rightarrow level(u), level(v)$ have switched order.

level's nondecreasing by key lemma

$\Rightarrow e$ gets deleted/added at most n times

Last observation

each iteration removes (at least)
one edge from residual graph

b/c we route as much as possible

= $O(mn)$ iterations

Running time

$O(m)$ per iteration

$O(mn)$ iterations

$O(m^2n)$ time

Key
Lemma $\forall v \in V$, distance from s to v
in resid. graph never decreases

Proof

Suppose we augment along $p: s \rightsquigarrow t$
need to show no levels decrease
induction on level before augmenting

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Base case

if level was 0, then cannot decrease

Key
Lemma $\forall v \in V$, distance from s to v
in resid. graph never decreases

Proof

Suppose we augment along $p: s \rightsquigarrow t$
need to show no levels decrease
induction on level before augmenting

General case suppose level of $v > 0$
(after augmentation)

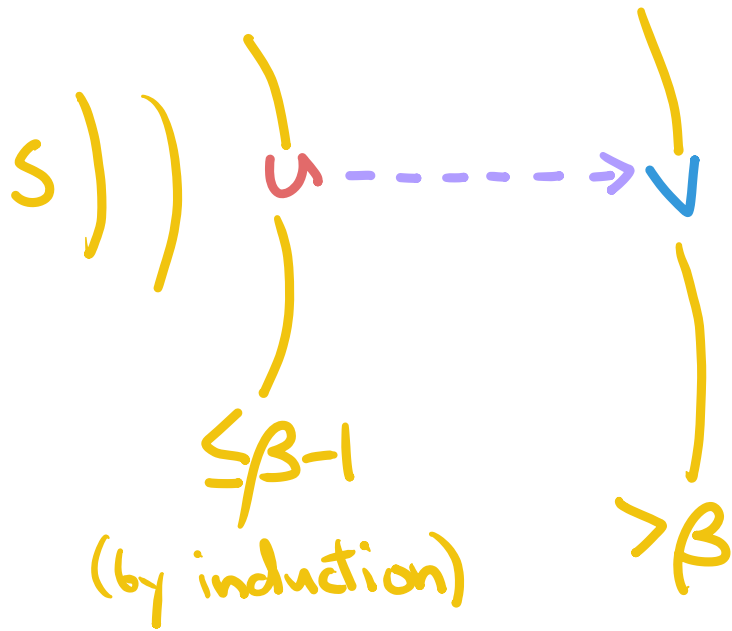
α = level before

β = level after

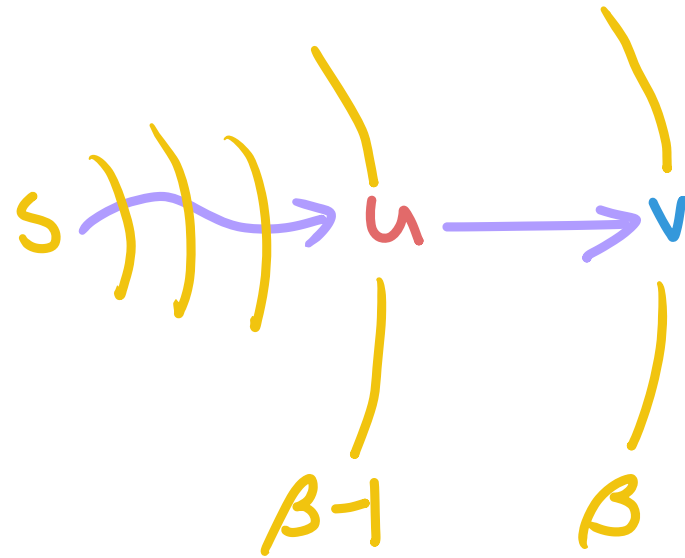
suppose by contradiction $\beta < \alpha$.

let u be previous vertex in $s \rightsquigarrow v$ path ^{shortest} after

BEFORE



AFTER



level $u = \beta - 1$ after

by induction, level of $u \leq \beta - 1$ before

$\Rightarrow u \rightarrow v$ not in RG before graph

$\Rightarrow v \rightarrow u$ in augmenting path (contradiction)

$\Rightarrow \text{level } v < \text{level } u \text{ before}$ ~~$=$~~

Analysis

Edmonds, Karp

① while there is a path $p: s \rightsquigarrow t$

② take shortest path p and
route as much flow as possible

③ update residual graph

Key

Lemma $\forall v \in V$, distance from s to v
in resid. graph never decreases

Running time

$O(m)$ per iteration

$O(mn)$ iterations

$O(m^2n)$ time

