The algorithmic challenges of local fast re-routing

Stefan Schmid (TU Berlin)

Kudos: Marco Chiesa

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**

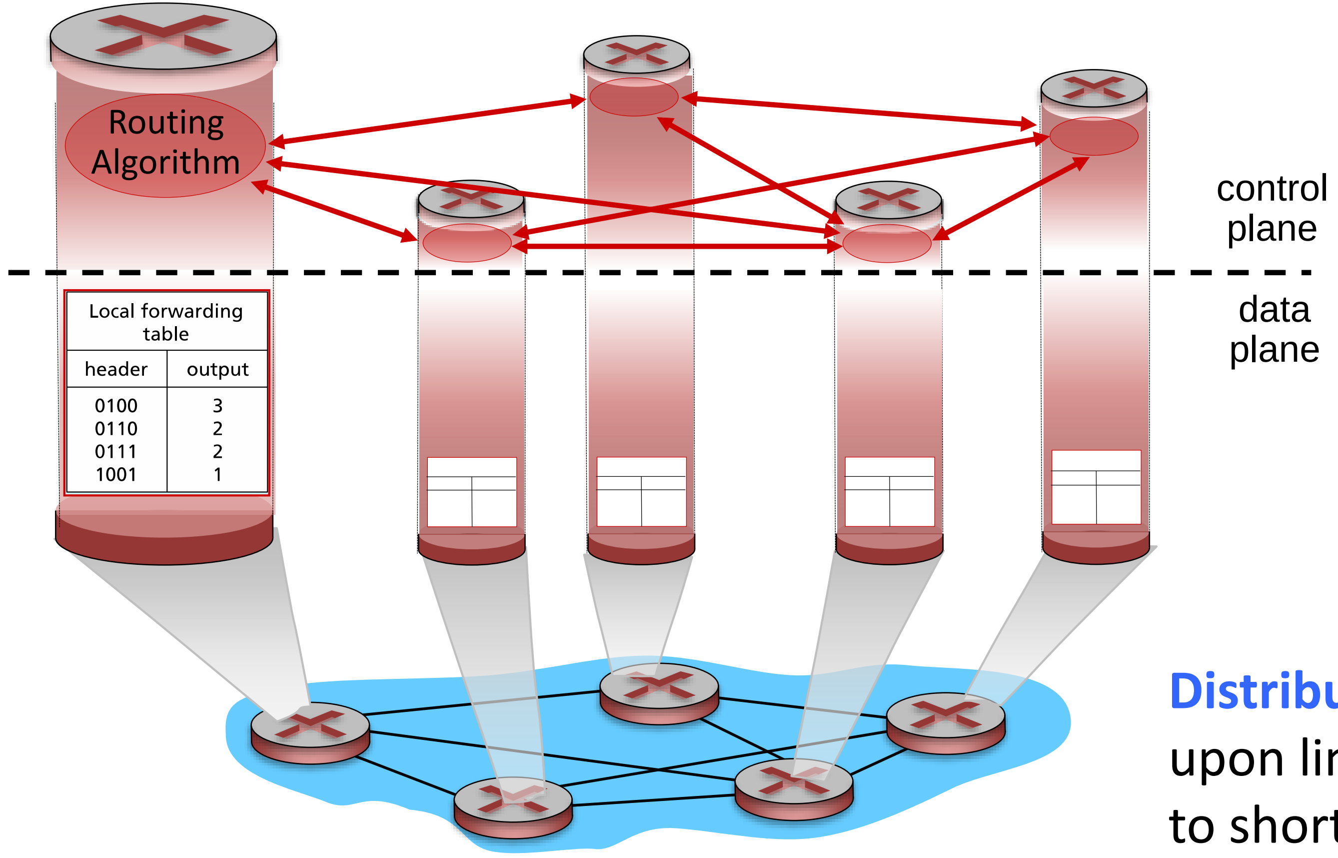
Facebook datacenter

Increasingly stringent dependability requirements!

Roadmap

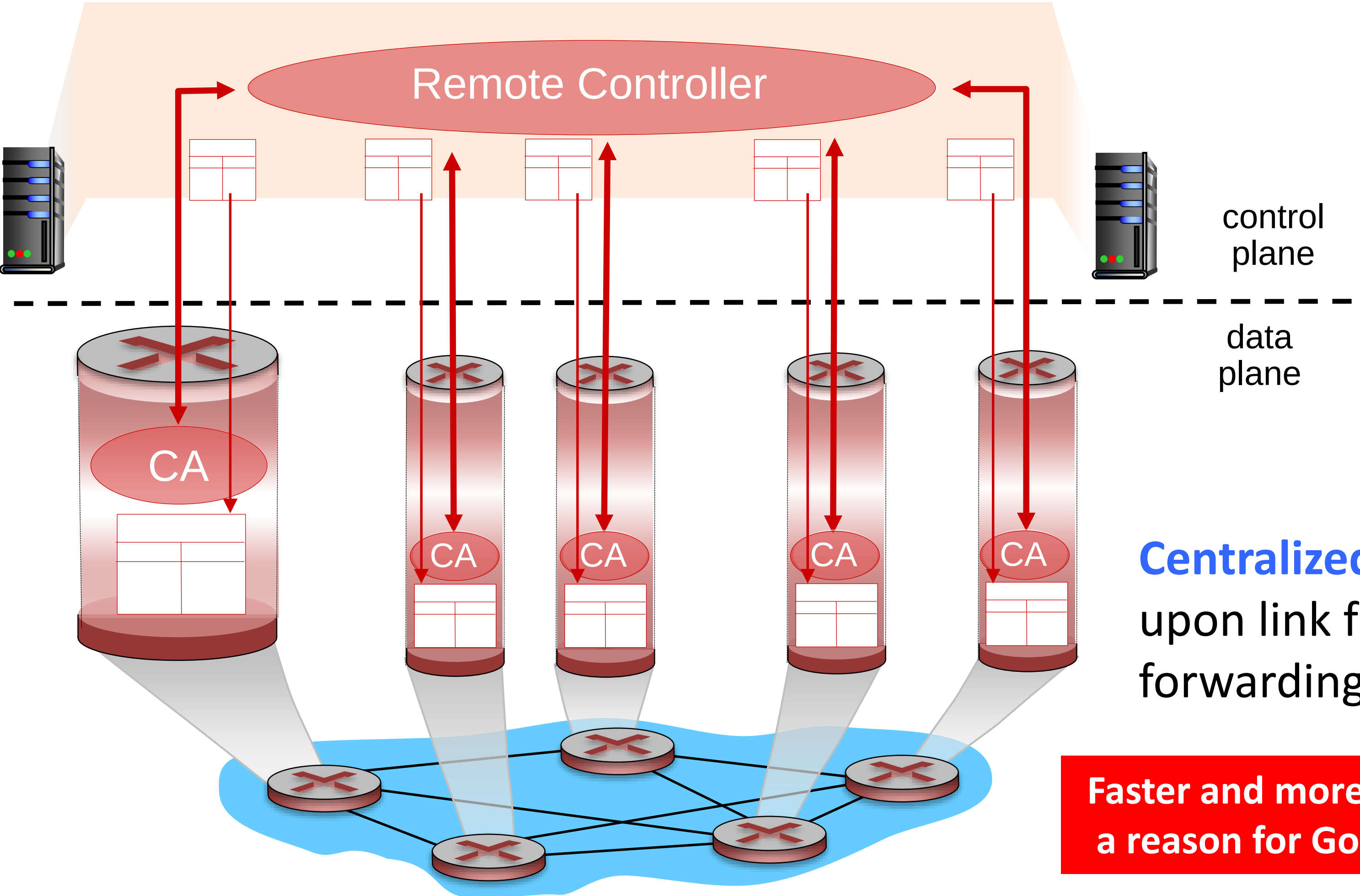
- **A Brief Background on Resilient Networking**
- Algorithms for Local Fast Re-Routing (FRR)

Traditional Networks



Distributed algorithms: upon link failure, ***reconverge*** to shortest paths

Software-Defined Networks (SDN)



Centralized algorithms: upon link failure, ***push*** new forwarding rules

Faster and more controlled reaction: a reason for Google's move to SDN!

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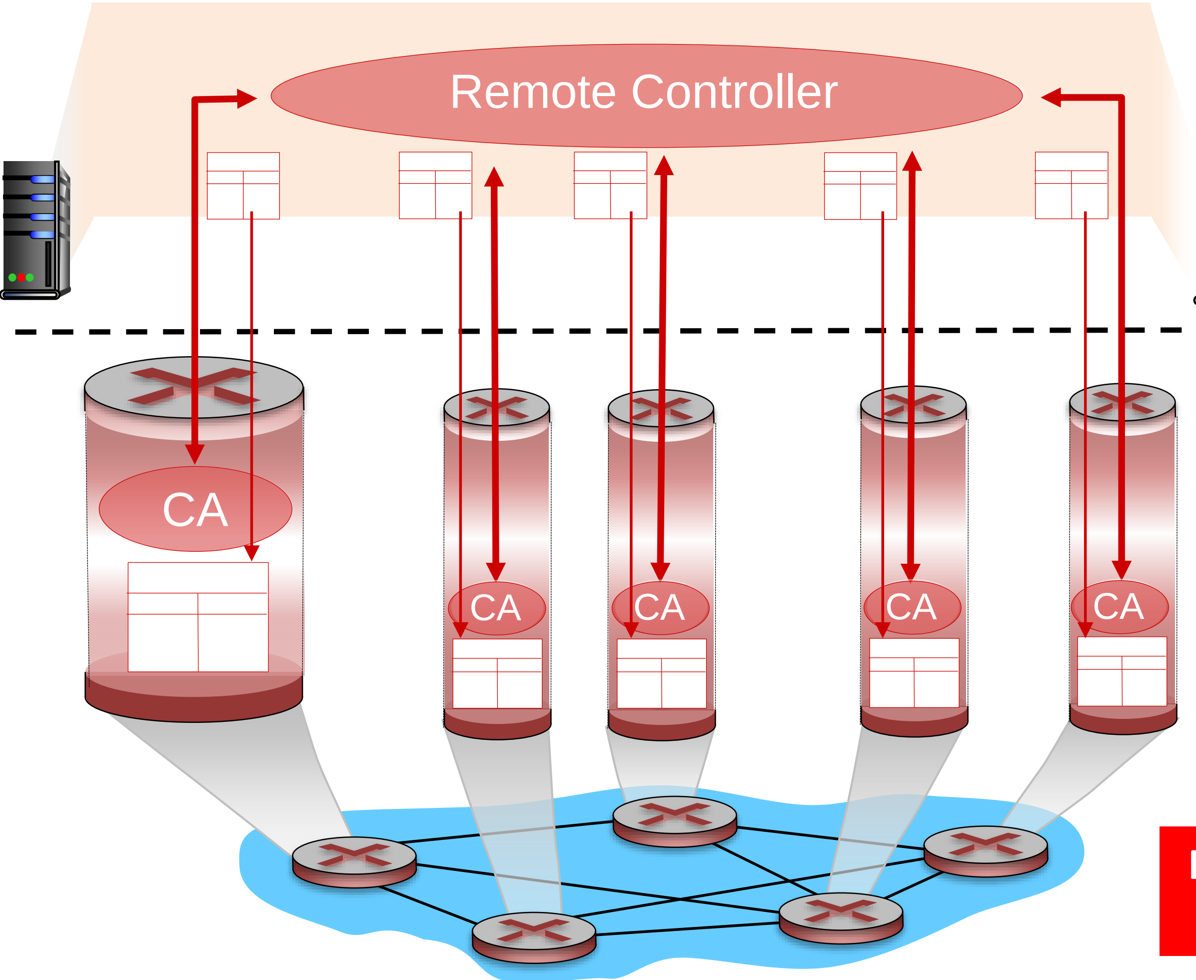

Centralized algorithms: upon link failure, ***push*** new forwarding rules

Faster and more controlled reaction: a reason for Google's move to SDN!

Restoration in control plane takes time -> packet drops!

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

Failover: Control Plane vs Data Plane

- Slower reaction in the **control plane** than in the **data plane**

vs

Minister of Education

Teacher in the Classroom

Approaches for Failover

In Control Plane

- Distributed recomputation of shortest paths ("**re-convergence**")
- Centralized recomputation of paths (SDN)
- **Link-reversal** algorithms (e.g., Gafni et al.)

vs

In Data Plane

- Static forwarding table
- Rules pre-installed ***before*** failures are known

Approaches for Failover

Slow but "globally informed".

In C[...]rol Plane

- Distributed recomputation of shortest paths ("**re-convergence**")
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vs

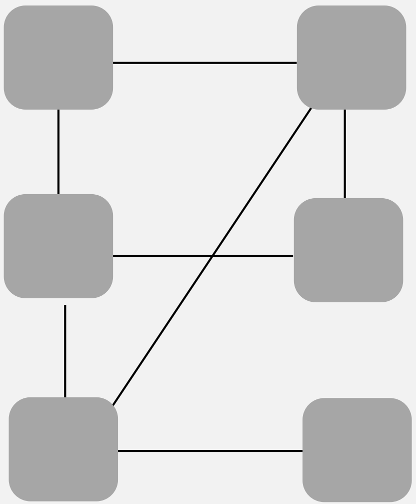
Fast but "local knowledge".

In D[...] Plane

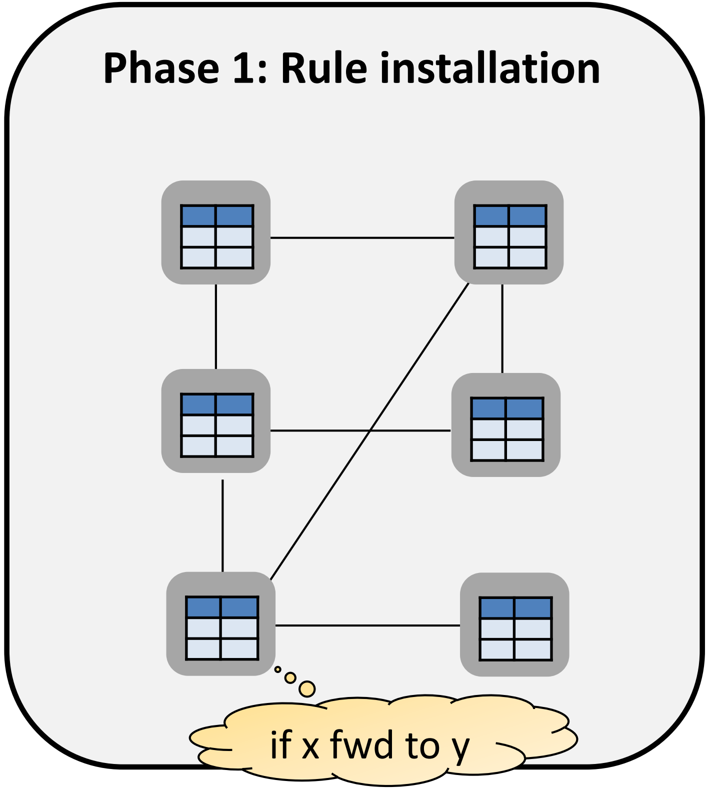
- Static forwarding table
- Rules pre-installed ***before*** failures are known

The FRR Problem

Phase 1: Rule installation



The FRR Problem



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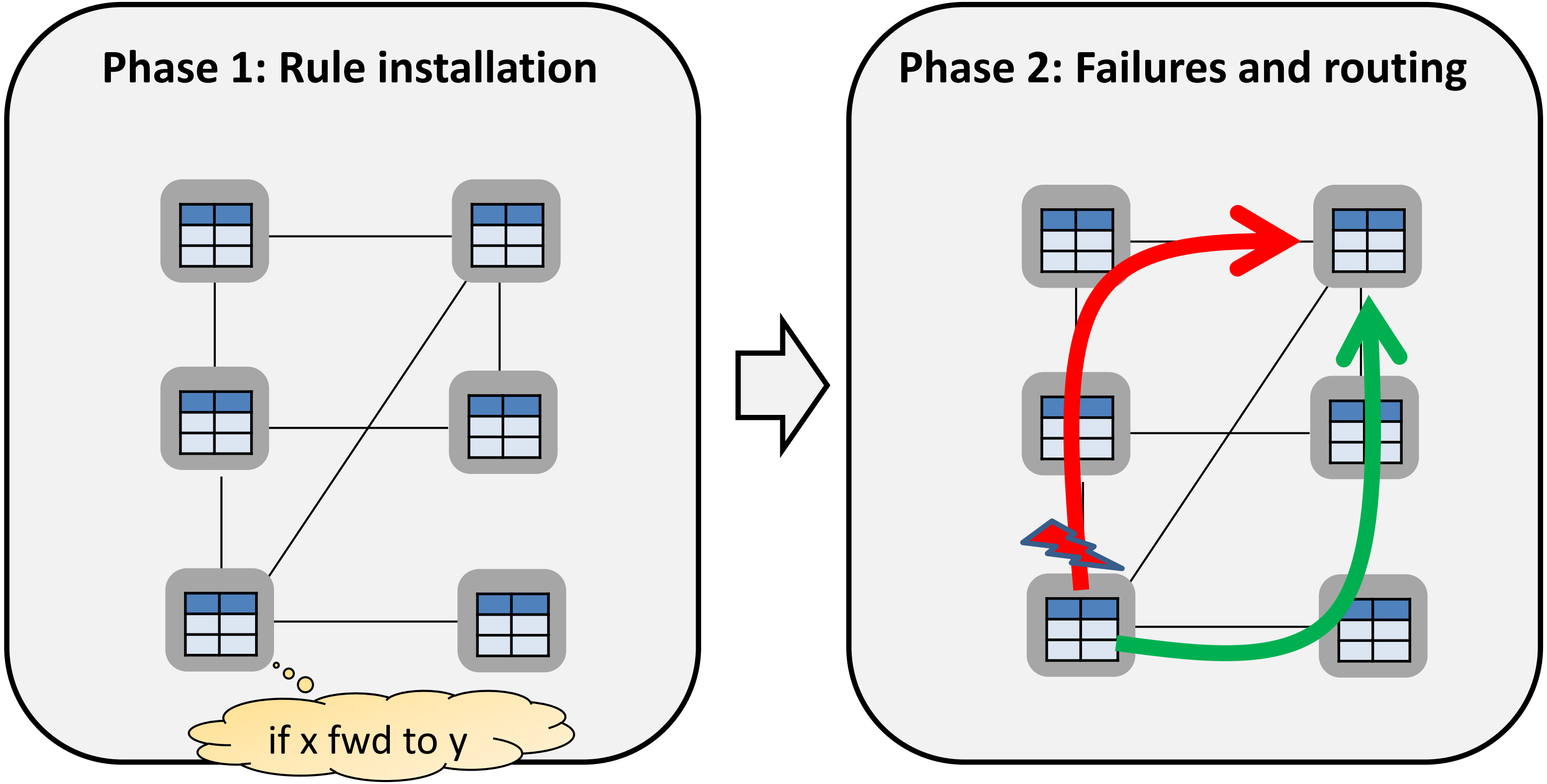

