Central Control over Distributed Asynchronous Systems: A Tutorial on Software-Defined Networks and Consistent Network Updates

Klaus-T. Foerster

Brief Preamble

- Focus on algorithmic/complexity issues in consistent updates in Software Defined Networks (SDNs)
  - Not so much on system etc. issues respectively SDNs themselves

- Two “bigger” connections to classic distributed computing halfway-in
  - Proof Labeling Schemes
  - Distributed Control Plane

universität wien

Network Updates

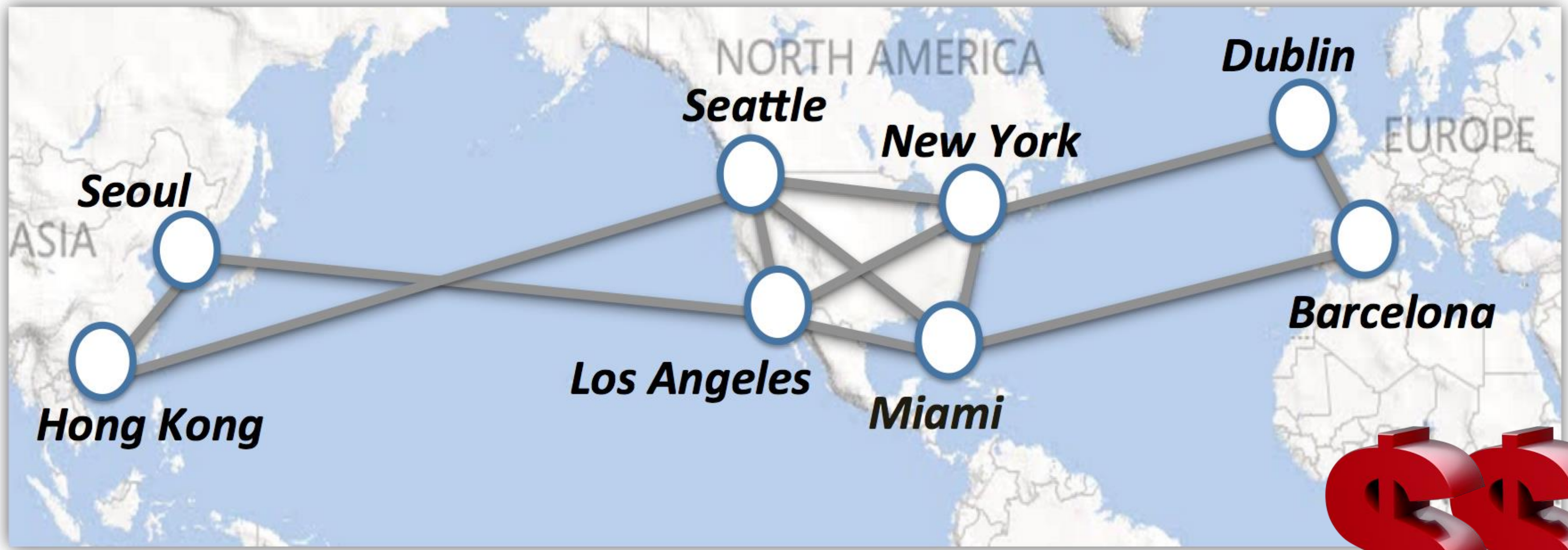
- The Internet: Designed for selfish participants
  - Often inefficient (low utilization of links), but robust

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

Also relevant in eg Data Center Networks, for ISPs etc

Network Updates

Eg update link capacity at runtime?*



Think: Google, Amazon, Microsoft

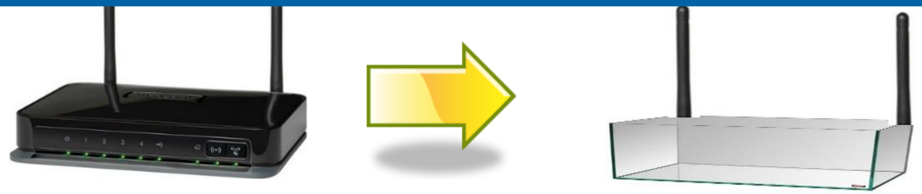
*:RADWAN: Rate Adaptive Wide Area Network. R. Singh, M. Ghobadi, K.-T. Foerster, M. Filer, P. Gill. ACM SIGCOMM 2018

Note: There is also a lot of (prior) research on consistency before SDNs – can't cover everything in this tutorial

See history section in:
Survey of Consistent Software-Defined Network Updates
Klaus-Tycho Foerster, Stefan Schmid, Stefano Vissicchio
IEEE Communications Surveys & Tutorials, 21(2), 2019

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

- Logically centralized controller (eg implemented with replication)

old network
rules

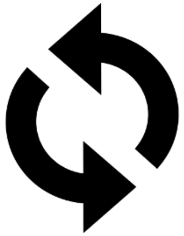
network updates

new network
rules

old network
rules

network updates

new network
rules



old network
rules

network updates

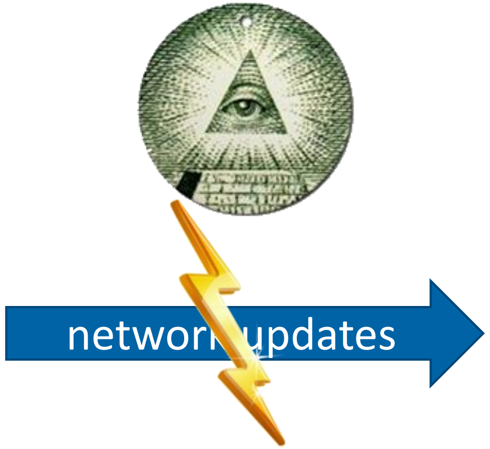
new network
rules

possible solution: be fast!

But they deviated from that a bit in the B4 2018 version…

e.g., B4 (Google, 2013)

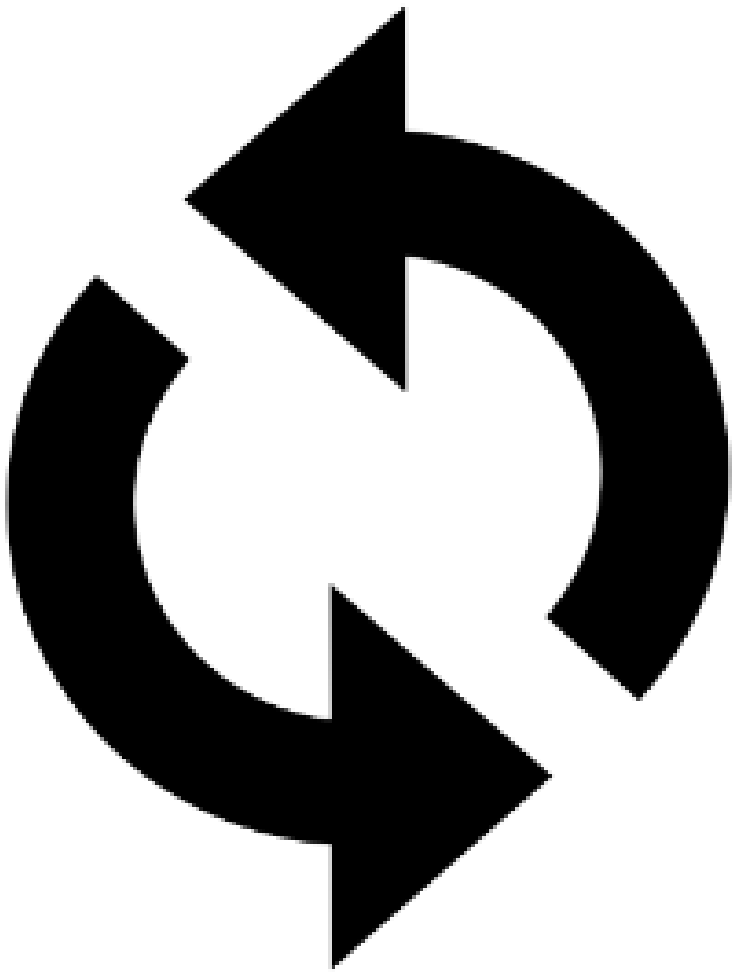
old network
rules



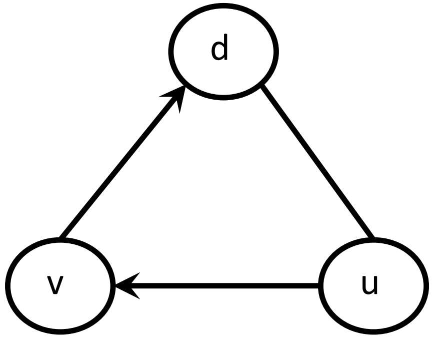
new network
rules

Alternative: Be consistent!

- Algorithms with guarantees

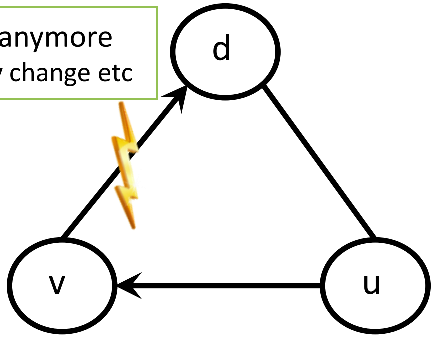


Toy Example

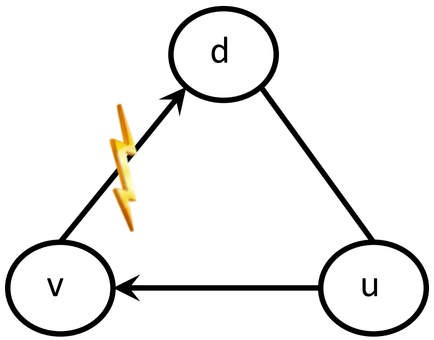


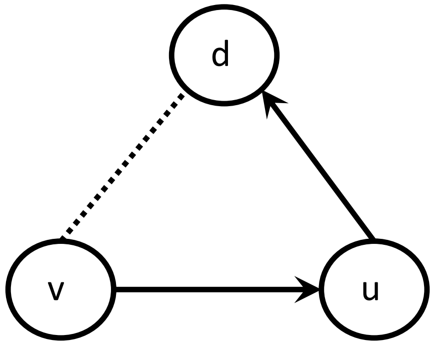
Toy Example

Link should not be used anymore
eg repair, congestion, policy change etc



Toy Example





Toy Example

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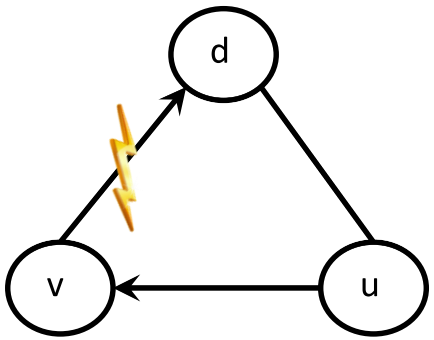
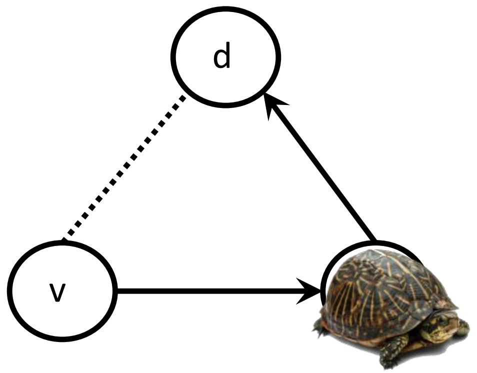
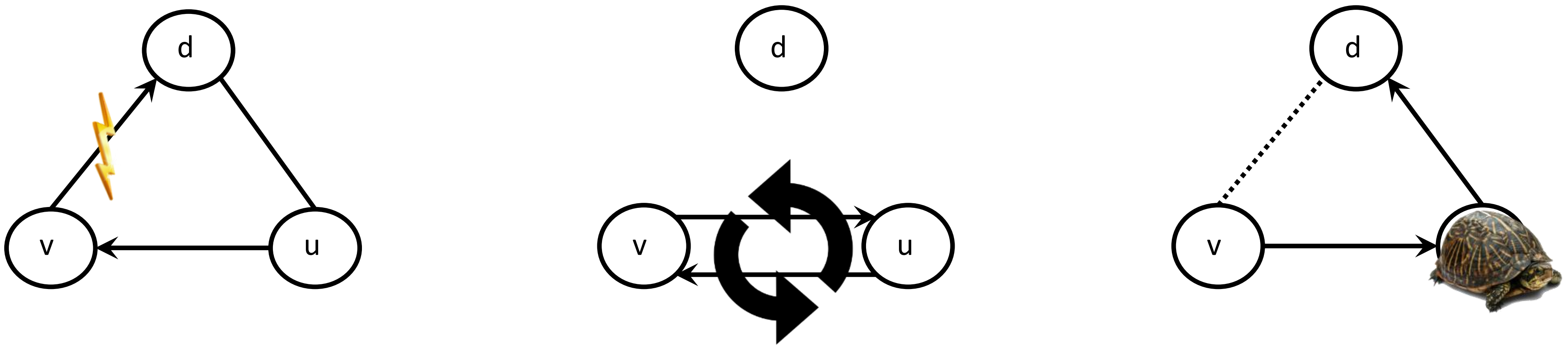
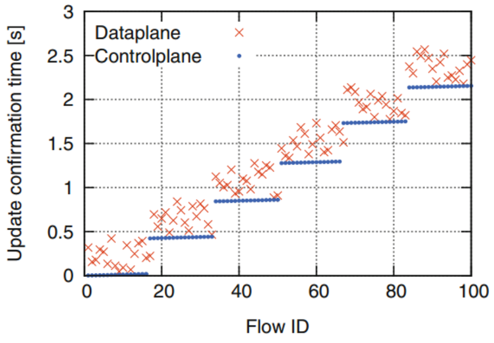




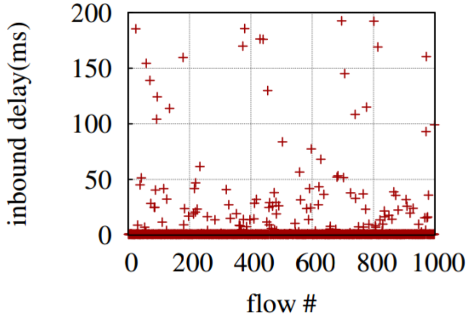
Toy Example



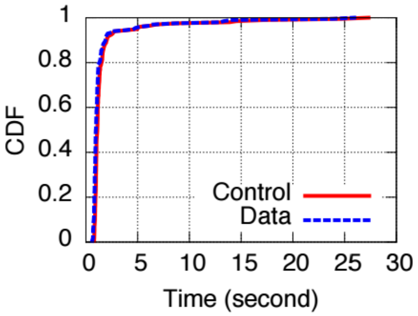
Appears in Practice



"Data plane ***updates may fall behind*** *the control plane acknowledgments and may be even* ***reordered****."*
Kuzniar et al., PAM 2015

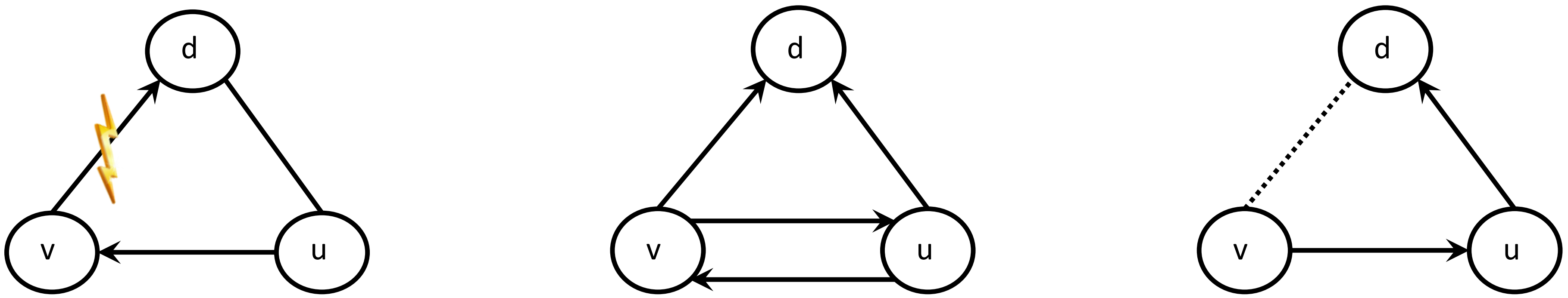


"…the inbound latency is ***quite variable*** *with a […] standard deviation of 31.34ms…"*
He et al., SOSR 2015



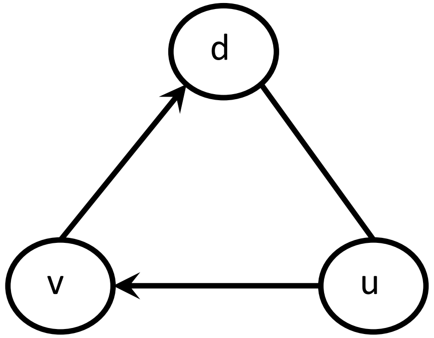
*"some switches can '****straggle****,' taking substantially* ***more time*** *than average (e.g., 10-****100x****) to apply an update"*
Jin et al., SIGCOMM 2014

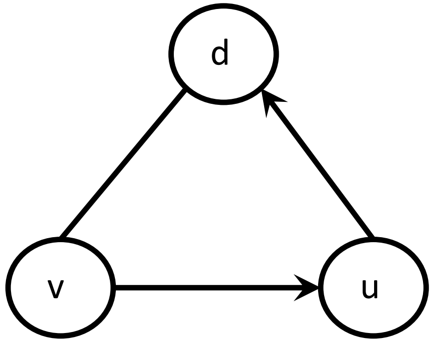
Toy Example



Old and new states exist simultaneously in a limbo state

Ordering Solution: Go backwards through the new routing tree





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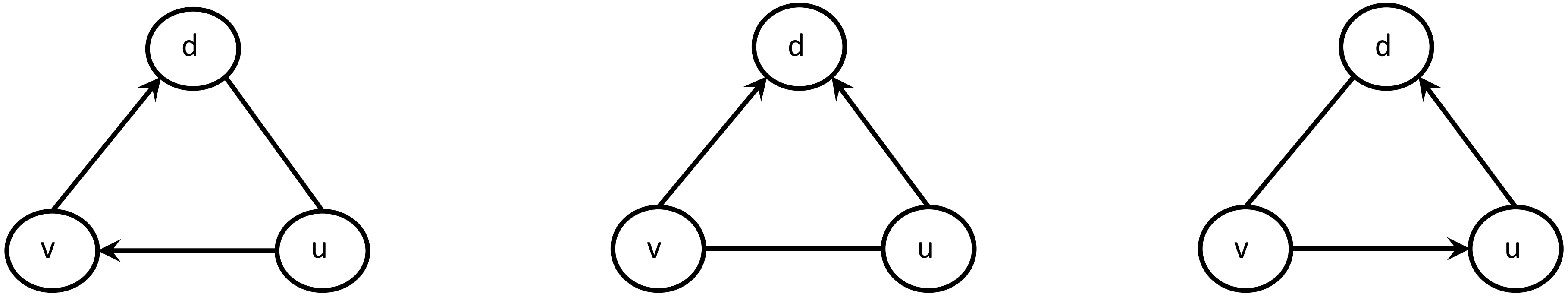

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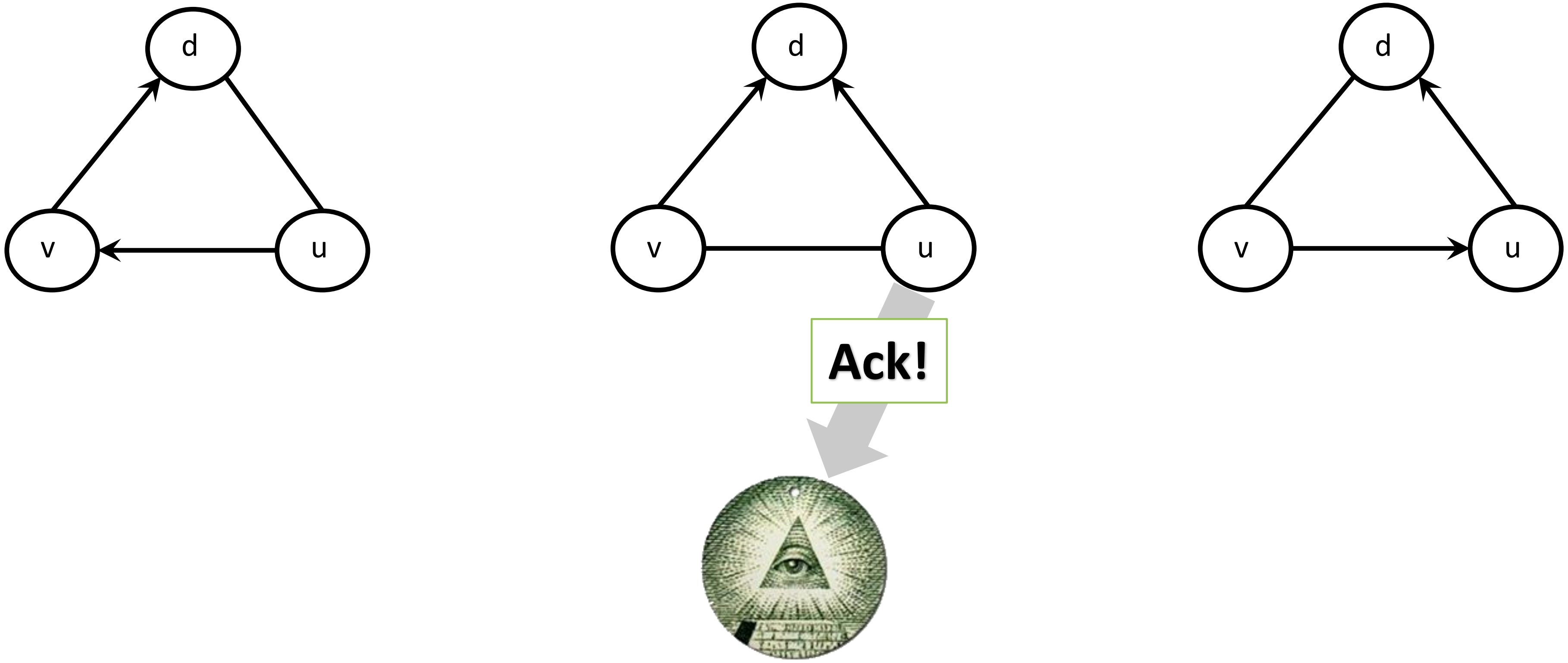

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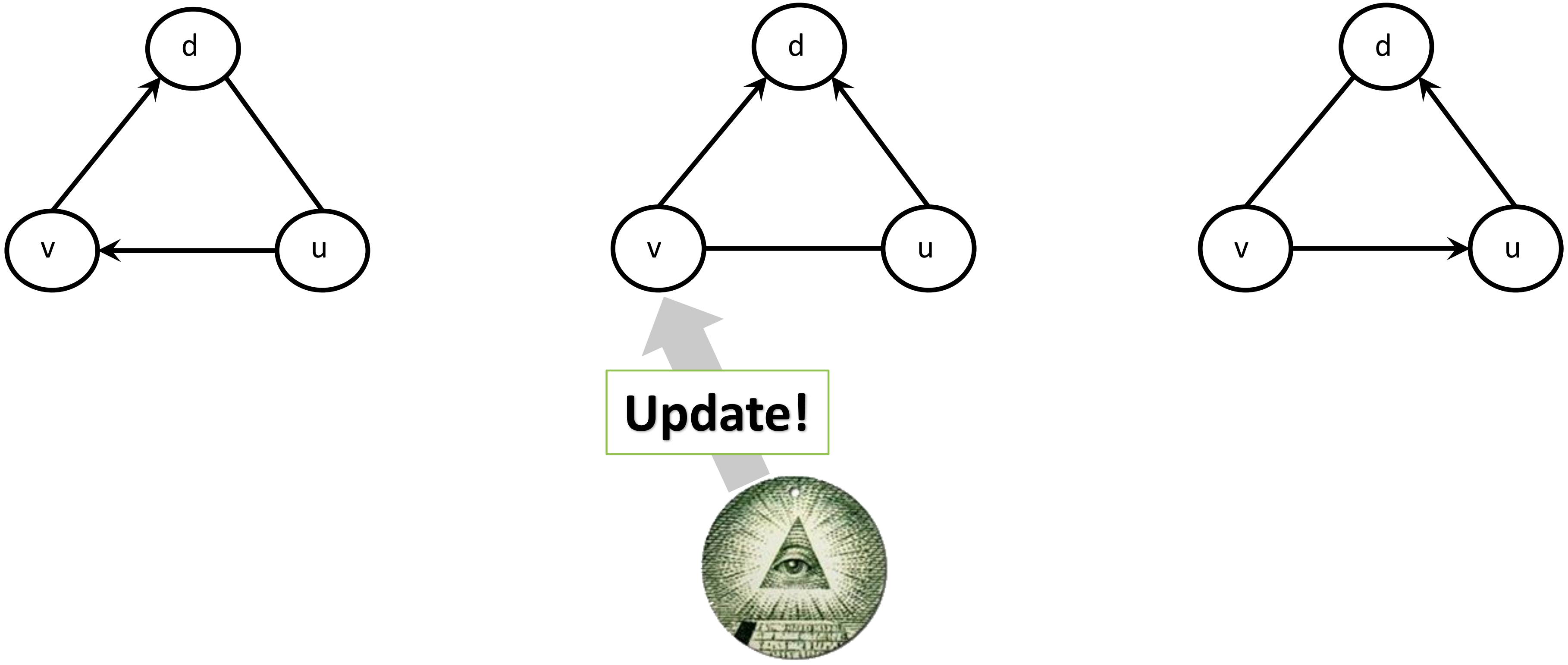

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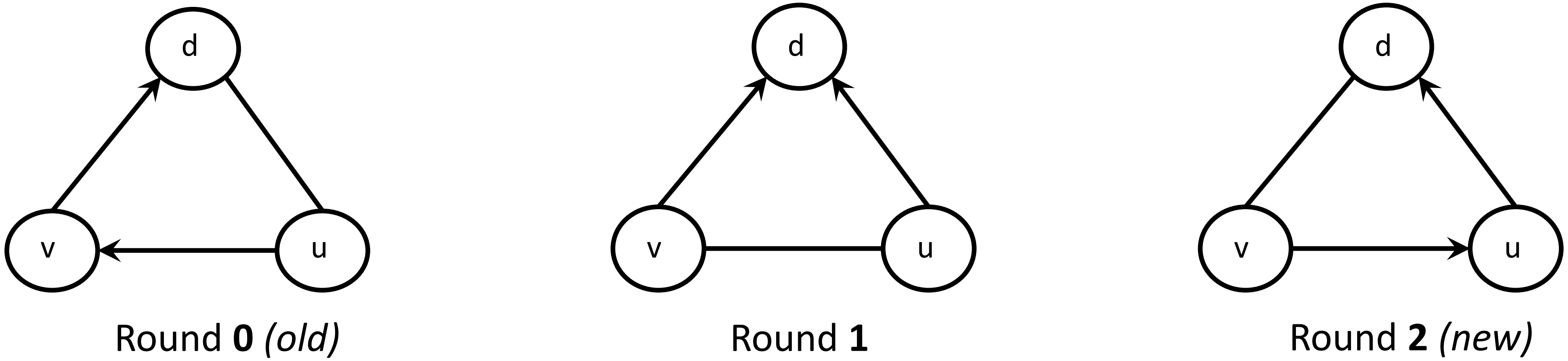
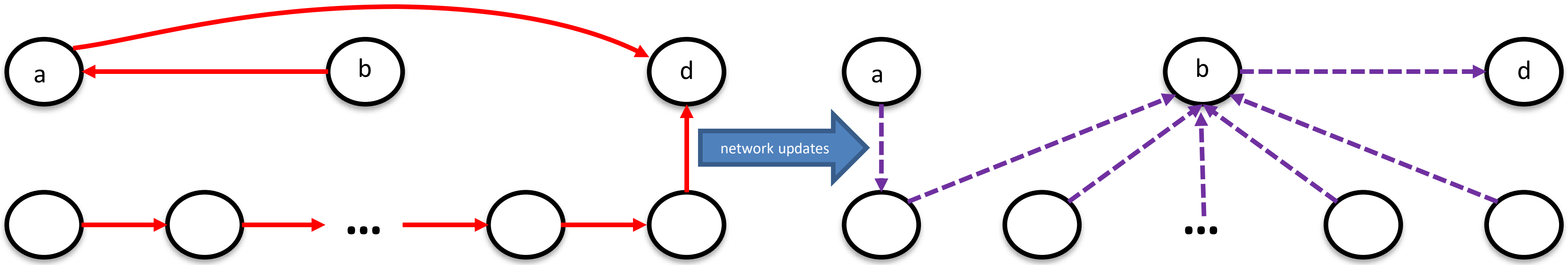


- Always works for single-destination rules
  - Also for multi-destination with sufficient memory (“split“)
- Schedule length: tree depth (up to Ω(n))
  - Optimal scheduling algorithms?

More on scheduling multiple policies:
Basta et al: Efficient Loop-Free Rerouting of Multiple SDN Flows. ToN 2018

Greedy? Update as many as possible per round

- Always works ☺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network updates
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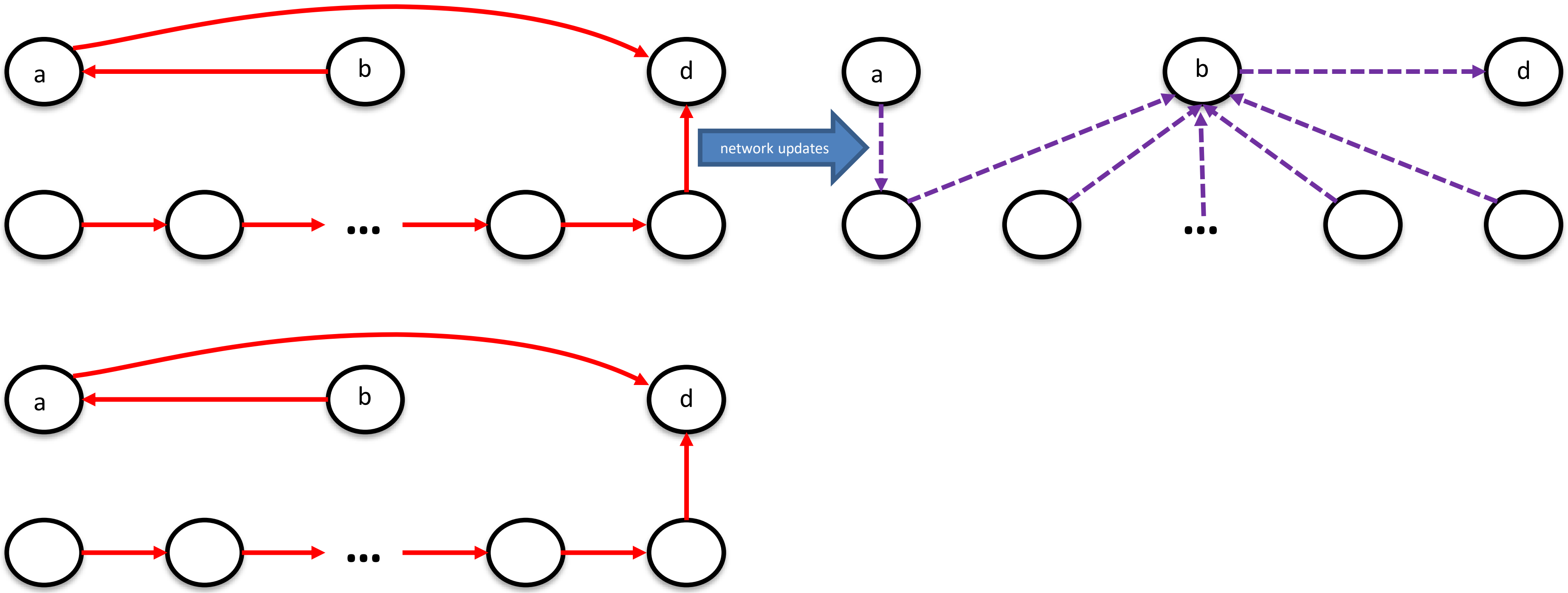
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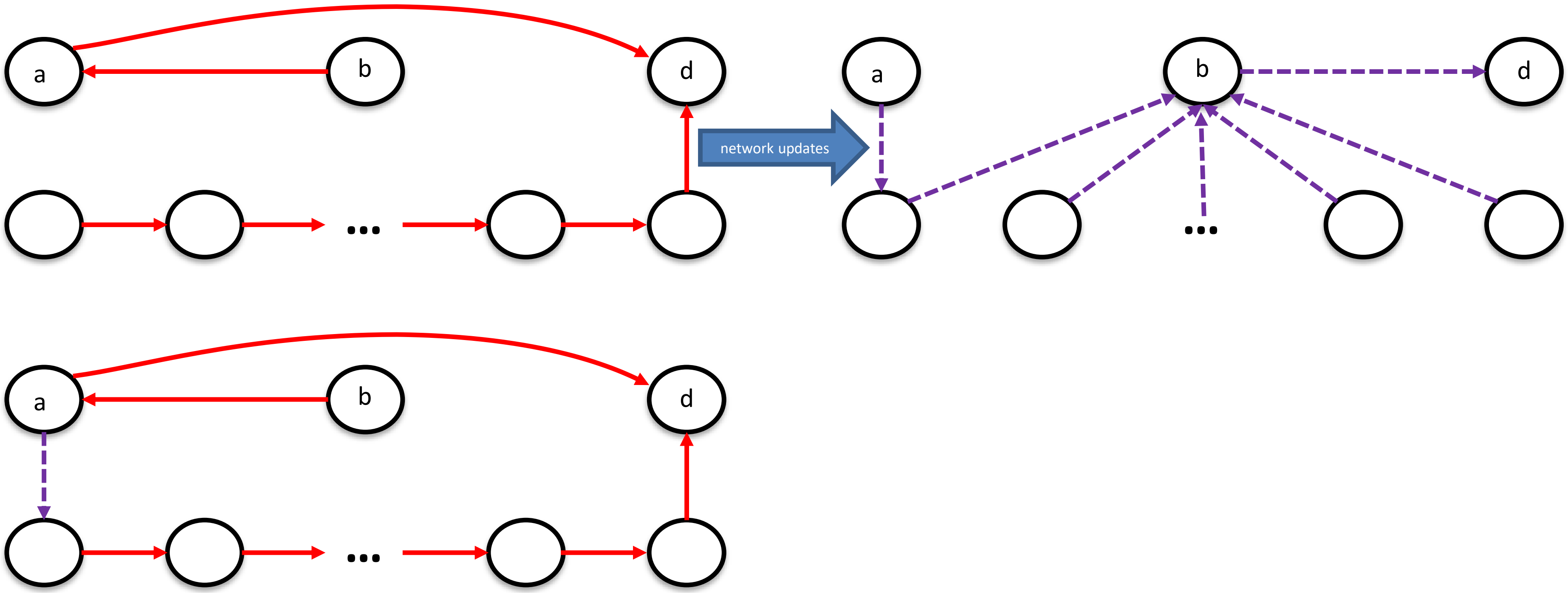
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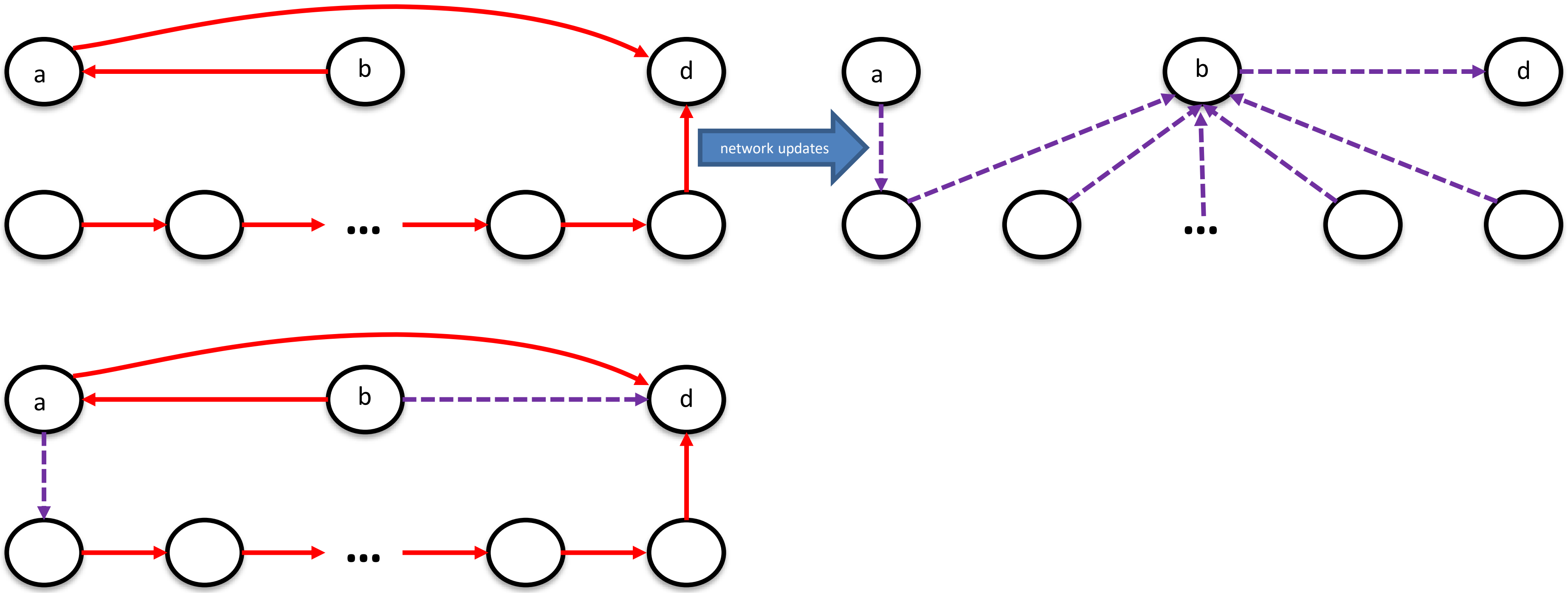
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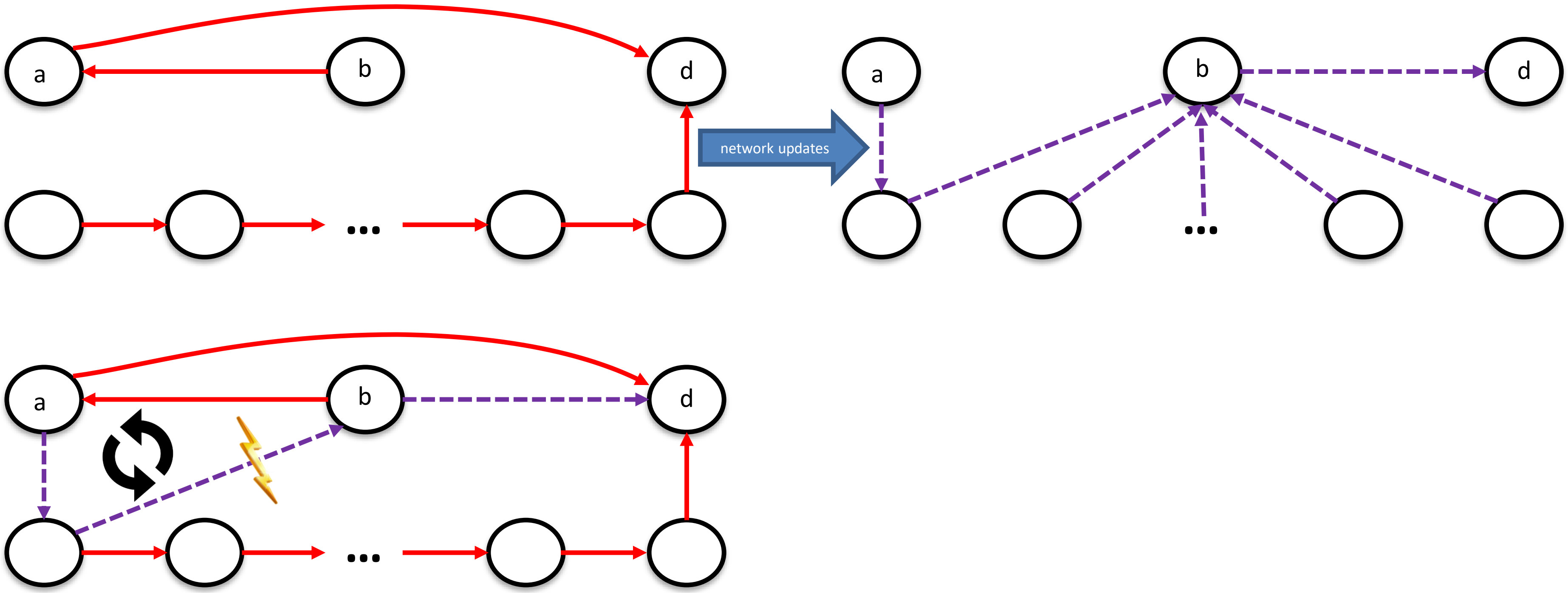
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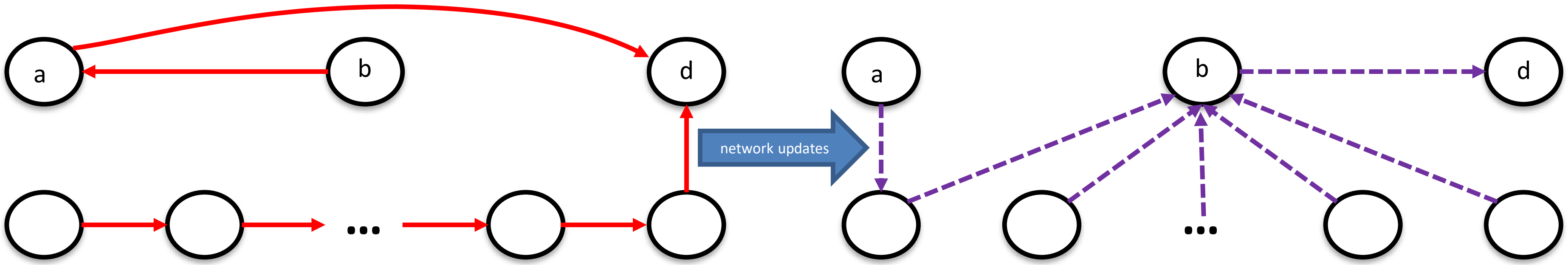
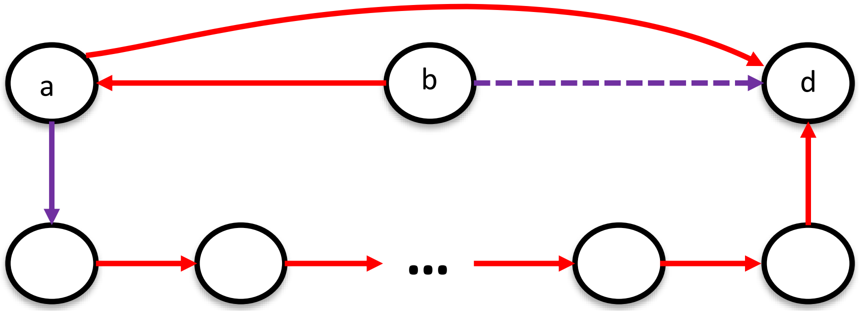
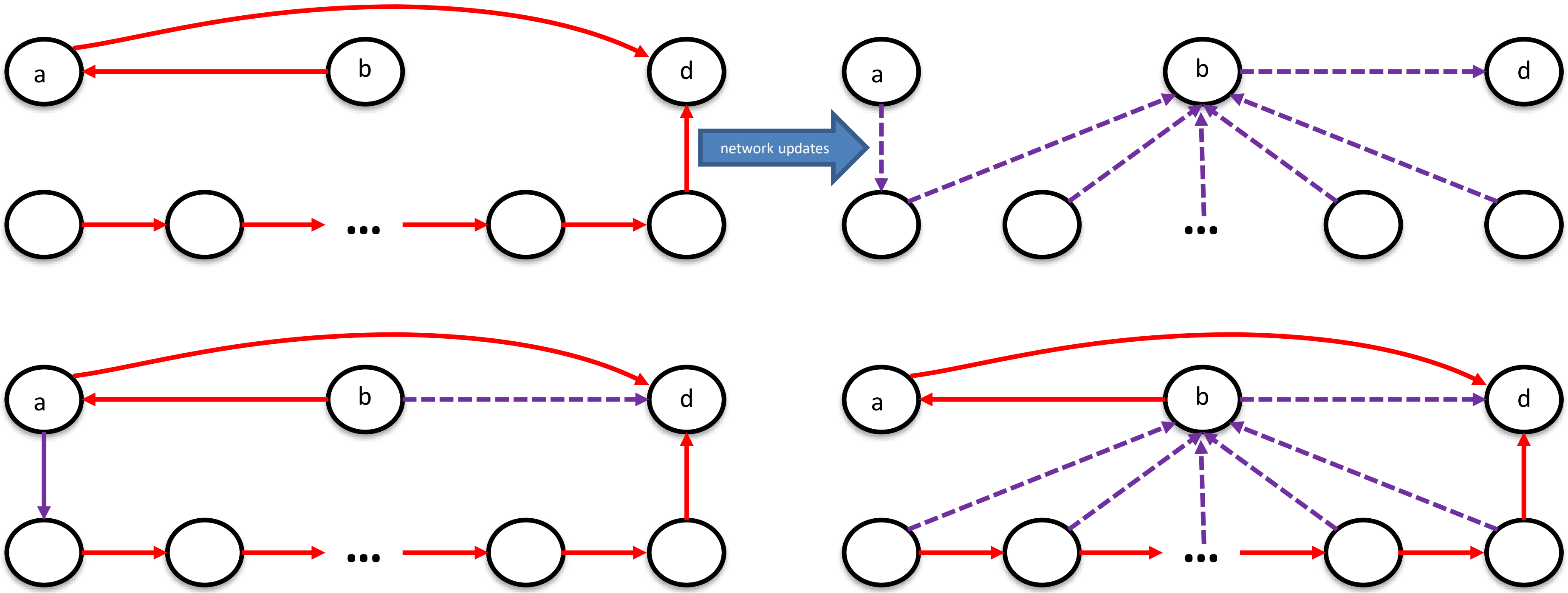




greedy **maximal** update
a & b update → all others wait
2 nodes update



greedy **maximal** update
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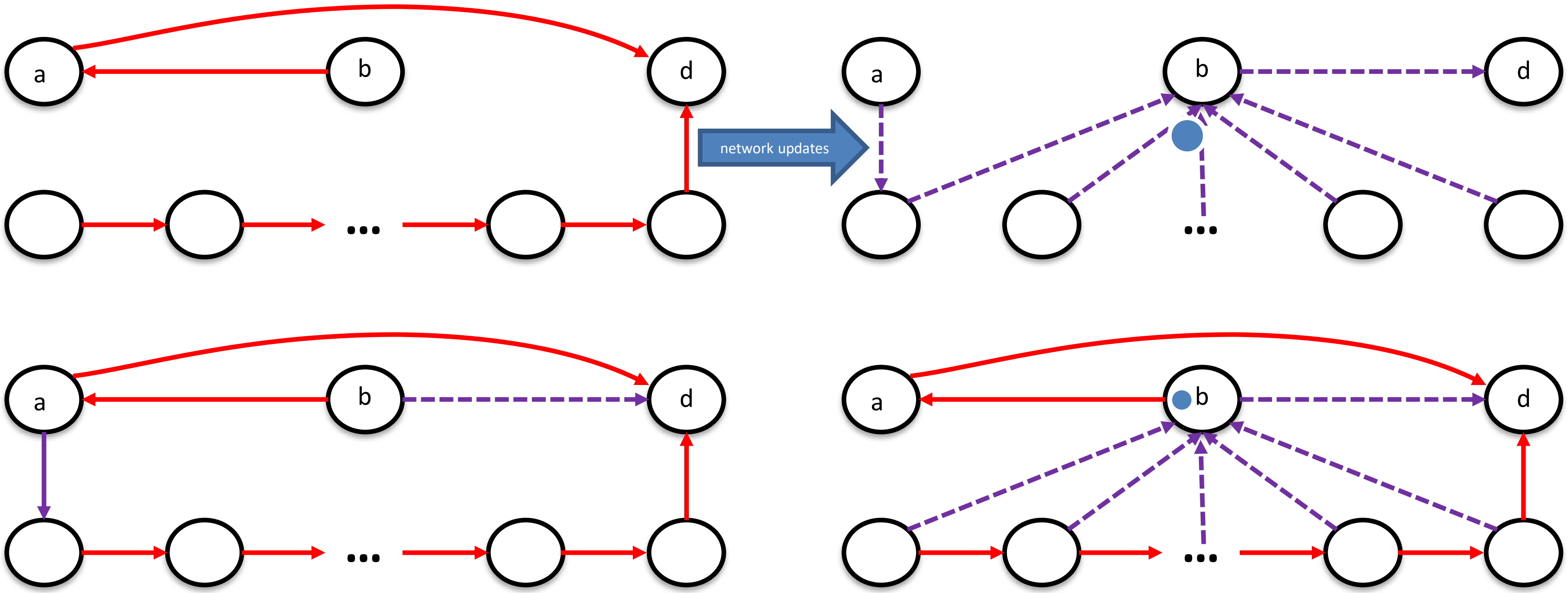
maximum update
a waits→ all others update
all but 1 update

How hard?



