Network Updates

Chapter 10

Distributed Systems lecture : Roger Wattenhofer
Today's lecturer: Klaus-Tycho Foerster

Overview

- Software-Defined Networking
- Blackhole-Free Updates
- Loop-Free Updates
- Packet Coherent Updates
- Capacity-Consistent Updates

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- **Software-Defined Networking**
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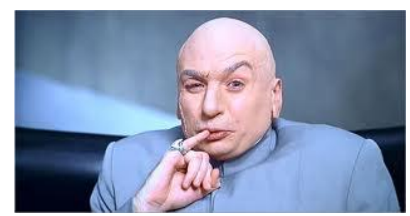
Network Updates

- The Internet: Designed for selfish participants
  - Often inefficient (low utilization of links), but robust

- But what happens if the WAN is controlled by a single entity?
  - Examples: Microsoft & Amazon & Google …
  - They spend hundreds of millions of dollars per year



Software-Defined Networking

- Possible solution: **S**oftware-**D**efined **N**etworking (**SDN**s)

- General Idea: Separate data & control plane in a network
- Centralized controller updates networks rules for optimization
  - Controller (*control plane*) updates the switches/routers (*data plane*)

Virtual Services ⟷ Controller ⟷ Physical Network

- Centralized controller implemented with replication, e.g. Paxos

When will the Network Updates be implemented?

old network rules

network updates

new network rules

Overview

- Software-Defined Networking
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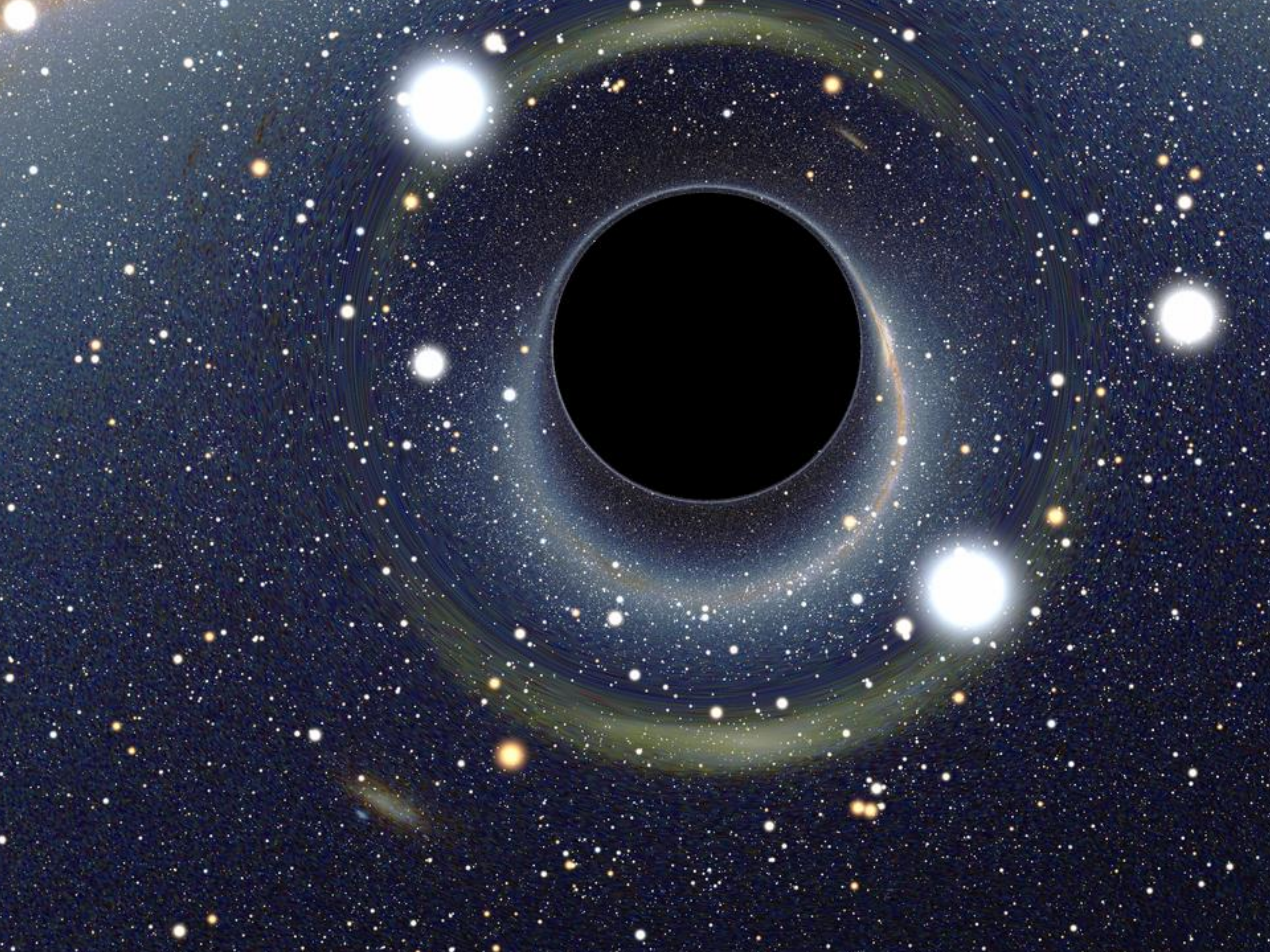
Dependencies	**None**
Eventual consistency	Always guaranteed



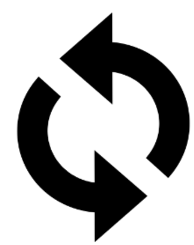
Blackholes

- Sounds scary? It is!*

- A packet arrives at some switch…
  - … while the switch deletes an old rule and implements a new one
  - So the switch does not know what to do with it?!
  - The packet gets dropped ☹

- What can we do?
  - Make sure that the switch always has some rule for every packet!

- How can we solve the problem?
  - “add before remove”
  - Just send everything back to the controller?
  - Send everything somewhere?
    - What is the issue with that?



*for network operators ☺

Overview

- Software-Defined Networking
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- **Loop-Free Updates**
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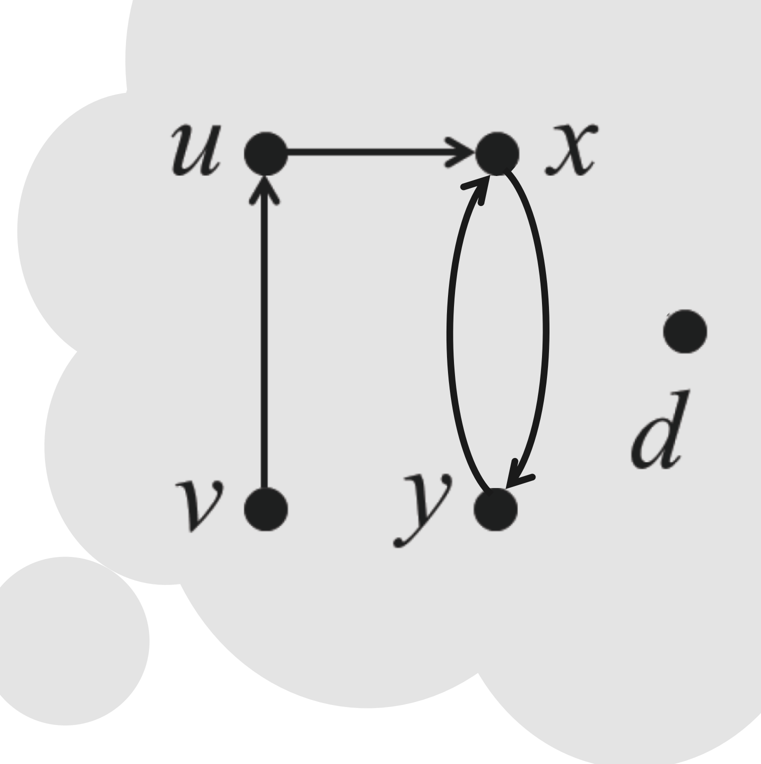
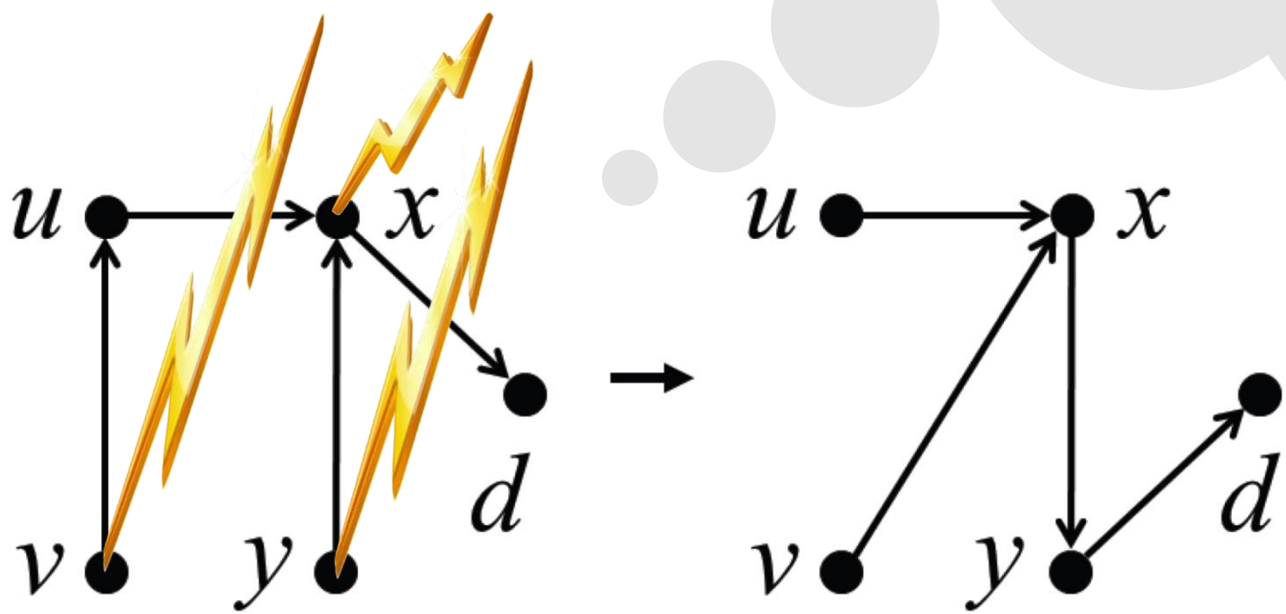
Dependencies	None	Self
Eventual consistency	Always guaranteed	
Blackhole freedom	Impossible	Add before remove

Loop-Free Updates

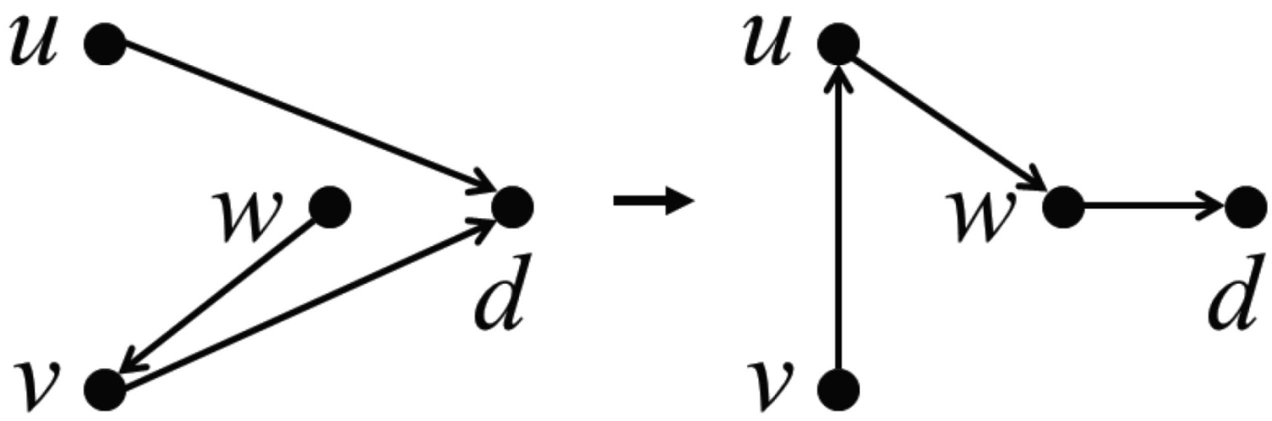
SDN Controller

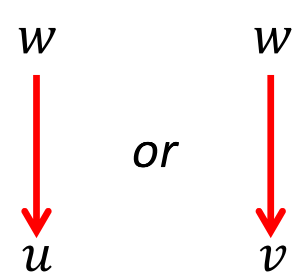




Minimum SDN Updates?