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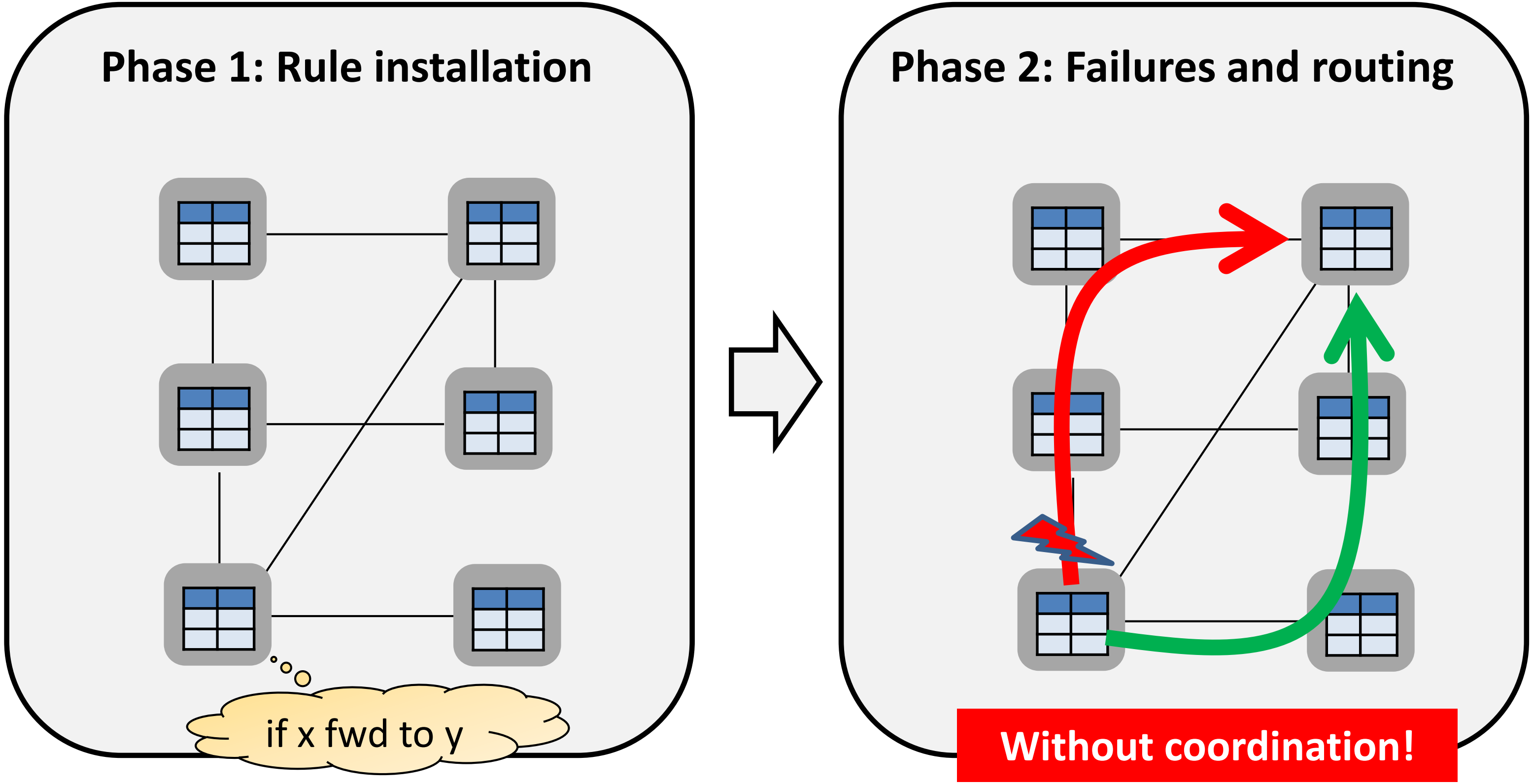
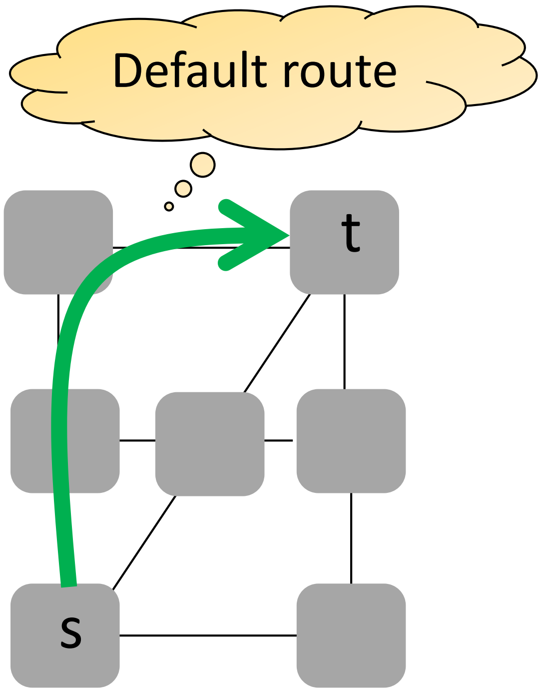


The FRR Problem

- **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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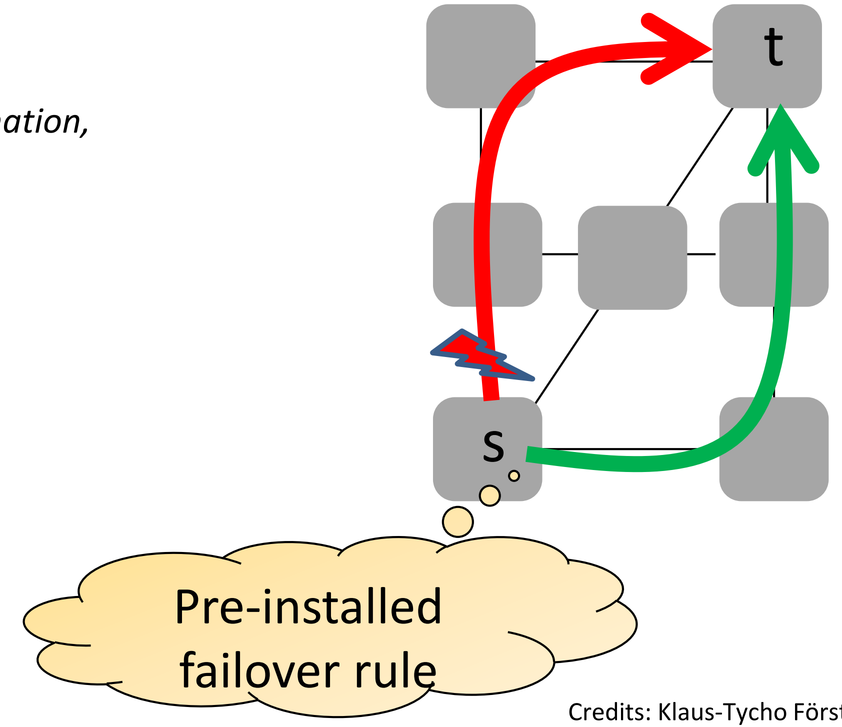

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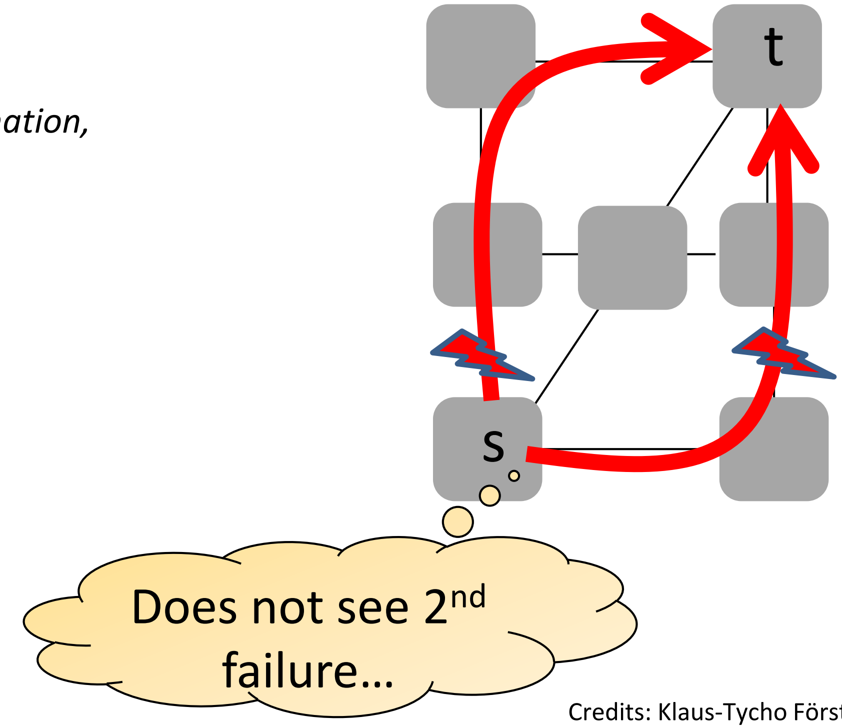

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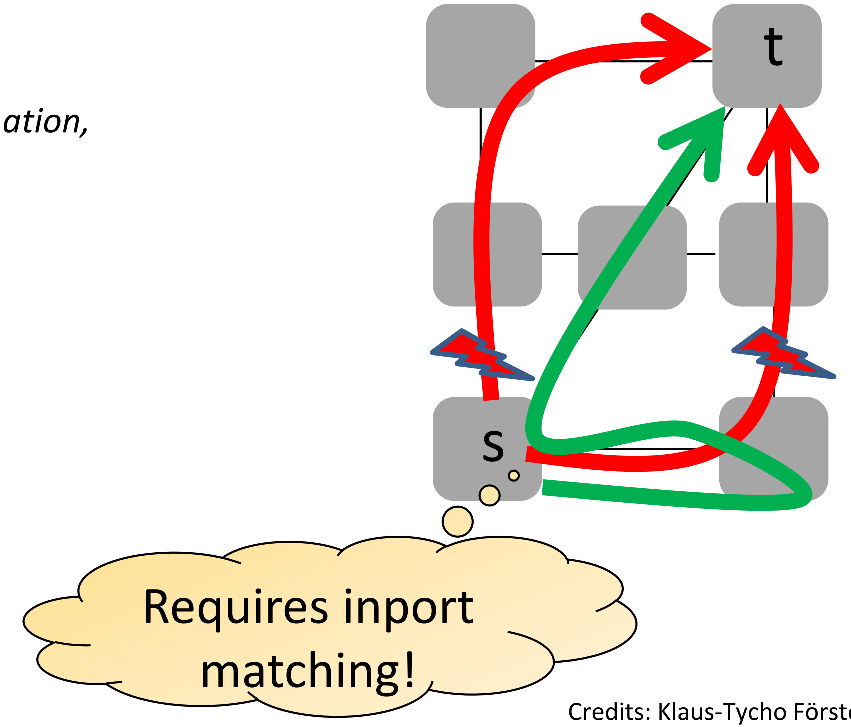
Can get complex under multiple failures..



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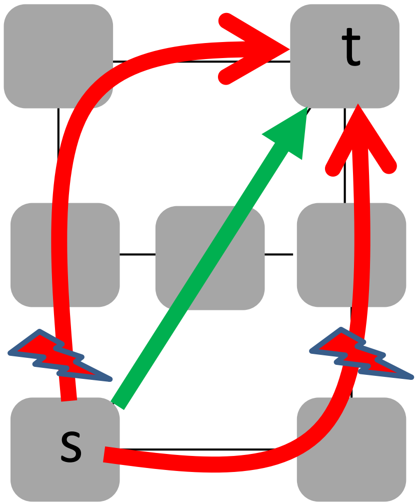
With global knowledge: simpler!

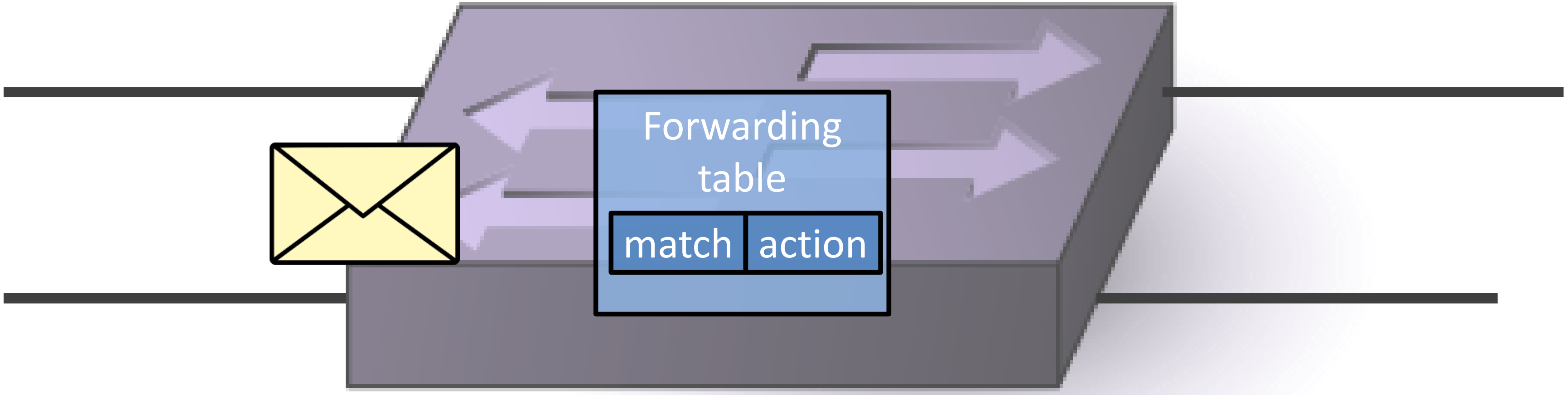


Credits: Klaus-Tycho Förster

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

Credits: Marco Chiesa

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



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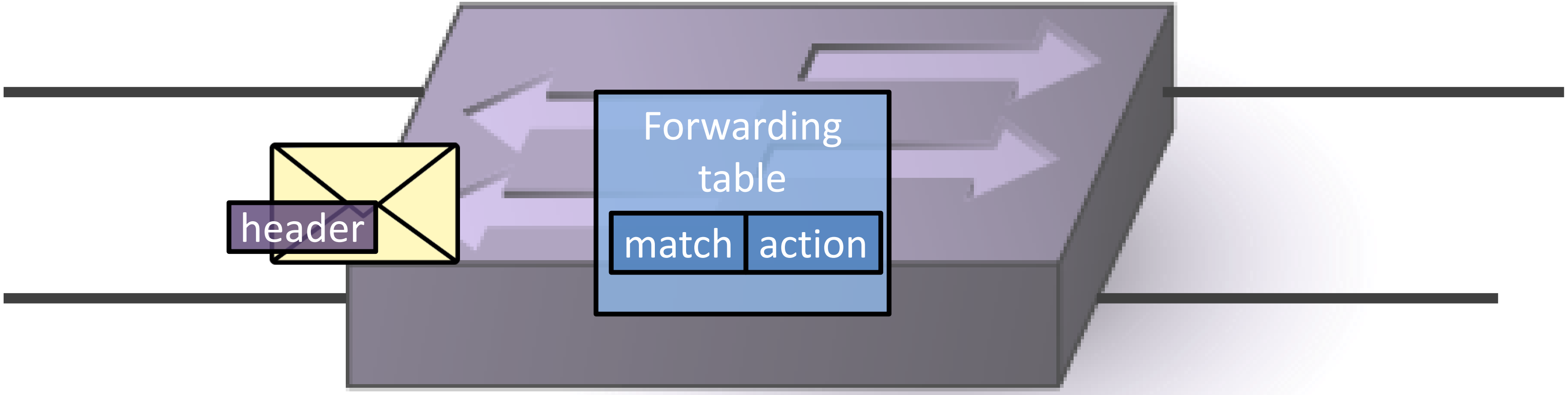
Locally Available Information:
The Packet Header



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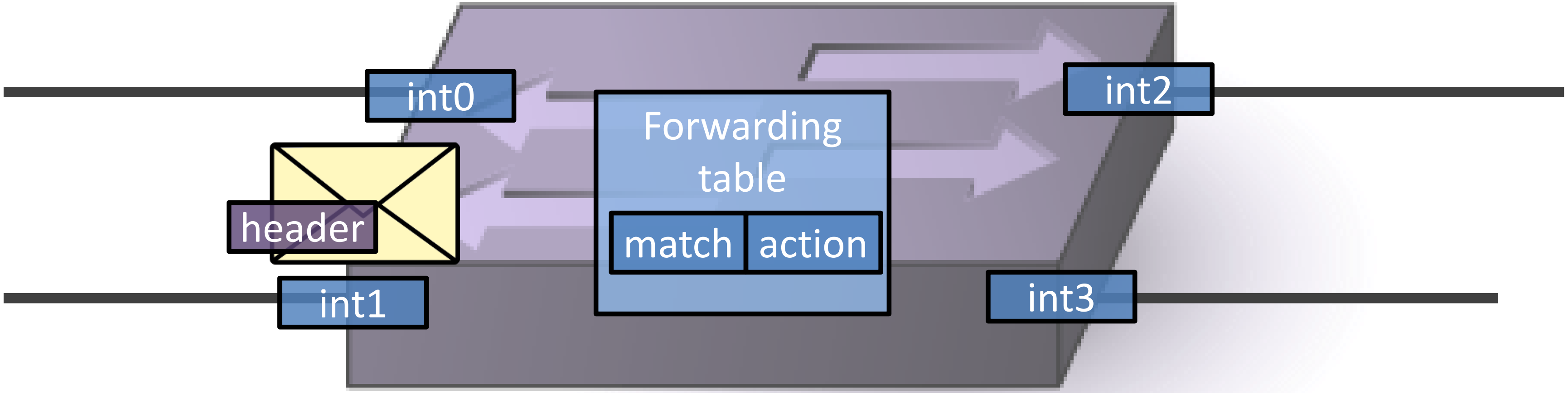
Locally Available Information: The Inport of the Received Packet