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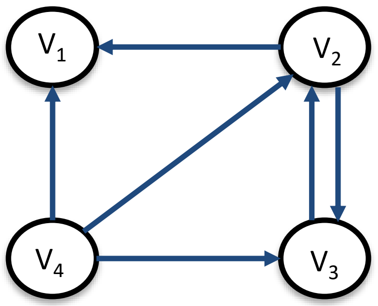
Find maximum update?

- Let’s go more general
- Delete all cycles in a graph



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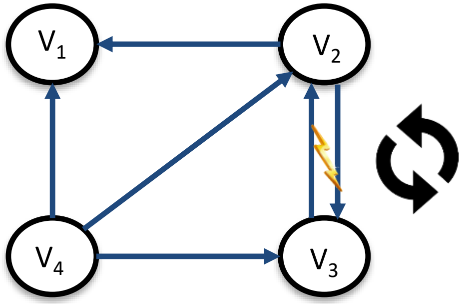

Find maximum update?

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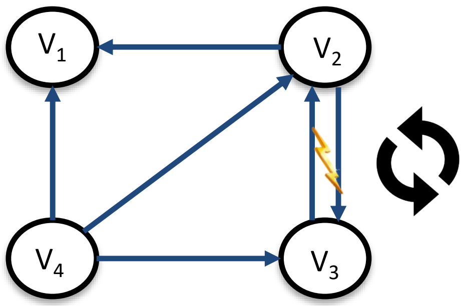
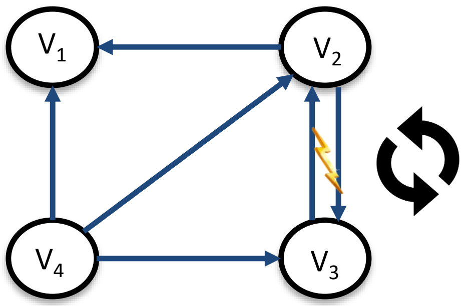
- Delete all cycles in a graph
- **NP-hard** to approximate
  – *Feedback Arc Set*



Find maximum update?

- Let’s go more general
- Delete all cycles in a graph
- **NP-hard** to approximate
  - *Feedback Arc Set*
- And it’s (essentially) equivalent ☹



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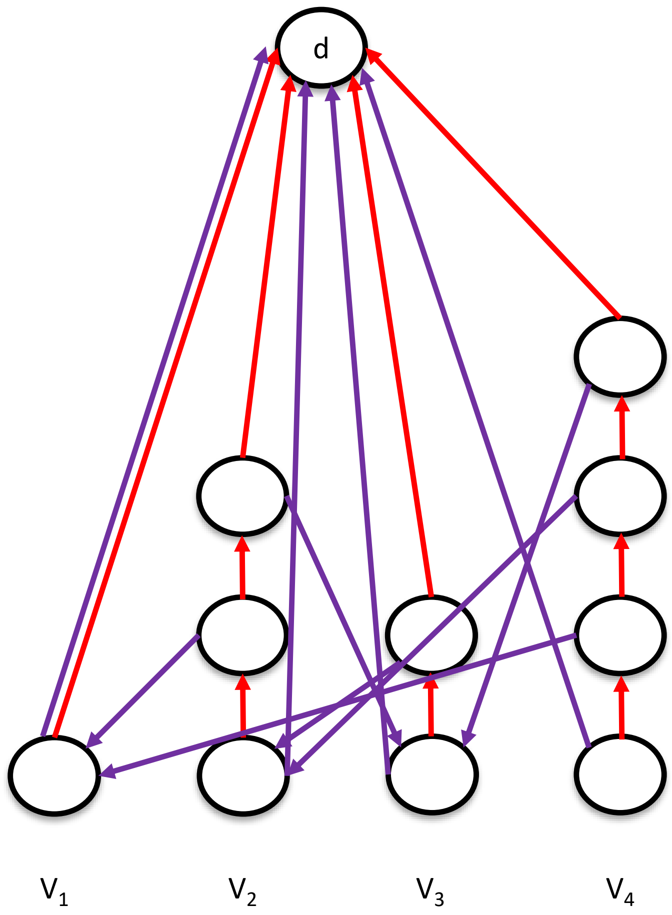

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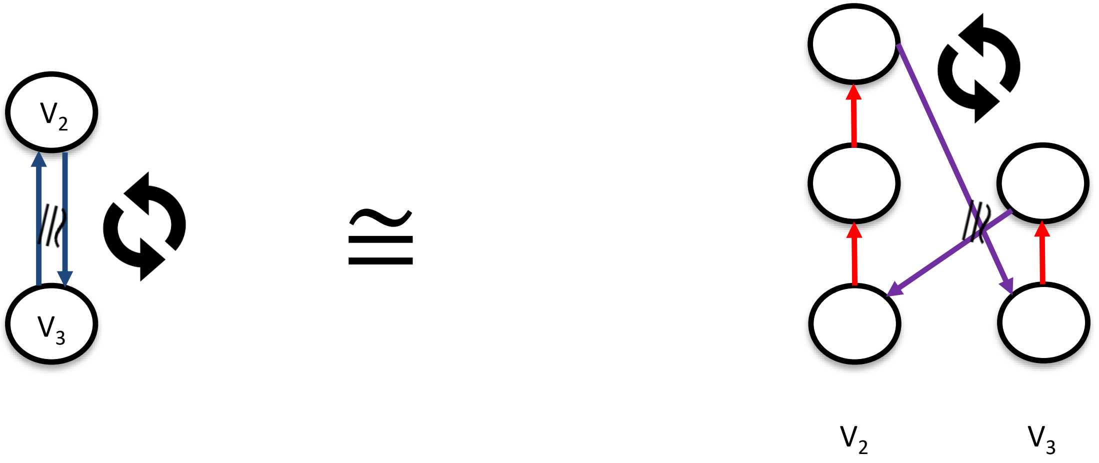


Also NP-hard for any o(n) for 2-destination policies:
F., Wattenhofer, ICCCN 2016

Greedy? Update as many as possible per round

- Always works ☺
- Maximizing is NP-hard ☹
  - *Transiently Consistent SDN Updates: Being Greedy is Hard*. S. Akhoondian Amiri, A. Ludwig, J. Marcinkowski, S. Schmid. In: SIROCCO 2016
  - *The Power of Two in Consistent Network Updates: Hard Loop Freedom, Easy Flow Migration*. K.-T. Foerster, R. Wattenhofer. In: ICCCN 2016
- Single greedy update: O(1) rounds ⇨ Ω(n) rounds ☹ ☹
  - *Loop-Free Route Updates for Software-Defined Networks*. K.-T. Foerster, A. Ludwig, J. Marcinkowski, S. Schmid. In: IEEE/ACM Trans. Netw. 2018
- In general: Does a 3-round schedule exist? NP-hard ☹ ☹ ☹
  - *Loop-Free Route Updates for Software-Defined Networks*. K.-T. Foerster, A. Ludwig, J. Marcinkowski, S. Schmid. In: IEEE/ACM Trans. Netw. 2018

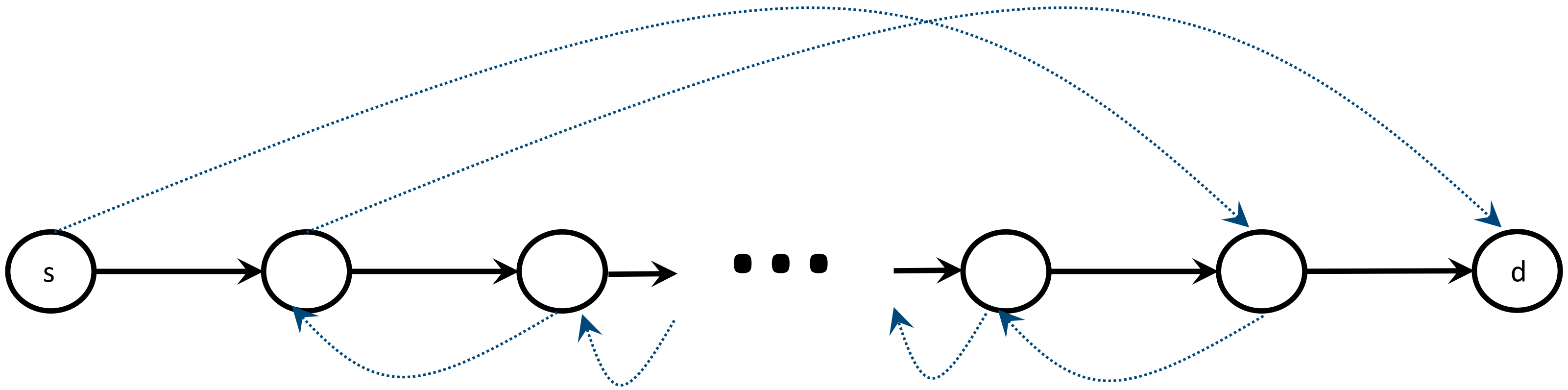

Relax And Take it Easy!
MY BABY FLOAT
INTEX
SURFER

Scheduling Loop-free Network Updates: It's Good to Relax! [Ludwig et al., PODC 2015]

Two key ideas:

1. ~~destination *d* based~~ source-destination pairs <*s*,*d*>
2. ~~no forwarding loops~~ no loops between <*s*,*d*>

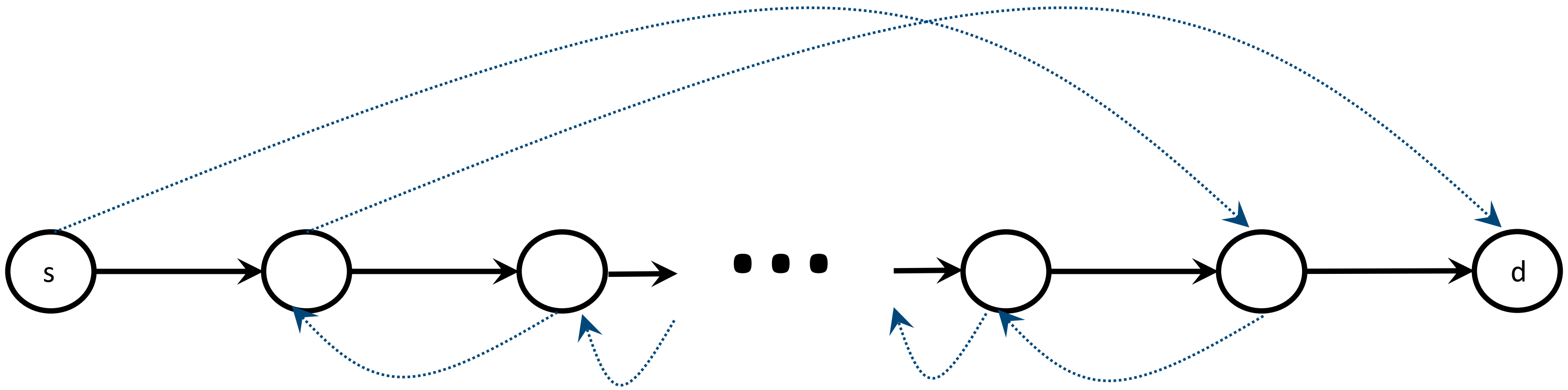
On its own:
Makes 2-round updates polynomial, 3 still NP-hard



Scheduling Loop-free Network Updates: It's Good to Relax!

- Non-relaxed? Ω(n) rounds

- Relaxed?



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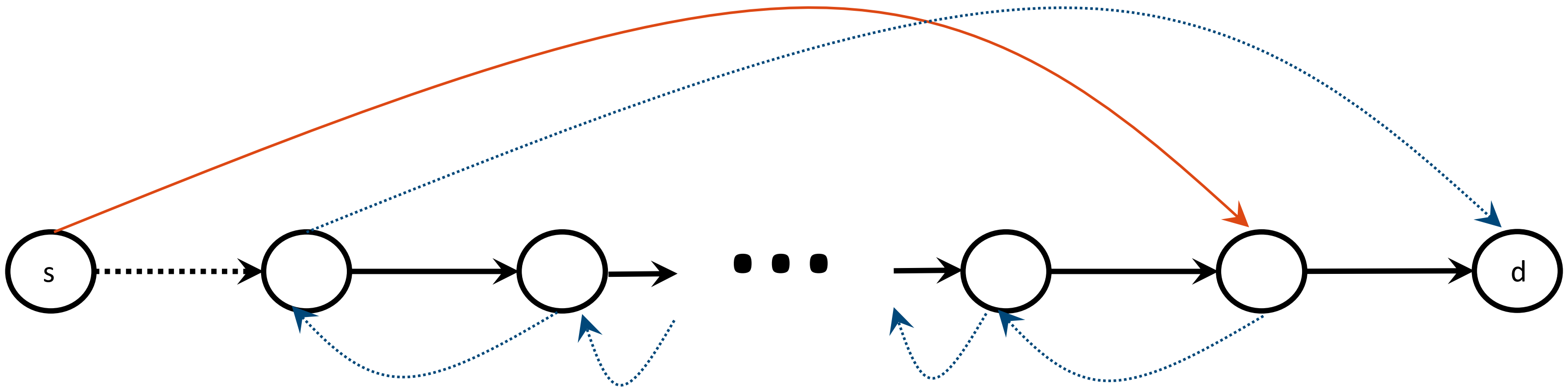

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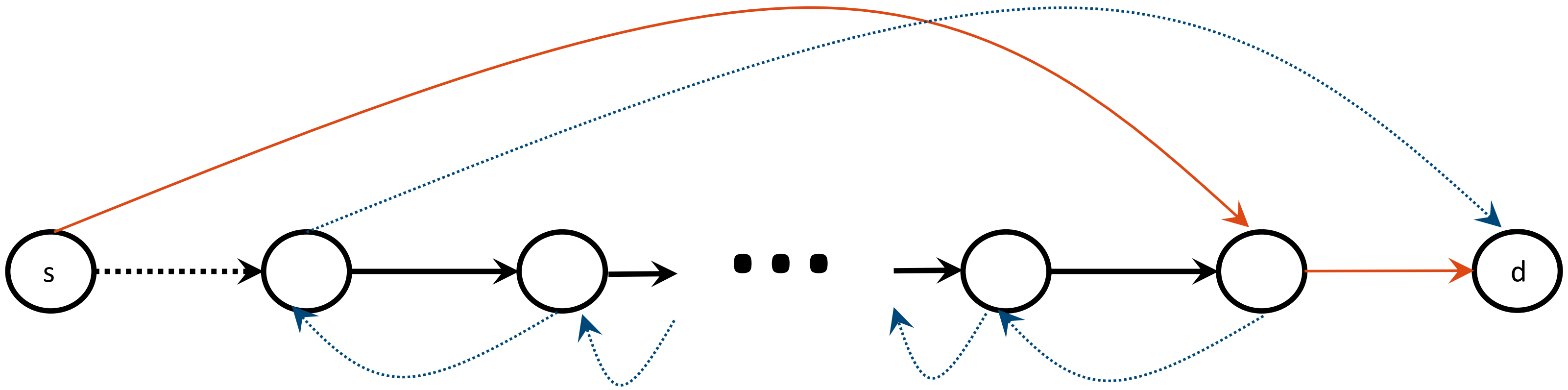

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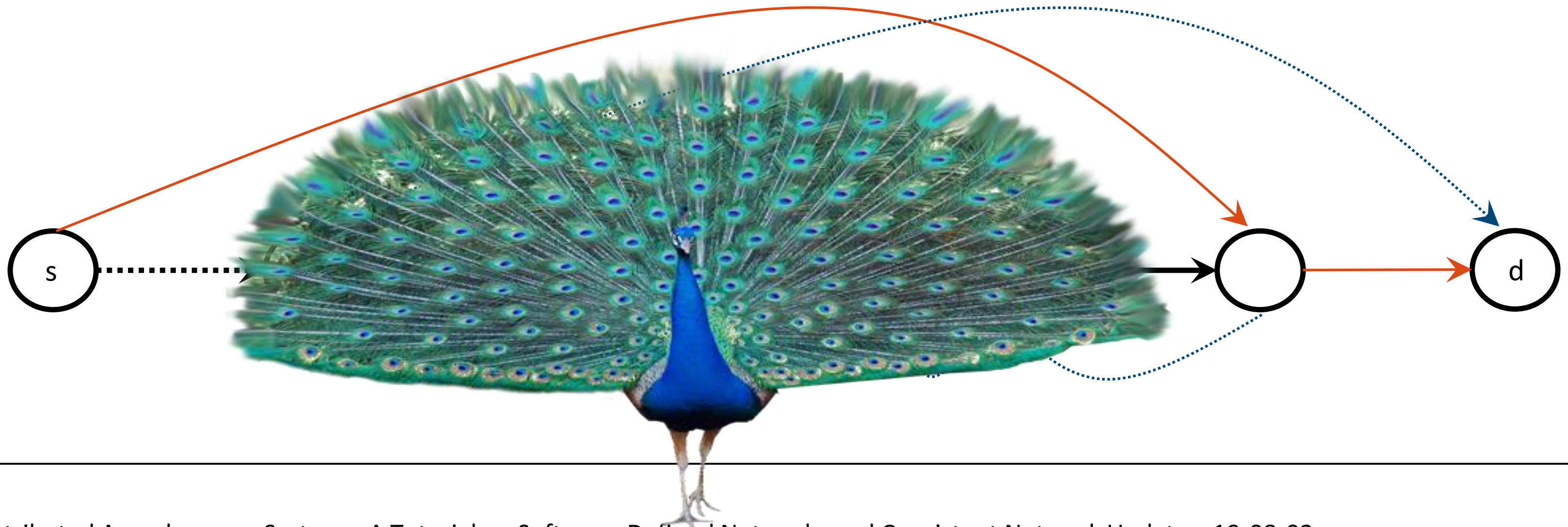
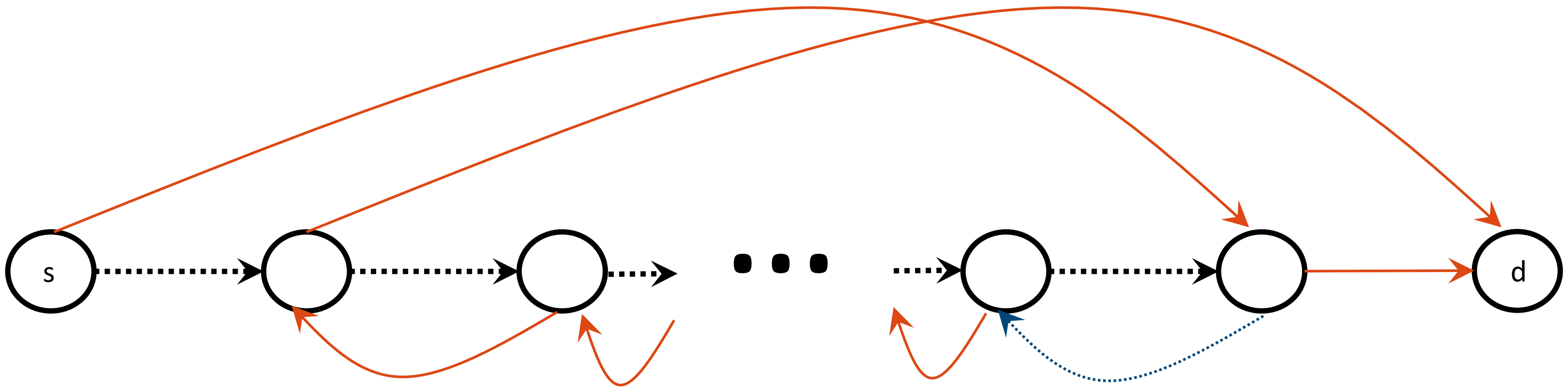


Scheduling Loop-free Network Updates: It's Good to Relax!

- Non-relaxed? Ω(n) rounds

- Relaxed?

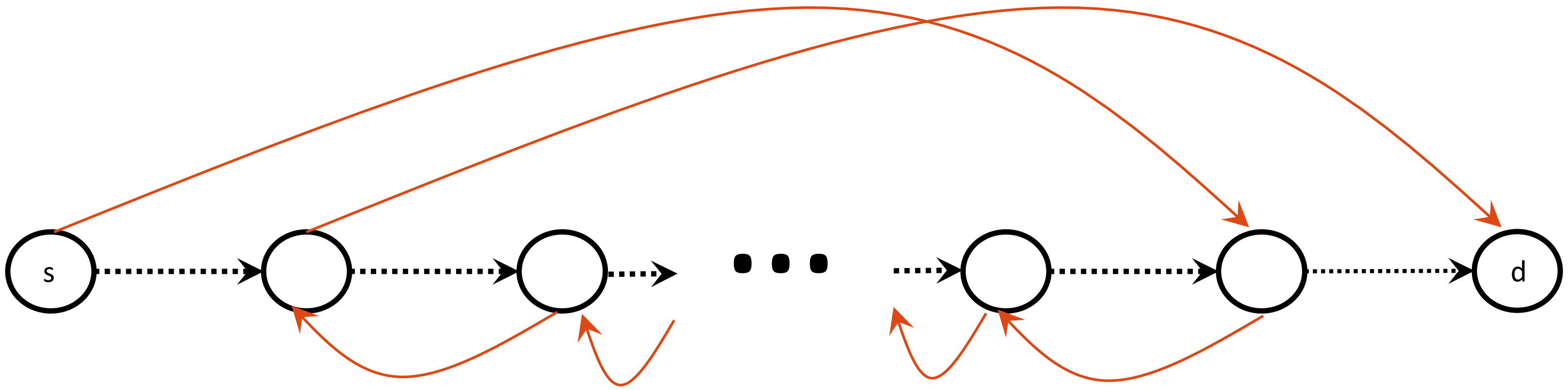
Round **2**



Scheduling Loop-free Network Updates: It's Good to Relax!

- Non-relaxed? Ω(n) rounds
- Relaxed? Just 3 rounds

Round **3**

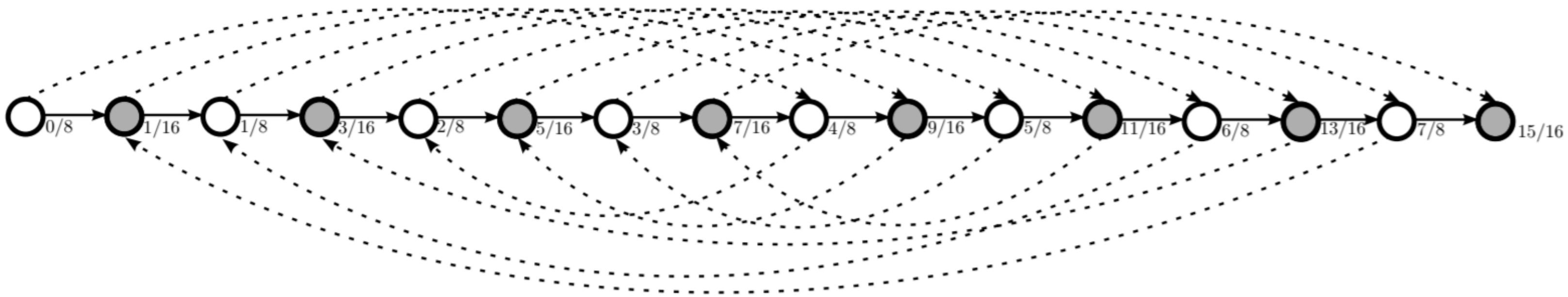


Scheduling Loop-free Network Updates: It's Good to Relax!

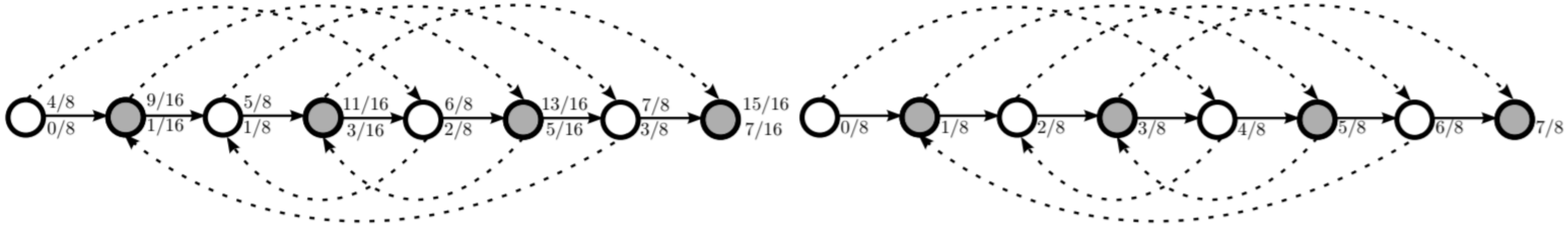
- Non-relaxed? Ω(n) rounds

- Relaxed? Just 3 rounds
  - In general: $O(\log n)$ rounds (“Peacock“)

Loop-Free Route Updates for Software-Defined Networks. K.-T. Foerster, A. Ludwig, J. Marcinkowski, S. Schmid. In: IEEE/ACM Trans. Netw. 2018

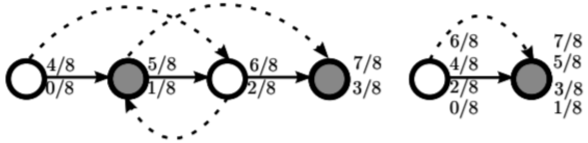


(a) The graph G_1 with 16 nodes. When *Peacock* selects the edge from $0/8$ to $4/8$ as a shortcut, pruning results in the graph in Fig. 10b.

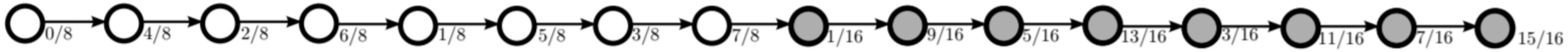


(b) After two rounds with *Peacock*, isomorphic to G_0 in Fig. 10c.

(c) The graph G_0 with 8 nodes. $0/8$ to $4/8$ is the next shortcut.



(d) To the left, the output of *Peacock* on G_0 after two rounds. To the right, after two more rounds, selecting the first forward edge as a shortcut each time.

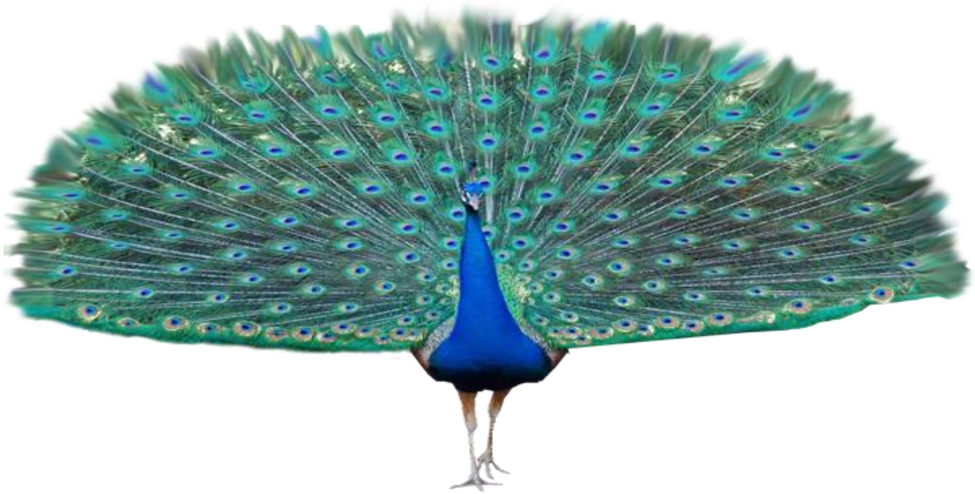


(e) The resulting updated graph, expanded into 16 nodes again.

Scheduling Loop-free Network Updates: It's Good to Relax!

- Non-relaxed? Ω(n) rounds

- Relaxed? Just 3 rounds
  - In general: $O(\log n)$ rounds (“Peacock“)
  - But: Peacock instances with $\Omega(\log n)$ rounds



Loop-Free Route Updates for Software-Defined Networks. K.-T. Foerster, A. Ludwig, J. Marcinkowski, S. Schmid. In: IEEE/ACM Trans. Netw. 2018

Some Open Questions for scheduling loop free updates:

- For both models: Approximation algorithms for #rounds?

In a bit..

Relaxed:

- Optimal #rounds: NP-hard or in P?
- What is the real lower bound?

More open questions and specifics:
Survey of Consistent Software-Defined Network Updates
Klaus-Tycho Foerster, Stefan Schmid, Stefano Vissicchio
IEEE Communications Surveys & Tutorials, 21(2), 2019

Non-relaxed:

- NP-hard for $O(1) < k < \Omega(n)$ rounds?

Eg Congestion?
Network functions?

So Far Everything Was Sort of Centralized…

- …can we make it more distributed?

Decentralized Updates for „Tree-Ordering“

- So far: every round:
  - Controller computes and sends out updates
  - Switches implement them and send acks
  - Controller receives acks

Decentralized Updates for „Tree-Ordering“

- So far: every round:
  - Controller computes and sends out updates
  - Switches implement them and send acks
  - Controller receives acks

- Alternative: Use dualism to so-called *proof labeling schemes*

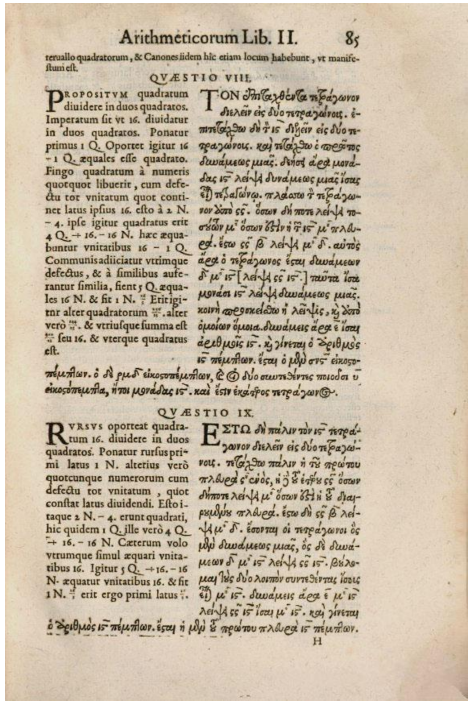
Centralized Controller
(Prover)

Eg P4 switch
(Verifier)

INTERMISSION

Proof-Labeling Schemes

Deciding vs Checking



Arithmeticorum Lib. II. 85

teruallo quadratorum, & Canones iidem hîc etiam locum habebunt, vt manifestum est.

QVÆSTIO VIII.

PROPOSITVM quadratum diuidere in duos quadratos. Imperatum sit vt 16. diuidatur in duos quadratos. Ponatur primus 1 Q. Oportet igitur 16 − 1 Q. æquales esse quadrato. Fingo quadratum à numeris quotquot libuerit, cum defectu tot vnitatum quot continet latus ipsius 16. esto à 2 N. − 4. ipse igitur quadratus erit 4 Q. + 16. − 16 N. hæc æquabuntur vnitatibus 16 − 1 Q. Communis adiiciatur vtrimque defectus, & à similibus auferantur similia, fient 5 Q. æquales 16 N. & fit 1 N. $\frac{16}{5}$ Erit igitur alter quadratorum $\frac{256}{25}$. alter verò $\frac{144}{25}$. & vtriusque summa est $\frac{400}{25}$ seu 16. & vterque quadratus est.

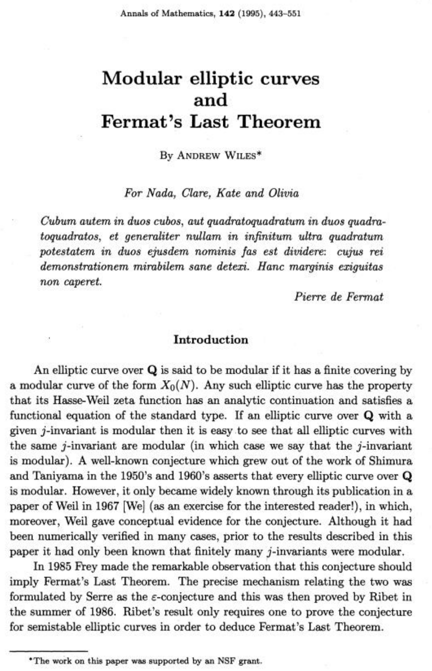
QVÆSTIO IX.

RVRSVS oporteat quadratum 16. diuidere in duos quadratos. Ponatur rursus primi latus 1 N. alterius verò quotcunque numerorum cum defectu tot vnitatum, quot constat latus diuidendi. Esto itaque 2 N. − 4. erunt quadrati, hic quidem 1 Q. ille verò 4 Q. + 16. − 16 N. Cæterum volo vtrumque simul æquari vnitatibus 16. Igitur 5 Q. + 16. − 16 N. æquatur vnitatibus 16. & fit 1 N. [illegible] erit ergo primi latus [illegible].

H

Prove

Verify



Annals of Mathematics, **142** (1995), 443–551

Modular elliptic curves and Fermat's Last Theorem

By ANDREW WILES*

For Nada, Clare, Kate and Olivia

Cubum autem in duos cubos, aut quadratoquadratum in duos quadratoquadratos, et generaliter nullam in infinitum ultra quadratum potestatem in duos ejusdem nominis fas est dividere: cujus rei demonstrationem mirabilem sane detexi. Hanc marginis exiguitas non caperet.

Pierre de Fermat

Introduction

An elliptic curve over **Q** is said to be modular if it has a finite covering by a modular curve of the form $X_0(N)$. Any such elliptic curve has the property that its Hasse-Weil zeta function has an analytic continuation and satisfies a functional equation of the standard type. If an elliptic curve over **Q** with a given j-invariant is modular then it is easy to see that all elliptic curves with the same j-invariant are modular (in which case we say that the j-invariant is modular). A well-known conjecture which grew out of the work of Shimura and Taniyama in the 1950's and 1960's asserts that every elliptic curve over **Q** is modular. However, it only became widely known through its publication in a paper of Weil in 1967 [We] (as an exercise for the interested reader!), in which, moreover, Weil gave conceptual evidence for the conjecture. Although it had been numerically verified in many cases, prior to the results described in this paper it had only been known that finitely many j-invariants were modular.

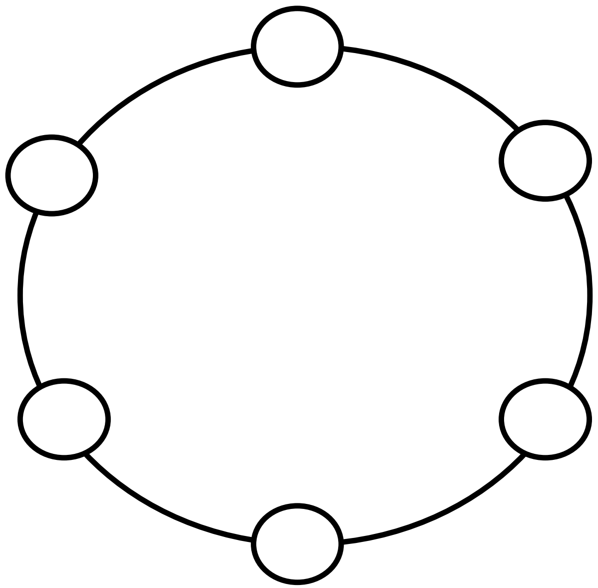
In 1985 Frey made the remarkable observation that this conjecture should imply Fermat's Last Theorem. The precise mechanism relating the two was formulated by Serre as the ε-conjecture and this was then proved by Ribet in the summer of 1986. Ribet's result only requires one to prove the conjecture for semistable elliptic curves in order to deduce Fermat's Last Theorem.

*The work on this paper was supported by an NSF grant.

Brief Selected Background

- [Naor and Stockmeyer, STOC 1993]:
  What can be computed locally?
- [Korman et al., PODC 2005]:
  Proof Labeling Schemes (PLS)
- [Göös and Suomela, PODC 2011]:
  Locally Checkable Proofs (LCP)
- [Fraigniaud et al., FOCS 2011,…]:
  Nondeterministic Local Decision (NLD)
- And many more recent works, e.g., on approximation, randomization etc.

Example



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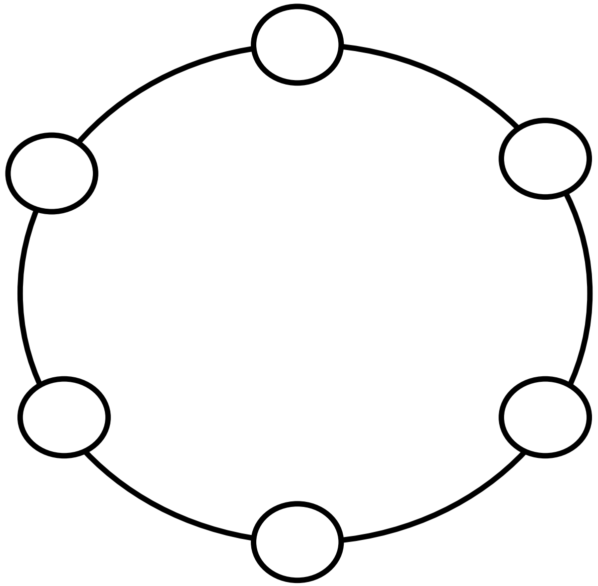
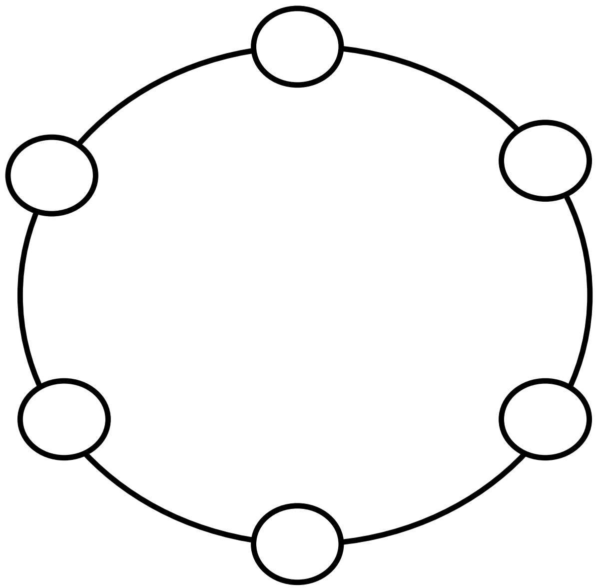
Example



Model

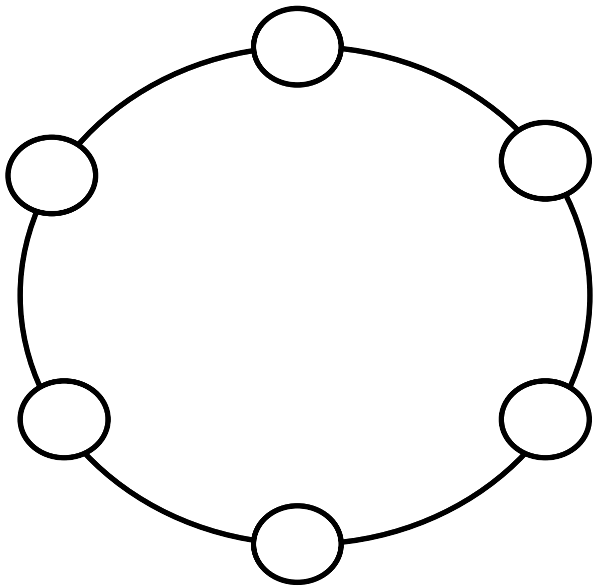
- Each of the n nodes is a computer, connected by links
- Synchronous rounds
  - Simplified: unlimited message size & computational power, unique identifiers for nodes

Example



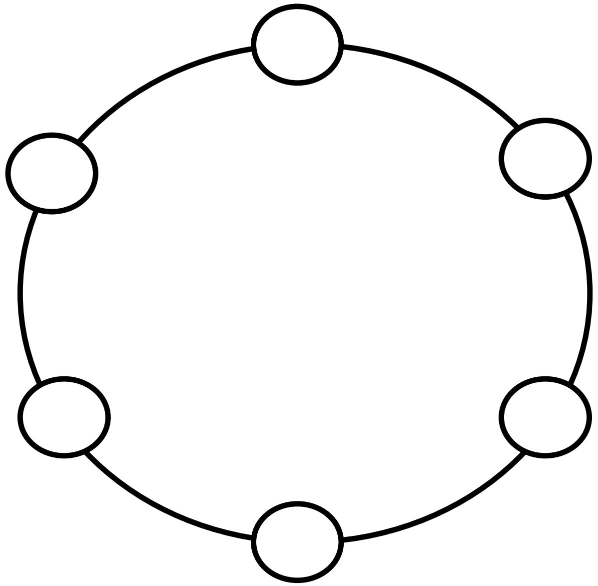
- Is n even?

Example



- Is n even?
- $\Omega(n)$ rounds

Example



- Is n even?
- $\Omega(n)$ rounds
- What if I tell you it is even? Why should you trust me ☺

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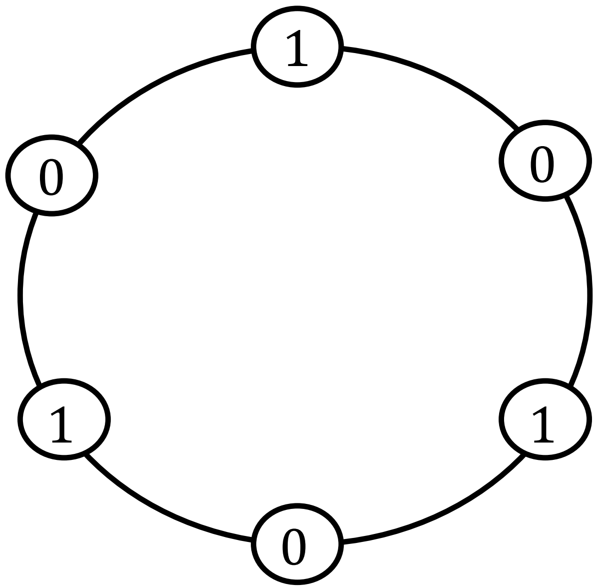
Example



- Is n even?
- $\Omega(n)$ rounds
- $\mathcal{P}$rover assigns 1 bit?

