# The Art of Consistent SDN Updates

**Stefan Schmid**

Aalborg University

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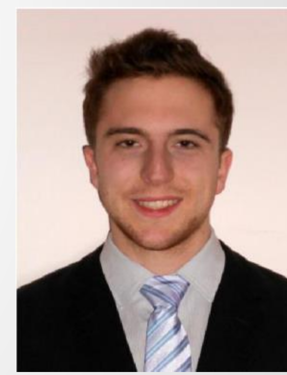
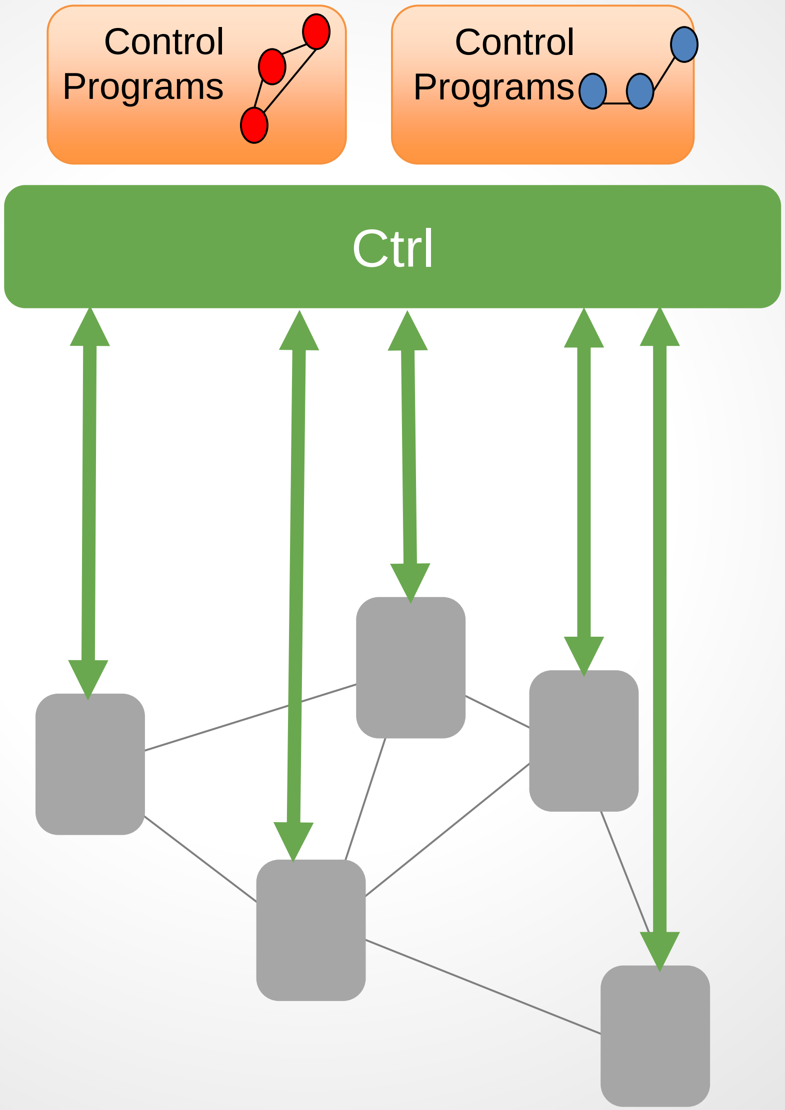



*Smart students in Berlin & Wroclaw:*
Arne Ludwig, Jan Marcinkowski,
Szymon Dudycz, Matthias Rost,
Damien Foucard, Saeed Amiri

# SDN: Algorithms *with a fundamental twist!*

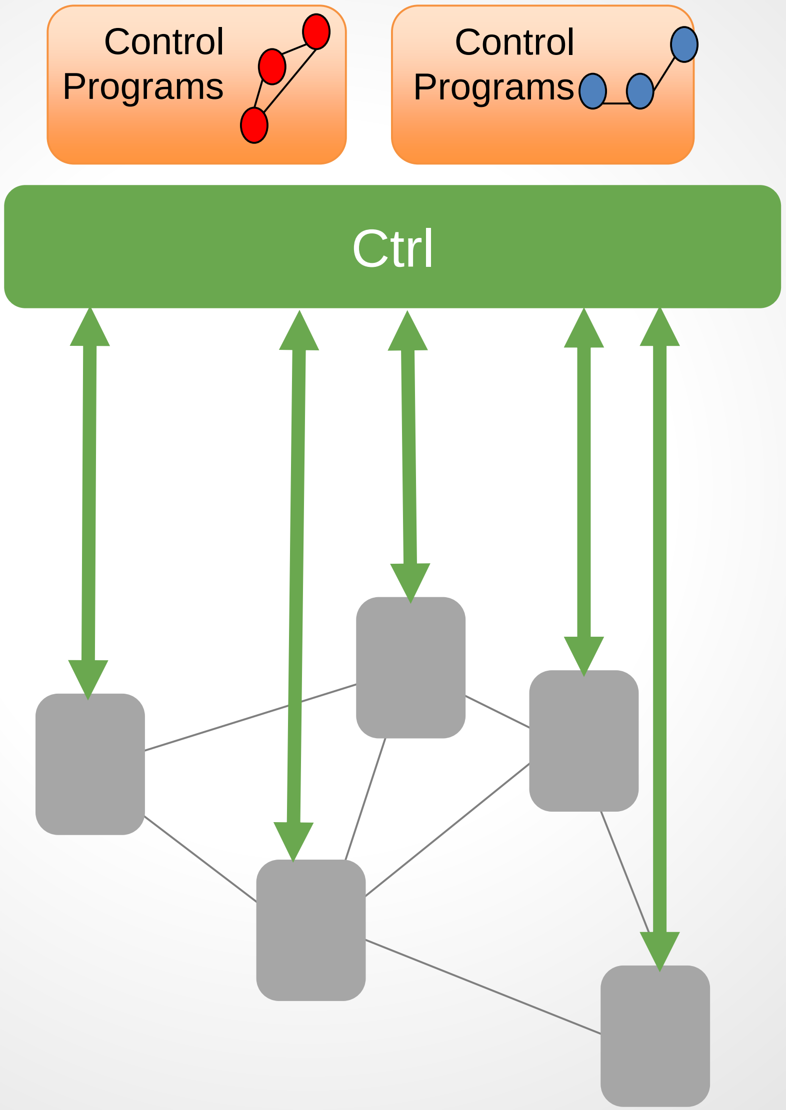


# SDN: Algorithms *with a fundamental twist!*

Applications and Control Plane

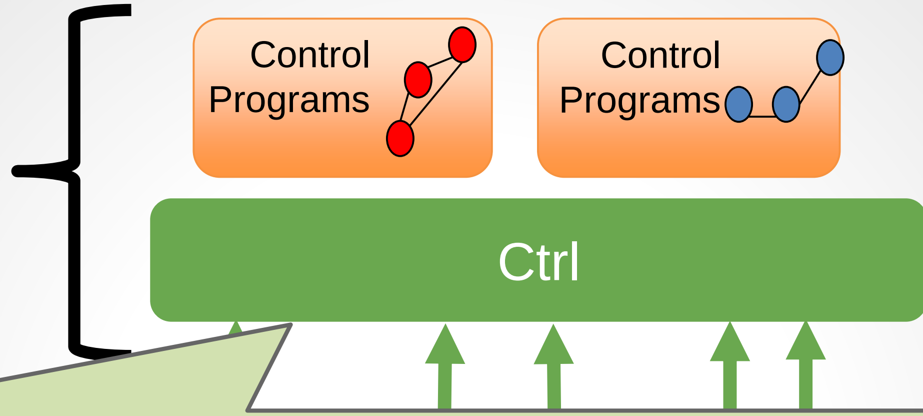
*… and regarding decoupling / inter-connect!*

Data Plane



# SDN: Flexiblities and Constraints

Applications and Control Plane



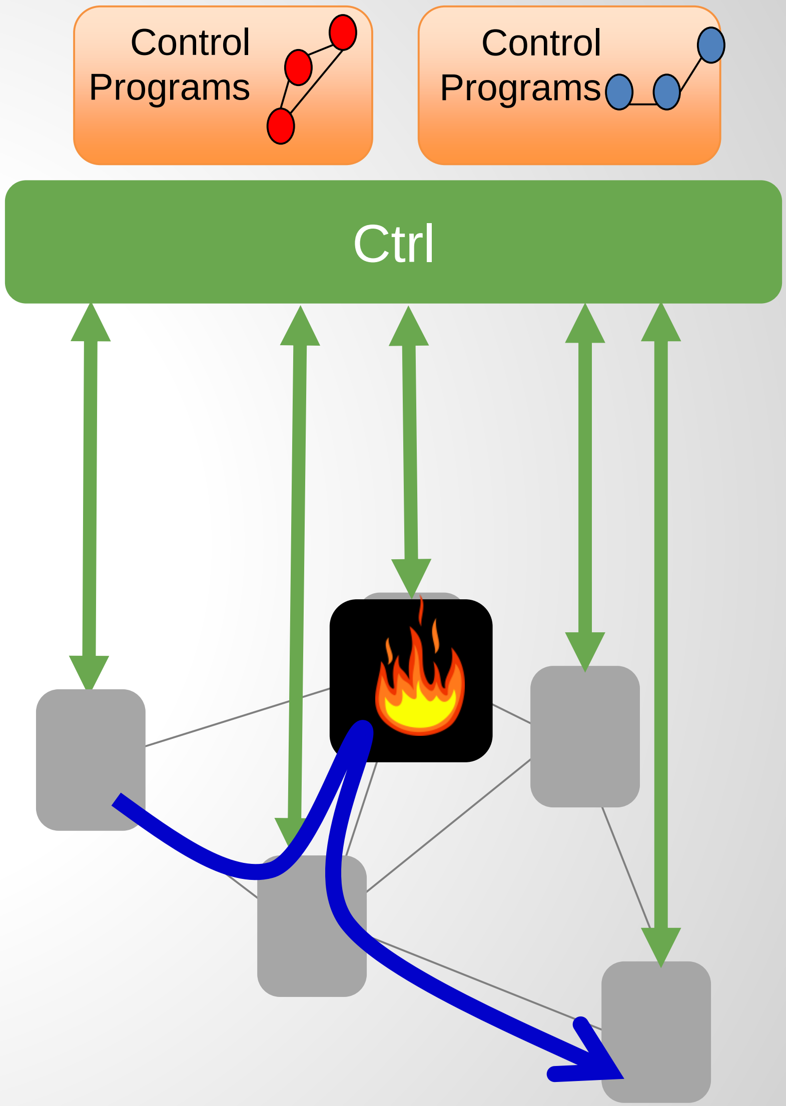

SDN/OpenFlow is about **generality and flexibility**: in terms of **how packets are matched** (L2-L4 header fields and beyond), how **flows are defined** (fine vs coarse granular, proactive vs reactive), events can be handled **centrally vs in a distributed manner**, etc.

Dat

But there are also constraints and challenges: SDN is an inherently **asynchronous distributed system** (controller decoupled), switches are **simple devices** (not a Turing or even state machine!), IP-routing is prefix based, careful use of dynamic flexibilities: **don't shoot in your foot!**

# Applications: Algorithms *with a twist!*

- Let's consider: Traffic Engineering
  - Circuit routing, **call admission**
  - Raghavan, Wolsey, Awerbuch, etc.
- *SDN twist*: more general/flexible!
  - **Non-shortest** paths and more
  - Enables **complex network services:** steer traffic through middleboxes i.e. **waypoints** (firewall, proxy etc.): paths may contain **loops**!
  - More than independent routing per segment: **none-or-all segment admission control, joint optimization**
  - E.g., LP relaxation (Raghavan et al.): how to **randomly round and decompose complex requests**?



# Applications: Algorithms *with a twist!*

Optionally *NFV twist*: where to place NFV (or hybrid SDN)? Facility location / capacitated dominating set, *but*: not distance to but distance *via function(s)* matters!

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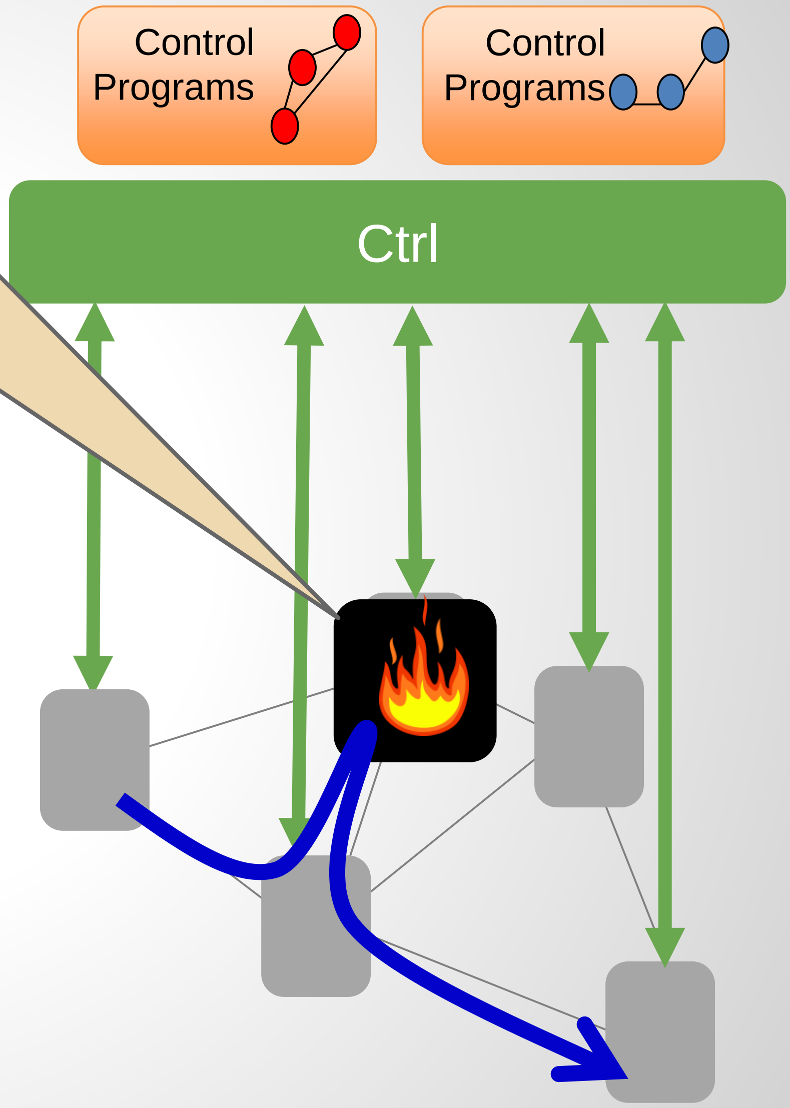

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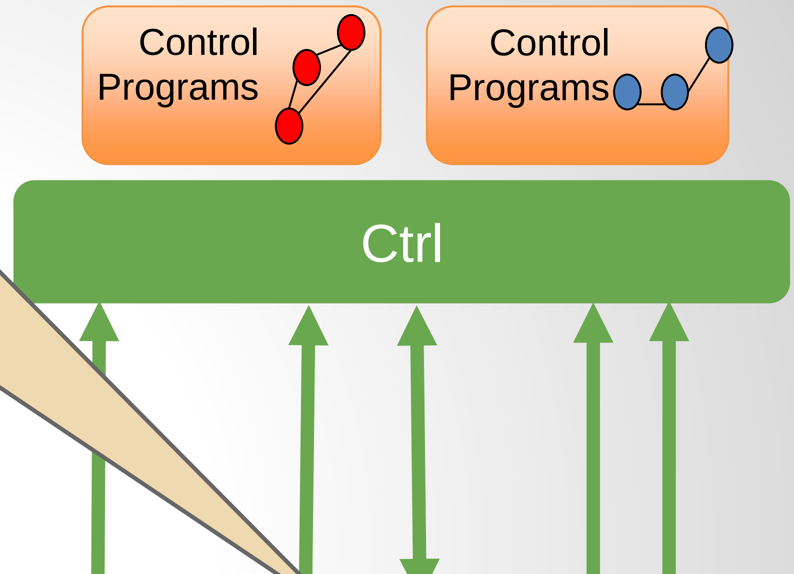


[Online Admission Control and Embedding of Service Chains](#)
Tamás Lukovszki and Stefan Schmid.
22nd International Colloquium on Structural Information and Communication Complexity (**SIROCCO**), Montserrat, Spain, July 2015.

[An Approximation Algorithm for Path Computation and Function Placement in SDNs](#)
Guy Even, Matthias Rost, and Stefan Schmid.
ArXiv Technical Report, March 2016.

[Service Chain and Virtual Network Embeddings: Approximations using Randomized Rounding](#)
Matthias Rost and Stefan Schmid.
ArXiv Technical Report, April 2016.

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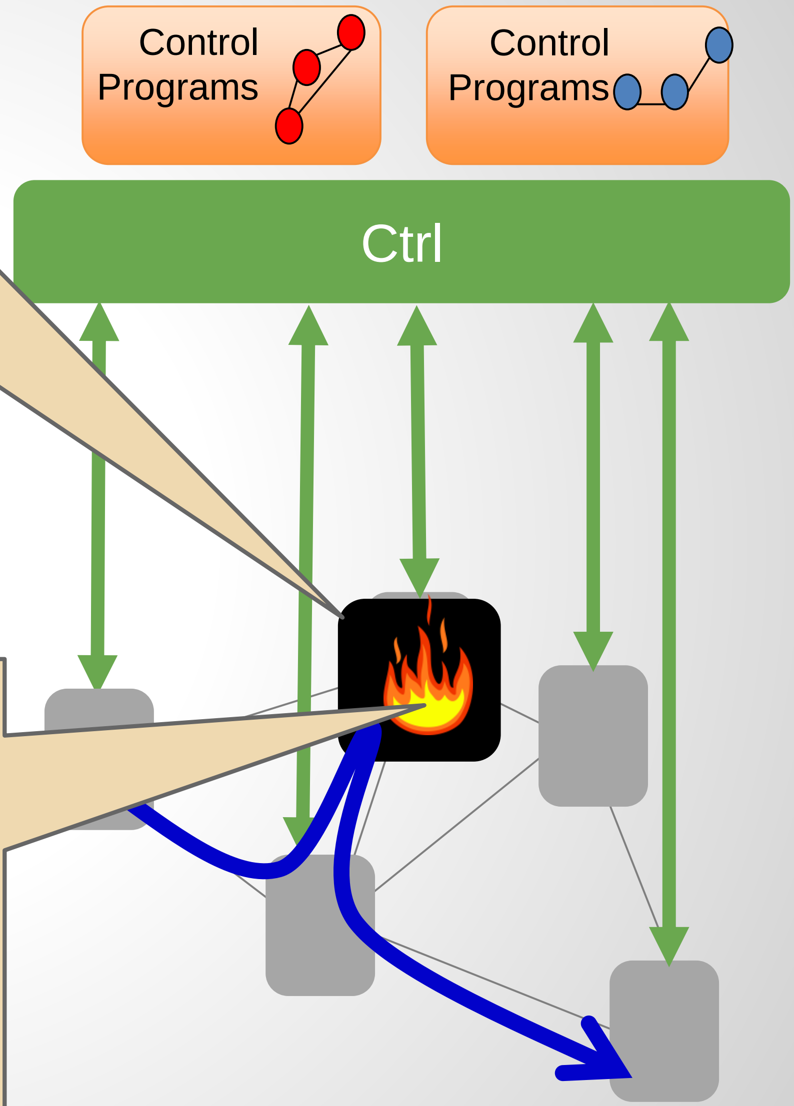
Migration upon each new request undesirable: want **incremental deployment**! Related to submodular capacitated set cover and scheduling (Fleischer, Khuller), *but* **end-to-end**.