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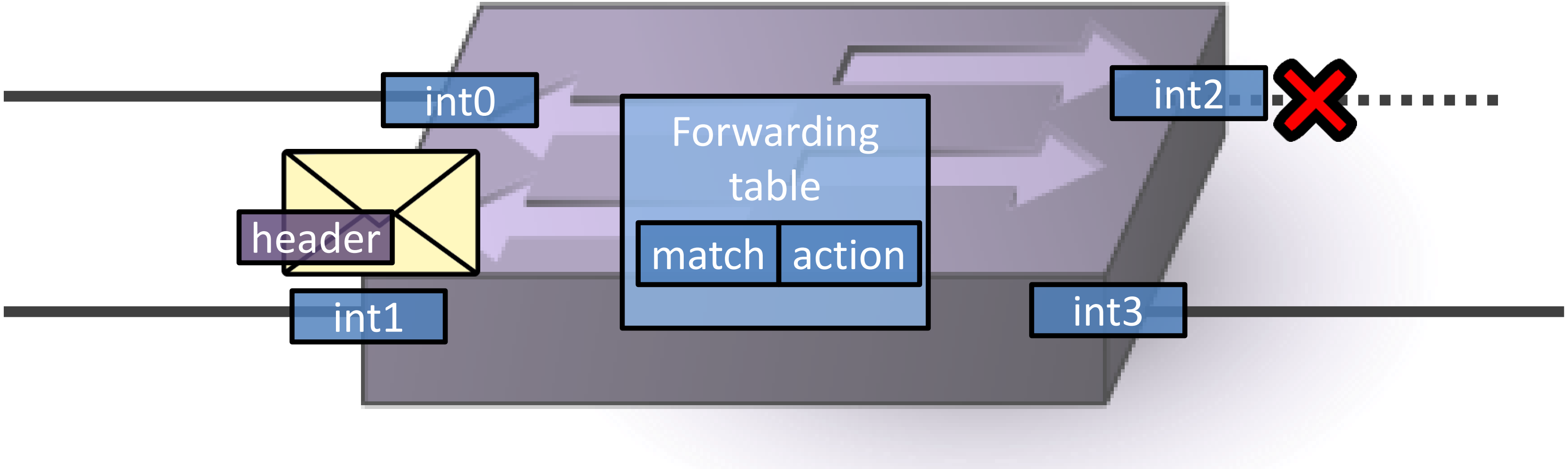
Locally Available Information: The Outgoing Port Depends on Failed Links



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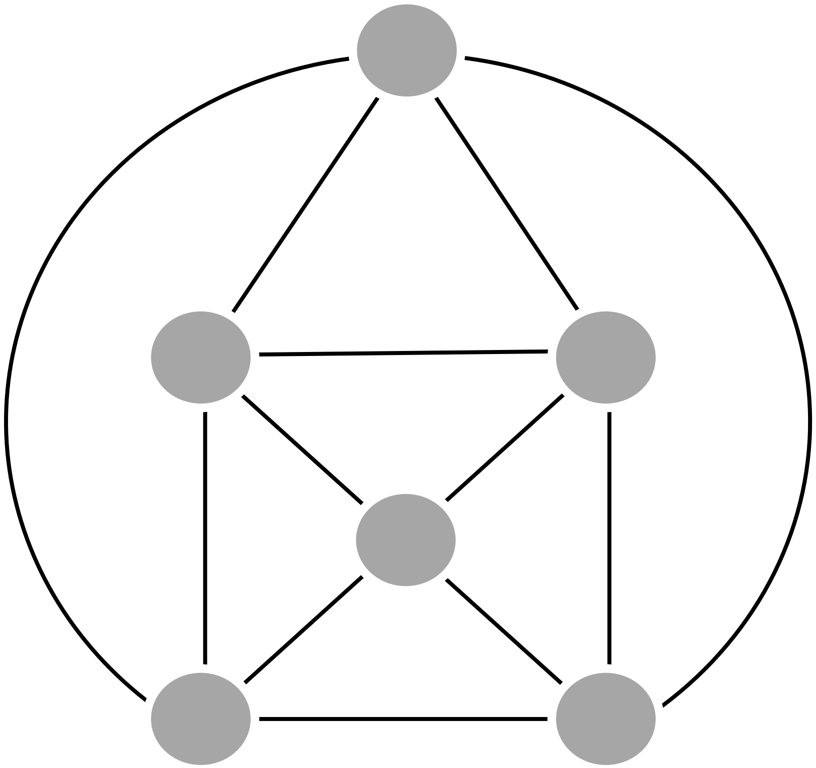
Raises an Interesting Question

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?

Roadmap

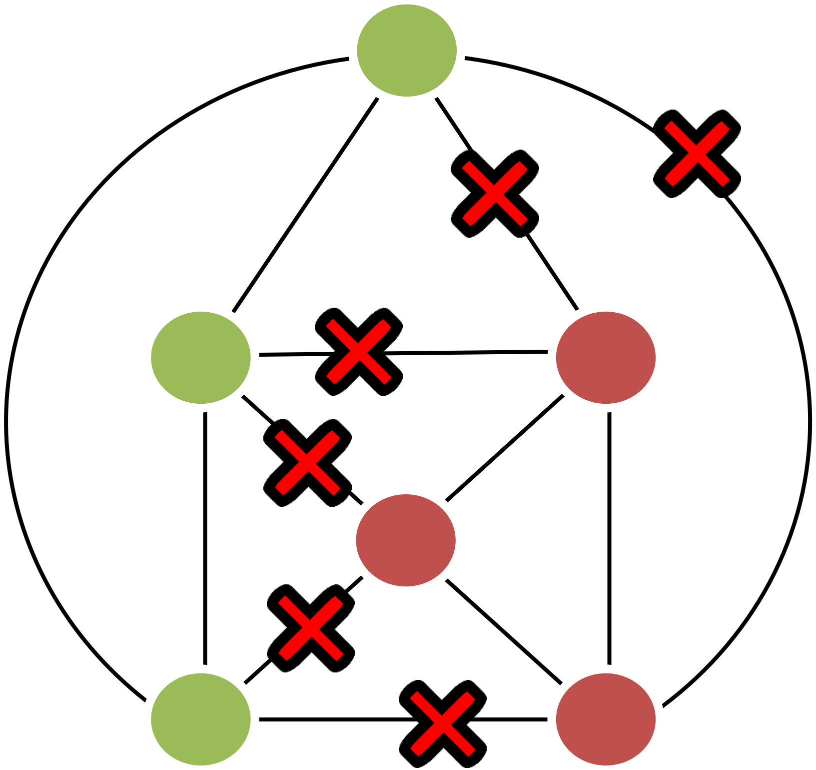
- A Brief Background on Resilient Networking
- **Algorithms for Local Fast Re-Routing (FRR)**

So: How many failures can be tolerated by static forwarding tables?



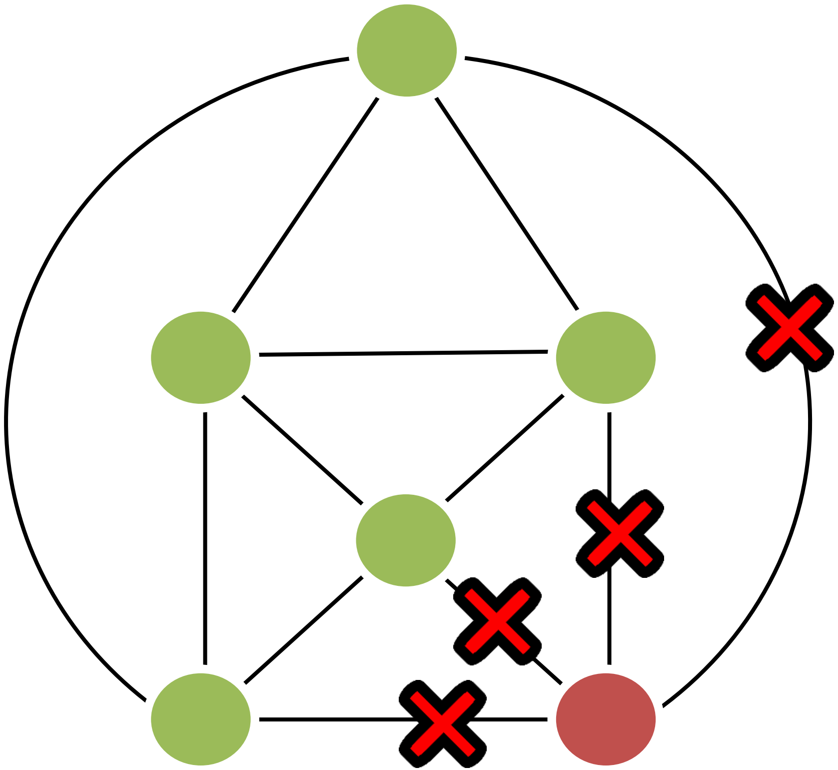
Credits: Marco Chiesa

If we partition the network, there is not much to do



Credits: Marco Chiesa

The connectivity k of a network N: the minimum number of link deletions that partitions N



The connectivity of this network is *four*

Credits: Marco Chiesa

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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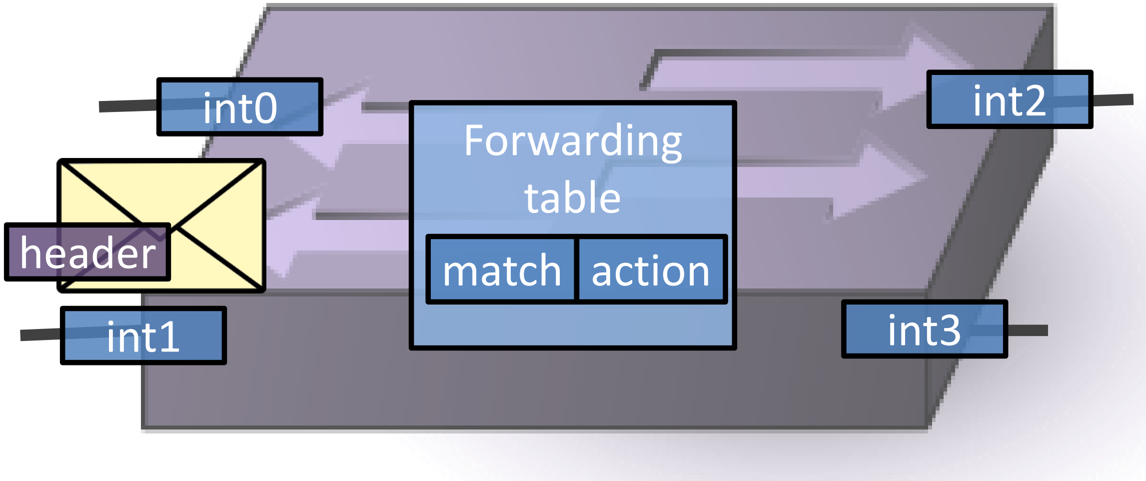
Spectrum of Models

Recall our switch model:



Achievable resilience depnds on *what can be matched*:

Per-destination	Per source	Incoming port	Probabilistic forwarding	Packet header rewriting

Credits: Marco Chiesa

Spectrum of Models

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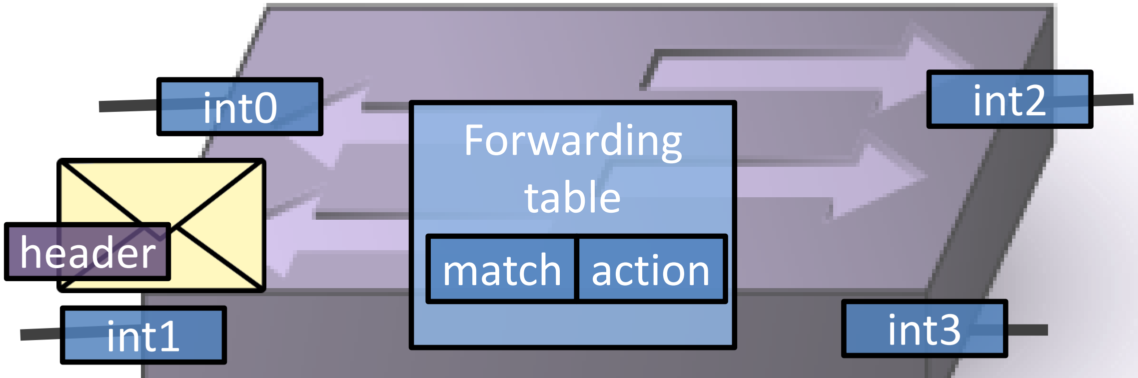


Can carry global information, but often undesirable

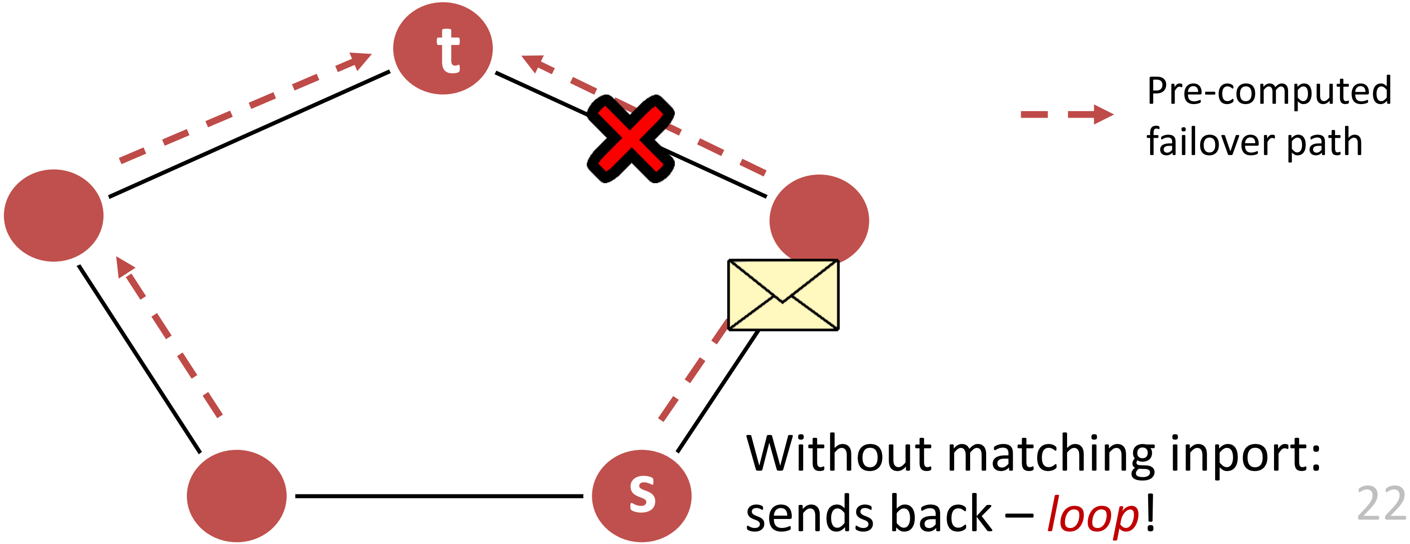
Achievable resilience depnds on

Per-destination	**Per source**	**Incoming port**	**Probabilistic forwarding**	**Packet header rewriting**

Credits: Marco Chiesa

Per-destination routing *cannot cope* with *even one* link failure

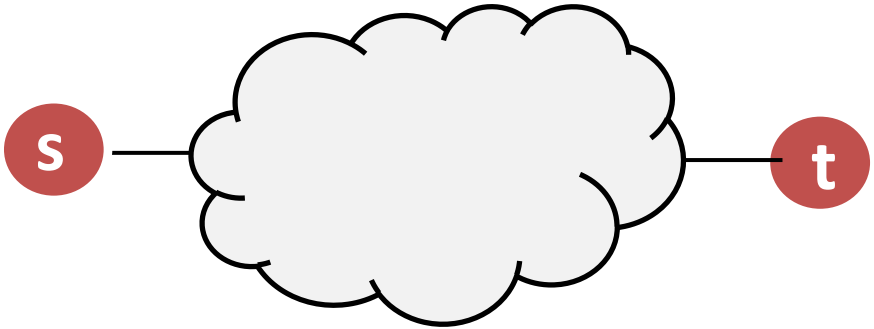
Per-destination	Per source	Incoming port	Probabilistic forwarding	Packet header rewriting	Resiliency
X					0



Without matching inport: sends back – *loop*!

Can we achieve k – 1 resiliency in k-connected graph here?

Per-destination	Per source	Incoming port	Probabilistic forwarding	Packet header rewriting	Resiliency
X	X	X			?



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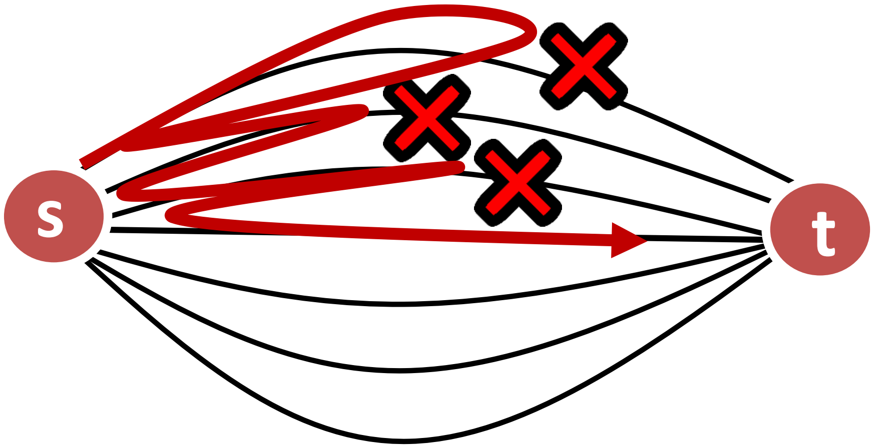


k disjoint paths: try one after the other, routing *back to source* each time.

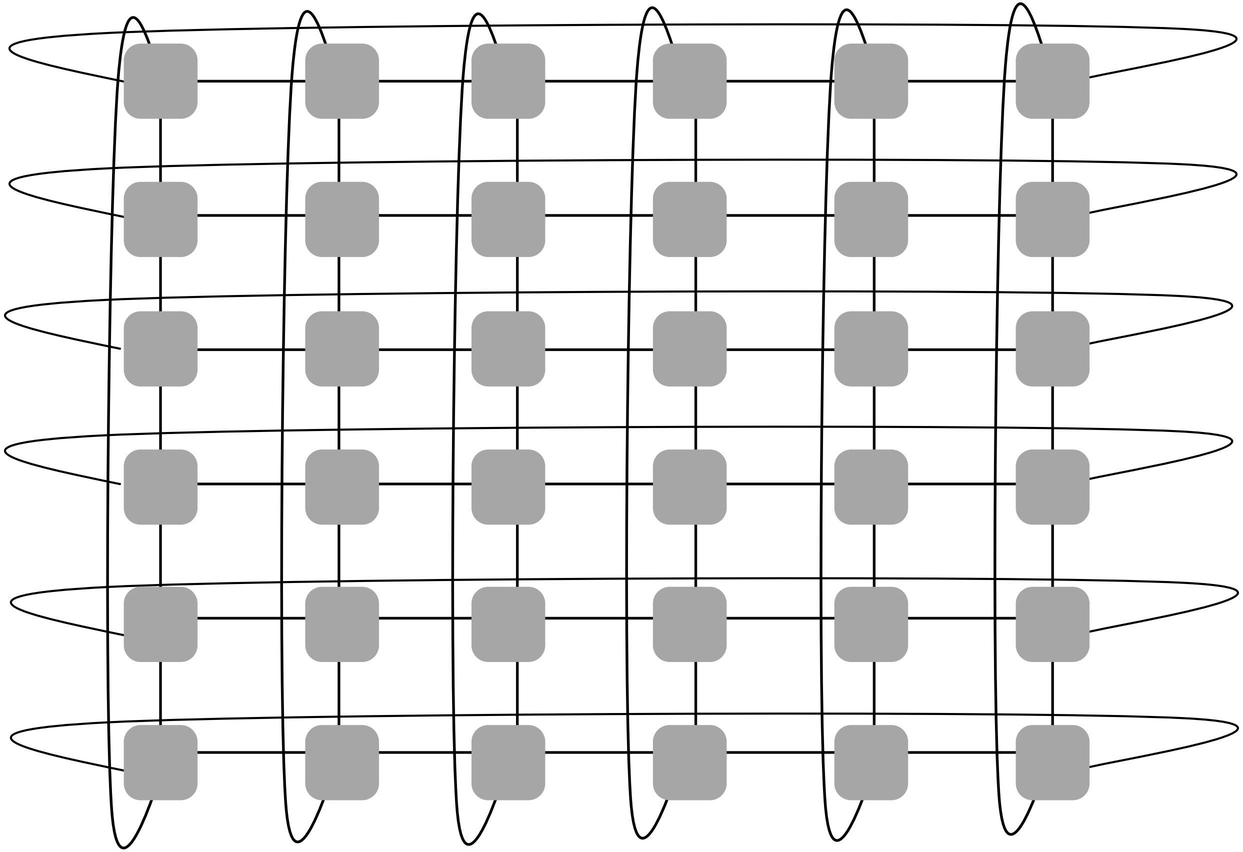
Credits: Marco Chiesa

Can we achieve k – 1 resiliency in k-connected graph here?

