Disconnected cooperation in resilient networks and the algorithmic challenges of local fast re-routing

Stefan Schmid @ International Teletraffic Congress (ITC)

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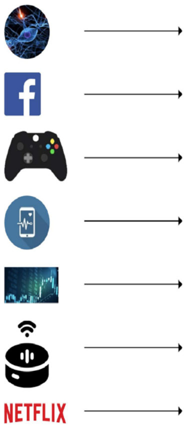
Kudos to Marco Chiesa for some slides!

Communication Networks

Critical infrastructure of digital society

- Popularity of **datacentric applications**: health, business, entertainment, social networking, AI/ML, etc.
- Evident during ongoing **pandemic**: online learning, online conferences, etc.
- Much traffic especially to, from, and inside **datacenters**



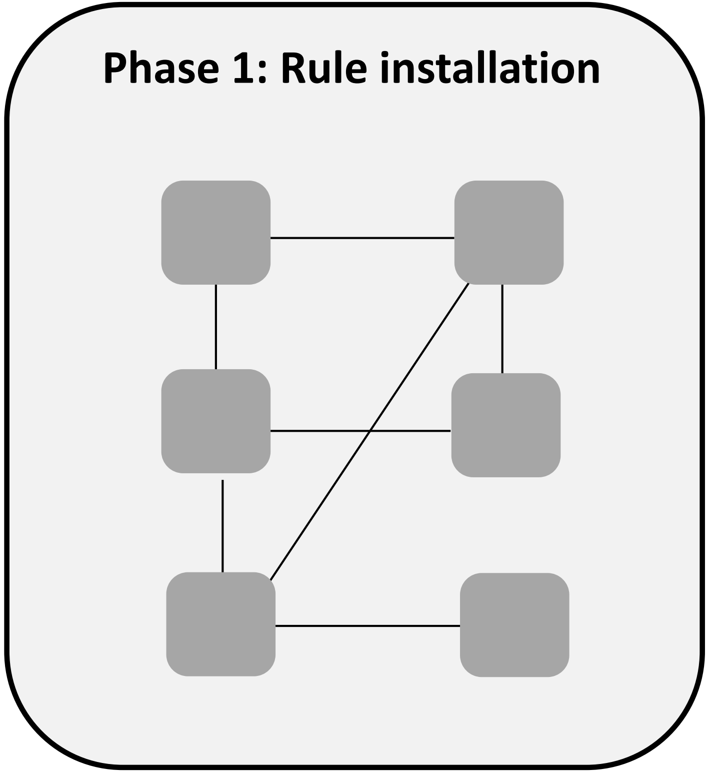
Facebook datacenter

Increasingly stringent dependability requirements!

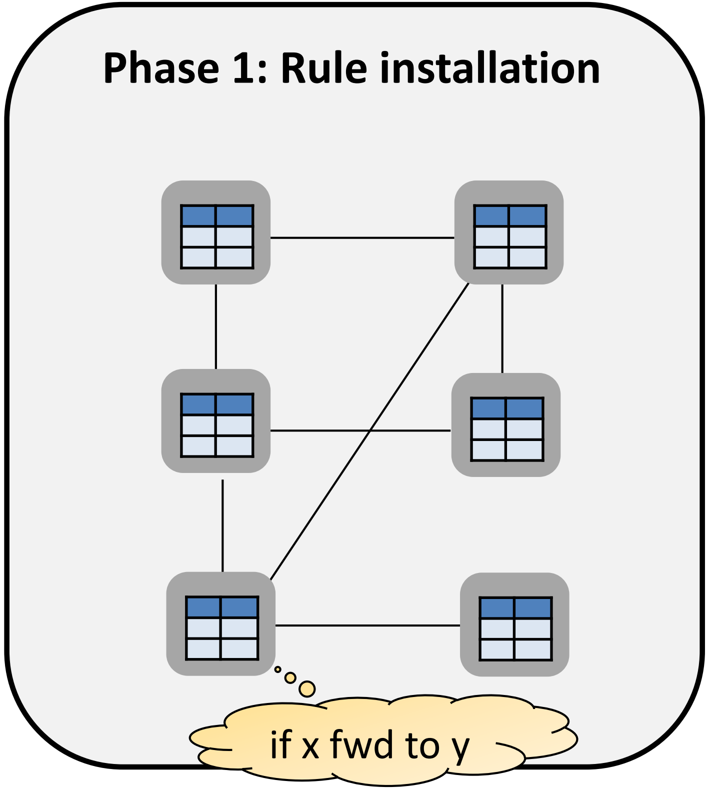
Restoration in control plane takes time -> packet drops!