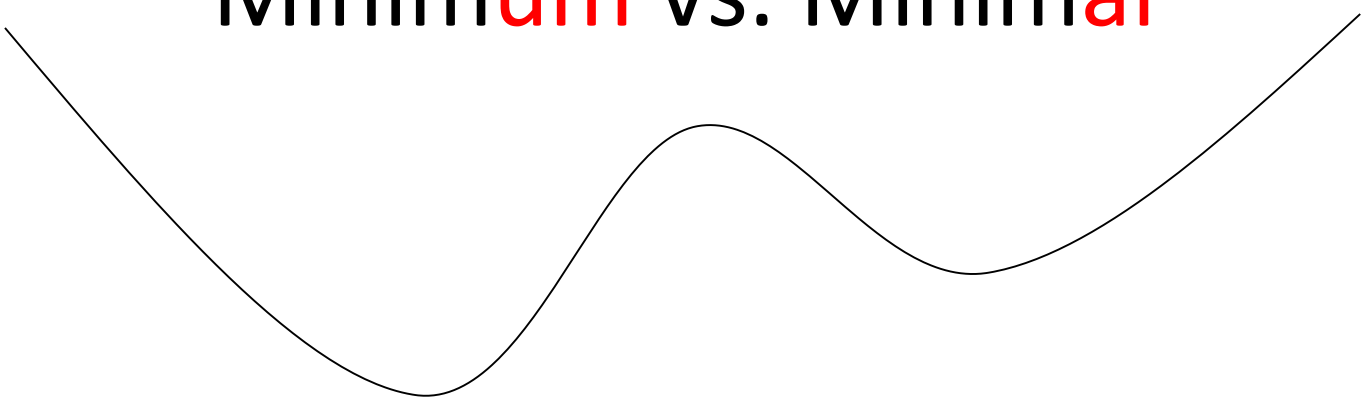
Minimum Updates: Another Example



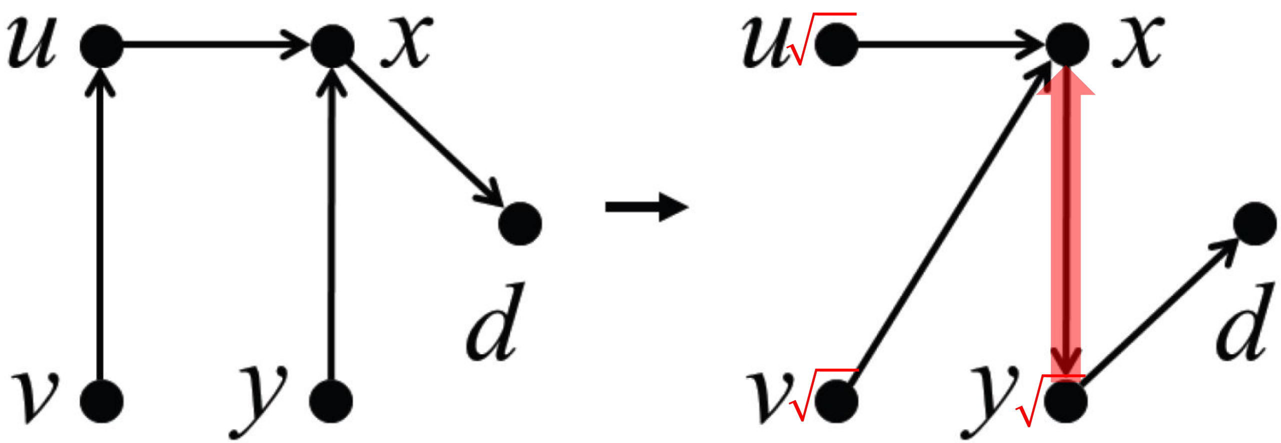


No node can improve without hurting another node

Minimum vs. Minimal



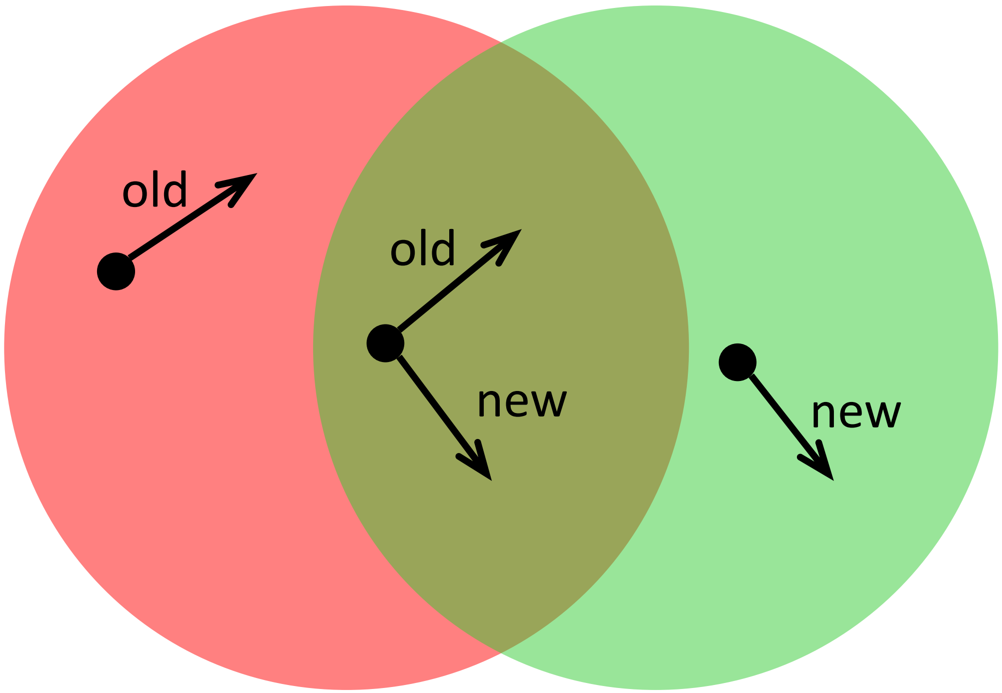
Minimal Dependency Forest



Next: An algorithm to compute minimal dependency forest.

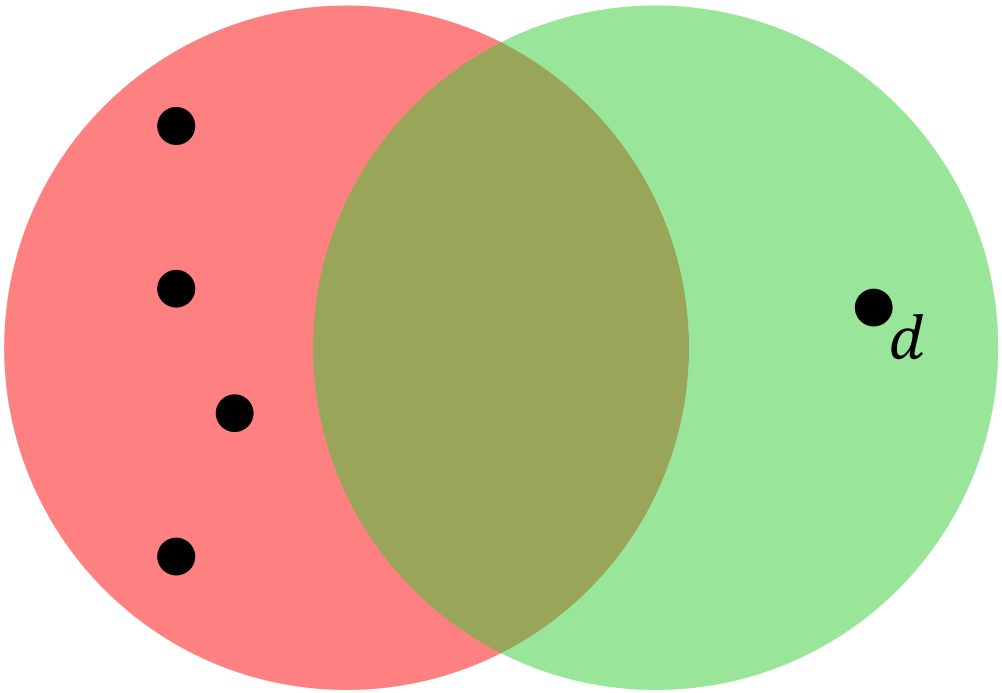
Algorithm for Minimal Dependency Forest

- Each node in one of three states: old, new, and limbo (both old *and* new)



Algorithm for Minimal Dependency Forest

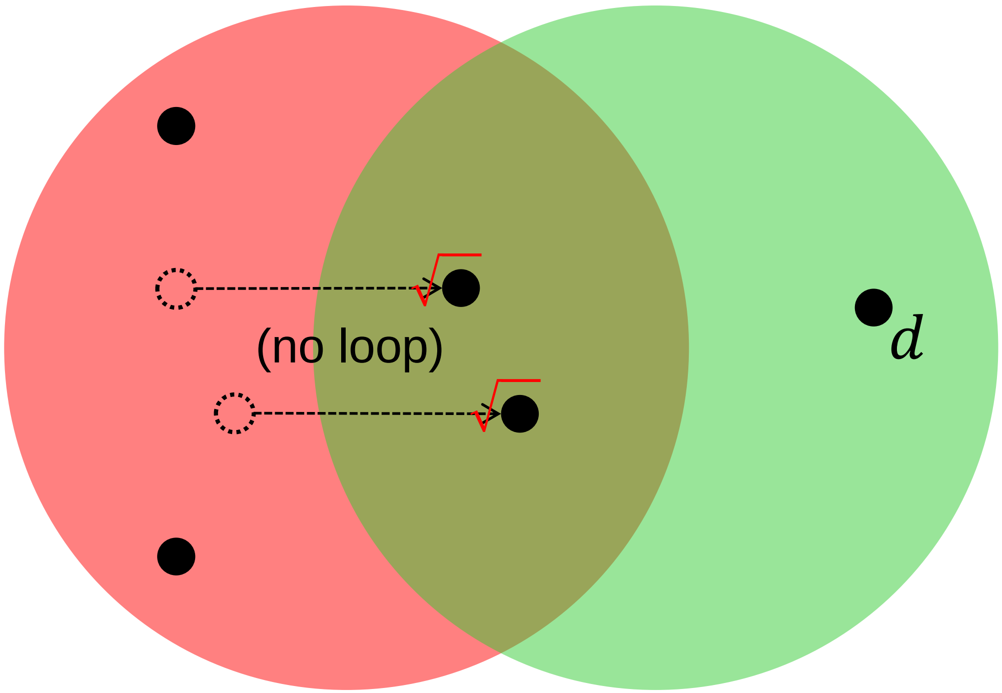
- Each node in one of three states: old, new, and limbo (both old *and* new)
- Originally, destination node in new state, all other nodes in old state
- Invariant: No loop!



Algorithm for Minimal Dependency Forest

Initialization

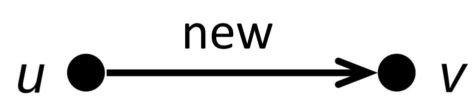
- Old node u: No loop* when adding new pointer, move node to limbo!
- This node u will be a root in dependency forest



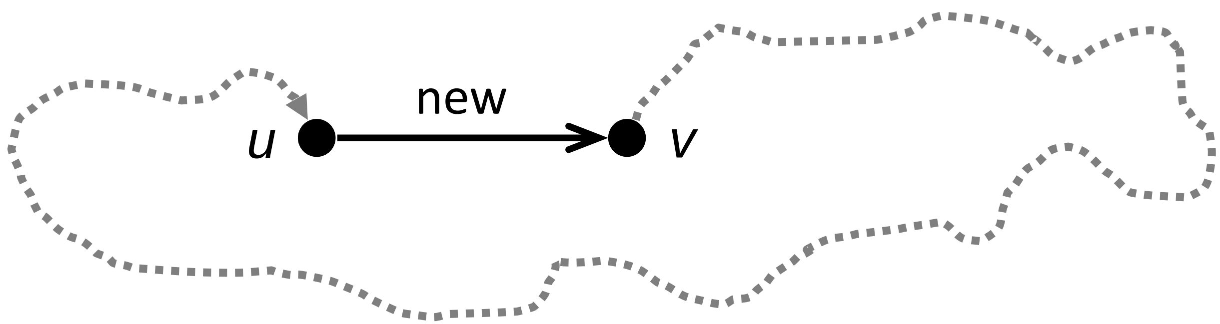
*Loop Detection: Simple procedure, see next slide

Loop Detection

- Will a new rule *u.new* = *v* induce a loop?
  - We know that the graph so far has no loops
  - Any new loop *must* contain the edge (*u,v*)



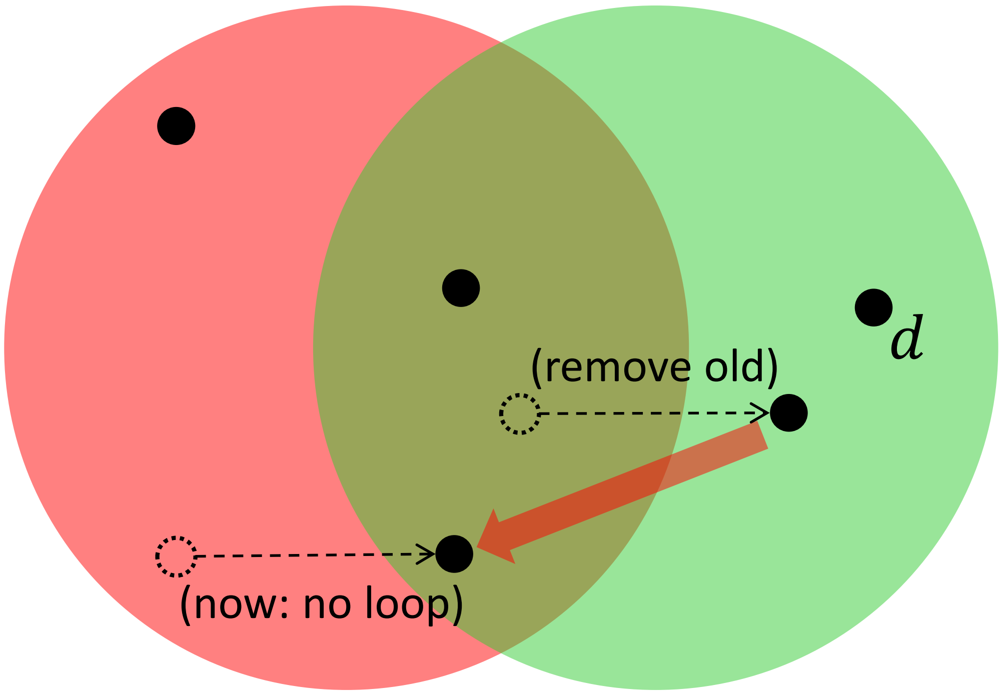
- In other words, is node *u* now *reachable* from node *v*?