**decompose complex requests**?



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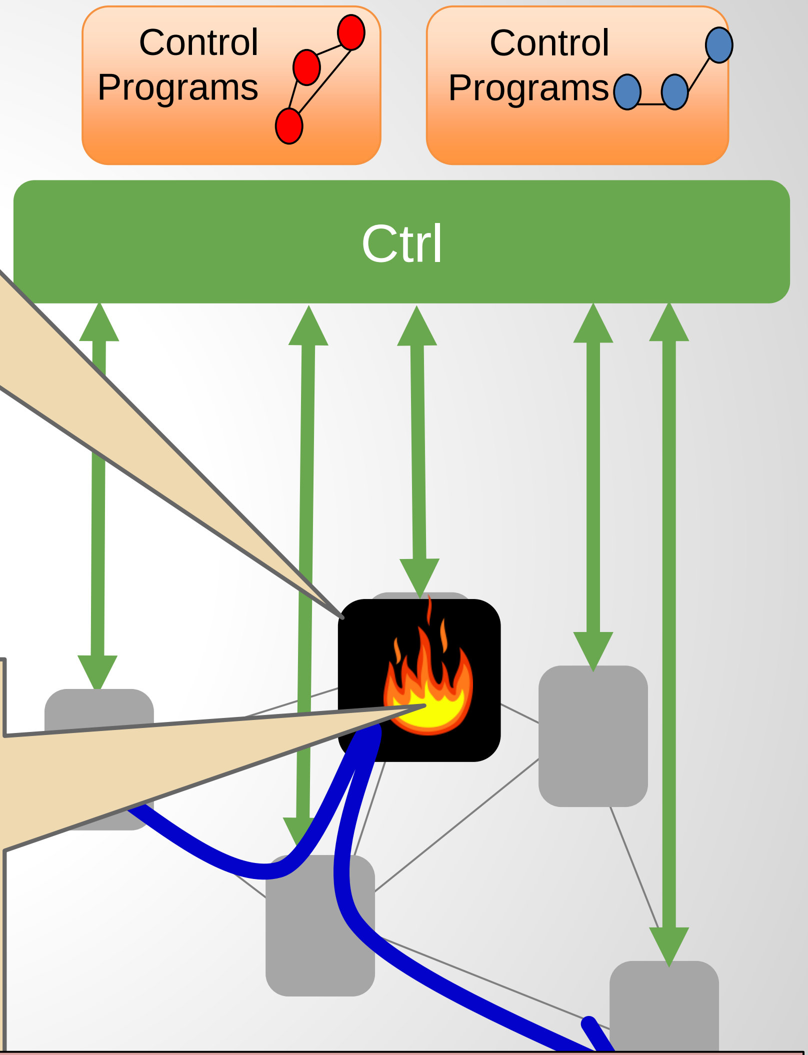
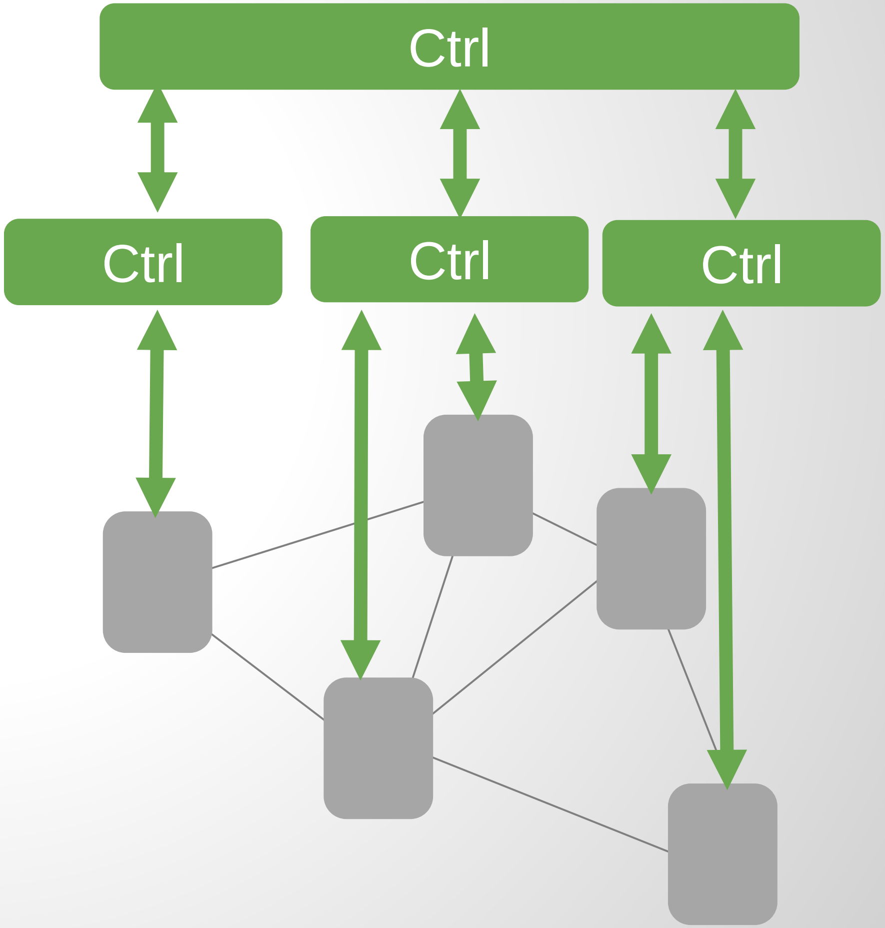



[It's a Match! Near-Optimal and Incremental Middlebox Deployment](#)
Tamás Lukovszki, Matthias Rost, and Stefan Schmid.
ACM SIGCOMM Computer Communication Review (**CCR**), January 2016.

# Control Plane: Algorithms *with a twist!*

- Reduce **latency and overhead**: What can be computed locally?
  - Routing vs heavy-hitter detection?
  - LOCAL model! Insights apply: **verification vs optimization**




- *SDN twist: pre-processing!*
  - Hard in LOCAL: **symmetry breaking**! But unlike **ad-hoc networks**: no need to discover network from scratch
  - Topology events **less frequent** than flow related events
  - If **links fail**: **subgraph**! Find recomputed structures that are still useful in subgraph (e.g., **proof labelings**)
  - Precomputation known to help for relevant problems: **load-balancing / matching**

# Control Plane: Algorithms *with a twist!*

How to make control plane robust? **Software transactional memory** problem:
**network configuration = shared memory,**
updates = **transactions**, but with a twist:
flows are uncontrolled, real-time transactions: do not abort! (And not only read!)

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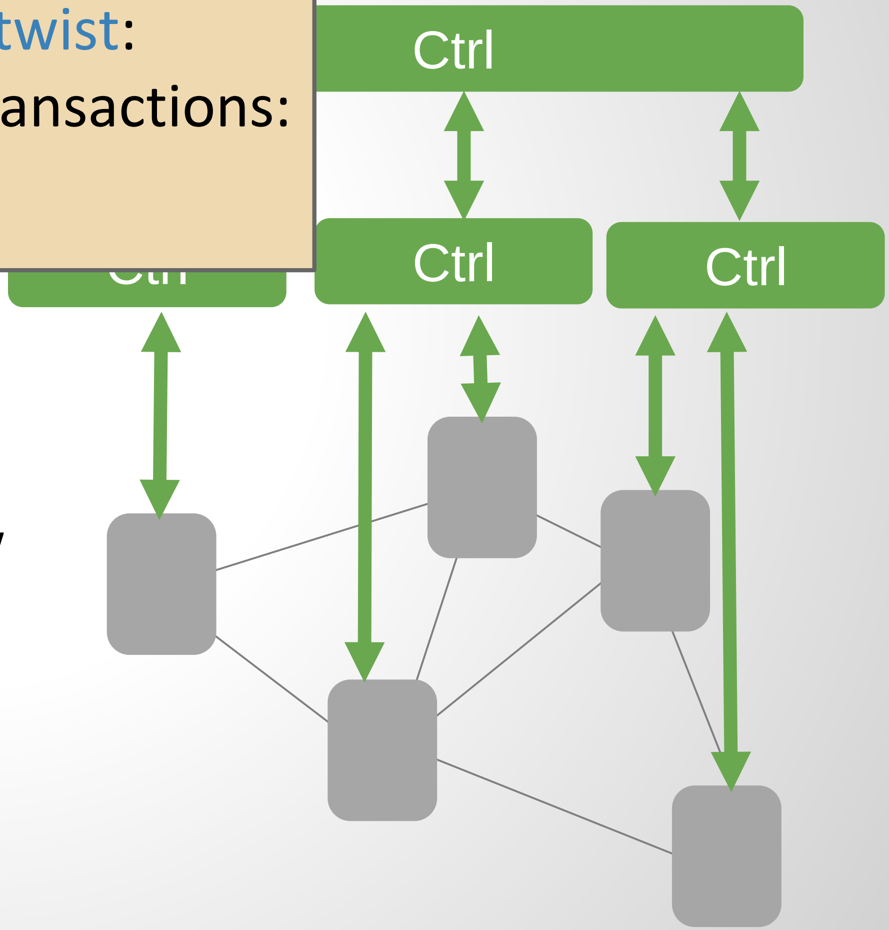

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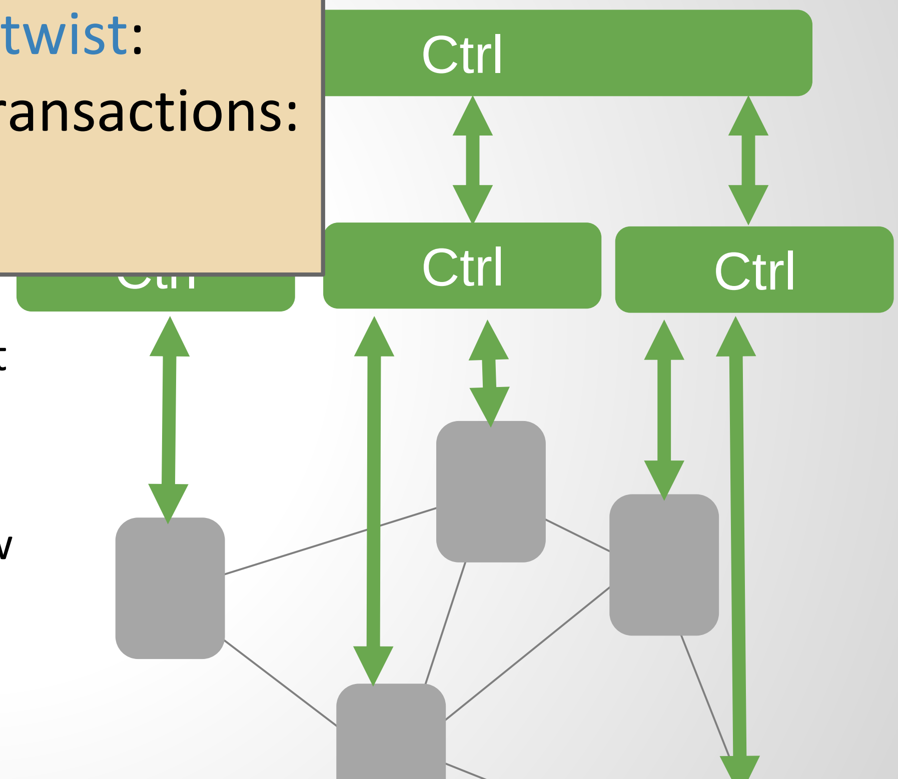


[A Distributed and Robust SDN Control Plane for Transactional Network Updates](#)
Marco Canini, Petr Kuznetsov, Dan Levin, and Stefan Schmid.
34th IEEE Conference on Computer Communications (**INFOCOM**), Hong Kong, April 2015.

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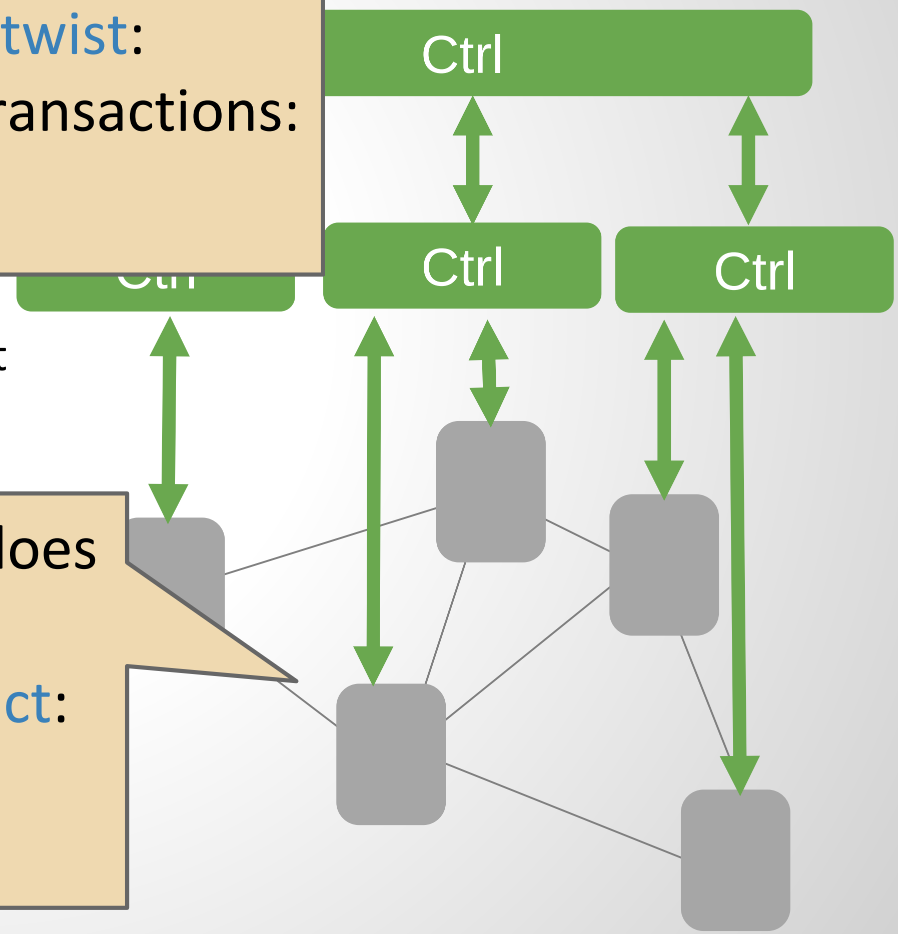
Careful: independent flow spaces does not imply that controllers can **concurrently** update without conflict:
e.g., due to **shared embedding**!
Atomic read-modify-write?




relevant problems: **load-balancing / matching**

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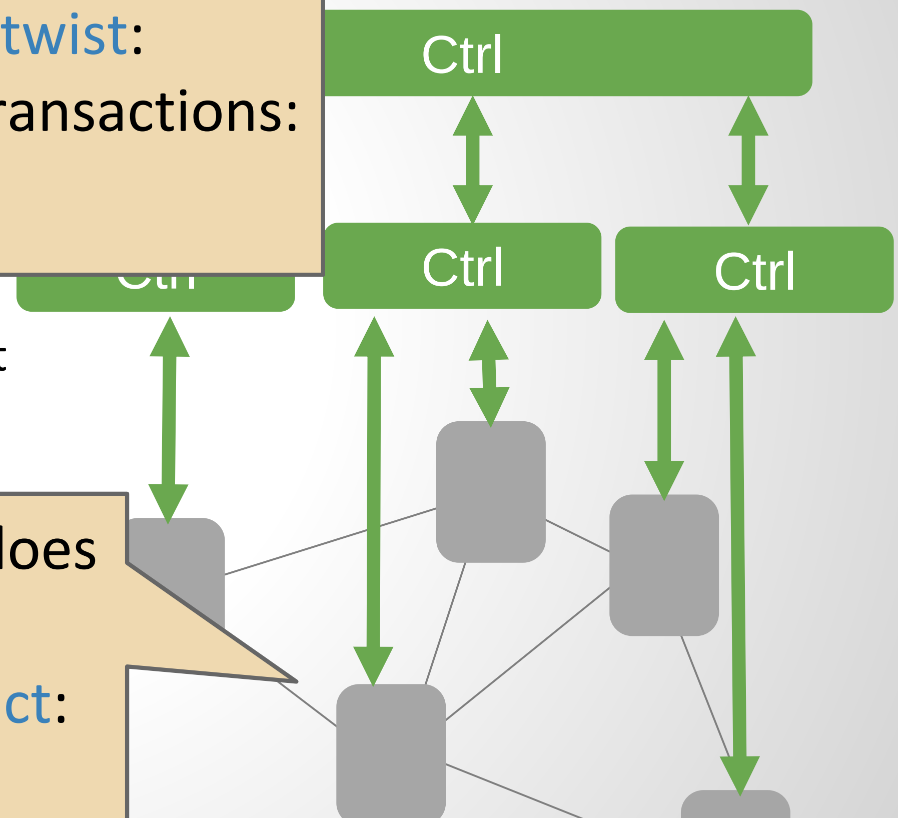


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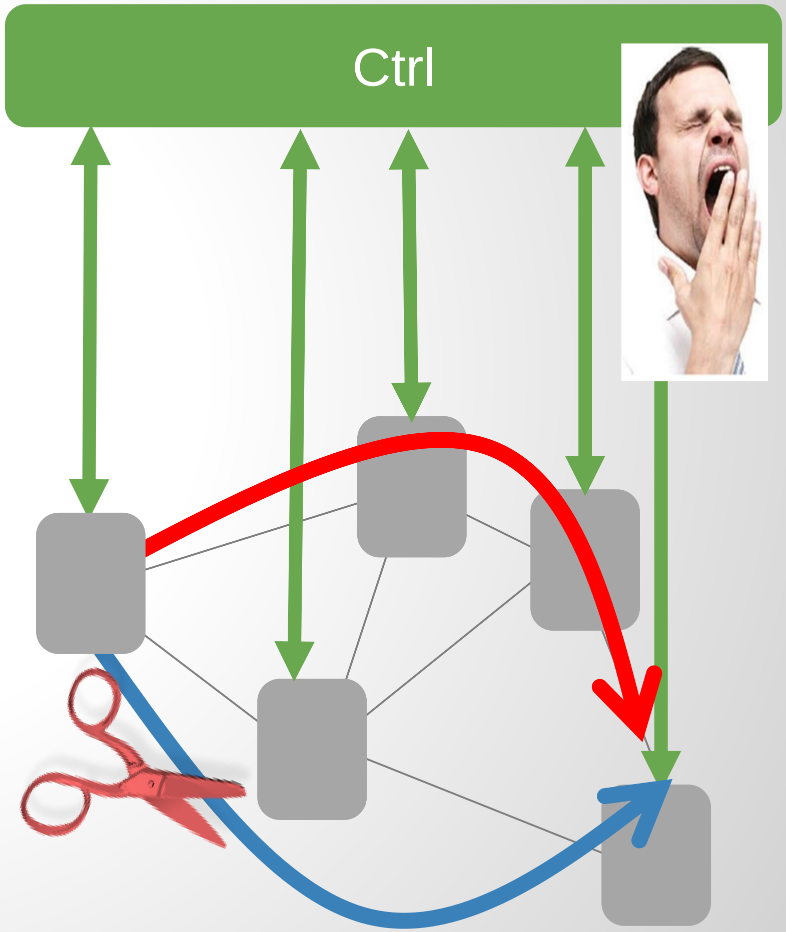
[In-Band Synchronization for Distributed SDN Control Planes](#)
Liron Schiff, Petr Kuznetsov, and Stefan Schmid.
ACM SIGCOMM Computer Communication Review (**CCR**), January 2016.

# Data Plane: Algorithms *with a twist!*

- Even in SDN: Keep some functionality in the data plane!
  - E.g., for **performance**: OpenFlow local fast failover: 1st line of defense

- SDN twist: data plane algorithms operate under **simple conditions**
  - Failover tables are **statically** (proactively) **preconfigured**, **w/o multiple faiures knowledge**
  - At runtime: **local view only** and **header space is scarce resource**
  - W/ tagging: **graph exploration**
  - W/o tagging: **combinatorial problem**
  - Later: **consolidate this with controller**!