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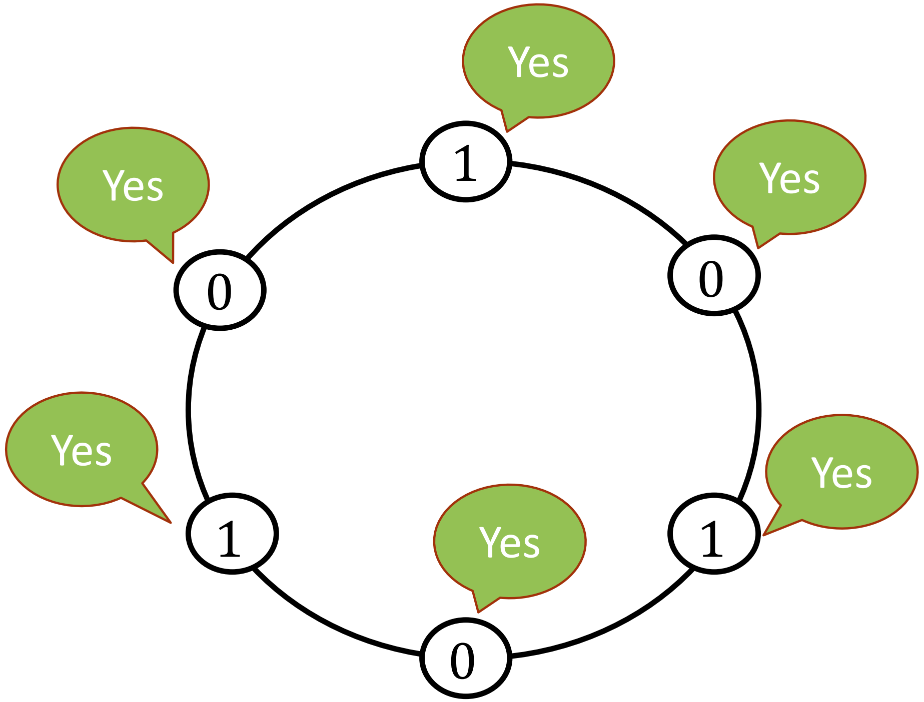
Example



- Is n even?
- $\Omega(n)$ rounds
- $\mathcal{P}$rover assigns 1 bit -> $\mathcal{V}$erify in 1 round

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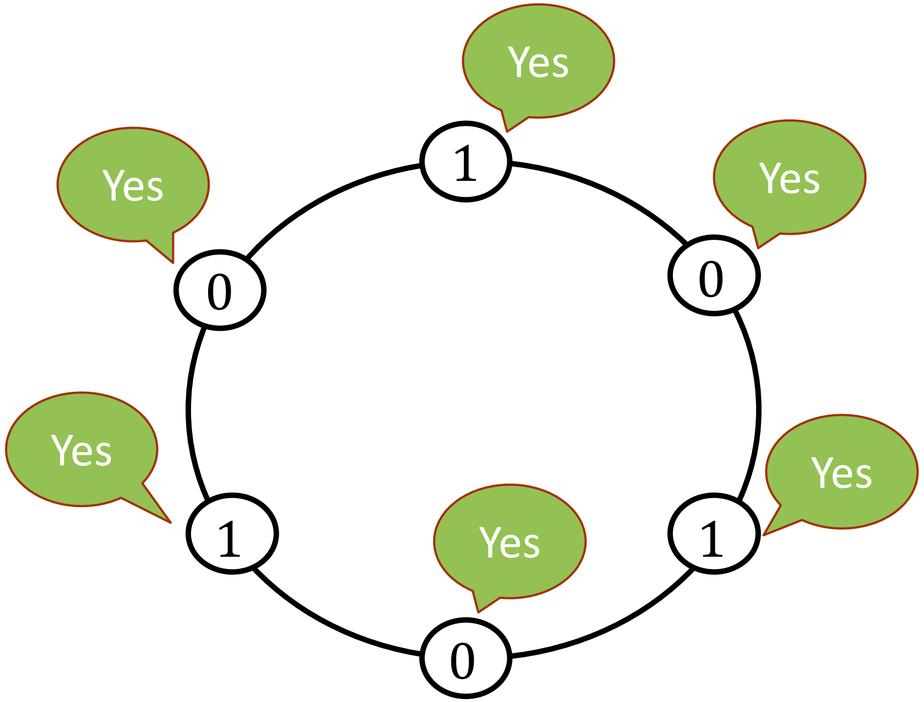
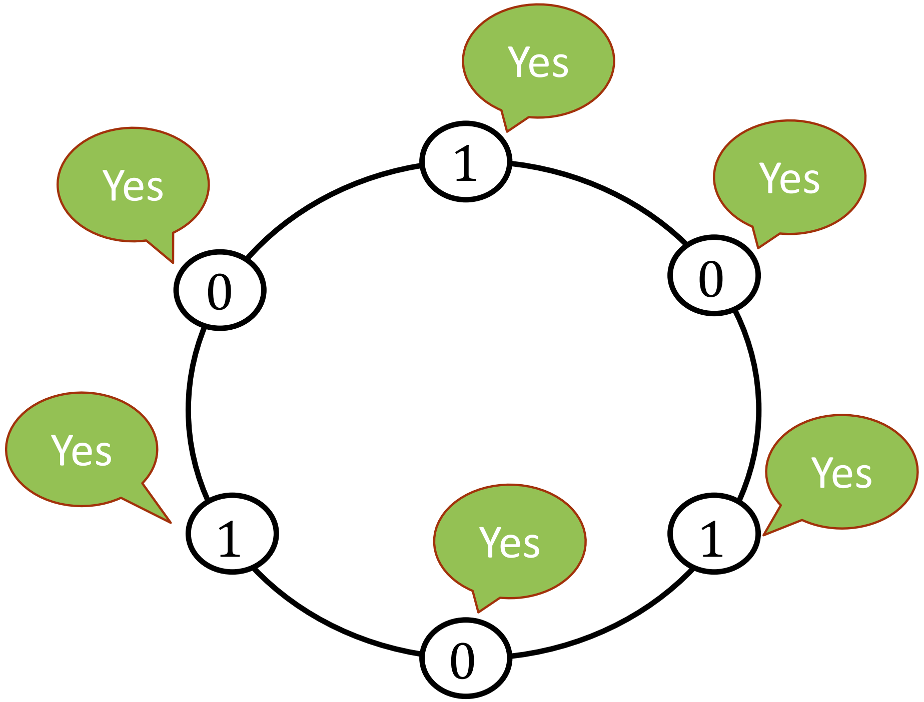


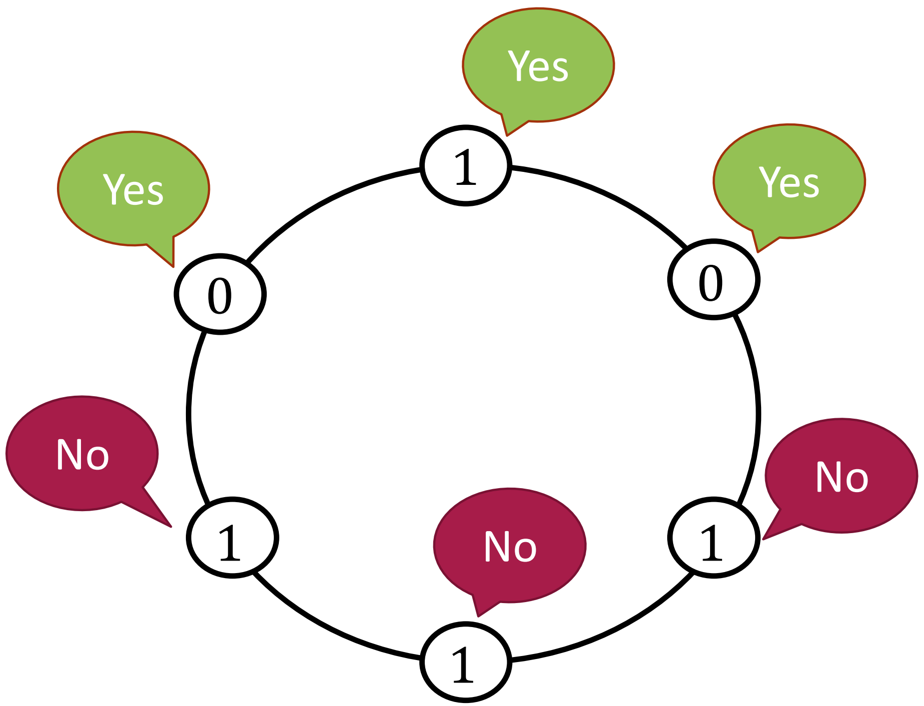
- Is n even?
- $\Omega(n)$ rounds
- $\mathcal{P}$rover assigns 1 bit -> $\mathcal{V}$erify in 1 round
- Other way to think of it: 1 bit of non-determinism
- General question: How many bits necessary/sufficient?

Accepting a proof



- Every node outputs **Yes** -> Proof accepted
- One node outputs **No** -> Proof rejected

Accepting a proof



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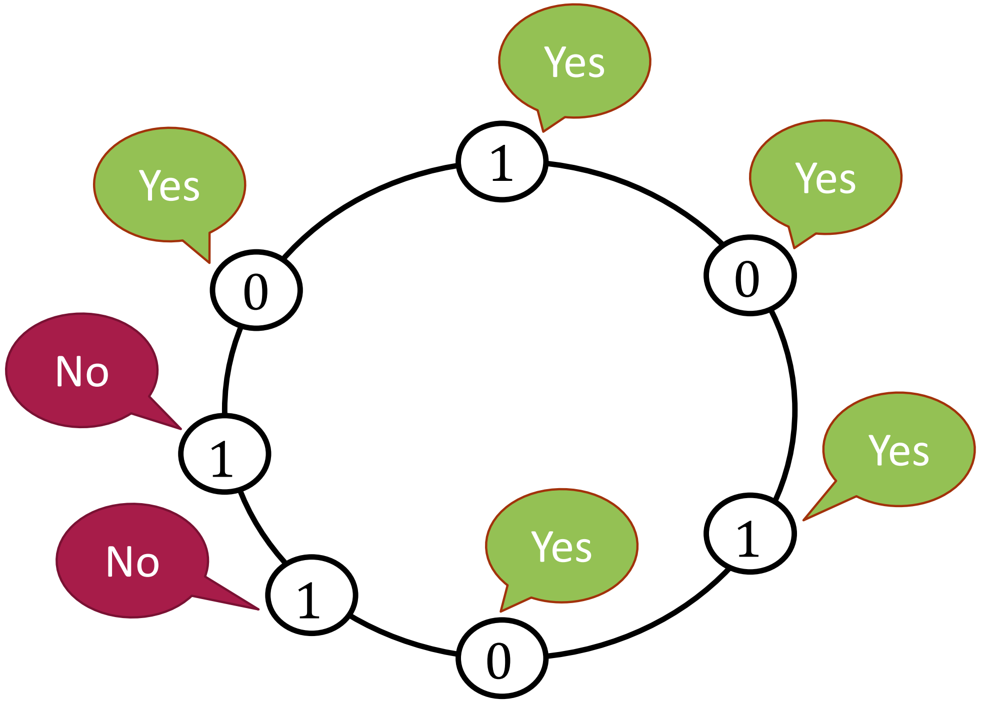

- Every node outputs **Yes** -> Proof accepted
- One node outputs **No** -> Proof rejected
  - $\mathcal{P}$rover chose the wrong proof
  - Property does not hold

Back to SDNs: Switch from a proof to another

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Decentralized ing“

When should I update?

Decentralized ing“

Once my parent updates!

Decentralized ing“

Once my parent updates!

Send parent ID

Decentralized Updates for „Tree-Ordering“

Decentralized … ing“

I‘ll update too!

I updated

Decentralized Updates for “Tree-Ordering“

+ Only one controller-switch interaction per route change
+ New route changes can be pushed before old ones done *(include “version#”)*
+ Incorrect updates can be locally detected *(include depth in tree, prevents loops)*

+/- Speed benefit/penalty depends on update scenario and topology

\- Requires switch-to-switch communication e.g., [Nguyen et al., SOSR 2017]

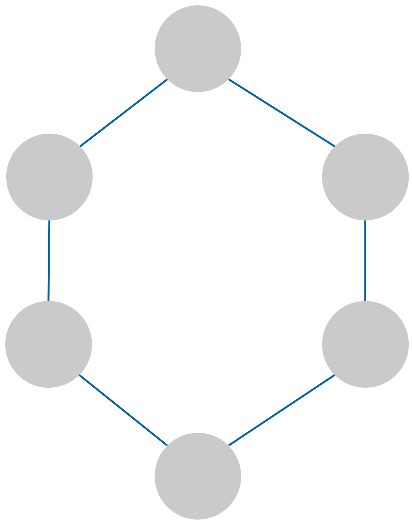
K.-T. Foerster, T. Luedi, J. Seidel, R. Wattenhofer: *Local Checkability, No Strings Attached: (A)cyclicity, Reachability, Loop Free Updates in SDNs* . In: Theoret. Comput. Sci. 2018
K.-T. Foerster, S. Schmid: *Distributed Consistent Network Updates in SDNs: Local Verification for Global Guarantees*. Under submission.

Can we also make the initial computation decentralized?

- Classic setting of distributed computing (e.g. LOCAL or CONGEST model)
  - Possible benefit in SDNs:
    - We do not need to compute from scratch!
      - In wired networks, problems depend on a subset of the network
        - Leverage **Preprocessing**

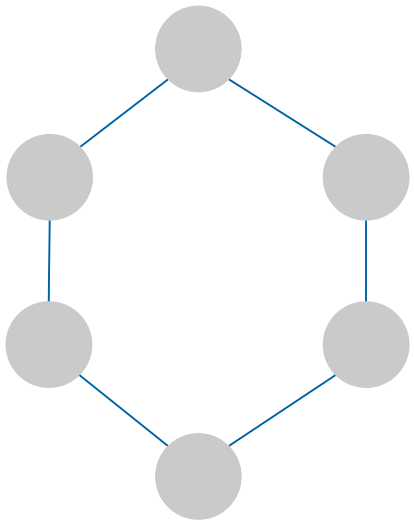
- Further explored in eg:
  - Exploiting Locality in Distributed SDN Control. S. Schmid, J. Suomela, HotSDN 2013
  - On the Power of Preprocessing in Decentralized Network Optimization. K.-T. Foerster, J. Hirvonen, S. Schmid, J. Suomela, INFOCOM 2019
  - BA: Does Preprocessing help under Congestion? K.-T. Foerster, J. Korhonen, J. Rybicki, S. Schmid, PODC 2019

Coloring of rings (LOCAL model)



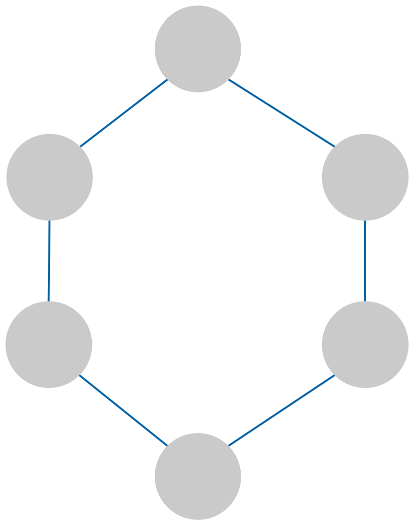
Coloring of rings (LOCAL model)

- 2-coloring:



Coloring of rings (LOCAL model)

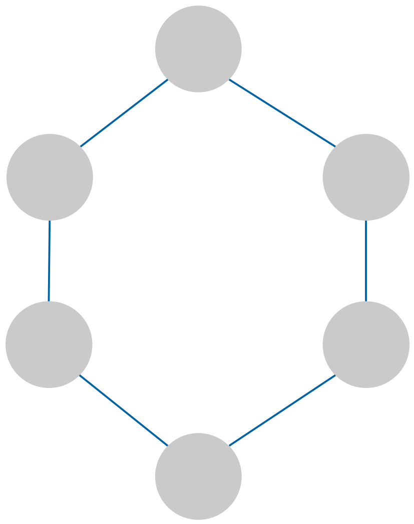
- 2-coloring:
  - Needs $\Omega(n)$ rounds



Coloring of rings (LOCAL model)

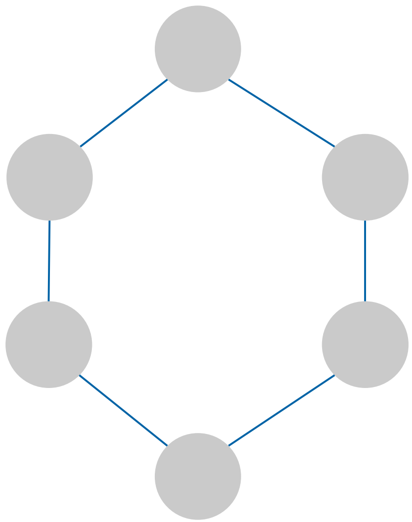
- 2-coloring:
  - Needs $\Omega(n)$ rounds

- 3-coloring:



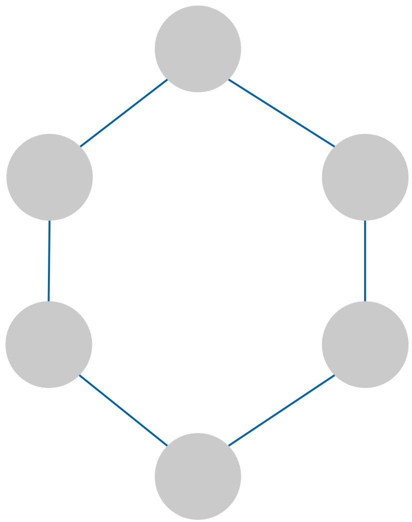
Coloring of rings (LOCAL model)

- 2-coloring:
  - Needs $\Omega(n)$ rounds
- 3-coloring:
  - Needs non-constant time



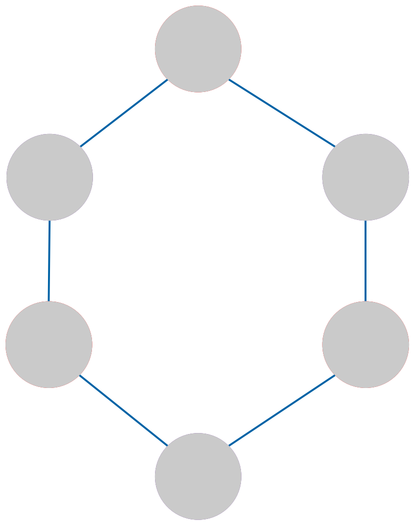
Coloring of rings (LOCAL model)

- 2-coloring:
  - Needs Ω(n) rounds
- 3-coloring:
  - Needs non-constant time
- Cannot improve in the LOCAL model ☹



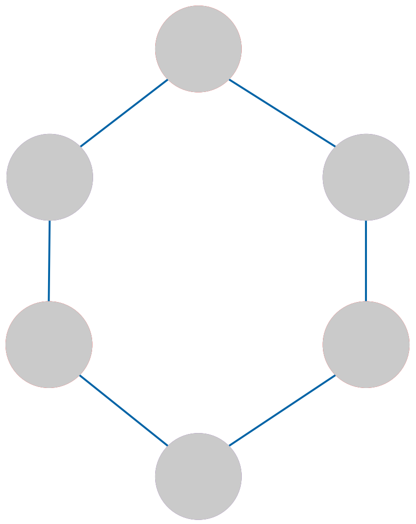
Coloring of rings (LOCAL model) – with Preprocessing

- 2-coloring:
- 3-coloring:



Coloring of rings (LOCAL model) – with Preprocessing

- 2-coloring:
  - 0 rounds ☺
- 3-coloring:
  - 0 rounds ☺



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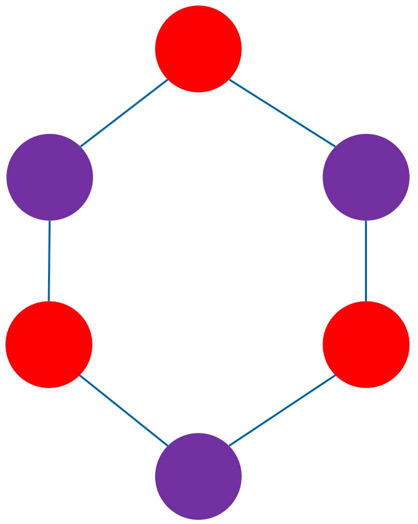
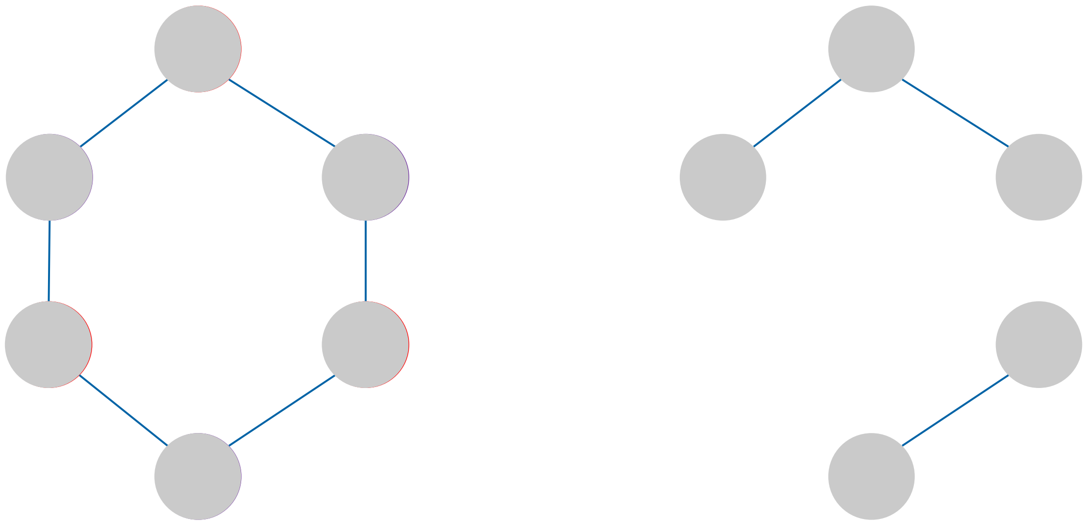


Coloring of rings (LOCAL model) – with Preprocessing & Subgraphs

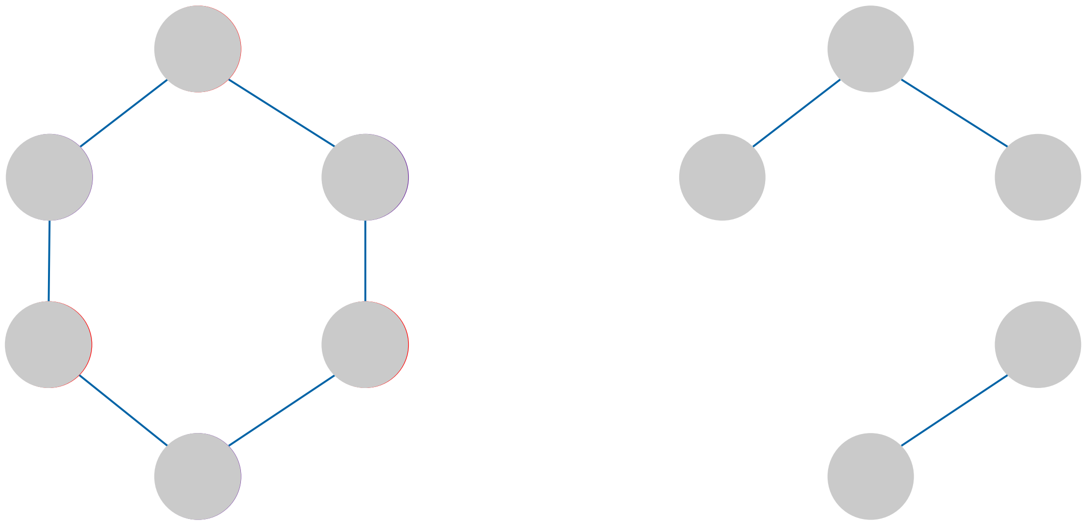
- How about a coloring of a subgraph?



Coloring of rings (LOCAL model) – with Preprocessing & Subgraphs

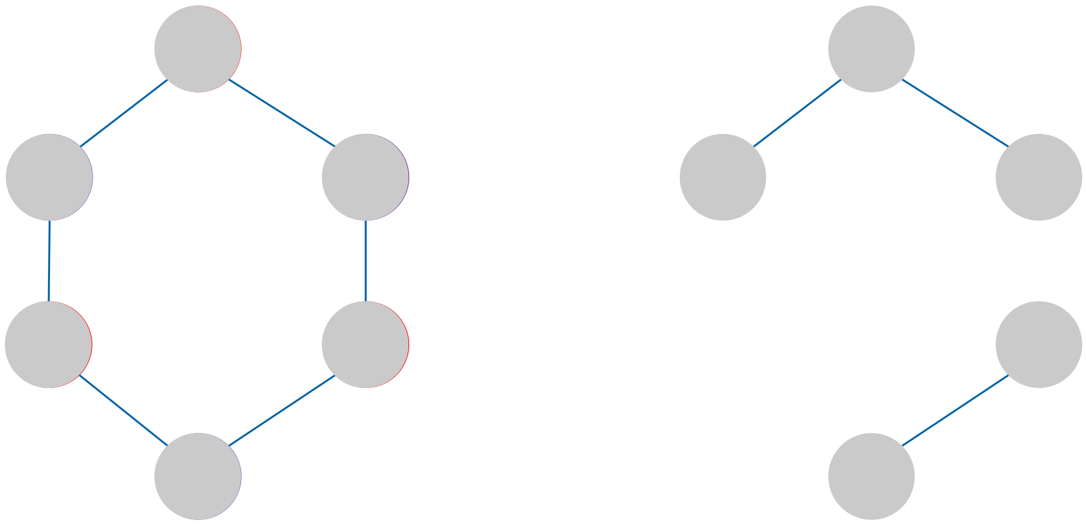
- How about a coloring of a subgraph?

- Local model: runtime does not change



Coloring of rings (LOCAL model) – with Preprocessing & Subgraphs

- How about a coloring of a subgraph?
- Local model: runtime does not change
- With preprocessing: fast!



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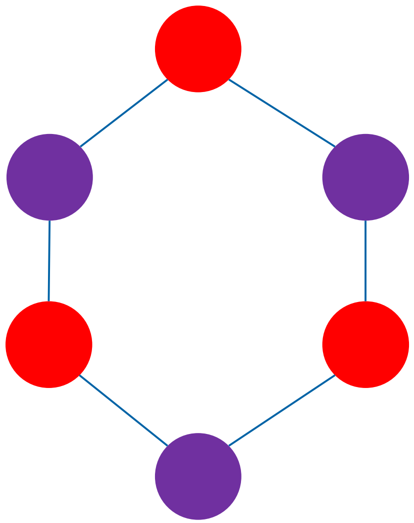

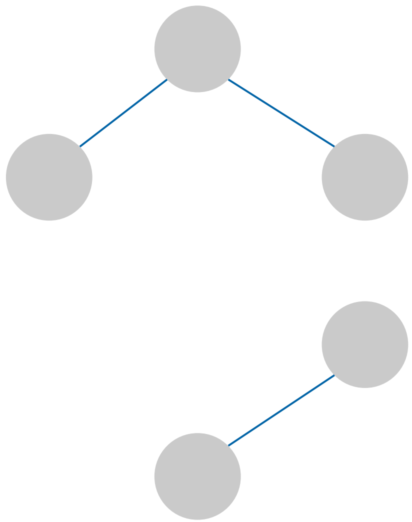

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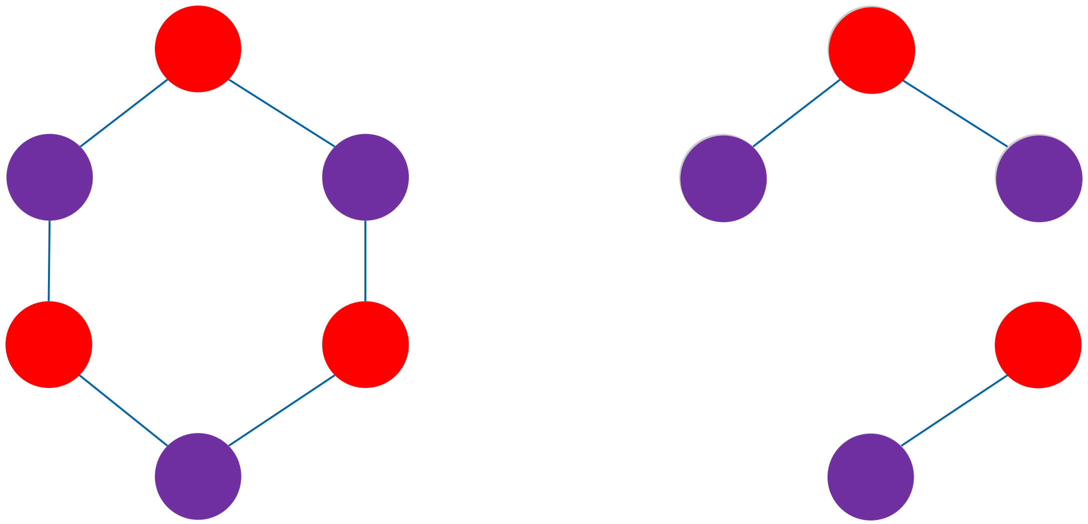

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- How about a coloring of a subgraph?
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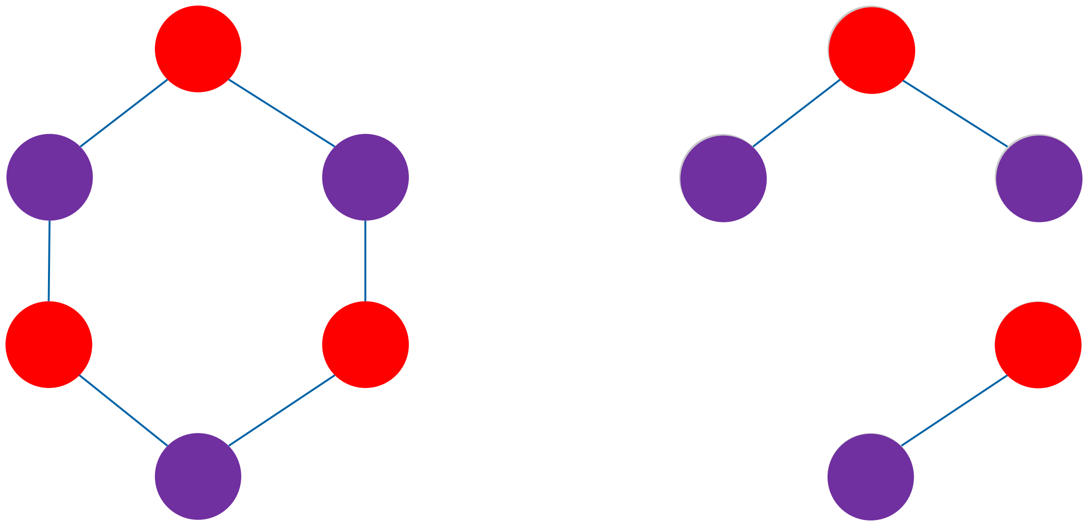
  - Coloring remains valid



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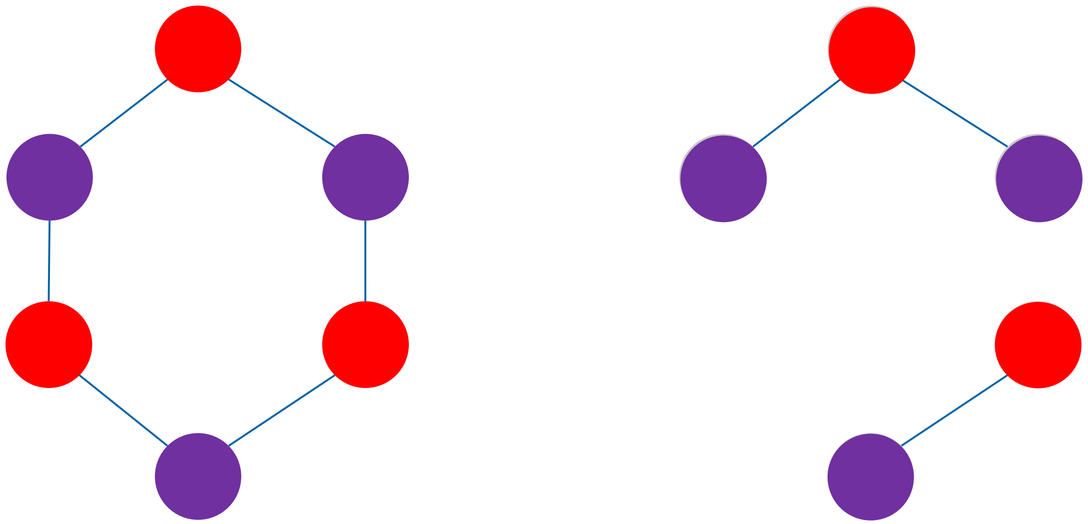

Coloring of rings (LOCAL model) – with Preprocessing & Subgraphs

- How about a coloring of a subgraph?
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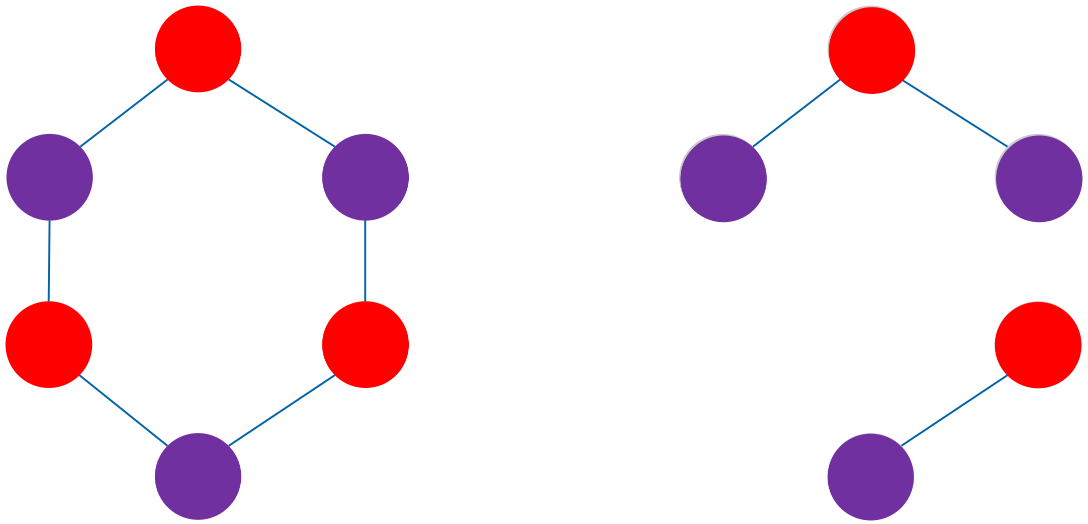
- With preprocessing: fast!
  - Coloring remains valid
- What are further application scenarios?
- What else can we do with the SUPPORT of Preprocessing?



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  - Often we just react to events, physical topology in wired networks does not grow suddenly

- Example: Software-Defined Networking, single (logically centralized) controller does not scale
  - Create many local controllers that can react quickly, that control small set of “dumb” nodes

The SUPPORTED Model

- Extends the LOCAL model (w. unique IDs) with preprocessing

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E.g. MAC-address

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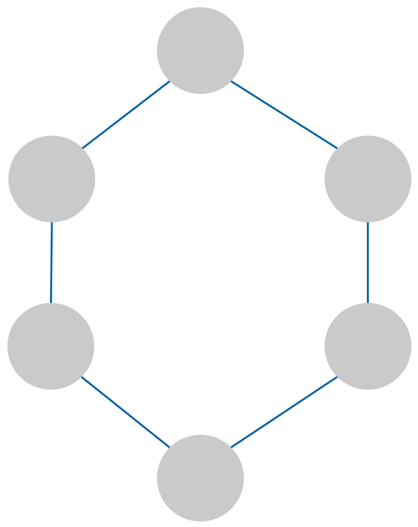
- Original structure given as the SUPPORT graph H=(V(H),E(H))



H

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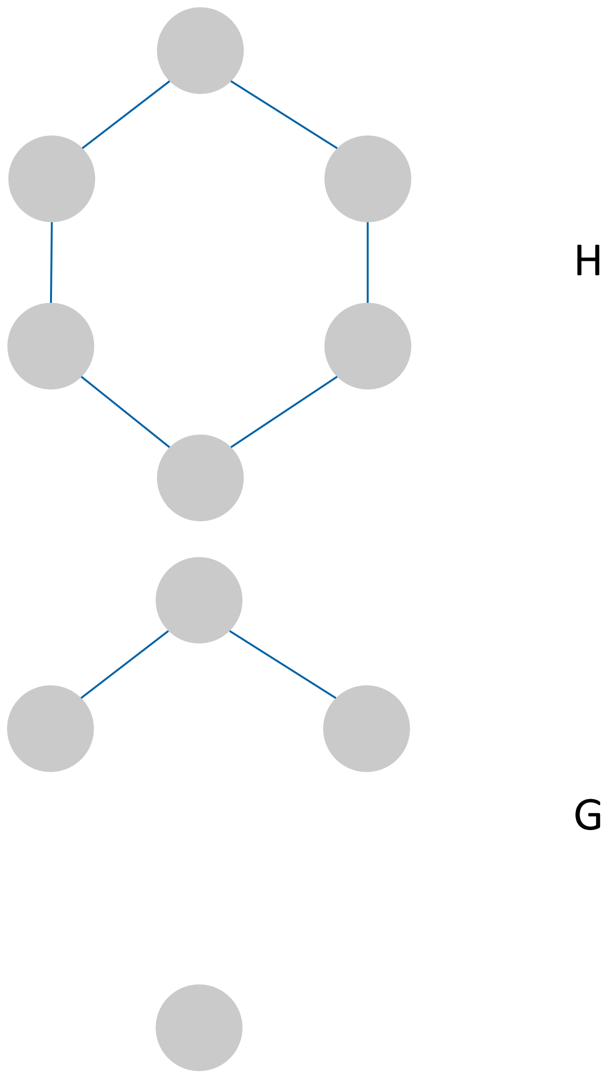

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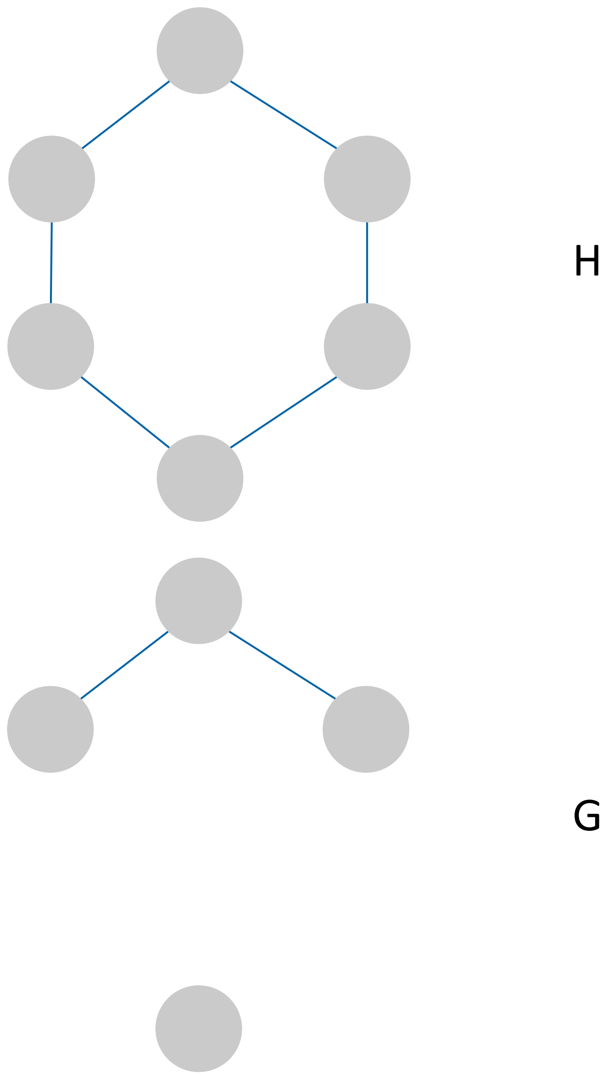
- Two phases:



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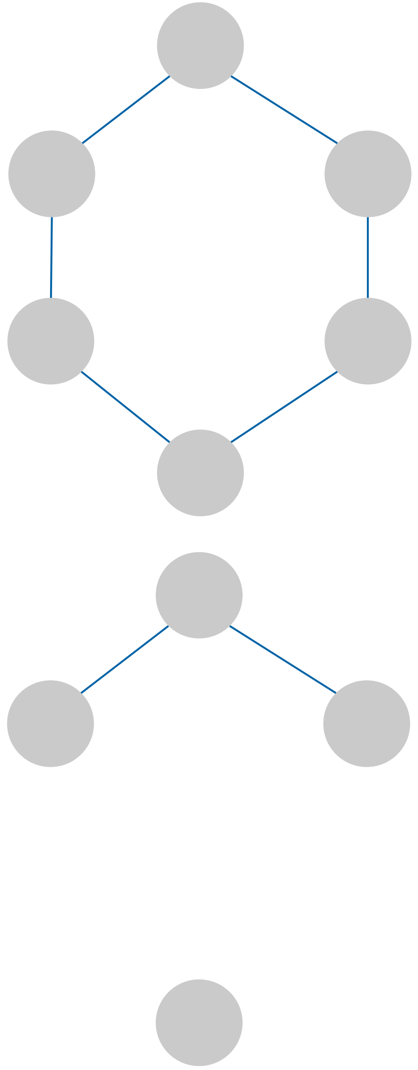

H

G

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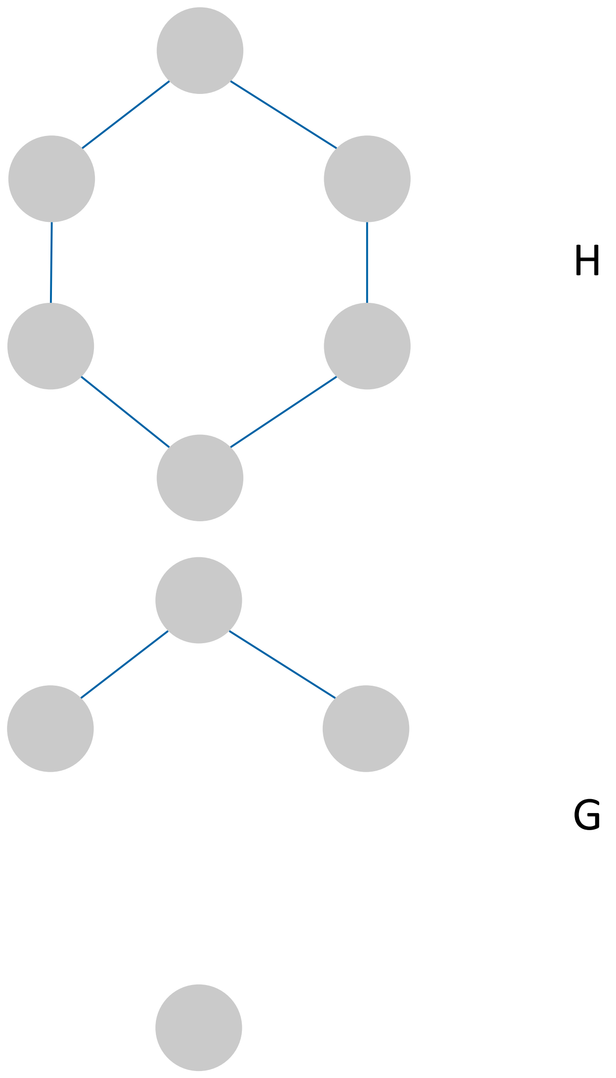

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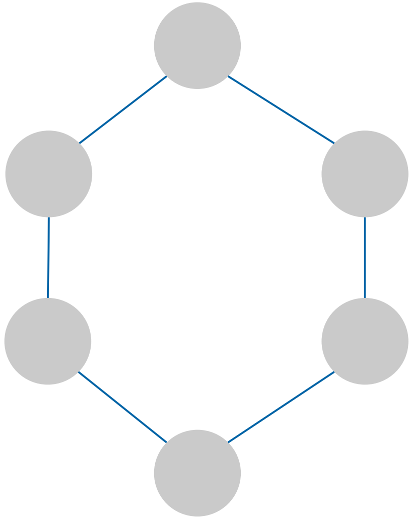
     - Runtime: Number of t rounds in (2), denoted as SUPPORTED(t)



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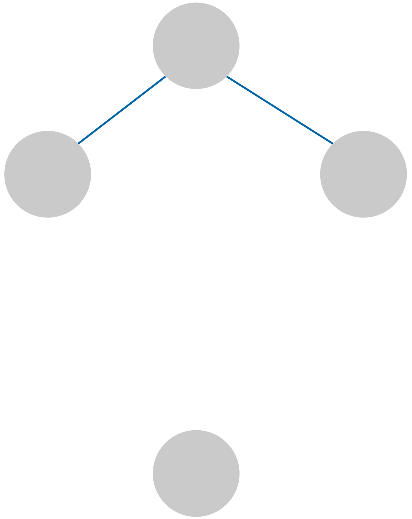

G

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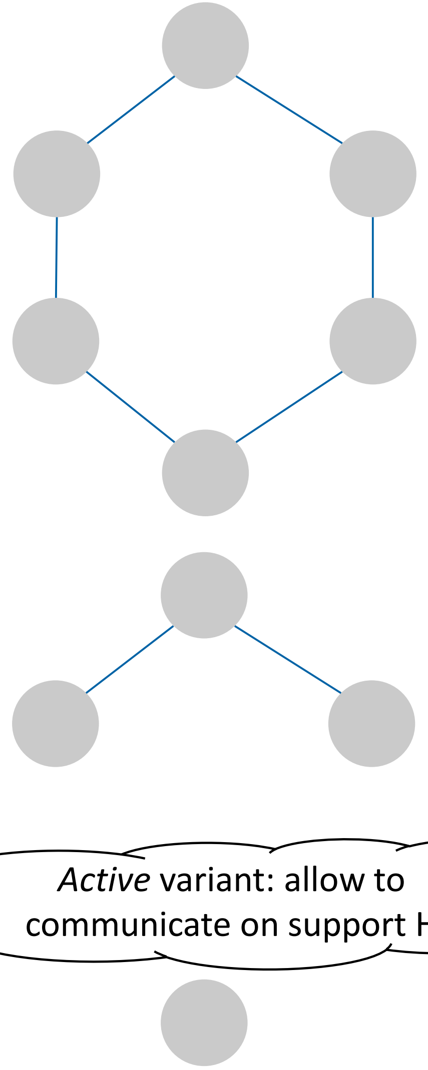

H

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  1. Preprocessing: compute any function on H and store output locally
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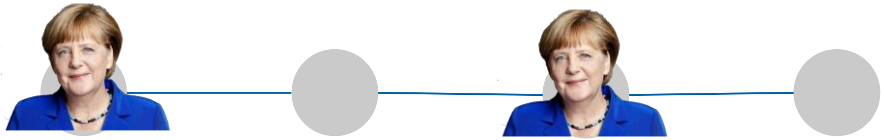
Active variant: allow to communicate on support H

Does the SUPPORTED Model make everything easy?