- Depth first search (DFS) at node *v*
  - If we visit node *u*: the new rule induces a loop
  - Else: no loop

Algorithm for Minimal Dependency Forest

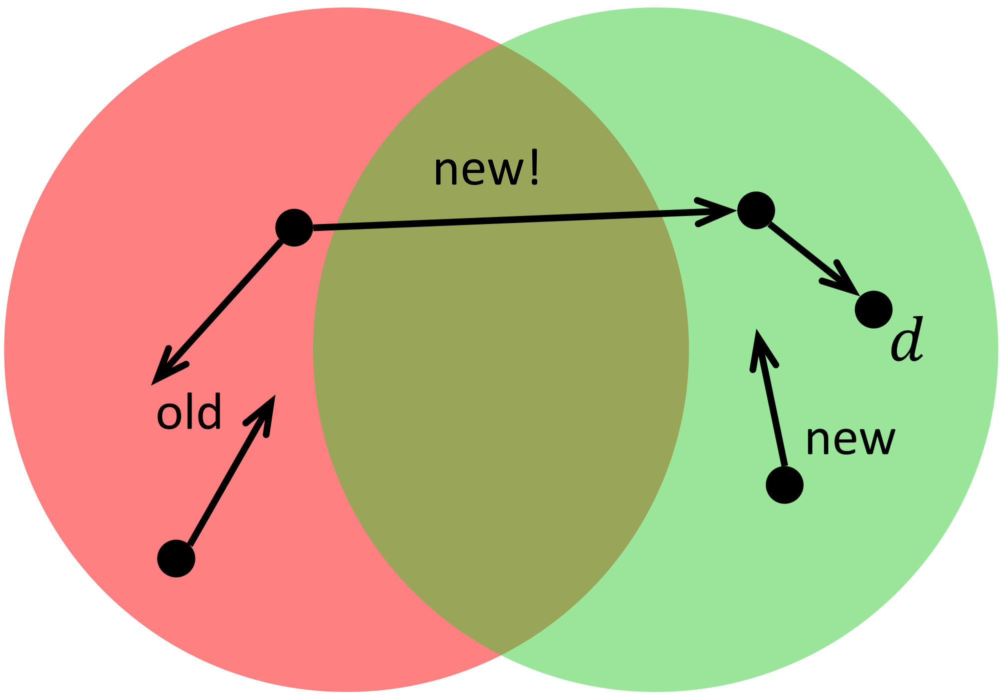
- Limbo node u: Remove old pointer (move node to new)
- Consequence: Some old nodes v might move to limbo!
- Node v will be child of u in dependency forest!



Algorithm for Minimal Dependency Forest

Process terminates

- You can always move a node from limbo to new.
- Can you ever have old nodes but no limbo nodes? No, because…

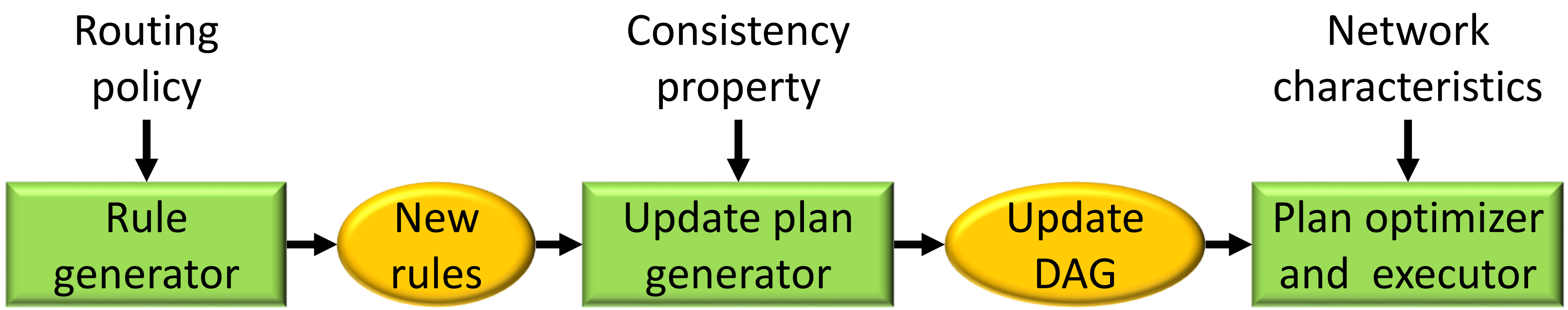


…one can easily derive a contradiction!

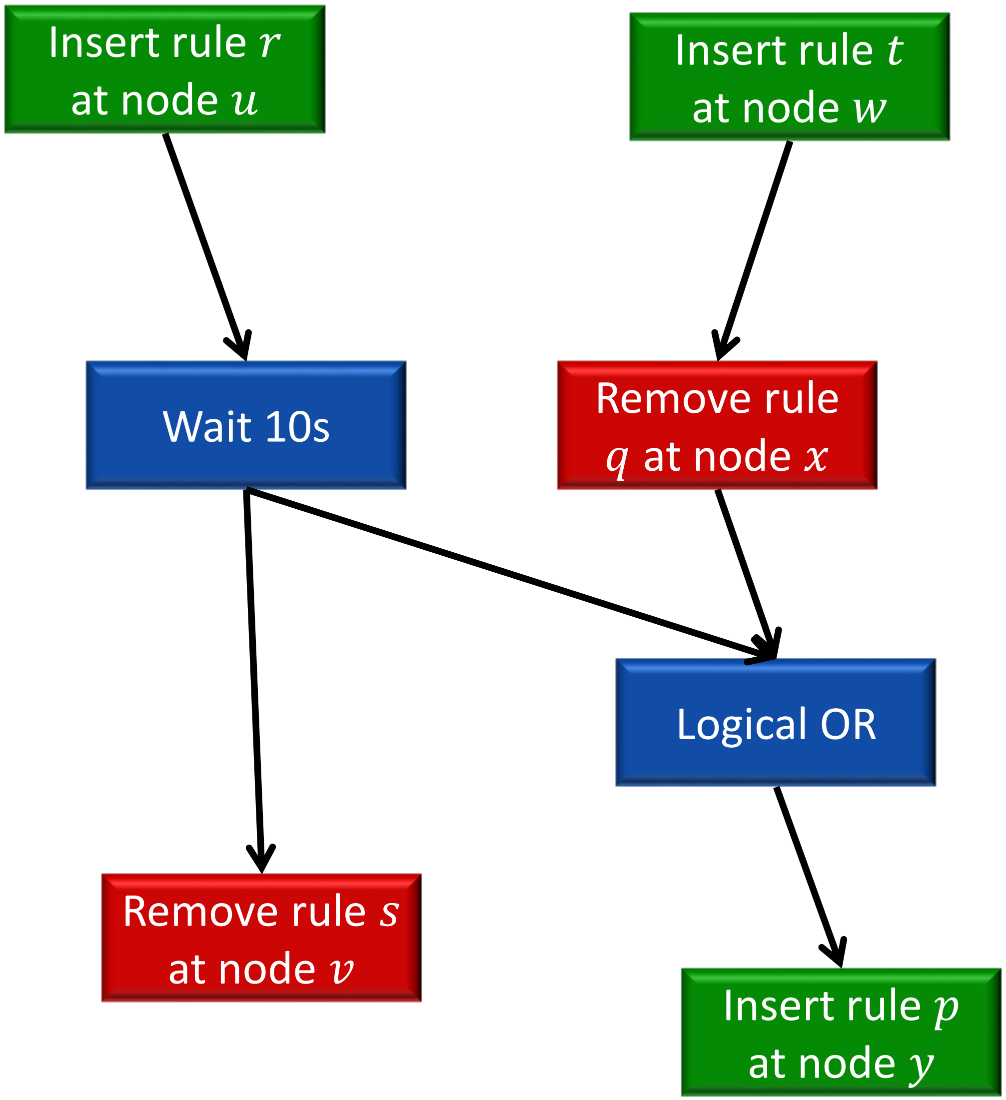
It's *not* just how to compute new rules.

It is also how to gracefully get from current to new configuration, respecting consistency.

Architecture

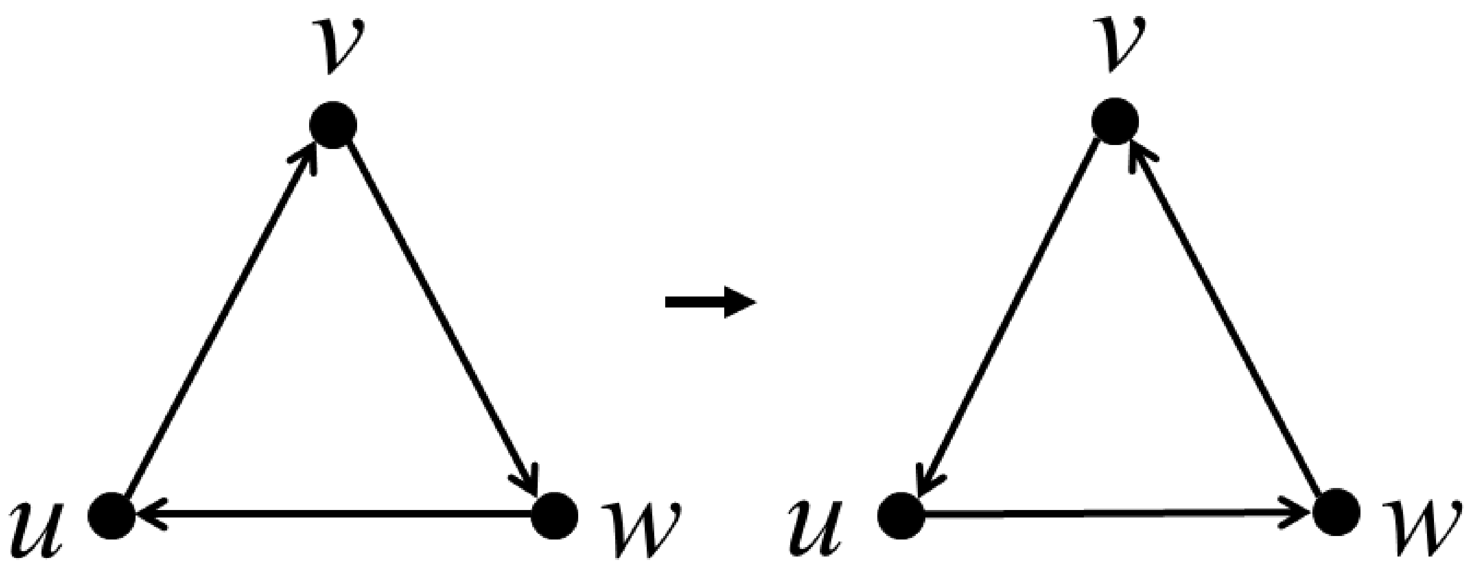


Update DAG



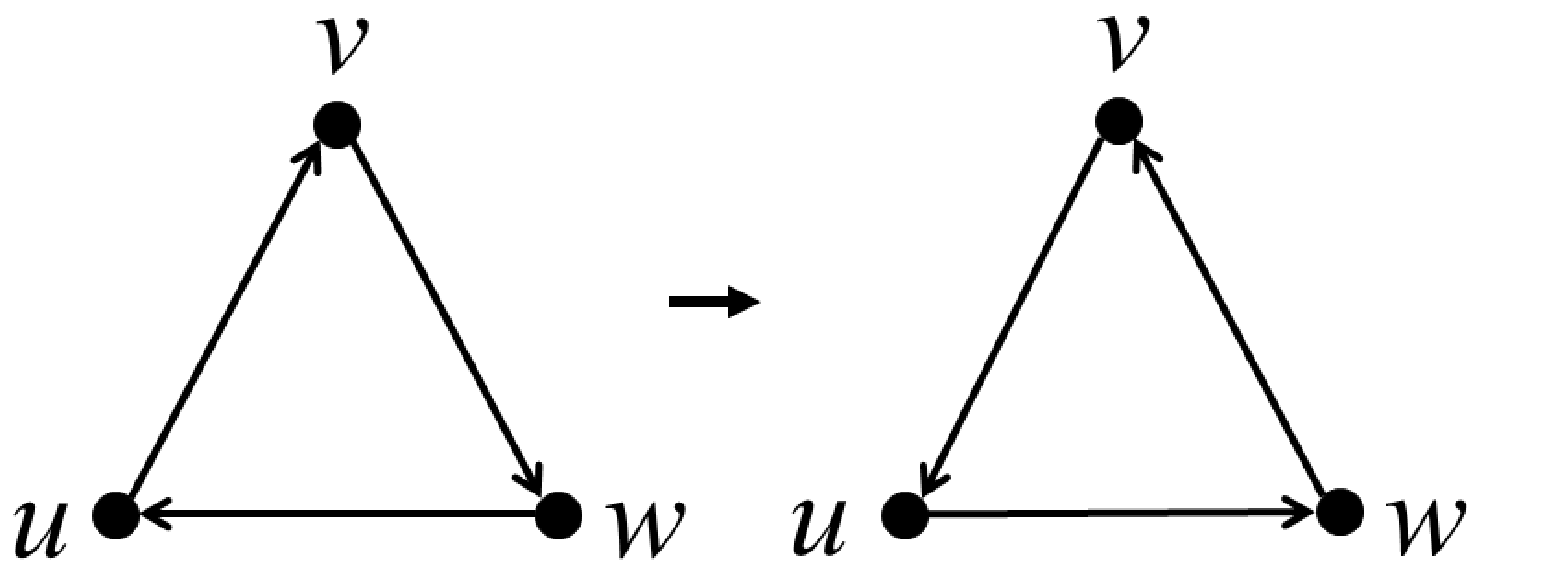
Insert rule r at node u
Insert rule t at node w
Wait 10s
Remove rule q at node x
Logical OR
Remove rule s at node v
Insert rule p at node y