# Data Plane: Algorithms *with a twist!*

With **infinite header space** ideal robustness possible. But what about bounded header space? And resulting route lengths?
**Without good algorithms, routing may disconnect way before physical network does!**

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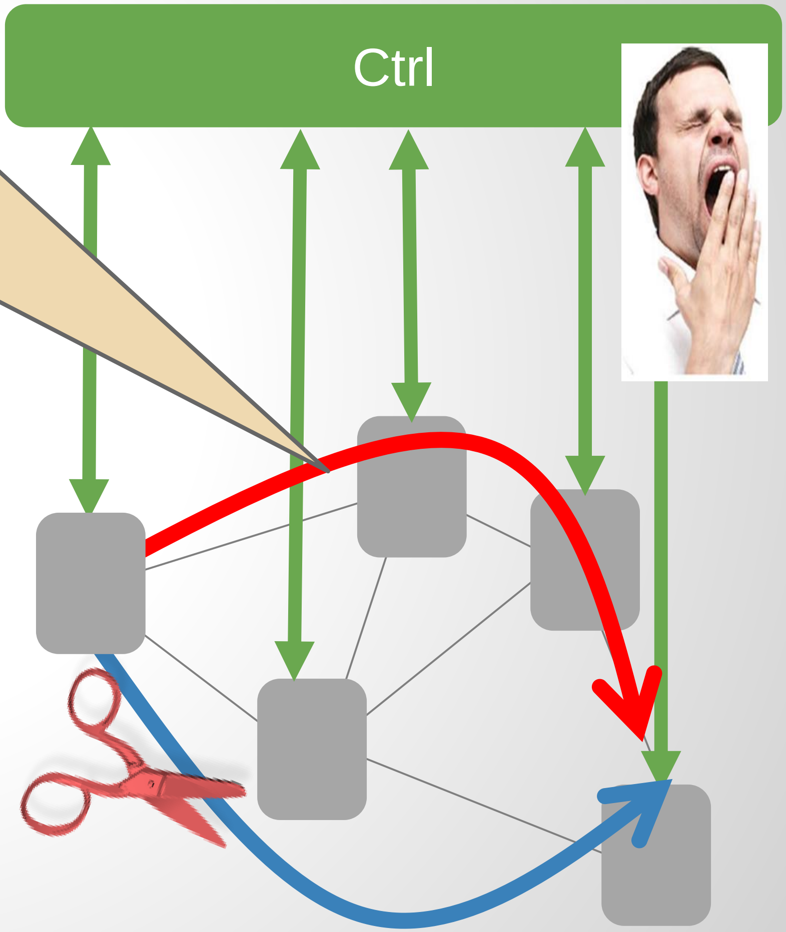

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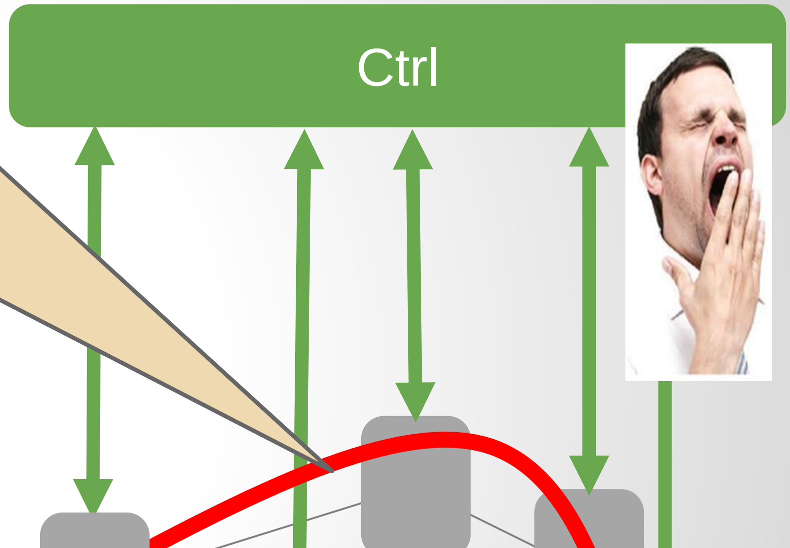
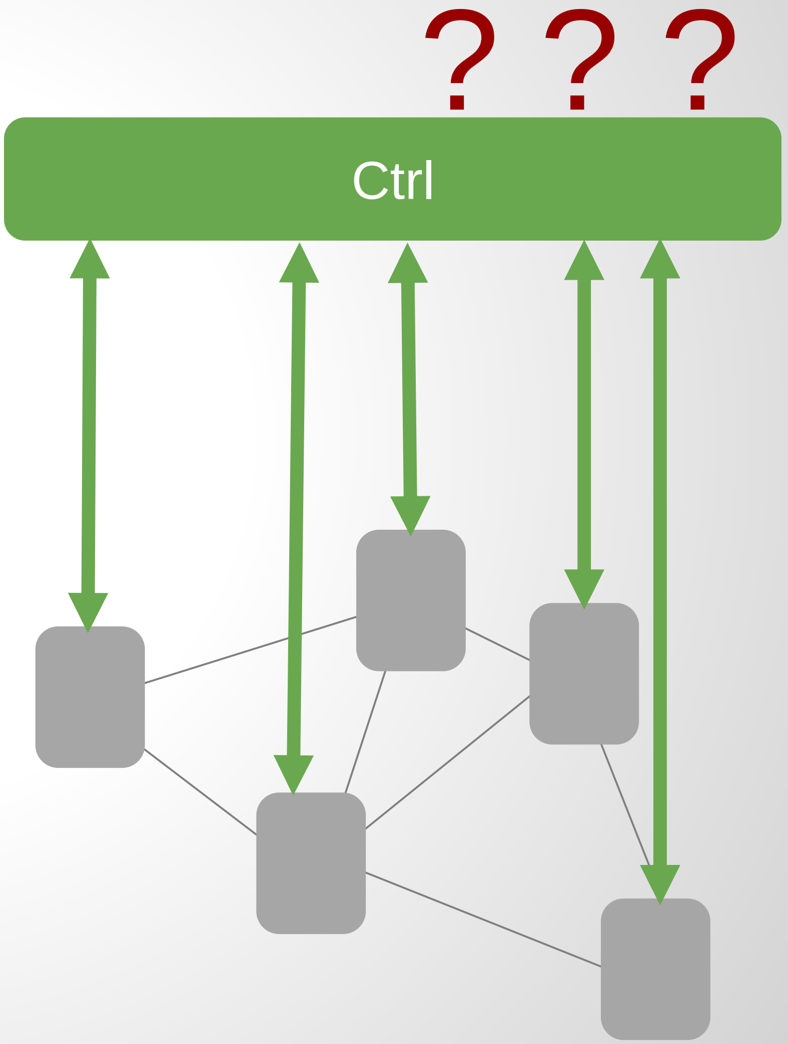



How (Not) to Shoot in Your Foot with SDN Local Fast Failover: A Load-Connectivity Tradeoff
Michael Borokhovich and Stefan Schmid.
17th International Conference on Principles of Distributed Systems (**OPODIS**), Nice, France, Springer LNCS, December 2013.

Provable Data Plane Connectivity with Local Fast Failover: Introducing OpenFlow Graph Algorithms
Michael Borokhovich, Liron Schiff, and Stefan Schmid.
ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking (**HotSDN**), Chicago, Illinois, USA, August 2014.

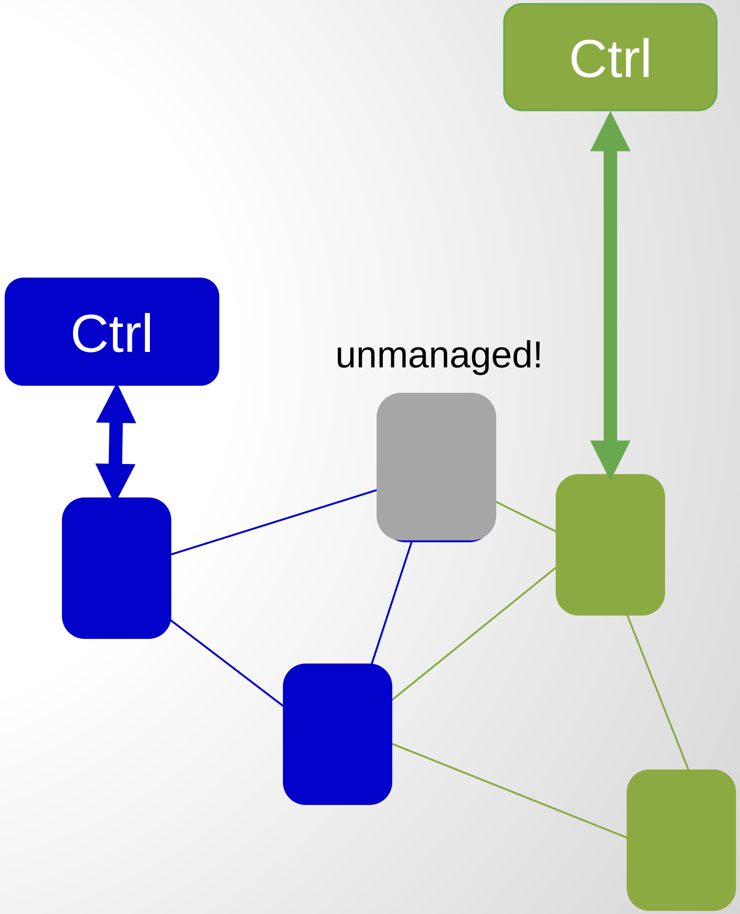
# Decoupling: Algorithms *with a twist!*

- Decoupling already challenging for a single switch!
- Network *Hello World* application: MAC learning
- MAC learning has *SDN twist*: MAC learning SDN controller is decoupled: may miss response and keep flooding!
- Need to **configure rules** s.t. controller stays informed when necessary!



# Decoupling: Algorithms *with a twist!*

- In-band control: cheap but algorithmically challenging!
  - Distributed coordination algorithms to manage switches?
  - Powerful fault-tolerance concept: **self-stabilization**
- *SDN twist*: switches **are simple**!
  - Cannot actively participate in **arbitrary self-stab spanning tree protocols**
  - Controller needs to install tree rules



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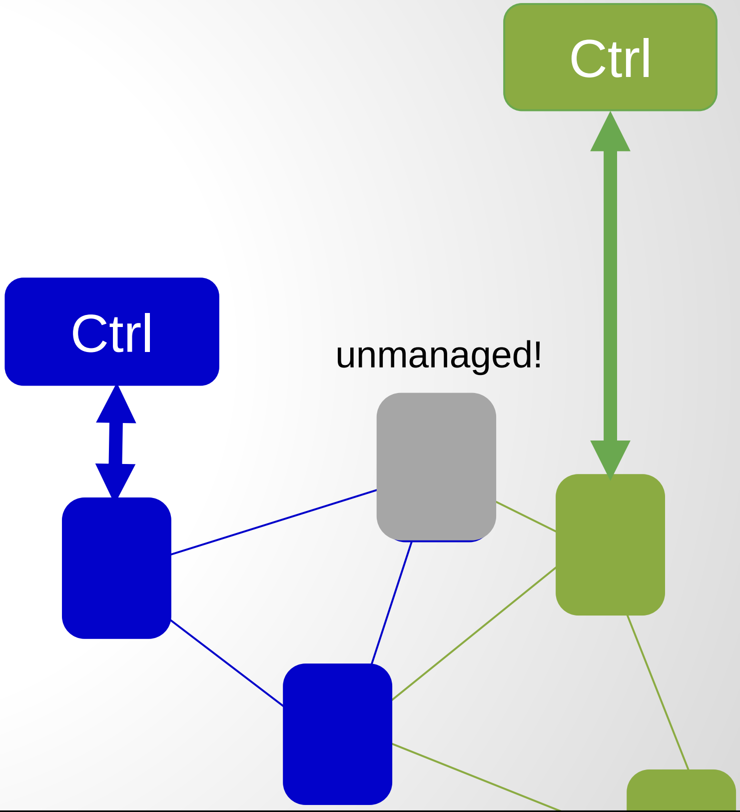
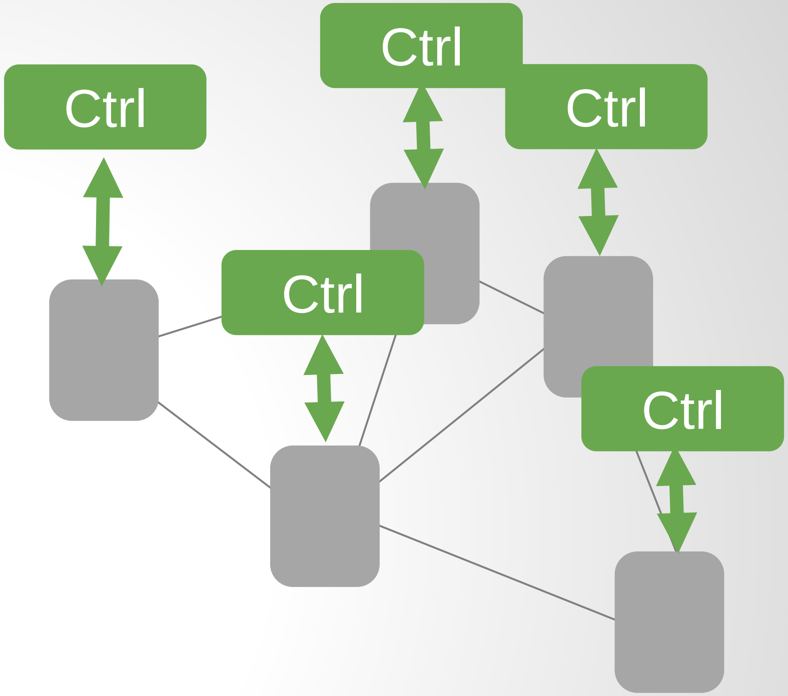


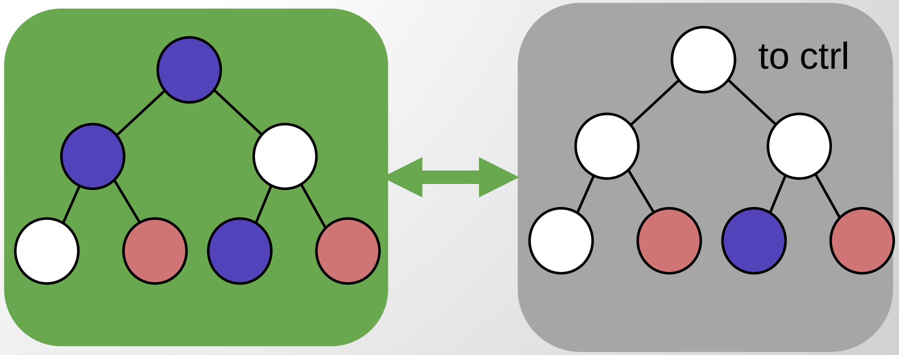

[Ground Control to Major Faults: Towards a Fault Tolerant and Adaptive SDN Control Network]
Liron Schiff, Stefan Schmid, and Marco Canini.
IEEE/IFIP DSN Workshop on Dependability Issues on SDN and NFV (**DISN**), Toulouse, France, June 2016.

# Decoupling: Algorithms *with a twist!*

- Researchers proposed to *exploit SDN* rule definition flexiblities to solve growing FIB size problem
  - OpenFlow-based IP router: **caching and aggregation**
  - **Zipf law**: many infrequent prefixes at controller
  - Extremely distributed control ☺




- Online paging *with SDN twist*
  - Forwarding semantic: **largest common prefix forwarding**, i.e., dependencies: only offload **root-contiguous** set in trie
  - Can do **bypassing**



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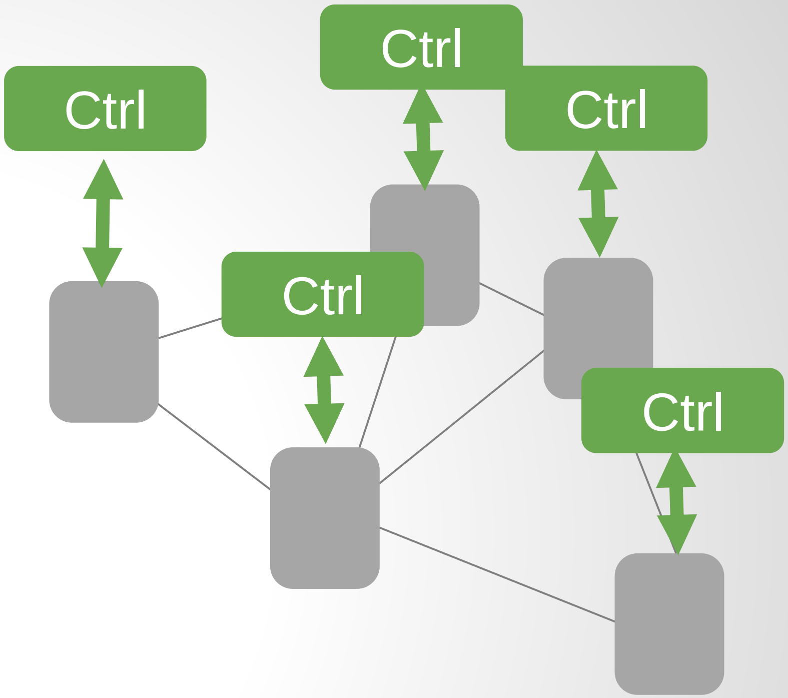


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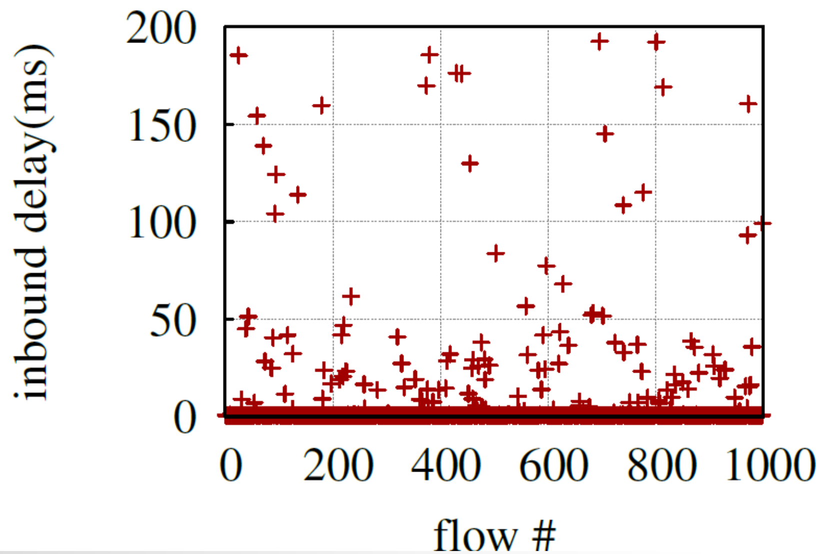
[Competitive FIB Aggregation without Update Churn](#)
Marcin Bienkowski, Nadi Sarrar, Stefan Schmid, and Steve Uhlig.
34th International Conference on Distributed Computing Systems (**ICDCS**), Madrid, Spain, June 2014.

[Online Tree Caching](#)
Marcin Bienkowski, Jan Marcinkowski, Maciej Pacut, Stefan Schmid, and Aleksandra Spyra.
ArXiv Technical Report, February 2016.

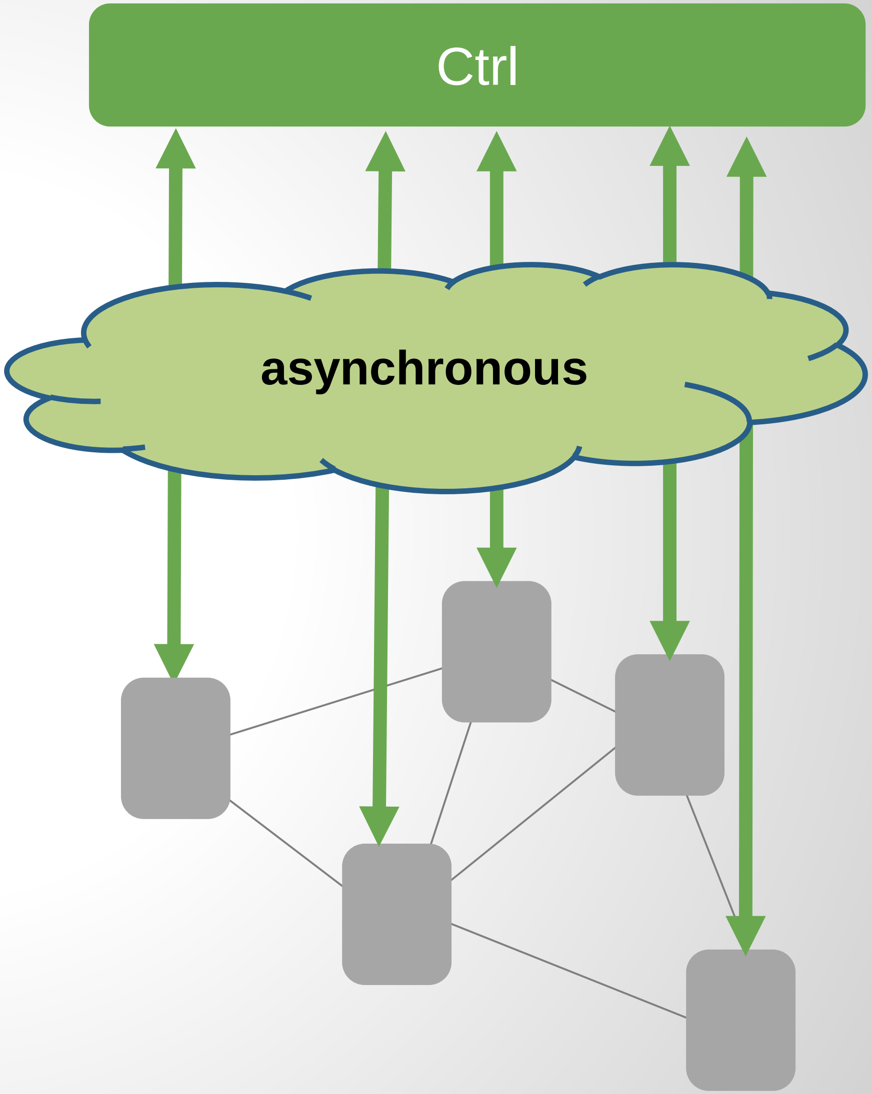
# Interconnect: Algorithms *with a twist!*