- Task: Leader election (Θ(diameter) runtime in LOCAL model)
  - Easy if G=H: precompute leader, 0 rounds
  - But for different G:
    - We need to compute a leader for each connected component of G!
      - Component has no leader? Re-elect ☹
      - Component has multiple leaders? Re-elect ☹
      - Components can have asymptotically same diameter ☹



- SUPPORTED model does not provide a “silver bullet”
  - Not even for the *active* variant

Maybe even useless in general?

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In *active* model:
Congested Clique

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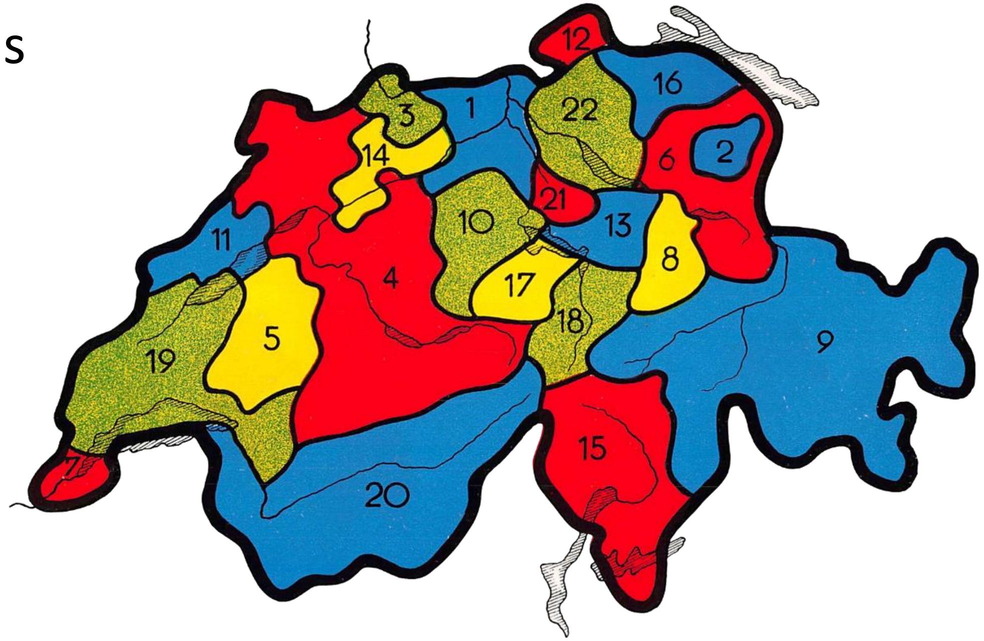
Idea: simulate that support graph H is a complete graph

But: Restricted Graph Families are Useful ☺

- Real topologies are usually not complete graphs

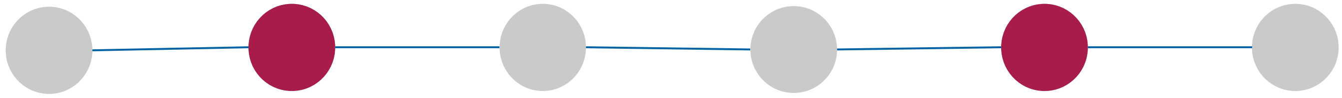
- Case study: planar graphs
  - Remain planar under edge deletions
  - Are 4-colorable



„Geloeste und ungeloeste Mathematische Probleme aus alter und neuer Zeit" by Heinrich Tietze
http://www.math.harvard.edu/~knill/graphgeometry/faqg.html

Case Study: Dominating Set

- Task: Find subset D of nodes s.t. every node
  - Has a neighbor in D or is in D



- Can we pre-compute?
  - A bad one yes: everyone in D!
  - But not an optimal one!
    - Graph can look very different

Case Study: Minimum Dominating Set in Planar Graphs

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SUPPORTED speed-up:
1) precompute 4-coloring
2) reduce 4-colored pseudo-forest to 3 colors in 2 rounds

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    - Also for planar graphs for maximum independent set & maximum matching

Further Results in the *Active* SUPPORTED Model

Use all edges of H
for communication

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Polylogarithmic-Time Deterministic Network Decomposition and Distributed Derandomization

Václav Rozhoň
ETH Zurich
rozhonv@student.ethz.ch

Mohsen Ghaffari*
ETH Zurich
ghaffari@inf.ethz.ch

Abstract

We present a simple polylogarithmic-time deterministic distributed algorithm for network decomposition. This improves on a celebrated $2^{O(\sqrt{\log n})}$-time algorithm of Panconesi and Srinivasan [STOC'93] and settles one of the long-standing and central questions in distributed graph algorithms. It also leads to the first polylogarithmic-time deterministic distributed algorithms for numerous other graph problems, hence resolving several open problems, including Linial's well-known question about the deterministic complexity of maximal independent set [FOCS'87].

Put together with the results of Ghaffari, Kuhn, and Maus [STOC'17] and Ghaffari, Harris, and Kuhn [FOCS'18], we get a general distributed derandomization result that implies P-RLOCAL = P-LOCAL. That is, for any distributed problem whose solution can be checked in polylogarithmic-time, any polylogarithmic-time randomized algorithm can be derandomized to a polylogarithmic-time deterministic algorithm.

By known connections, our result leads also to substantially faster *randomized* algorithms for a number of fundamental problems including $(\Delta+1)$-coloring, MIS, and Lovász Local Lemma.

Through known connections, this general derandomization leads to better *deterministic* and *randomized* distributed algorithms for numerous problems. A sampling of end-results includes poly$(\log n)$-round deterministic algorithms for MIS, $\Delta+1$ coloring, the Lovász Local Lemma[3], hypergraph splitting, and defective coloring. These also lead to substantially improved randomized algorithms, including a poly$(\log \log n)$-time randomized $\Delta+1$ coloring [CLP18] and a poly$(\log \log n)$-time randomized algorithm for Lovász Local Lemma in constant degree graphs [GHK18].

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- Locally Checkable Labelings LCL:

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  - Cannot be approximated by o(Δ/log Δ) in time o($\log_\Delta$ n) in the active SUPPORTED model

Bigger Open Question/Opportunity

How to efficiently leverage such preprocessing/distributed computing to efficiently scale controllers (and network updates)?

So far largely unexplored

So let's get back things we know about ☺
Congestion and network functions?


CONGESTION
AHEAD
NEXT 20
YEARS

Congestion?

- “Stronger” consistency constraint: also do not violate link capacities

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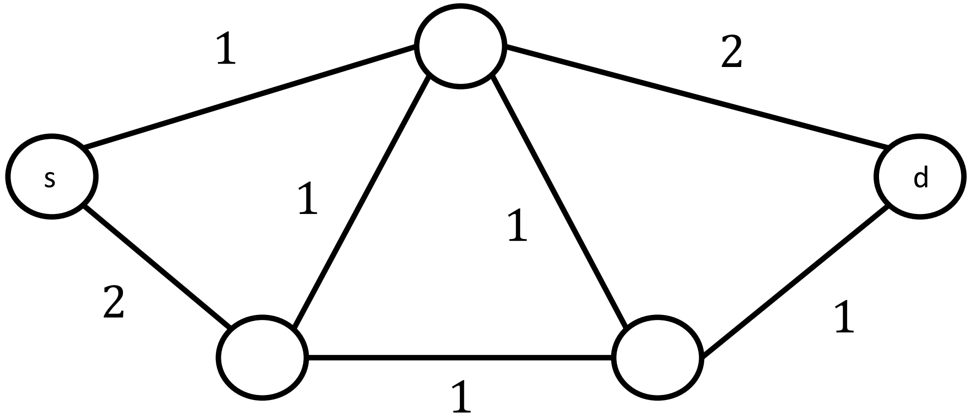

Congestion?

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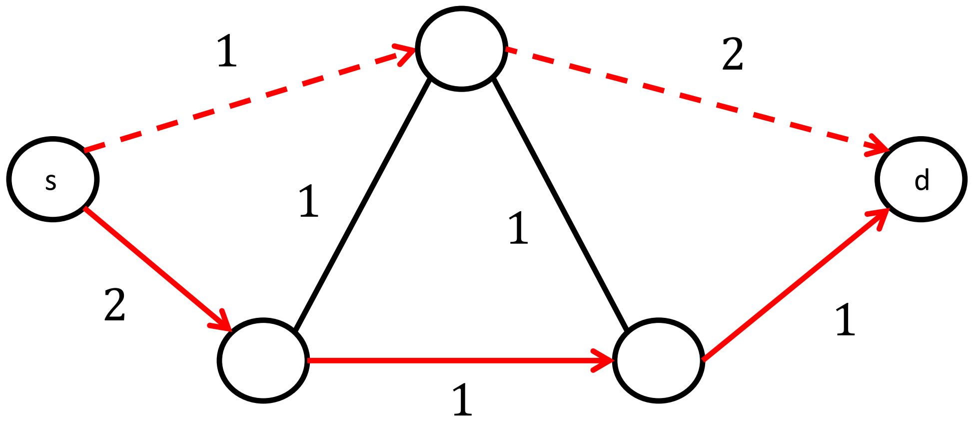
  - Flow size: 1



Round **0**

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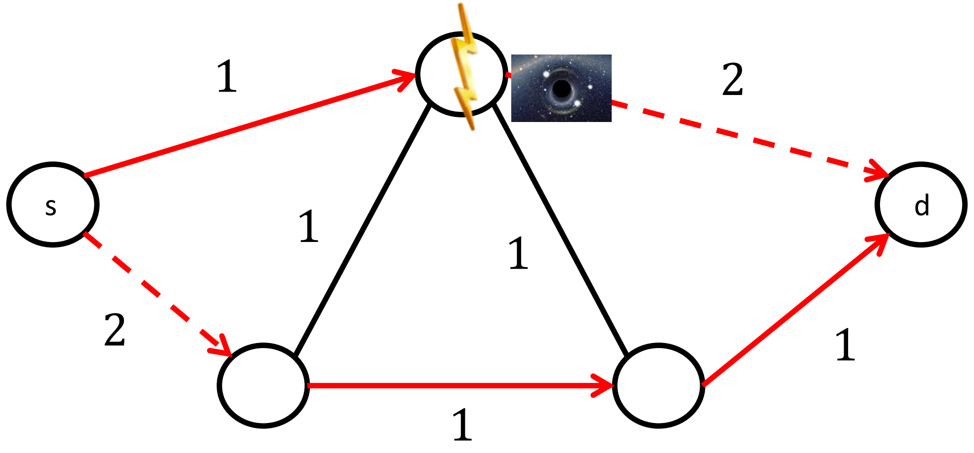

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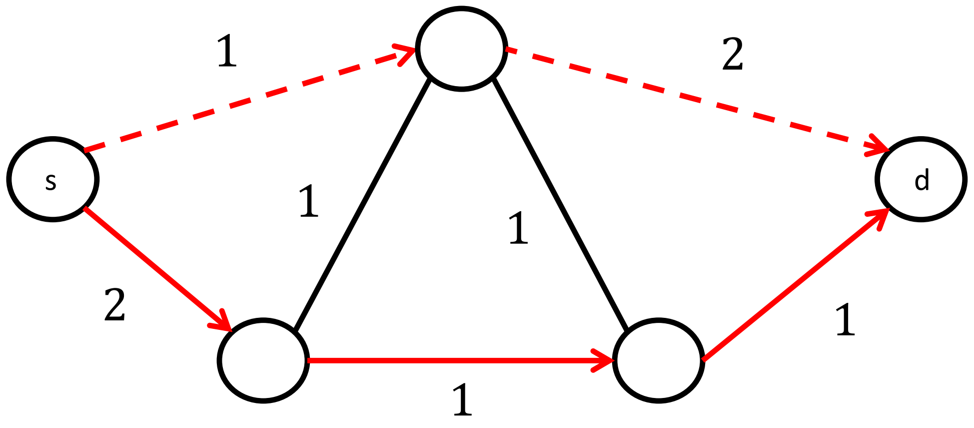

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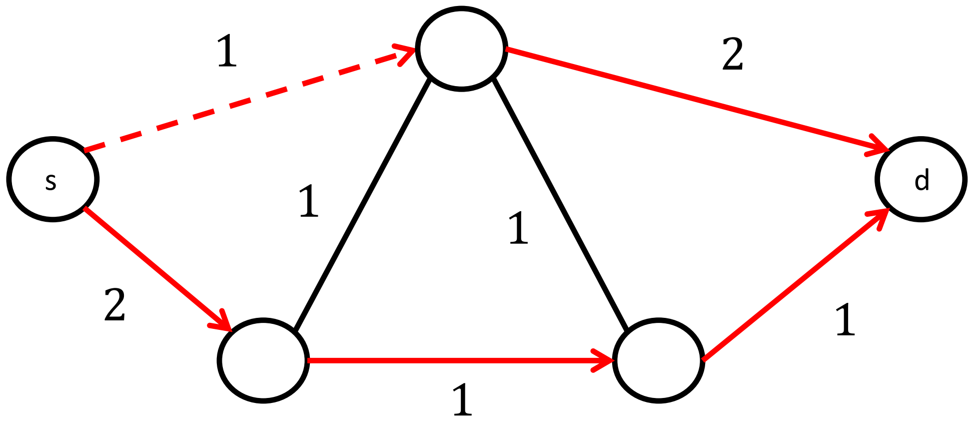

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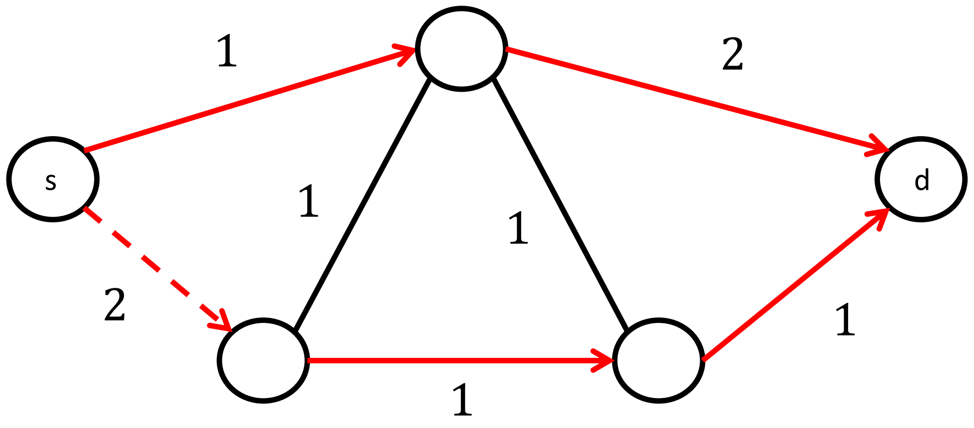

Round **2**

Congestion?

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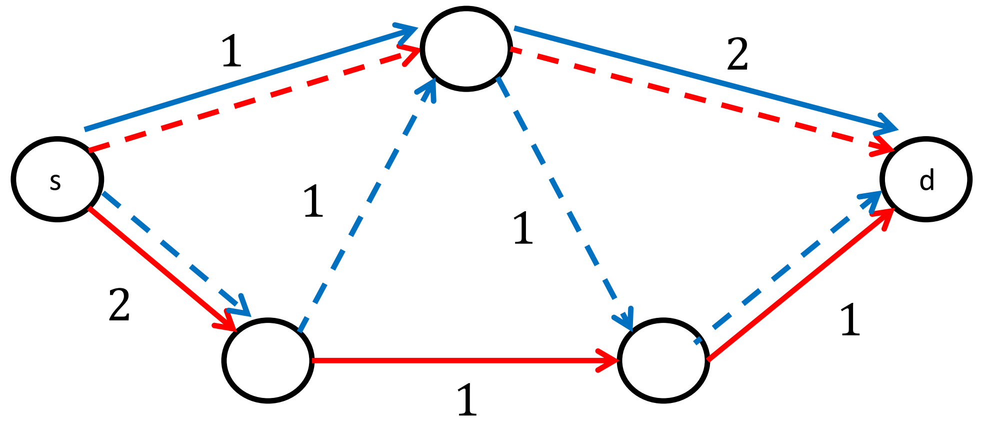

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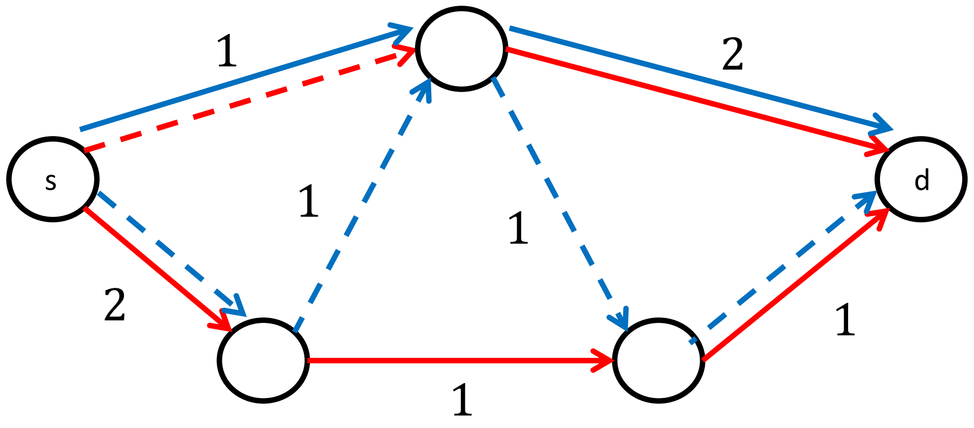

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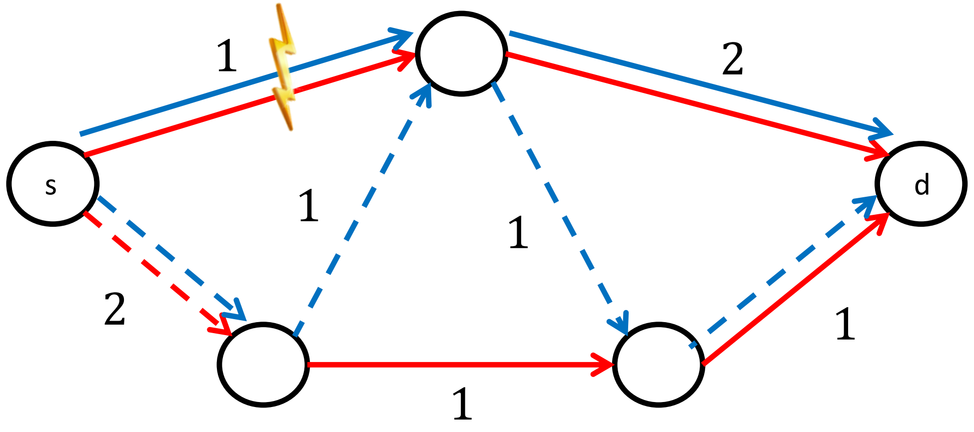

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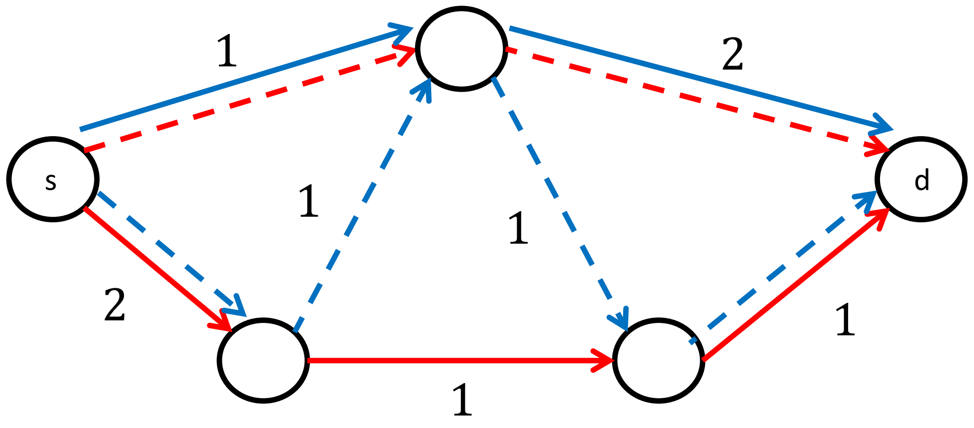

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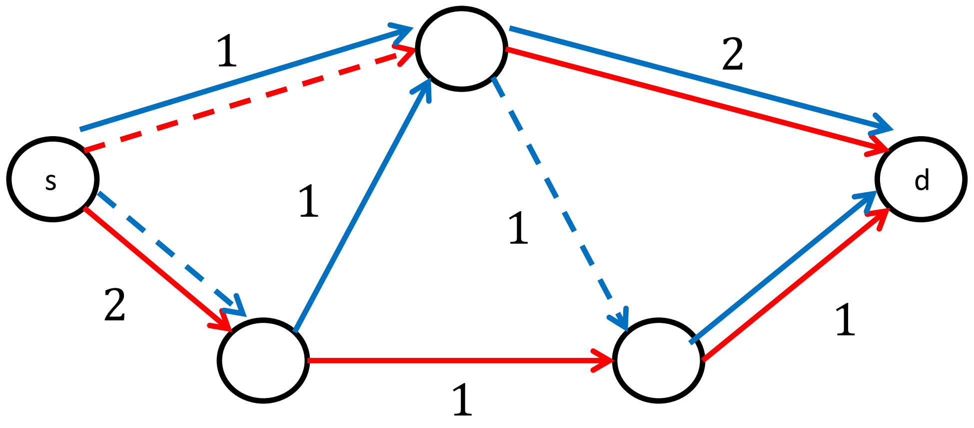

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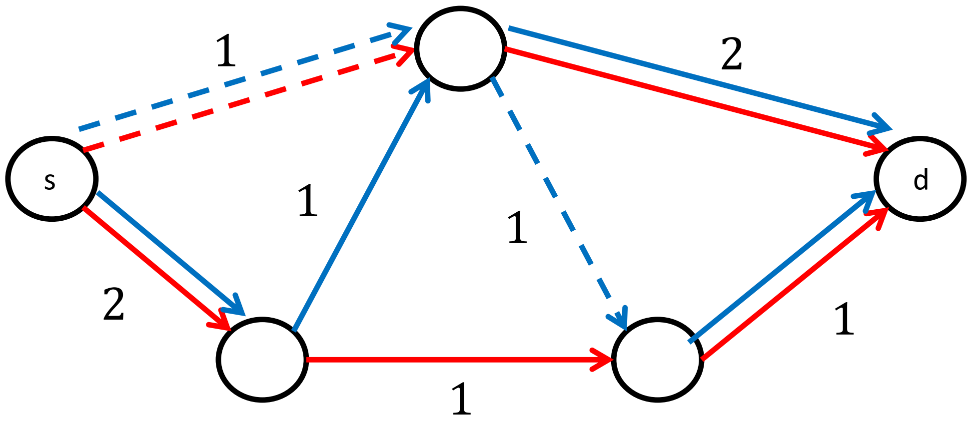

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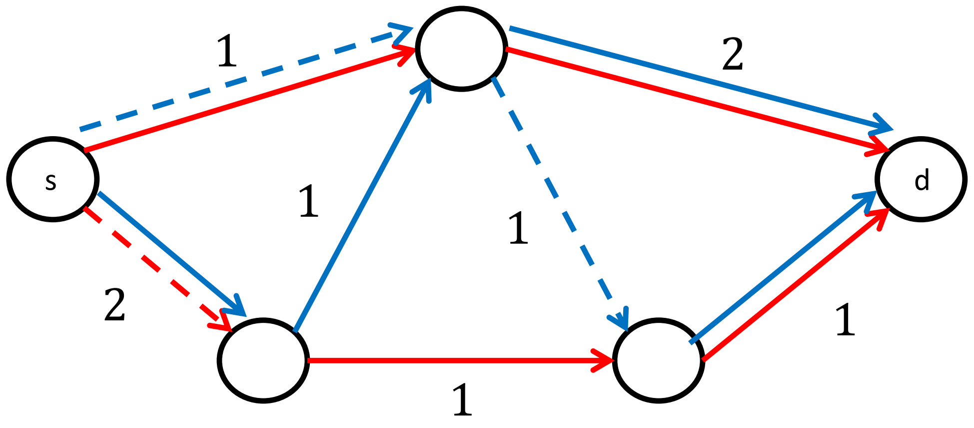

Round **3**

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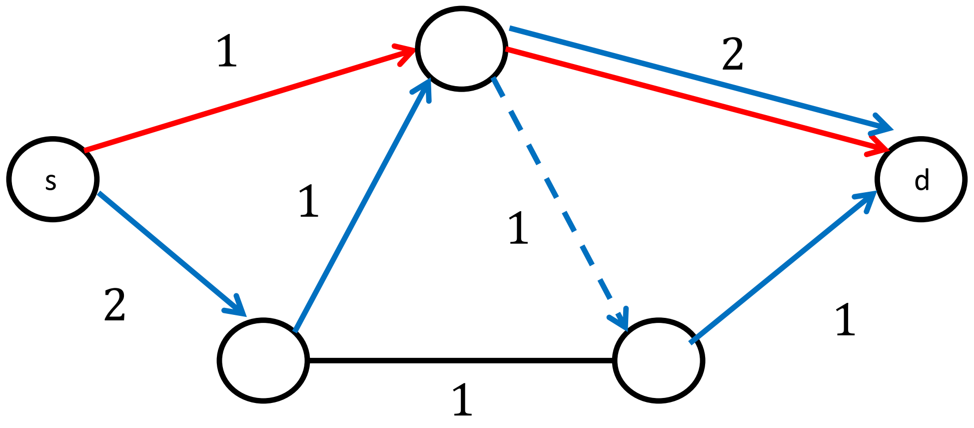

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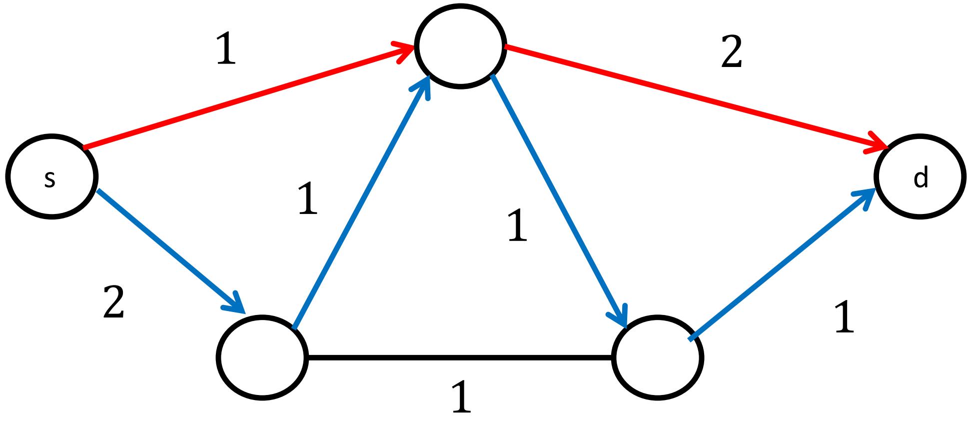

Round **4**

Complexity of Avoiding Congestion?

- NP-hard already for 2 unit size flows on general graphs

- Also NP-hard on acyclic graphs for k flows
  - But can be FPT characterized for k flows on acyclic graphs: $O\left(2^{O(k \log k)}|G|\right)$
    - In other words, linear runtime for constant k on DAGs

- For just 2 unit size flows (where old/new ***individually*** is a DAG): Optimal schedule in P (NPH for 6)

Congestion-Free Rerouting of Flows on DAGs. S. Akhoondian Amiri, S. Dudycz, S. Schmid, S. Widerrecht, ICALP'18
On Polynomial-Time Congestion-Free Software-Defined Network Updates. AA, D., M. Parham, S., S. W., Networking'19

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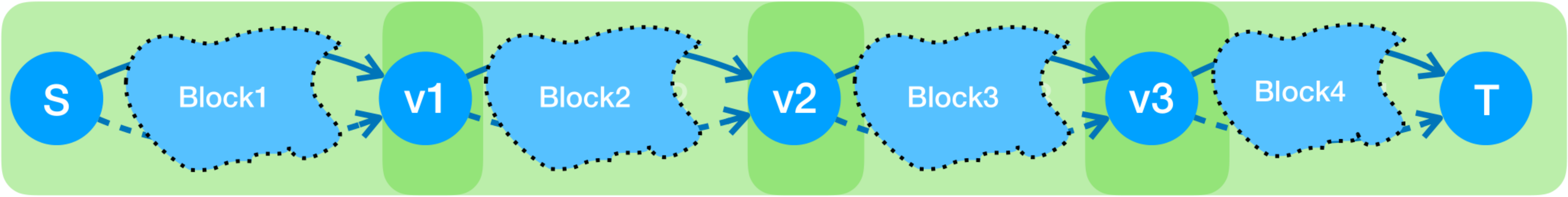

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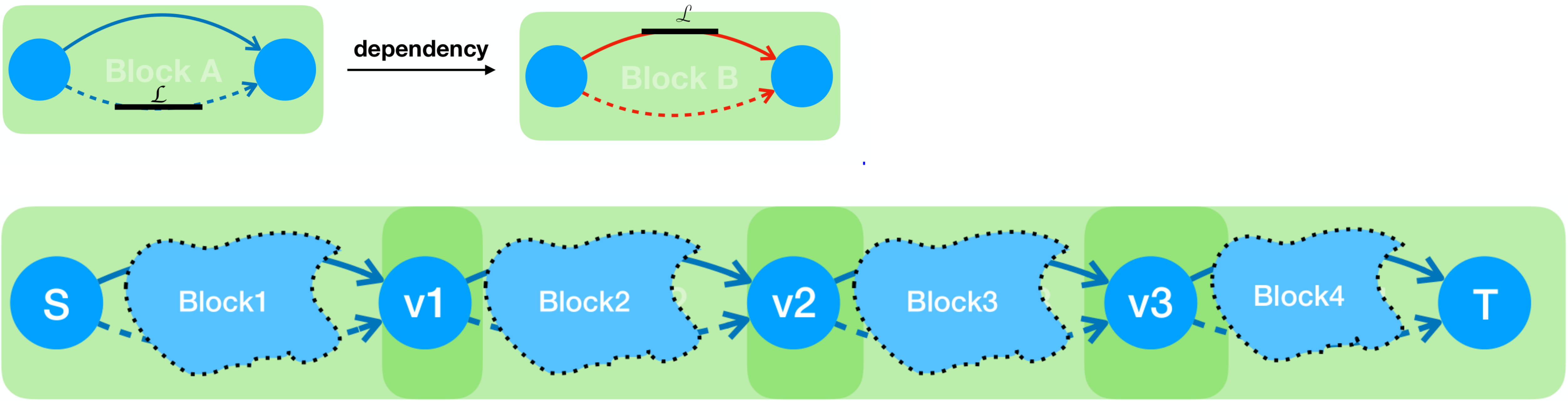

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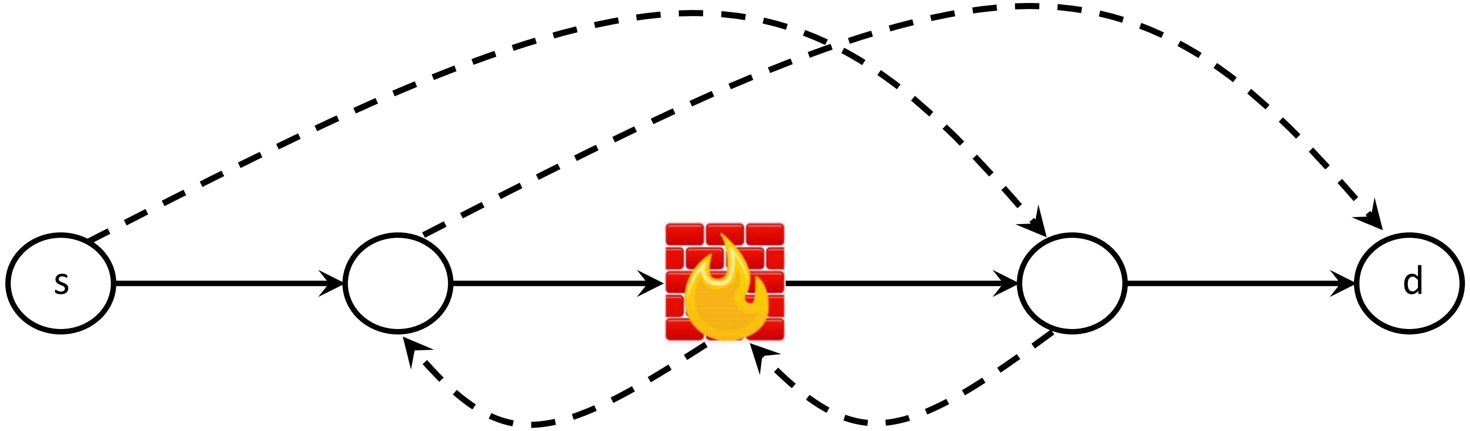
- Also NP-hard on acyclic graphs for 6 flows
  - But can be FPT characterized for k flows on acyclic graphs: $O\left(2^{O(k \log k)}|G|\right)$
    - In other words, linear runtime for constant k on DAGs

- For just 2 unit size flows (where old/new individually is a DAG): Optimal schedule in P

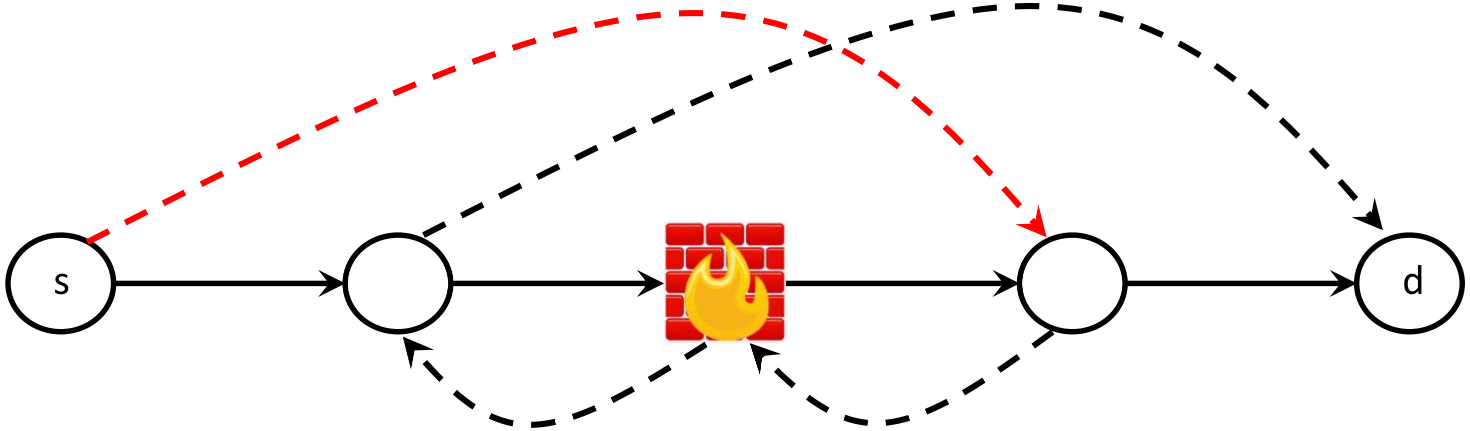
Congestion-Free Rerouting of Flows on DAGs. S. Akhoondian Amiri, S. Dudycz, S. Schmid, S. Widerrecht, ICALP'18
On Polynomial-Time Congestion-Free Software-Defined Network Updates. AA, D., M. Parham, S., S. W., Networking'19

Take a Step Back: No Loops and a Firewall

Which forwarding rule to update first?



Take a Step Back: No Loops and a Firewall



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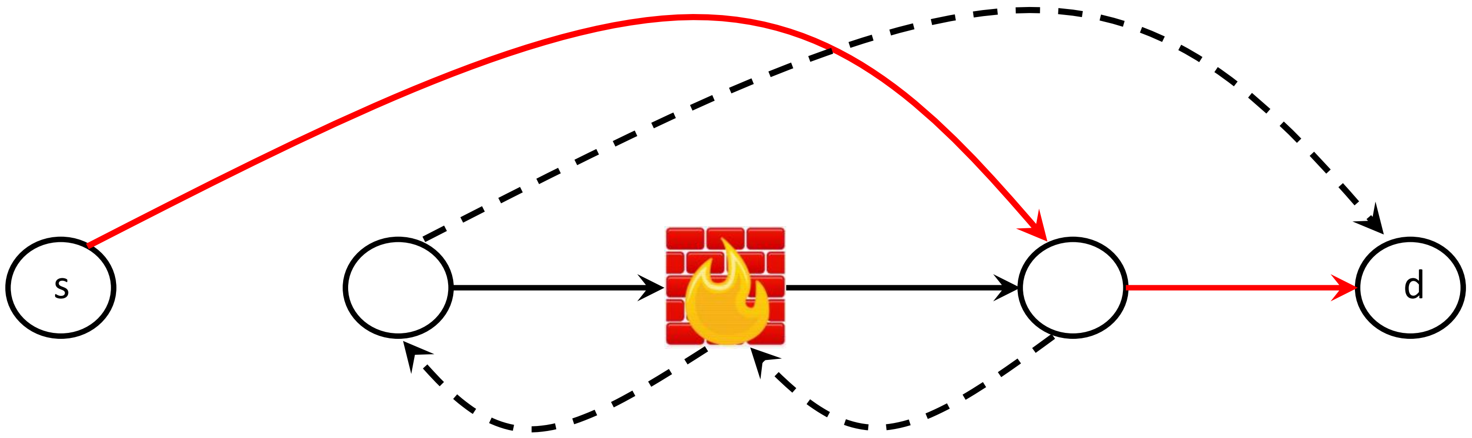

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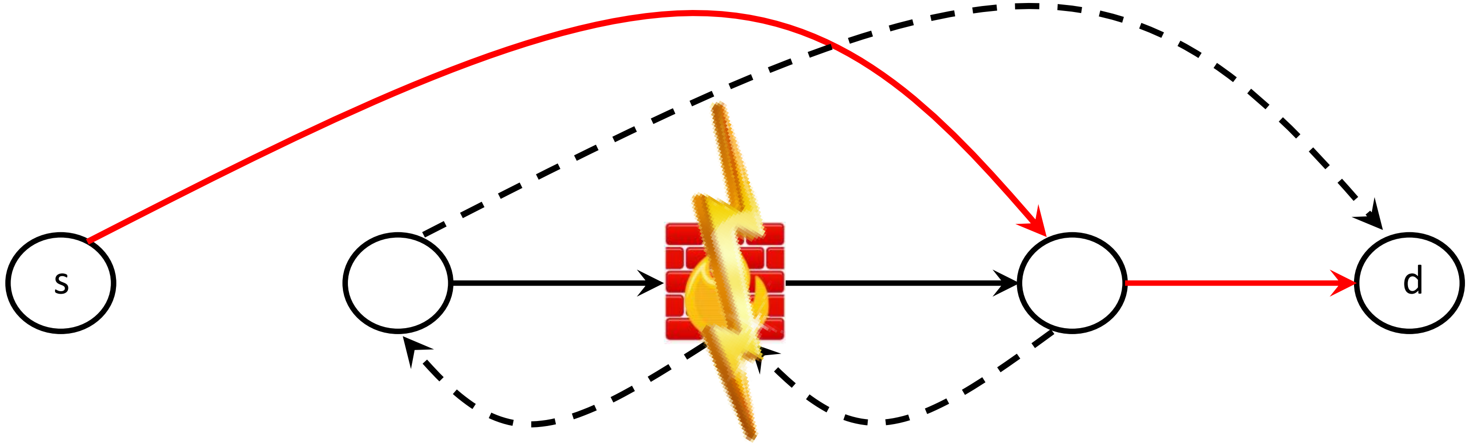

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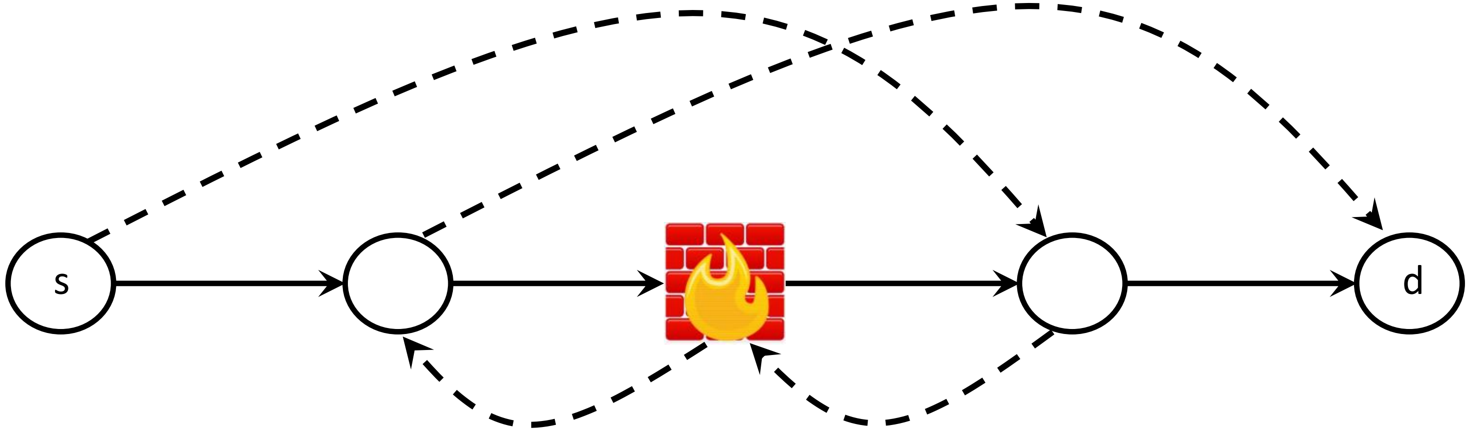

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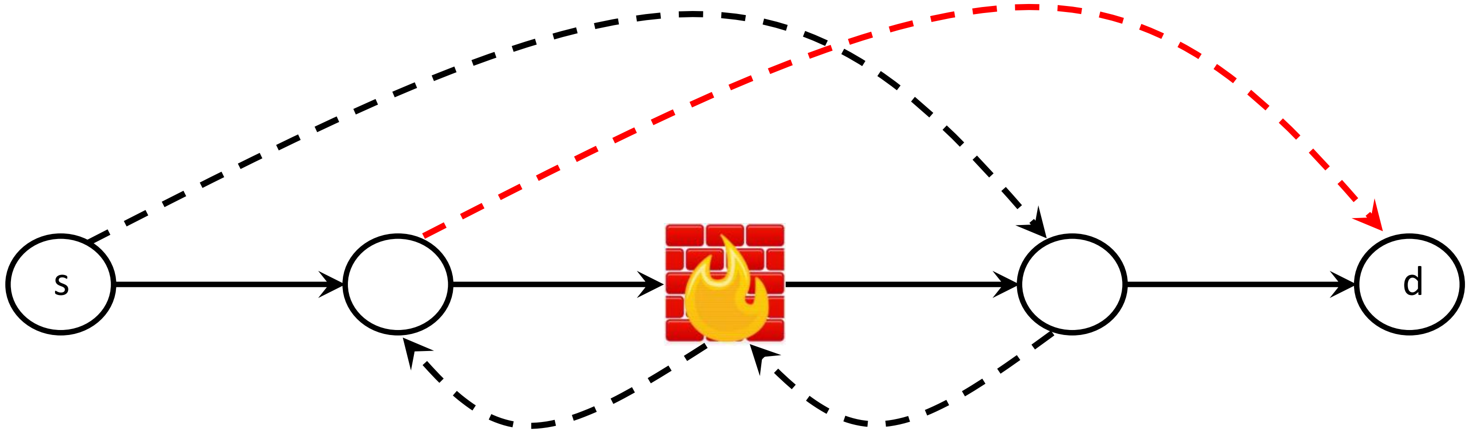

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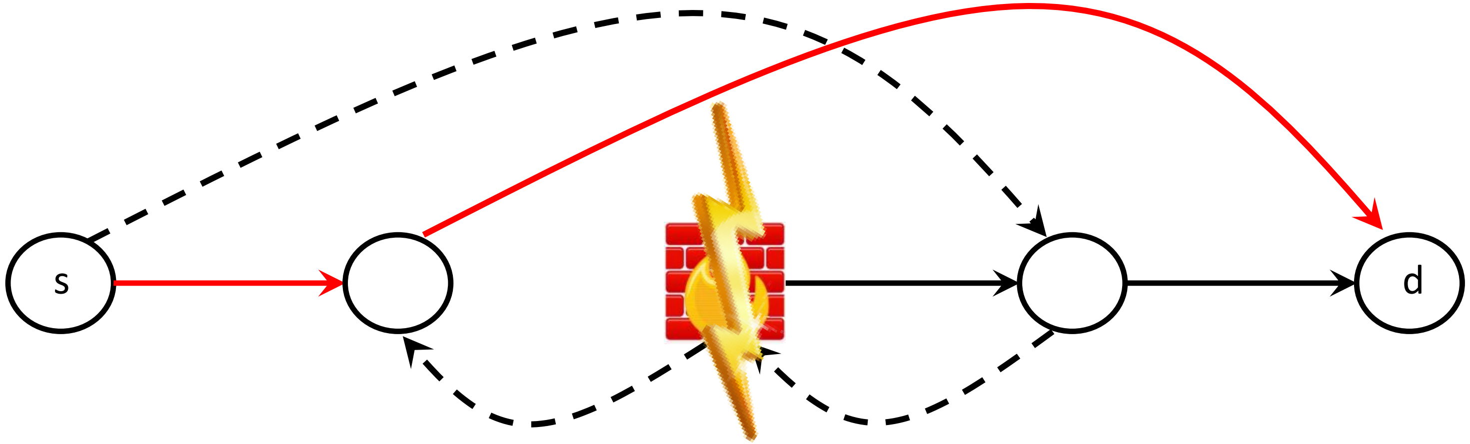