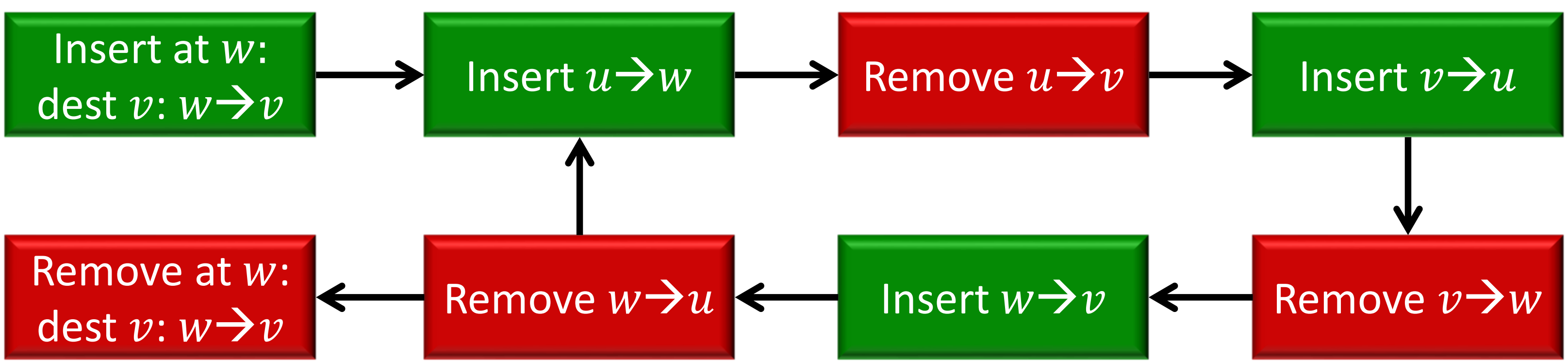
Multiple Destinations using Prefix-Based Routing



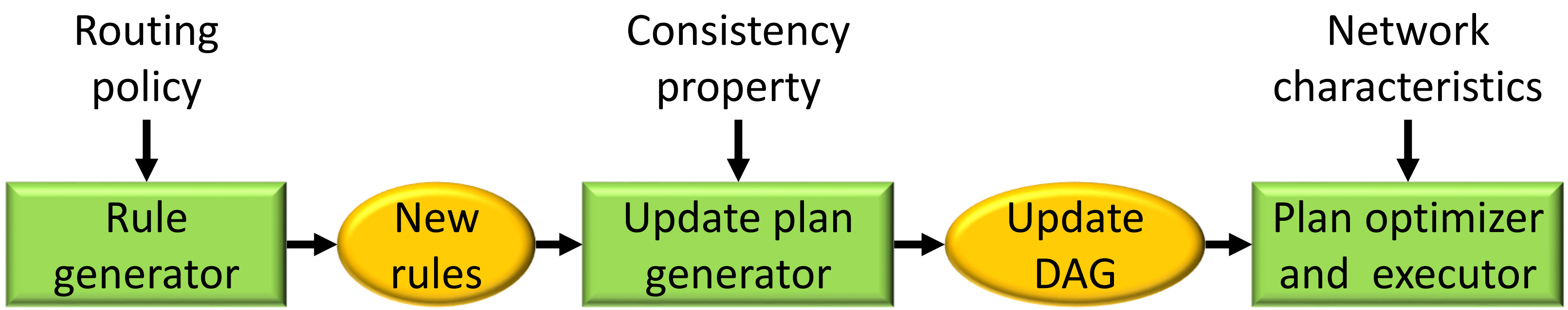
- No new “default” rule can be introduced without causing loops
- Solution: Rule-Dependency Graphs!
- Deciding if simple update schedule exists is hard!

Breaking Cycles

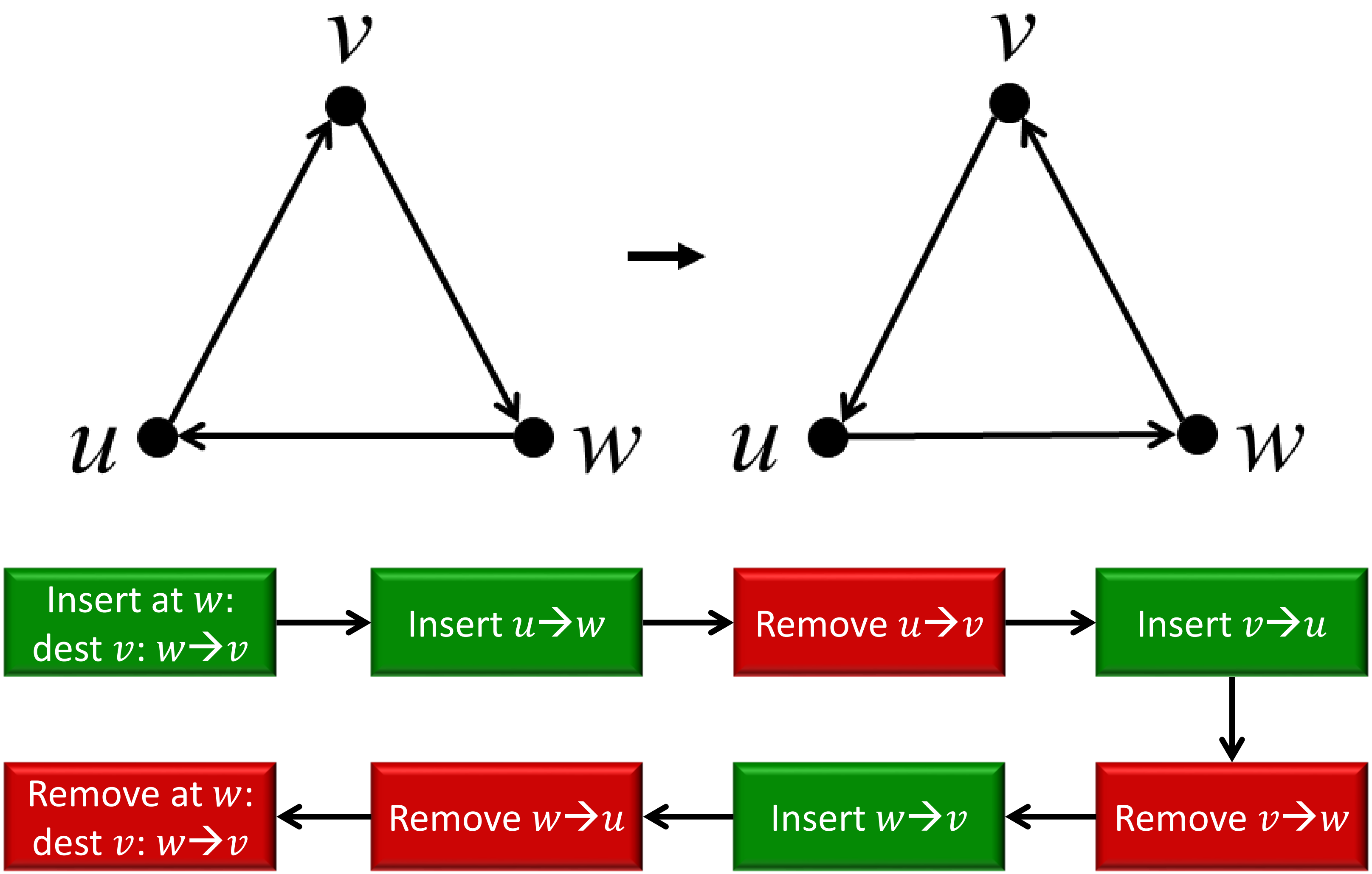




Architecture



Breaking Cycles



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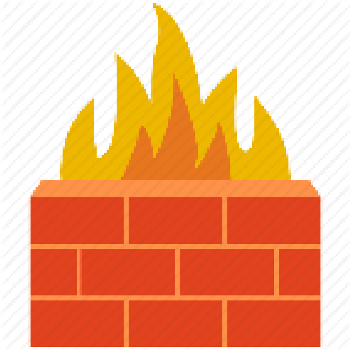
- Capacity-Consistent Updates

Dependencies	None	Self	Downstream subset
Eventual consistency	Always guaranteed		
Blackhole freedom	Impossible	Add before remove	
Loop freedom	Impossible		Rule dep. forest

Packet-Coherent Updates

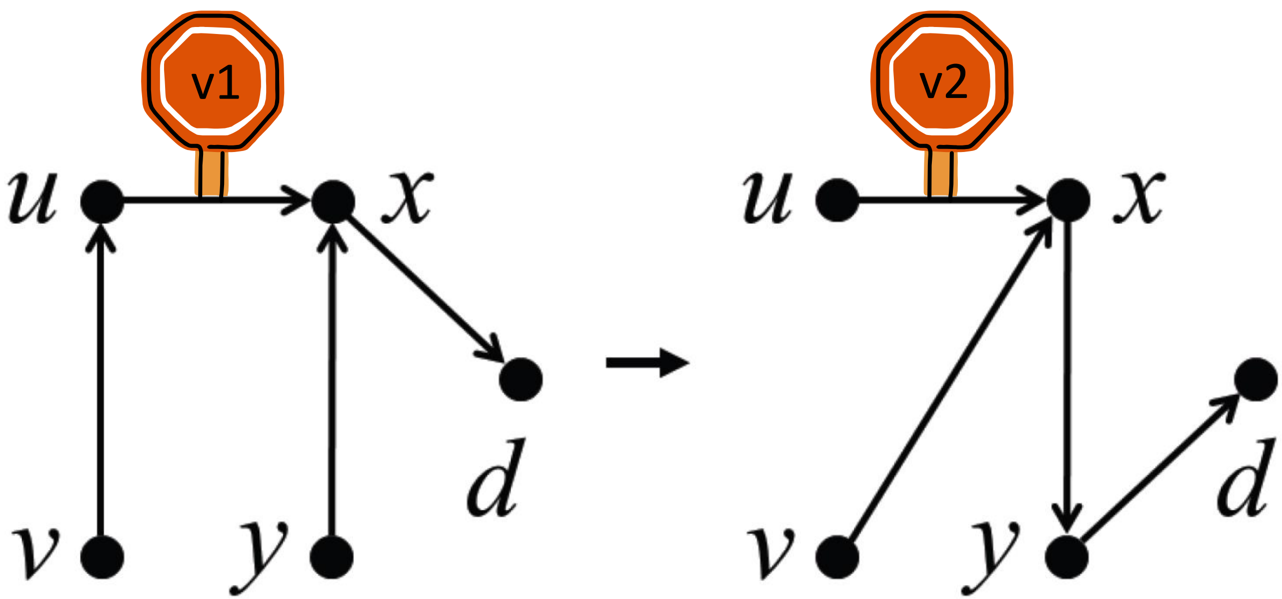


- Definition: A packet should always either
  - Use the old rules
  - Use the new rules
  - Important for waypointing (e.g., firewalls)

- General idea:
  - Stamp every packet with a version number
  - Send new rules to all switches
  - When all switches confirmed:
    - Stamp all packets with the next version number
  - Once all old packets are gone
    - Delete old rules

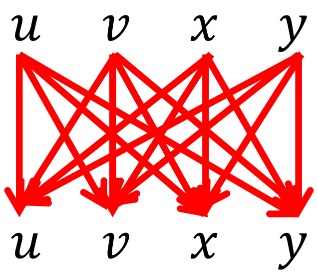
Example

SDN Controller

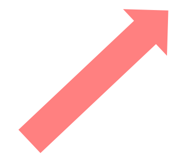


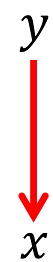
Comparison

Version Numbers



Loop Free Solution





<u>version numbers</u>

- no mix of old and new rules
- loop freedom & packet coherence
- "programmers dream“

- more switch memory
- changes packets
- update all involved switches
- when can we delete old rules?

<u>loop free updates</u>

- mix of old and new rules
- loop freedom, but **no** packet coherence
- needs algorithms