Video shot taken from “Lemmings”
designed and developed by DMA Design

The FRR Problem



The FRR Problem



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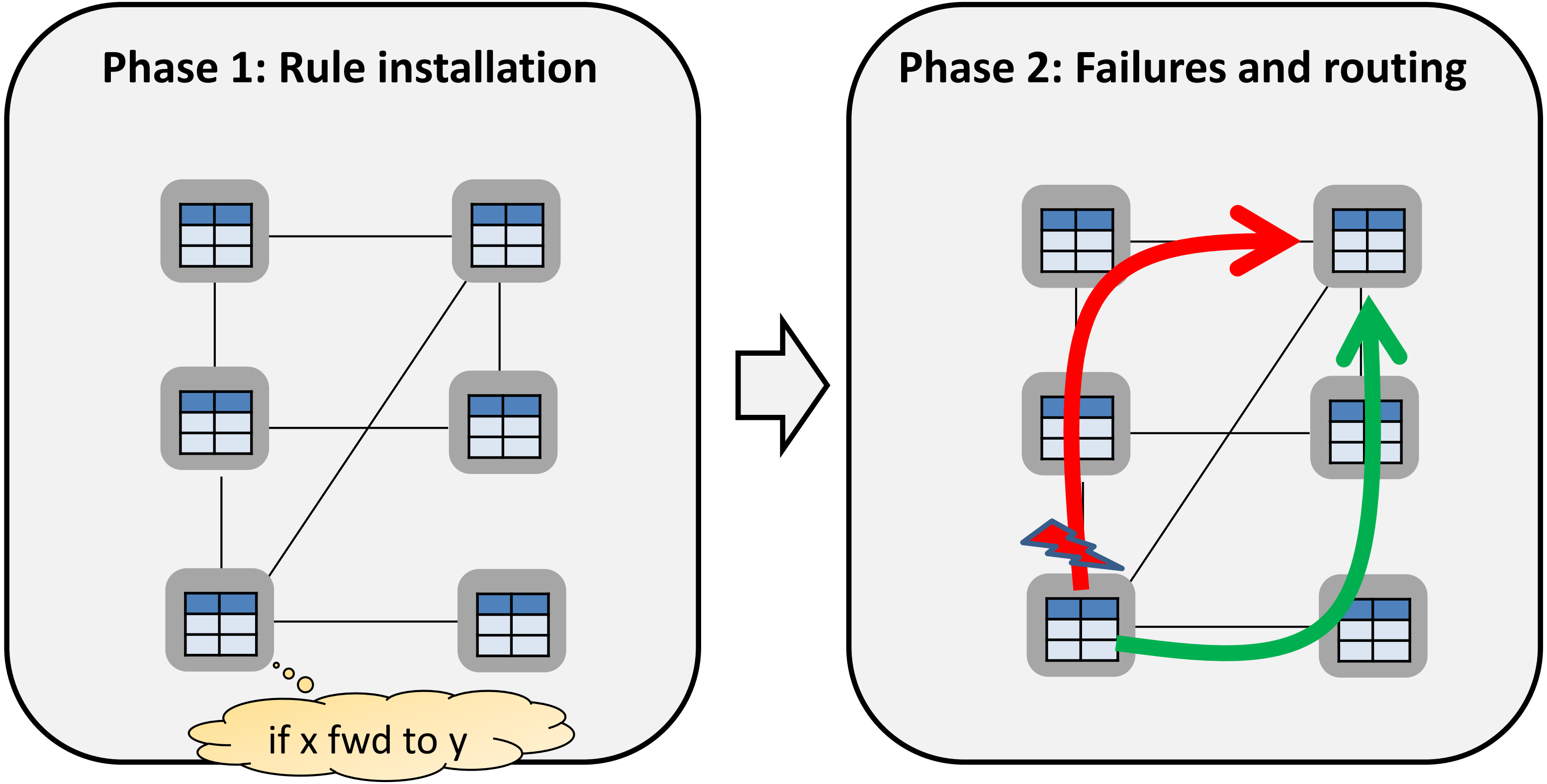

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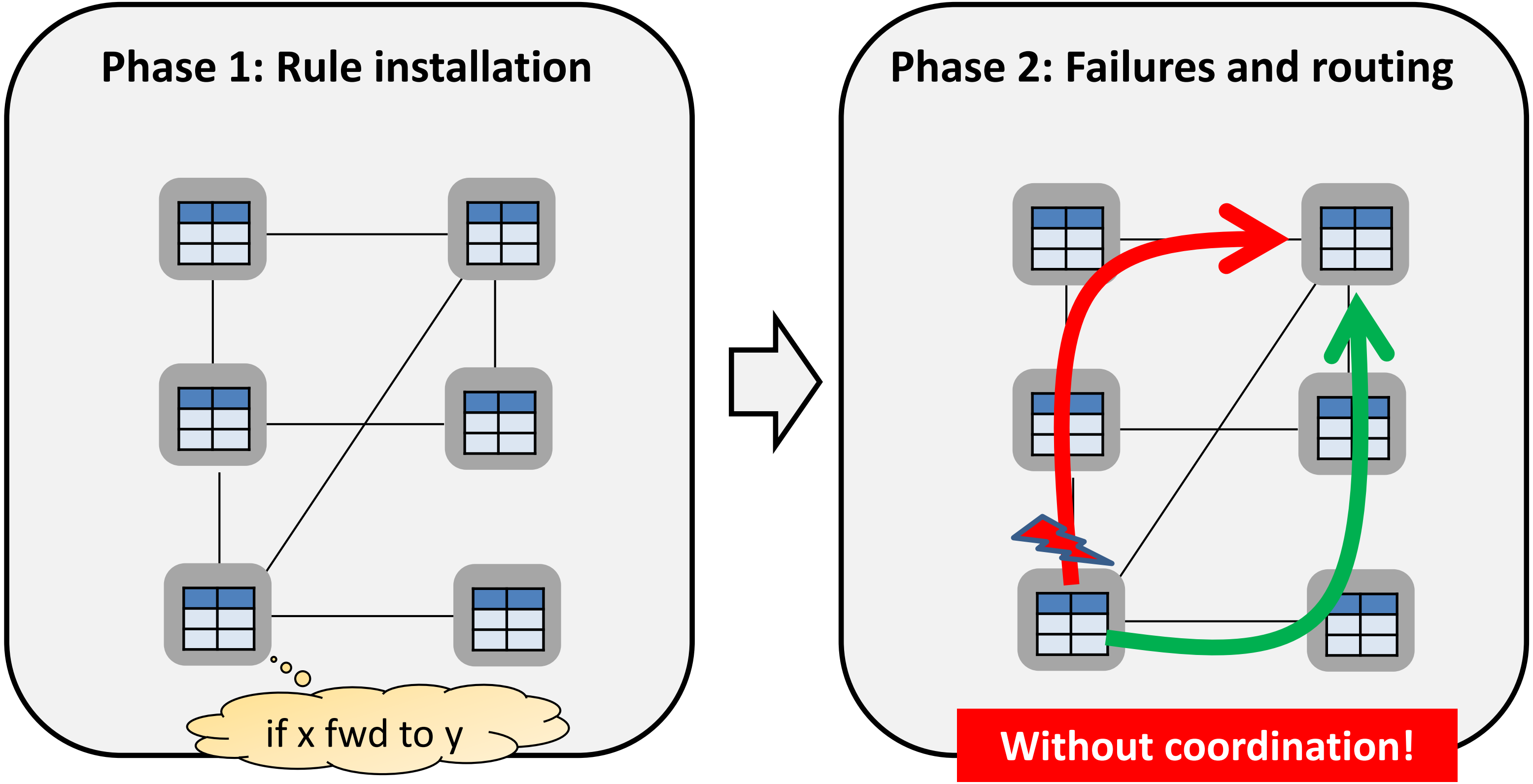
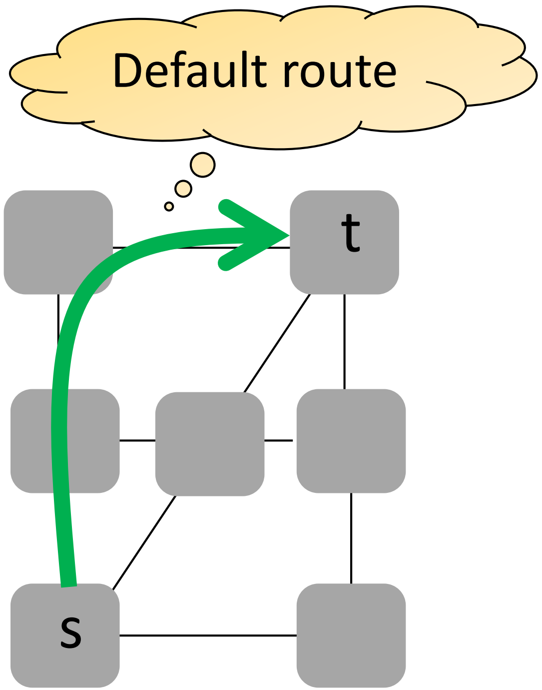


The FRR Problem

- **Pre-installed** local-fast failover rules
  - *Can depend on local failures and, e.g., destination, inport, source*
- **At runtime**, rules are just *"executed"*

Advantage: no need to wait for reconvergence.