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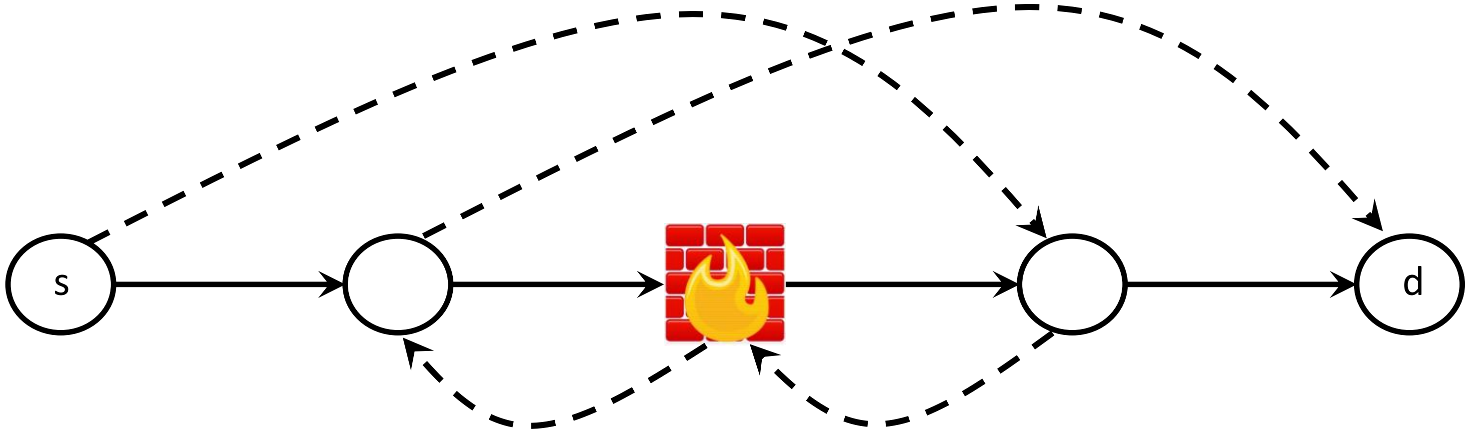

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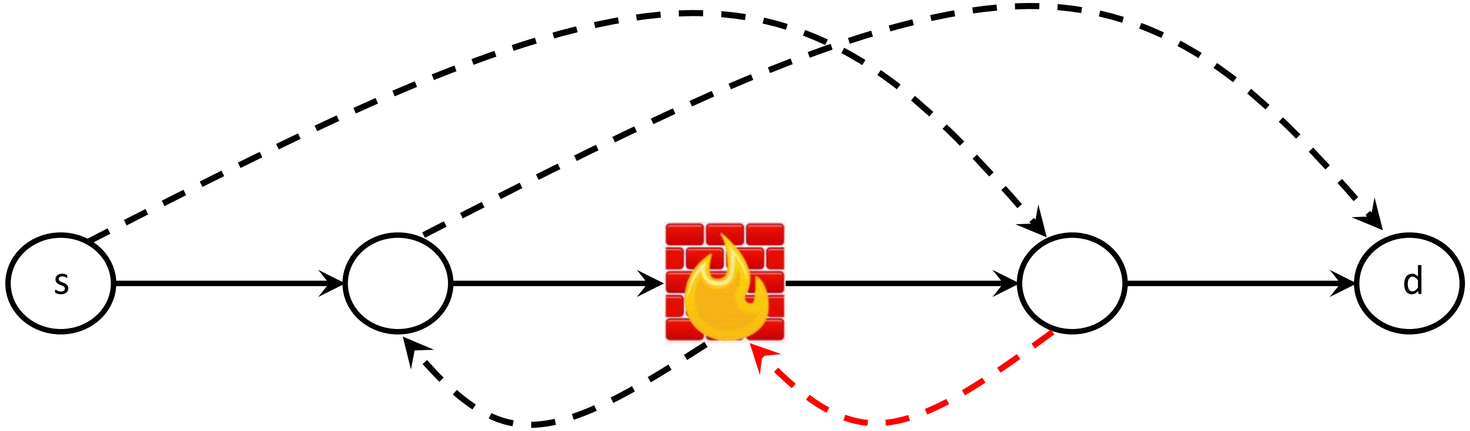

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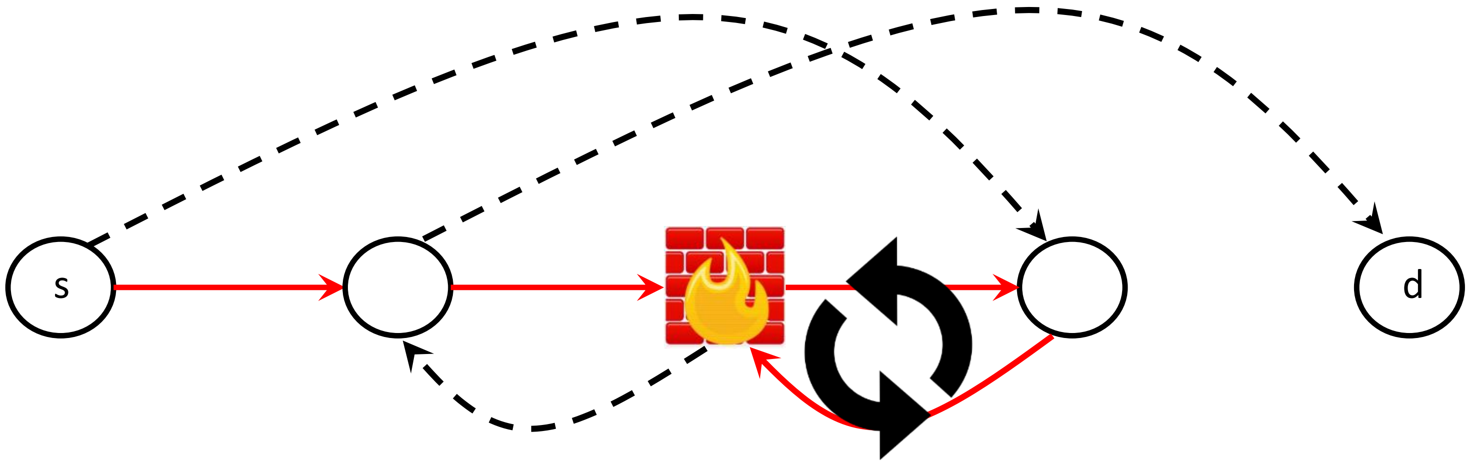

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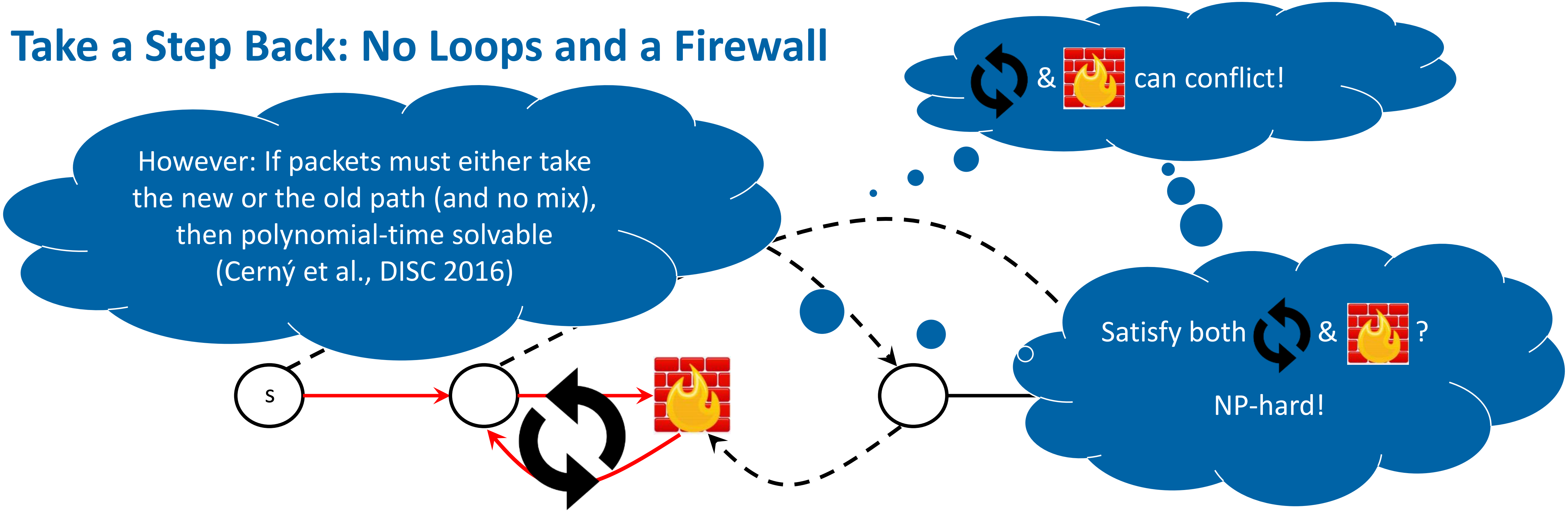


Transiently Secure Network Updates. A. Ludwig, S. Dudycz, M. Rost, S. Schmid. SIGMETRICS 2016.

Different model: “tagged” Flows

- Identified by a “tag“ in the packet header, update via
  - Install new tag‘ rules
  - Switch from tag to tag‘ at source

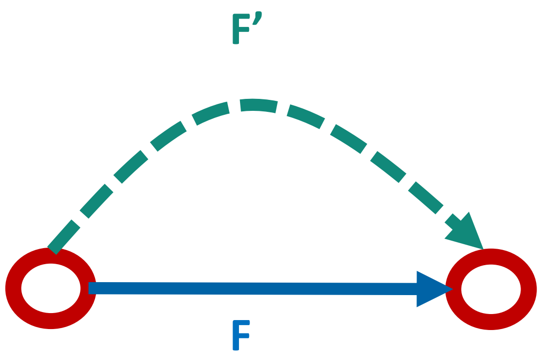
If we move a flow, will there be congestion?

If we move a flow, will there be congestion?

- How do we move a flow **F**? Usually: 2-phase commit: [*Reitblatt et al., SIGCOMM'12*]

If we move a flow, will there be congestion?

- How do we move a flow F? Usually: 2-phase commit:
  - Deploy new flow rules F'



If we move a flow, will there be congestion?

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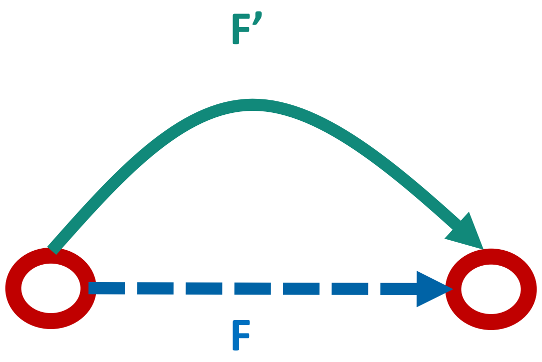
  - Deploy new flow rules **F’**
  - Change packet tag at source from **F** to **F’**



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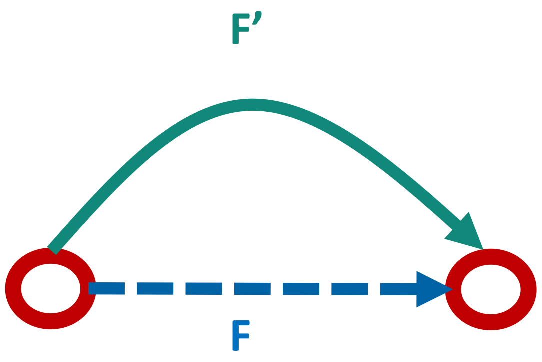


Can also be implemented by proof-labeling techniques

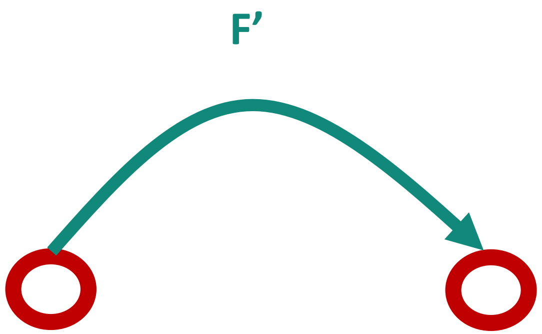
“hand holding”?

Respects network functions!

Go backwards with distance information

If we move a flow, will there be congestion?

- How do we move a flow **F**? Usually: 2-phase commit:
  - Deploy new flow rules **F'**
  - Change packet tag at source from **F** to **F'**
  - Clean-up of old rules



universität wien

If we move a flow, will there be congestion?

- How do we move a flow **F**? Usually: 2-phase commit:
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  - Change packet tag at source from **F** to **F’**
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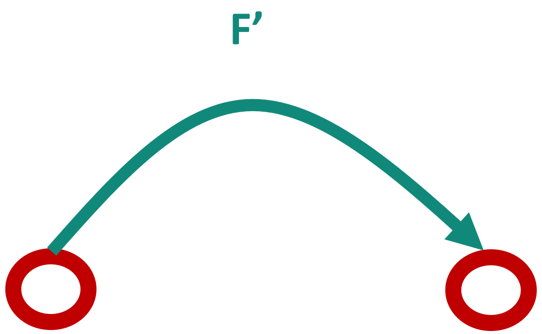
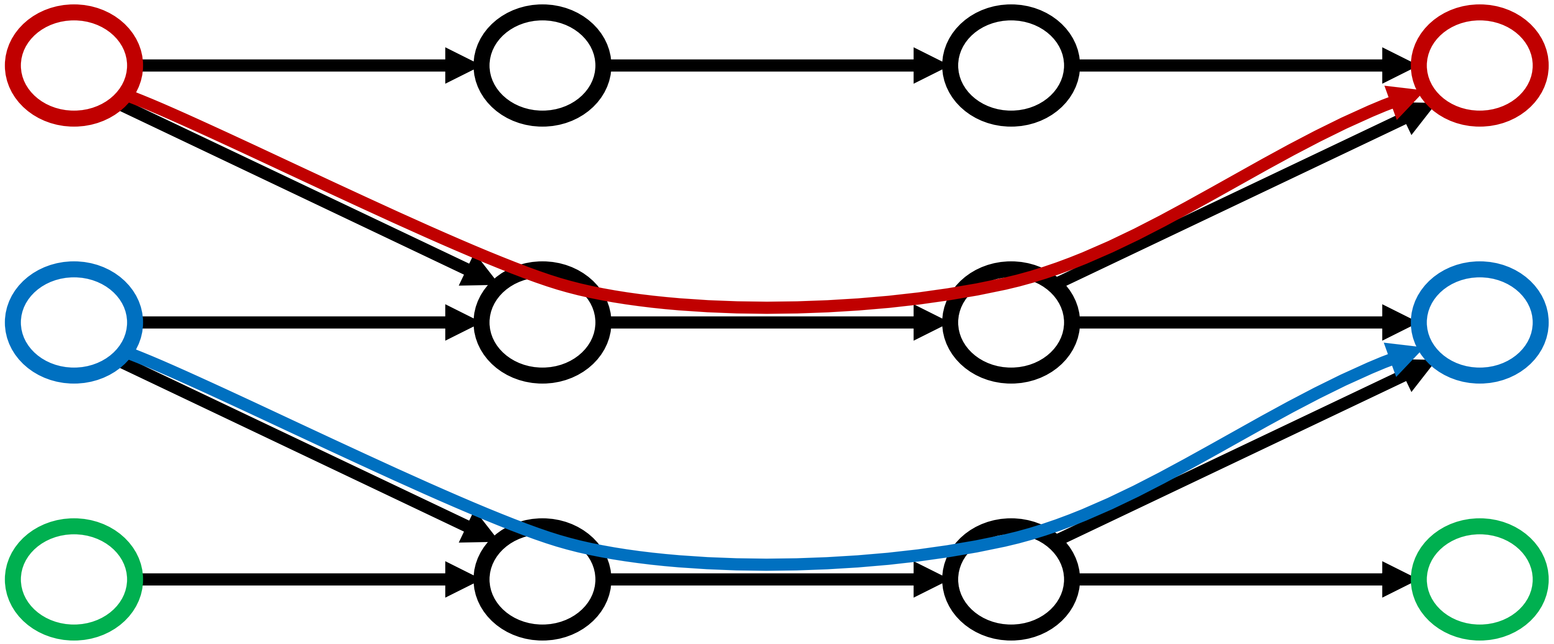


- First check:
  - Is the new network state without congestion?
  - Easy ☺ (flow size versus capacity)

Also verifiable by proof-labeling techniques

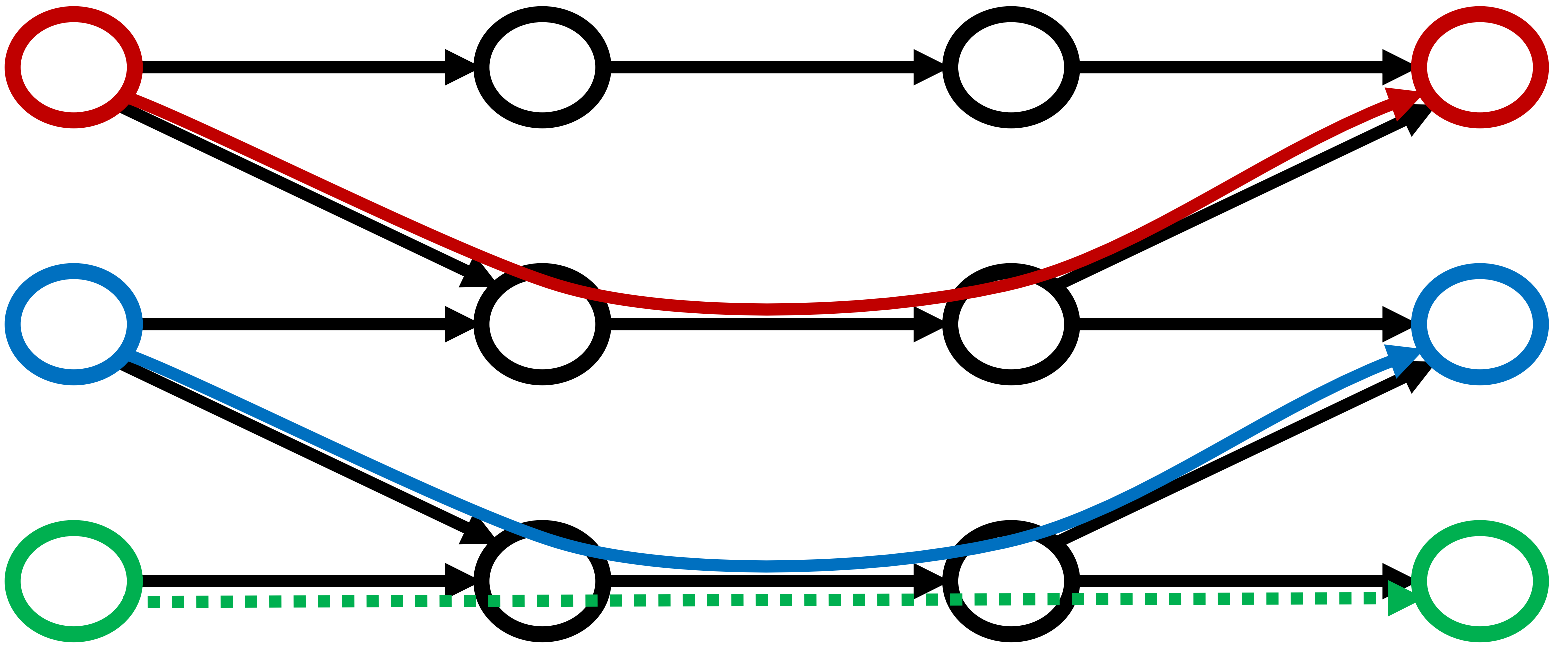
- Is that it?

A Small Sample Network



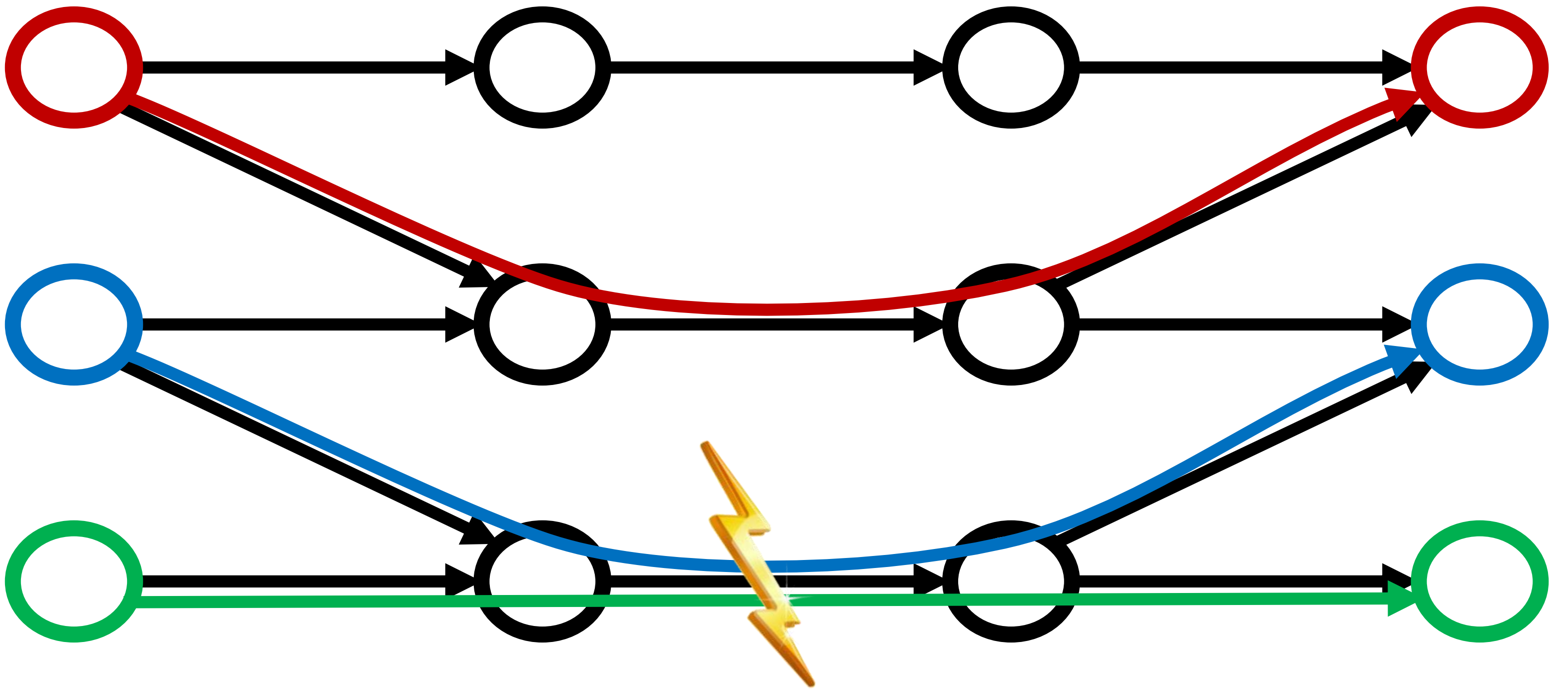
Unit size flows and capacities

Green wants to send as well



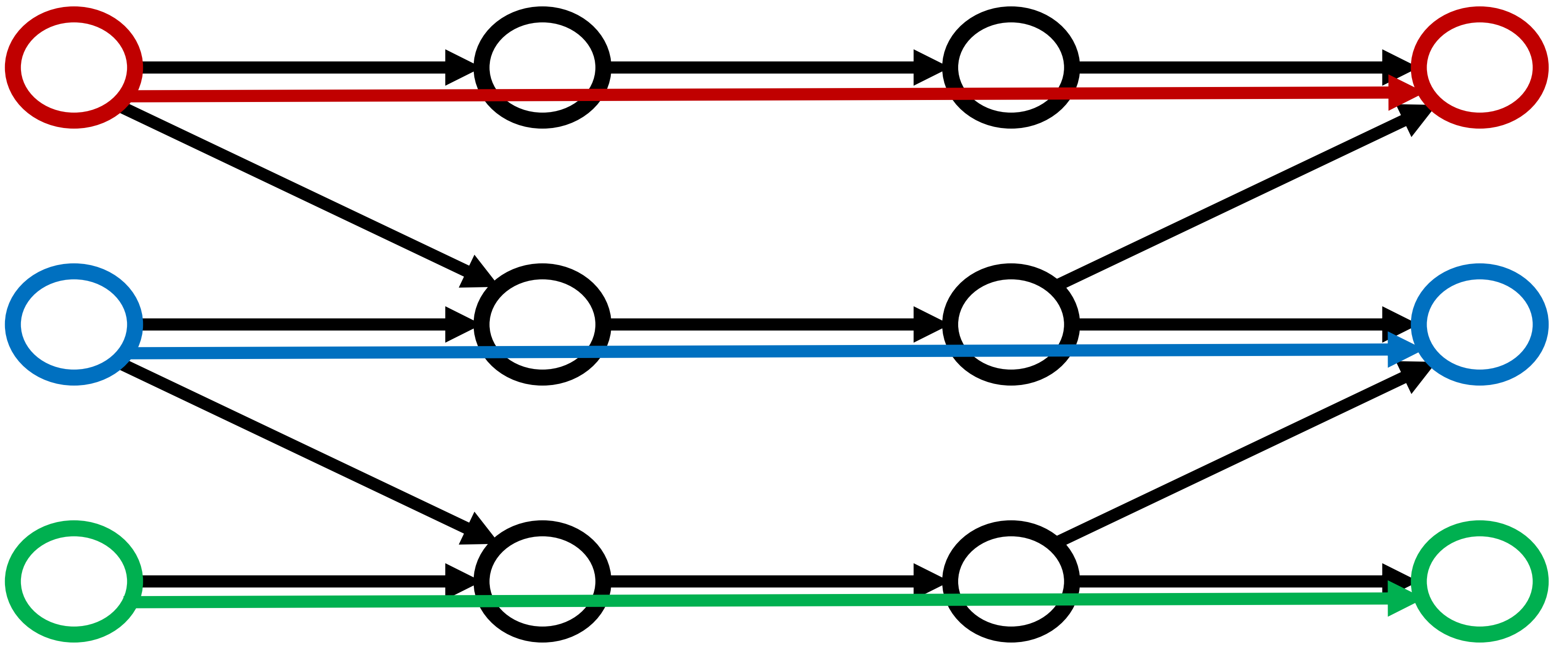
Unit size flows and capacities

Congestion!



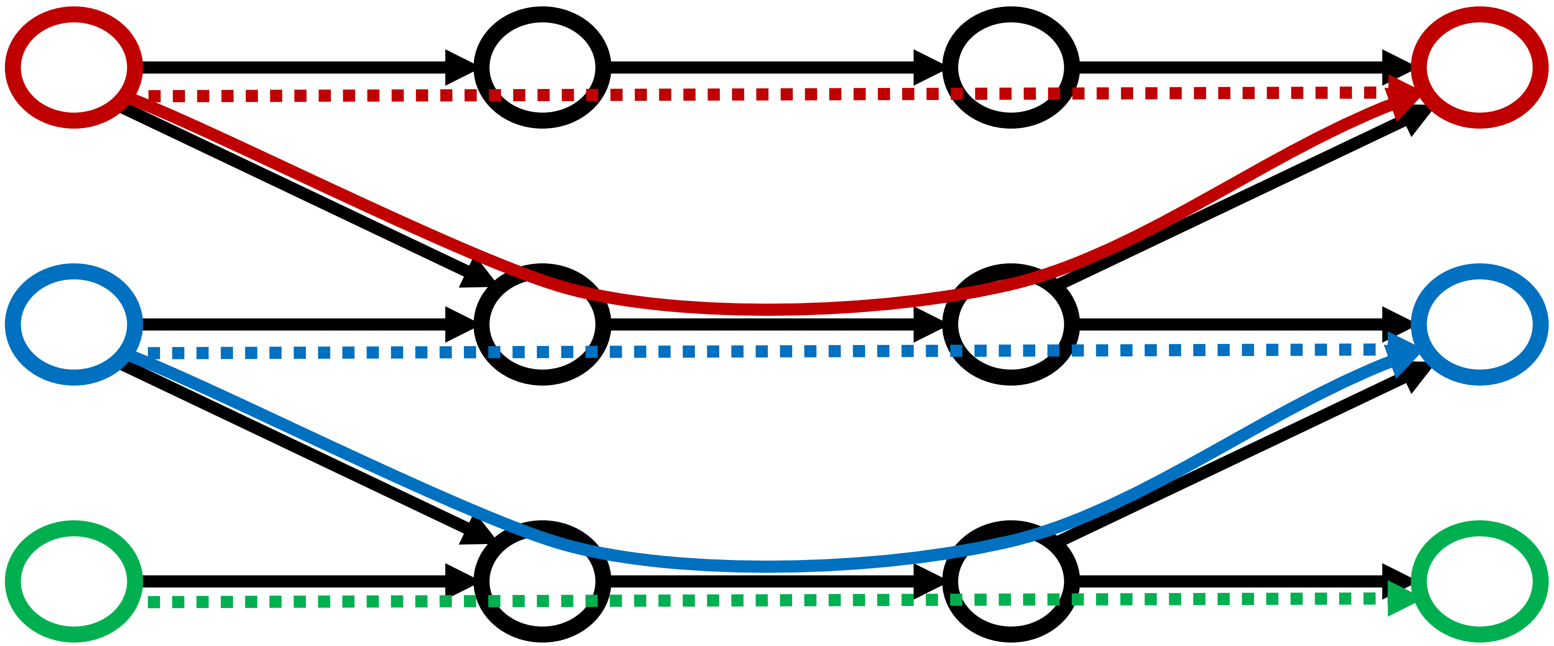
Unit size flows and capacities

This would work



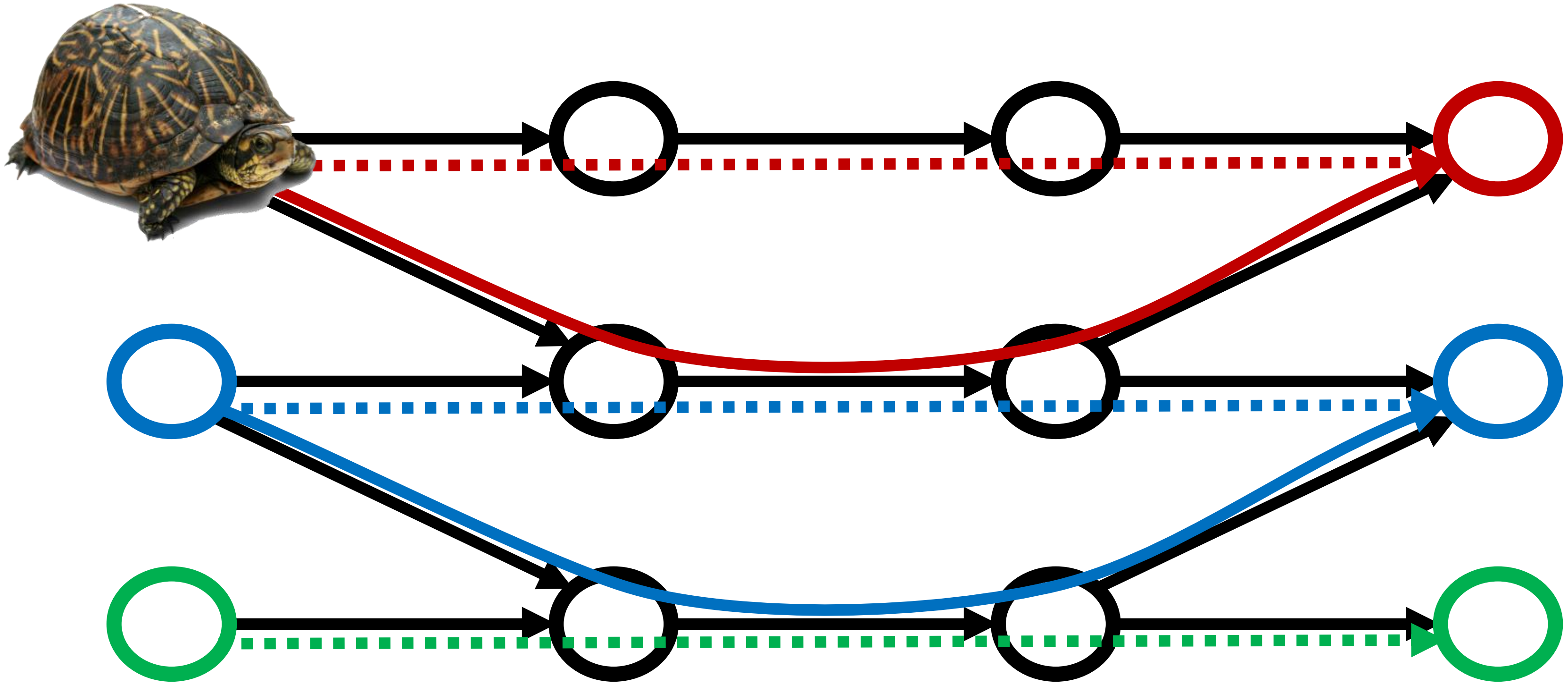
Unit size flows and capacities

So lets go back



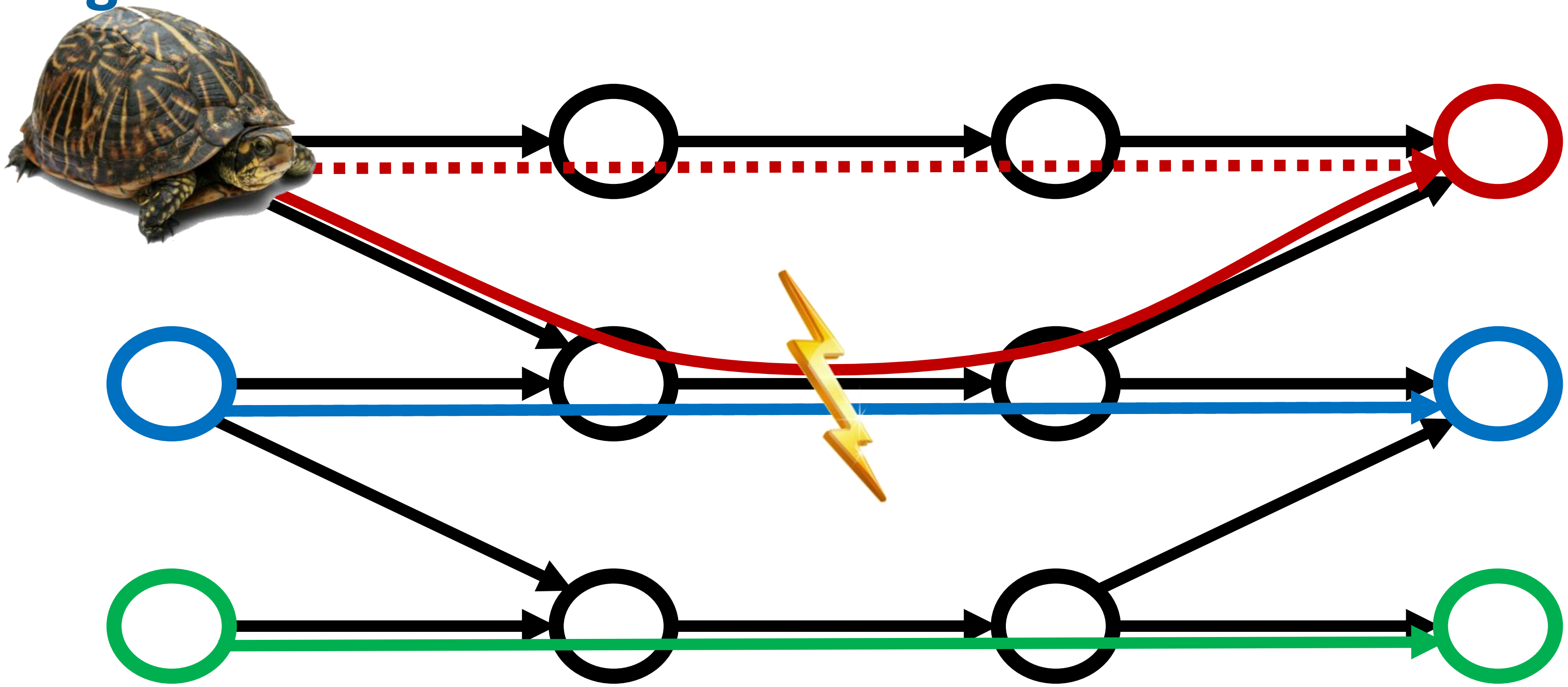
Unit size flows and capacities

But Red is a bit Slow..



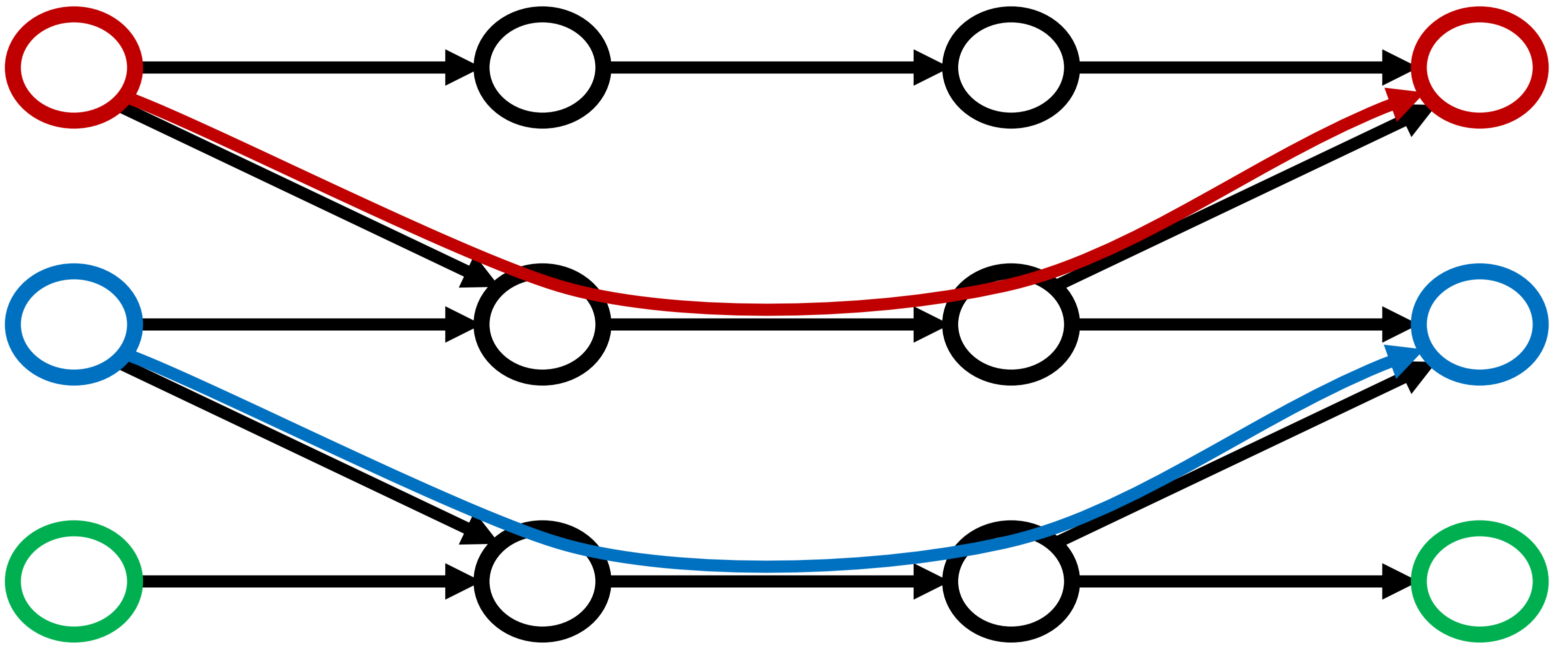
Unit size flows and capacities

Congestion Again!