Per-destination	Per source	Incoming port	Probabilistic forwarding	Packet header rewriting	Resiliency
X		X			?

What about this scenario? Practically important. From now on called "ideal resilience".

Ideal Resilience: Example 2-dim Torus?



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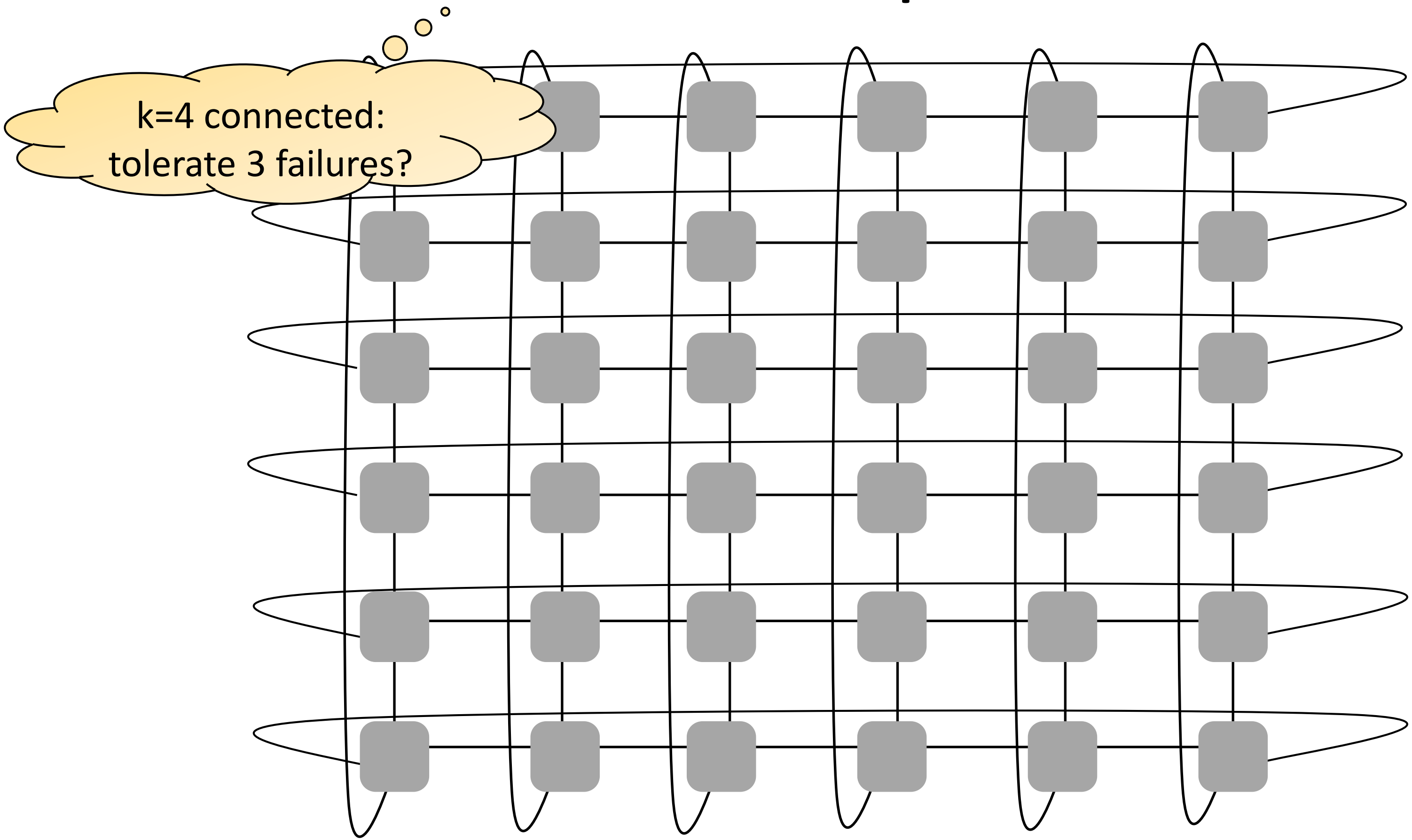
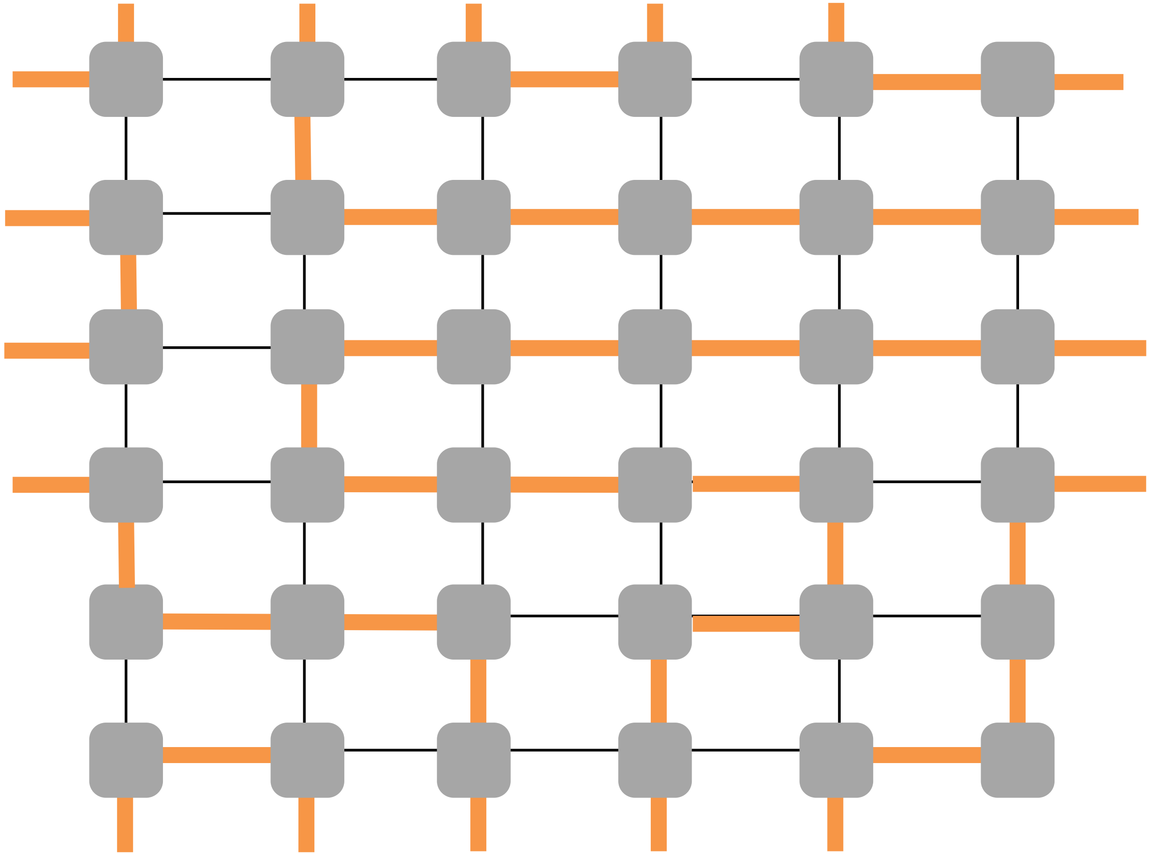


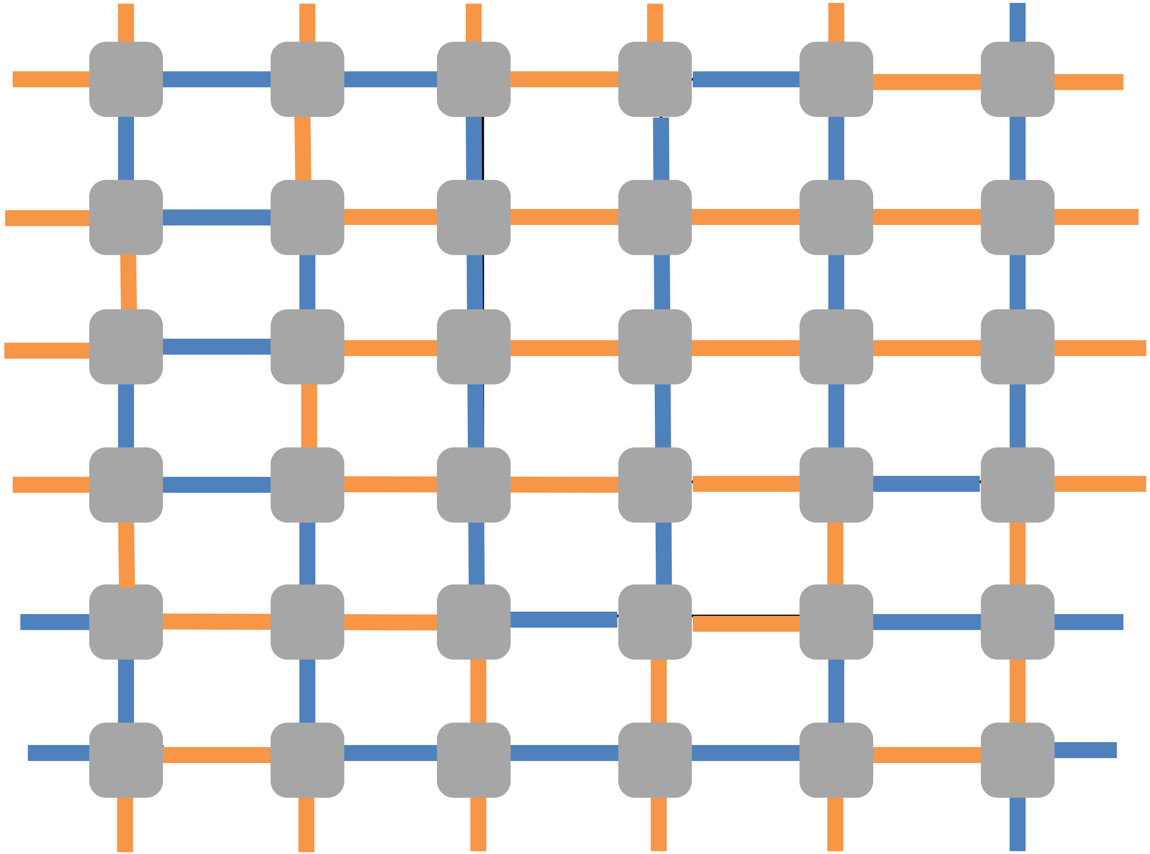
Idea: Decomposition into Hamilton Cycles



- Decompose torus into 2-edge-disjoint Hamilton Cycles (HC)

1st Hamilton cycle

Idea: Decomposition into Hamilton Cycles



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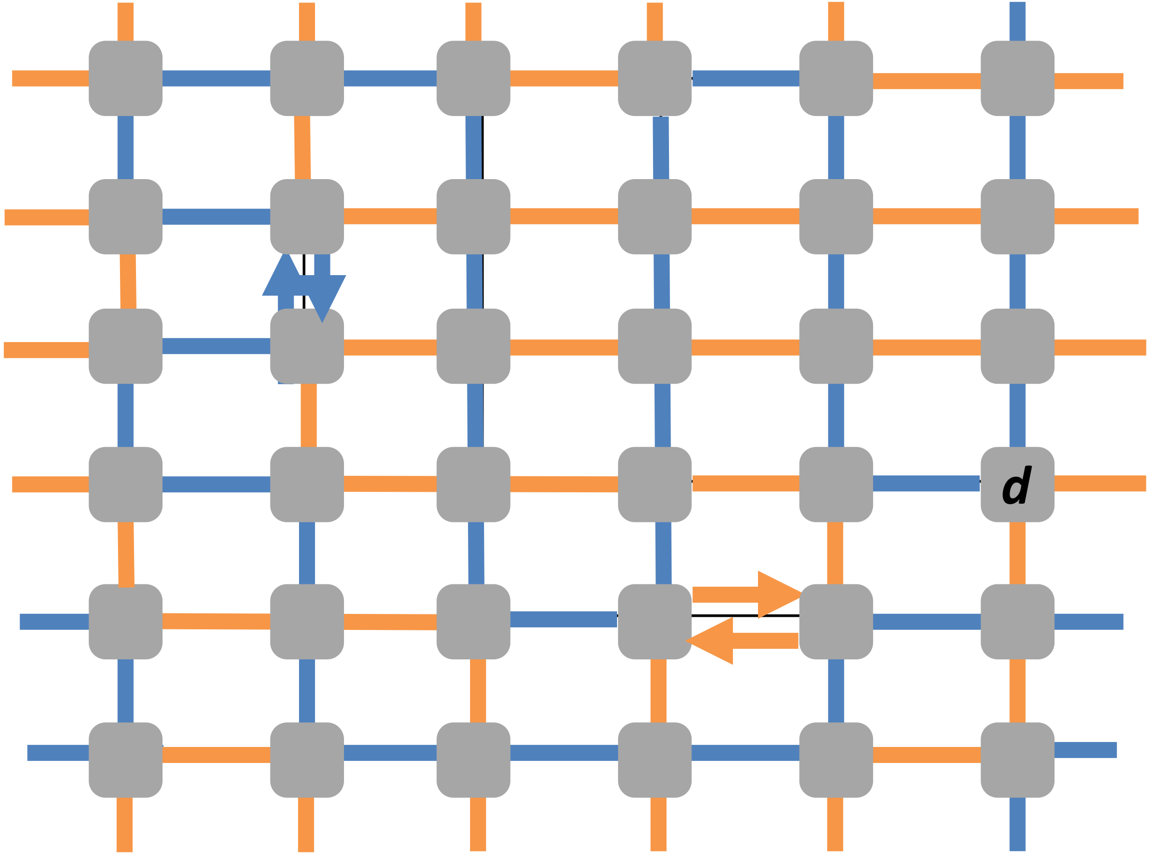

- Decompose torus into 2-edge-disjoint Hamilton Cycles (HC)
- Can route in both directions: *4-arc-disjoint* HCs

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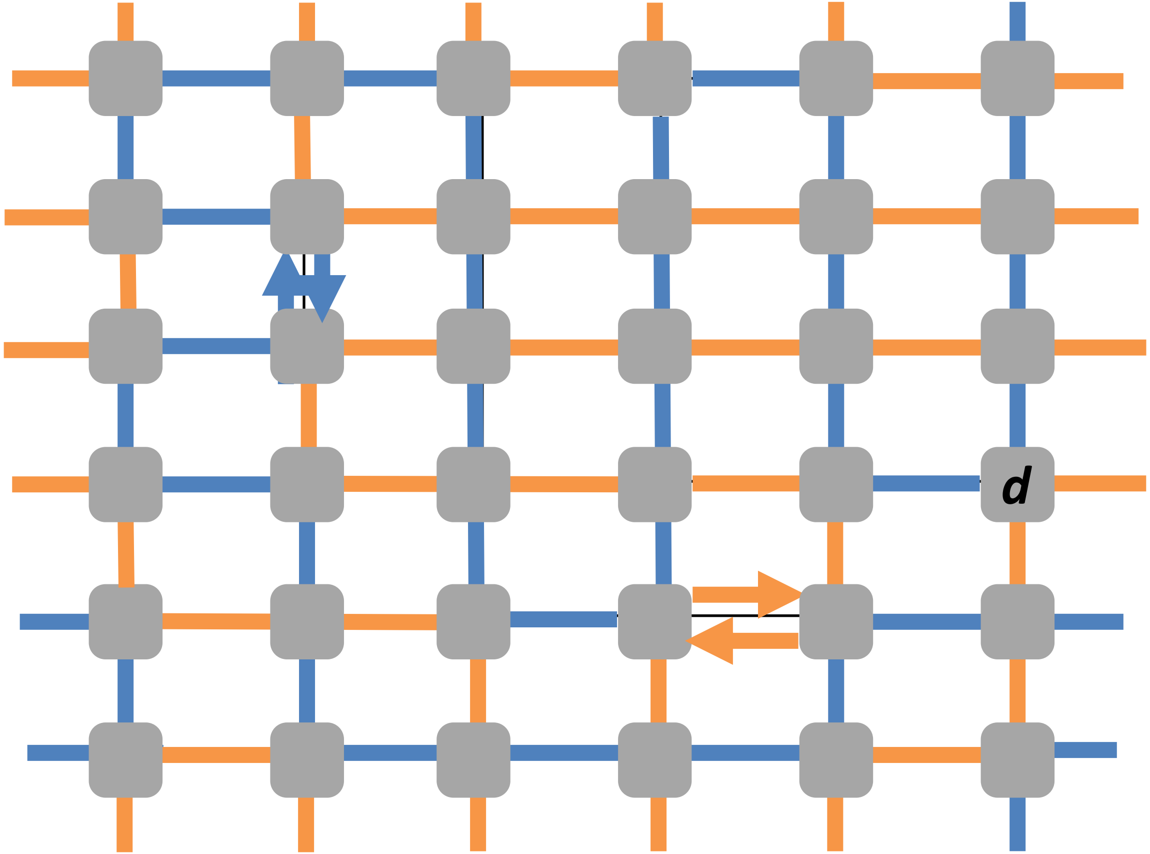

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3-resilient routing to destination d:

- go along *1st directed HC*, if hit failure, *reverse* direction
- if again failure switch to *2nd HC*, if again failure *reverse direction*
- No more failures possible!