- Another challenge: asynchronous communication channel




He et al., ACM SOSR 2015:

without network latency



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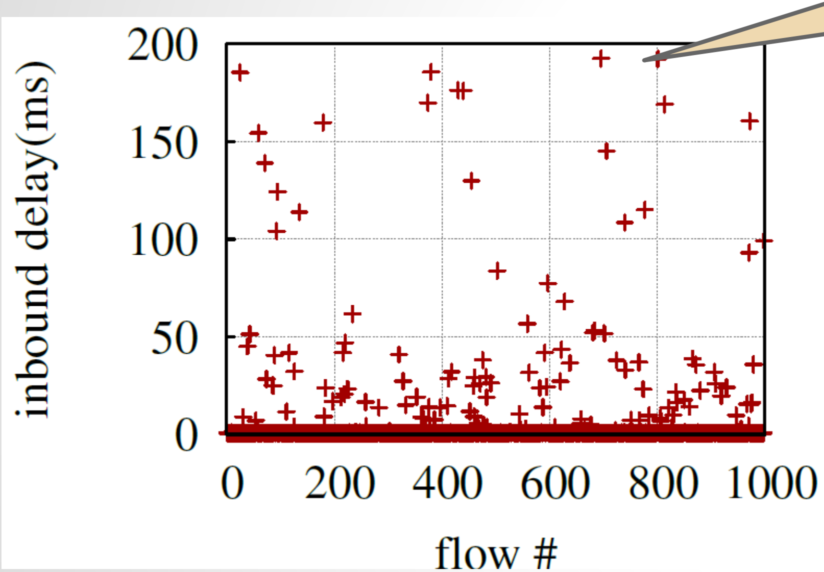
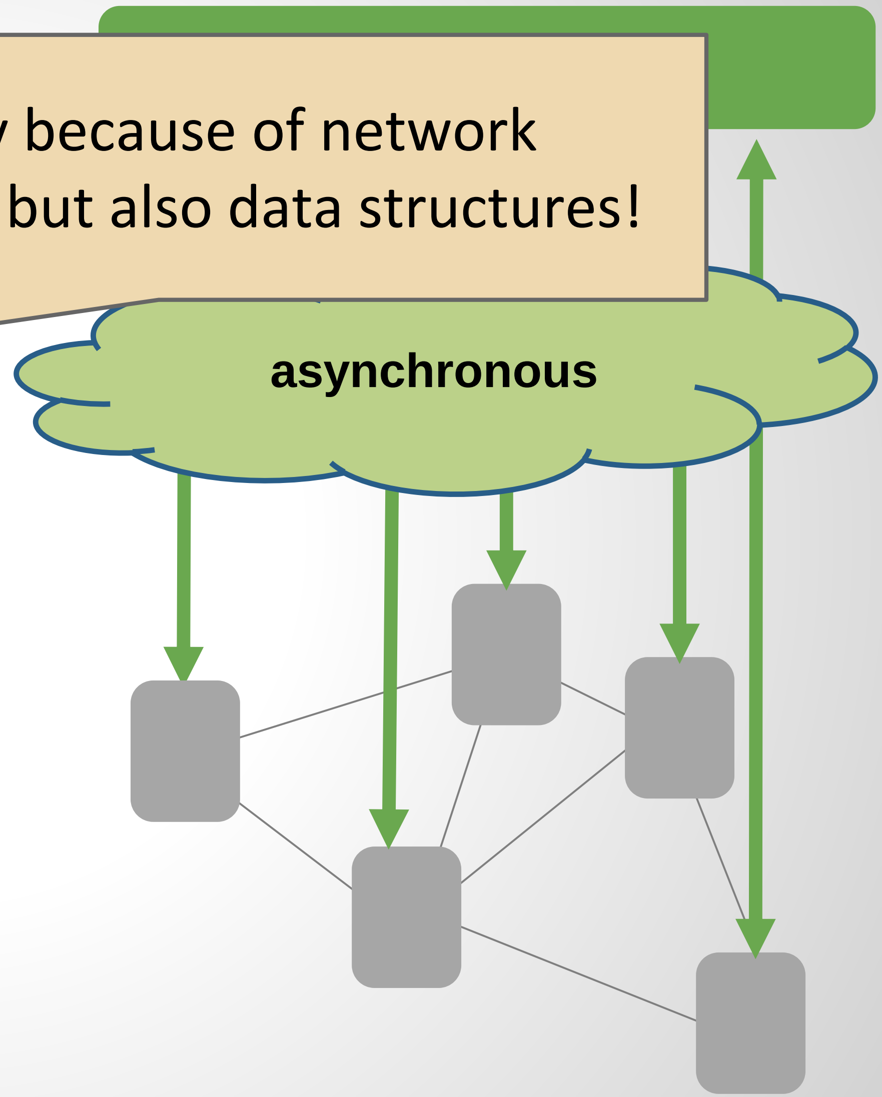
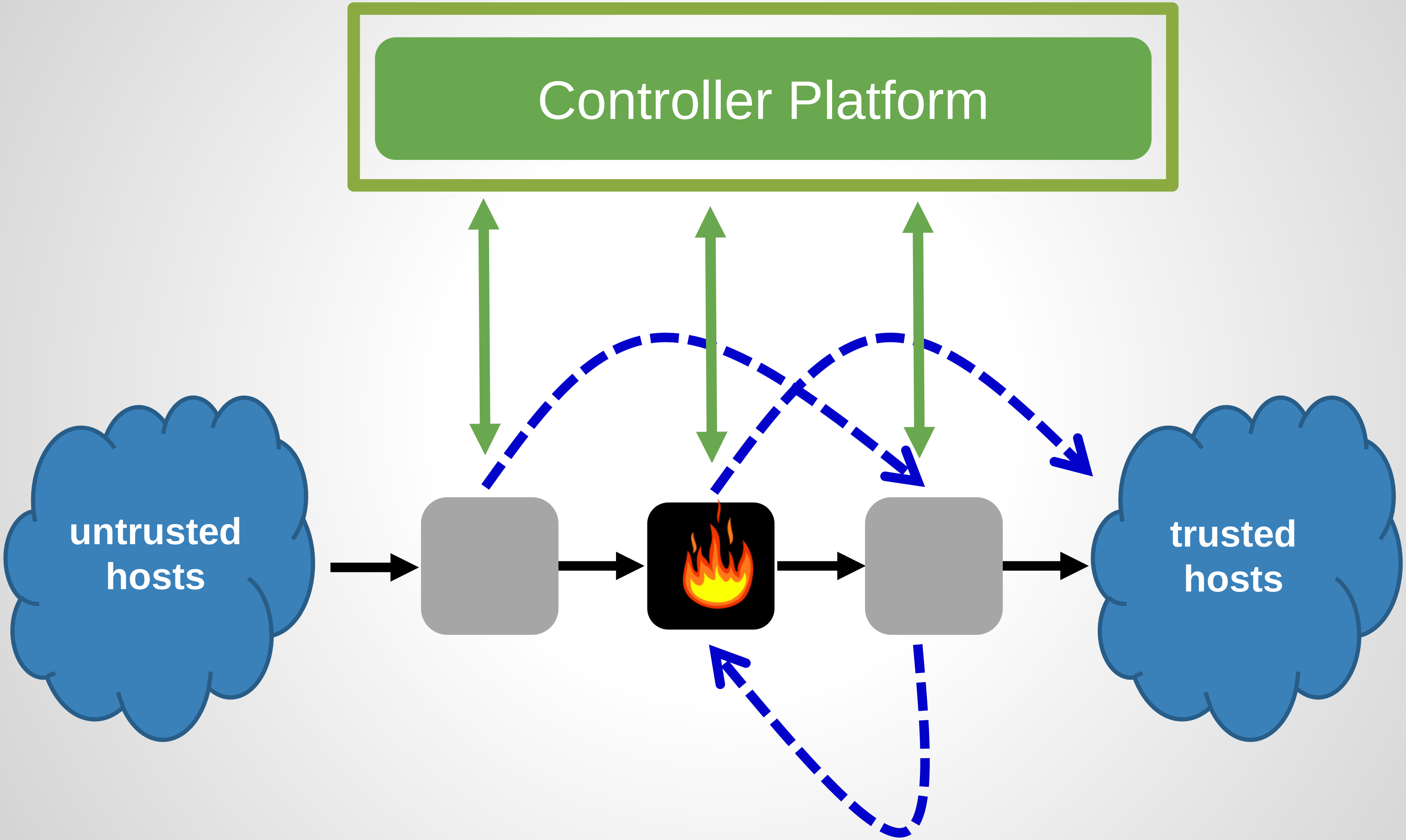



He et al., ACM SOSR 2015:
without network latency

Not only because of network latency, but also data structures!



# What can possibly go wrong?




**Invariant:** Traffic from untrusted hosts to trusted hosts via firewall!

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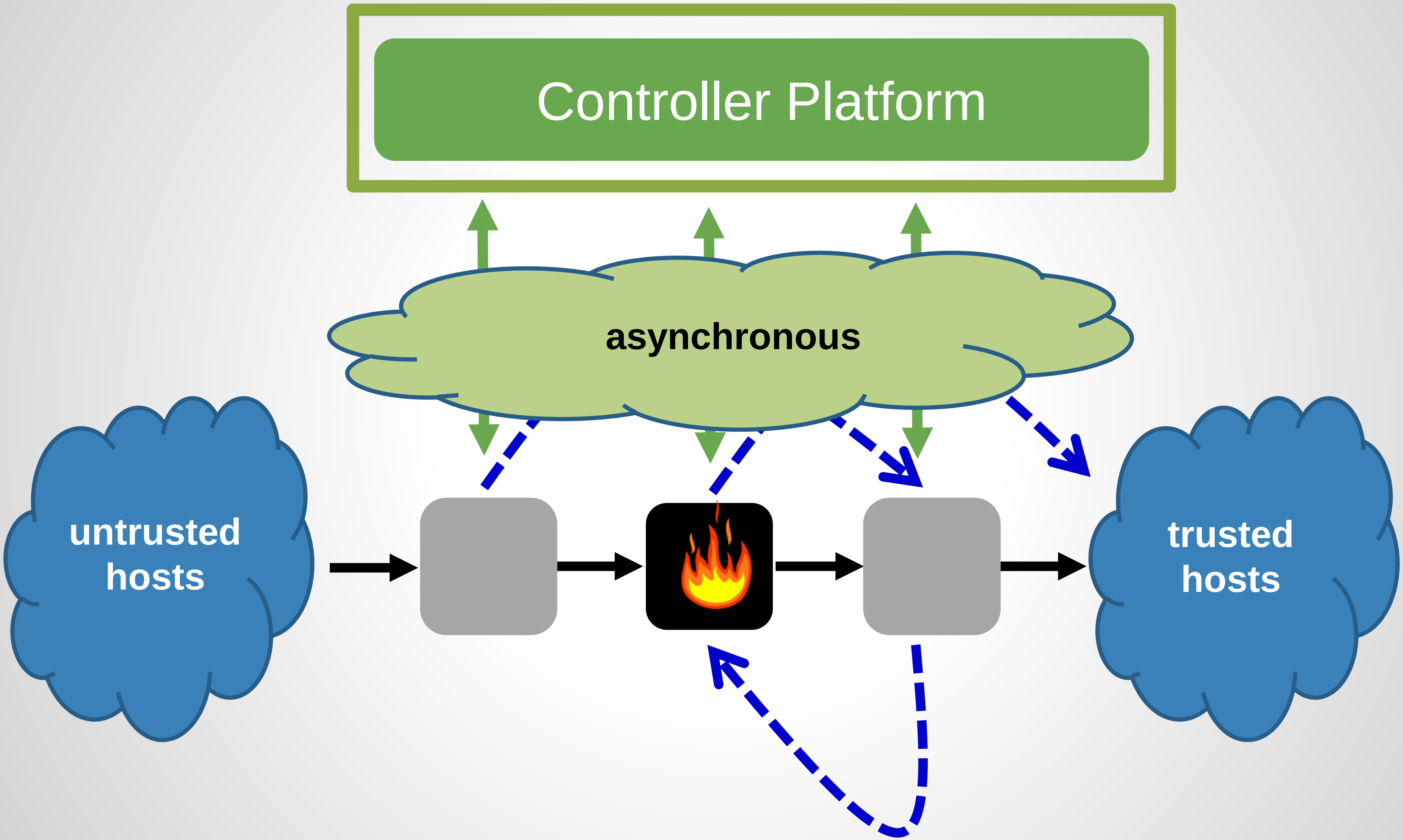


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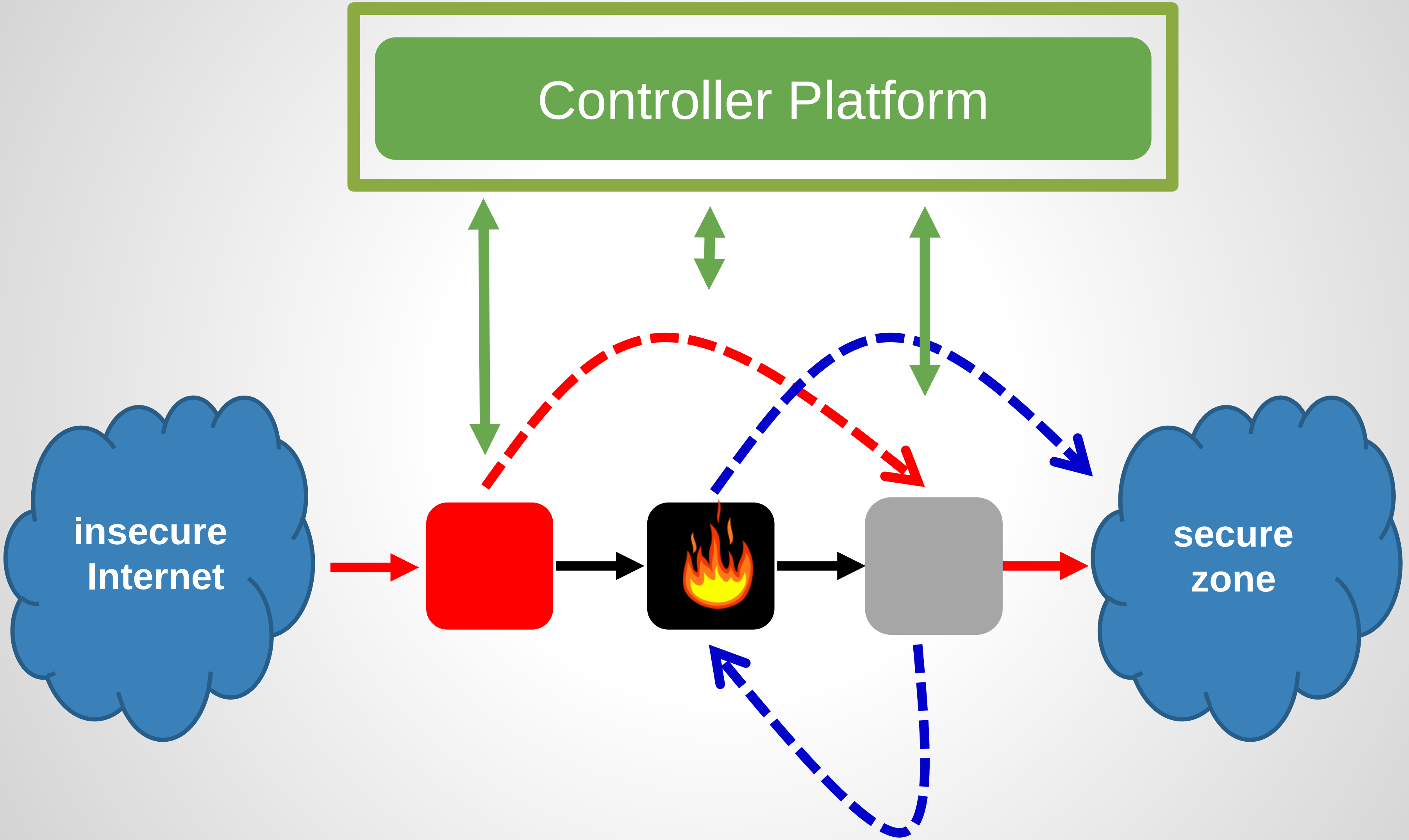
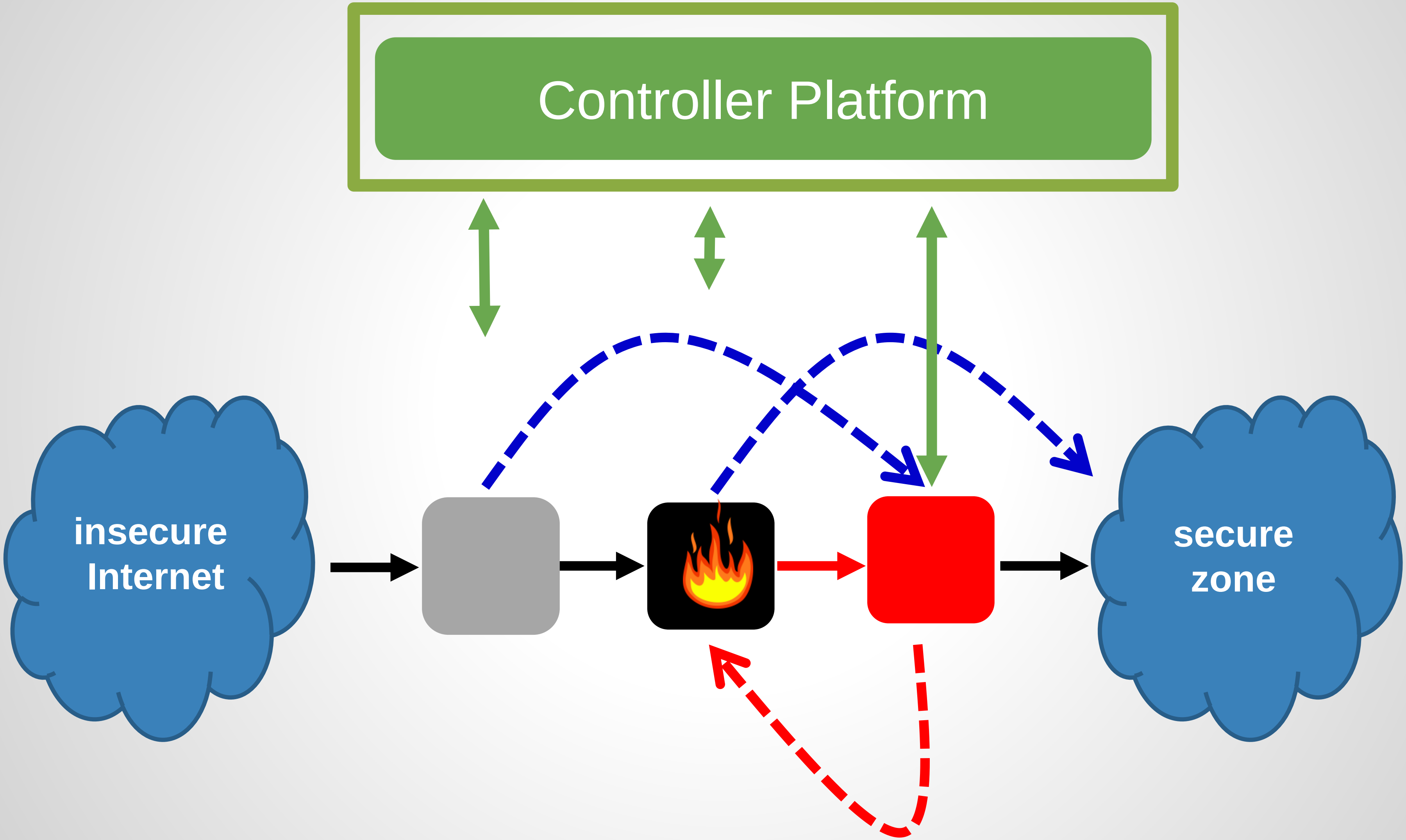
# Example 1: Bypassed Waypoint

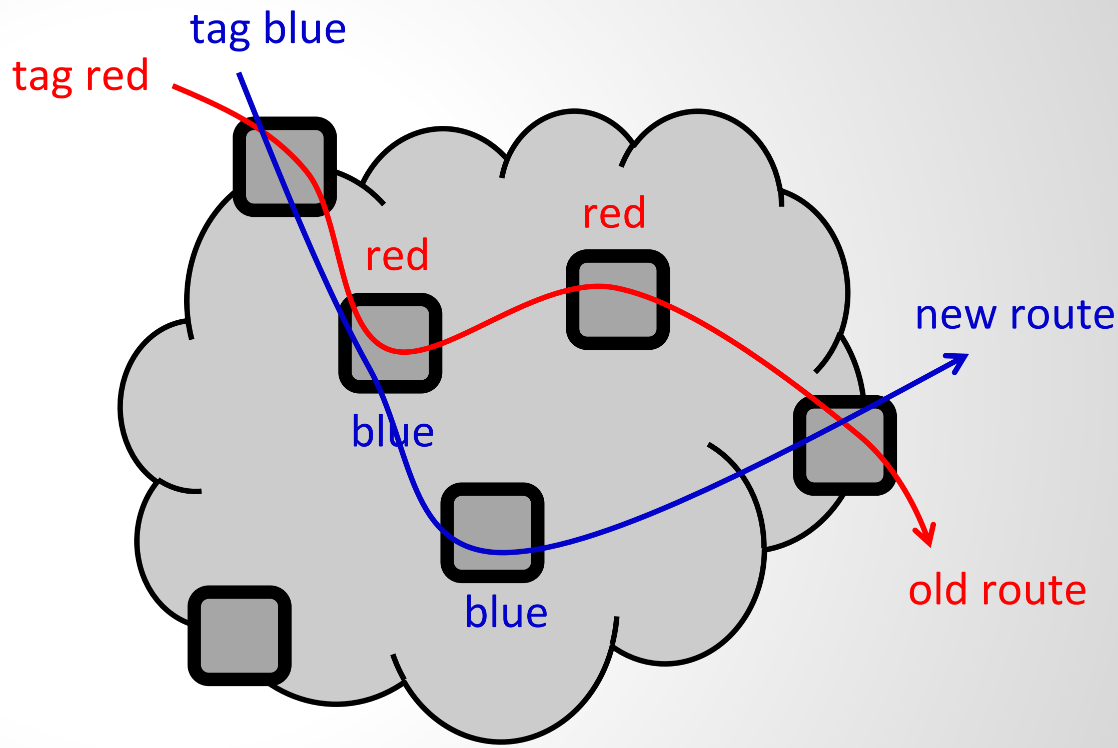


# Example 2: *Transient* Loop



# Tagging: A Universal Solution?

- Old route: red
- New route: blue
- 2-Phase Update:
  - Install blue flow rules internally
  - Flip tag at ingress ports



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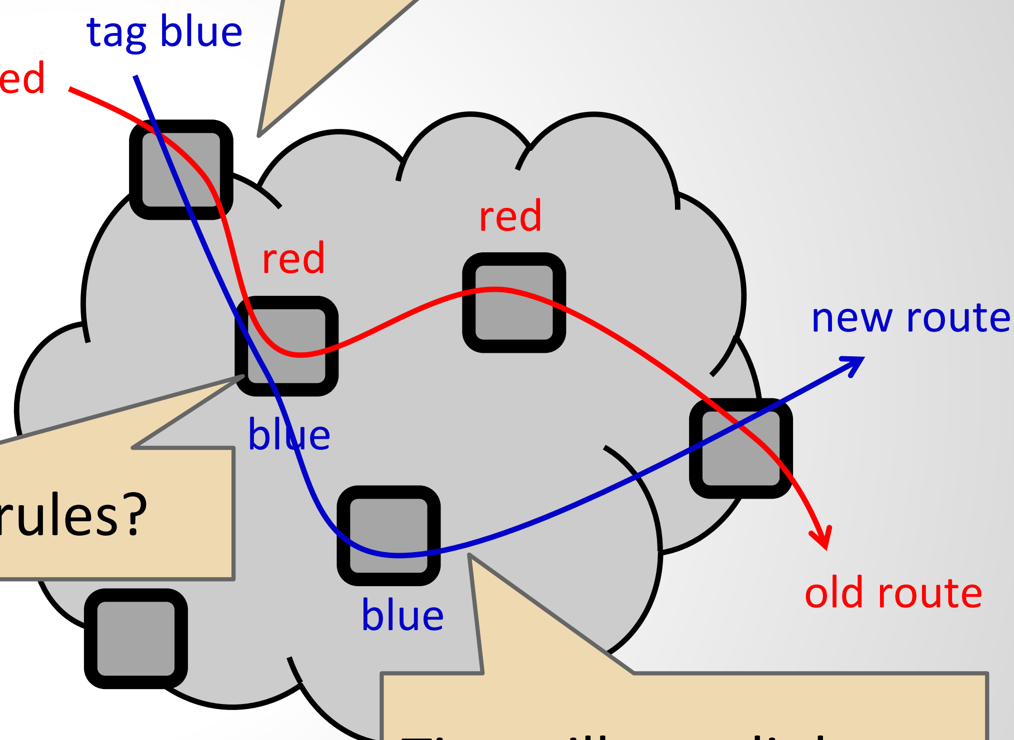



Where to tag?
Header space?
Overhead?