Unit size flows and capacities

So lets go Back …



Round **0** *(old)*

Unit size flows and capacities

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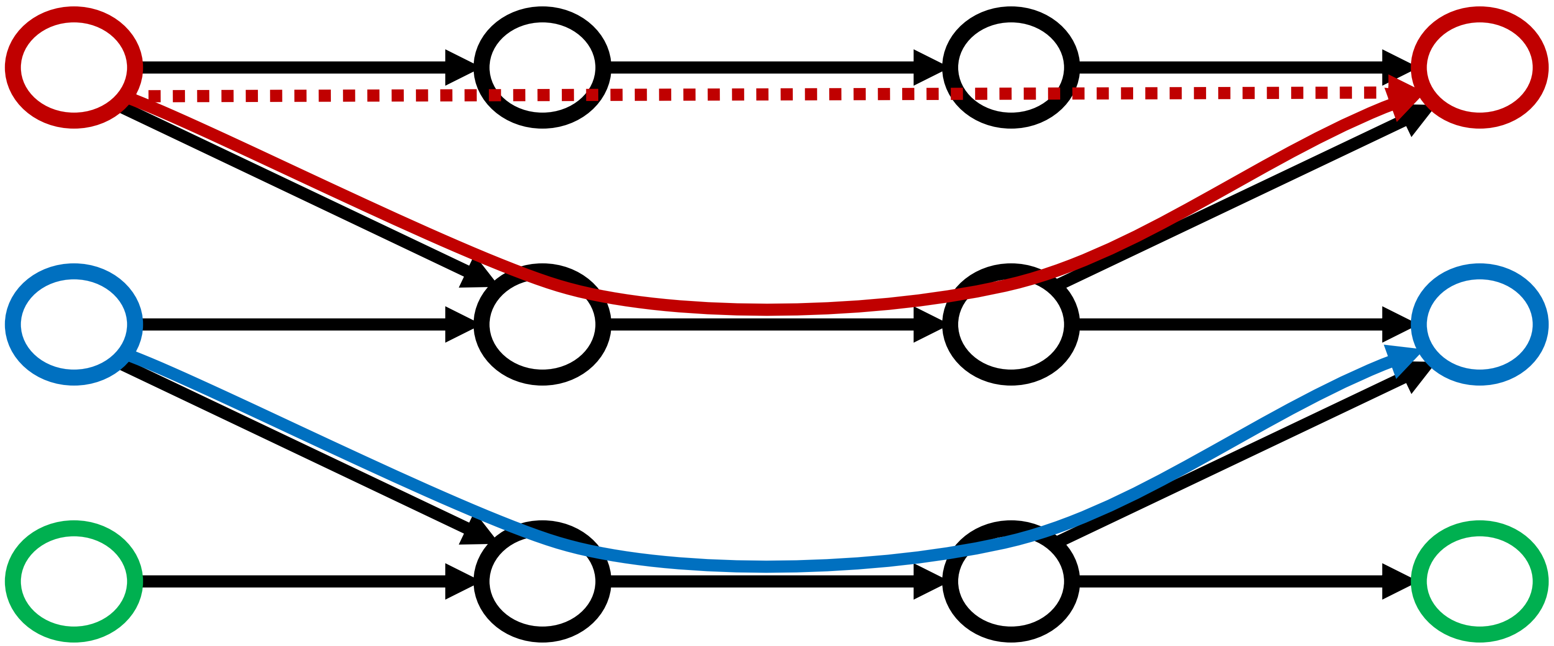
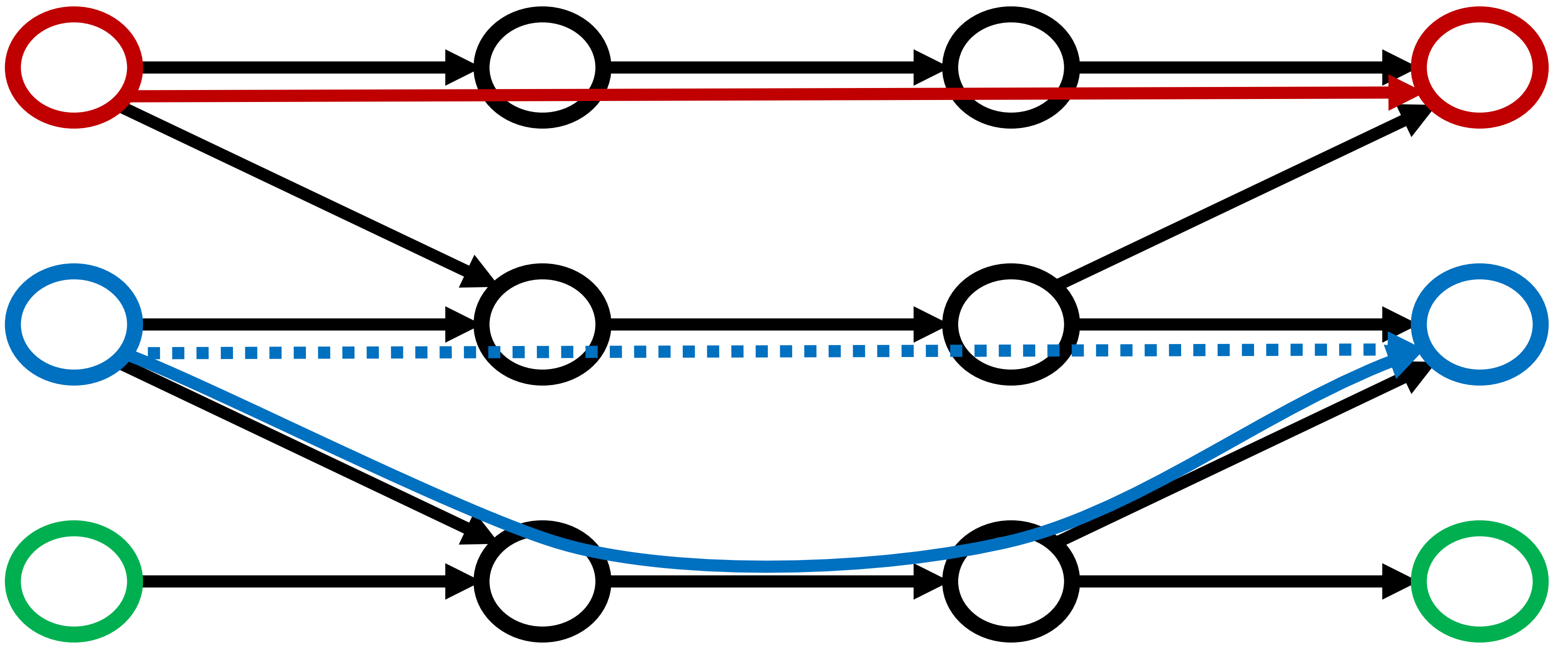
First, Red switches



Round **1**

Unit size flows and capacities

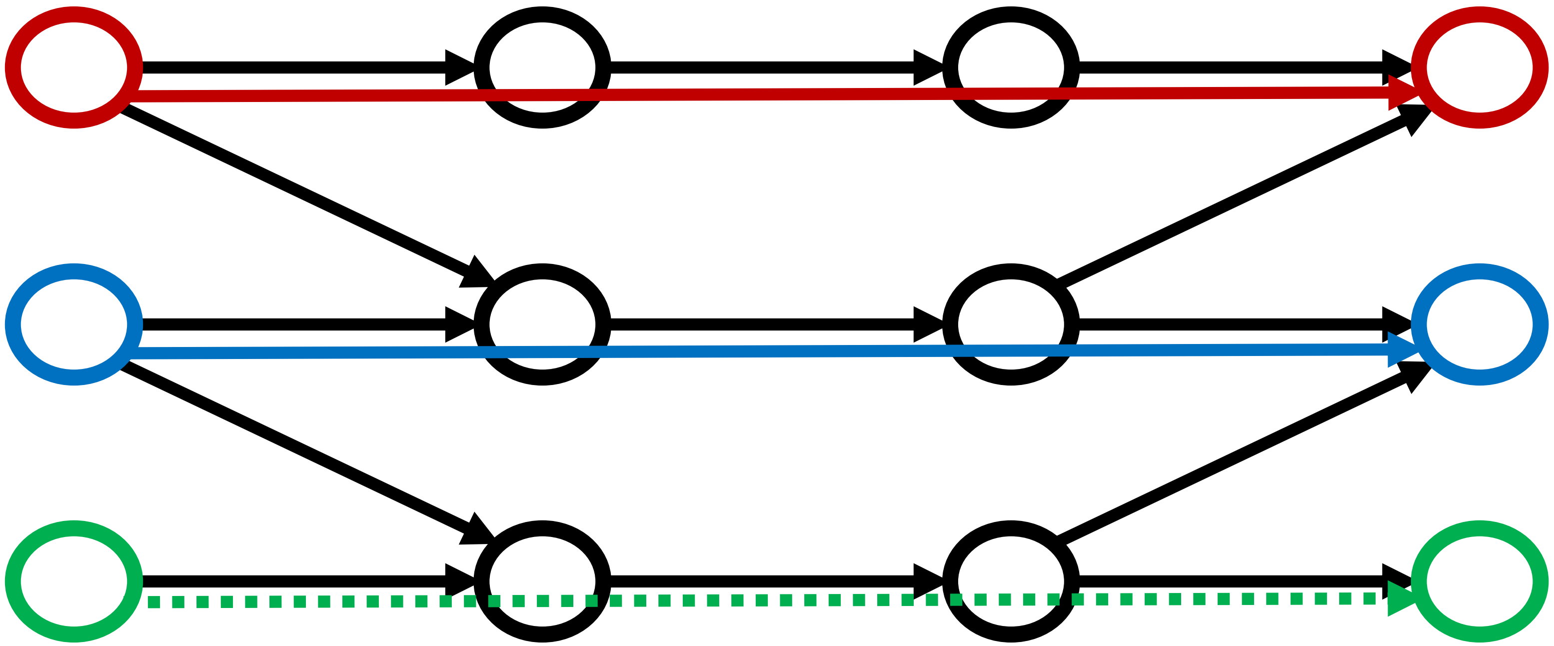
Then, Blue …



Round **2**

Unit size flows and capacities

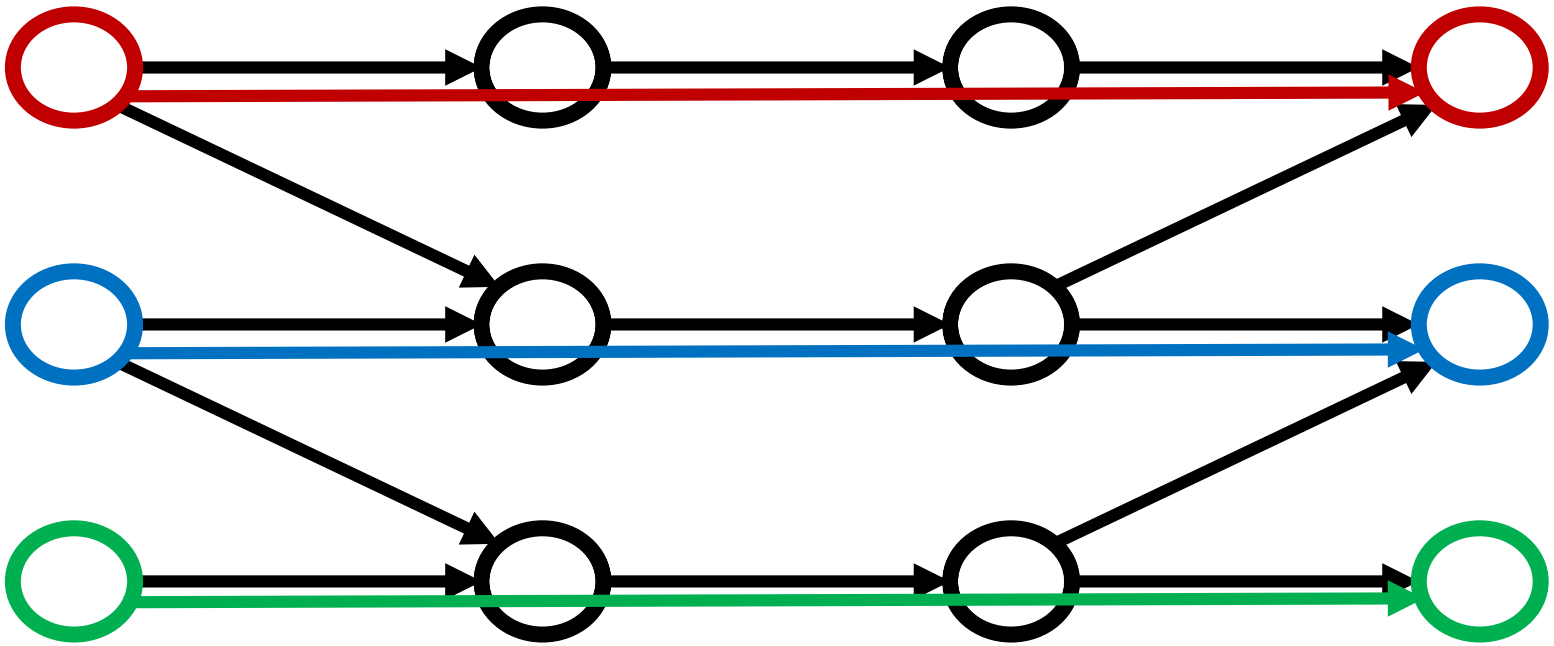
And then, Green …



Round **3**

Unit size flows and capacities

Done



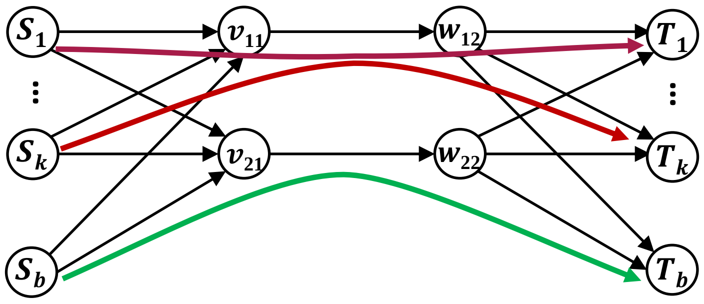
Round **3** *(new)*

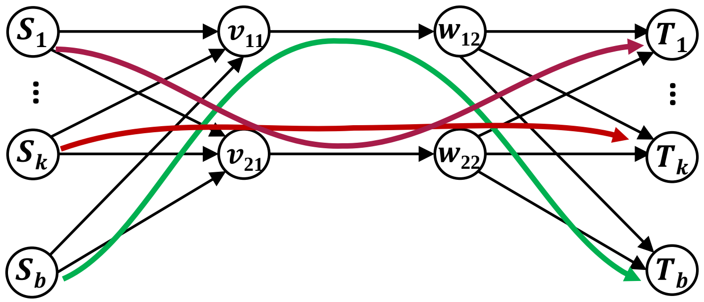
Unit size flows and capacities

How hard is this (feasibility)?

Flows may only take *old* or *new* paths:

- NP-hard via reduction from Partition





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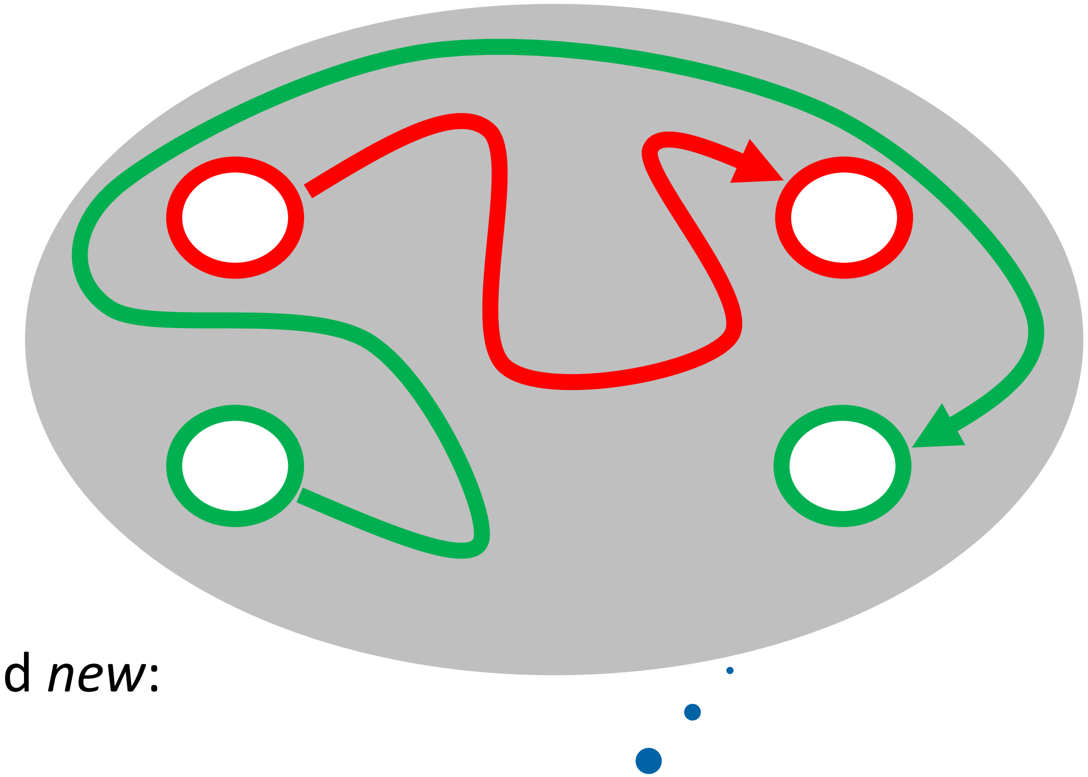
Intermediate flow allocations not restricted to *old* and *new*:

- NP-hard already for just 2 unit size flows



Hardness intuition: find intermediate path for “storage”

On the Consistent Migration of Unsplittable Flows: Upper and Lower Complexity Bounds (Foerster, NCA 2017)

How hard is this (feasibility)?

Flows may only take *old* or *new* paths:

- NP-hard via reduction from Partition

Intermediate flow allocations not restricted to *old* and *new*:

- NP-hard already for just 2 unit size flows

- Is the problem at least in NP?

Some flows might need to move back and forth repeatedly° ☹

On the Consistent Migration of Unsplittable Flows: Upper and Lower Complexity Bounds (Foerster, NCA 2017)

How hard is this (feasibility)?

Flows may only take *old* or *new* paths:

- NP-hard via reduction from Partition

How about *splittable* flows?

Intermediate flow allocations not restricted to *old* and *new*:

- NP-hard already for just 2 unit size flows

Not clear if the problem is in NP! (It is known to be in EXPTIME)

On the Consistent Migration of Unsplittable Flows: Upper and Lower Complexity Bounds (Foerster, NCA 2017)

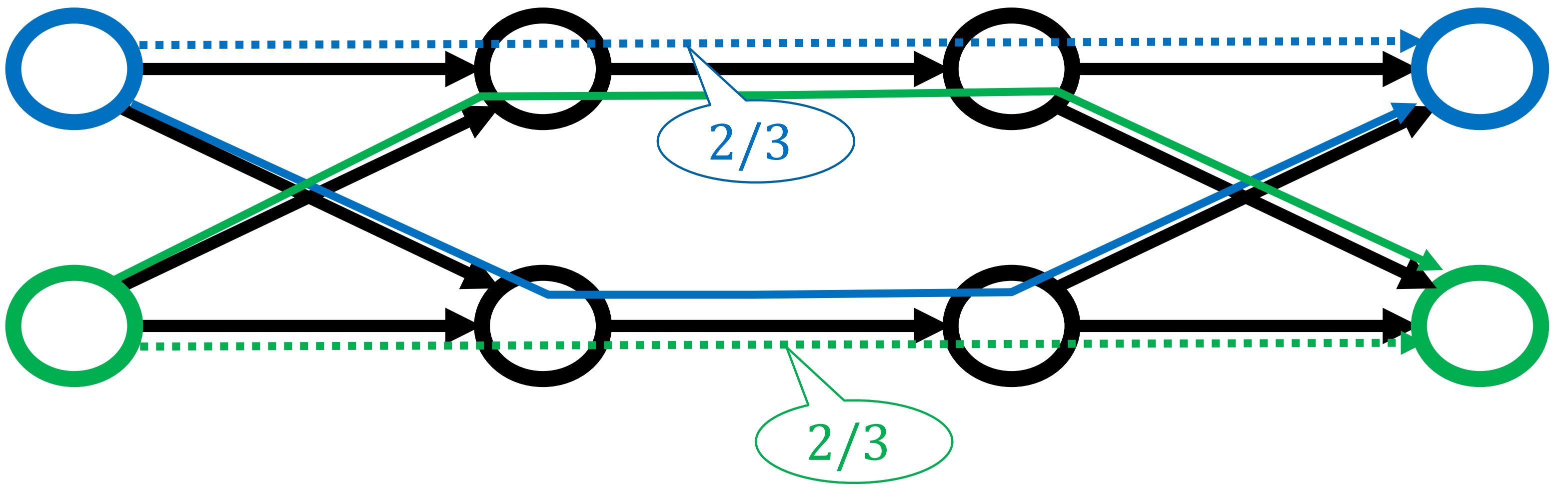
Captures Asynchrony

Consistent Migration of Splittable Flows

Idea: Flows can be on the **old** or **new** route w.r.t. an update

For all edges: $\sum_{\forall F} \max\left(\mathbf{old}, \mathbf{new}\right) \leq capacity$

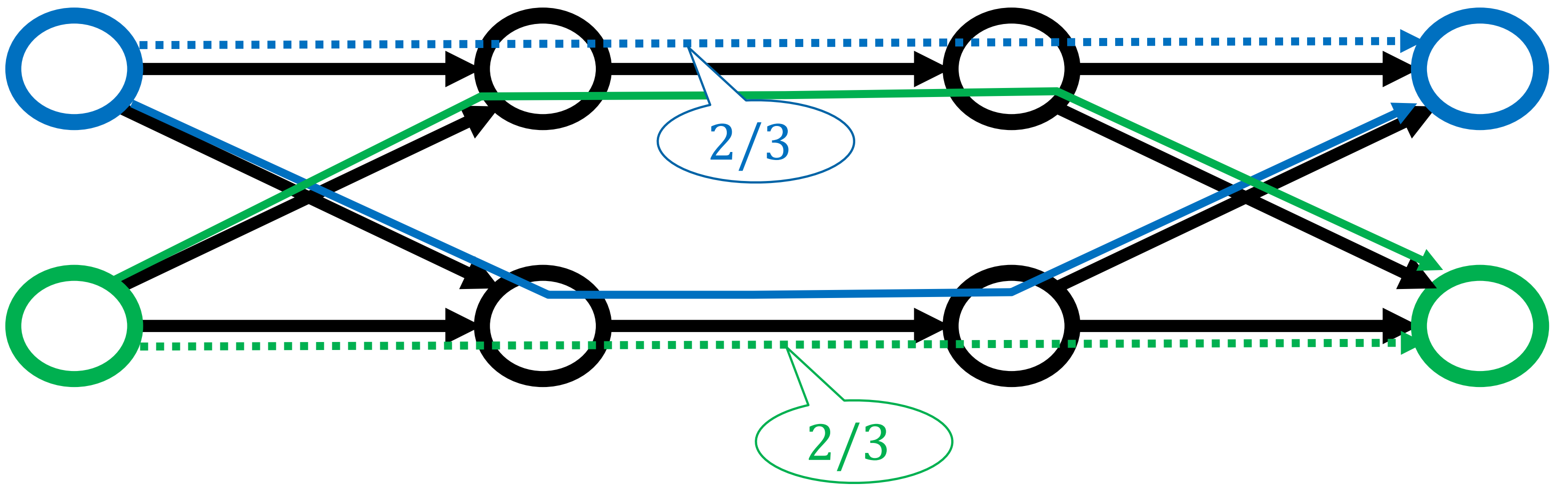
No ordering exists $(2/3 + 2/3 > 1)$



Consistent Migration of Splittable Flows

Approach of *SWAN**: use slack x (i.e., **%**)

- Here $x = 1/3$
- Move slack $x \Rightarrow \lceil 1/x \rceil - 1$ staged partial moves



*: Achieving High Utilization with Software-Driven WAN, SIGCOMM 2013

Consistent Migration of Splittable Flows

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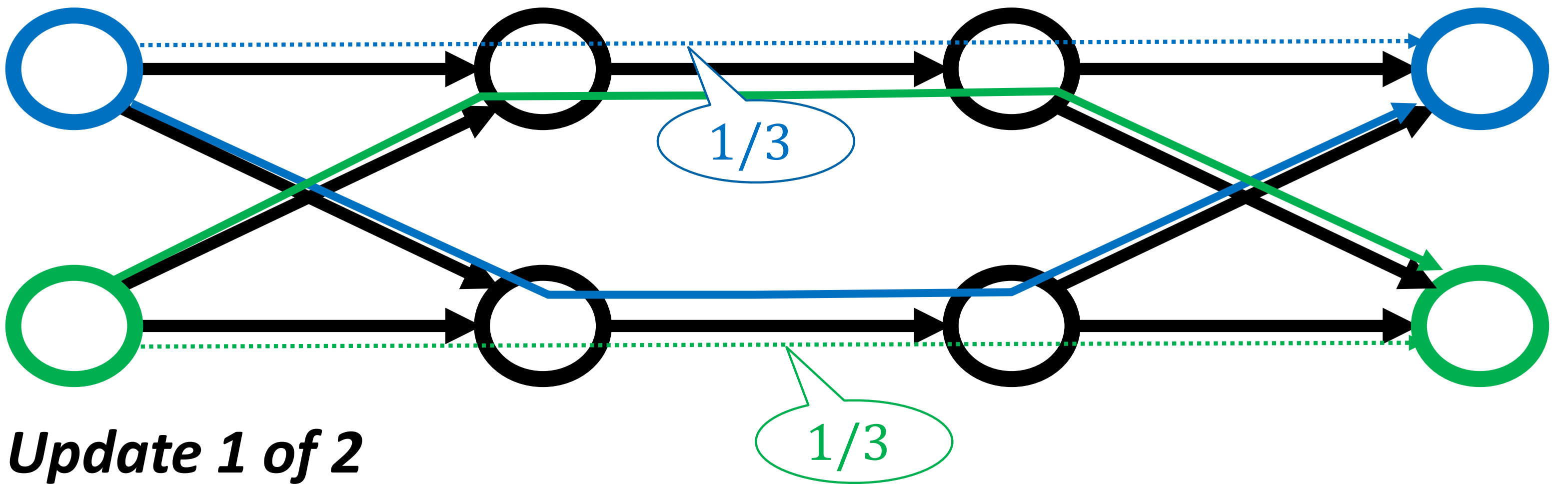

Update 1 of 2

Consistent Migration of Splittable Flows

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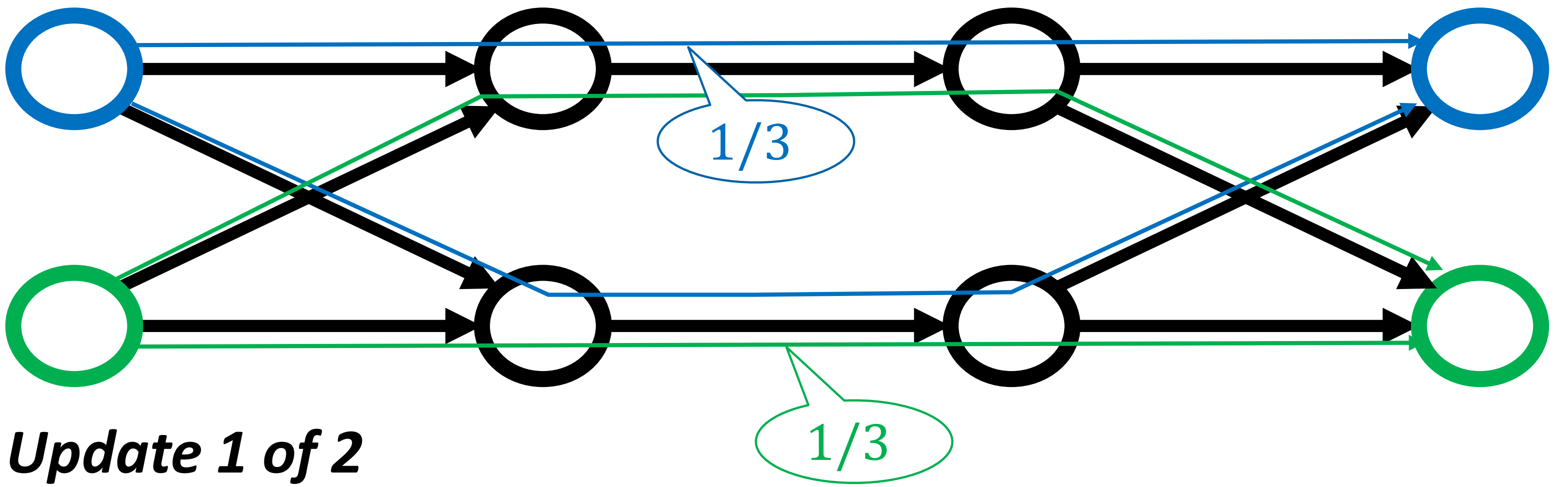

Update 1 of 2

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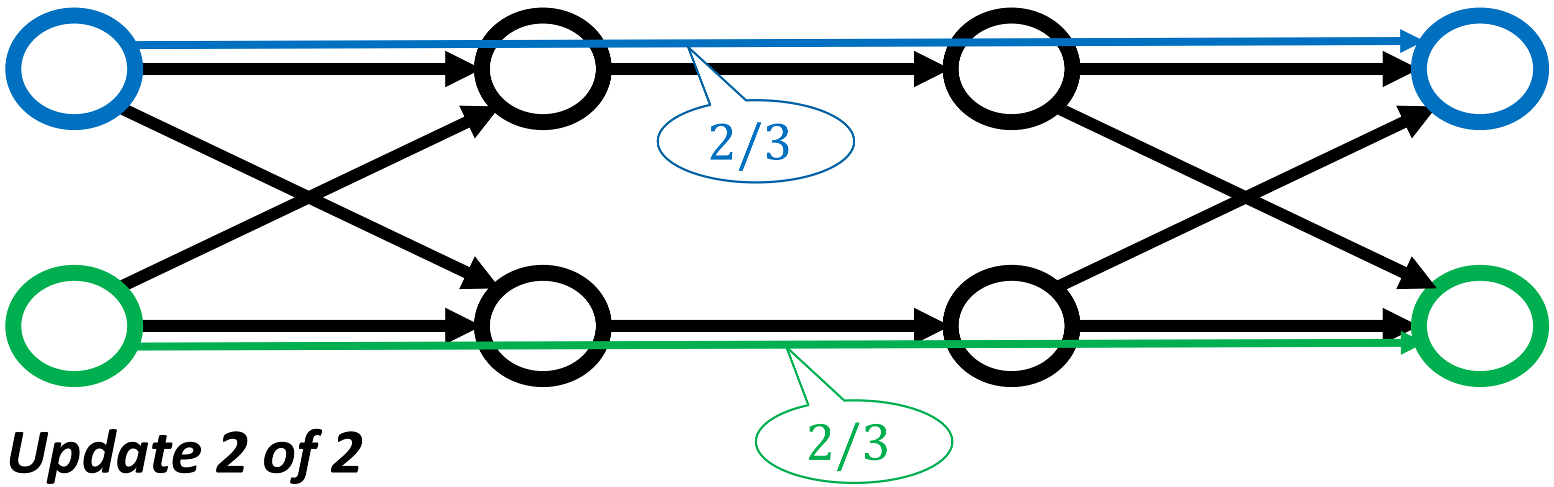
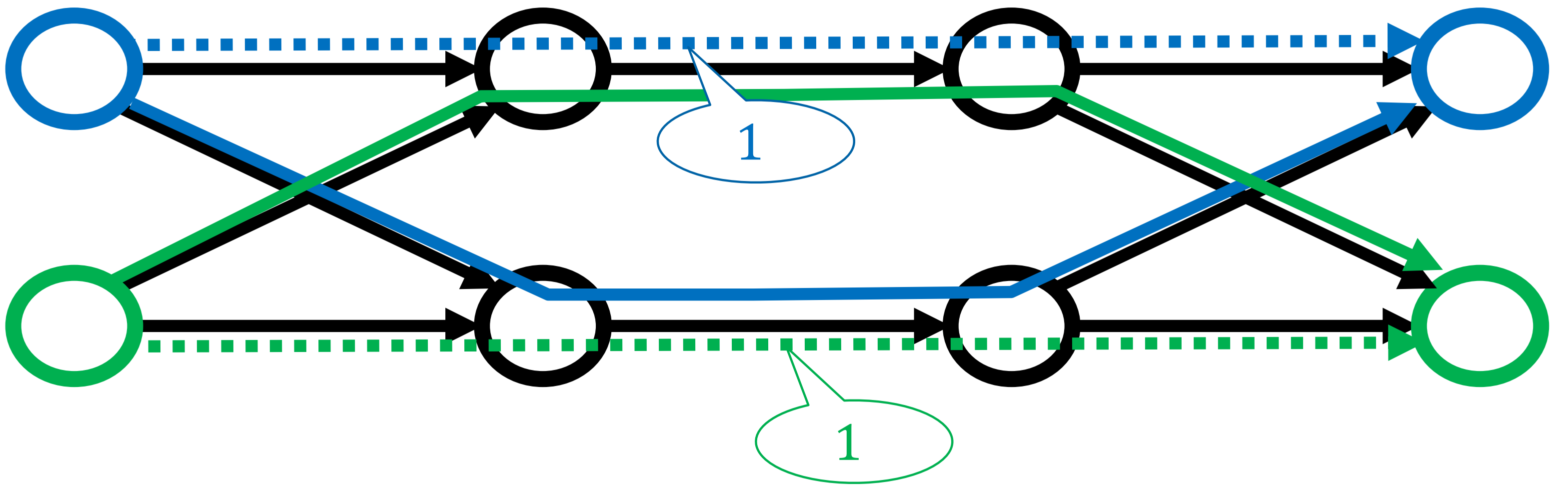


Update 2 of 2

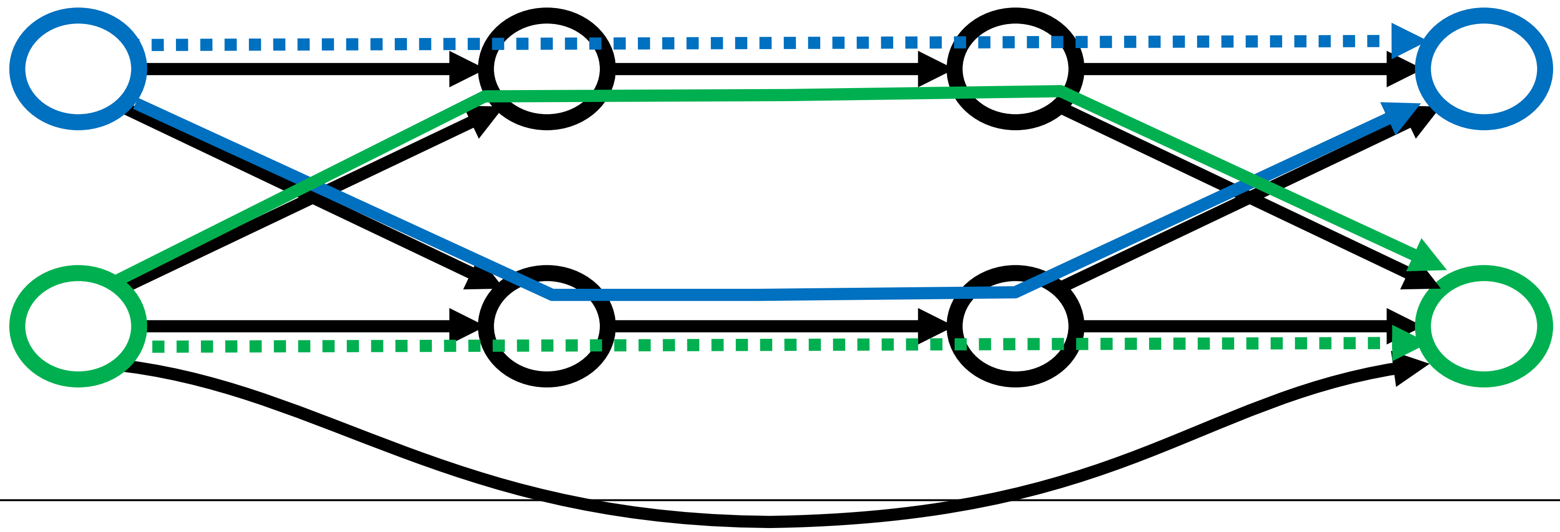
Consistent Migration of Splittable Flows

No slack on flow edges?



Consistent Migration of Splittable Flows

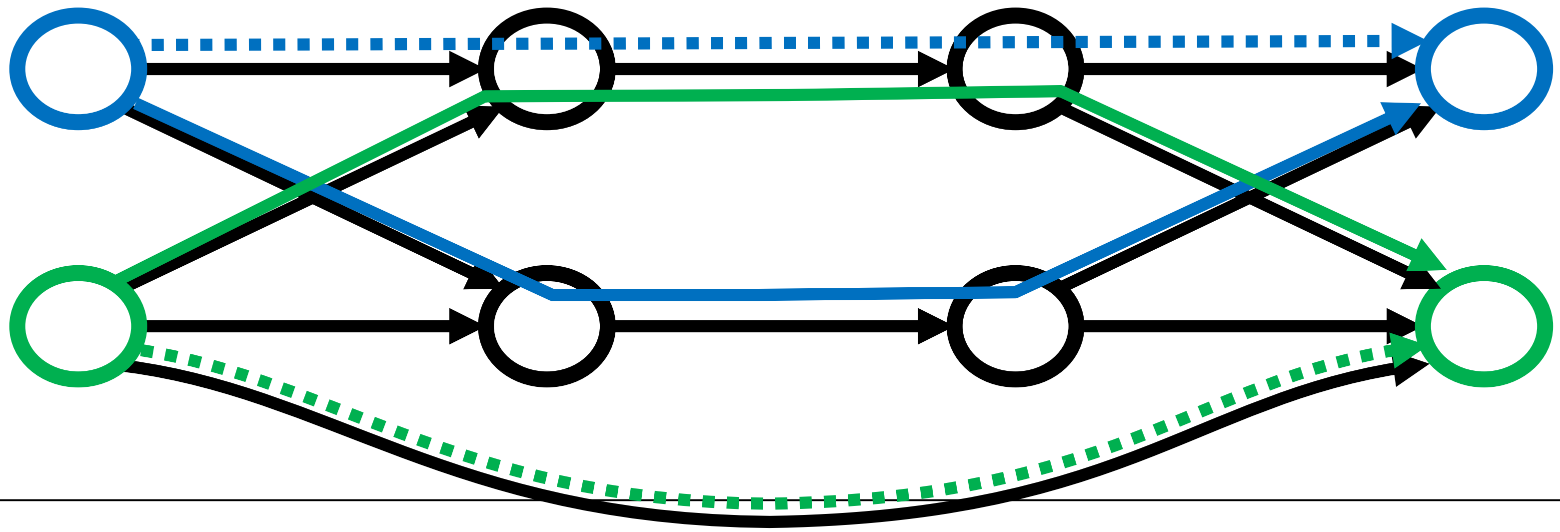
Alternate routes?



Consistent Migration of Splittable Flows

Think: variable swapping of b & g

1. $x \coloneqq b$, 2. b $\coloneqq g$, 3. $g \coloneqq x$



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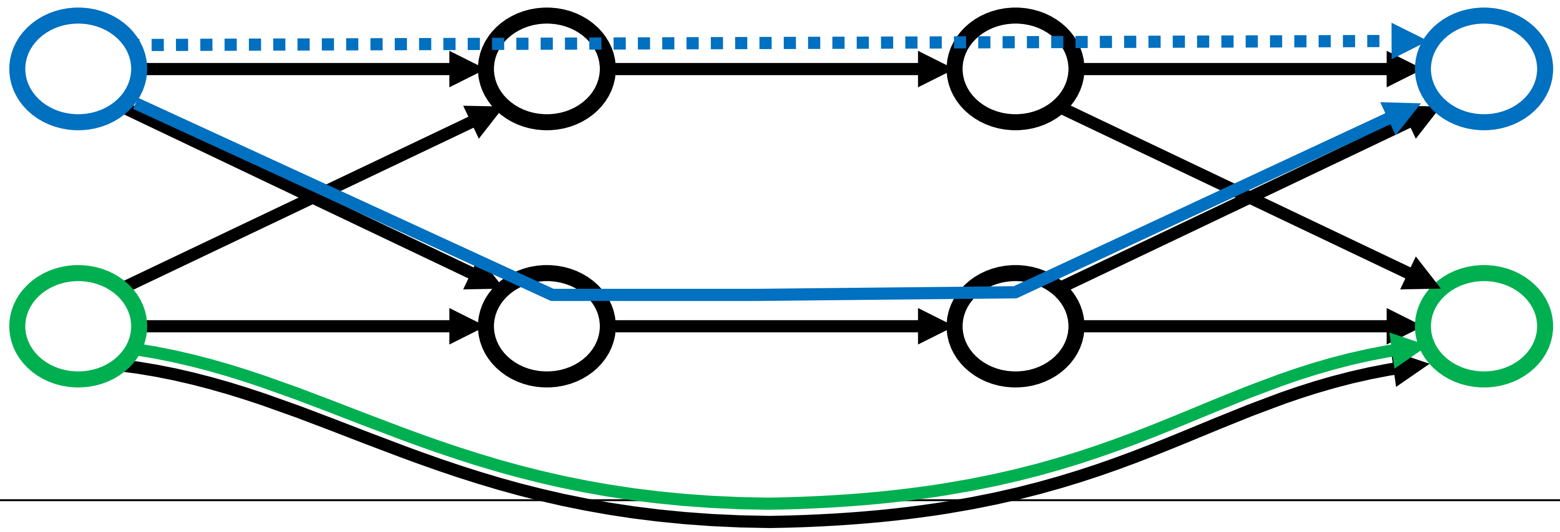

Consistent Migration of Splittable Flows

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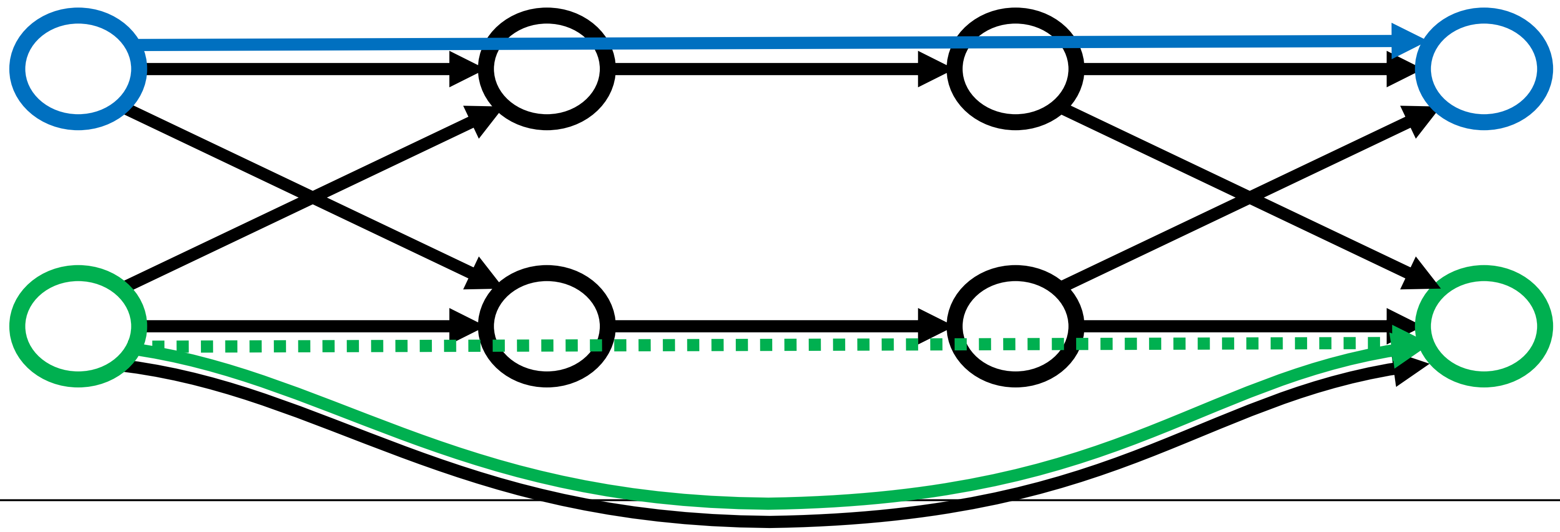
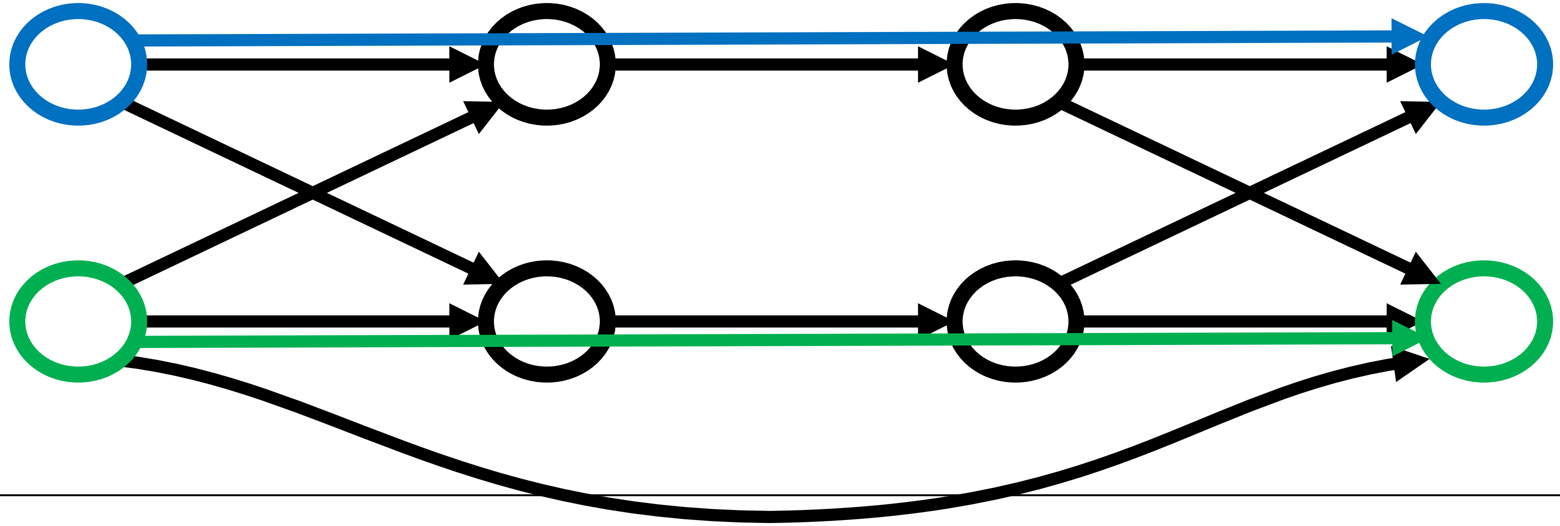


Consistent Migration of Splittable Flows

SWAN: LP-approach with binary search

1 update? 2 updates? 4 updates? …



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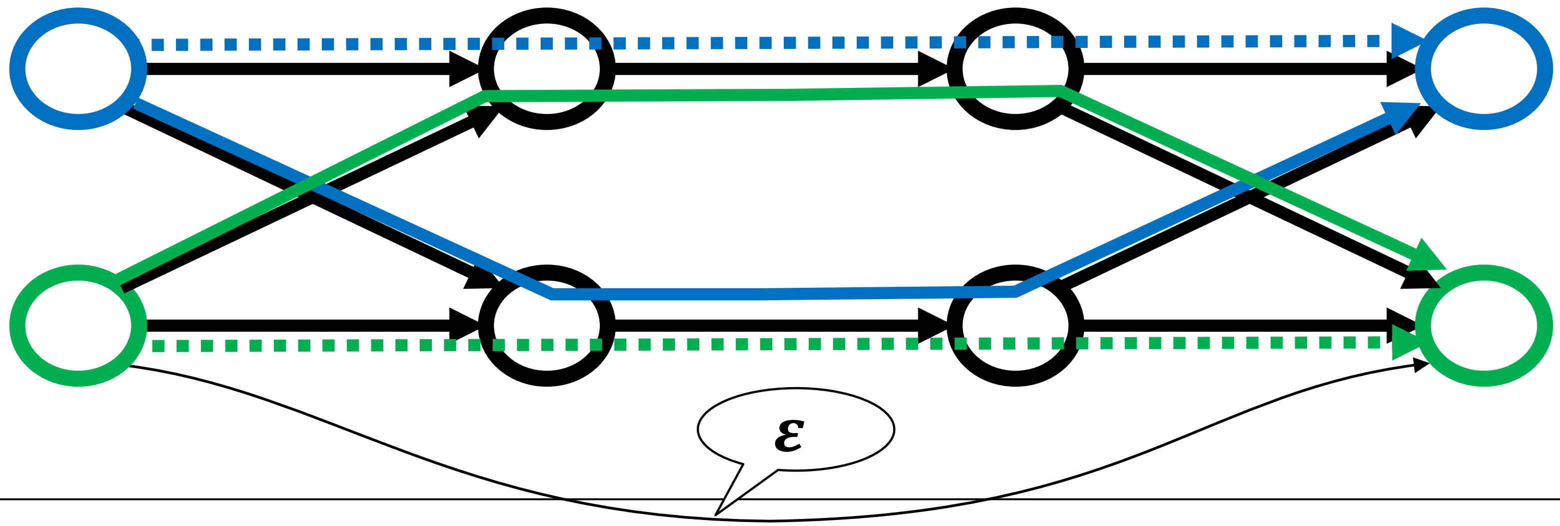
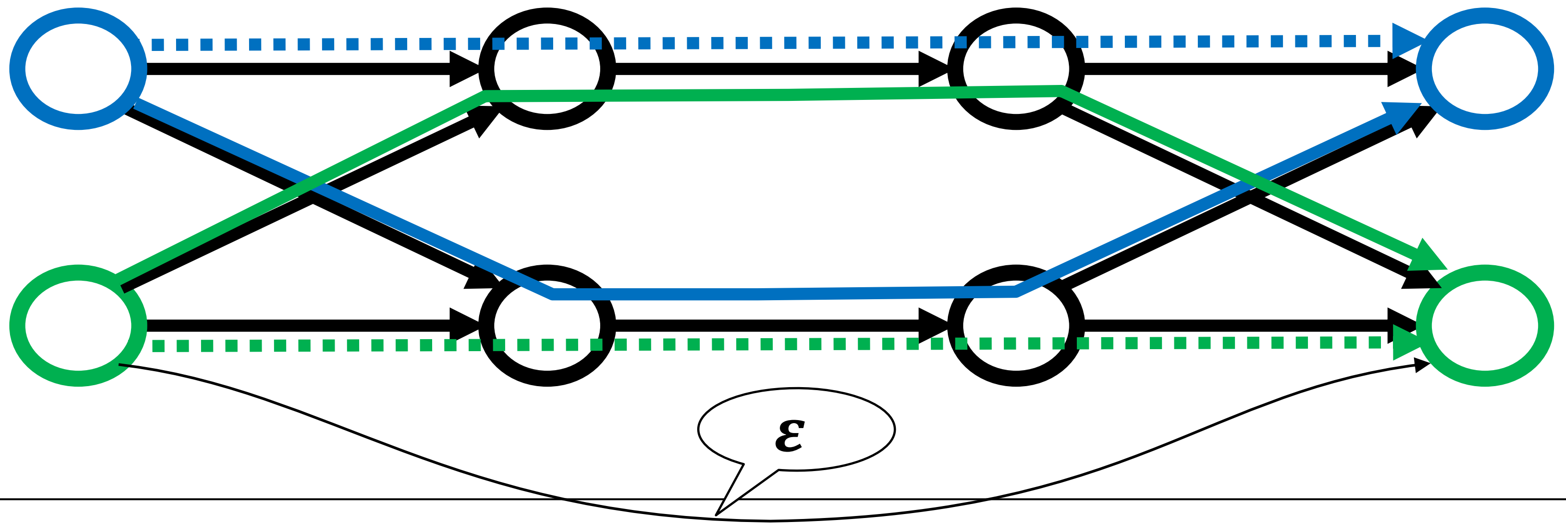


Consistent Migration of Splittable Flows

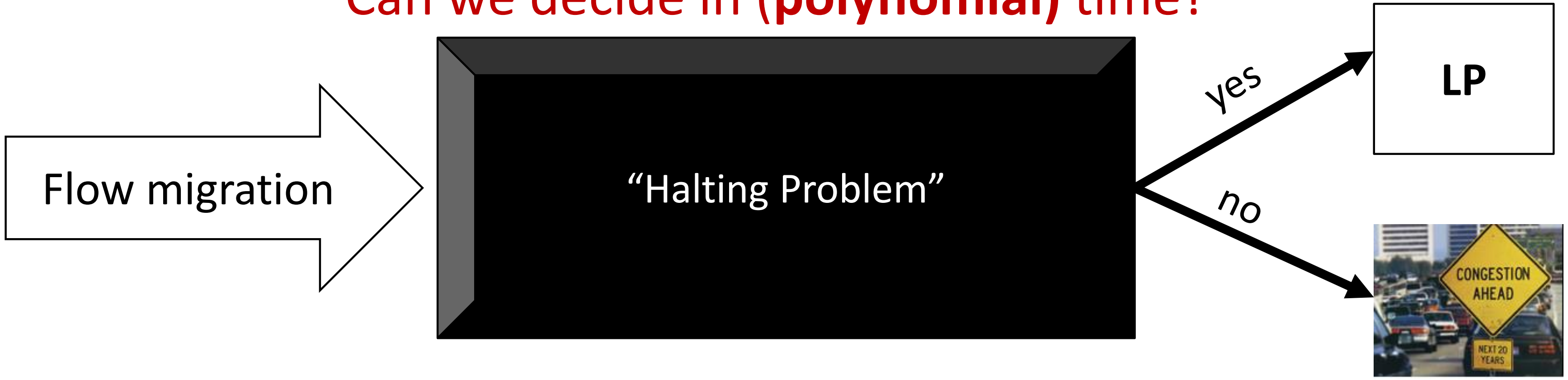
SWAN: LP-approach with binary search

$\Theta(1/\varepsilon)$ updates ☹



Consistent Migration of Splittable Flows

Can we decide in (**polynomial**) time?