Credits: Klaus-Tycho Förster

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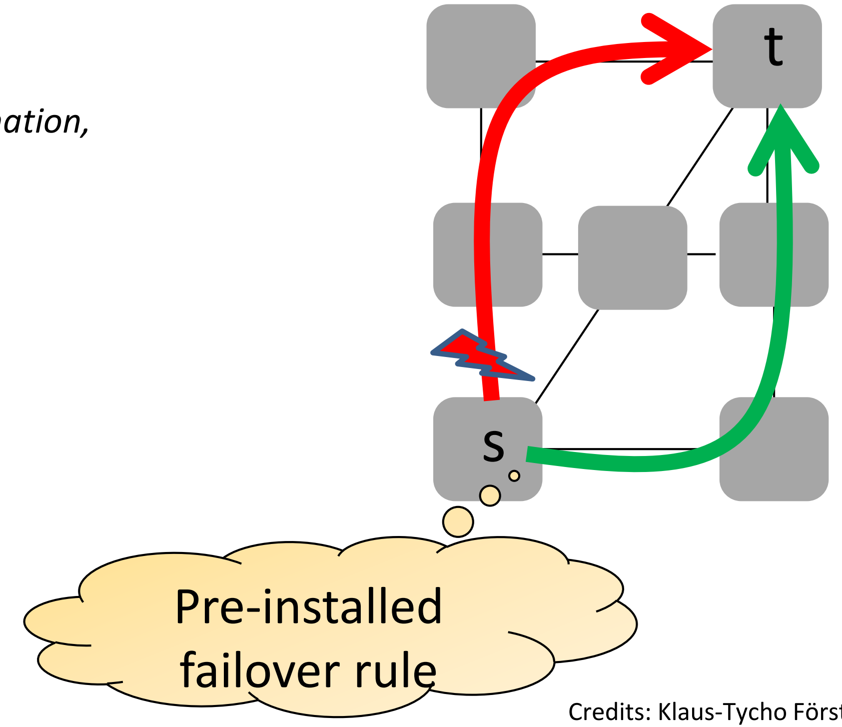
Good alternative under 1 failure!



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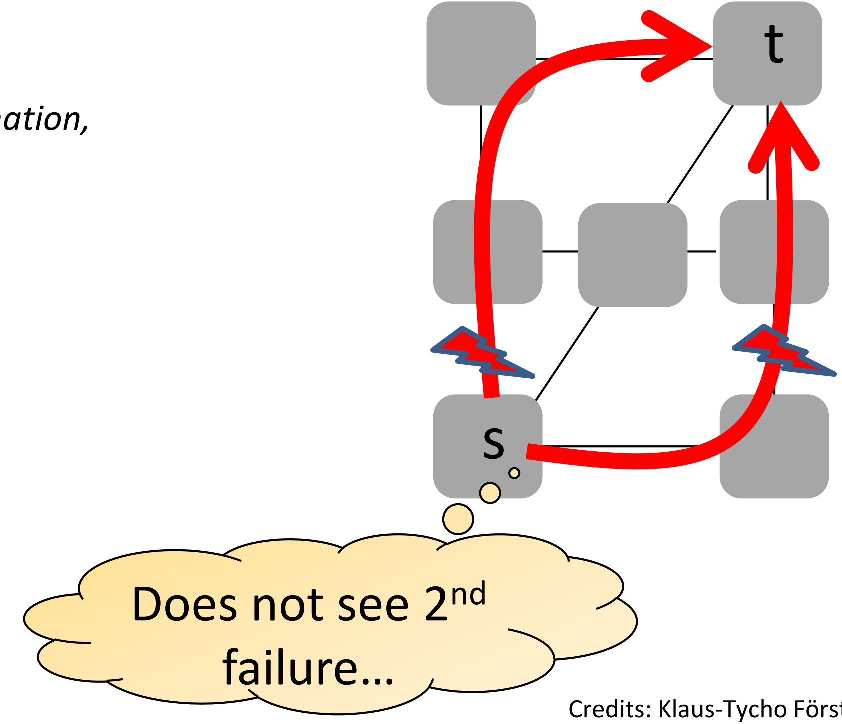

Credits: Klaus-Tycho Förster

The FRR Problem

Can get complex under multiple failures..

- **Pre-installed** local-fast failover rules
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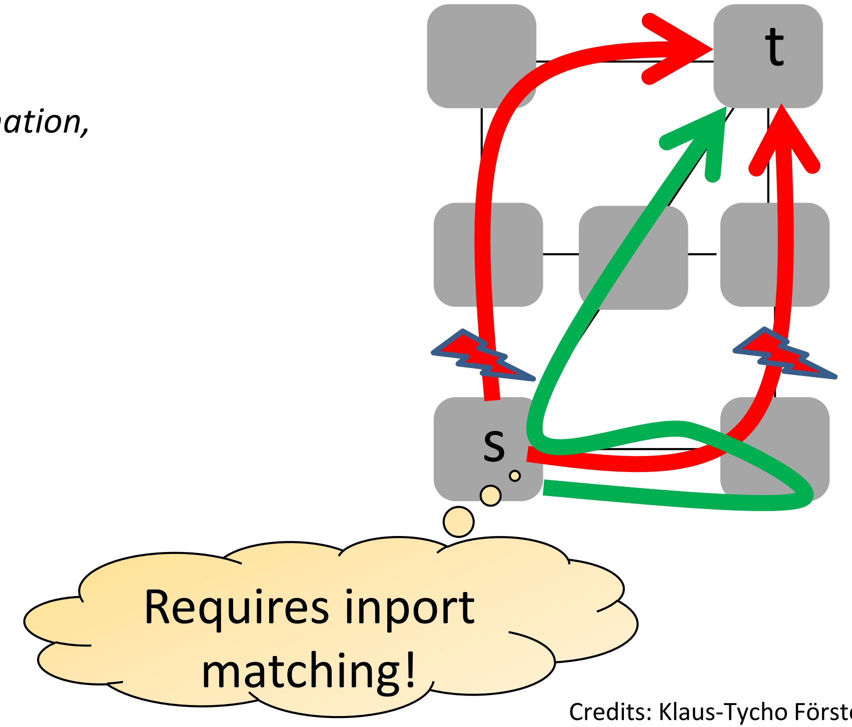