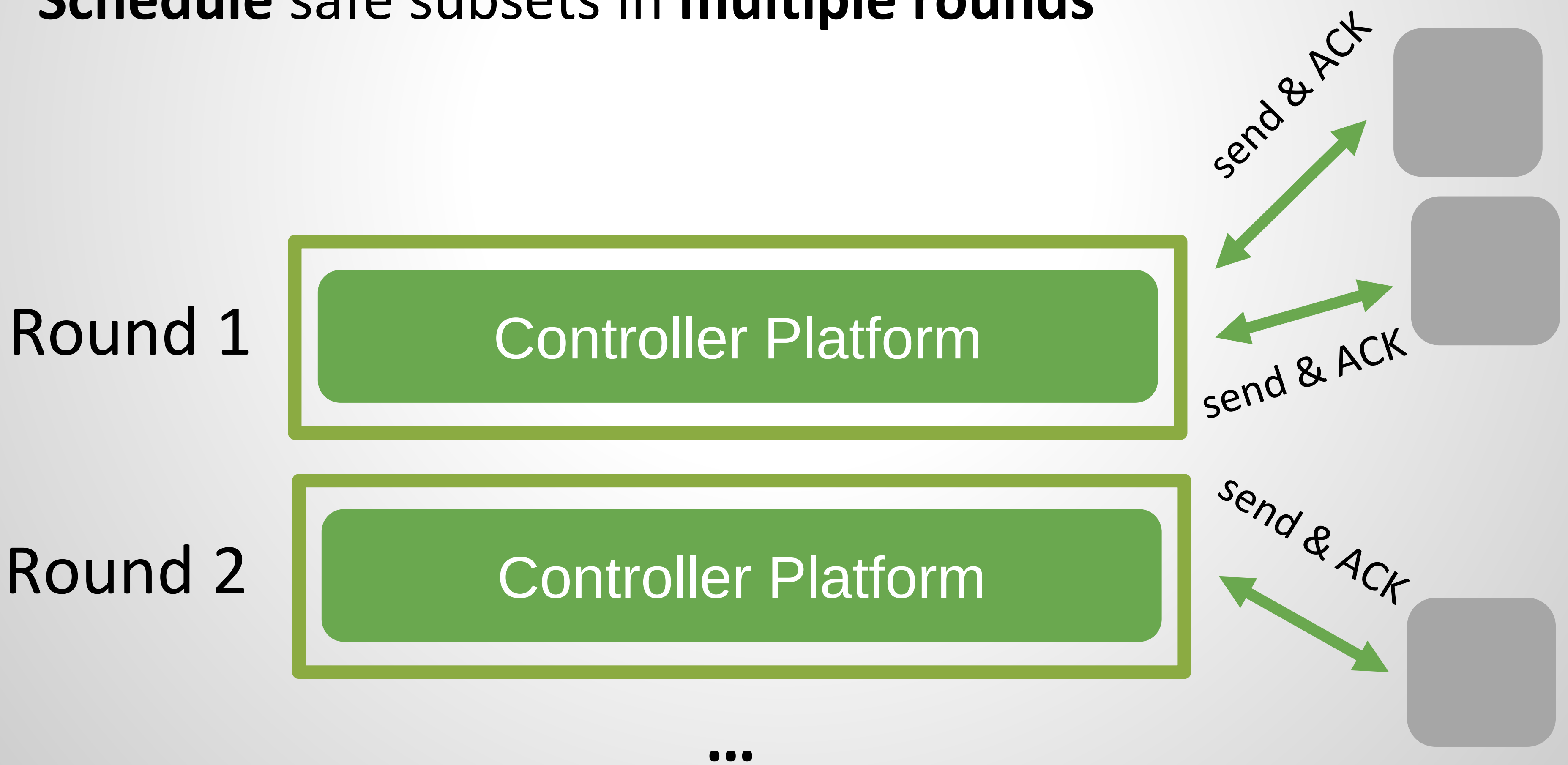
Cost of extra rules?

Time till new link becomes available?

# Alternative: Weaker Transient Consistency

Idea: Packet may take a mix of old and new path, as long as weaker consistencies are fulfilled transiently, e.g. Loop-Freedom (LF) and Waypoint Enforcement (WPE).

**Schedule** safe subsets in **multiple rounds**



# The Spectrum of Consistency

**per-packet consistency**

Reitblatt et al., SIGCOMM 2012

**correct network virtualization**

Ghorbani and Godfrey, HotSDN 2014

**weak, transient consistency**

(loop-freedom, waypoint enforced)

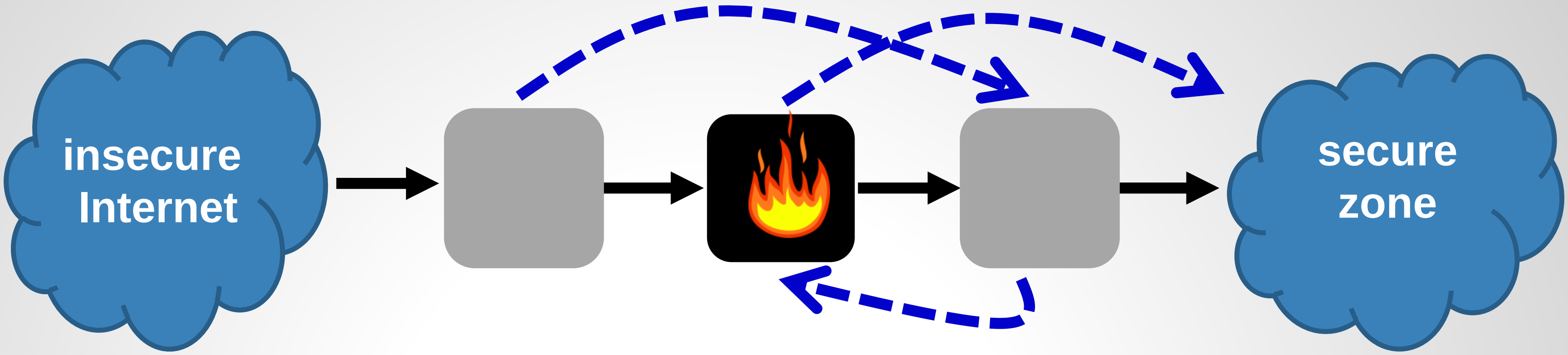
Mahajan and Wattenhofer, HotNets 2014

Ludwig et al., HotNets 2014

Strong

Weak

# Going Back to Our Examples: LF Update?



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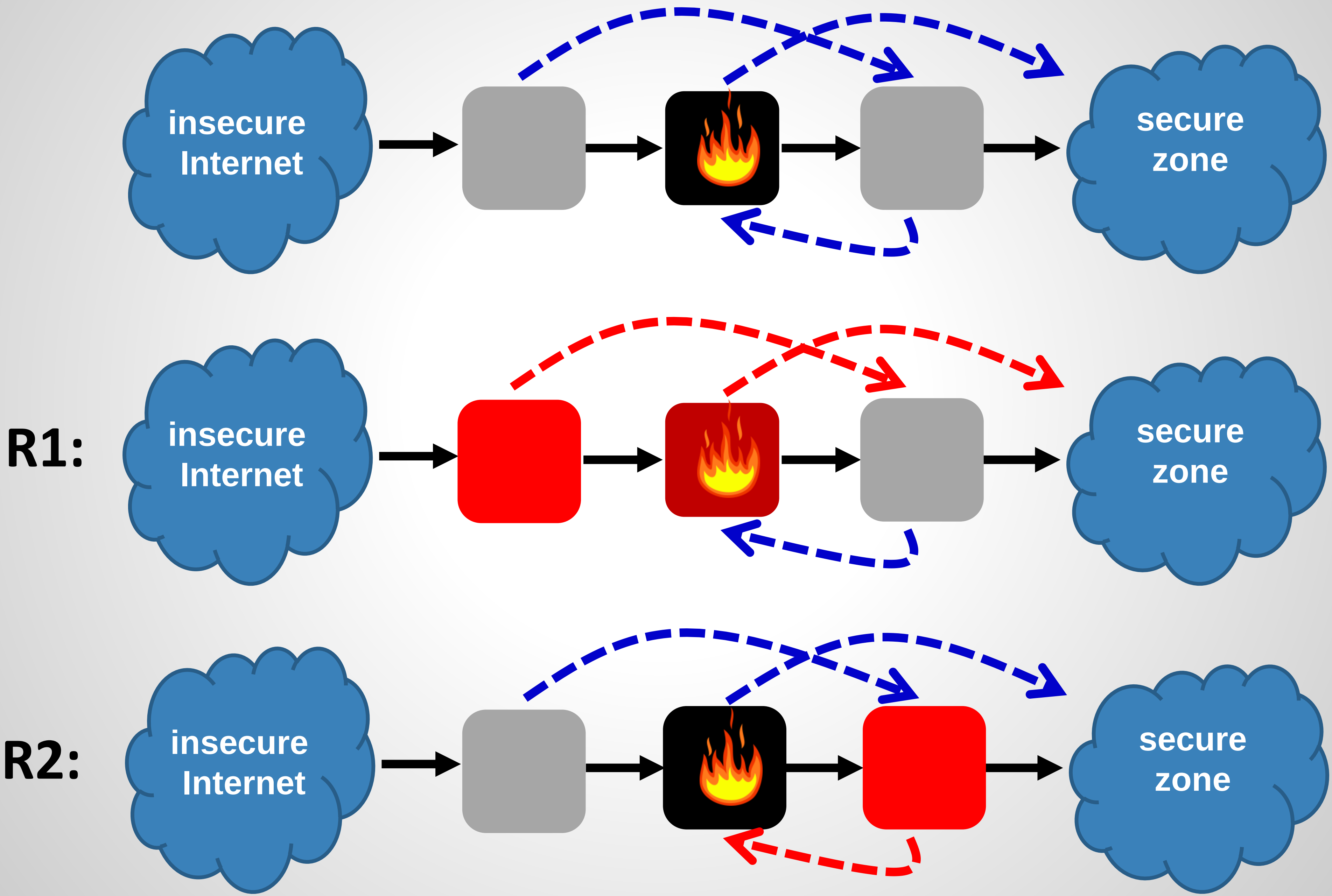

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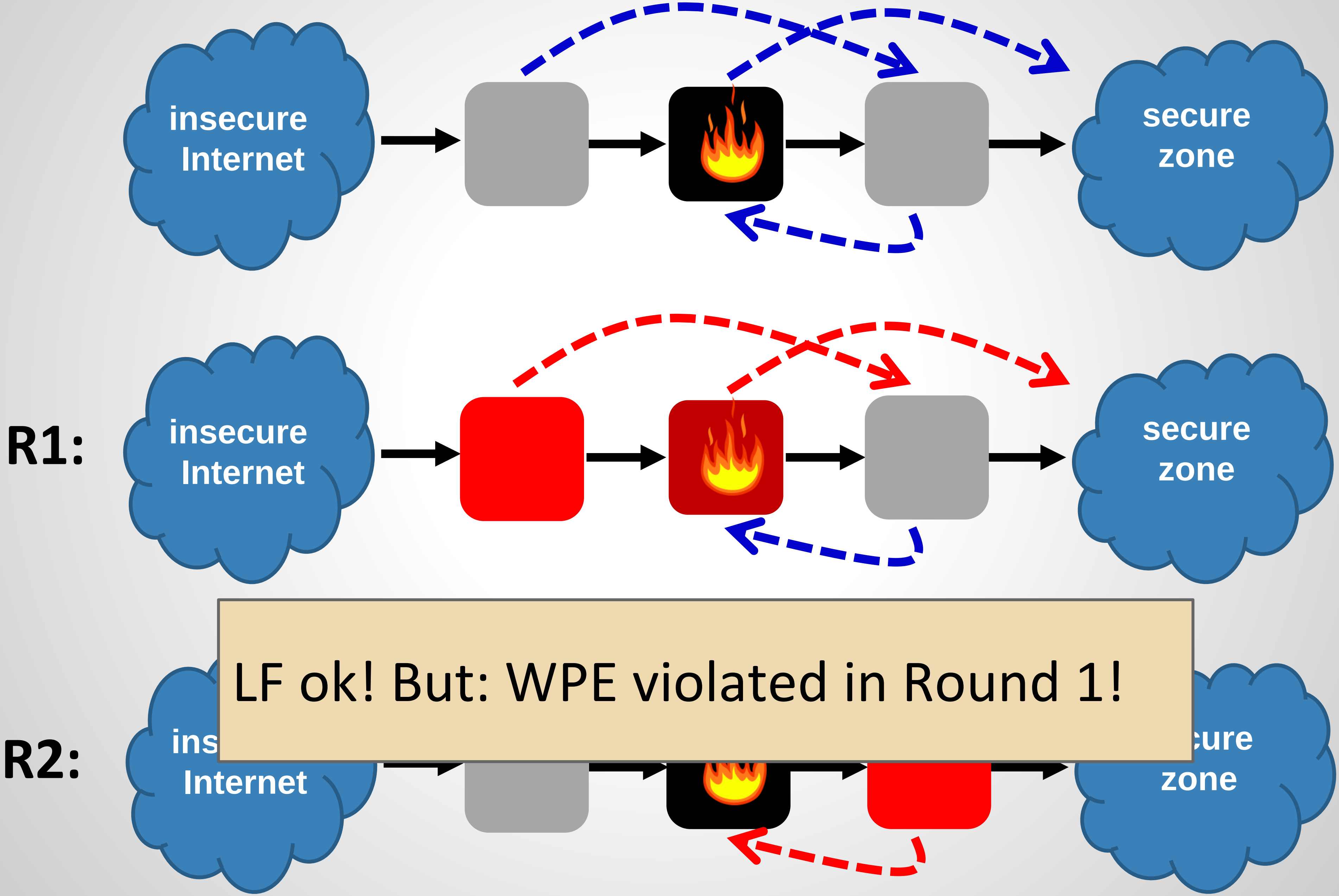
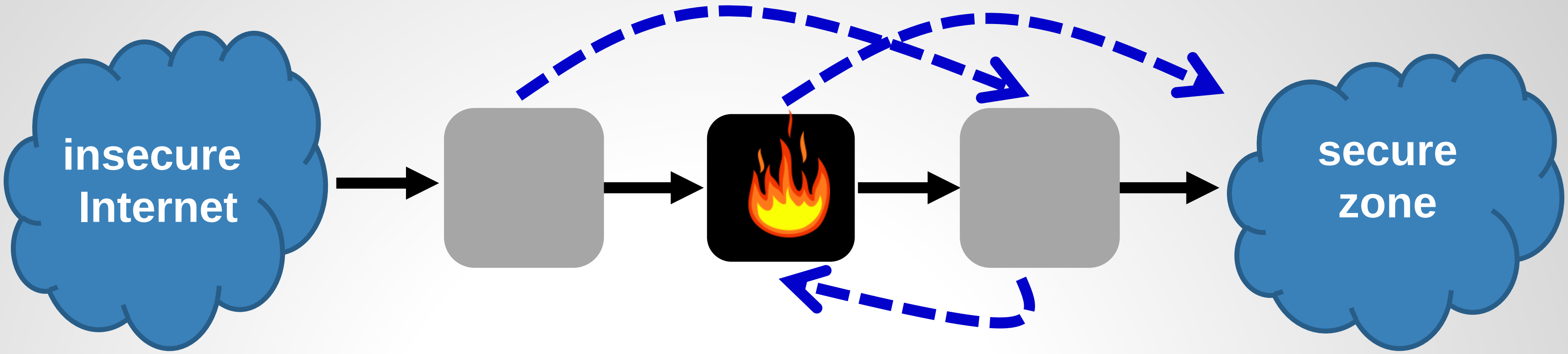


# Going Back to Our Examples: WPE Update?



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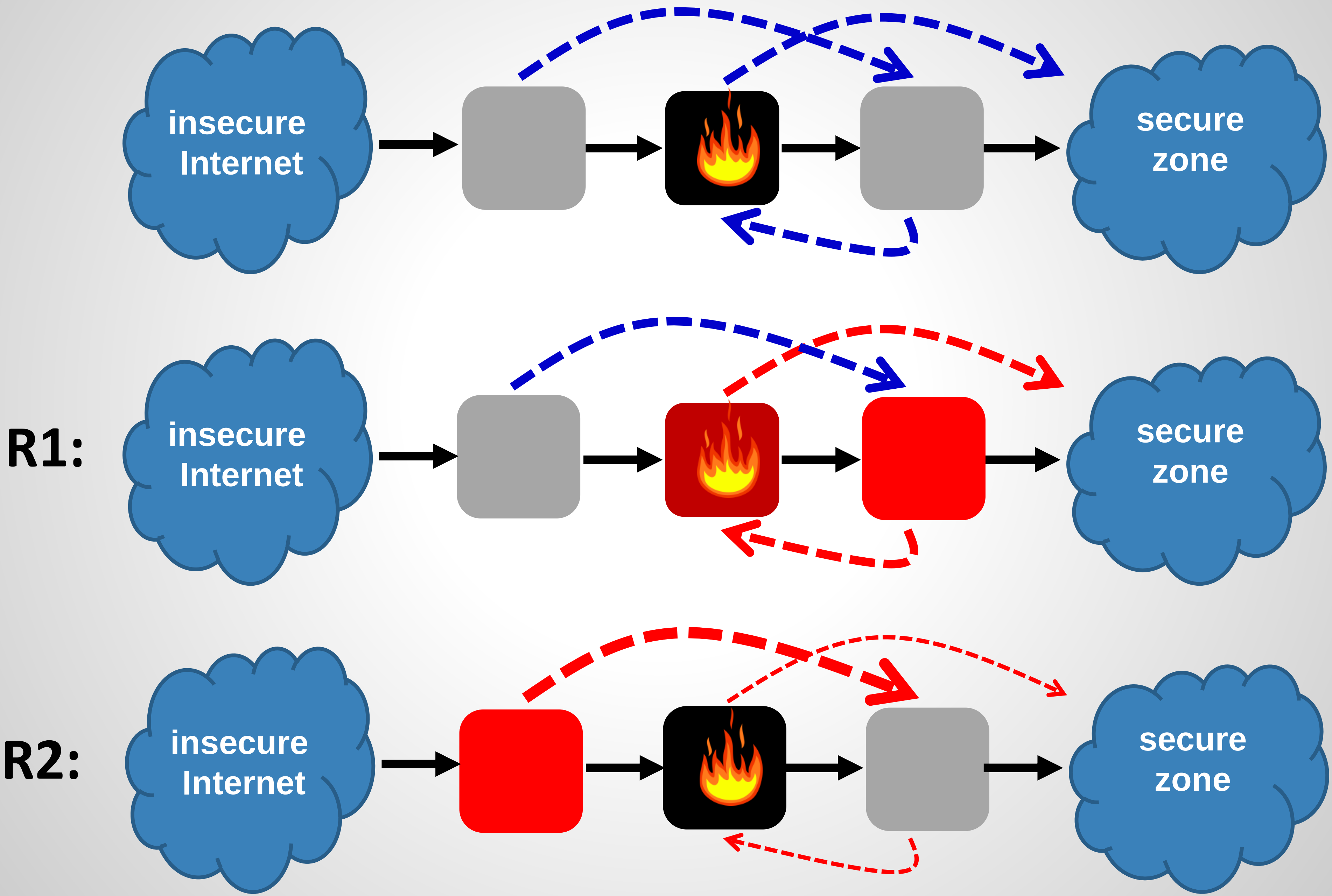