To Slack or not to Slack?

Slack of x on all flow edges?

$\lceil 1/x \rceil - 1$ updates

To Slack or not to Slack?

What if not?

Try to create slack

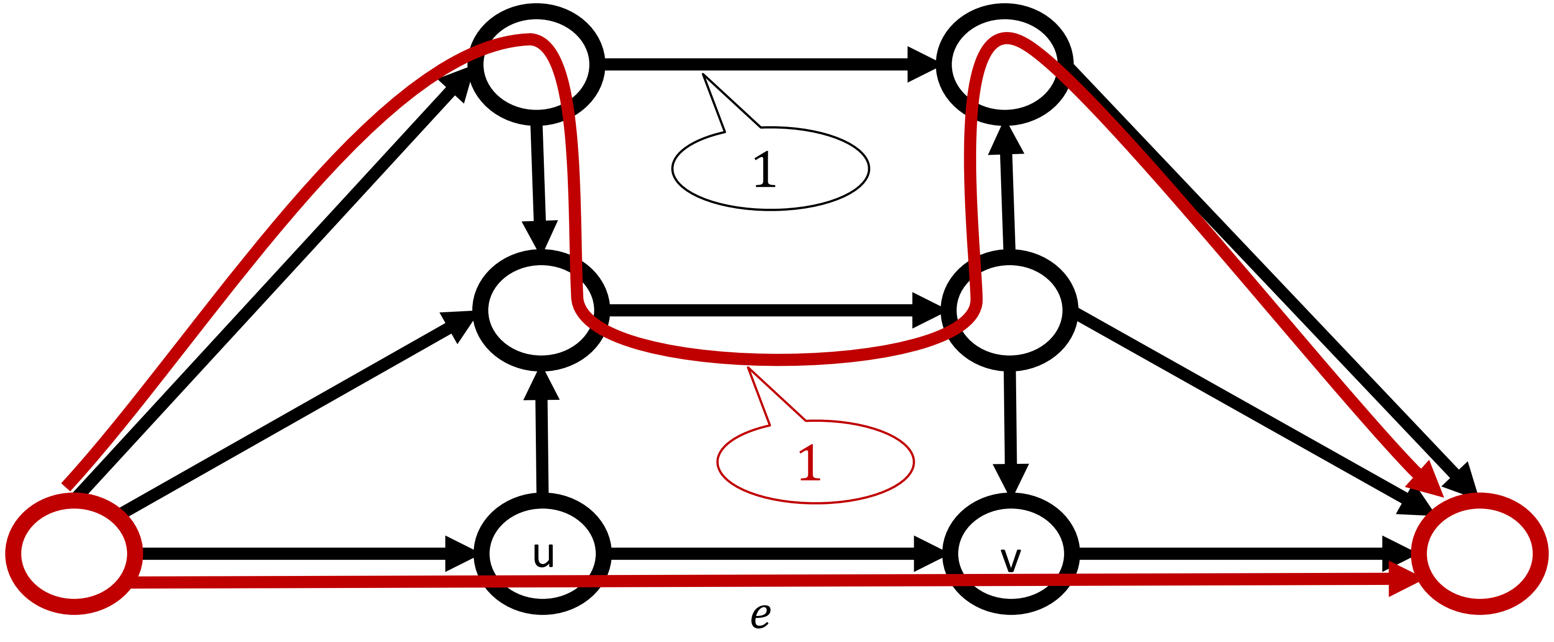
To Slack or not to Slack?

Combinatorial approach

Augmenting paths

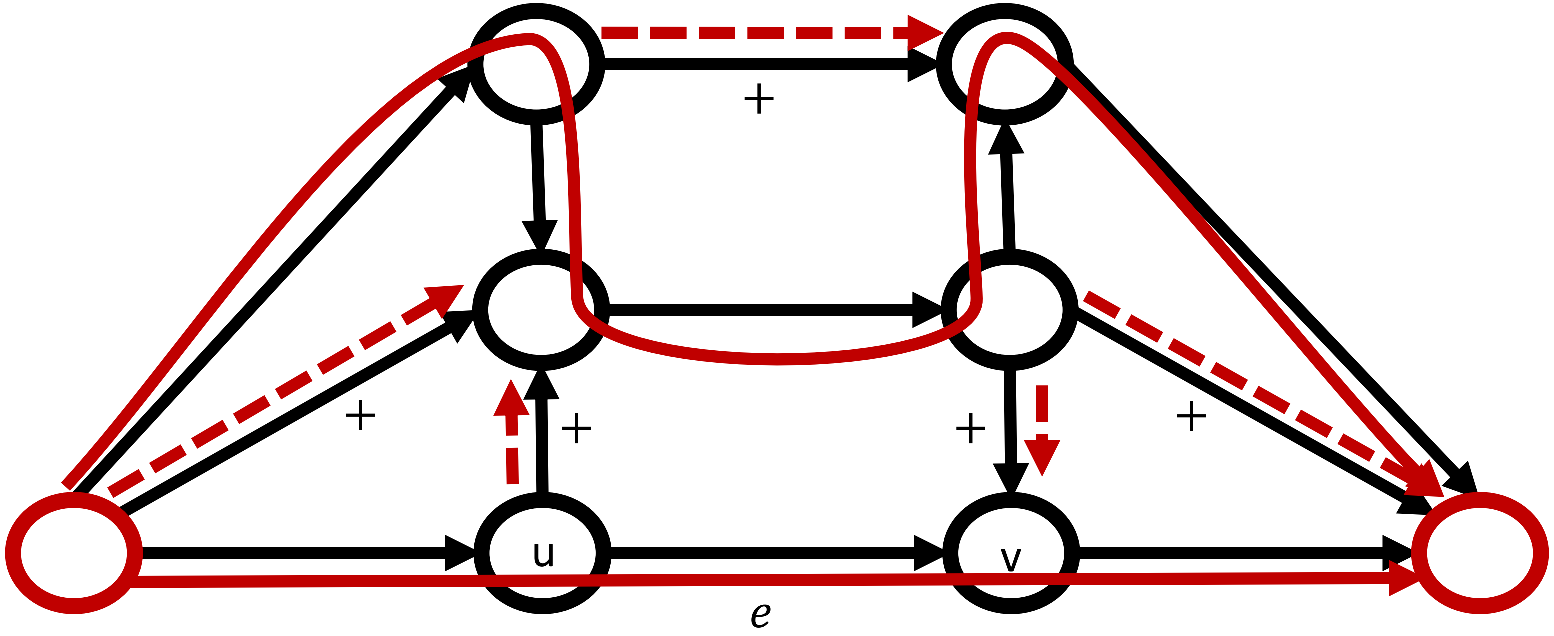
Combinatorial Approach

Move single commodities at a time



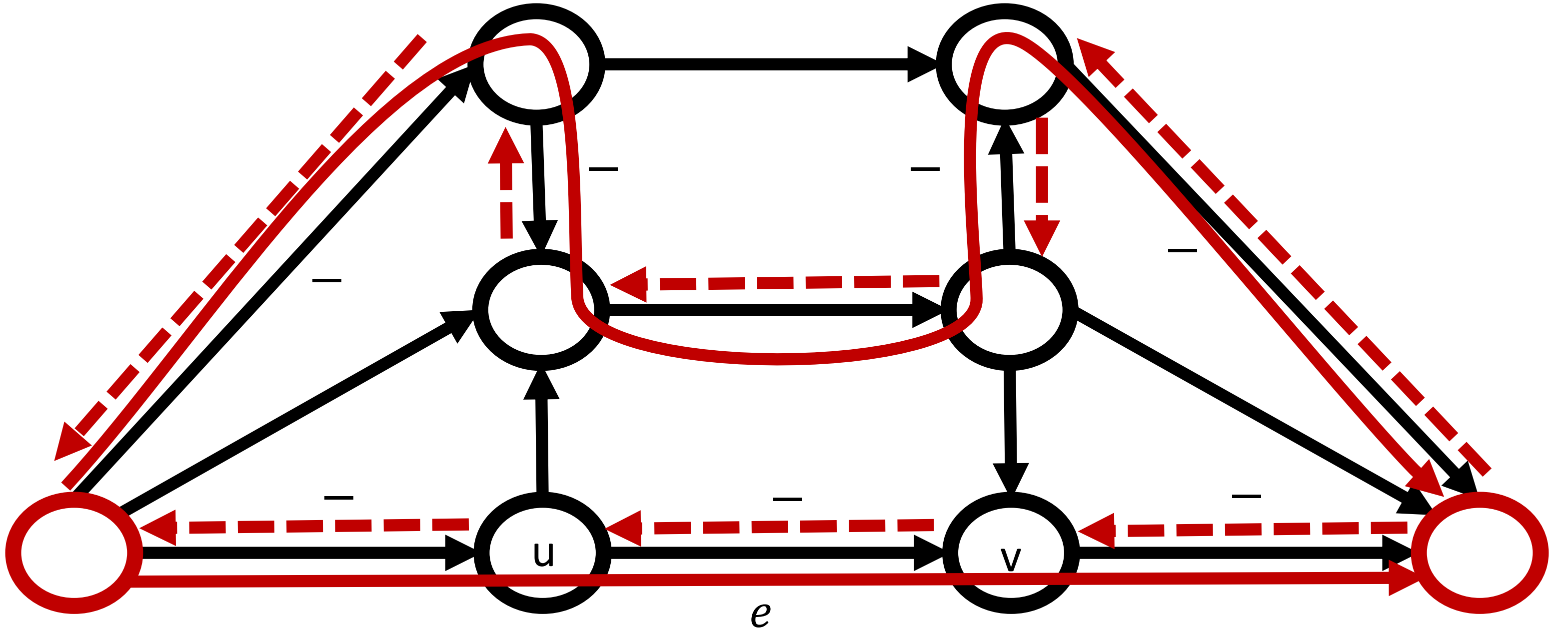
Combinatorial Approach

Where to increase flow?



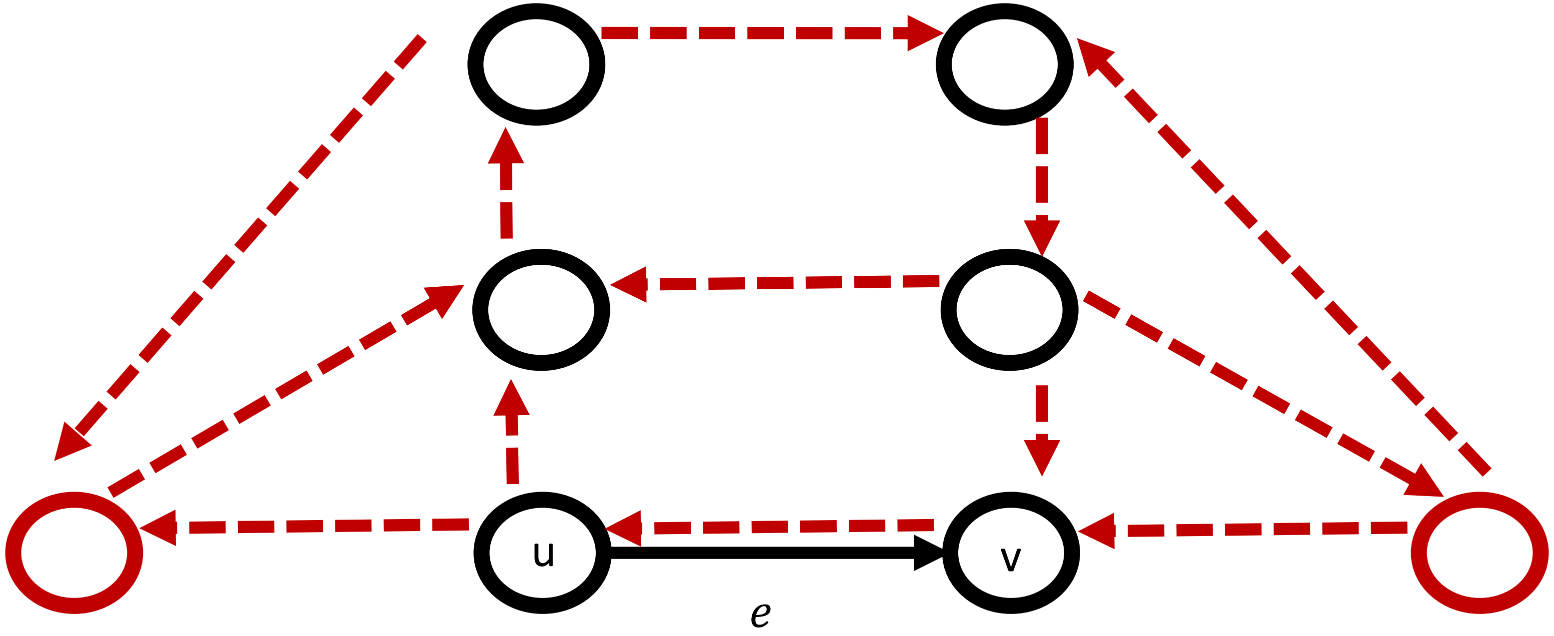
Combinatorial Approach

Where to push back flow?



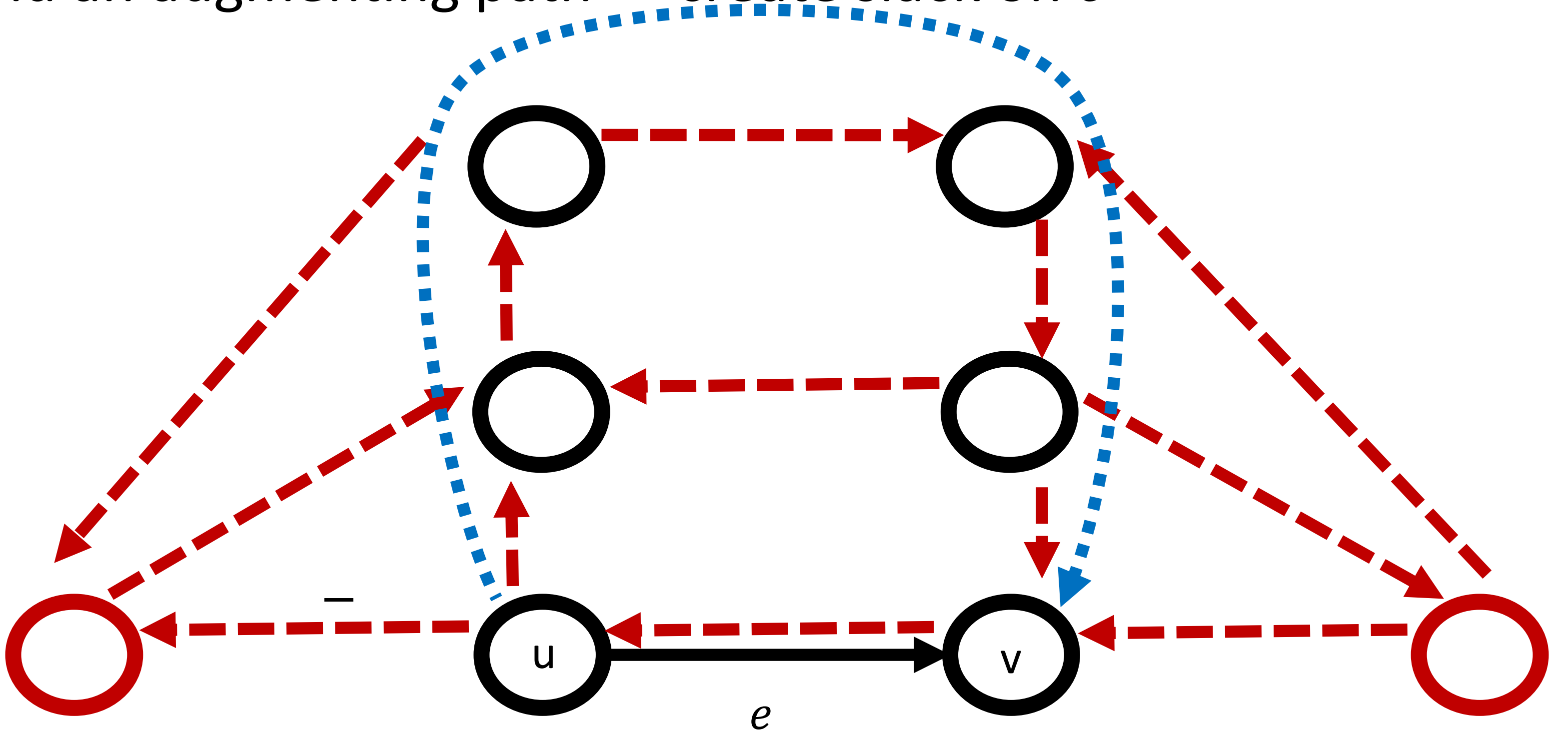
Combinatorial Approach

Resulting residual network



Combinatorial Approach

We found an augmenting path ⇒ create slack on e



High-level Algorithm Idea

- No slack on flow edges? Find augmenting paths
  - On both initial and desired state (updates can be performed in reverse)
  - Success? Use *SWAN* method to migrate

- Can't create slack on some flow edge?
  - Consistent migration impossible
    By contradiction (else augmenting paths would create slack)

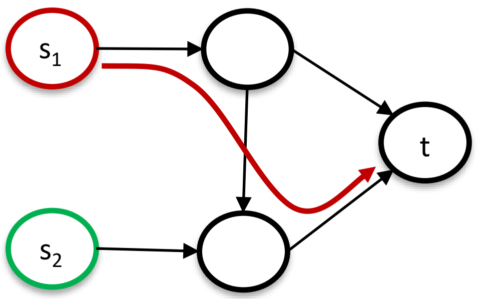
- Runtime: $O(Fm^3)$
  - (F being #commodities, m being #edges)

On Consistent Migration of Flows in SDNs. S. Brandt, K.-T. Foerster, R. Wattenhofer, INFOCOM 2016

Maybe surprisingly:
If the new flows fit in somehow,
we can migrate consistently!

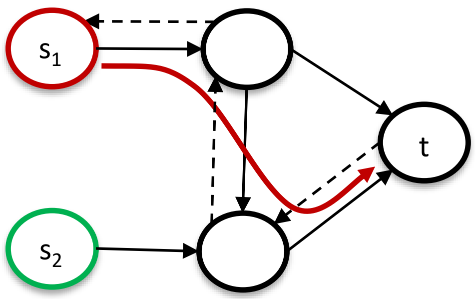
Open problems for scheduling flow migration

- What happens when we can pick the new paths?
  - Idea: Fit the flows in, does not matter where
    - Only studied so far for a single destination and multiple sources [Brand, Foerster, Wattenhofer, PMC 2017]



size of each flow: 1

capacity of links: 1



size of each flow: 1
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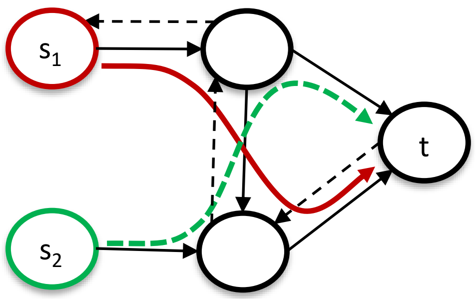
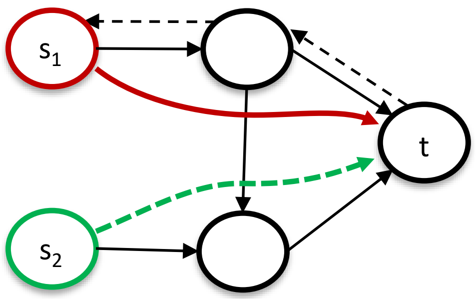


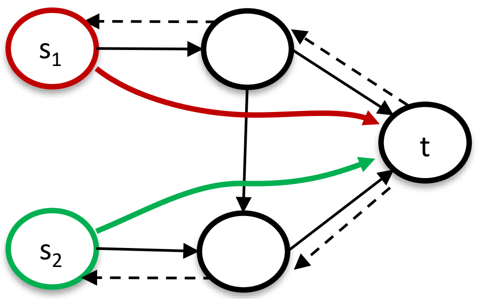
size of each flow: 1

capacity of links: 1



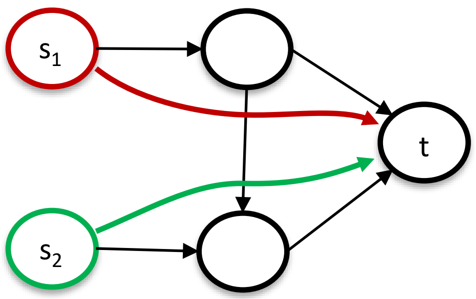
size of each flow: 1

capacity of links: 1



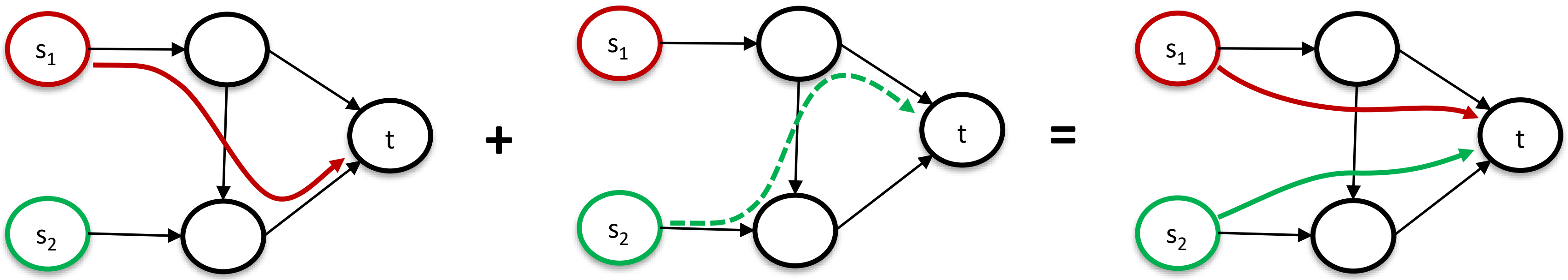
size of each flow: 1

capacity of links: 1



size of each flow: 1

capacity of links: 1



size of each flow: 1

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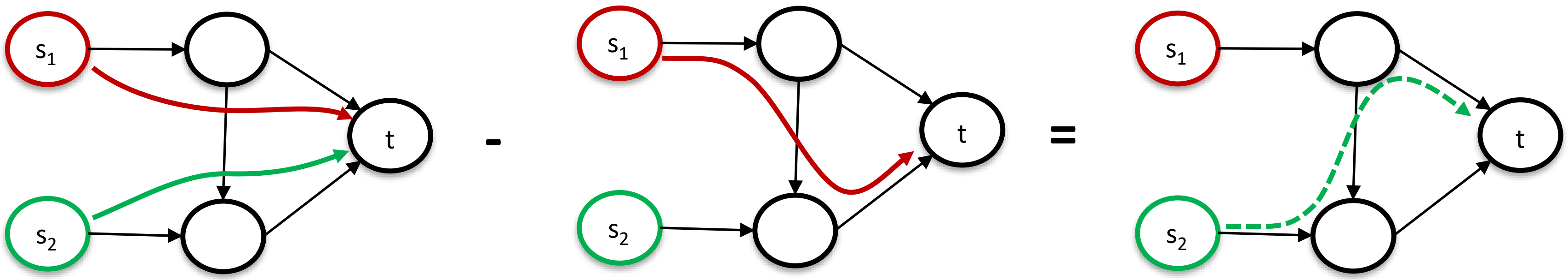
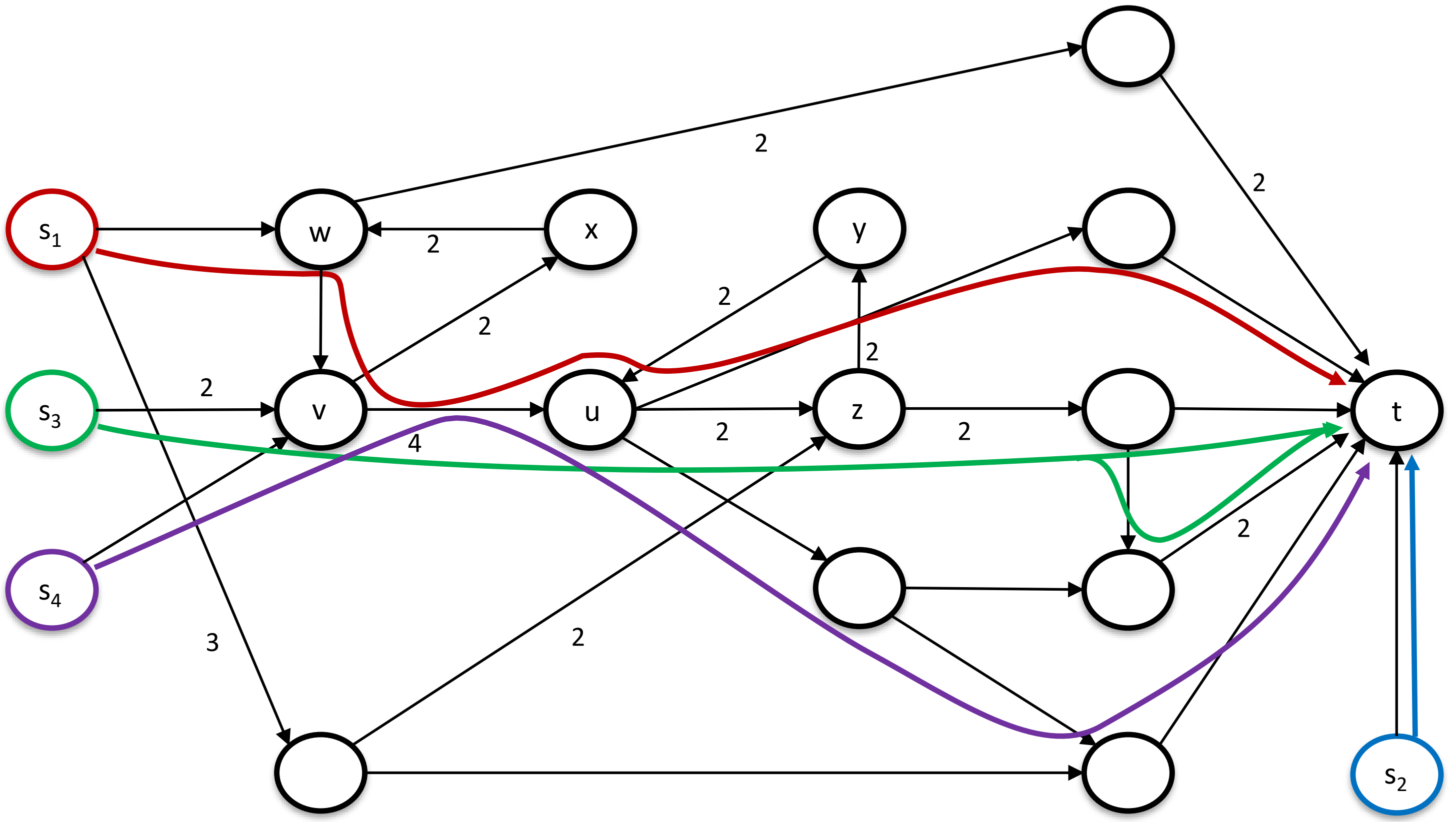


size of each flow: 1

capacity of links: 1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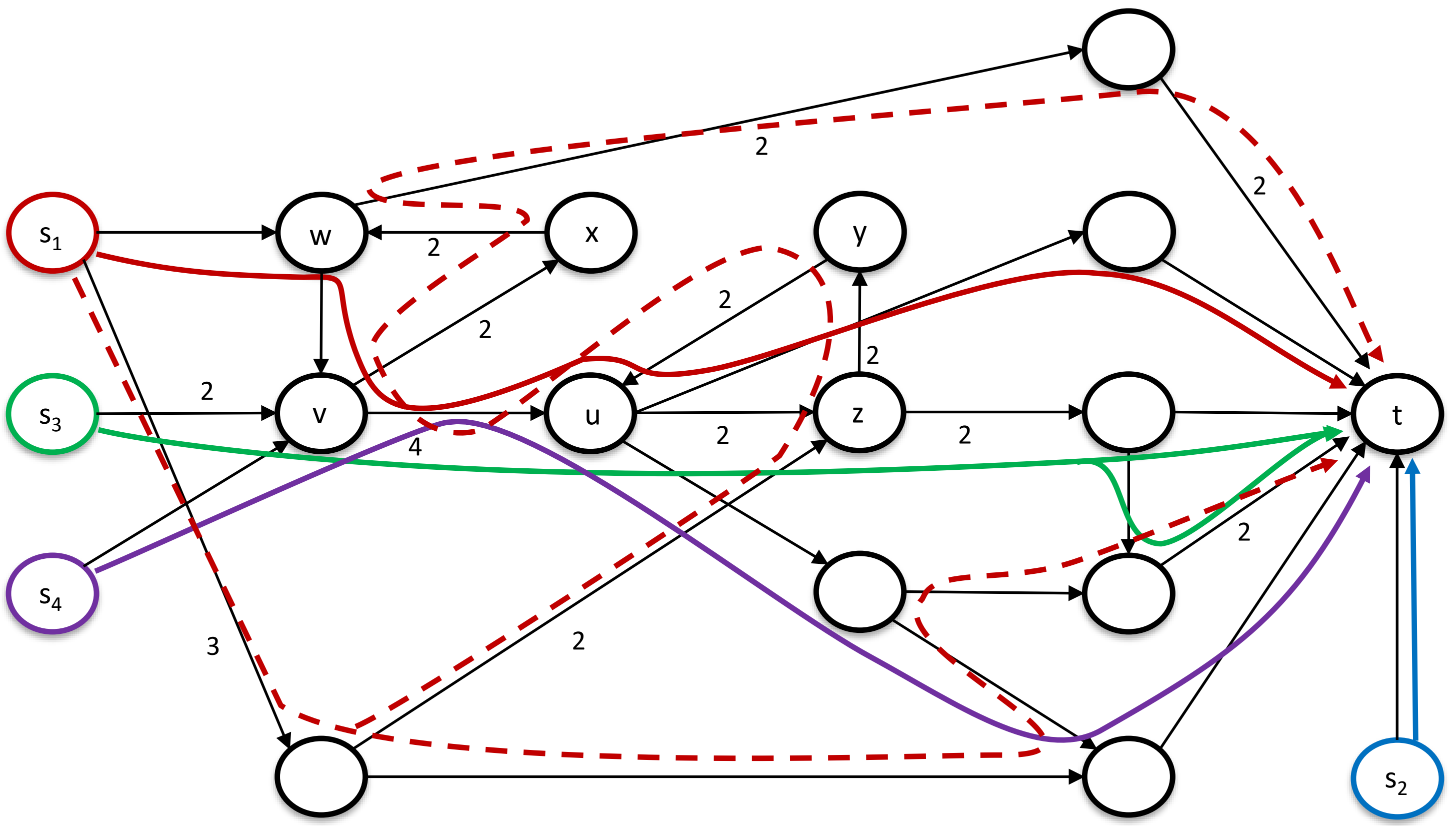
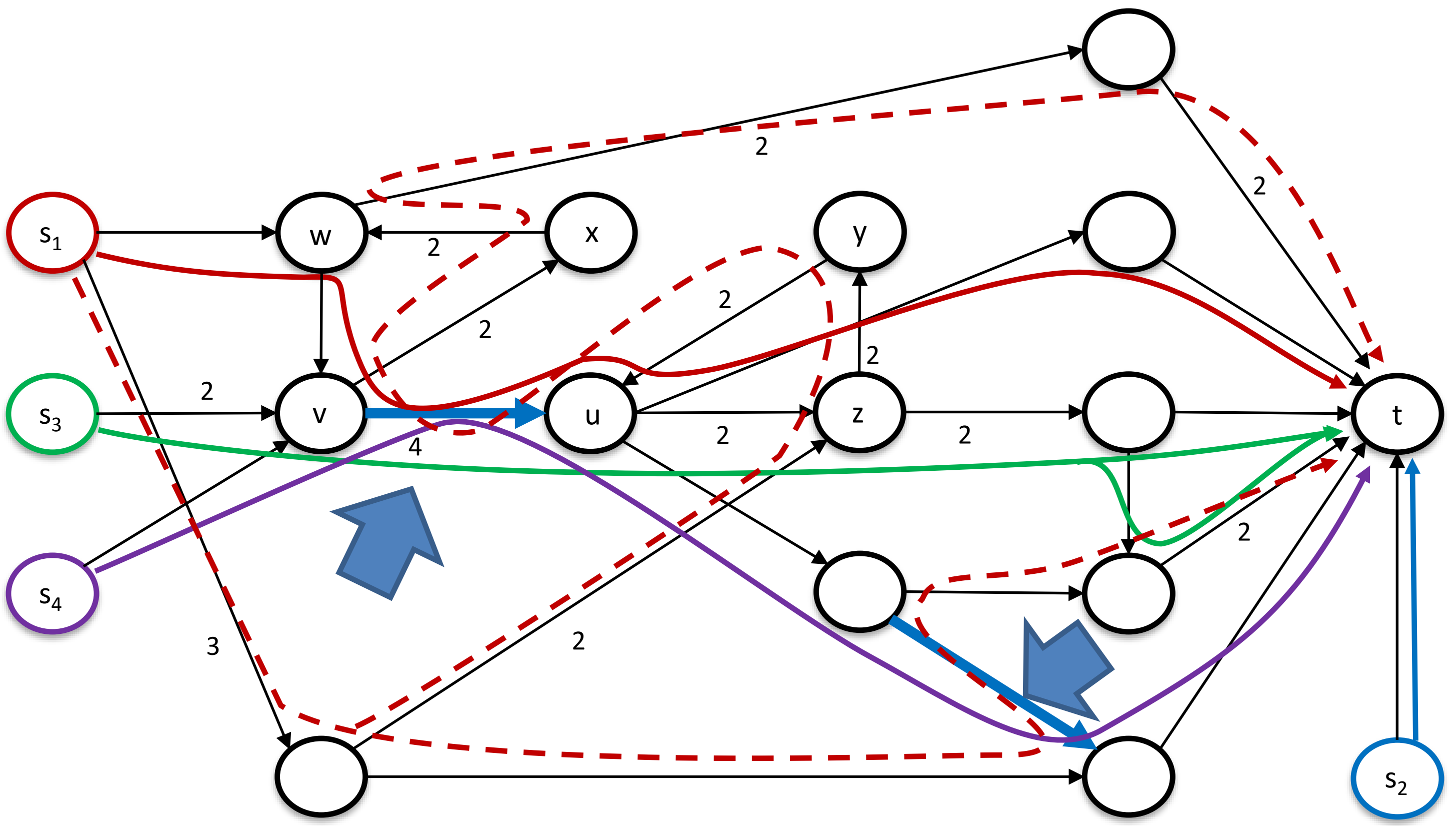


size of flows: 1, 2, 1, 1

capacity of links: 1 (or marked)



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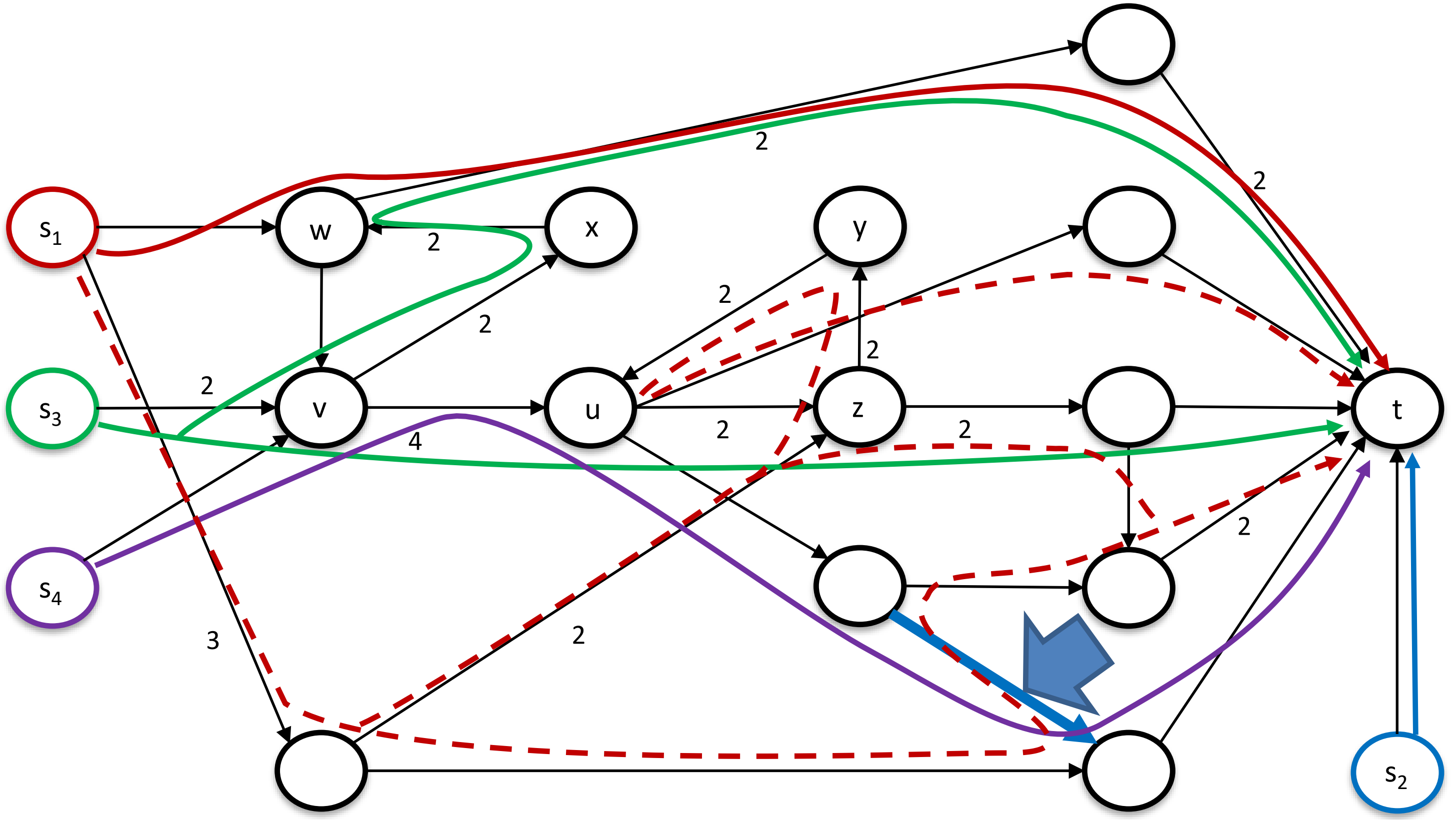

size of flows: 1, 2, 1, 1

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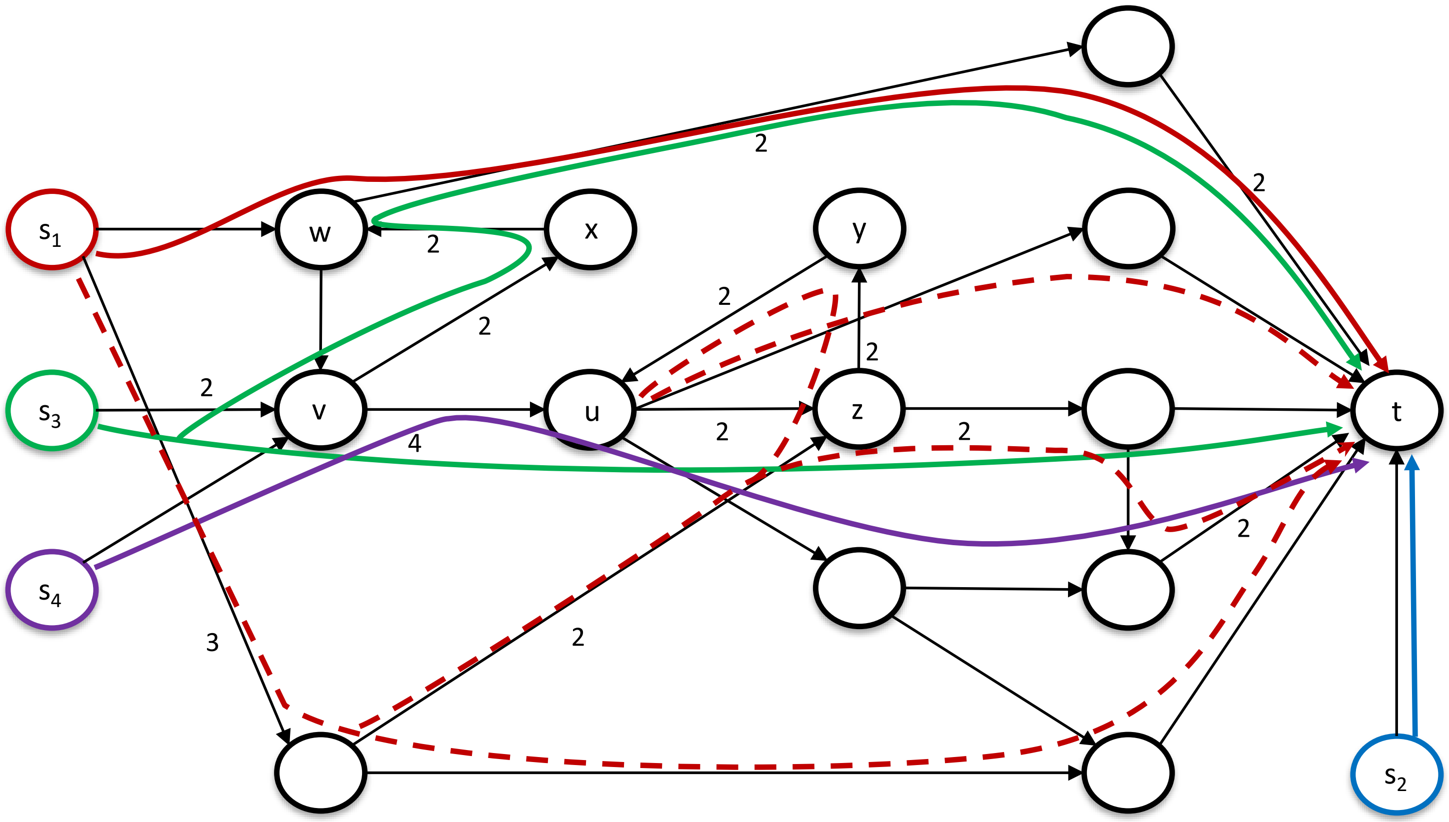