- early first effects
- **packets unaffected**

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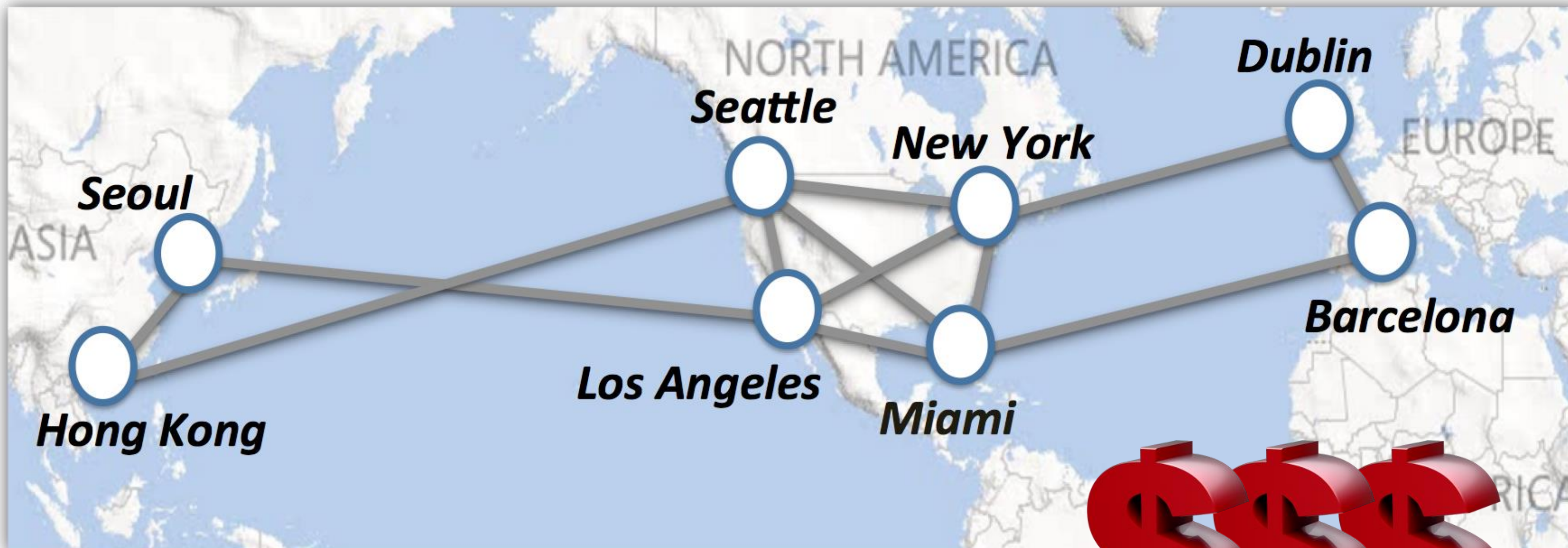
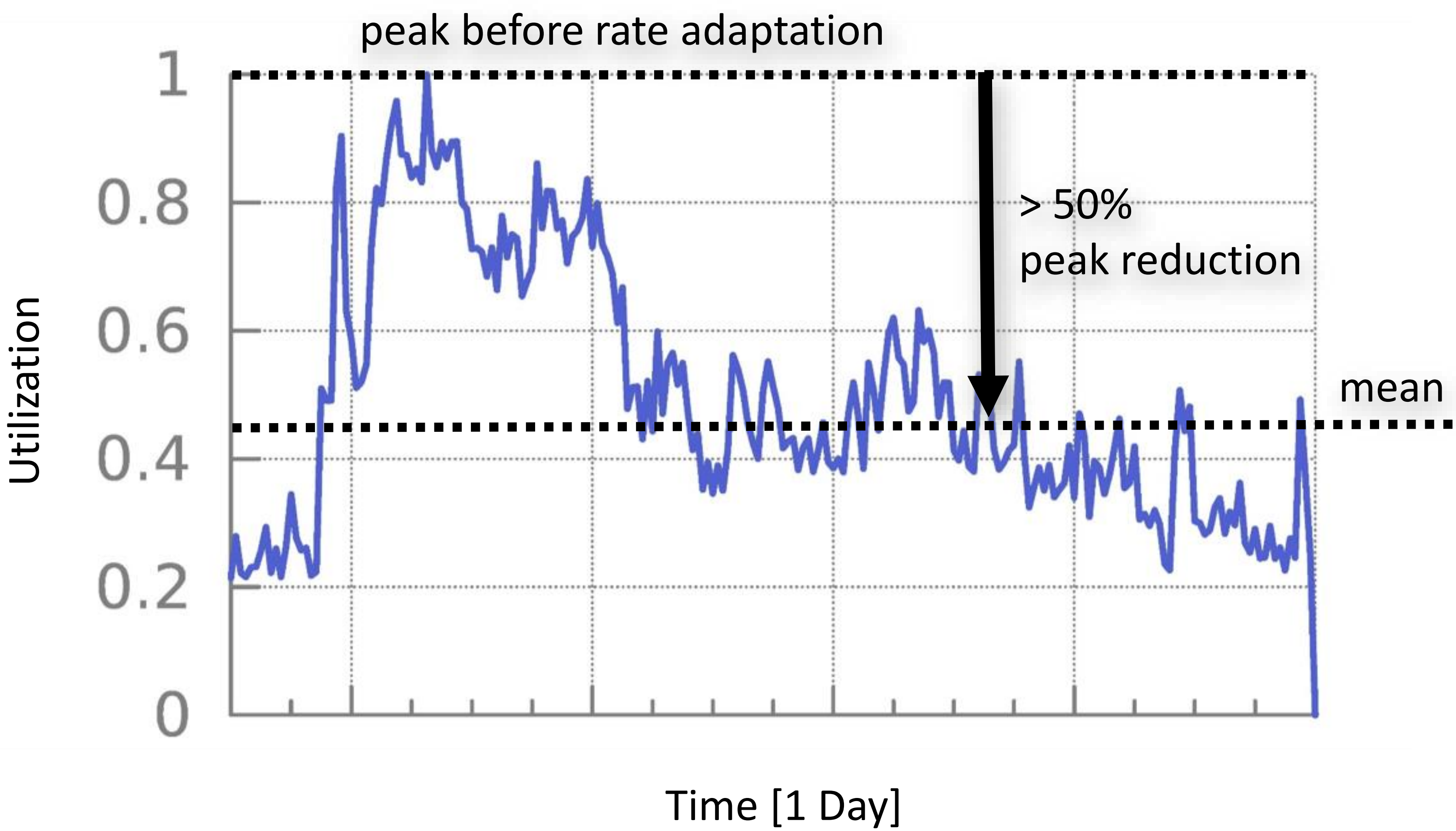
Dependencies	None	Self	Downstream subset	Downstream all
Eventual consistency	Always guaranteed			
Blackhole freedom	Impossible	Add before remove		
Loop freedom	Impossible		Rule dep. forest	
Packet coherence	Impossible			Version numbers

Real Application: Inter-Data Center WANs



Think: Google, Amazon, Microsoft

Problem: Typical Network Utilization



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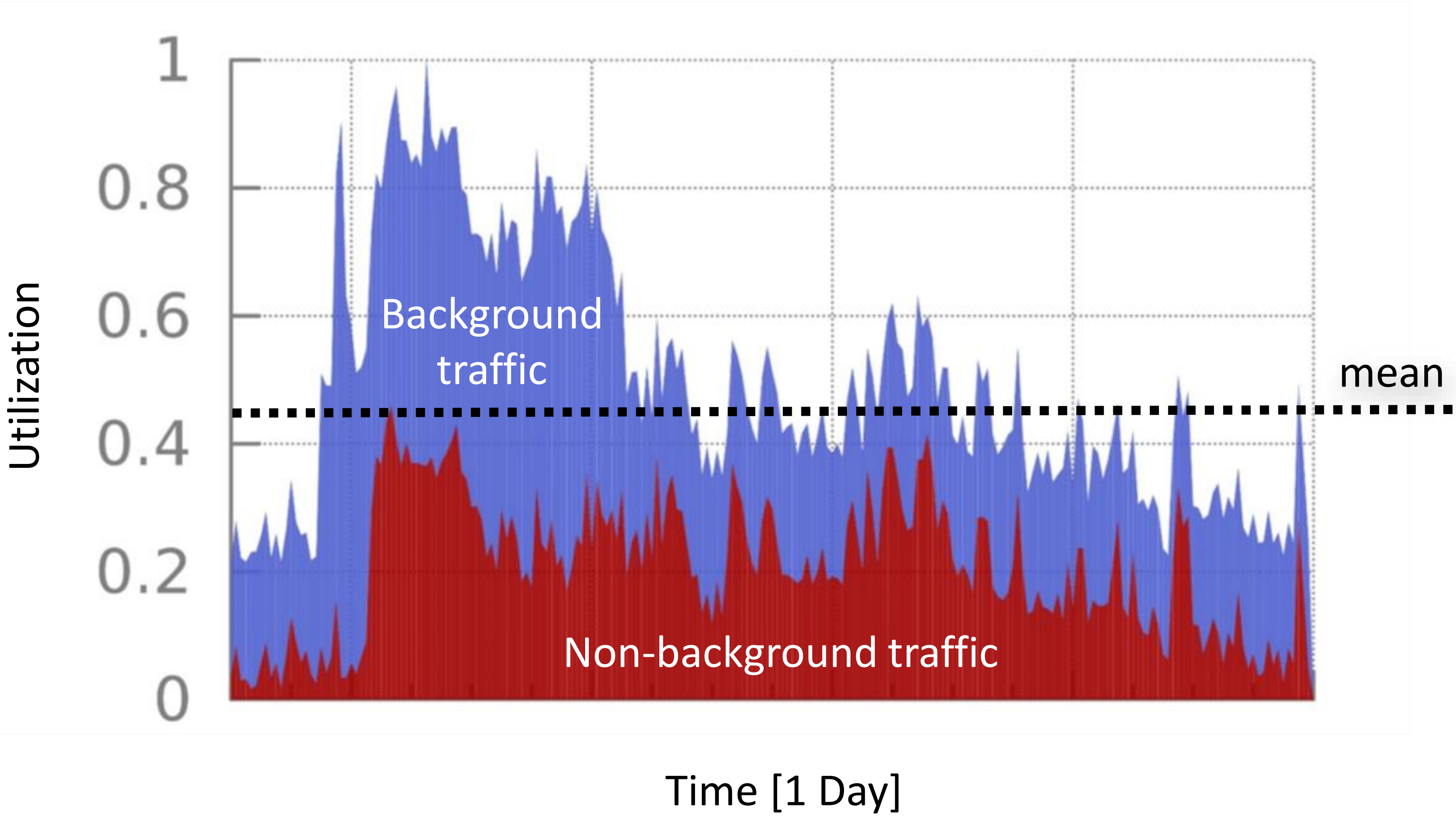
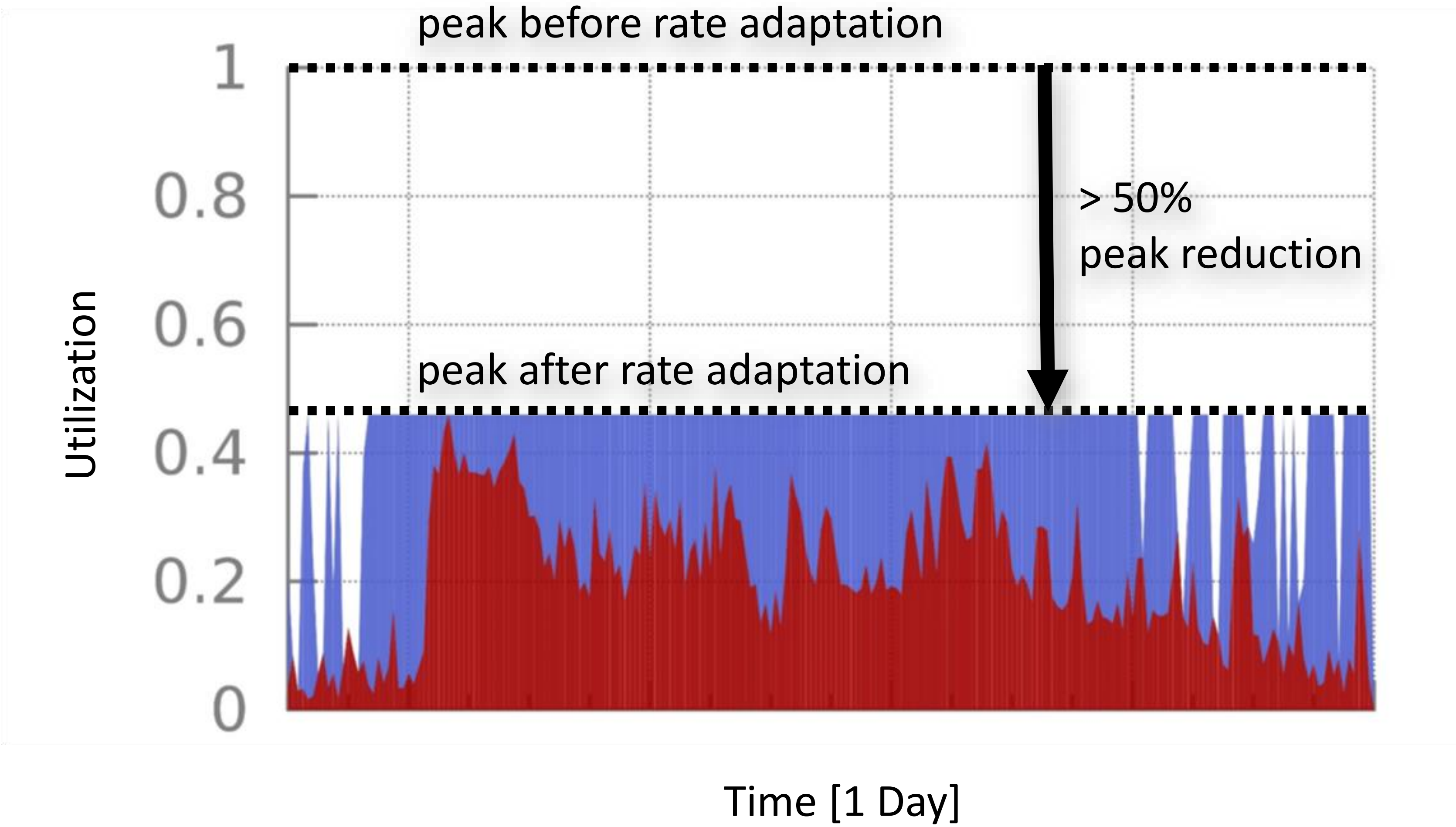


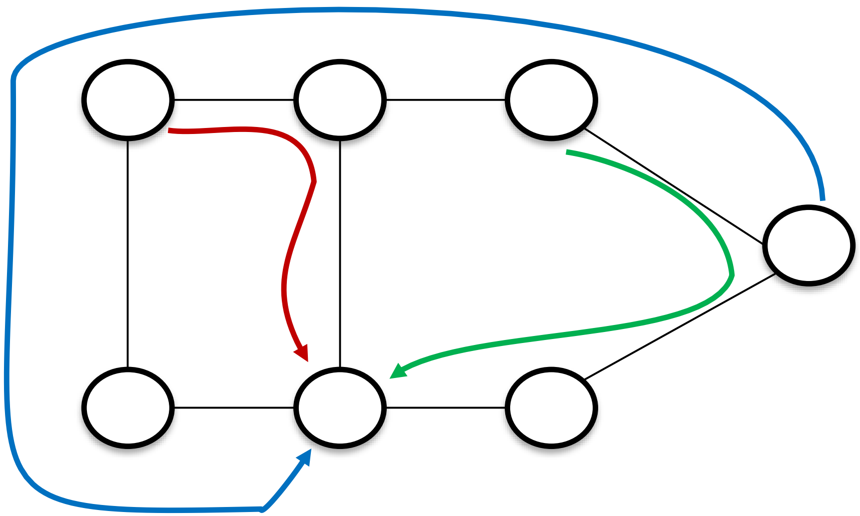
Problem: Typical Network Utilization



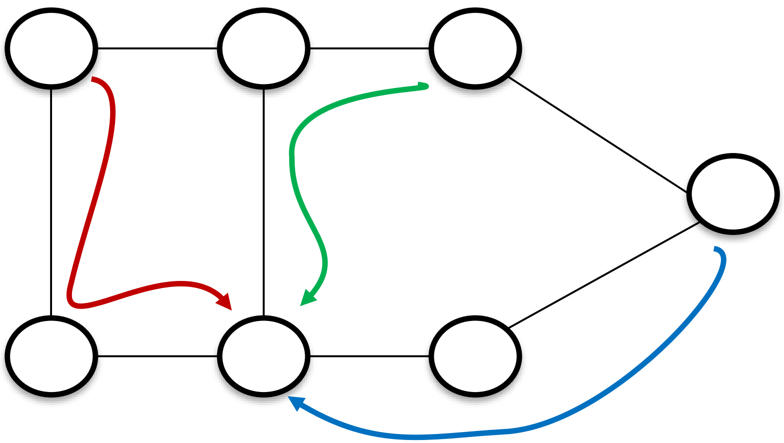
Another Problem: Online Routing Decisions

flow arrival order: A, B, C

each link can carry at most one flow (in both directions)