Ideal Resilience with Hamilton Cycles

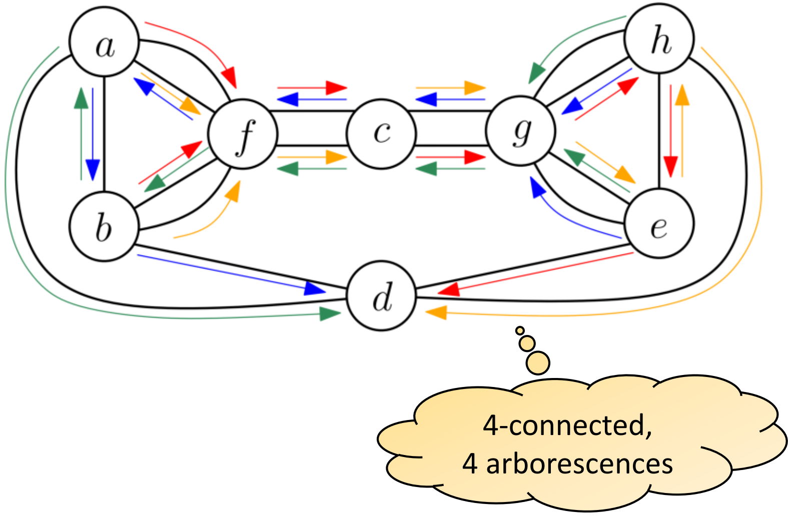
Chiesa et al.: if k-connected graph has k arc disjoint Hamilton Cycles, k-1 resilient routing can be constructed!

What about graphs which cannot be decomposed into Hamilton cycles?

Chiesa et al. **On the Resiliency of Static Forwarding Tables.** IEEE/ACM Transactions on Networking (ToN), 2017.

Ideal Resilience in General k-Connected Graphs

- Use directed trees (i.e. *arborescences*) instead of Hamilton cycles
  - *Arc-disjoint*, spanning, and *rooted* at destination
- Classic result: k-connectivity guarantees k-arborescence decomposition



Basic idea:

- Idea: route towards root on one arborescence
- After failure: change arborescence (e.g. in circular fashion)
- Incoming port defines current arborescence
- After k-1 failures: At least one arborescence intact

J. Edmonds, **Edge-disjoint branchings**. Combinatorial Algorithms, 1972.

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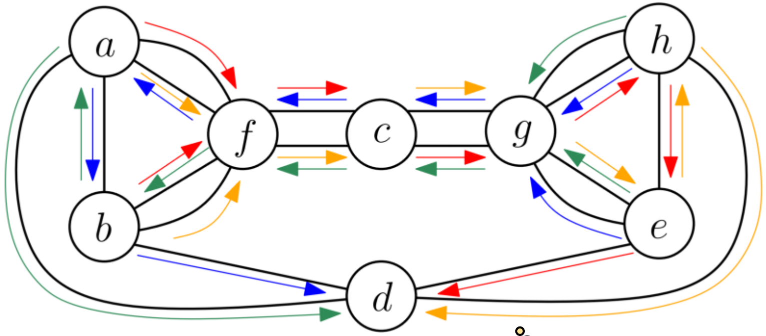

4-connected,
4 arborescences

Basic idea:
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The challenge: how to avoid earlier tree?

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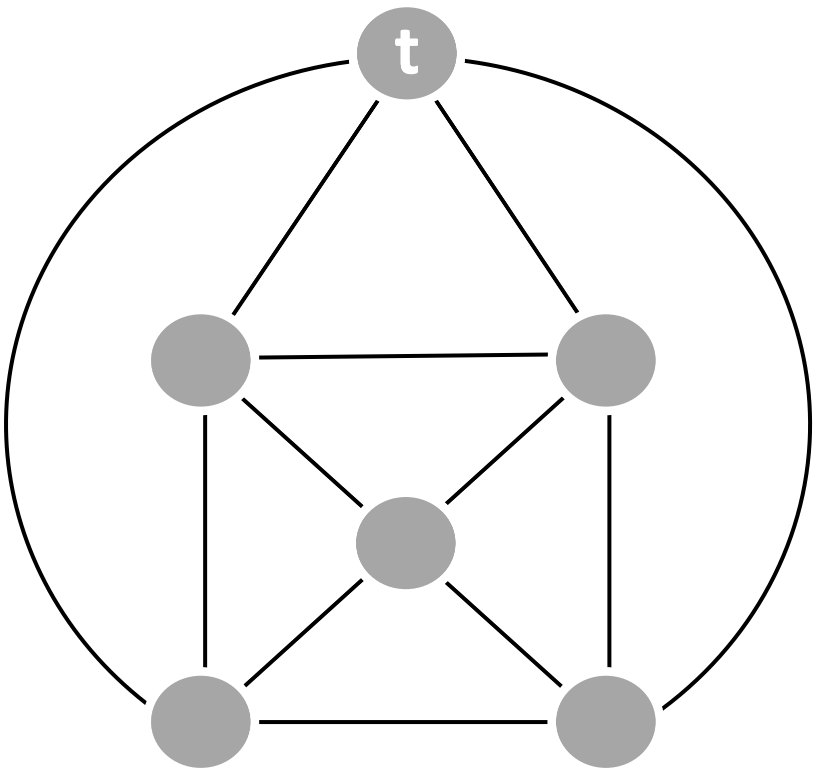
A k-connected network contains k arc-disjoint spanning arborescences [Edmonds, 1972]



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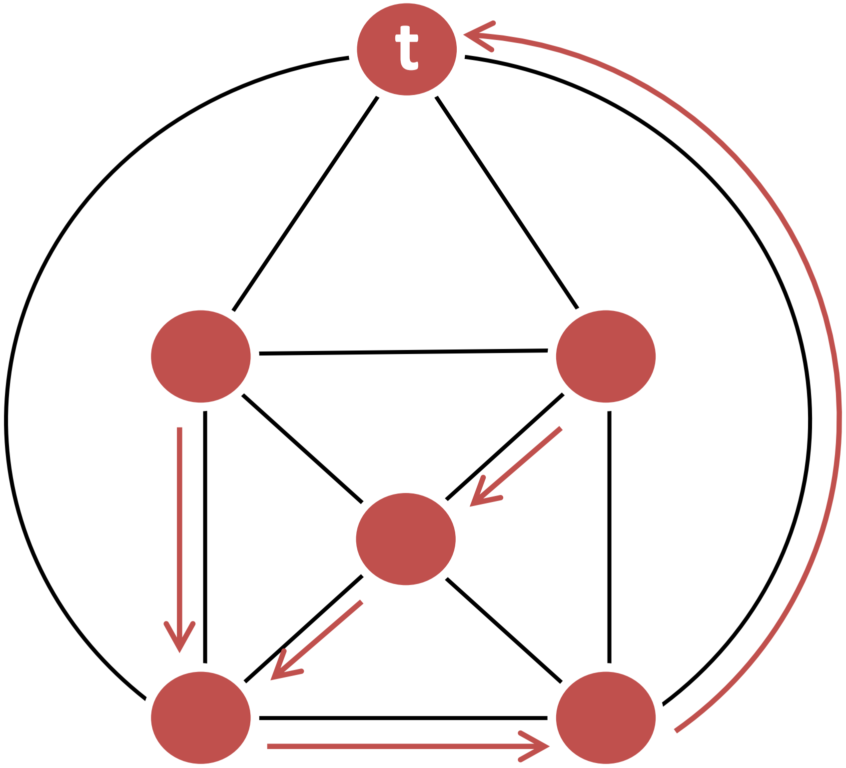

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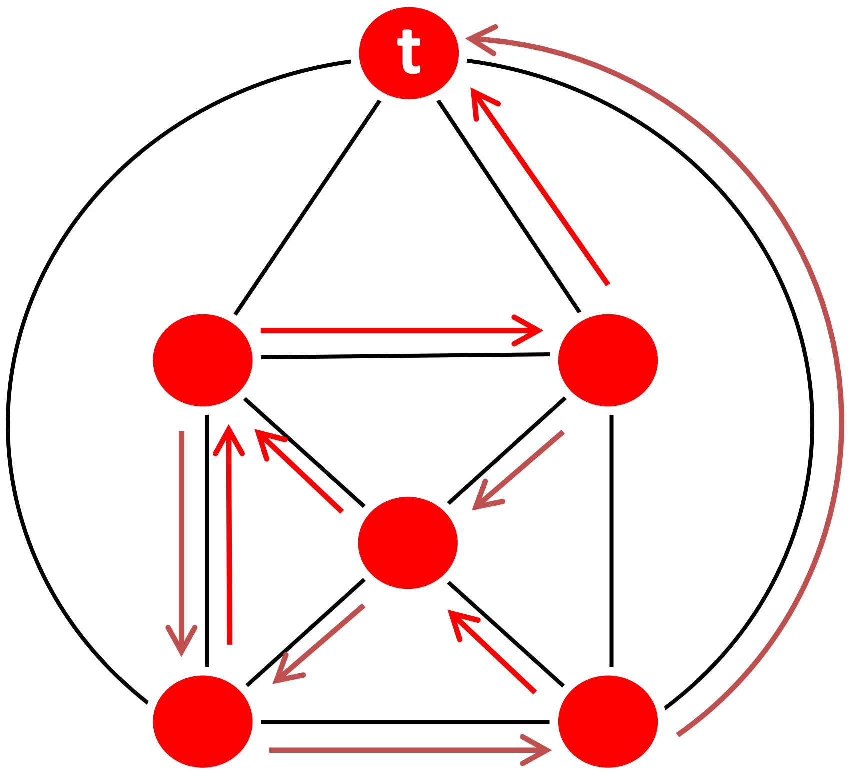

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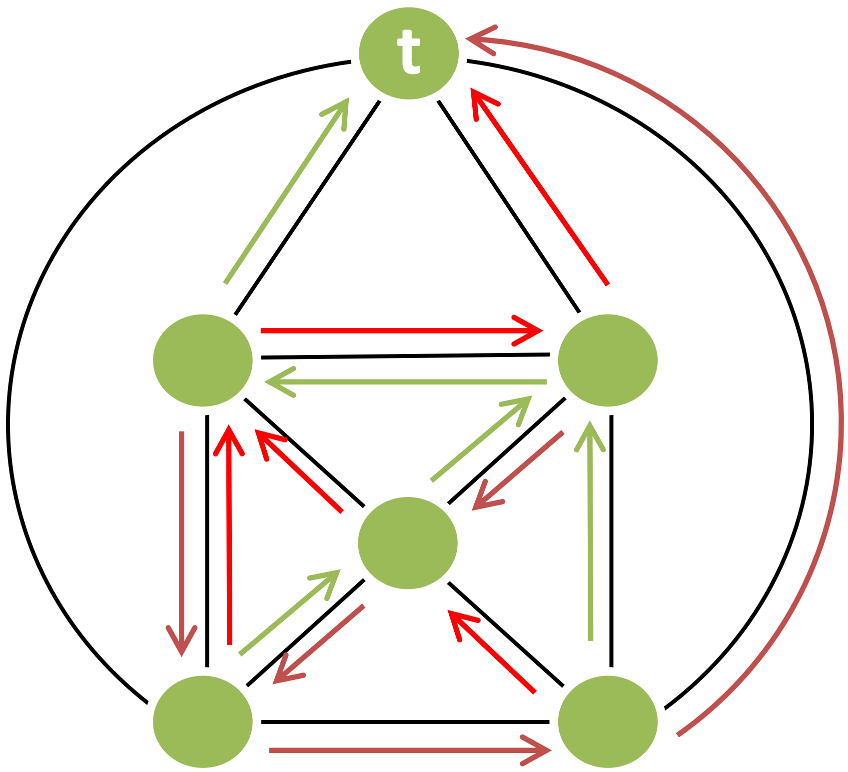

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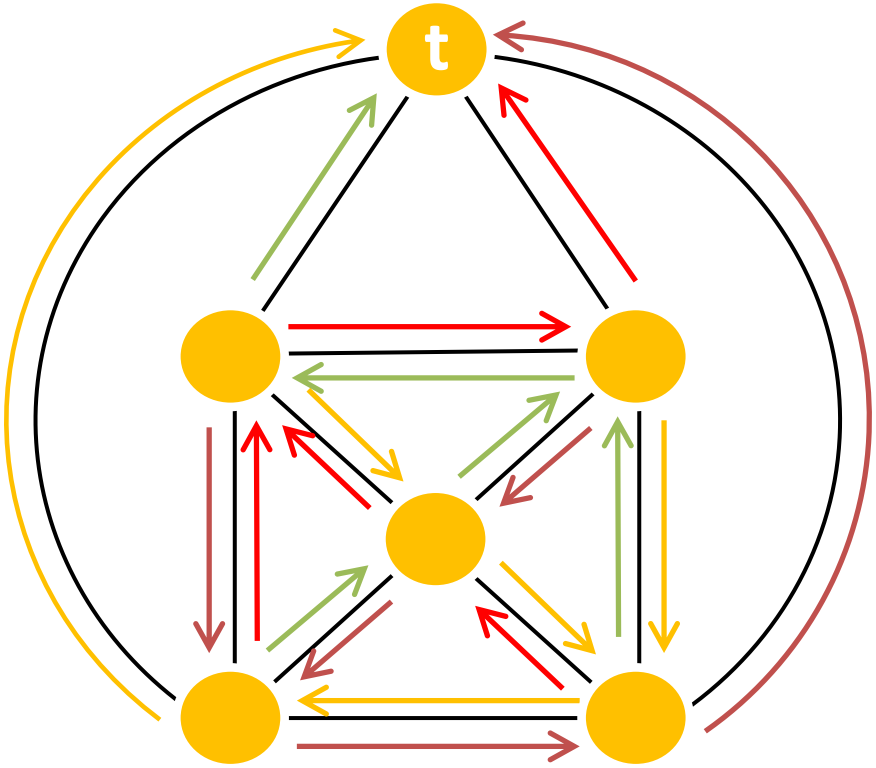

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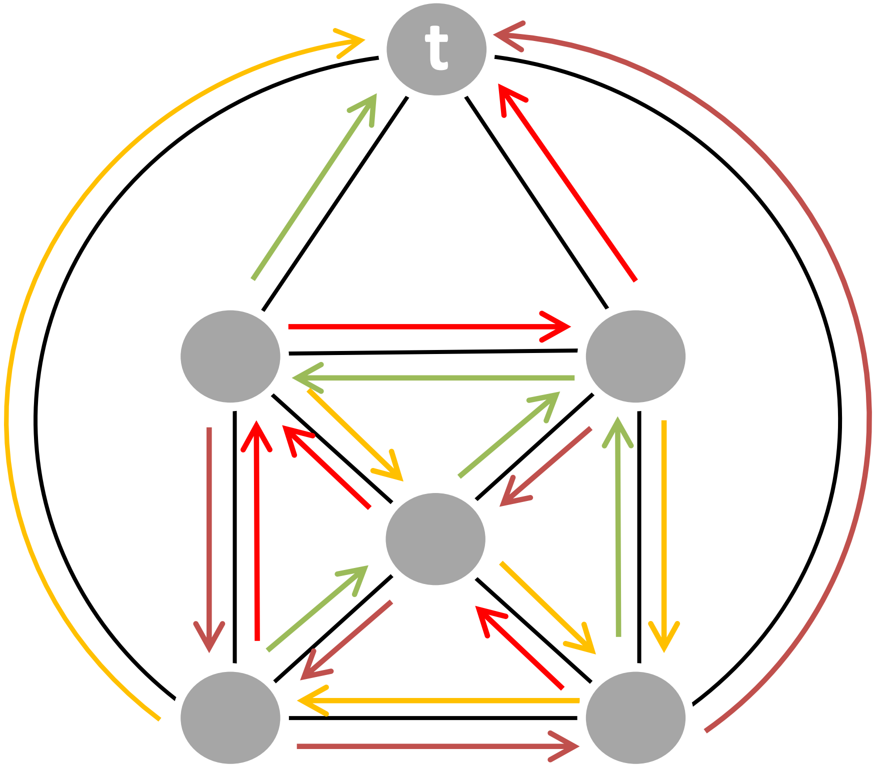

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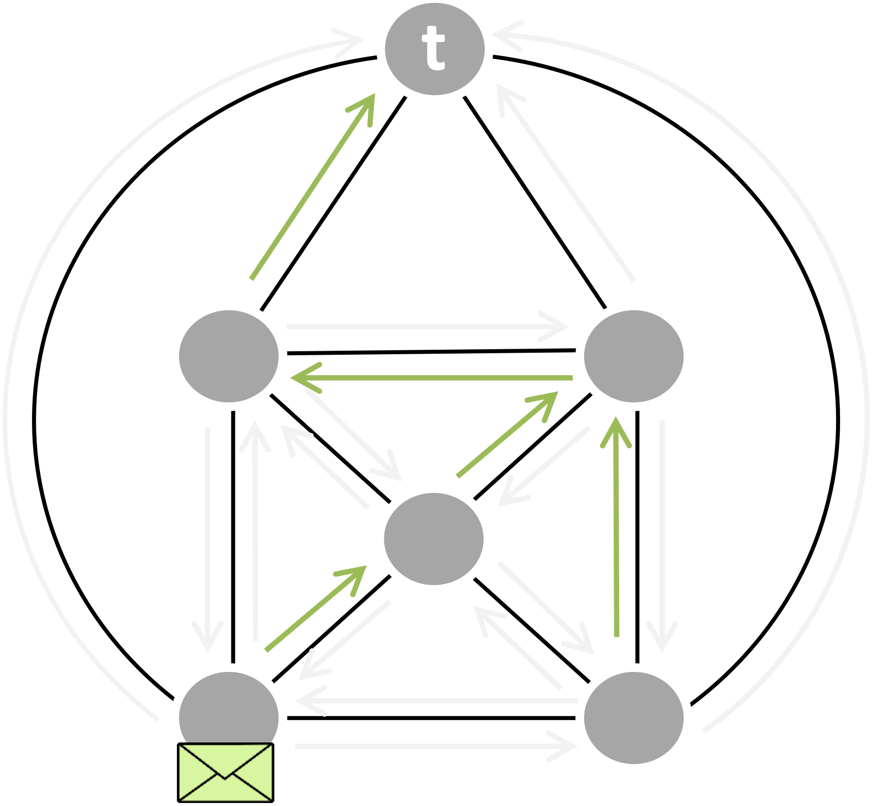
General technique: routing along the same tree



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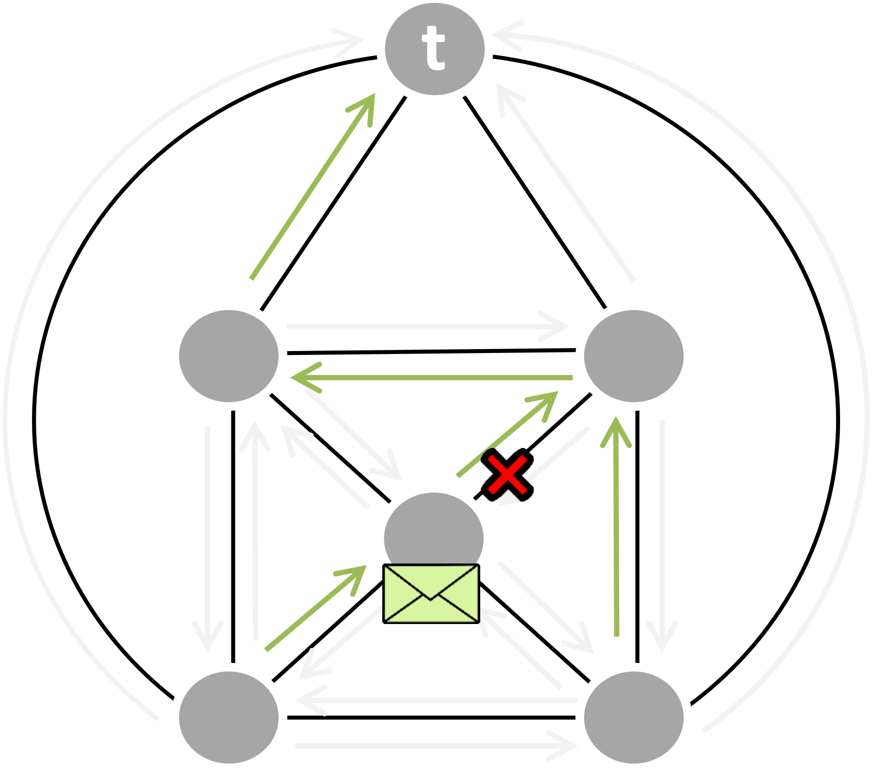
When a failed link is hit…