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The FRR Problem

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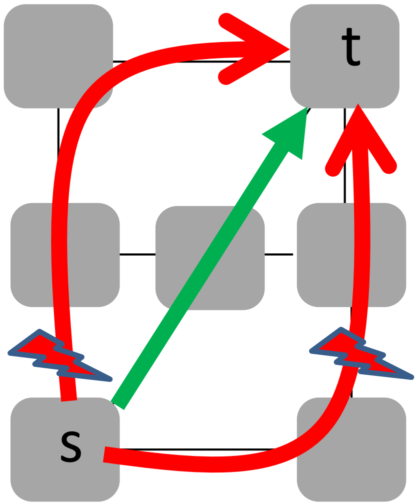
Advantage: no need to wait for reconvergence.

With global knowledge: simpler!

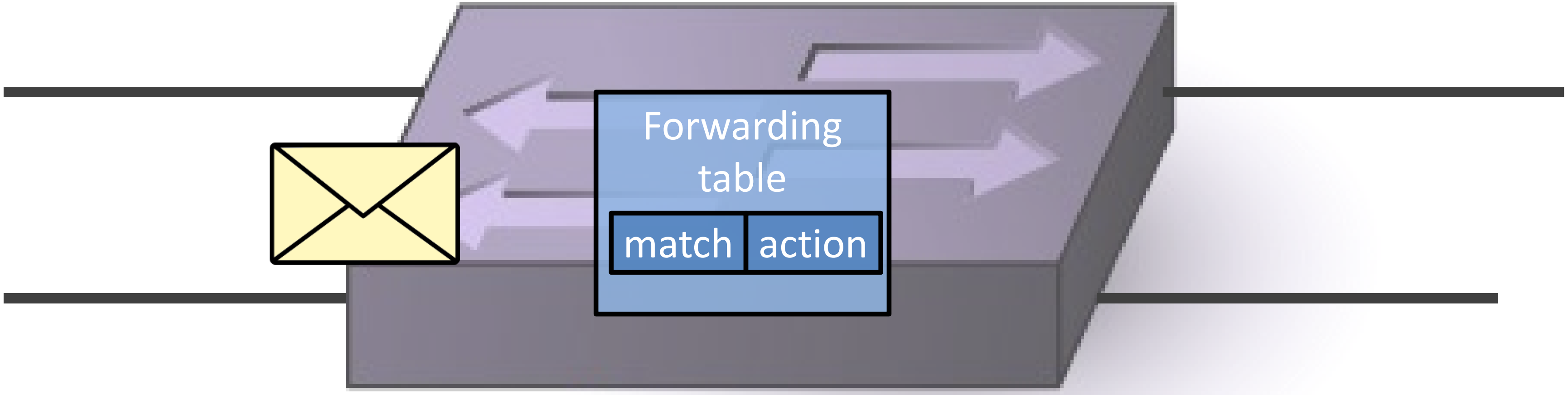


Credits: Klaus-Tycho Förster

What information is locally available in a switch for handling a packet?