MPLS-TE



Better

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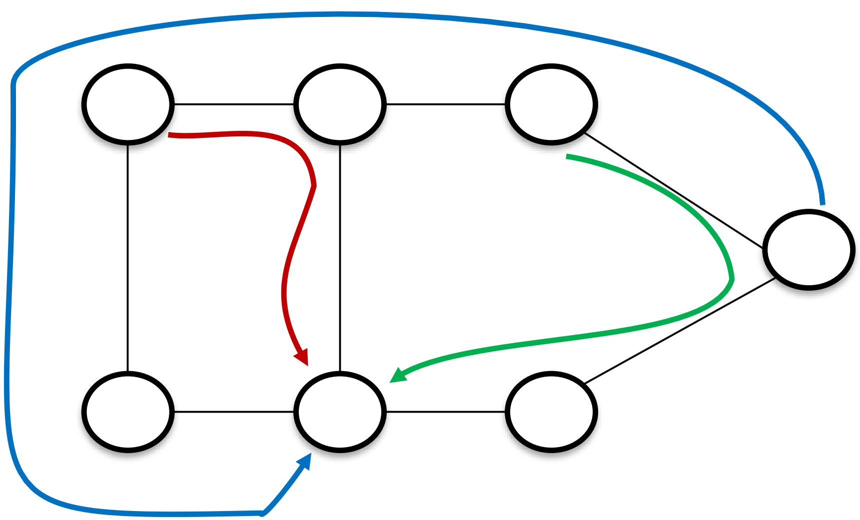

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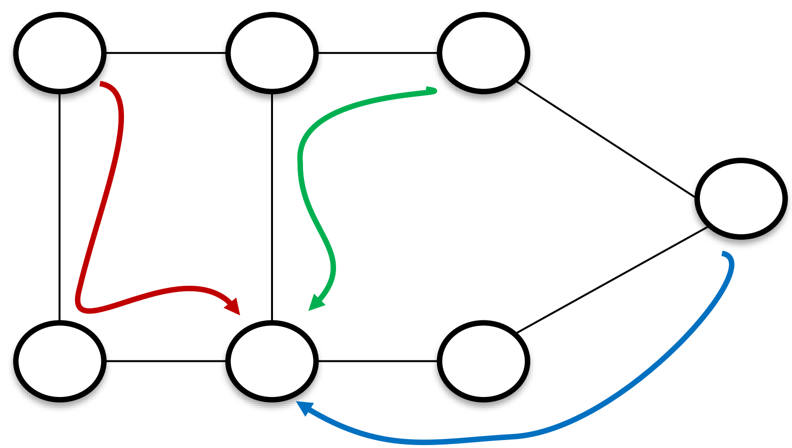
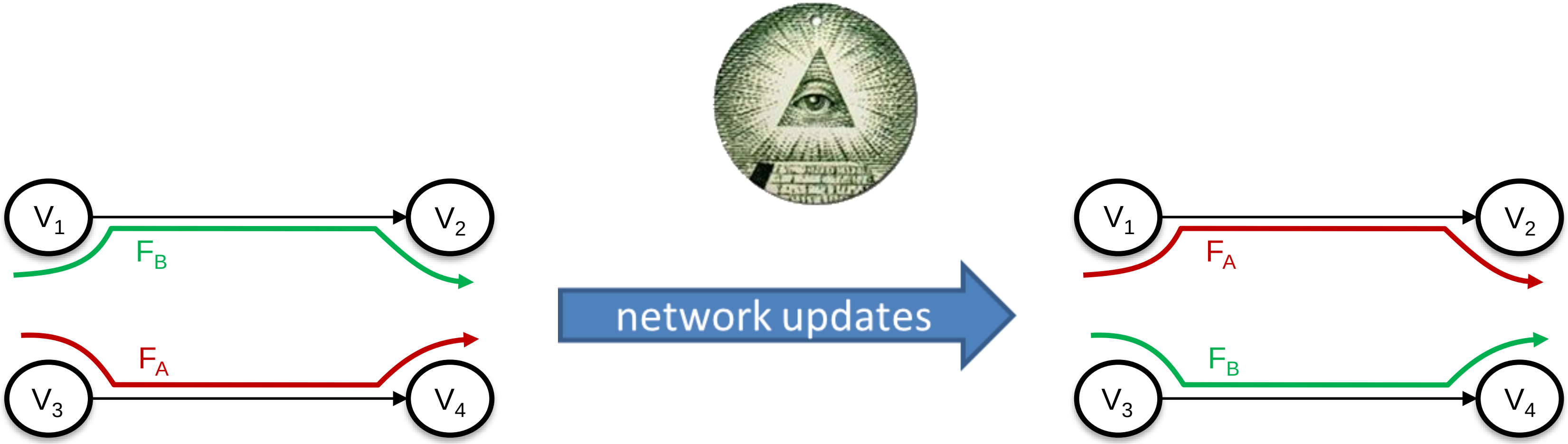


Better

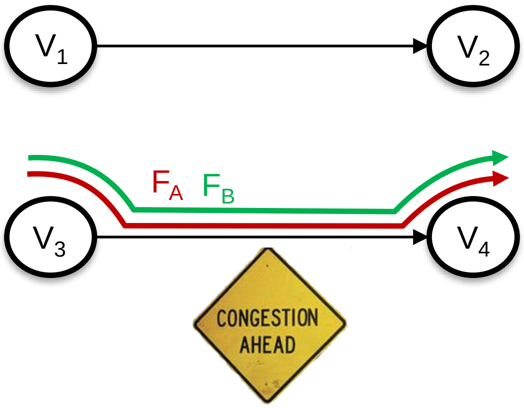
How to move flows?

Introductory Example



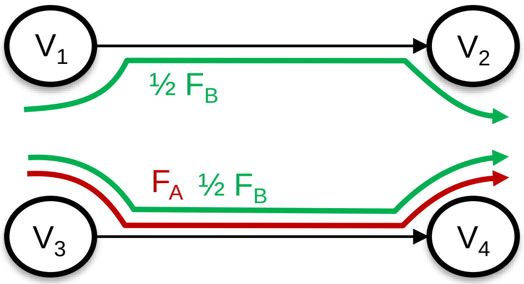
size of each flow: 2
capacity of links: 3

Just Switch? Congestion!



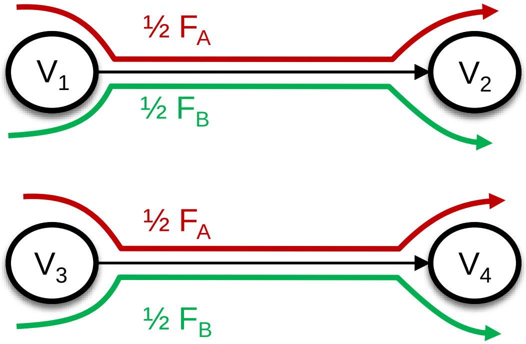
size of each flow: 2
capacity of links: 3

Migrate only parts of the flow



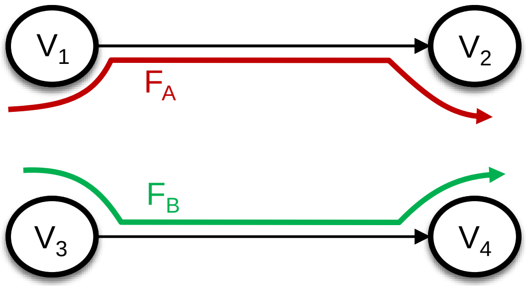
size of each flow: 2
capacity of links: 3

Can even do both flows at once



size of each flow: 2
capacity of links: 3

Done in two steps



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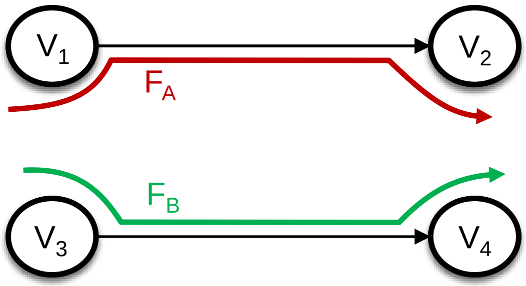
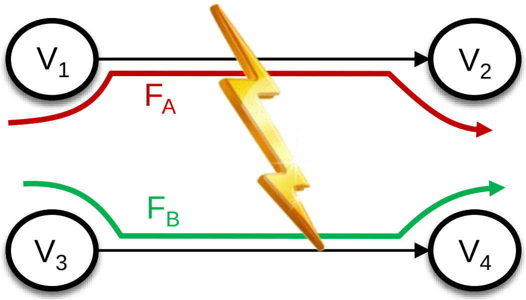


If all links have a slack of x, then -1+1/(x) steps
E.g., 20% free capacity everywhere? -1+1/(1/5)=4 steps

size of each flow: 2
capacity of links: 3

But not always possible!



size of each flow: 2

capacity of links: **2**

Two-fold approach of SWAN

a) free capacity on every link

$$
\textbf{Inputs:} \begin{cases} q, & \text{sequence length} \\ b^0_{i,j} = b_{i,j}, & \text{initial configuration} \\ b^q_{i,j} = b'_{i,j}, & \text{final configuration} \\ c_l, & \text{capacity of link } l \\ I_{jl}, & \text{indicates if tunnel } j \text{ using link } l \end{cases}
$$

Outputs: $\{b^a_{i,j}\}\ \ \forall a \in \{1, \ldots q\}$ if feasible

$$
\begin{aligned}
\text{maximize} \quad & c_{\text{margin}} \text{ // remaining capacity margin} \\
\text{subject to} \quad & \forall i, a : \textstyle\sum_j b^a_{i,j} = b_i; \\
& \forall l, a : c_l \geq \textstyle\sum_{i,j} \max(b^a_{i,j}, b^{a+1}_{i,j}) \cdot I_{j,l} + c_{\text{margin}}; \\
& \forall (i,j,a) : b^a_{i,j} \geq 0;\ c_{\text{margin}} \geq 0;
\end{aligned}
$$

Figure 7: LP to find if a congestion-free update sequence of length q exists.

b) LP-based search

Two-fold approach of SWAN

a) free capacity on every link

Inputs:
$$\begin{cases} q, & \text{sequence length} \\ b^0_{i,j} = b_{i,j}, & \text{initial configuration} \\ b^q_{i,j} = b'_{i,j}, & \text{final configuration} \\ c_l, & \text{capacity of link } l \\ I_{jl}, & \text{indicates if tunnel } j \text{ using link } l \end{cases}$$

Outputs: $\{b^a_{i,j}\}\ \forall a \in \{1, \dots q\}$ if feasible

maximize c_{margin} // remaining capacity margin

subject to
$$\forall i, a : \textstyle\sum_j b^a_{i,j} = b_i;$$
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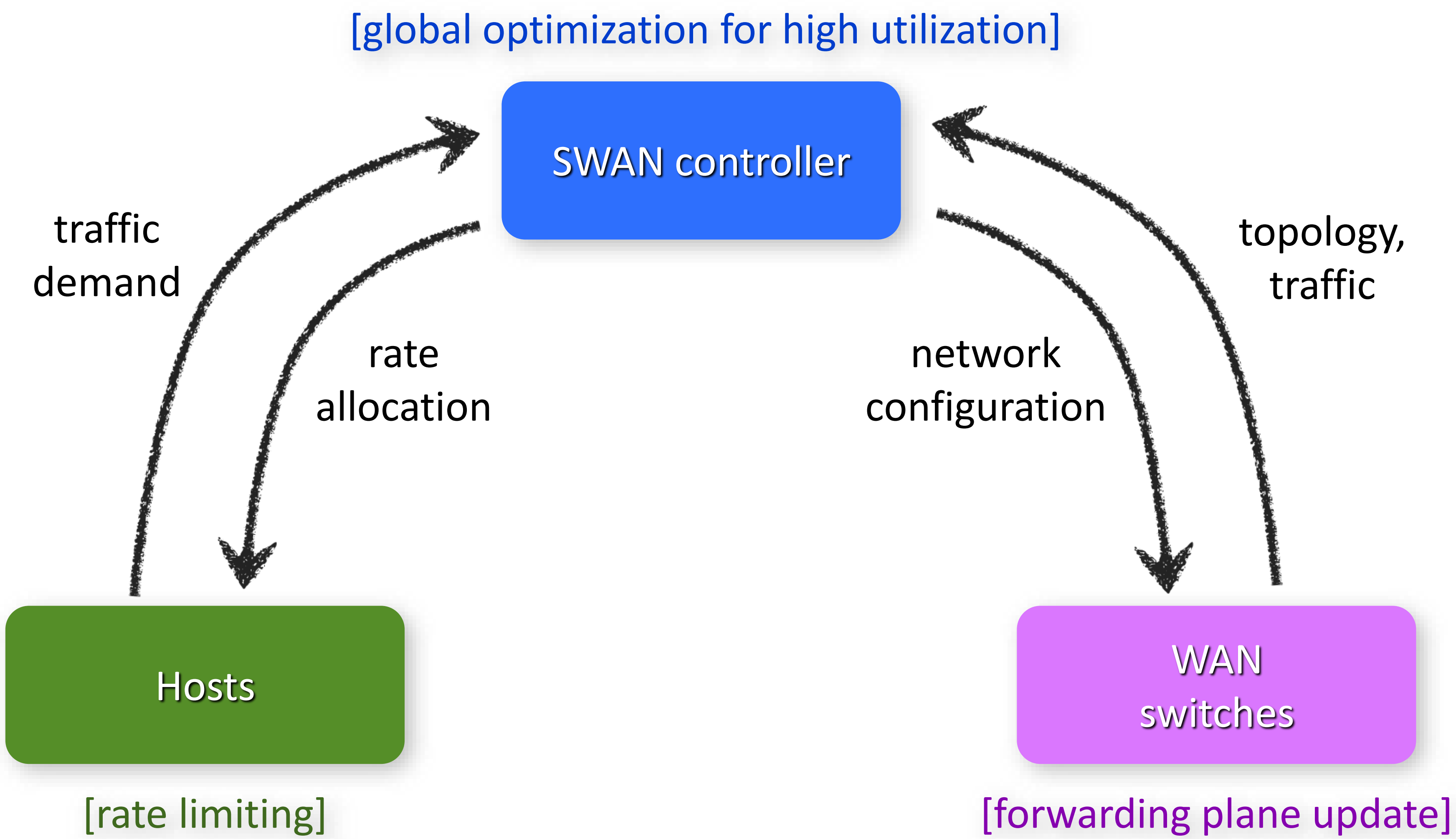
$$\forall (i,j,a) : b^a_{i,j} \geq 0;\ c_{\text{margin}} \geq 0;$$

Figure 7: LP to find if a congestion-free update sequence of length q exists.

b) LP-based search

Note: The SWAN framework does much more!