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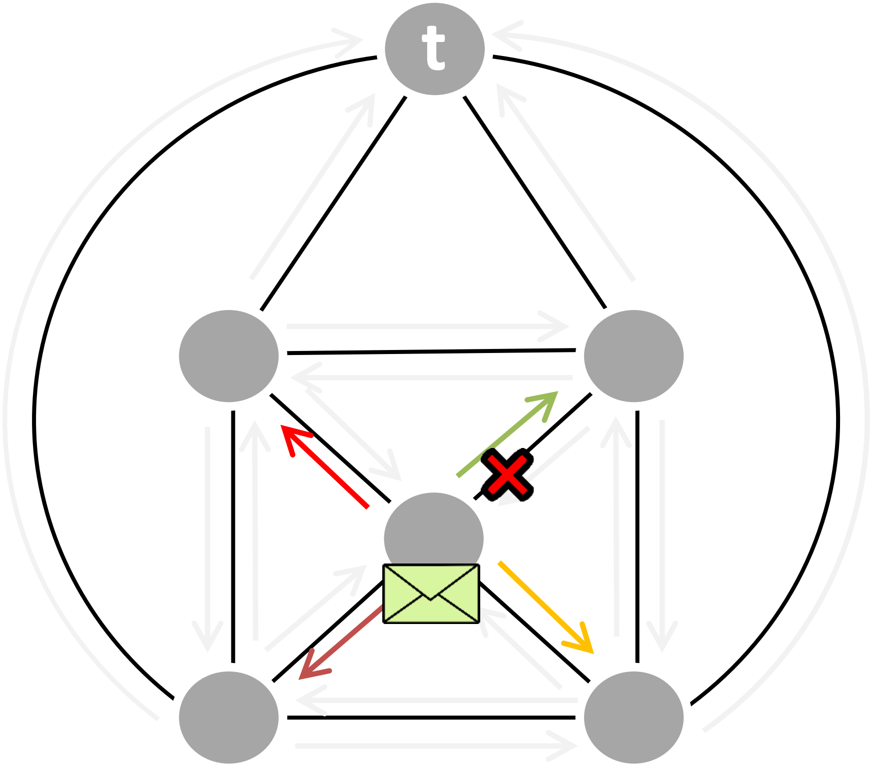
… how do we choose the next arborescence?



Credits: Marco Chiesa

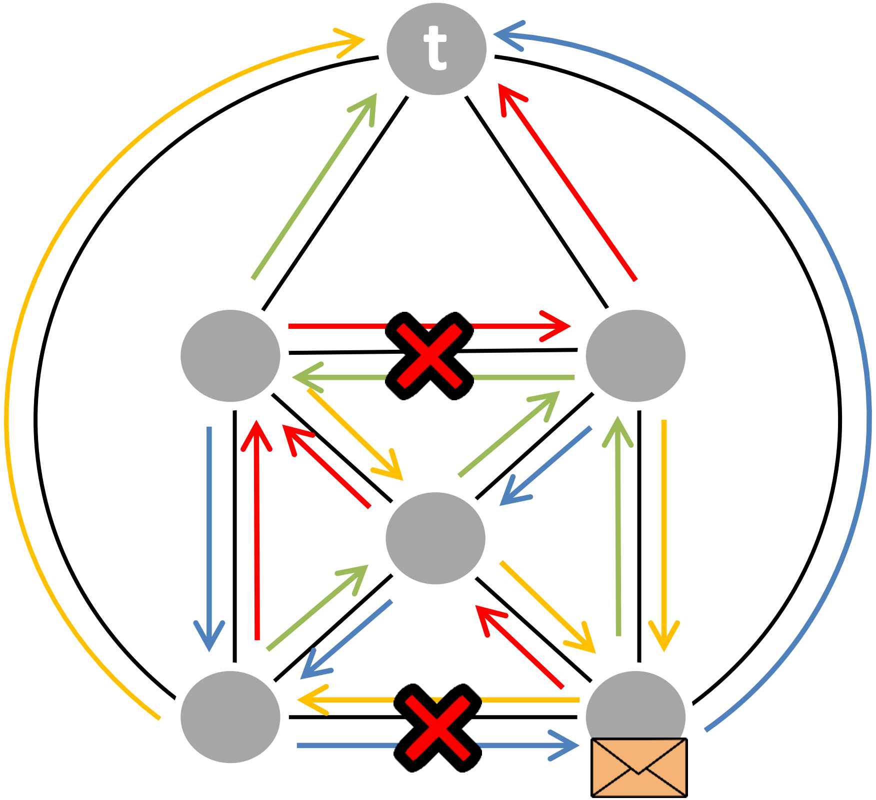
But how do we choose the next arborescence?

Circular-arborescence routing:

- compute an order of the arborescences
- switch to the next arborescence when hitting a failed link

Circular arborescence-routing is (k/2-1)-resilient

Arborescence order



Intuition: each single failure may affect two arborescences

Credits: Marco Chiesa

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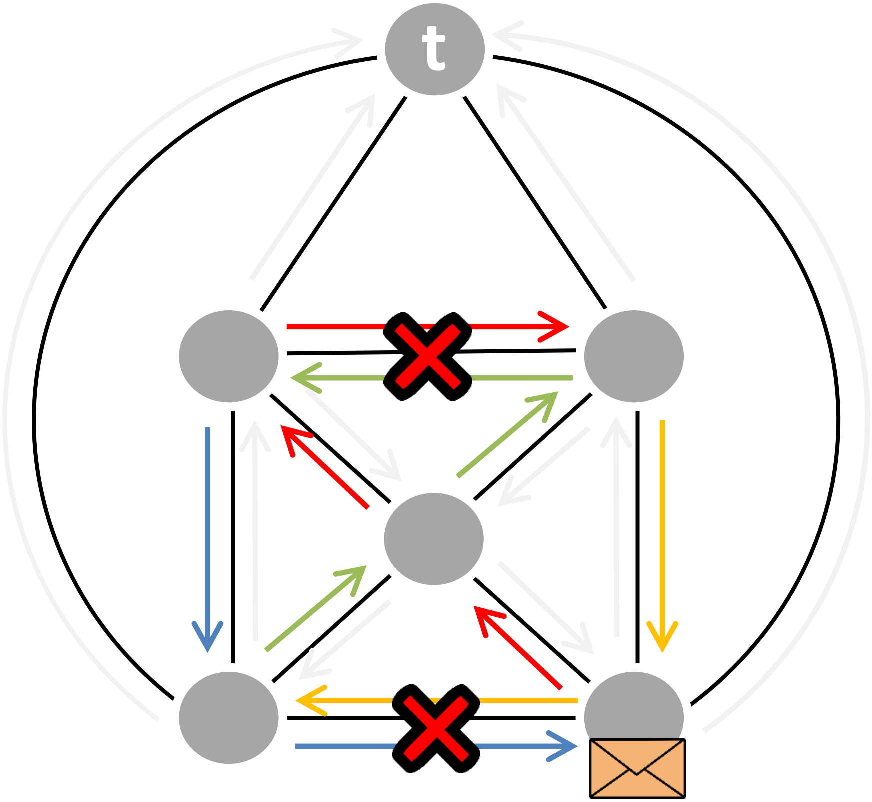
Arborescence order

Go along arborescence 1 to destination...



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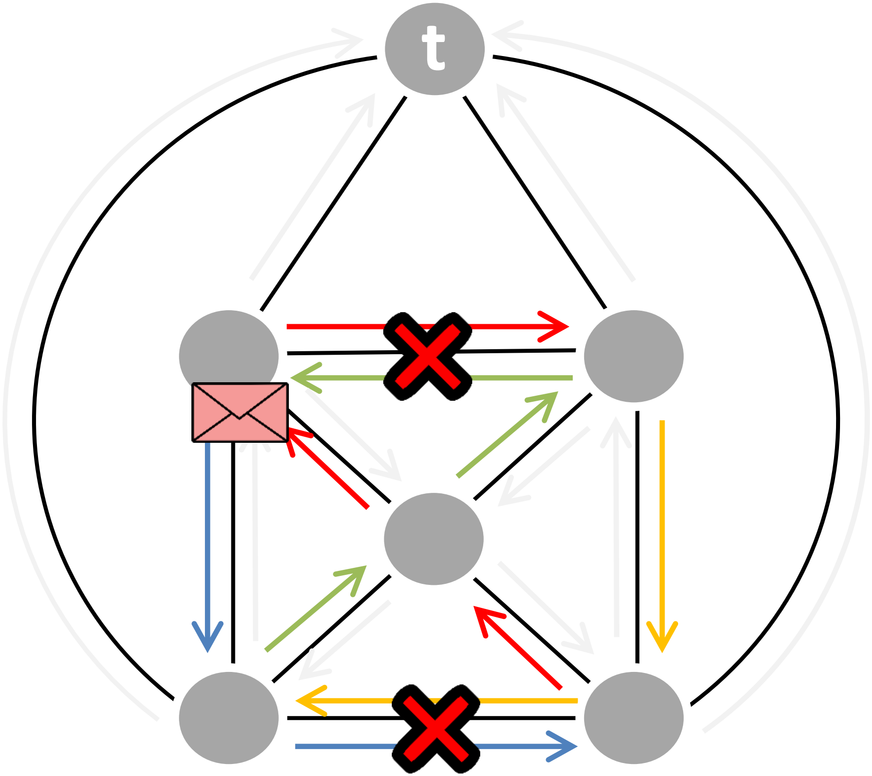
Circular arborescence-routing is (k/2-1)-resilient

Arborescence order

1	2	3	4

Go along arborescence 2 to destination...



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Arborescence order

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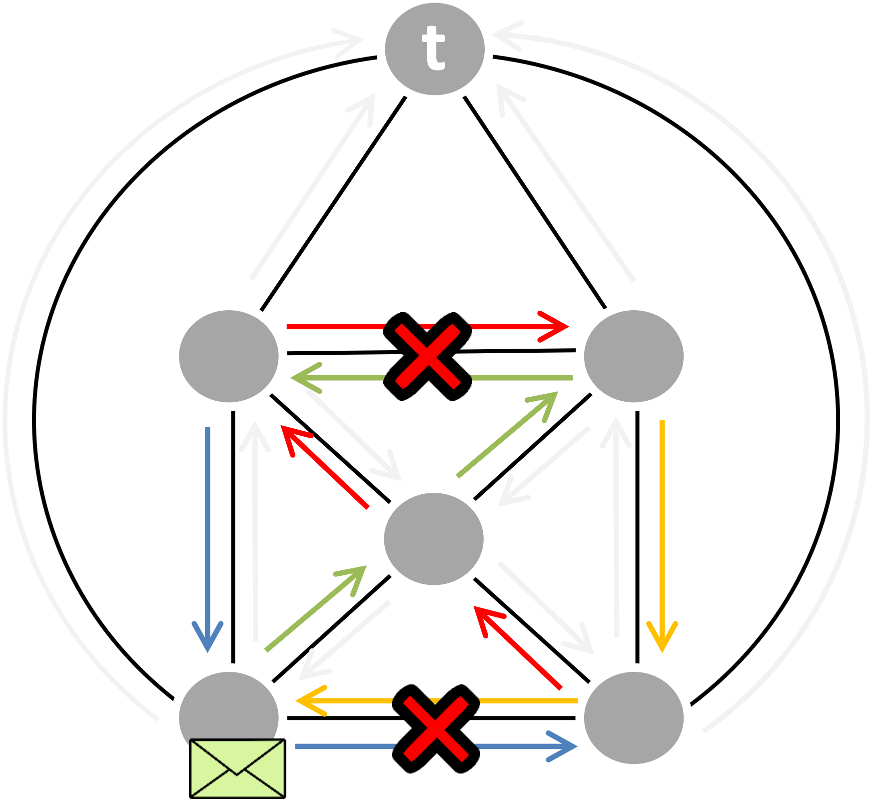
Go along arborescence 3 to destination...



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Arborescence order

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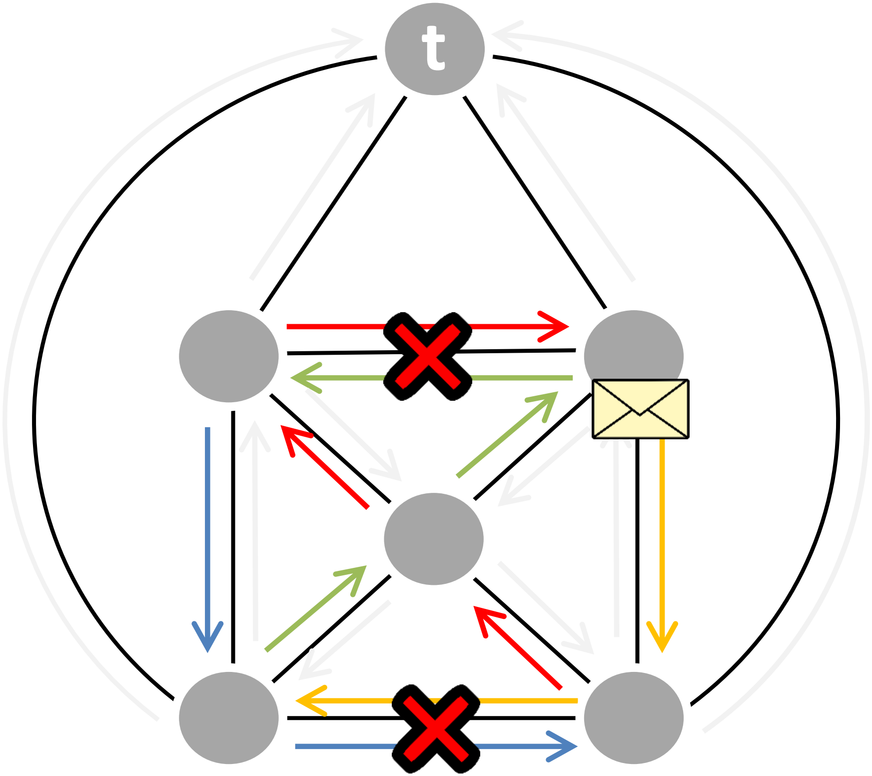
Go along arborescence 4 to destination...



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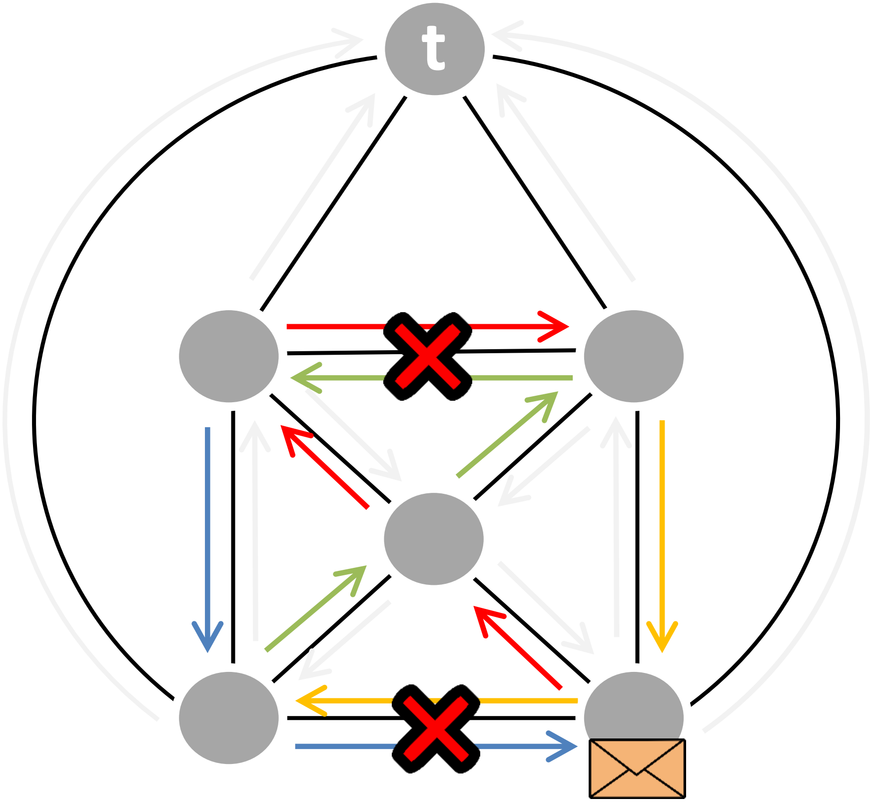


Intuition: each single failure may affect two arborescences

All k=4 arborescences used (2 failures disconnected affected all four): LOOP!

Credits: Marco Chiesa

An Alternative Algorithm: Bouncing Arborescence

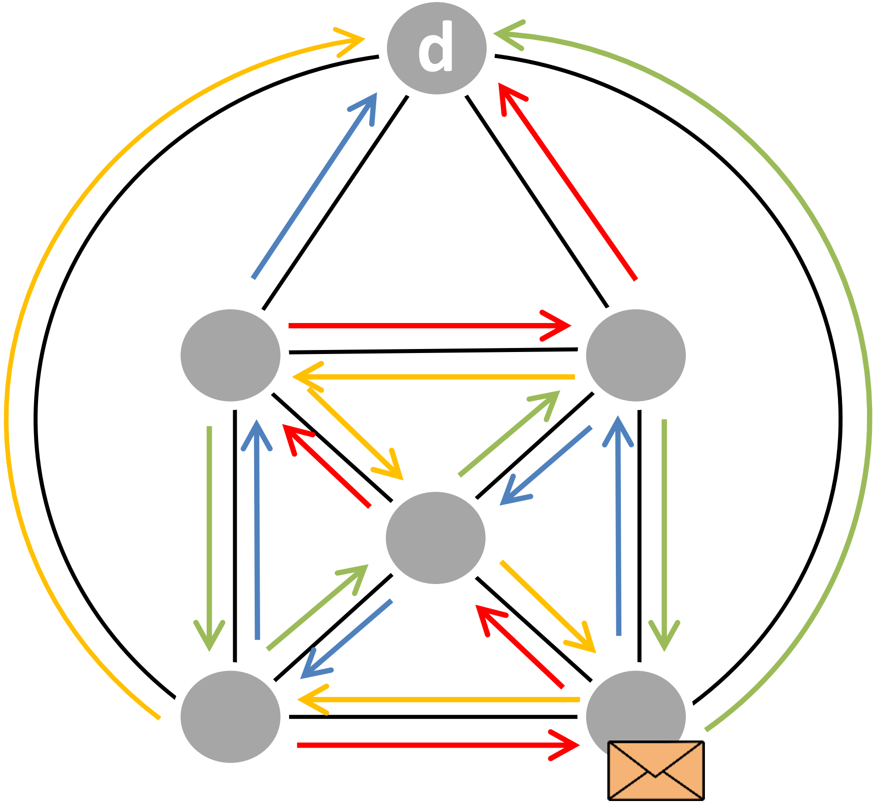
Bouncing-arborescence algorithm:

- Reroute on the tree that shares the failed link

This algorithm is ***1-resilient***.