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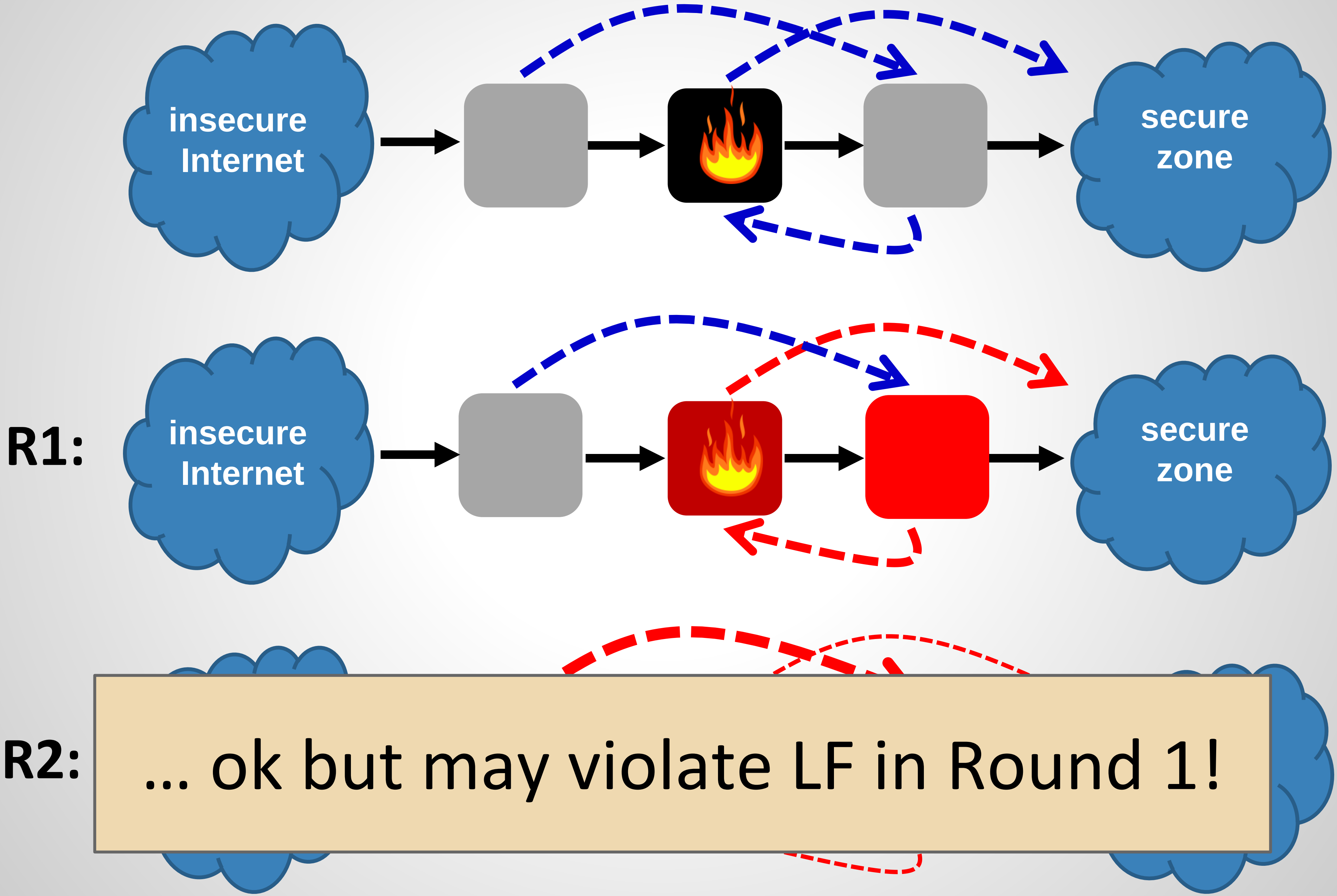
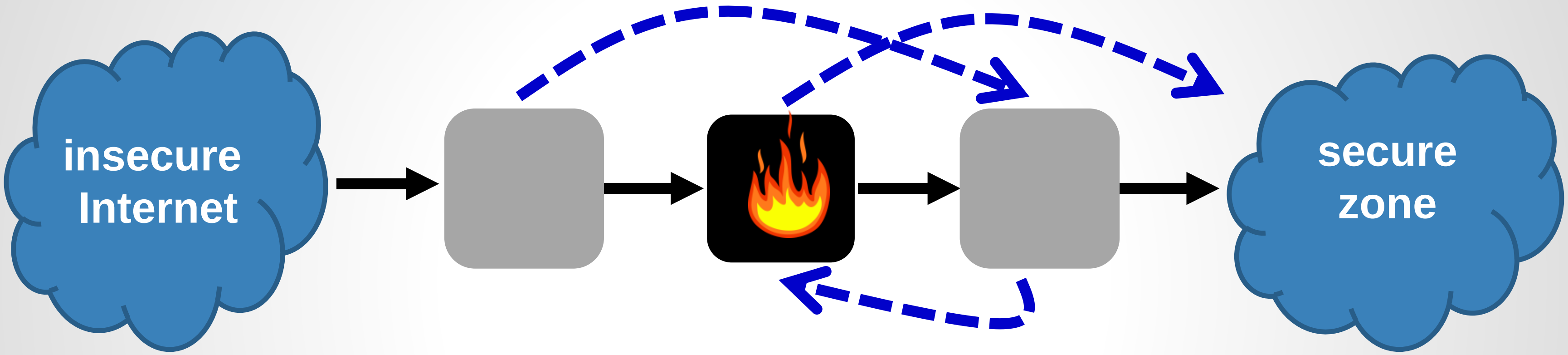
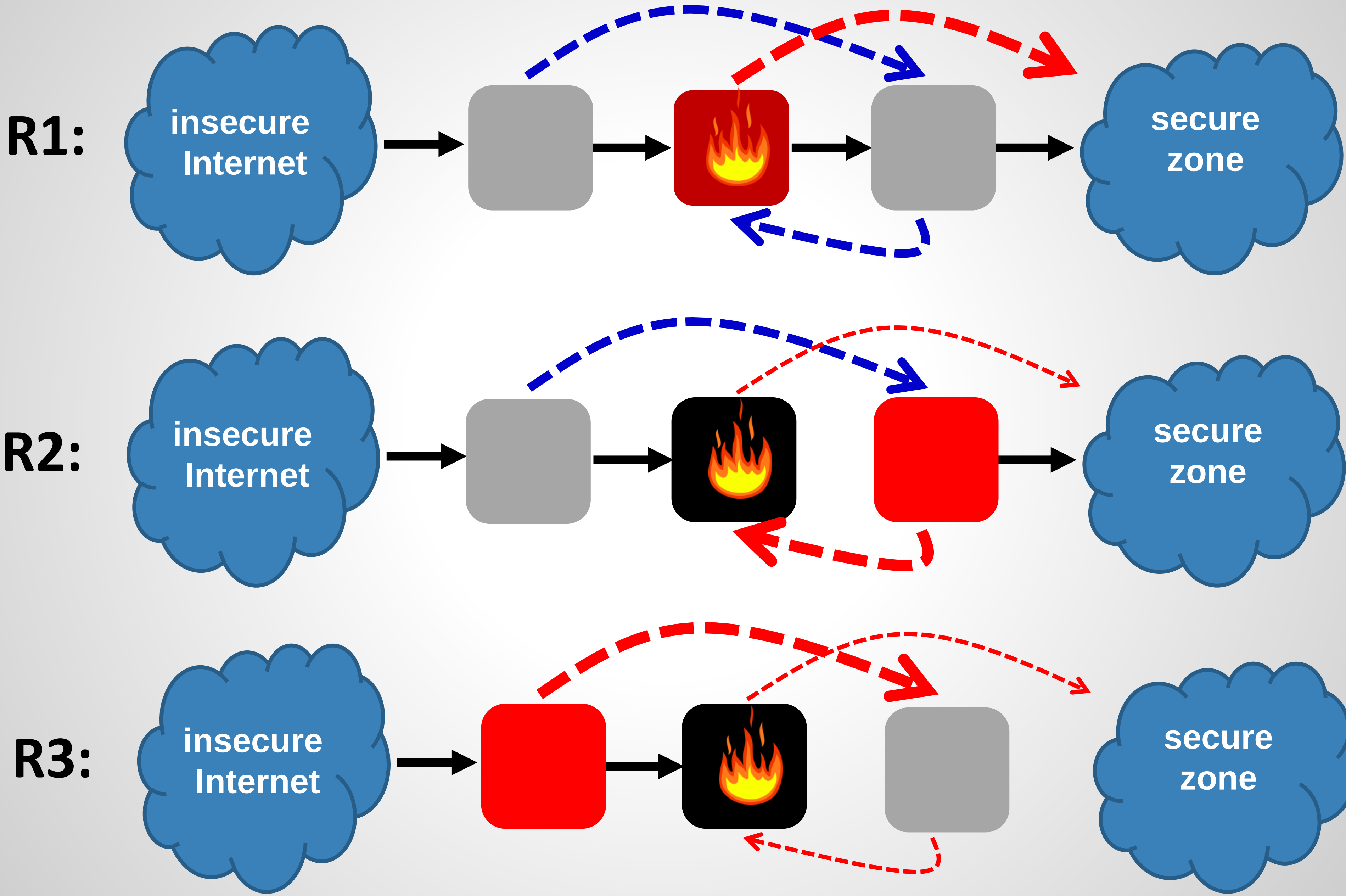



... ok but may violate LF in Round 1!

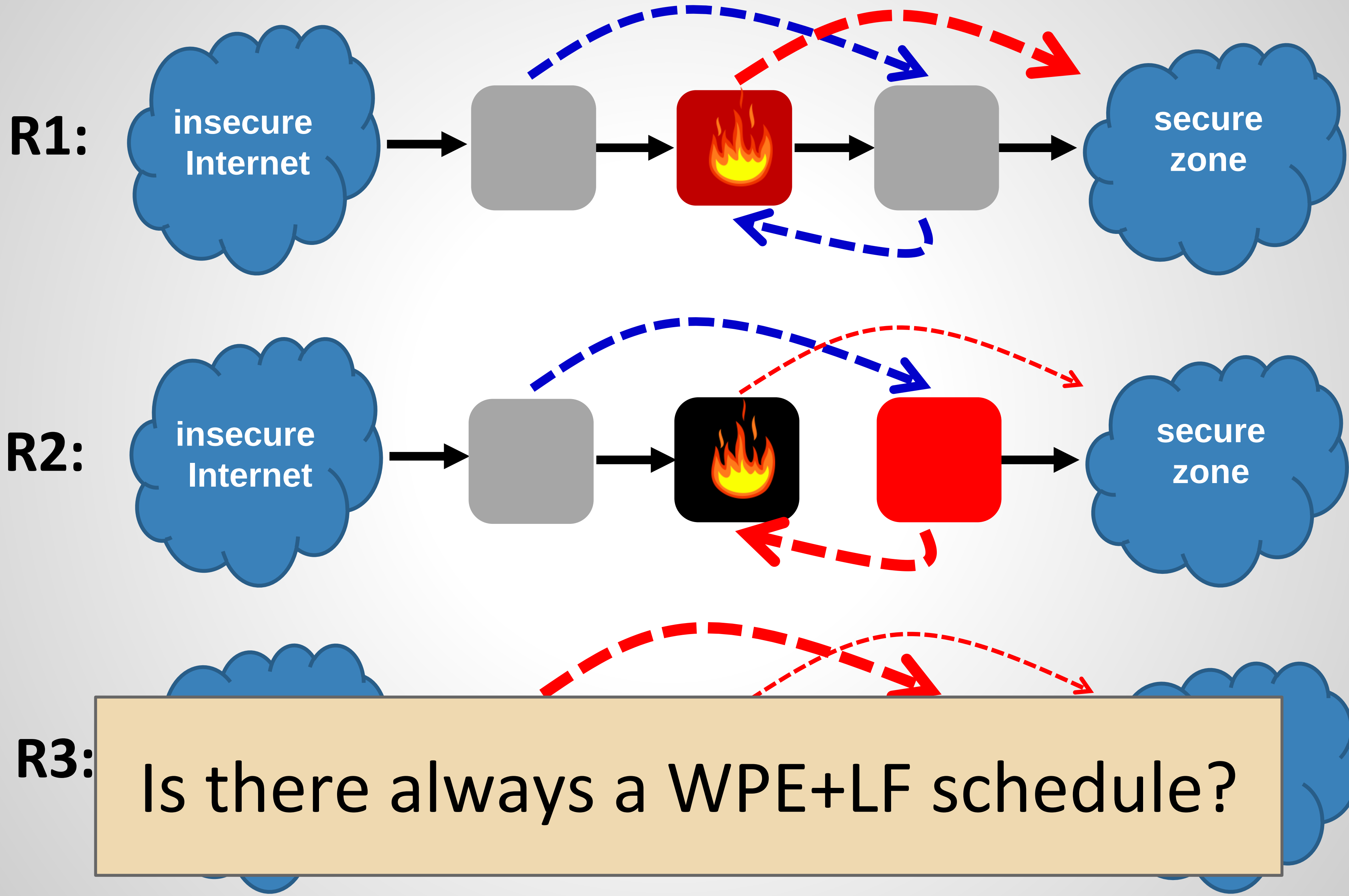
# Going Back to Our Examples: Both WPE+LF?



# Going Back to Our Examples: WPE+LF!

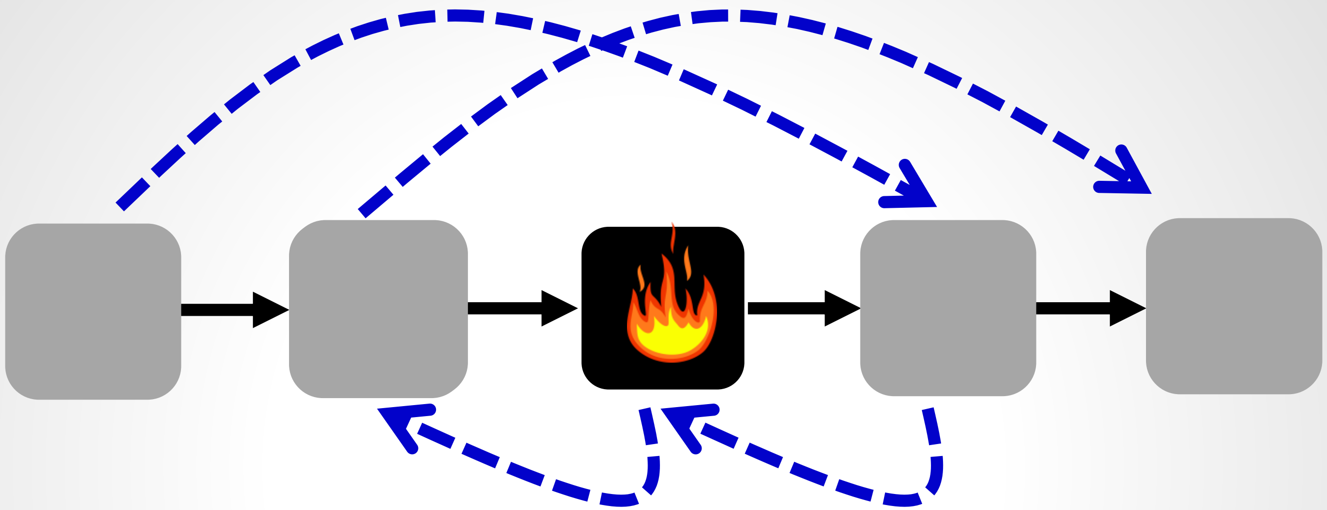


# Going Back to Our Examples: WPE+LF!

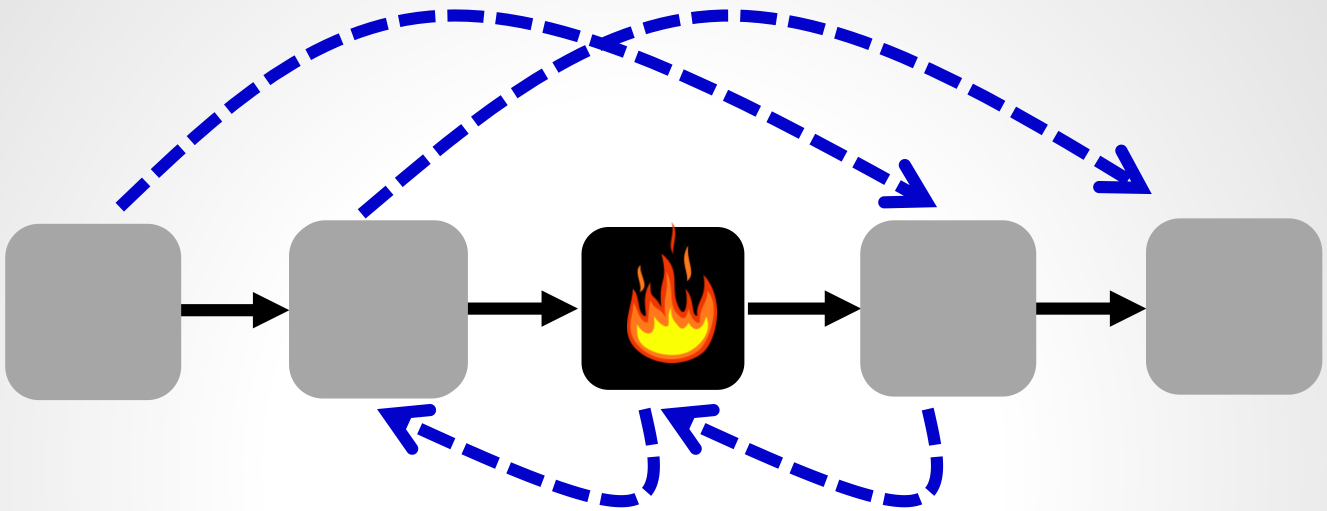



Is there always a WPE+LF schedule?

# What about this one?



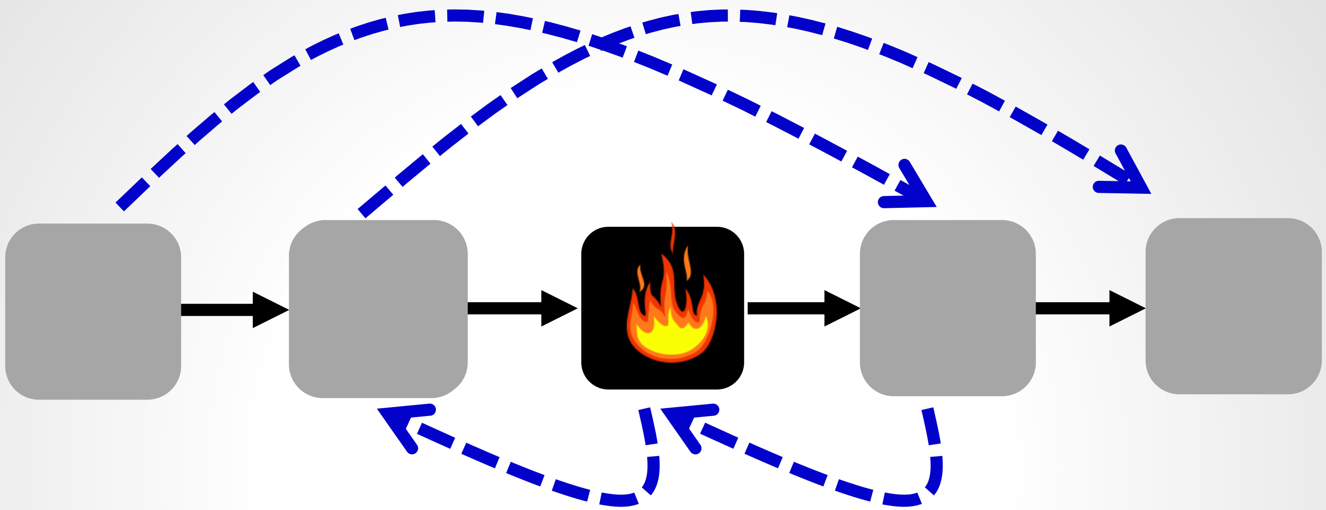
# LF and WPE may conflict!



- ❑ Cannot update any **forward edge** in R1: WP
- ❑ Cannot update any **backward edge** in R1: LF

No schedule exists!