The SWAN Project



Do proper network updates exist?

network updates

Inputs:
$$\begin{cases} q, & \text{sequence length} \\ b^0_{i,j} = b_{i,j}, & \text{initial configuration} \\ b^q_{i,j} = b'_{i,j}, & \text{final configuration} \\ c_l, & \text{capacity of link } l \\ I_{jl}, & \text{indicates if tunnel } j \text{ using link } l \end{cases}$$

Outputs: $\{b^a_{i,j}\}\ \forall a \in \{1, \dots q\}$ if feasible

maximize c_{margin} // remaining capacity margin

subject to $\forall i, a : \sum_j b^a_{i,j} = b_i;$

$\forall l, a : c_l \geq \sum_{i,j} \max(b^a_{i,j}, b^{a+1}_{i,j}) \cdot I_{j,l} + c_{\text{margin}};$

$\forall (i,j,a) : b^a_{i,j} \geq 0;\ c_{\text{margin}} \geq 0;$

Figure 7: LP to find if a congestion-free update sequence of length q exists.

?

Number of steps can be unbounded

network updates

ε capacity

Calculate for an infinite amount of time?

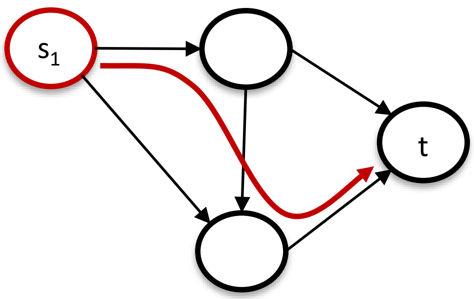
An old method for a new problem

- Key observation in SWAN:
  - only migrate flows to links with free capacity

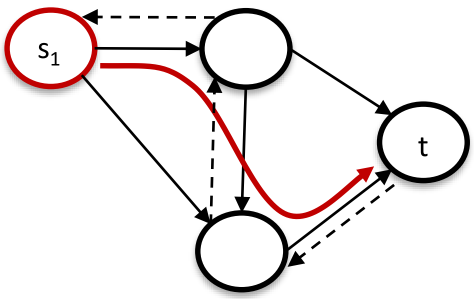
- However, LPs do not seem to be the way to go

- Other method: Augmenting flows!
  - “push back” flows to free link capacity

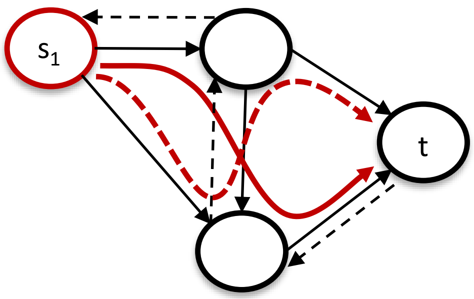
Short introduction to augmenting flows



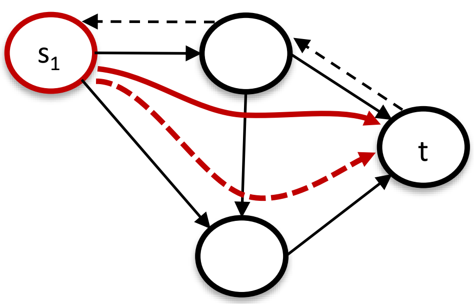
Consider the residual network too



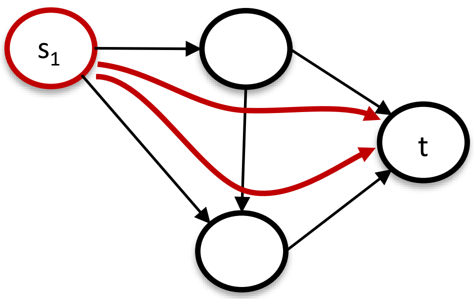
Now we can find a new flow



Push back the old flow



And insert the new flow



some edge can be reduced from full capacity

⟺

a augmenting path exists that creates slack on some full edge*

thus, we can decide in polynomial time ☺

*not necessarily the same

Recap of the situation

- the **good**: deciding and finding a schedule is fast
  - by creating slack everywhere, if possible
  - let us keep the speed that way ☺
- the **bad**: fastest schedule can be arbitrarily long
  - limit them to linear time!
  - idea: we choose where to put flows
  - lets use augmenting paths again

Flow augmentation for many destinations

- **Advantage:** Flows are only re-routed along free paths!

Flow augmentation for many destinations

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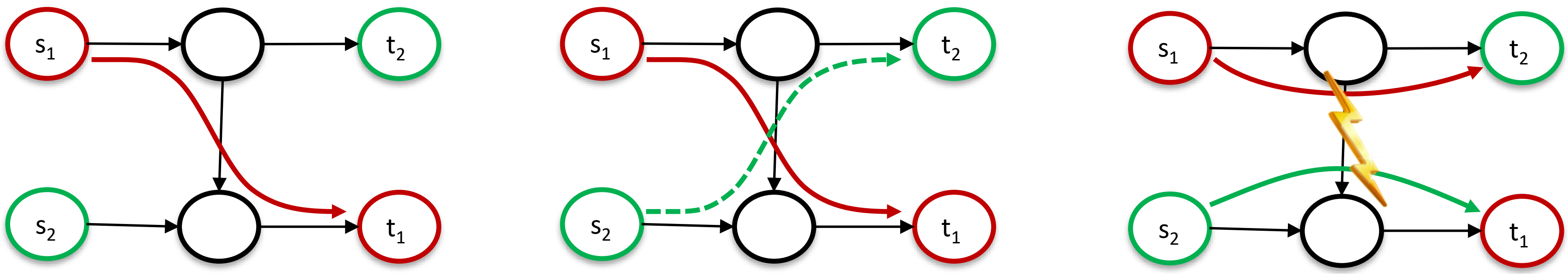
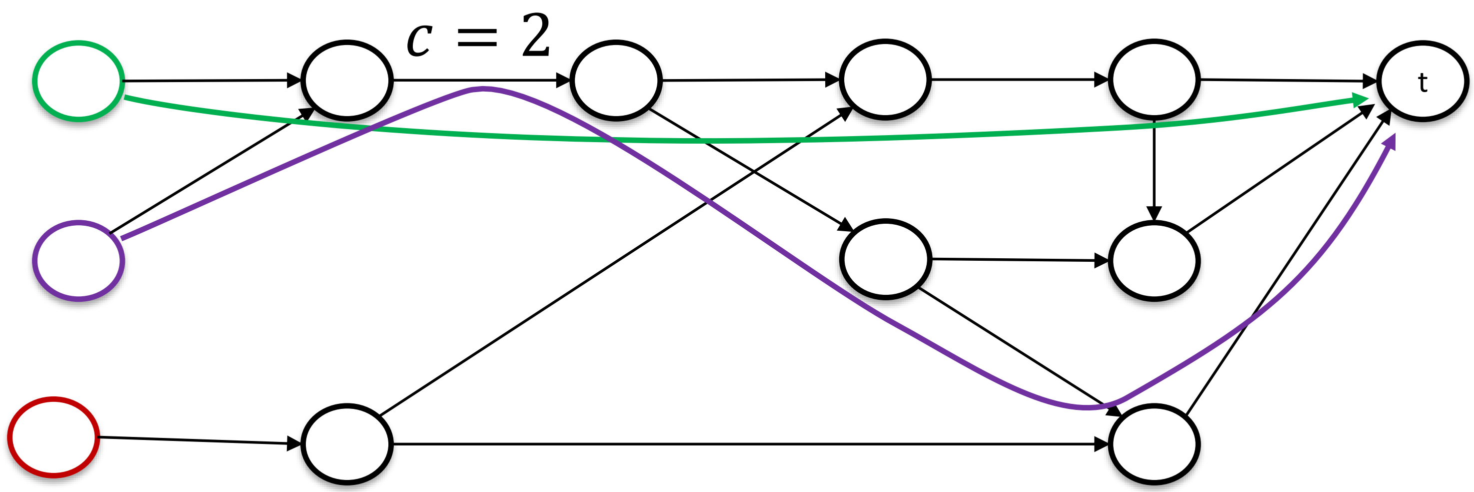


- **Downside:** Flows end up at the wrong destination!

- So let's stick with one destination for now
  - E.g., a server in another network with multiple entry-points