Bouncing-Arborescence is 1-Resilient

Start with red…



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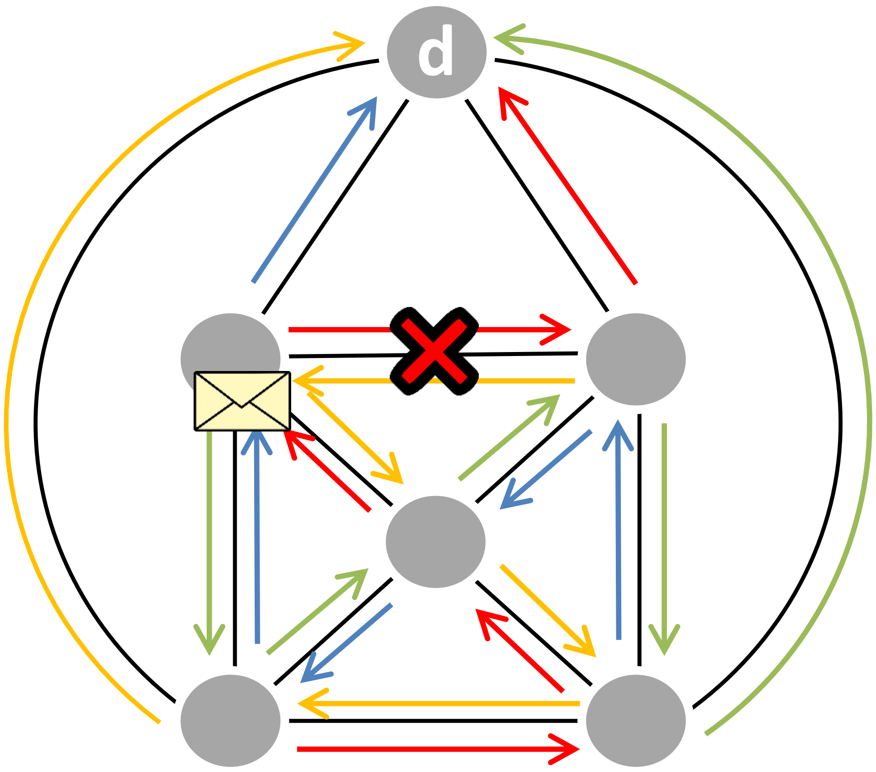
Bouncing-Arborescence is 1-Resilient

… bounce to yellow…



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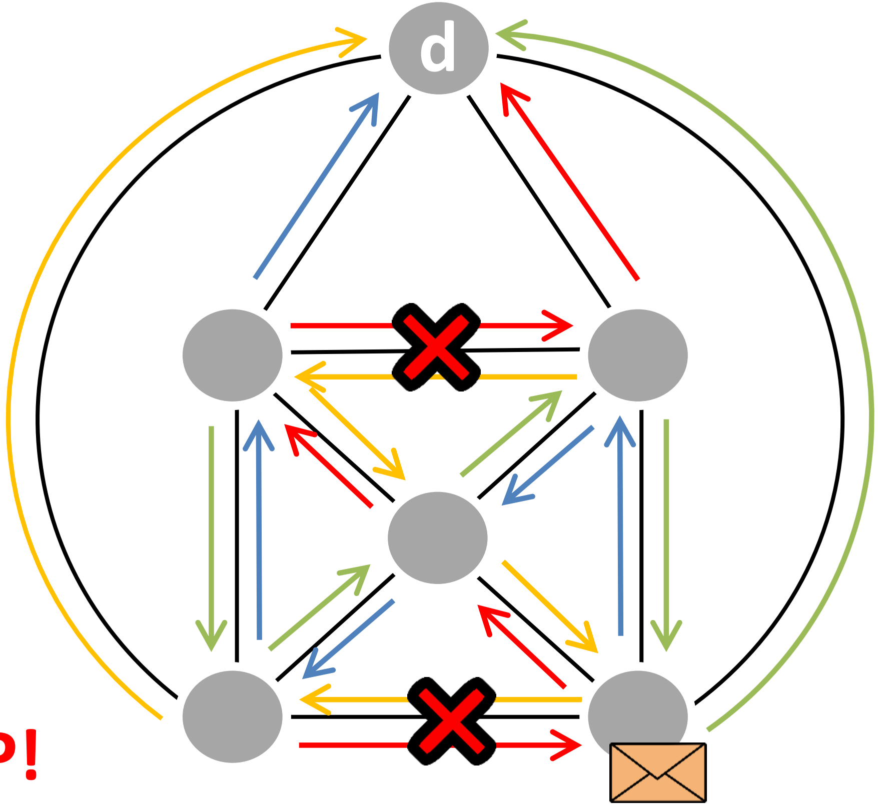
Bouncing-Arborescence is 1-Resilient

… bounce to red (again!)…

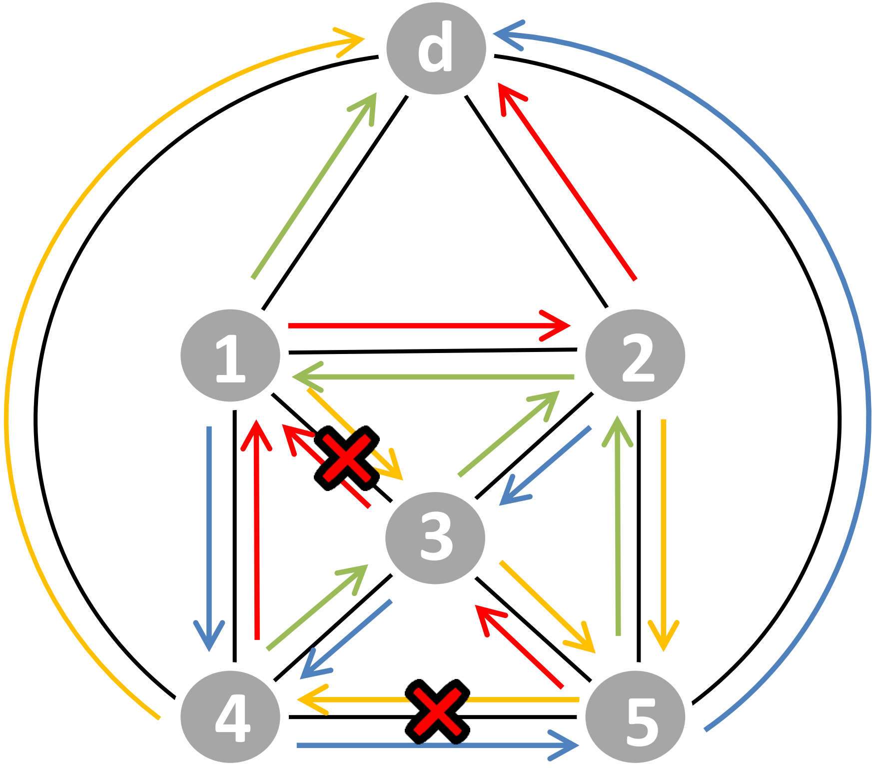


LOOP!

Credits: Marco Chiesa

Idea: Bounce on „Good Arborescences“

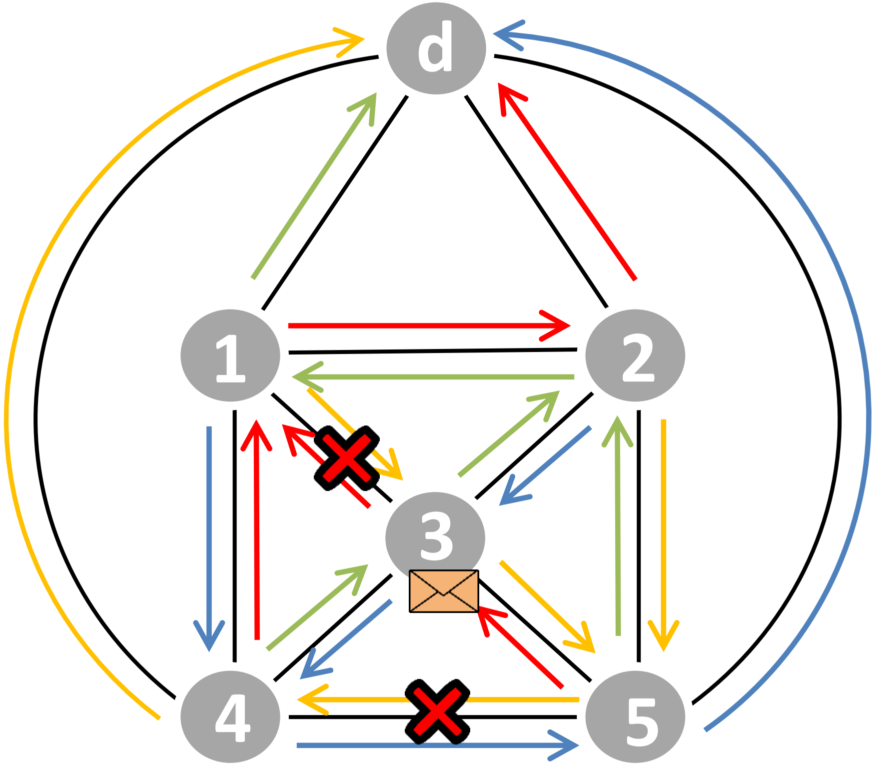
- Define **well-bouncing arc**:
  - When bounce get to the destination
  - Without hitting any other failures



Credits: Marco Chiesa

Idea: Bounce on „Good Arborescences“

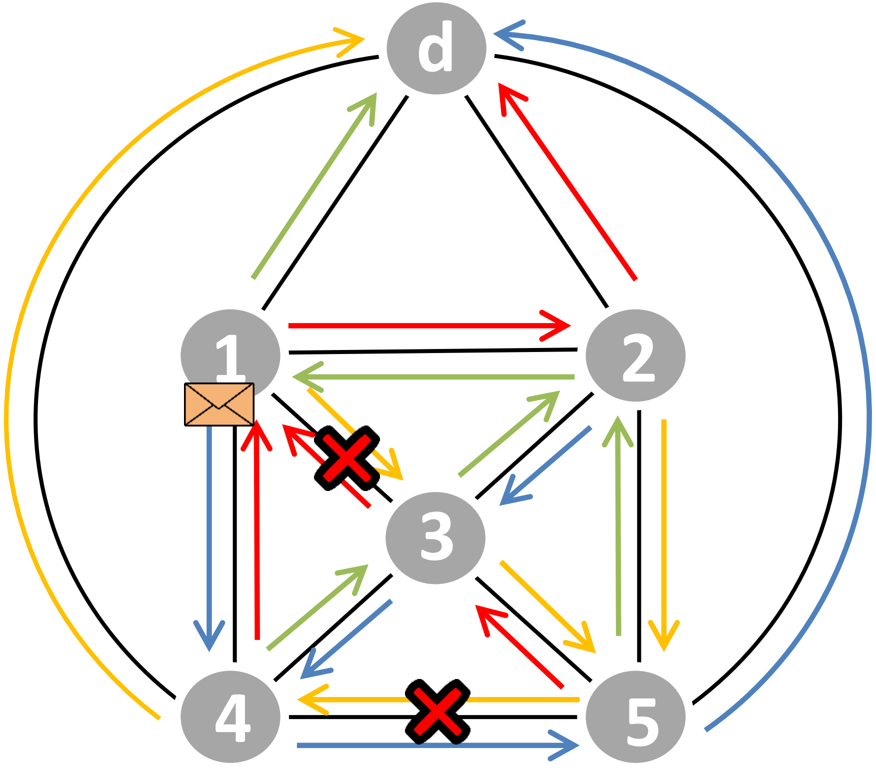
- Define **well-bouncing arc**:
  - When bounce get to the destination
  - Without hitting any other failures
  - (3,1) is not well-bouncing



Credits: Marco Chiesa

Idea: Bounce on „Good Arborescences“

- Define **well-bouncing arc**:
  - When bounce get to the destination
  - Without hitting any other failures
  - (3,1) is not well-bouncing
  - (1,3) is well-bouncing



Credits: Marco Chiesa

Idea: Bounce on „Good Arborescences“

- Define **well-bouncing arc**:
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  - (3,1) is not well-bouncing
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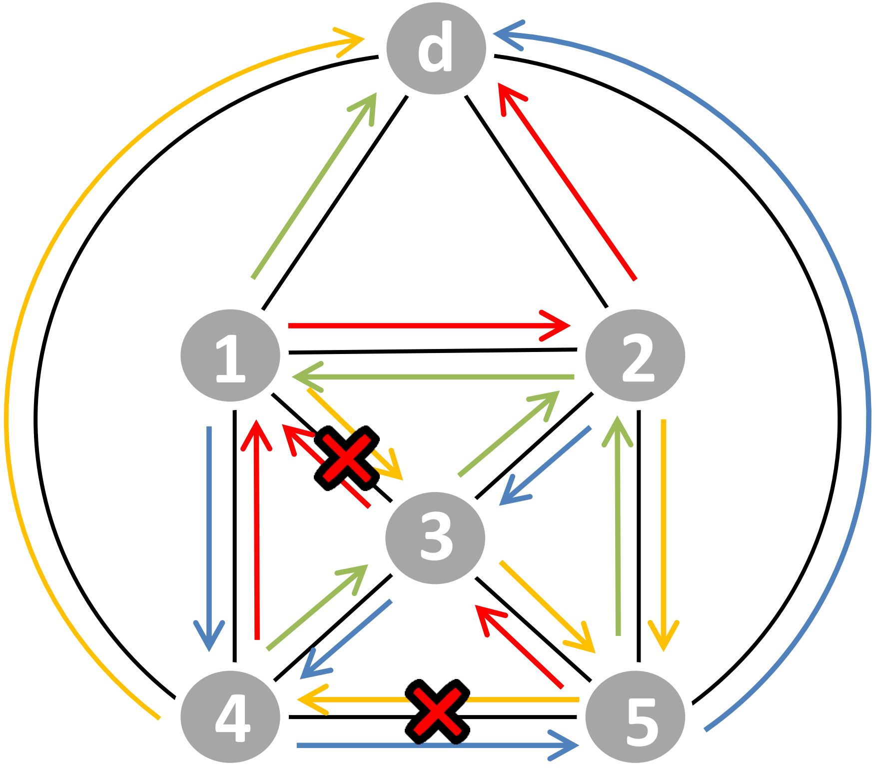
- Define **good arborescence**:
  - every failed arc is well-bouncing



Credits: Marco Chiesa

Idea: Bounce on „Good Arborescences“

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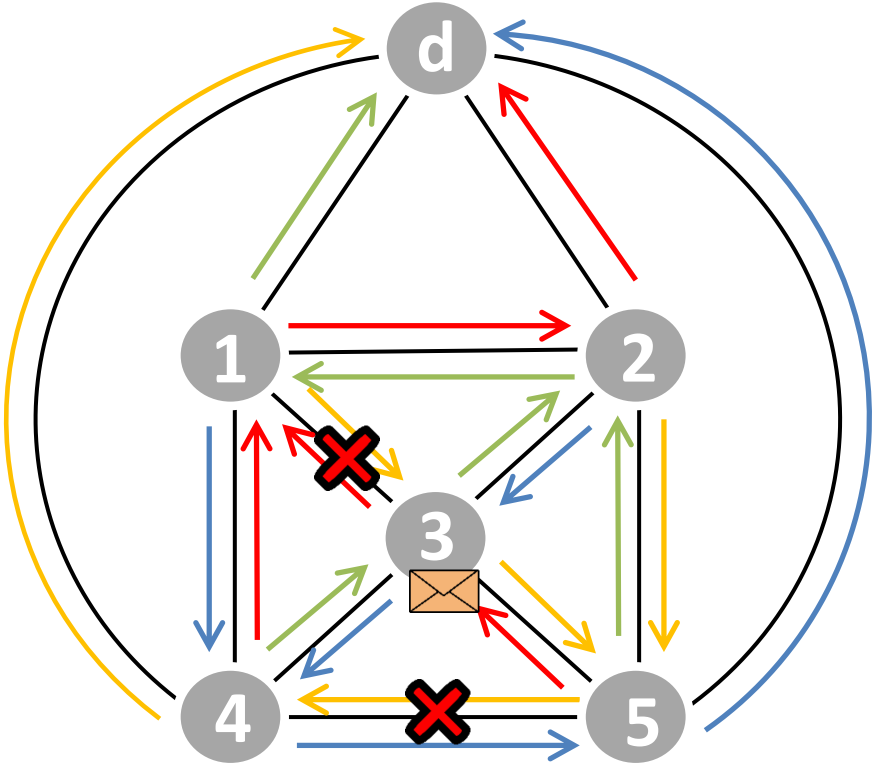
- Define **good arborescence**:
  - every failed arc is well-bouncing
  - Red is not a good arborescence

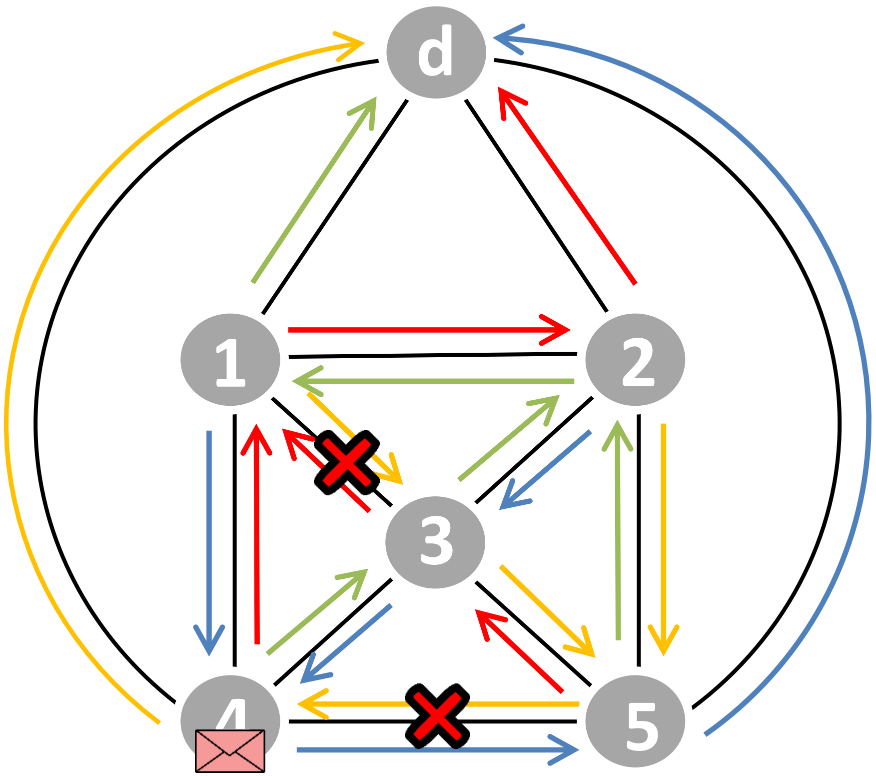


Credits: Marco Chiesa

Idea: Bounce on „Good Arborescences“

- Define **well-bouncing arc**:
  - When bounce get to the destination
  - Without hitting any other failures
  - (3,1) is not well-bouncing
  - (1,3) is well-bouncing

- Define **good arborescence**:
  - every failed arc is well-bouncing
  - Red is not a good arborescence
  - Blue is a good arboresence



Credits: Marco Chiesa

Ideas

- One can show that there is always a good arborescence

- An tempting idea:
  – route on an arborescence X until a failed link is hit:
    - if X is a good arborescence, bounce!
    - otherwise, route circular

- Too good to be true:
  – The "goodness" of an arborescence depends on the actual set of failed links!
  – How do we know a arborescence is good?