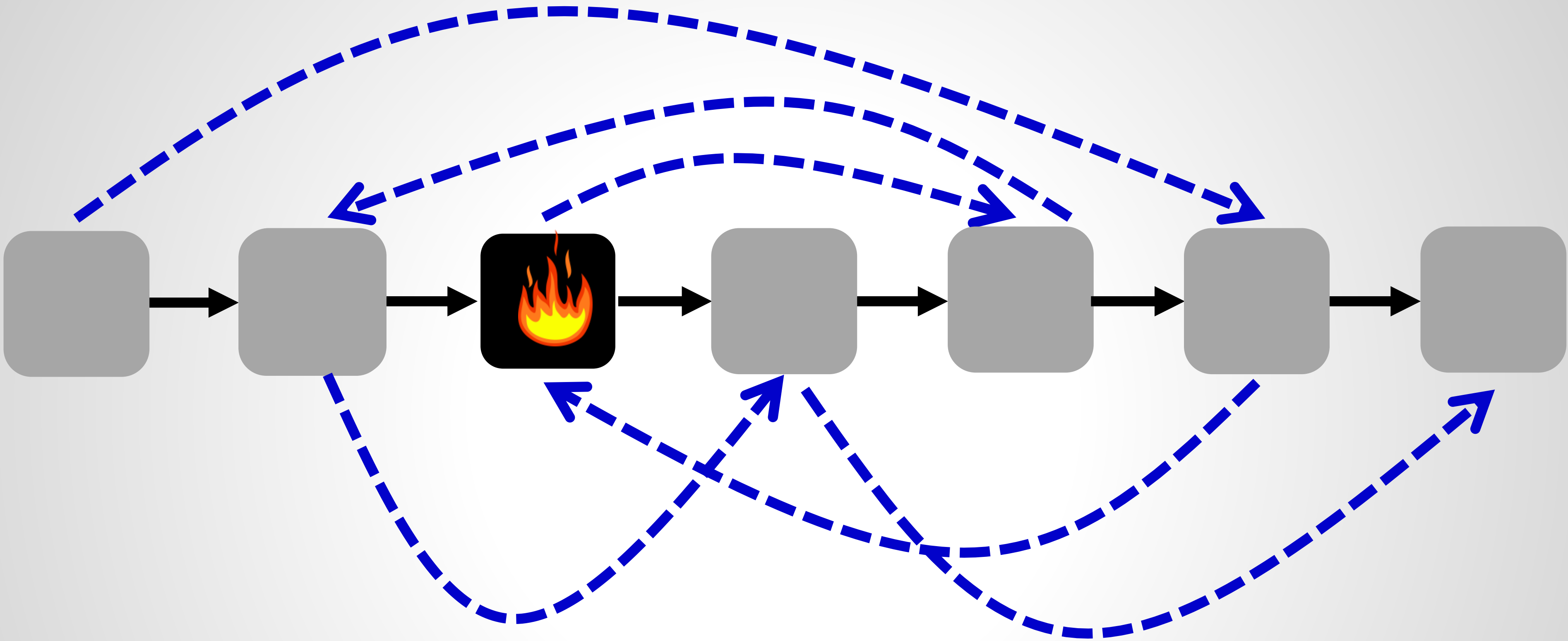
# LF and WPE may conflict!



- ❑ Cannot update any **forward edge** in R1: WP
- ❑ Cannot update any **backward edge** in R1: LF


Good Network Updates for Bad Packets: Waypoint Enforcement Beyond Destination-Based Routing Policies
Arne Ludwig, Matthias Rost, Damien Foucard, and Stefan Schmid.
13th ACM Workshop on Hot Topics in Networks (**HotNets**), Los Angeles, California, USA, October 2014.

# What about this one?



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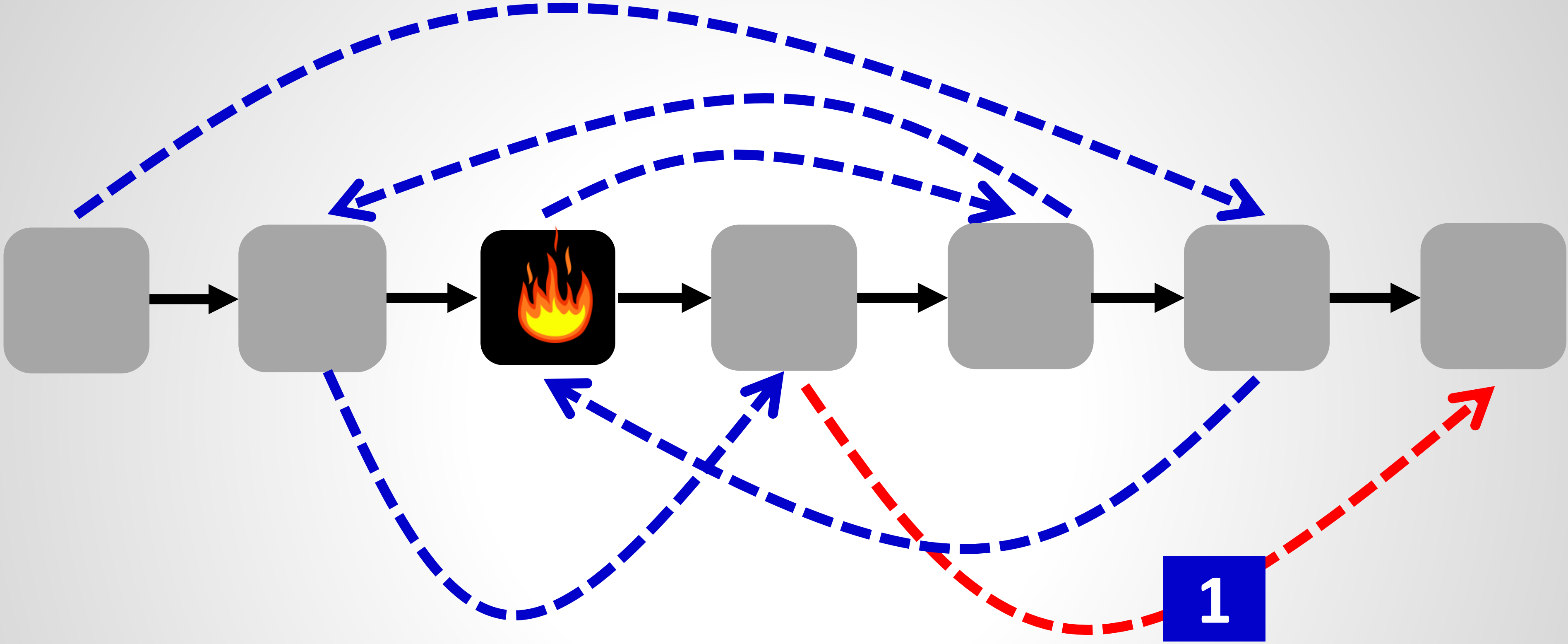
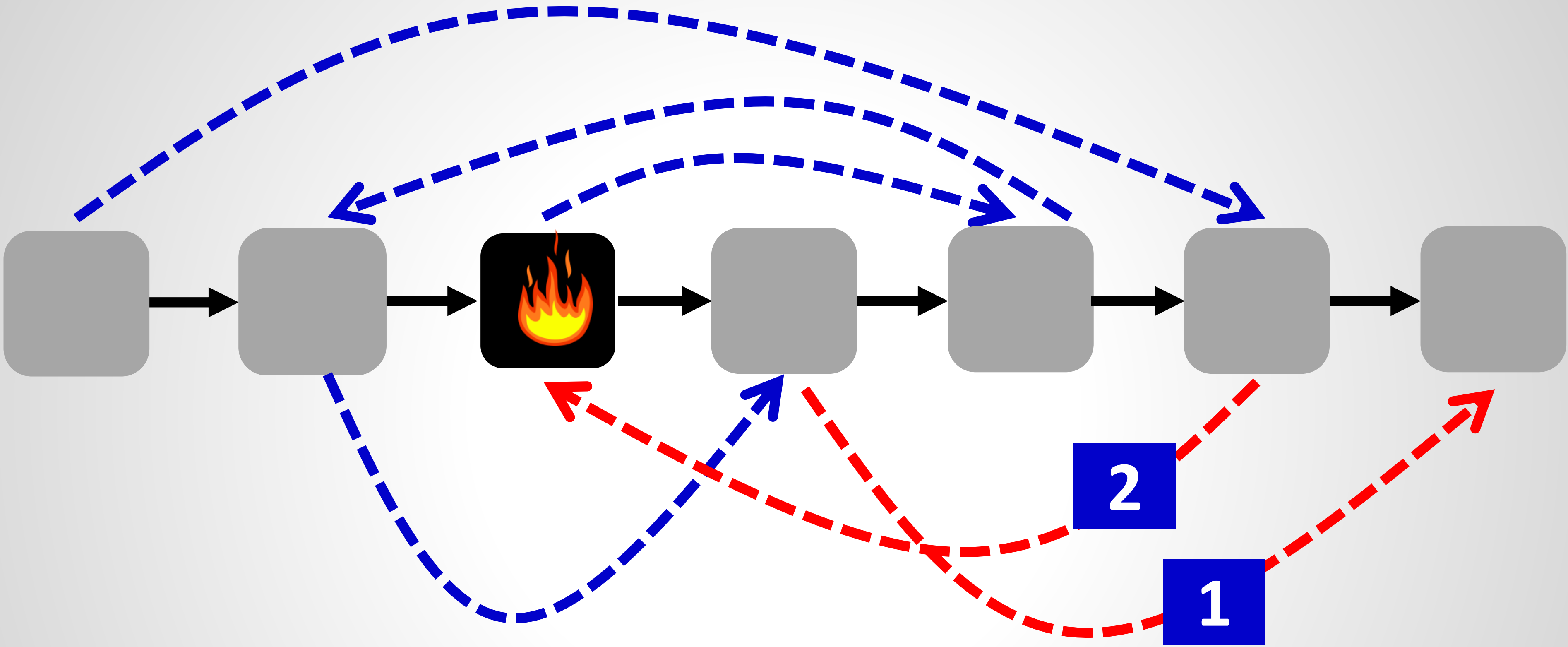


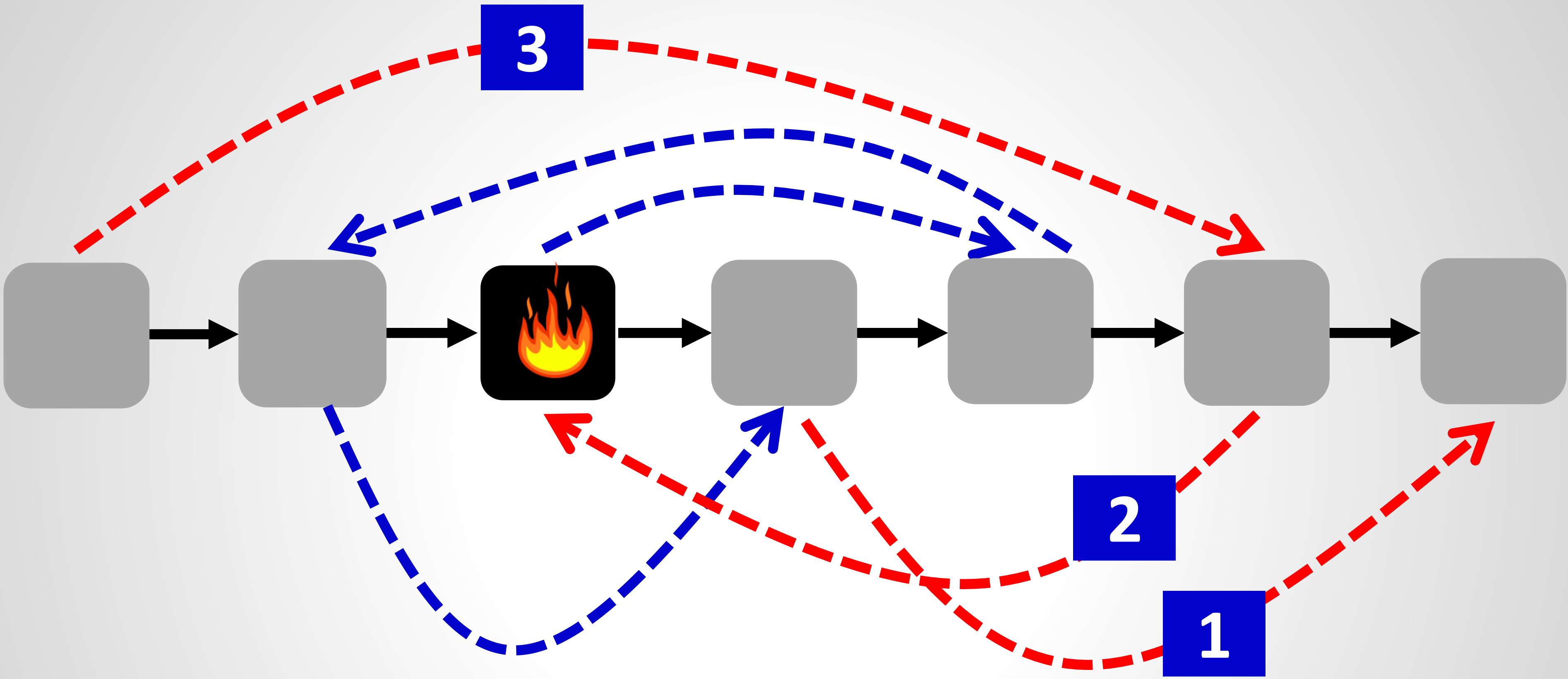

- Forward edge after the waypoint: safe!
  - No loop, no WPE violation

# What about this one?



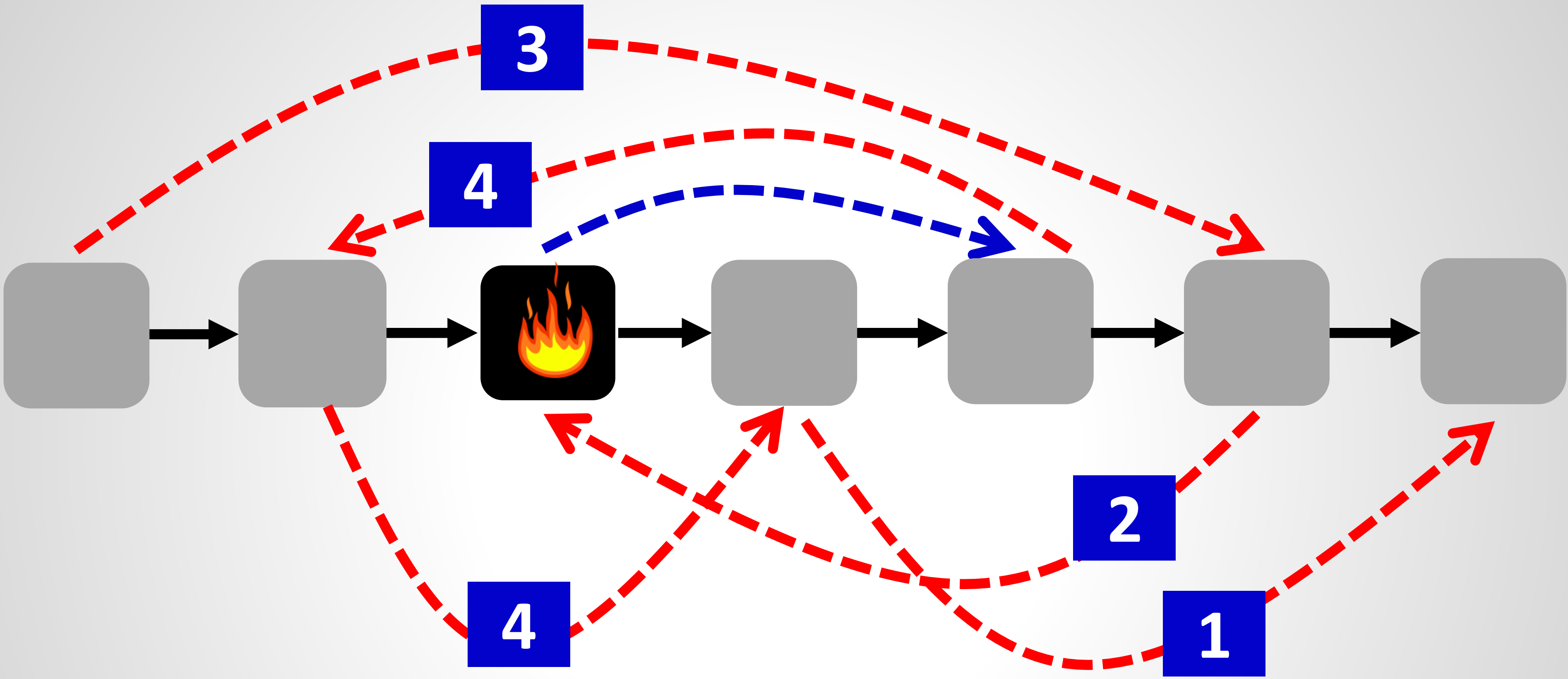

- ❑ Now this backward is safe too!
  - ❑ No loop because exit through 1

# What about this one?



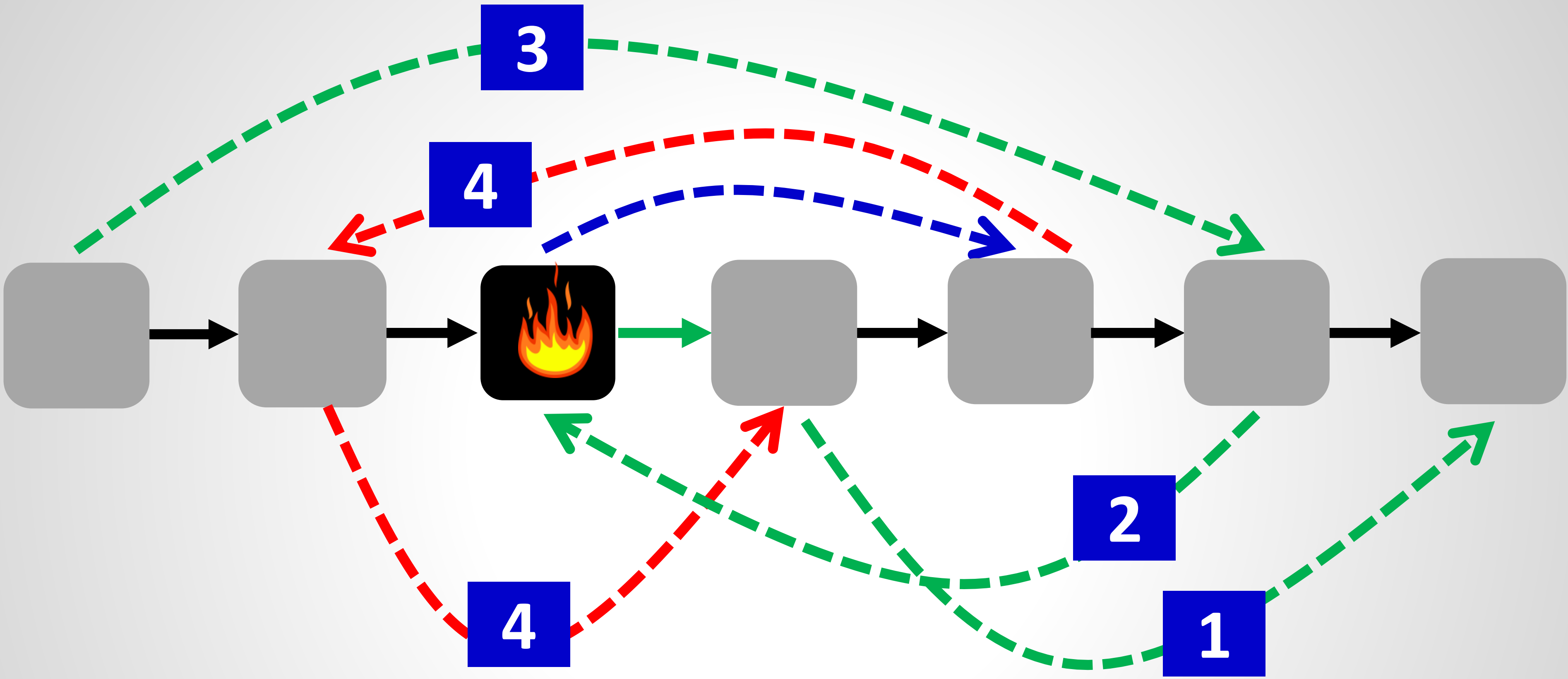

- ❑ Now this is safe: **2** ready back to WP!
    - ❑ No waypoint violation

# What about this one?



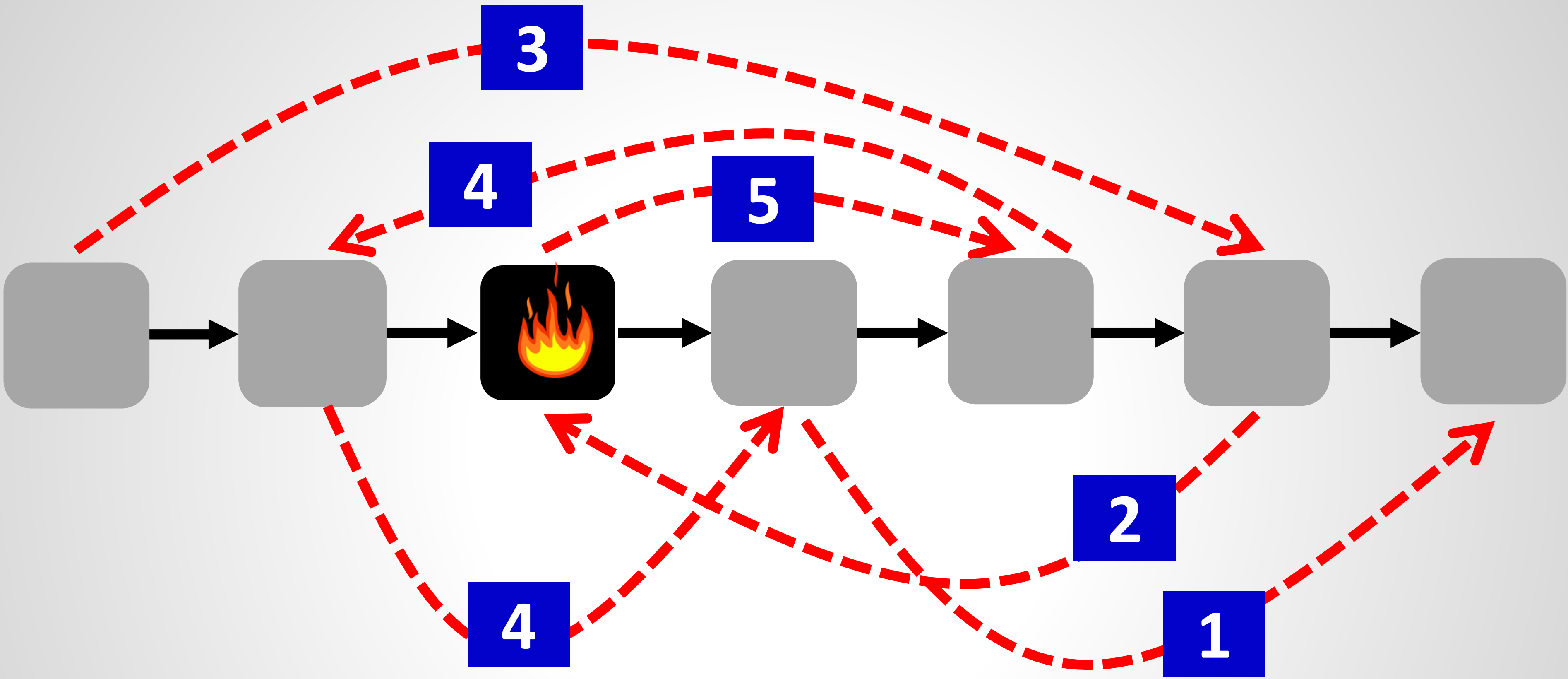

- ❑ Ok: loop-free and also not on the path (exit via 1 )