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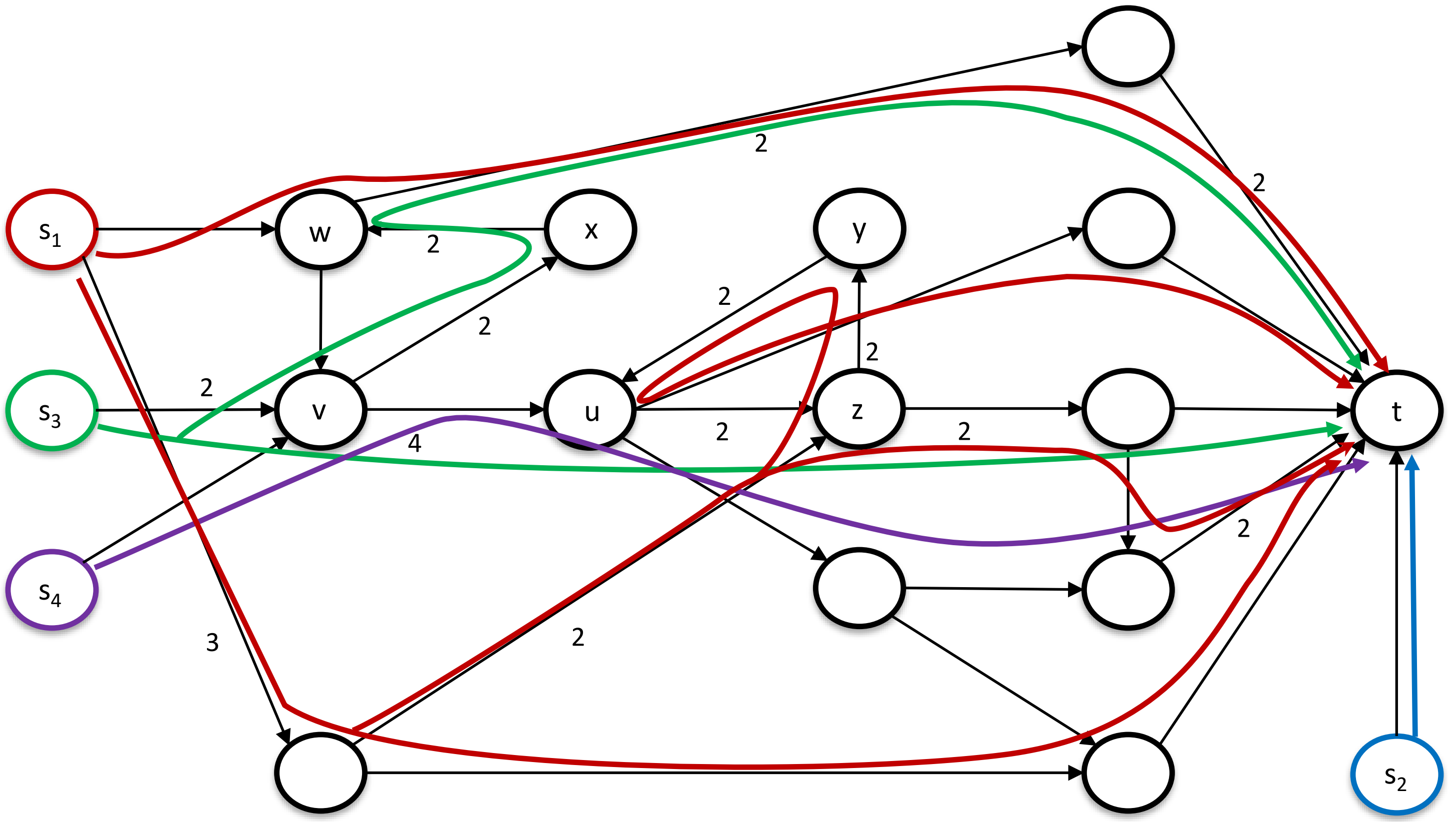
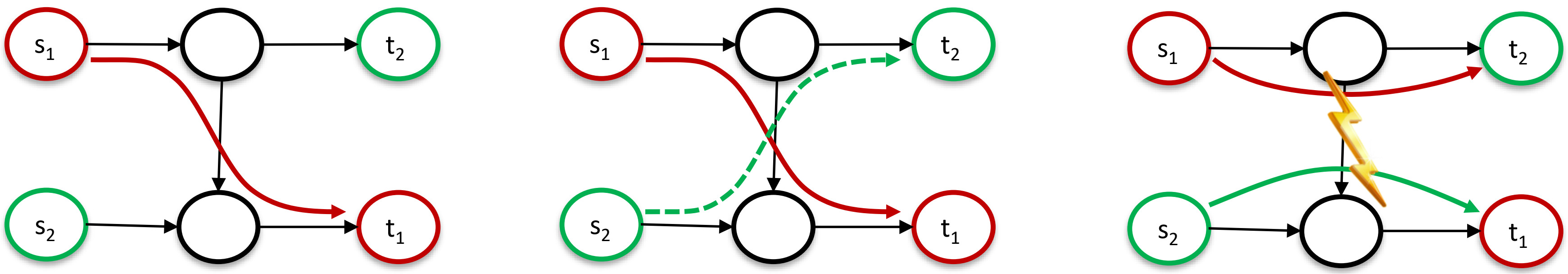
capacity of links: 1 (or marked)

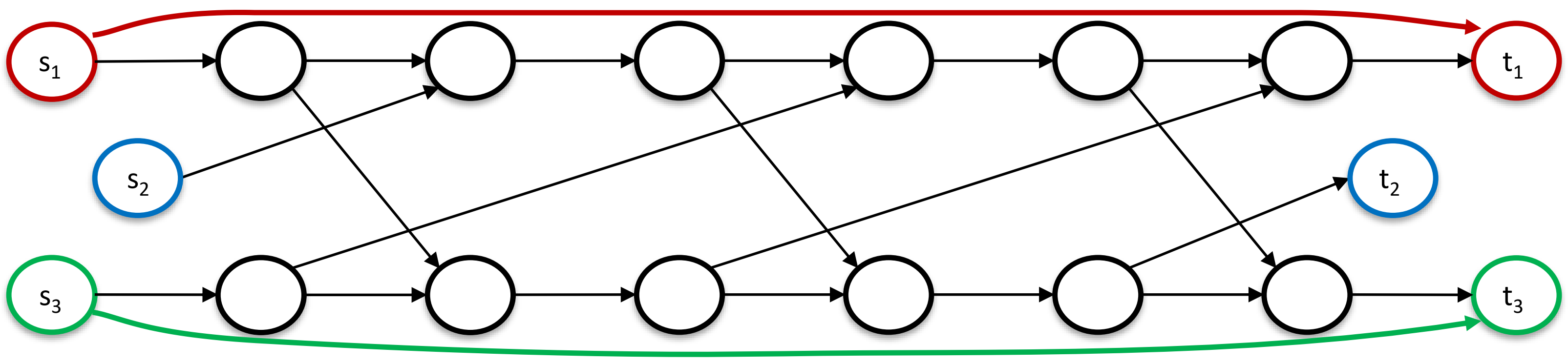


size of flows: 1+3=4, 2, 1, 1

capacity of links: 1 (or marked)

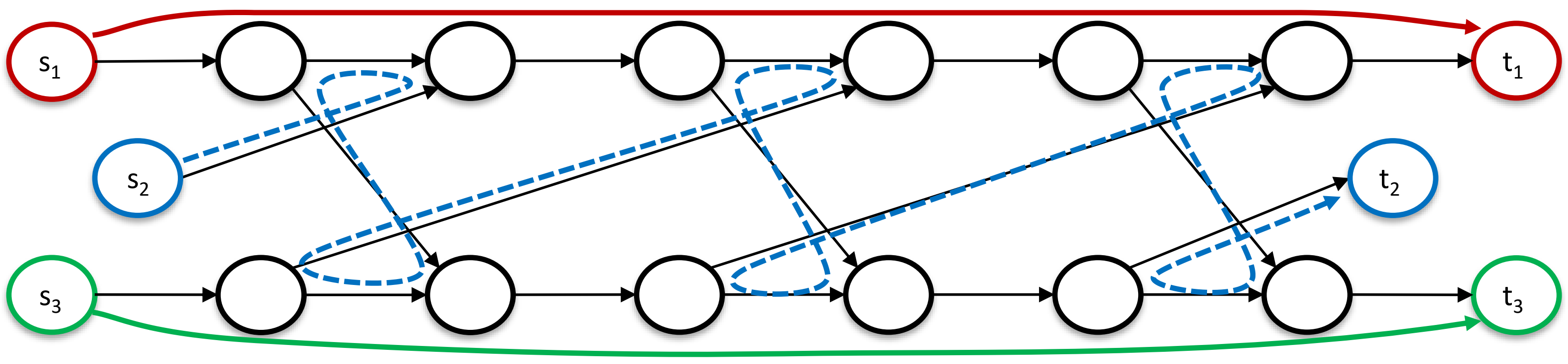


- Flows end up at the wrong destination!
- So let’s stick with augmenting flows that don’t mix destinations



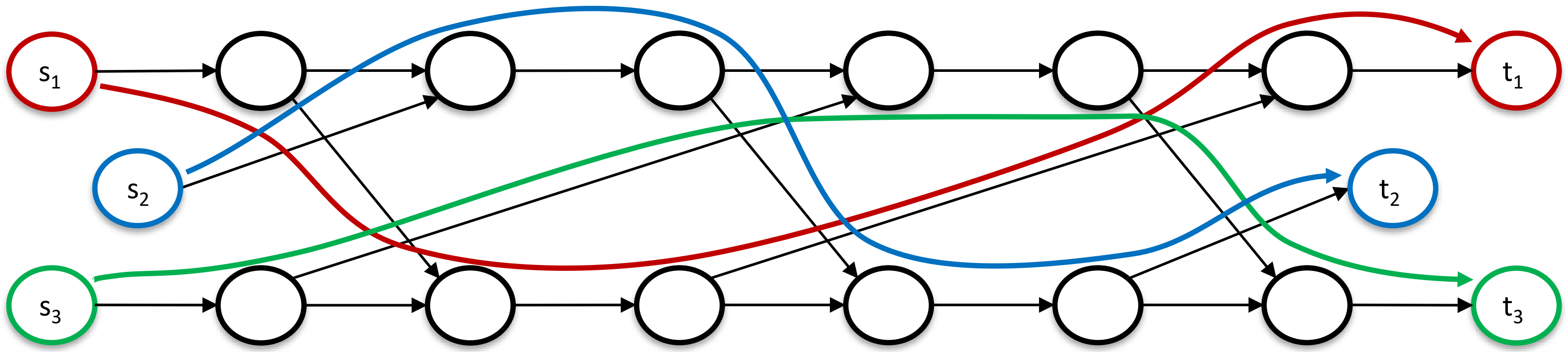
size of each flow: 1

capacity of each links: 1



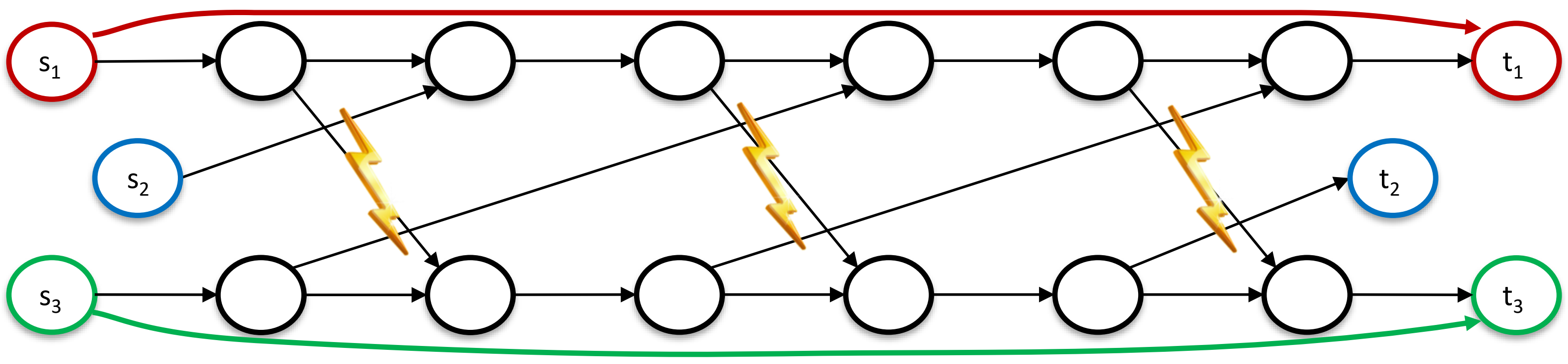
size of each flow: 1

capacity of each links: 1



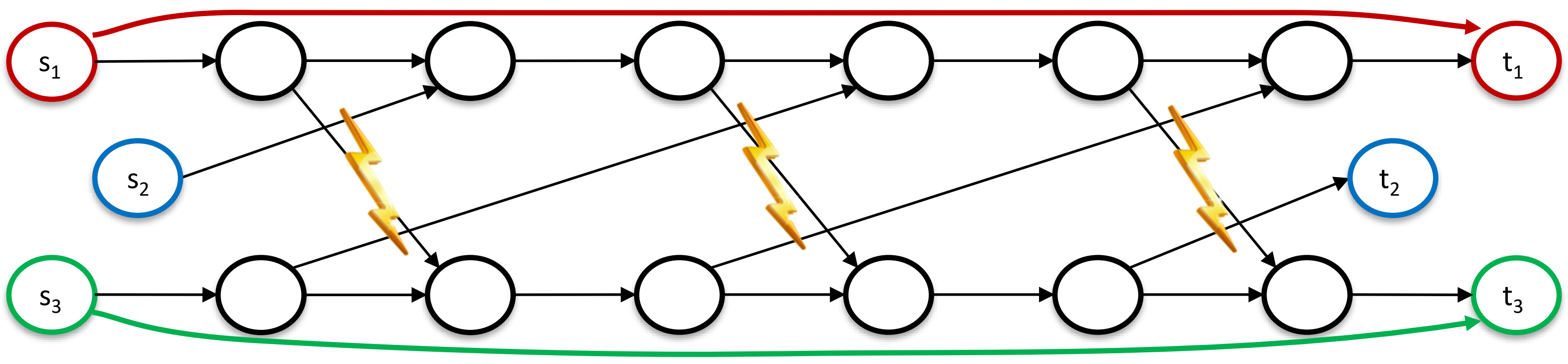
size of each flow: 1

capacity of each links: 1



size of each flow: 1

capacity of each links: 1



"it is unlikely that similar techniques can be developed for constructing multicommodity flows"

[Hu, 1963]

size of each flow: 1

capacity of each links: 1

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Maybe surprisingly:
If the new flows fit in somehow,
we can migrate consistently!

Open Problems for scheduling flow migration

- What happens when we can pick the new paths?
  - Idea: Fit the flows in, does not matter where
    - Only studied so far for a single destination and multiple sources [Brand, Foerster, Wattenhofer, PMC 2017]

Maybe further development
needs better understanding of
augmenting flows?

- Unsplittable flow migration:
  - In general: NP-, PSPACE-, or EXPTIME-complete?
    - (recall: flows might need to switch back and forth repeatedly)
  - ”Interesting“ polynomial cases?

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More open questions and specifics:
Survey of Consistent Software-Defined Network Updates
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IEEE Communications Surveys & Tutorials, 21(2), 2019

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- What happens when considering **Link Latency**?

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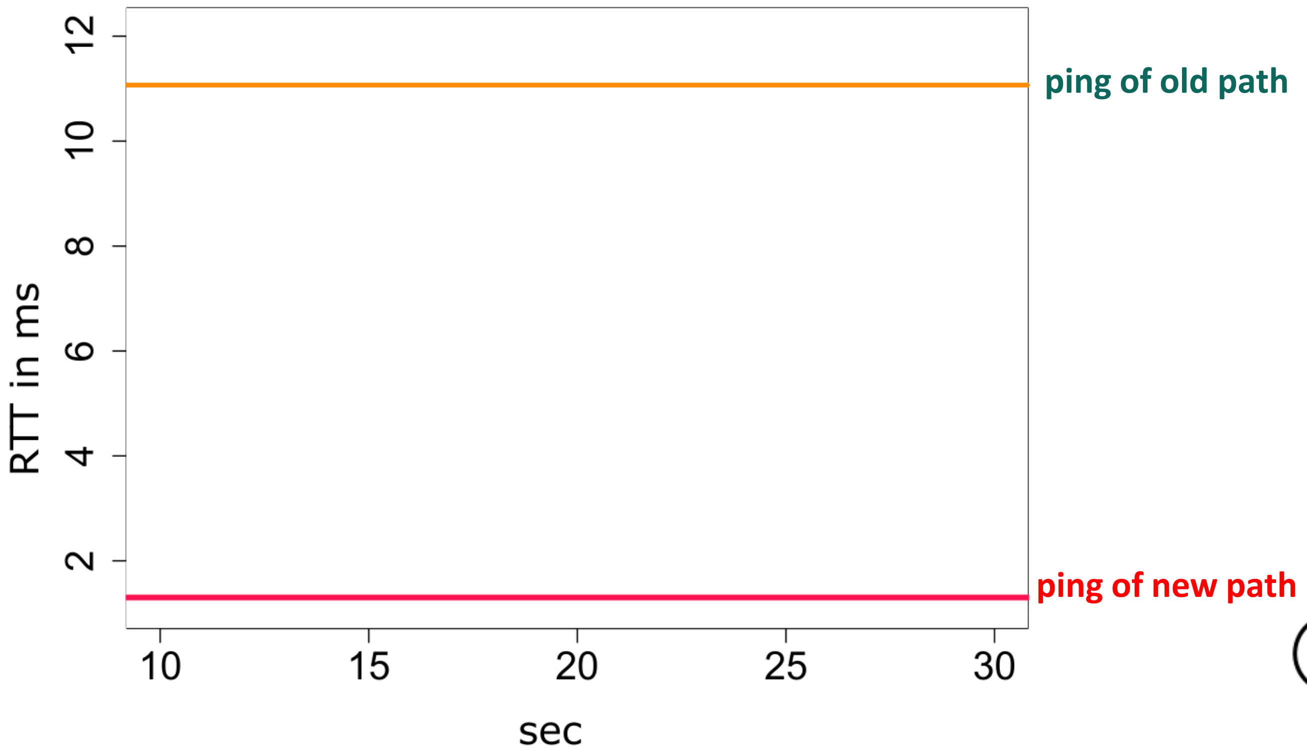
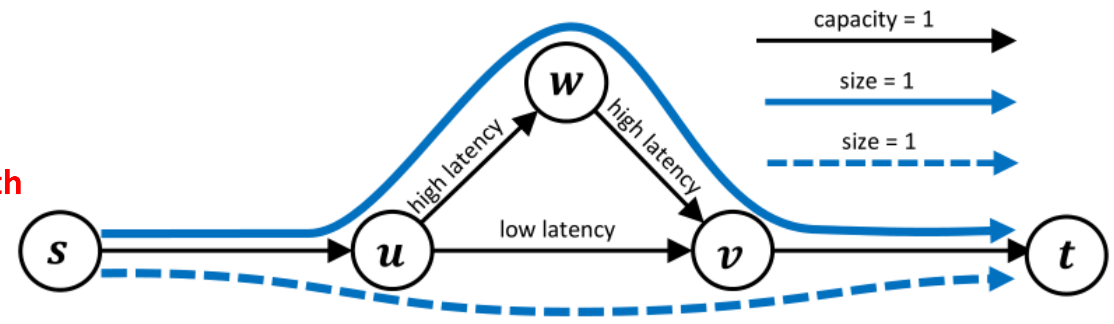
The Impact of Latency (in Testbed)





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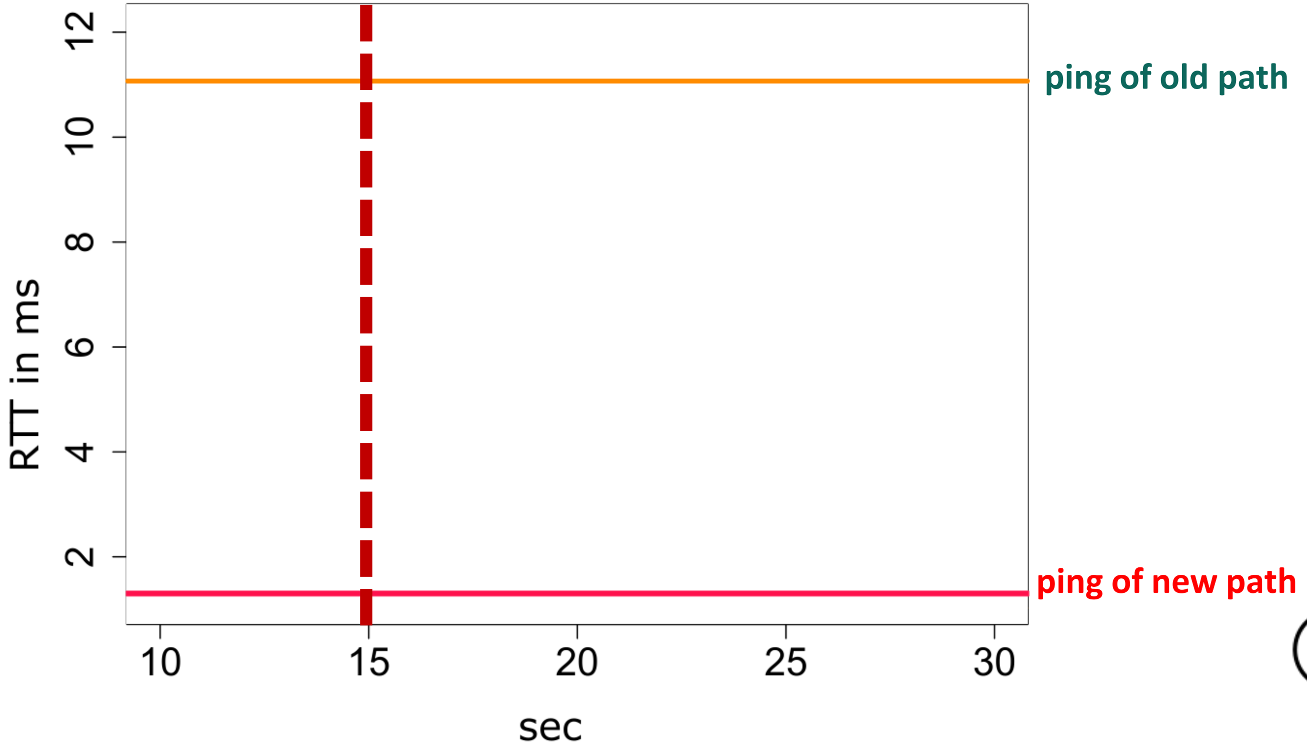
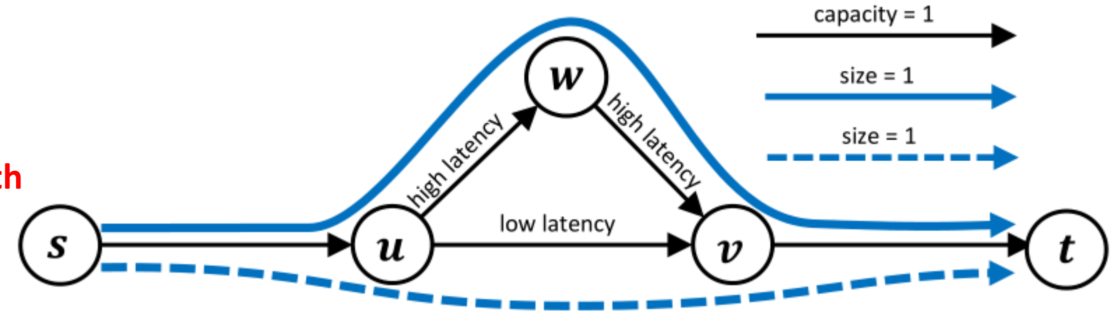
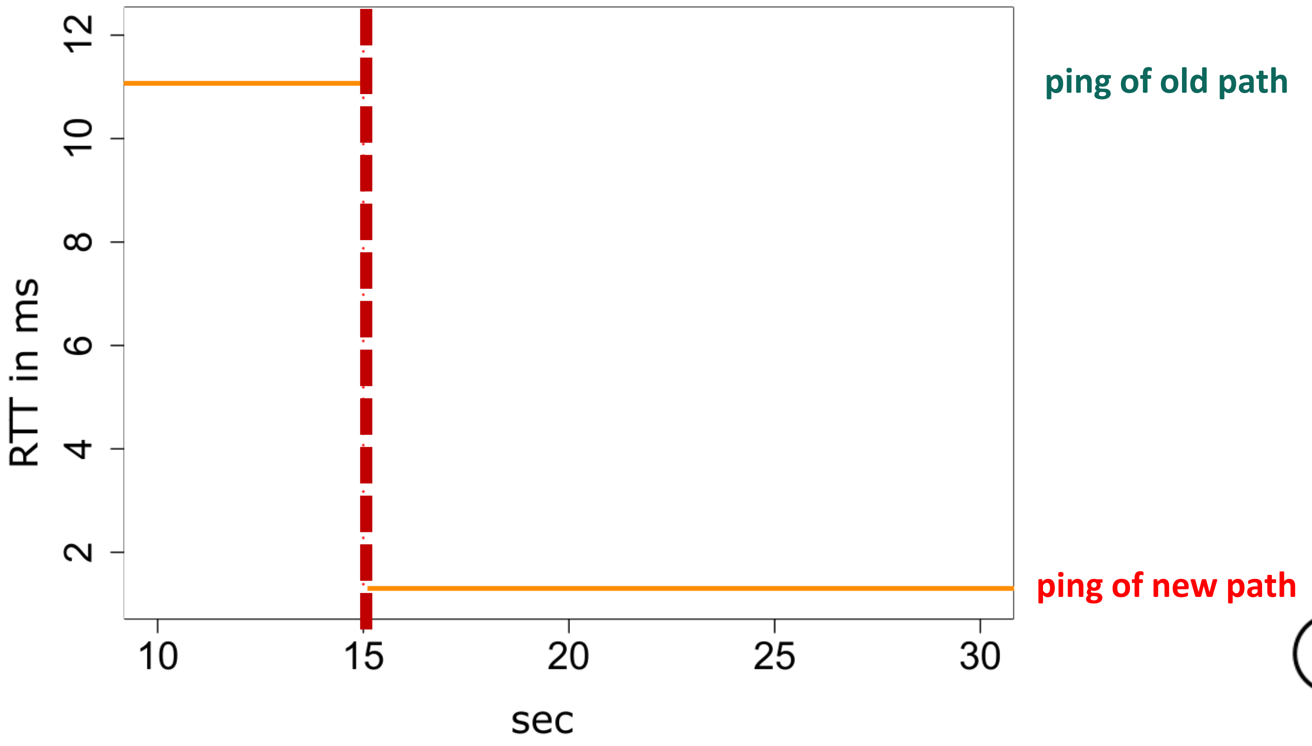
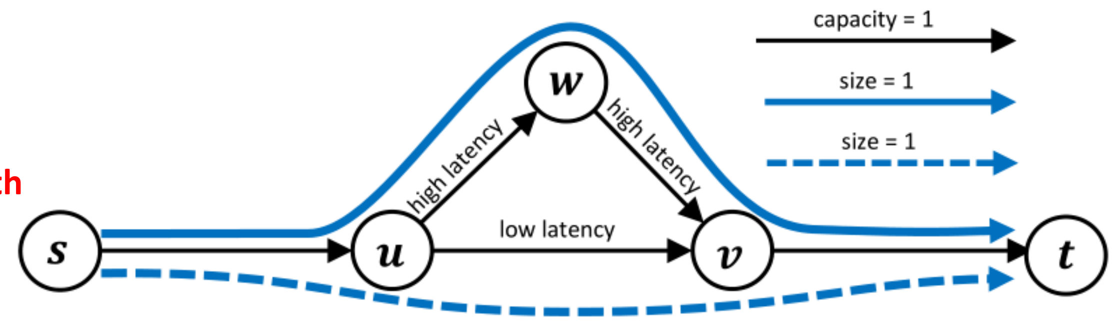




The Impact of Latency (in Testbed)





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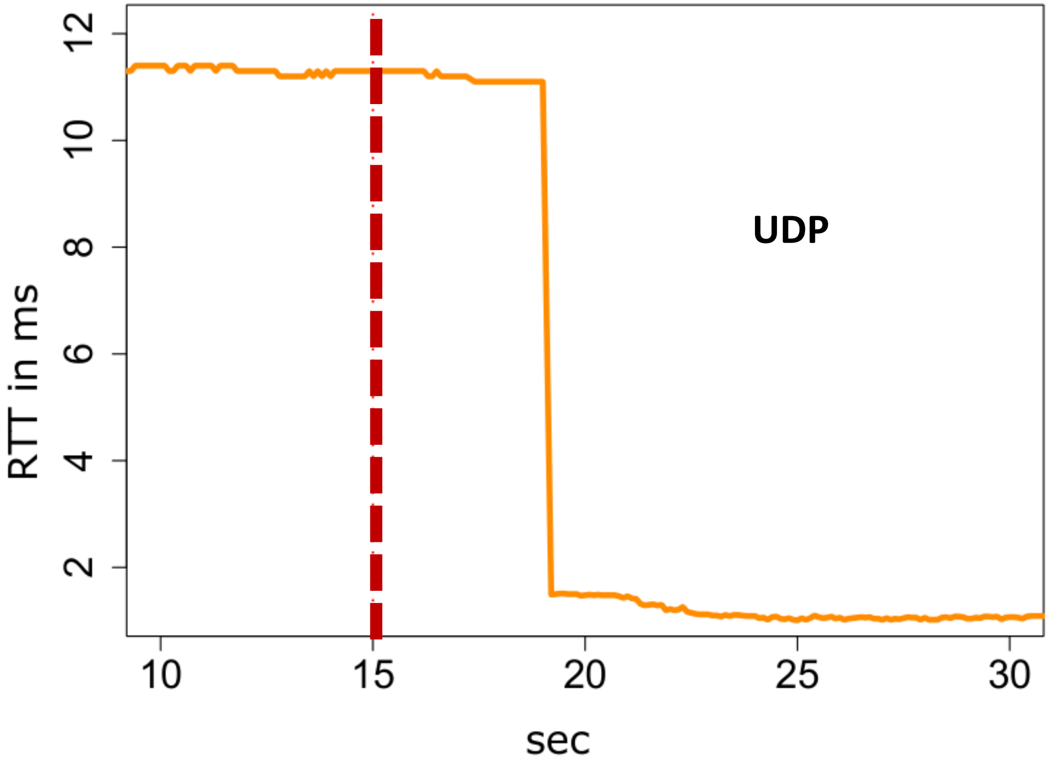
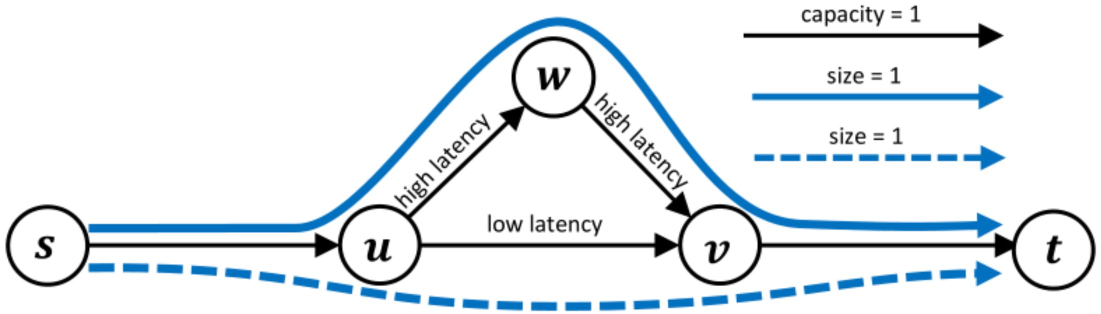
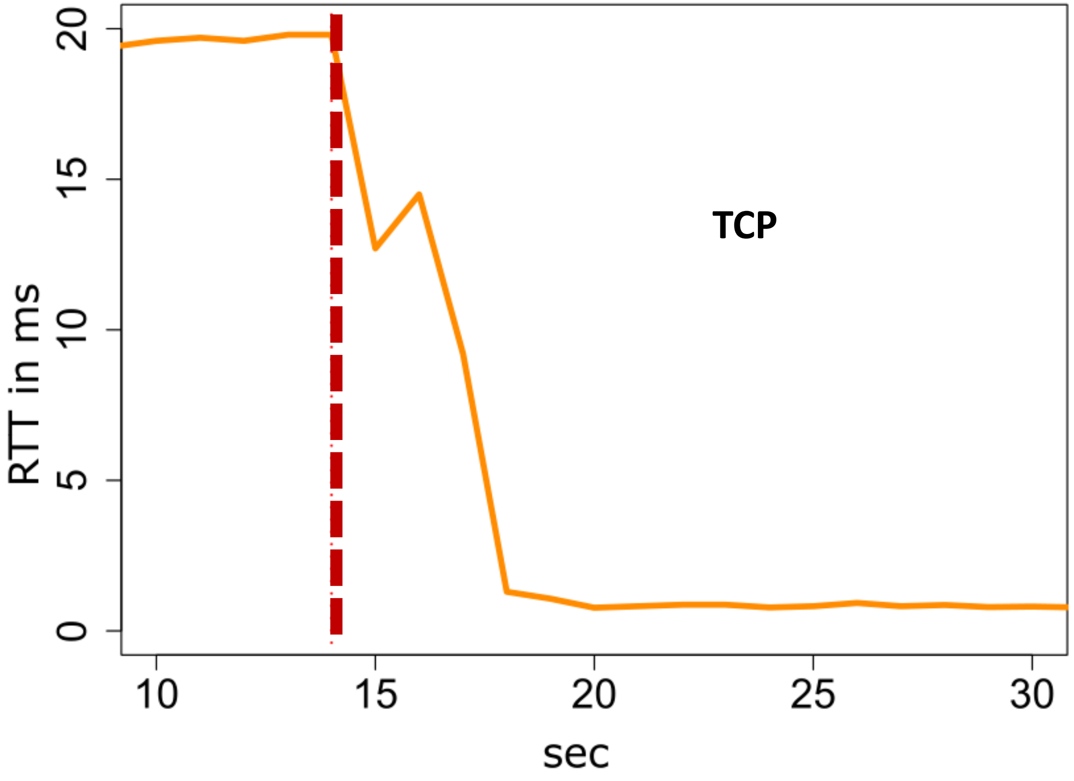
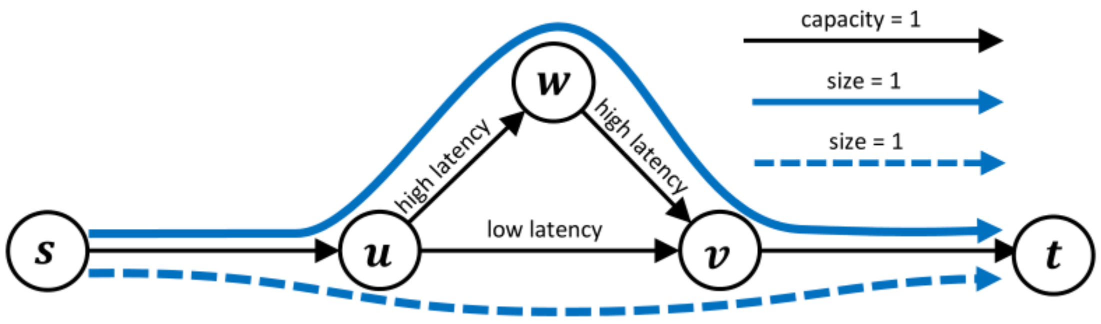




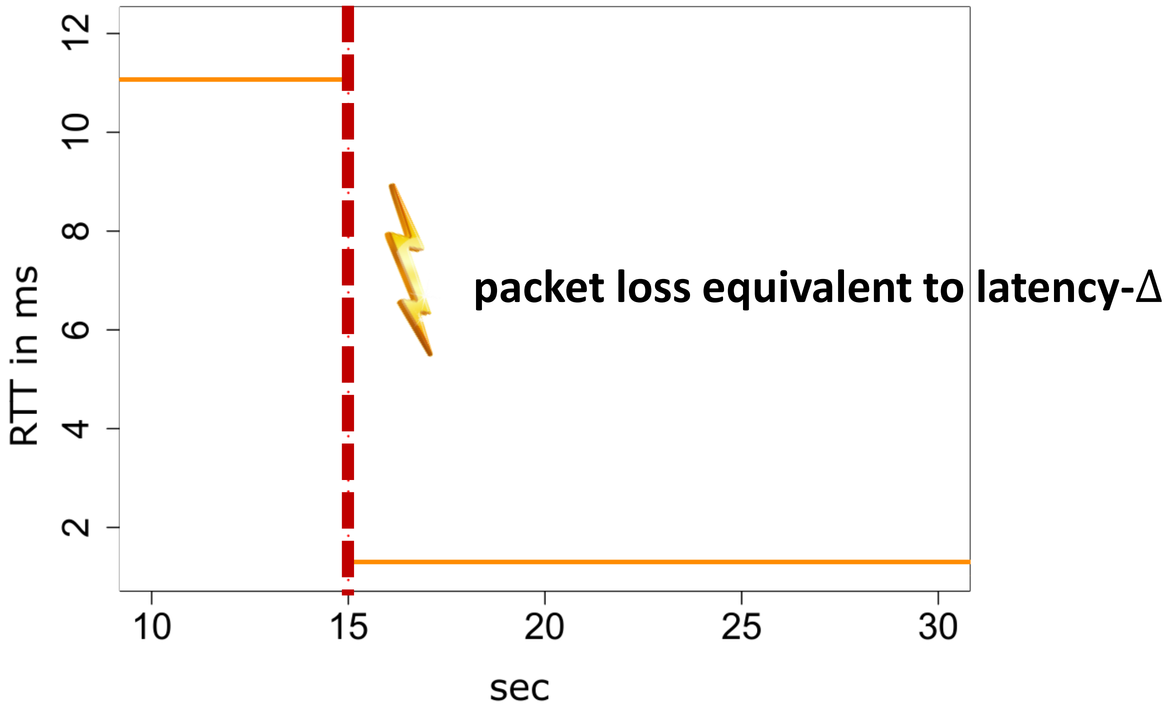
The Impact of Latency (in Testbed)

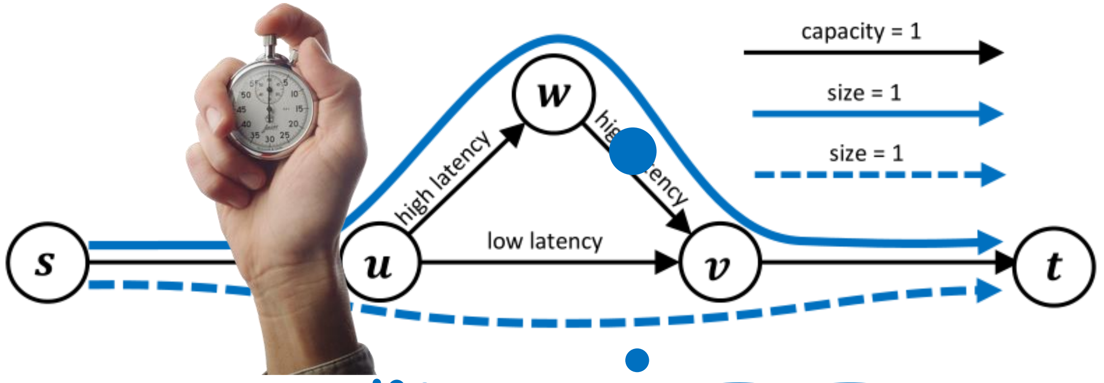




The Impact of Latency (in Testbed)

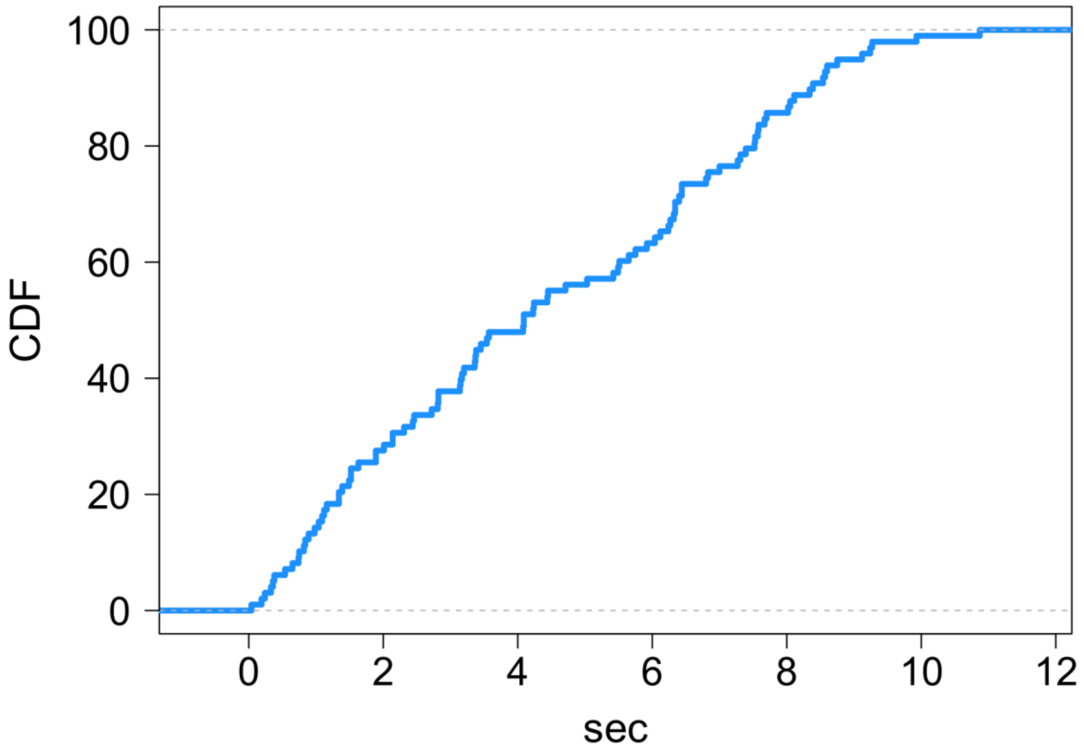
Because there is also work that focuses on better *time synchronization*, notably by *Mizrahi et al.*
https://sites.google.com/site/timedsdn/





Even holds without asynchrony

CDF of the Congestion Duration



Recap

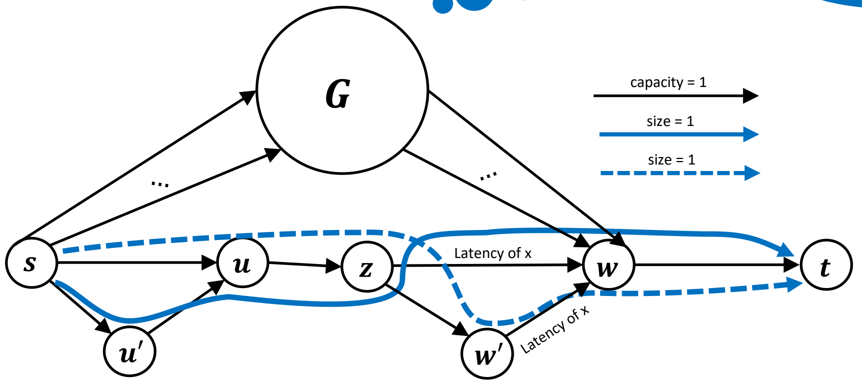
- Common (coarse-grained) model:
  - Sum for all flows: Max(**old flow rules** , **new flow rules**) does not violate capacity [SWAN, SIGCOMM’13]
  - Decidable in polynomial time [Brandt et al., INFOCOM’16]
    - For unsplittable flows: NP-hard already for 2 flows

- Does not capture congestion due to flows congesting themselves!
  - How hard?

How hard?

- Unit latencies and splittable flow of unit size:
  - Already NP-hard for a single flow!

Find a temporary path to offload parts of the flow



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Recap of the last few slides

- Common (coarse-grained) model:
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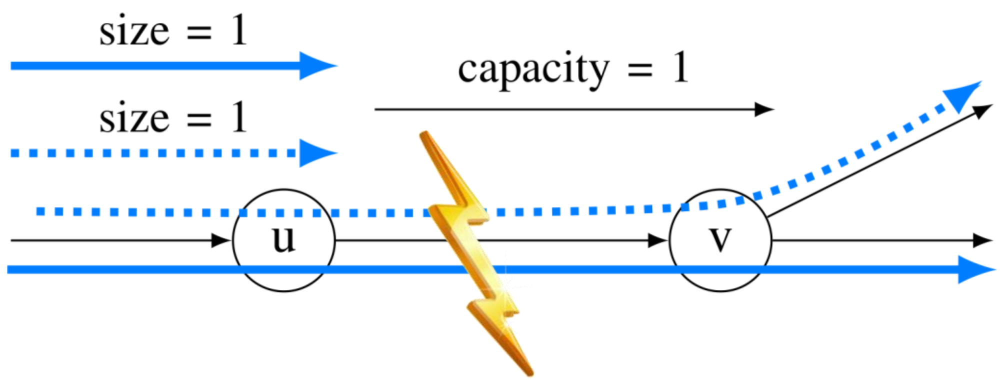
- Does not capture congestion due to flows congesting themselves!
  - How hard?
    - NP-hard for unit size/latency and splittable flows ☹
- How to fix?
  - Treat old and new flow rules as separate flows?

Old and New as Different Entities

- Idea: We can handle interplay between different flows
  - Handle old and new as different flows?
    - Prevents such congestion in popular approaches, eg SWAN, Dionysus, zUpdate etc.




Relax And Take it Easy!
MY BABY FLOAT
INTEX

Relax for Polynomial-Time Lossless Updates

- Idea: Relax the problem formulation
  - Be congestion-free for *any* set of latencies
    - (I.e., adversary may change latencies at any time)

- Now congestion-free intermediate steps become **reversible**

Achieved by spreading the network load

- Rough structure of the algorithm (for splittable flows):
  - Take old (new) state, reach intermediate state where critical set of edges have spare capacity
    - Not possible? No congestion-free migration possible.

Recap of the last few slides

How to extend beyond a single destination?

- Common (coarse-grained) model:
  - Sum for all flows: Max(**old flow rules** , **new flow rules**) does not violate capacity [SWAN, SIGCOMM'13]
  - Decidable in polynomial time [Brandt et al., INFOCOM'16]
    - For unsplittable flows: NP-hard already for 2 flows
- Does not capture congestion due to flows congesting themselves!
  - NP-hard for unit size/latency and splittable flows ☹

But requires non-fixed new flow paths

- By relaxing latency constraints:
  - Again polynomial-time decidable
- Interestingly: Augmenting flow idea still works **even without relaxing latency constraints!**

Open Problems and Outlook in General

- Various algorithmic and complexity questions for a centralized controller
  - See recent survey

- First connections to more classic distributed computing topics are made
  - *Proof-labeling*
    - Very basic right now, how to build more complex/efficient systems?

- Maybe the bigger question: How to properly distribute the centralized controller
  - Opportunity: The SUPPORTED model / *preprocessing*

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Some References

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Not all, if some are missing, should be listed on slides directly

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Central Control over Distributed Asynchronous Systems: A Tutorial on Software-Defined Networks and Consistent Network Updates

Klaus-T. Foerster