Credits: Marco Chiesa

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.

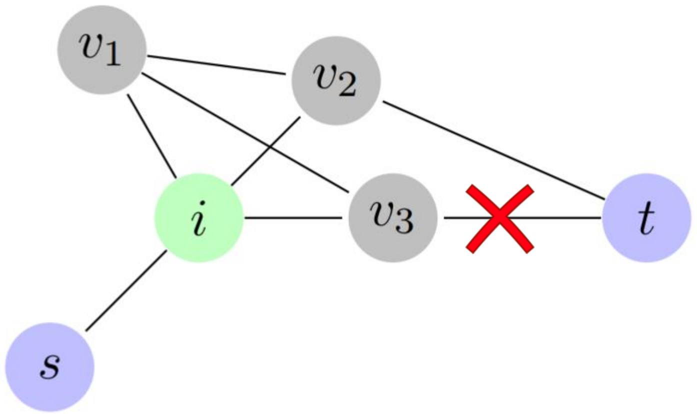
Resilience Criteria

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

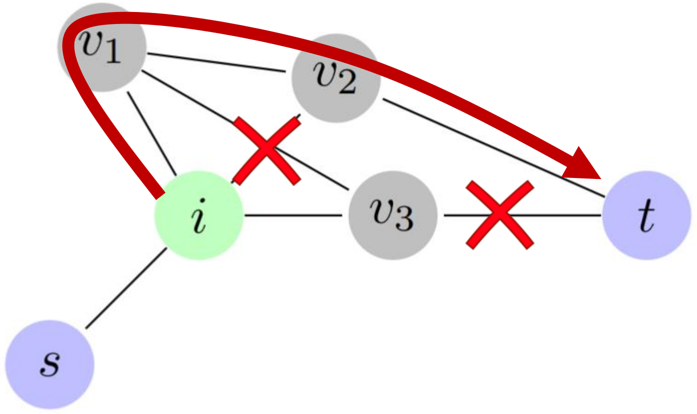
- But not all neighbors are **relevant**: only if potentially required to reach destination!
  - *Without local failures*: just v_2, v_3 for i, since v_1 does not give extra connectivity



Relevant Neighbors

- Routing table of node i: matches in-ports of i to out-ports of i
  - ... 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
  - *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!

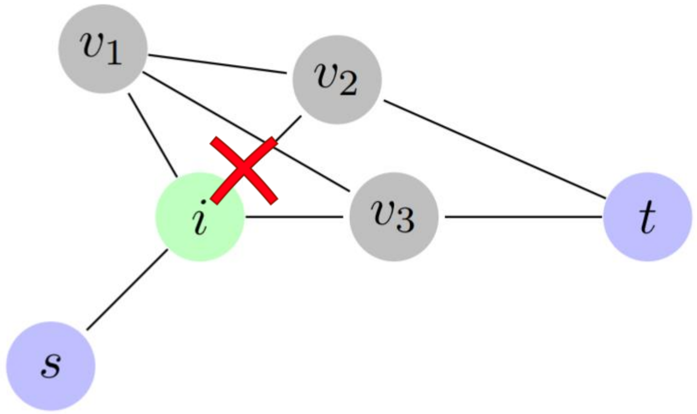


High-level definition of ***relevant***: From the local view-point of the node i, a relevant neighbor might be only neighbor to reach destination (without taking a detour over a current neighbor).

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***

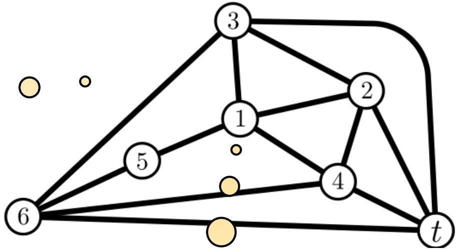
Impossibility: On Planar Graphs

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***

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.

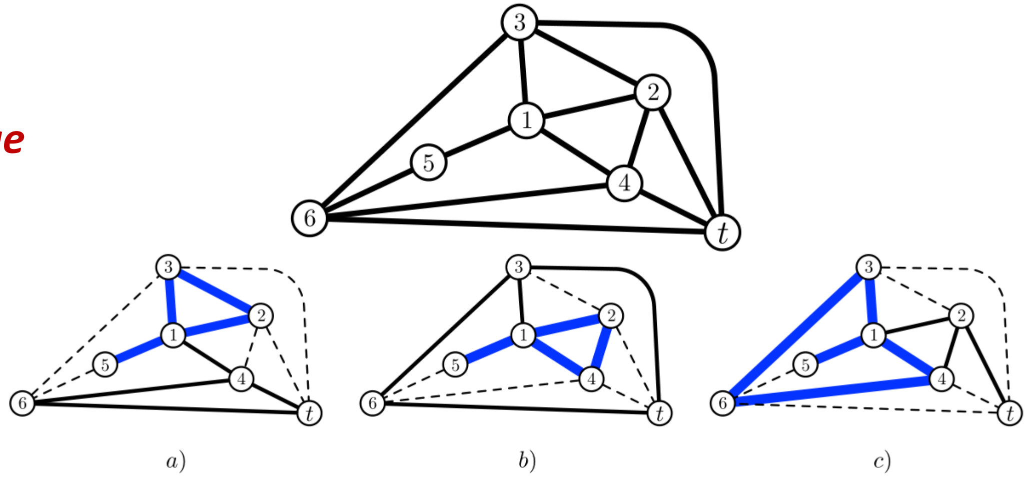
Impossibility: On Planar Graphs

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***

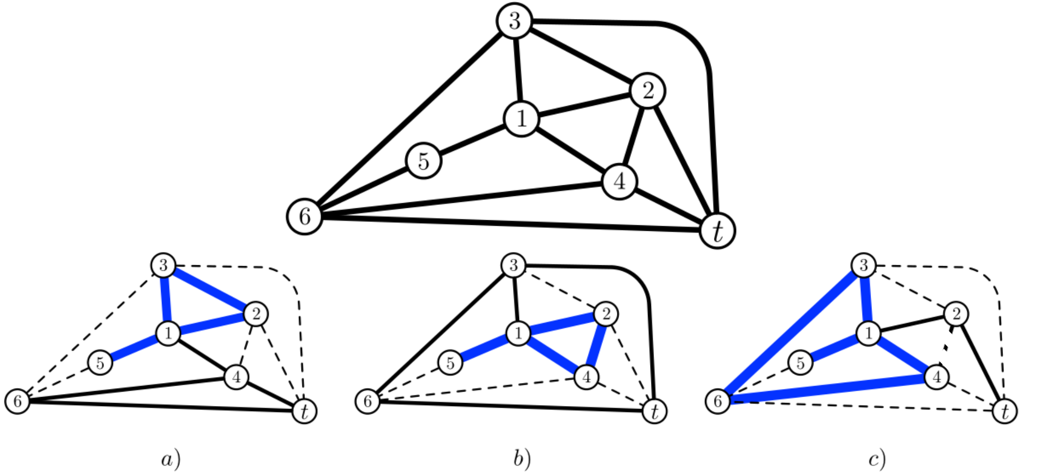
Proof idea, with three cases:

- 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

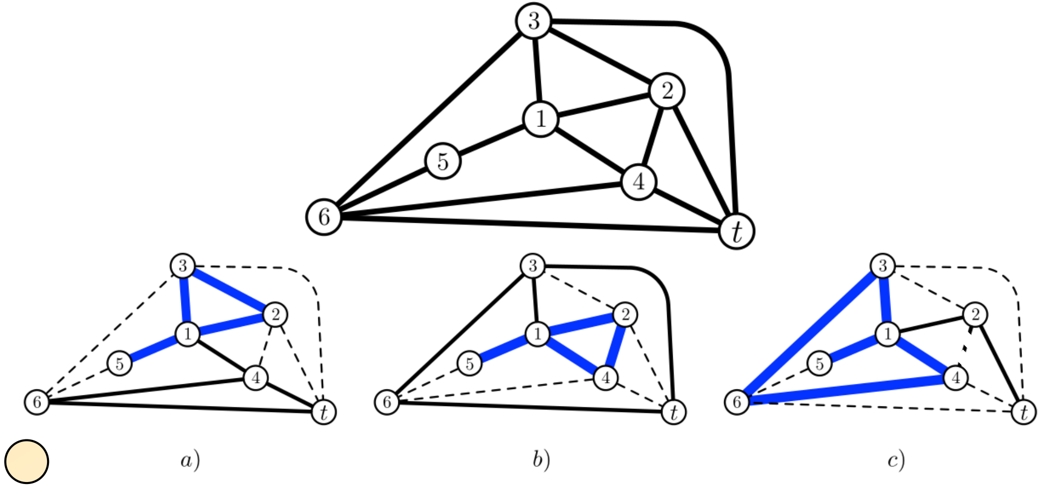


Arriving on inport 5, forwarded to 2.

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



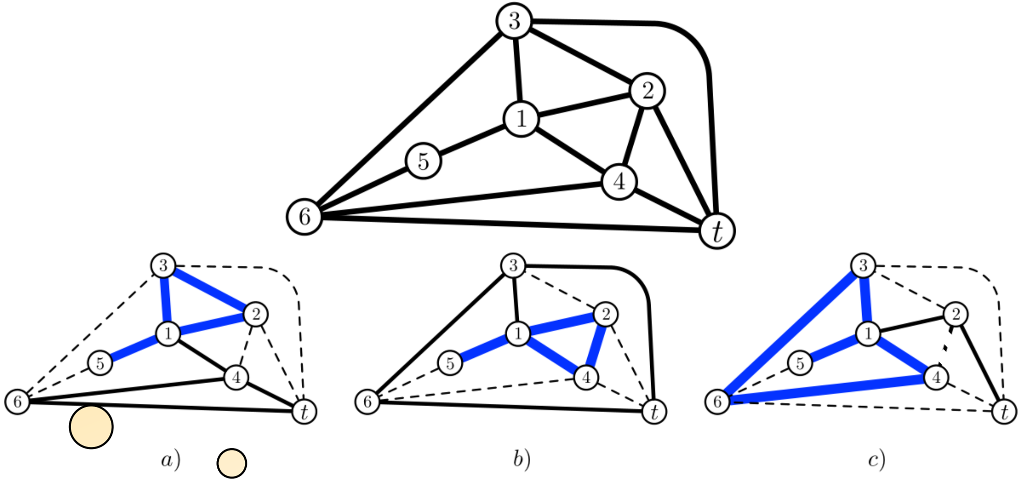
Arriving on inport 5, forwarded to 3.

For node 1:
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)

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



Arriving on inport 5, forwarded to 4.

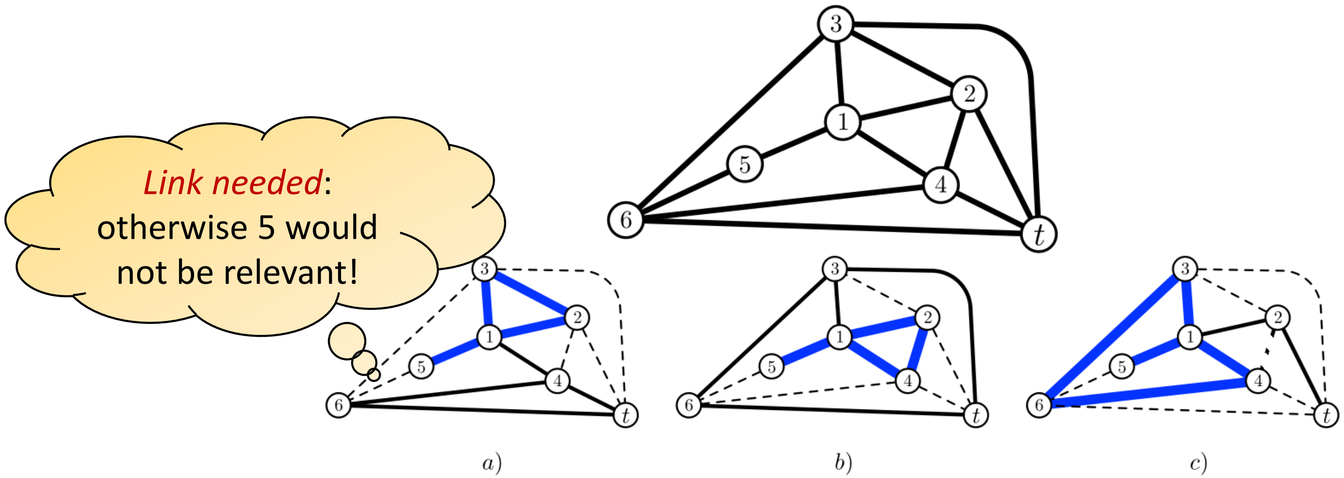
For node 1: 5->2 implies (5,2,3,4) (b) (5,2,4,3) (a)

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.

Impossibility: On Planar Graphs



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

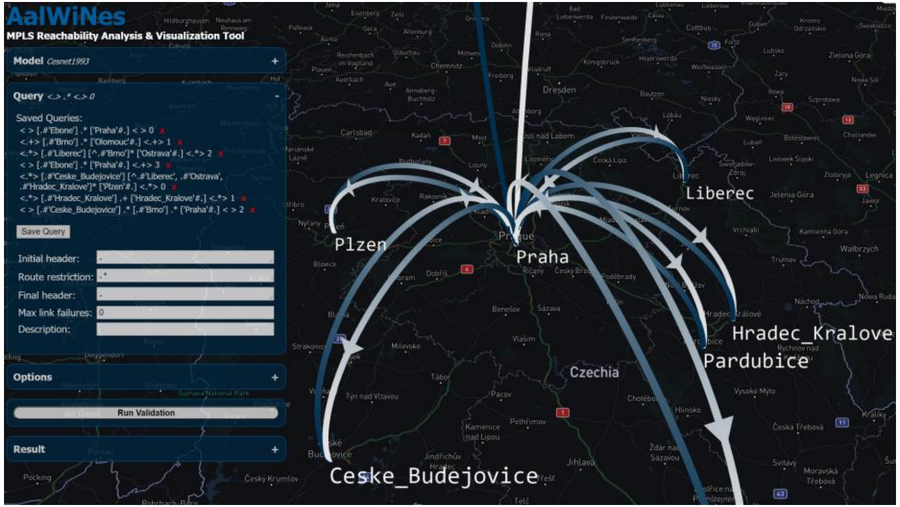
For node 1:
5->3 implies
(5,3,4,2) (a)
(5,3,2,4) (c)

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.

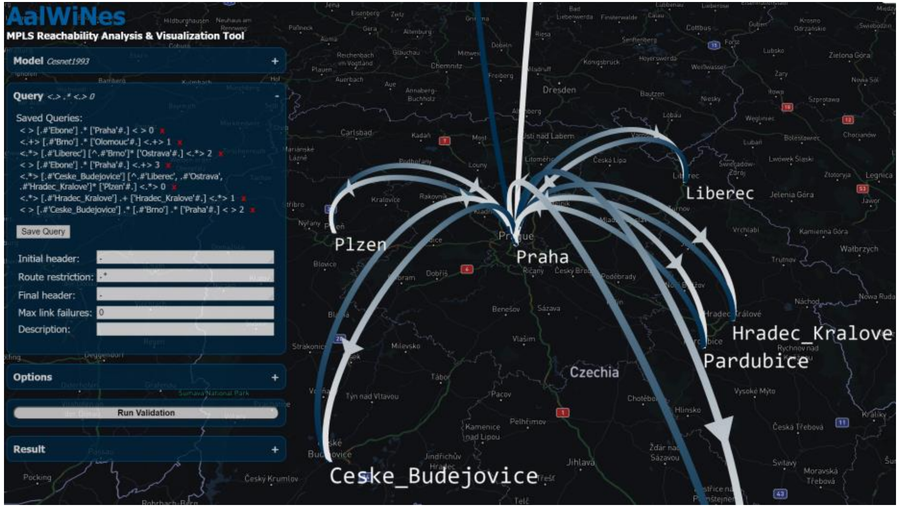
A Pity: Planar Graphs Are Important

- 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**:

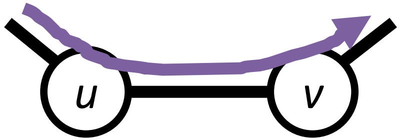
- Via *geometric routing*, well studied in sensor networks etc.
- Embed graph in the plane s.t. all nodes are on the outer face
  - Note: If a link l belongs to the outer face of a planar graph G, it also belongs to the outer face for all subgraphs of G
- Apply *right-hand rule* to forwarding (skipping 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)

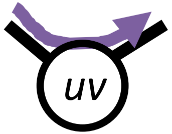
Some Observations

- 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

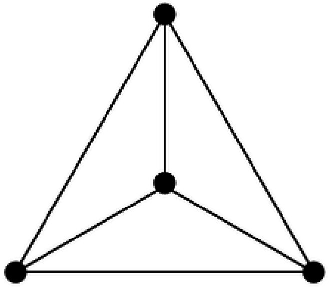


- Combined: Perfect resilience on graph G -> any minor G‘ of G as well
  - But since K_5, $K\_3,3$ not: *non-planar graphs not perfectly resilient*

What we know about perfect resilience

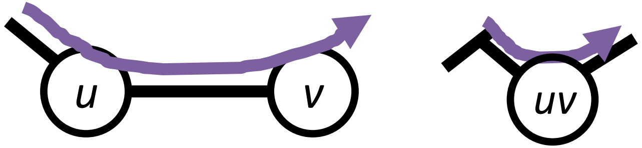
Possible:

- 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



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Questions?