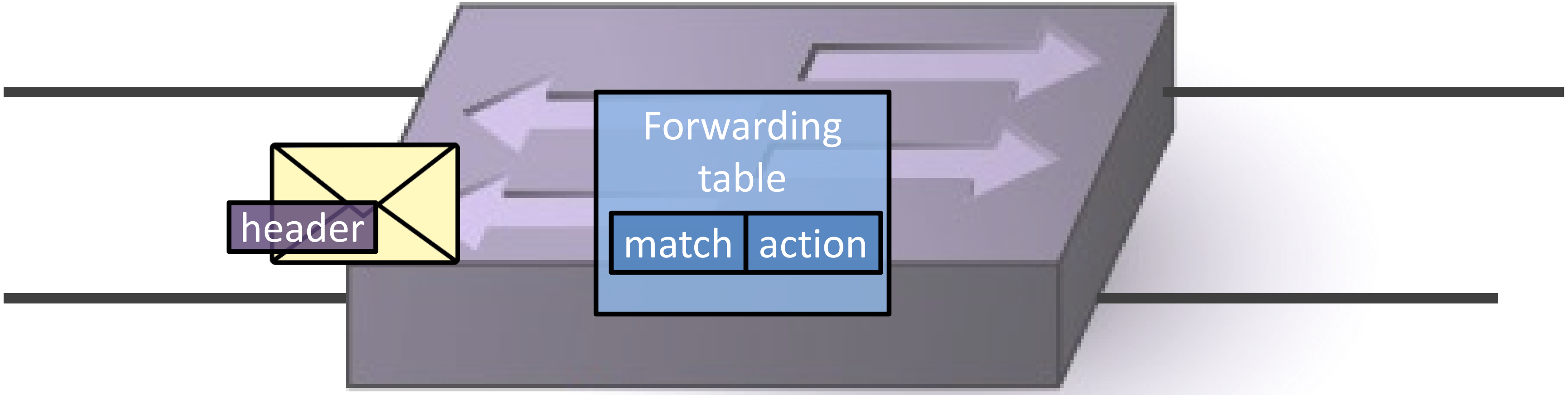
Credits: Marco Chiesa

Locally Available Information: The Forwarding Table: Match -> Action



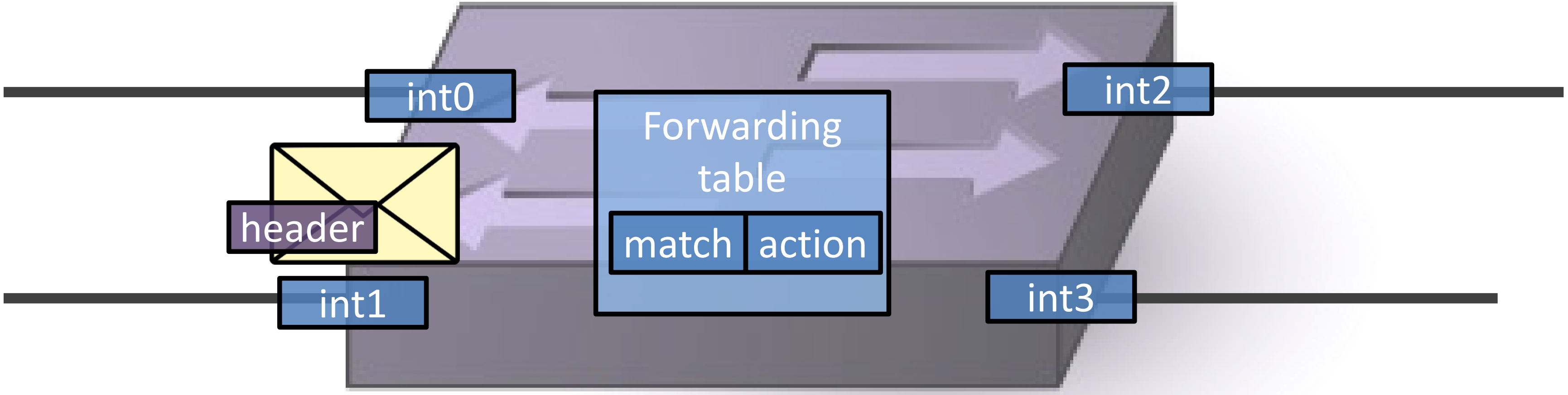
Credits: Marco Chiesa

Locally Available Information: The Packet Header



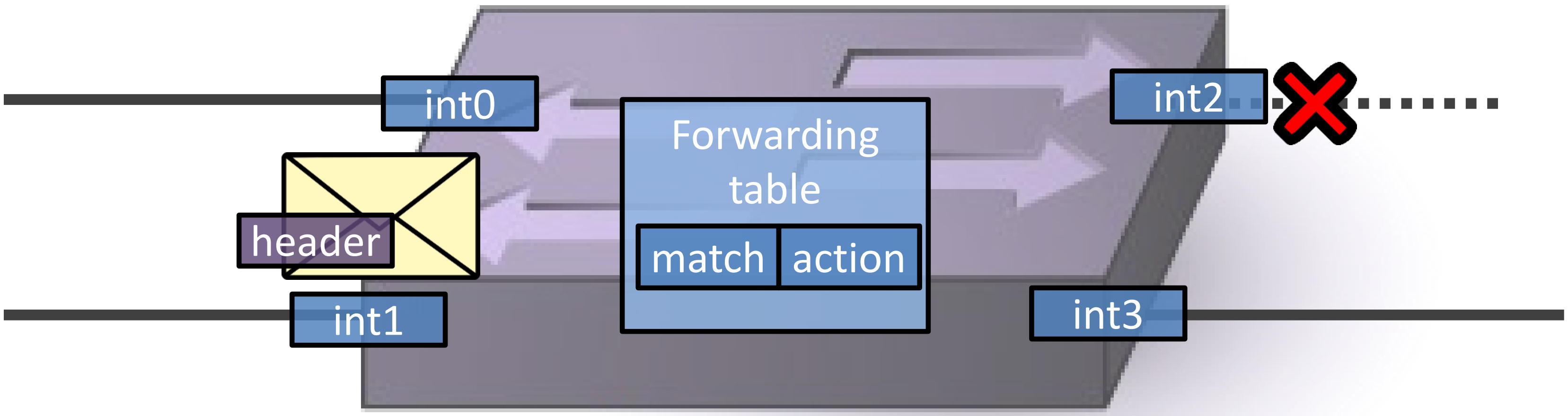
Credits: Marco Chiesa

Locally Available Information:
The Inport of the Received Packet



Credits: Marco Chiesa

Locally Available Information:
The Outgoing Port Depends on Failed Links



Credits: Marco Chiesa

Raises an Interesting Question

Can we pre-install local fast failover rules which ensure reachability under multiple failures? *In particular: How many failures* can be tolerated by static forwarding tables?

Resilience Criteria

Ideal resilience

Given a *k*-connected graphs, we can tolerate *any k-1 link failures.*

Perfect resilience

Any source *s* can always reach any destination *t* as long as the unterlying network is *physically connected*.

Can this be achieved? Assume undirected link failures.

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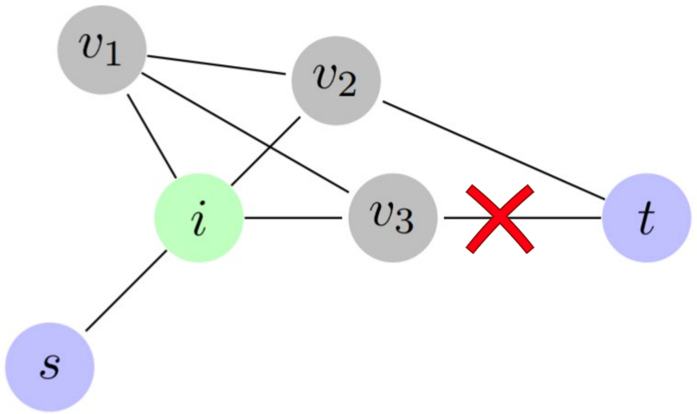
Resilience Criteria

Perfect resilience is impossible to achieve in general.

Relevant Neighbors

- Routing table of node i: matches in-ports of i to out-ports of i
  - ... depending on the incident failures
- But not all neighbors are **relevant**: only if potentially required to reach destination!
  - *Without local failures*: just v_2, v_3 for *i*, since v_1 does not give extra connectivity