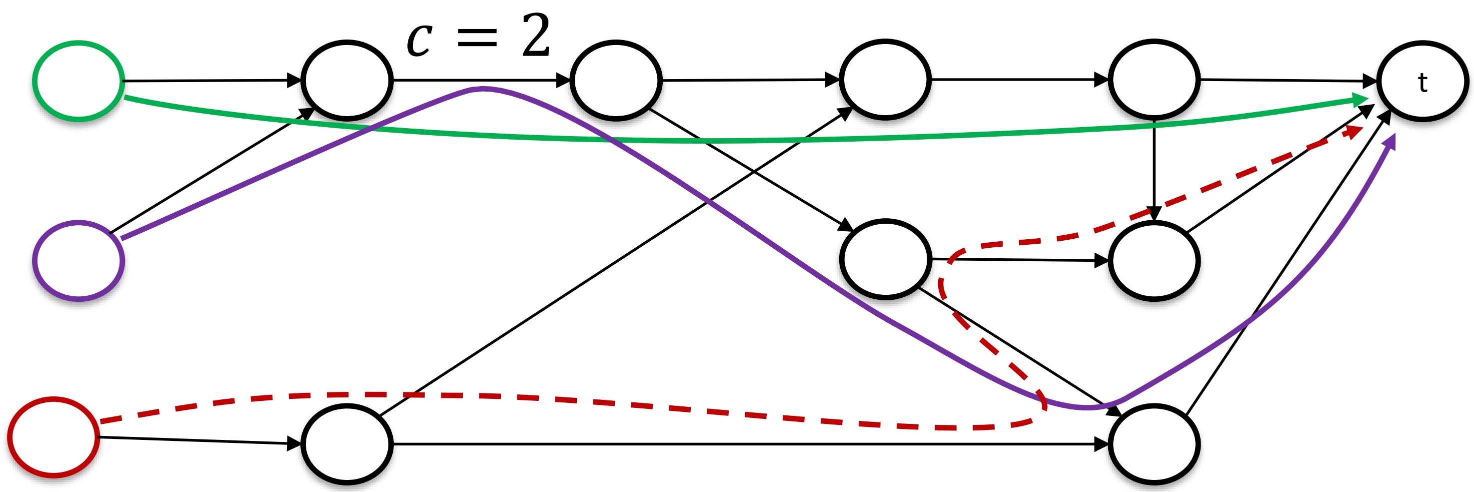
No free path to the destination



size of each flow: 1

capacity of each links: 1

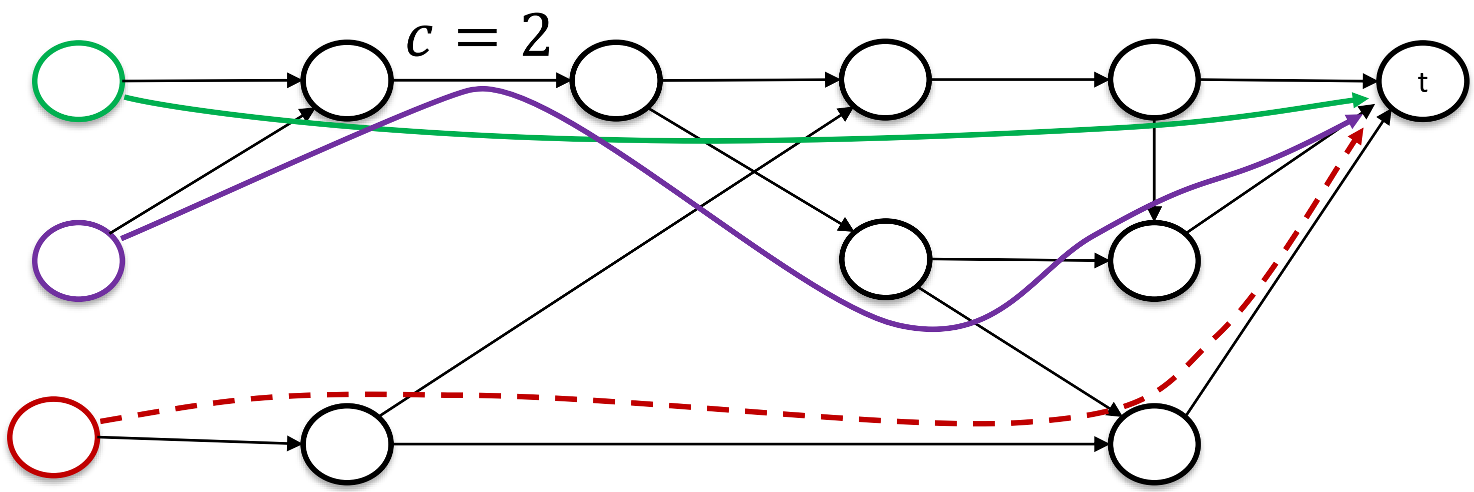
But an augmenting flow exists



size of each flow: 1

capacity of each links: 1

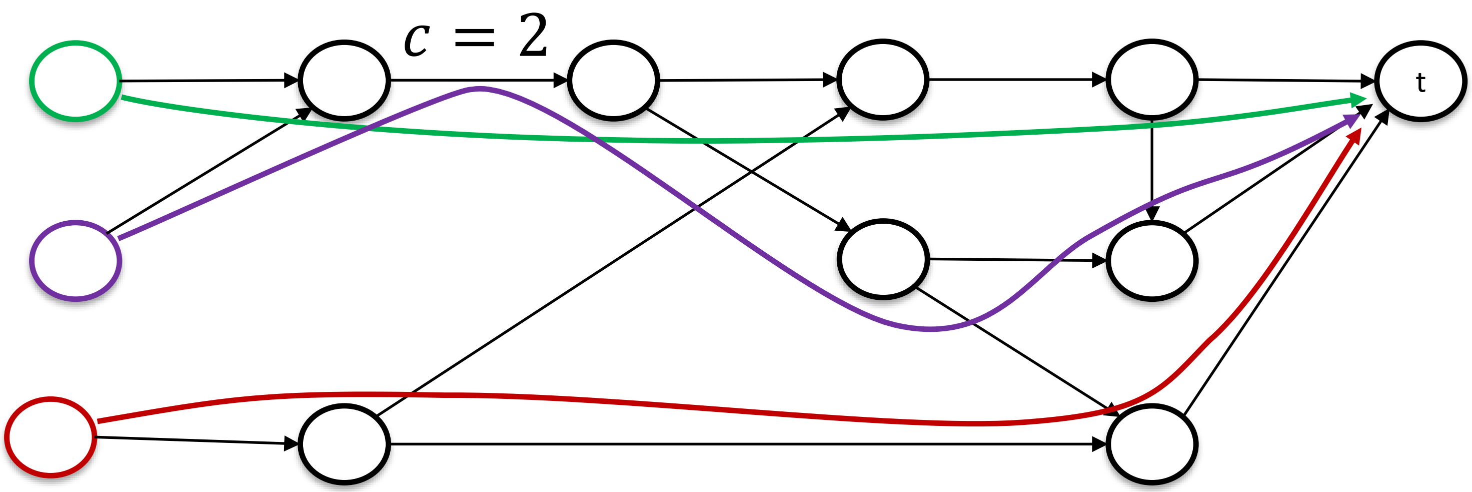
Old flows get re-routed



size of each flow: 1

capacity of each links: 1

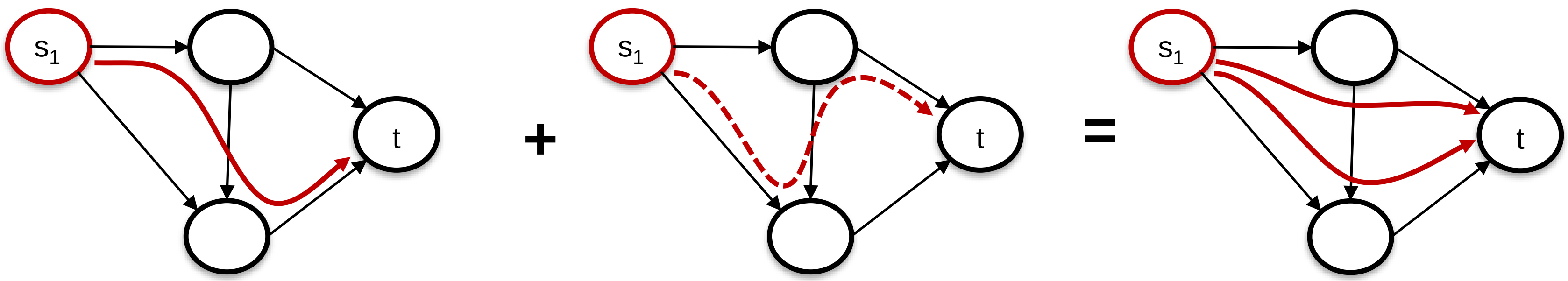
And new flow inserted



size of each flow: 1
capacity of each links: 1

High-level mechanism idea

1. *Difference* between two flows → augmenting flow



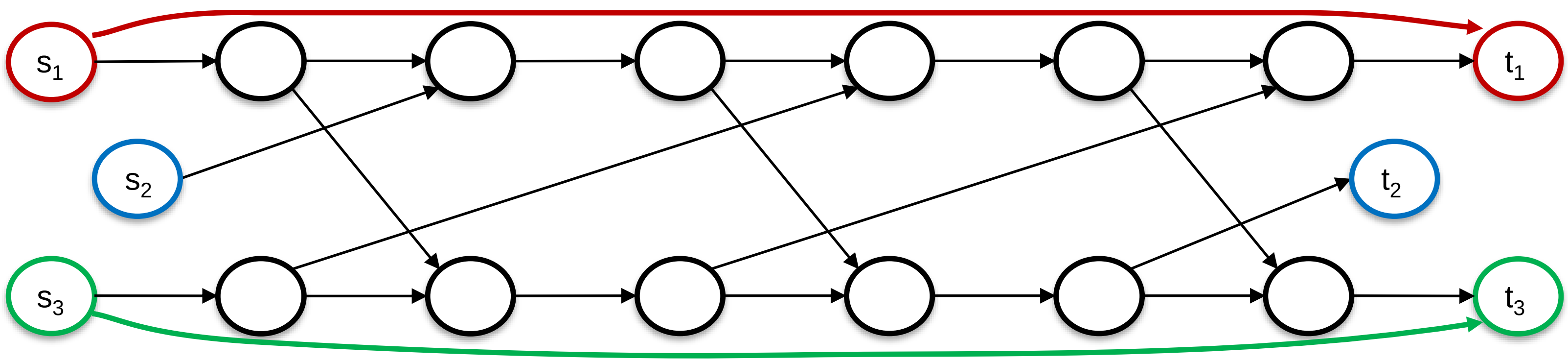
High-level mechanism idea

1. *Difference* between two flows → augmenting flow

2. Calculate desired flow sizes with LP
   - *offline* computation

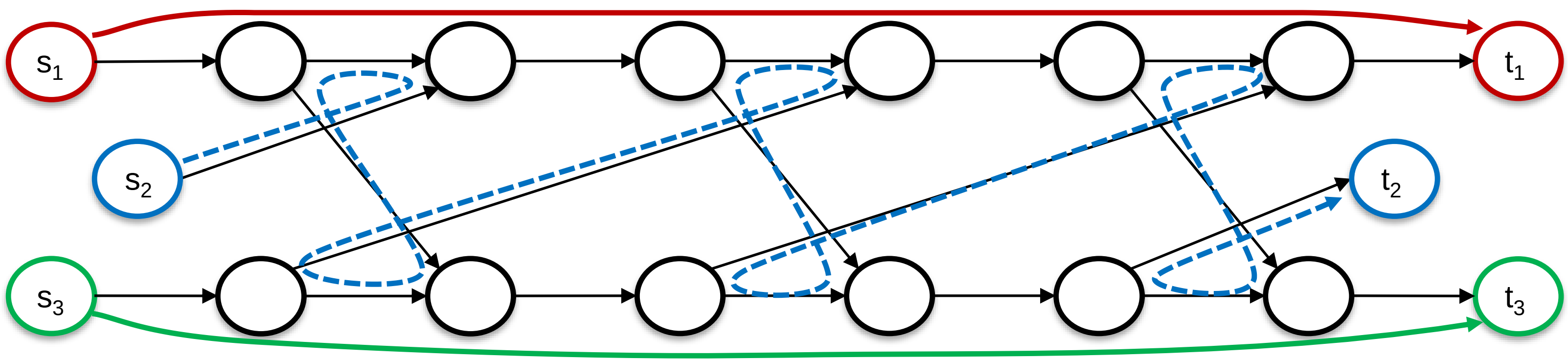
3. Apply augmenting flow for each commodity
   - linear # re-routing *in the network*

Extension beyond one logical destination?



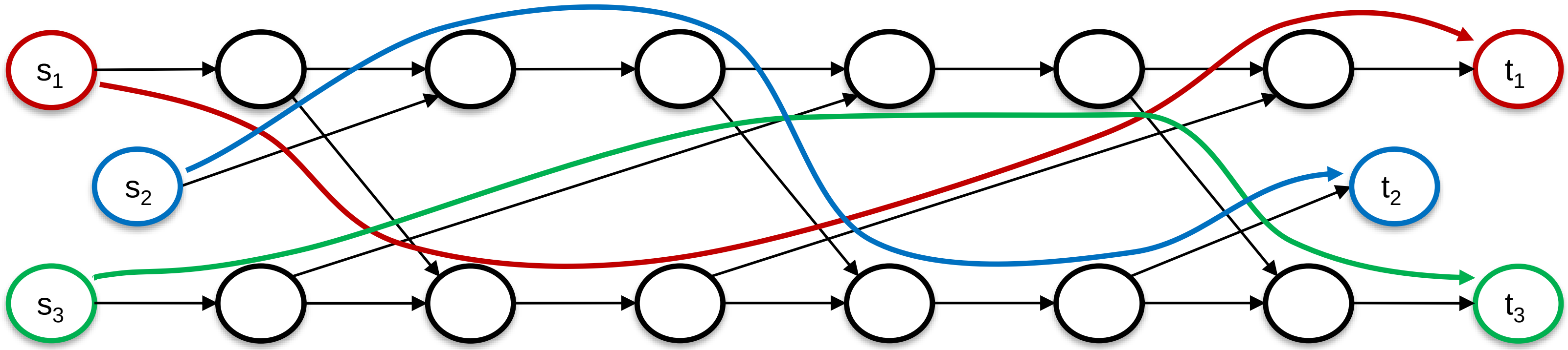
size of each flow: 1
capacity of each links: 1

Augmenting flows that don’t mix up the destinations?



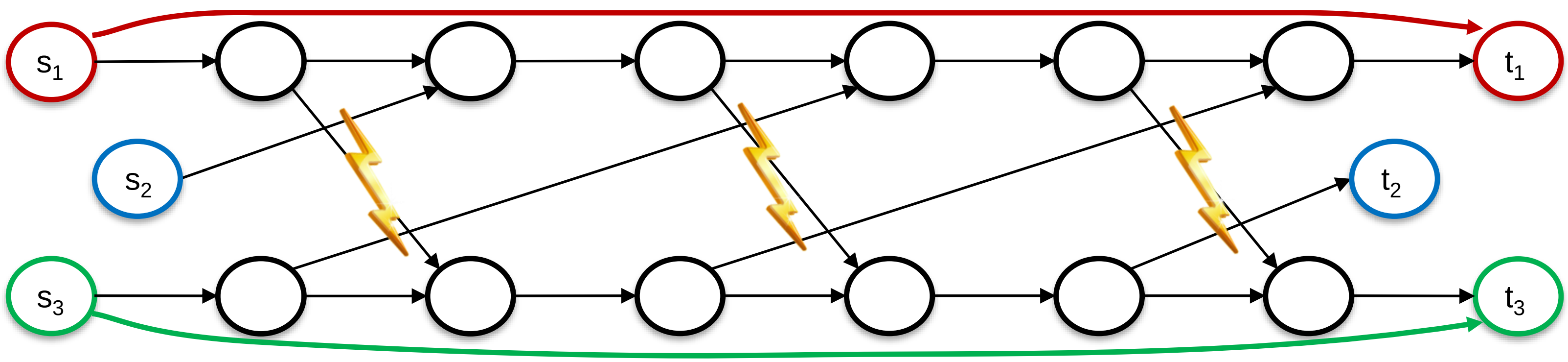
size of each flow: 1
capacity of each links: 1

Augmenting flows that don’t mix up the destinations?



size of each flow: 1
capacity of each links: 1

But impossible to migrate!



size of each flow: 1

capacity of each links: 1

Capacity-Consistent Updates

- Fast if enough slack everywhere
- Decidable in polynomial time
- Migrate in linear time with one destination
- Open: Extend fast mechanisms beyond one destination

Summary

Dependencies	None	Self	Downstream subset	Downstream all	Global
Eventual consistency	Always guaranteed				
Blackhole freedom	Impossible	Add before remove			
Loop freedom	Impossible		Rule dep. forest		
Packet coherence	Impossible			Version numbers	
Bandwidth limits	Impossible				Staged partial moves

References

- Introducing consistent network updates, Reitblatt et al., SIGCOMM 2012
- For minimal dependencies in updates in general, and loop-free updates in particular, see Ratul Mahajan et al., HotNets 2013
- Deciding if a simple update schedule exists is hard was proven in Laurent Vanbever et al., IEEE/ACM Trans. Netw. 2012
  - See also his recent inaugural lecture @ETH: http://goo.gl/TMZCyg (watch 14:50 - 19:25, or better yet, the whole video)
- Loop-detection by Tarjan, Depth-first search & linear graph alg., 1972
- Google B4 SDN project, Sushant Jain et. al., SIGCOMM 2013
- SWAN SDN project, Chi-Yao Hong et. al., SIGCOMM 2013
- Deciding if flows can be moved, Sebastian Brandt et al., INFOCOM 2016
- Fast method for one destination, Sebastian Brandt et al., ICDCN 2016

Thank You!

Questions & Comments?