Relevant Neighbors

- Routing table of node i: matches in-ports of i to out-ports of i
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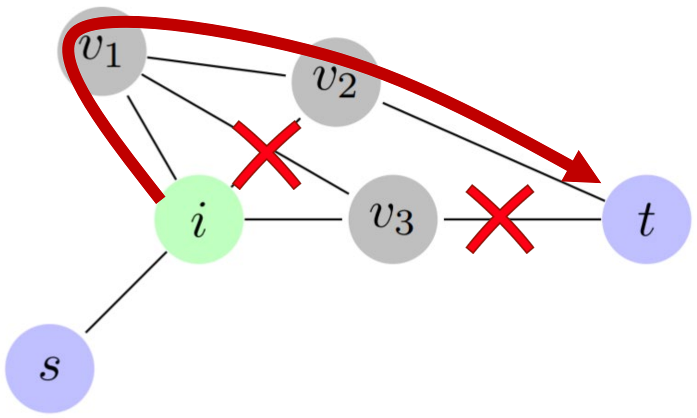
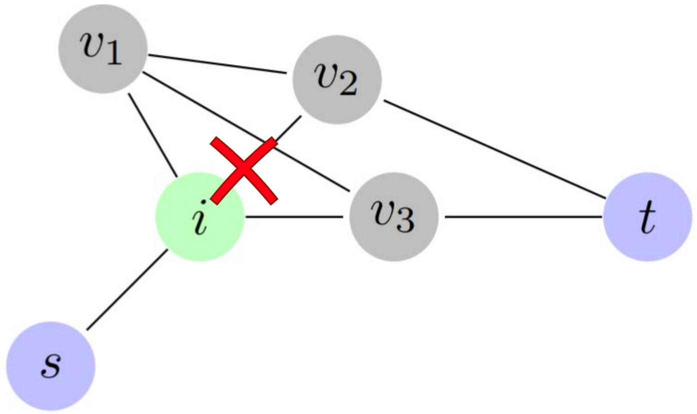
- But not all neighbors are **relevant**: only if potentially required to reach destination!
  - *Without local failures*: just v_2, v_3 for *i*, since v_1 does not give extra connectivity
  - *With additional failures* v_1 becomes relevant, since v_1 might be only choice to reach destination t
    - Note: v_1 is unaware of these non-incident failures!



High-level definition of ***relevant***: From the local view-point of the node i, a relevant neighbor might be only neighbor to reach destination (without taking a detour over a current neighbor).

How to Achieve Perfect Resilience?

- Necessary: need to *try all relevant* neighbors
  - Here, if local link to v_2 broken: v_1 and v_3
- That is, if packet
  - comes from v_3: eventually try v_1
  - comes from v_1: eventually try v_3



Impossibility: On Planar Graphs

Some observations:

- Additional failures only ***add relevant neighbors*** to nodes
- Any node of ***degree 2*** of G after failures must forward packets with incoming port p to port p'
- If all neighbors are relevant, the forwarding function of a node must be a ***cyclic permutation***

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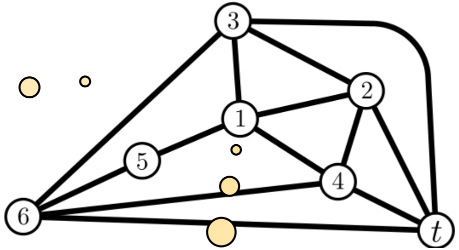
Idea of the counter example:

All neighbors of all nodes are relevant (even without failures).



So we must fix a permutation for node 1.

Considered node 1 will not see any local failures.

Impossibility: On Planar Graphs

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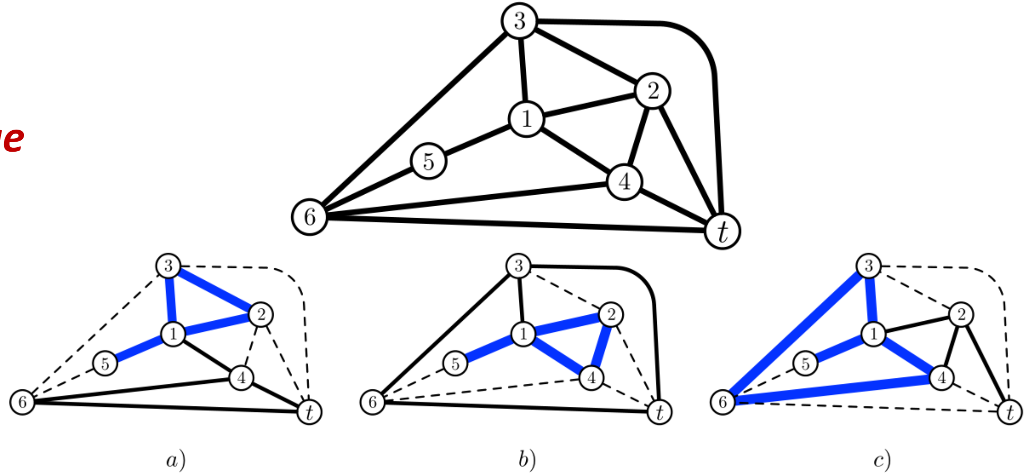
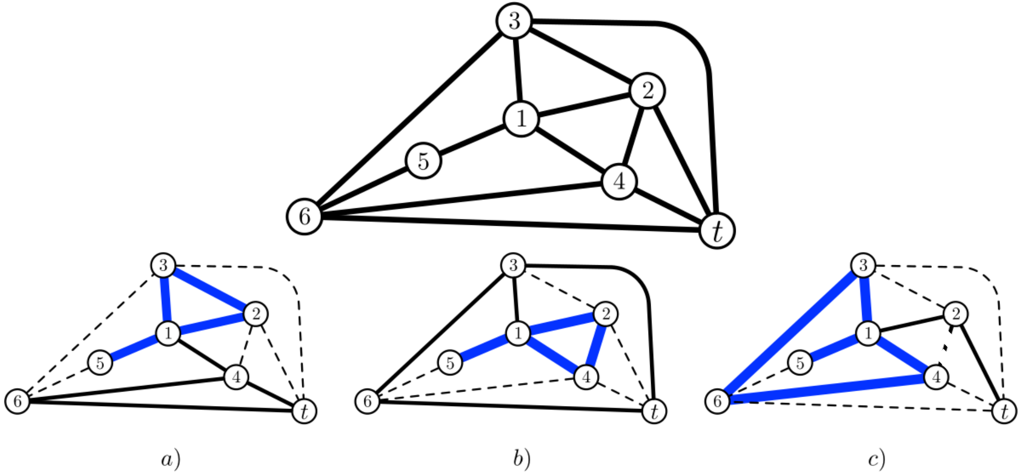
Proof idea, with three cases:

- If the ***dashed*** links fail (***non-local*** to node 1), in any forwarding pattern, packets will be stuck in one of the ***blue loops***…
- … even though there is at least one ***remaining path*** to the target



Go through all possible permutations @1 and give counter example.

Impossibility: On Planar Graphs

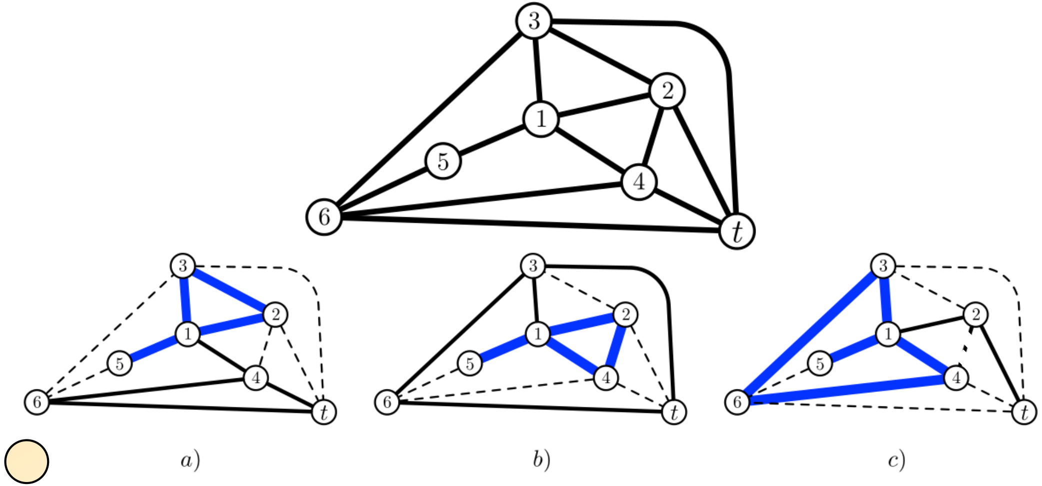


Arriving on inport 5, forwarded to 2.

For node 1:
5->2 implies
(5,2,3,4) (b)
(5,2,4,3) (a)

Possible cyclic permutations: when a packet arrives from 2, due to cyclic permutation, it can only be forwarded to either 3 or 4. Leads to *loops* in scenarios (b) (4 goes to 5, 2 can only go to 4) and (a) (3 goes to 5, 2 can only go to 3), respectively.

Impossibility: On Planar Graphs



Arriving on inport 5, forwarded to 3.

For node 1:
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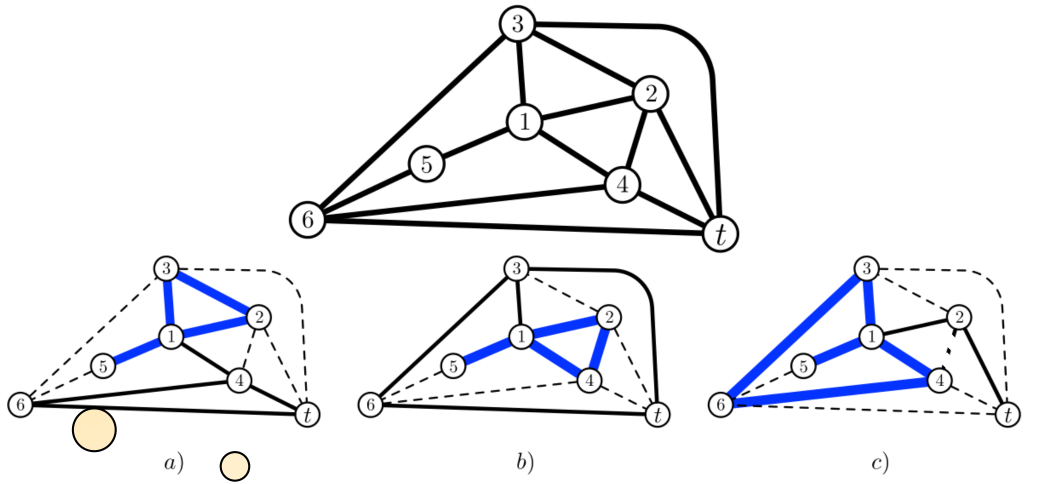
(5,2,4,3) (a)

For node 1:
5->3 implies
(5,3,4,2) (a)
(5,3,2,4) (c)

Possible cyclic permutations: when a packet then arrives on port 4, it can only be forwarded to either 2 or 5. Leads to *loops* in scenarios (a) (2 will go to 5, 5 can only go to 1 and 3 only to 2) and (c) (5 goes to 3, 4 goes to 5, rest degree-2), respectively.

Impossibility: On Planar Graphs



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For node 1:
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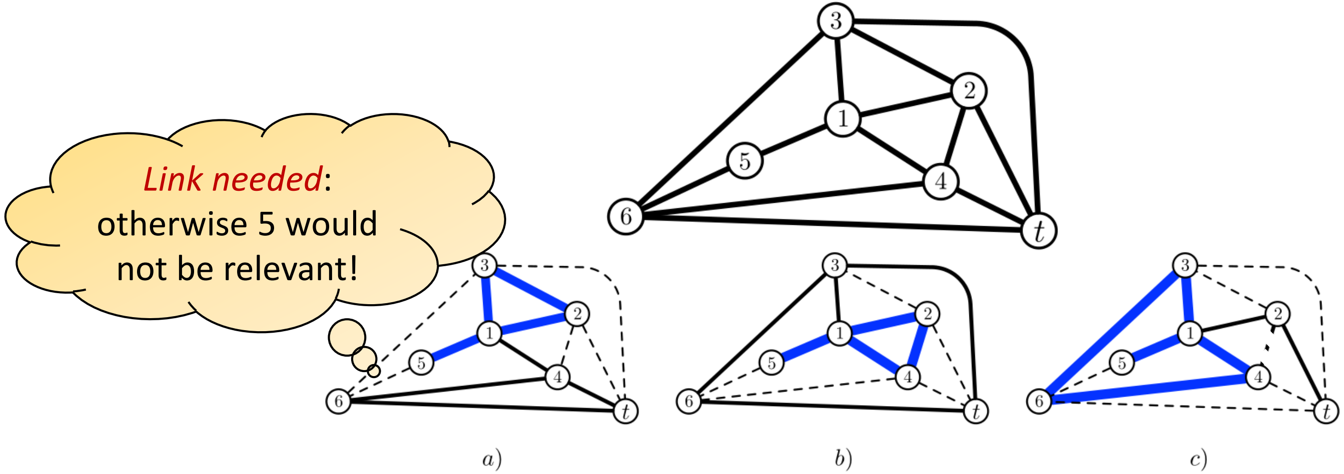
(5,3,2,4) (c)

For node 1:
5->4 implies
(5,4,2,3) (c)
(5,4,3,2) (b)

Possible cyclic permutations: packet arriving on port 3 can only be forwarded to either 5 or 2. Leads to *loops* in scenarios (c) and (b), respectively.

Impossibility: On Planar Graphs

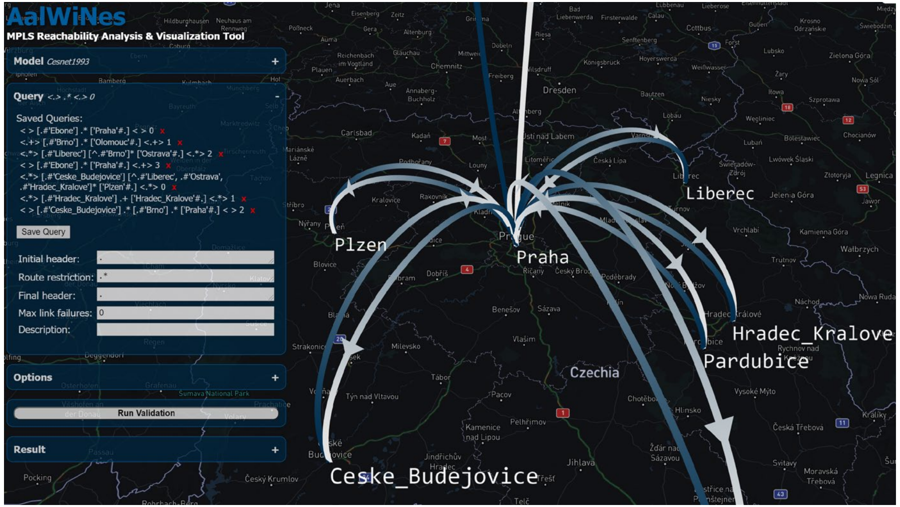


For node 1: 5->2 implies (5,2,3,4) (b) (5,2,4,3) (a)	For node 1: 5->3 implies (5,3,4,2) (a) (5,3,2,4) (c)	For node 1: 5->4 implies (5,4,2,3) (c) (5,4,3,2) (b)

Possible cyclic permutations: packet arriving on port 3 can only be forwarded to either 5 or 2. Leads to *loops* in scenarios (c) and (b), respectively.

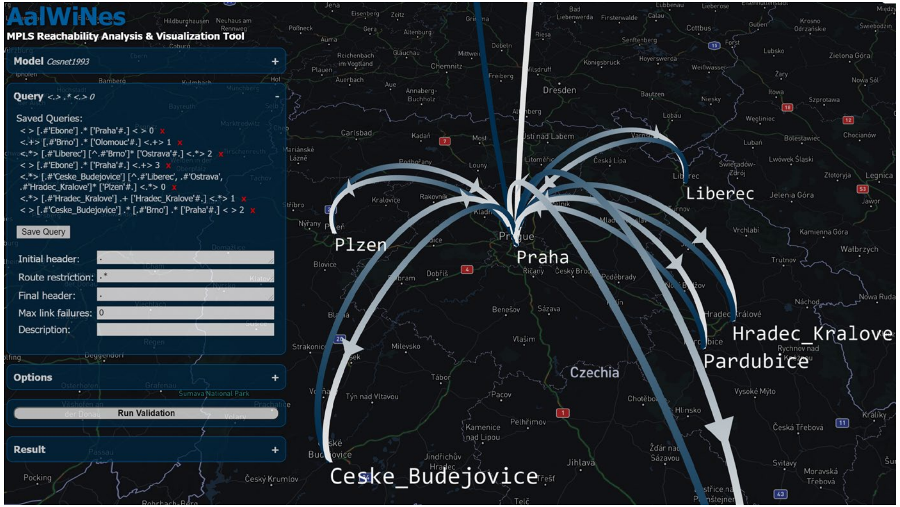
A Pity: Planar Graphs Are Important

- Internet Topology Zoo and Rocketfuel topologies
  - 88% of the graphs are ***planar***



A Pity: Planar Graphs Are Important

- Internet Topology Zoo and Rocketfuel topologies
  - 88% of the graphs are ***planar***
  - However:
    - Almost a third (32%) belong to the family of ***cactus*** graphs
    - Roughly half of the graphs (49%) are ***outerplanar***
    - … and they work ☺



Where Can Perfect Resilience Be Achieved?

For example on **outerplanar graphs**:

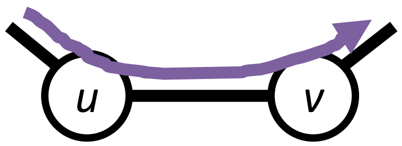
- Via *geometric routing*, well studied in sensor networks etc.
- Embed graph in the plane s.t. all nodes are on the outer face
  - Note: If a link l belongs to the outer face of a planar graph G, it also belongs to the outer face for all subgraphs of G
- Apply *right-hand rule* to forwarding (skipping failures)
  - Ensures packets use only the links of the outer face and do not change the direction despite failures
- Strategy traverses all nodes on the outer face

- Also works for any graph which is *outerplanar without the source* (e.g., K4)

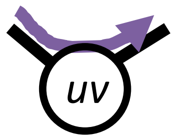
Some Observations

- K_5, K_3,3: *no perfect resilience*

- Perfect resiliency on graph G -> any *subgraph* G‘ of G also allows for perfect resiliency
  - Idea: Take routing on G, fail edges to create G‘, routing must still work



- Contraction works as well, by a simulation argument
  - A bit technical

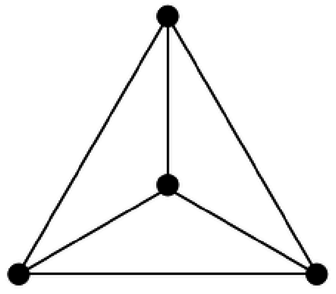


- Combined: Perfect resilience on graph G -> any minor G‘ of G as well
  - But since K_5, K_3,3 not: *non-planar graphs not perfectly resilient*

What we know about perfect resilience

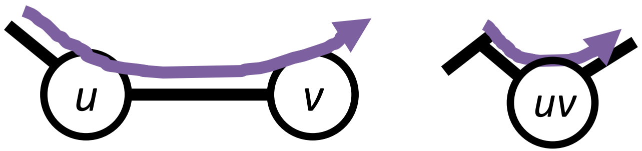
Possible:

- On all outerplanar graphs [right-hand rule]
- On every graph that is outerplanar without the destination (e.g. non-outerplanar planar K_4)



Impossible:

- On some planar graphs
- Every non-planar graph
- Perfect resilience must hold on minors



Foerster et al. **On the Feasibility of Perfect Resilience with Local Fast Failover.** SIAM Symposium on Algorithmic Principles of Computer Systems (APOCS), 2021.

Thank you!

A Recent Survey:

A Survey of Fast-Recovery Mechanisms in Packet-Switched Networks
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Questions?