# What about this one?

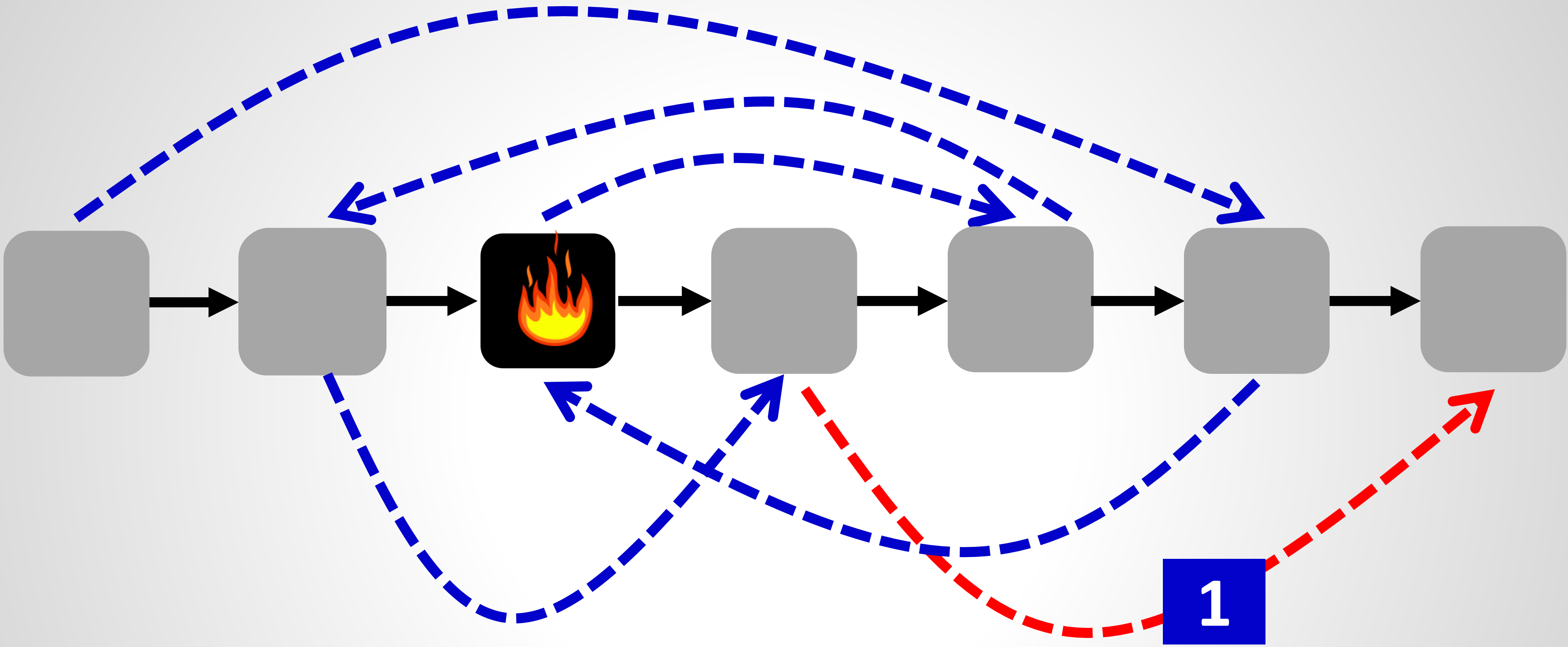



- ❑ Ok: loop-free and also not on the path (exit via 1 )

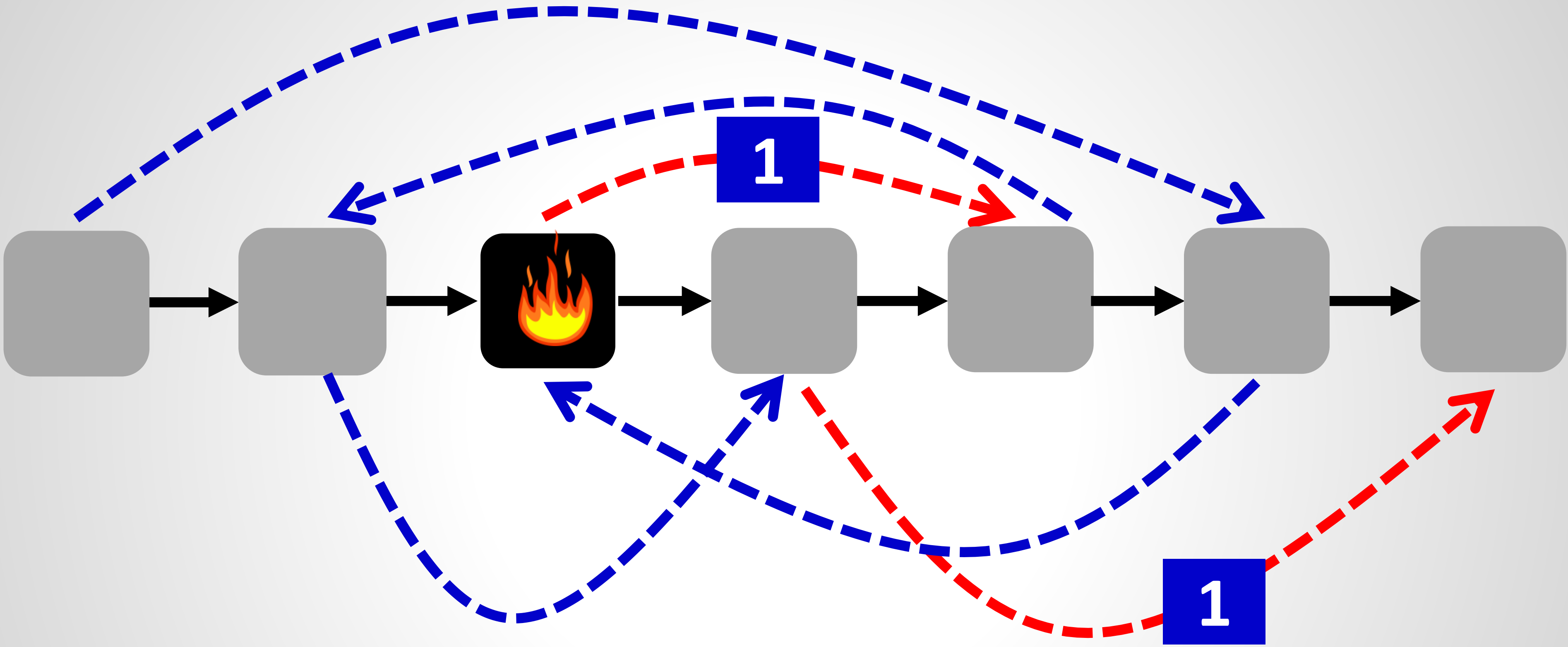
# What about this one?



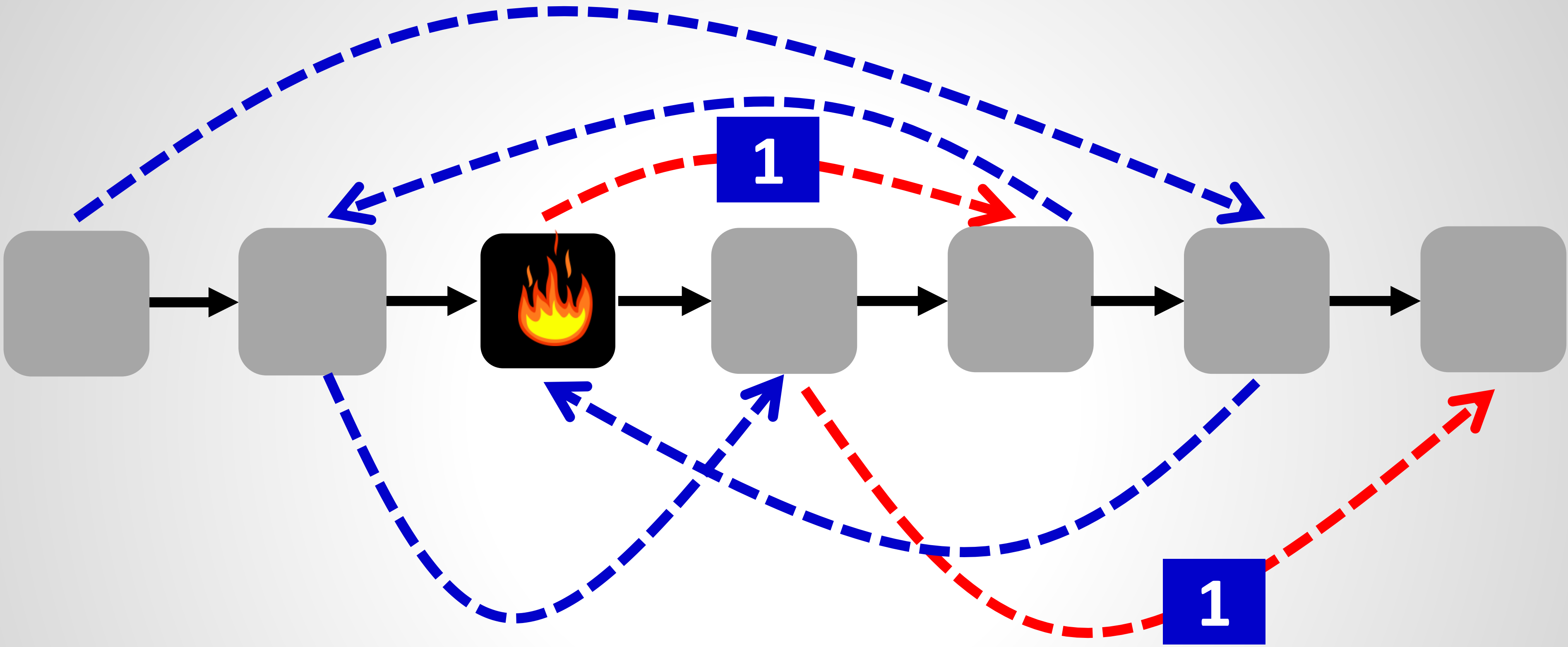
# Back to the start: What if….



# Back to the start: What if…. also this one?!

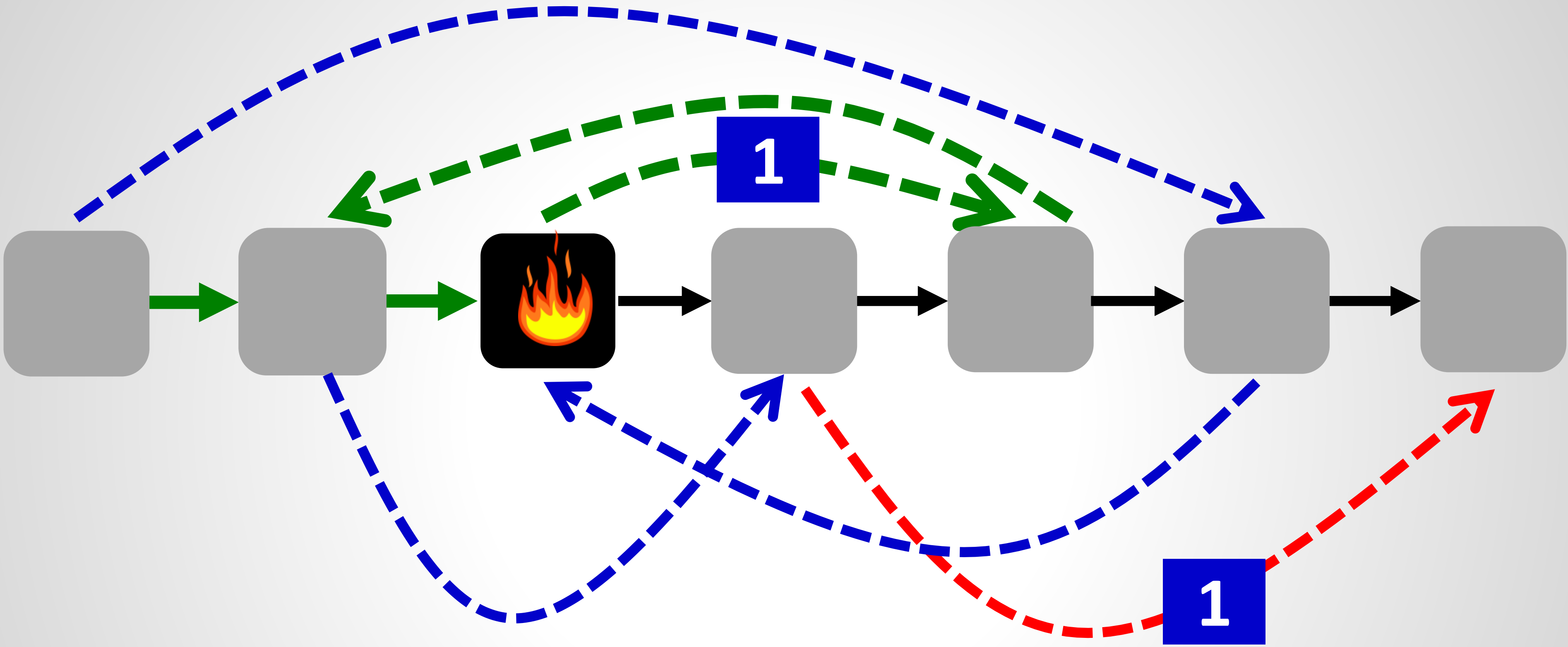


# Back to the start: What if…. also this one?!



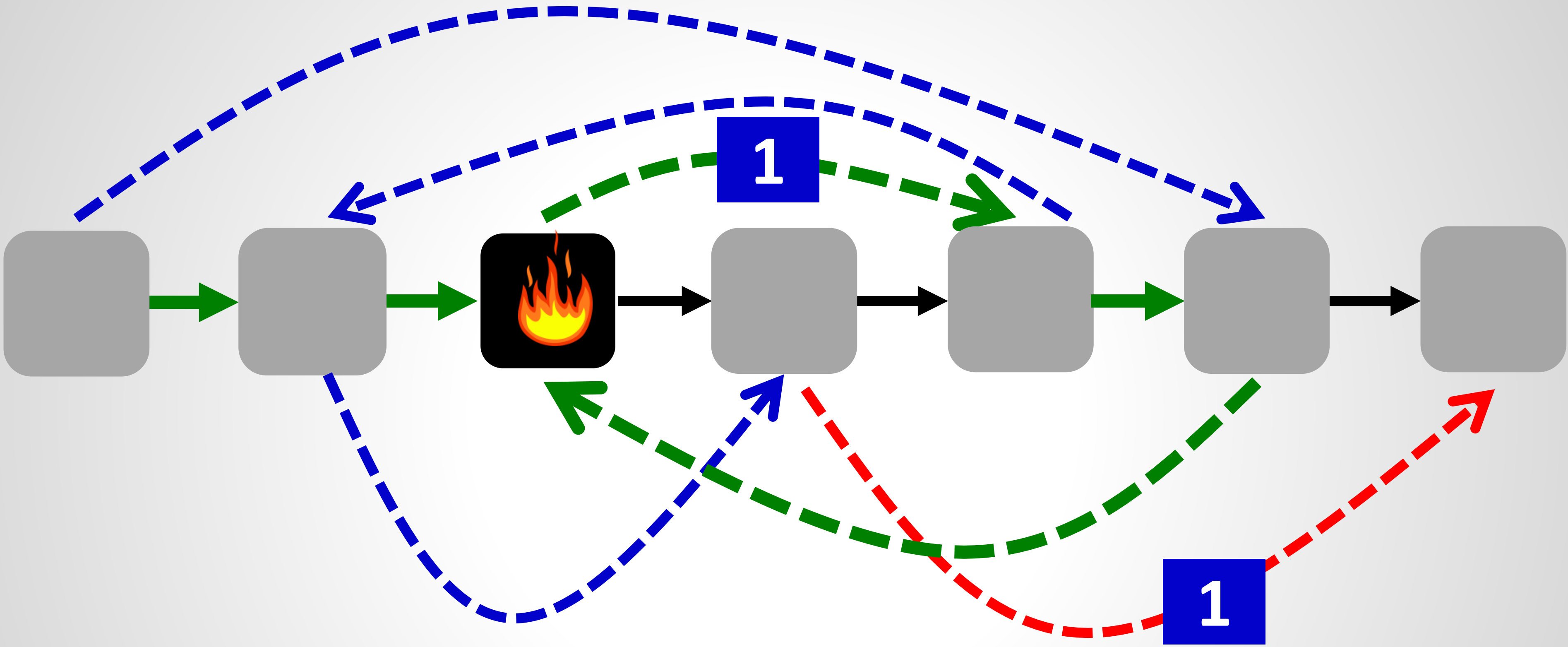

❑ Update any of the 2 backward edges? LF ☹

# Back to the start: What if…. also this one?!



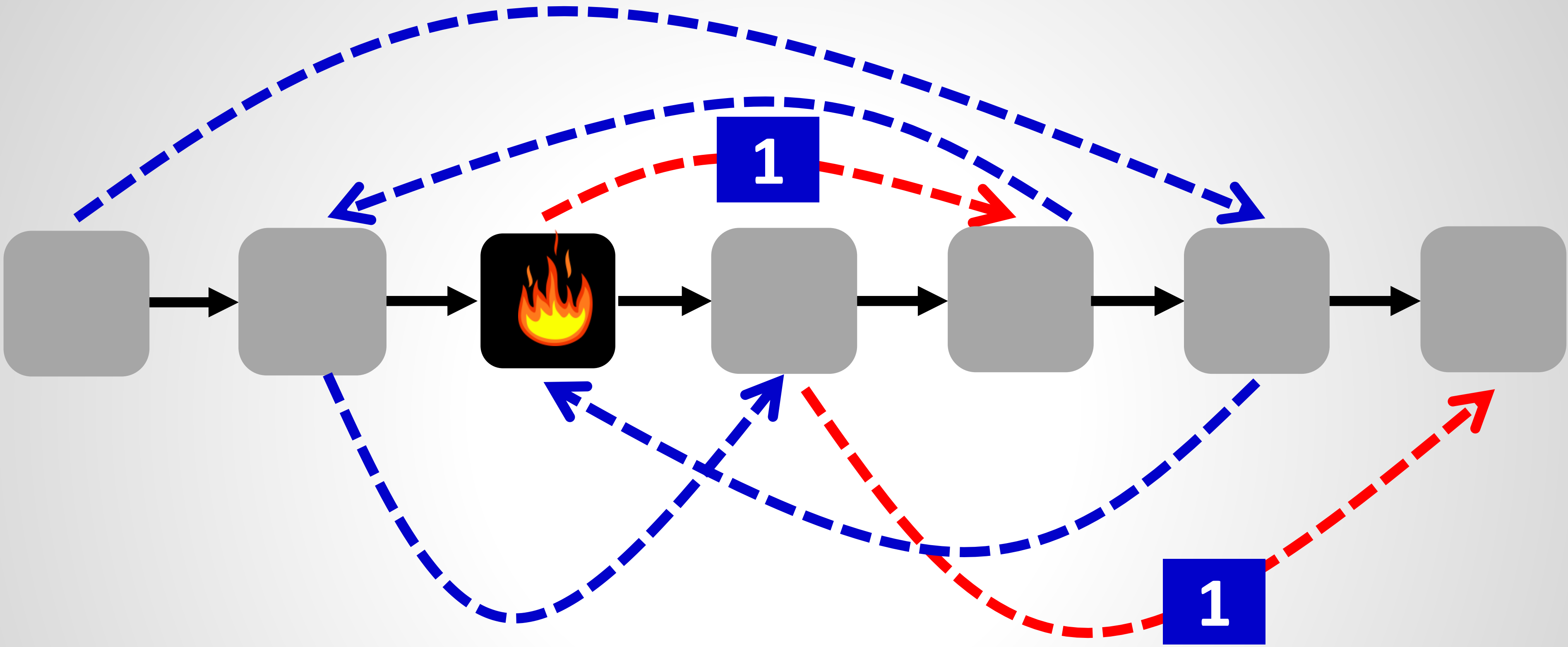

❑ Update any of the 2 backward edges? LF ☹

# Back to the start: What if…. also this one?!



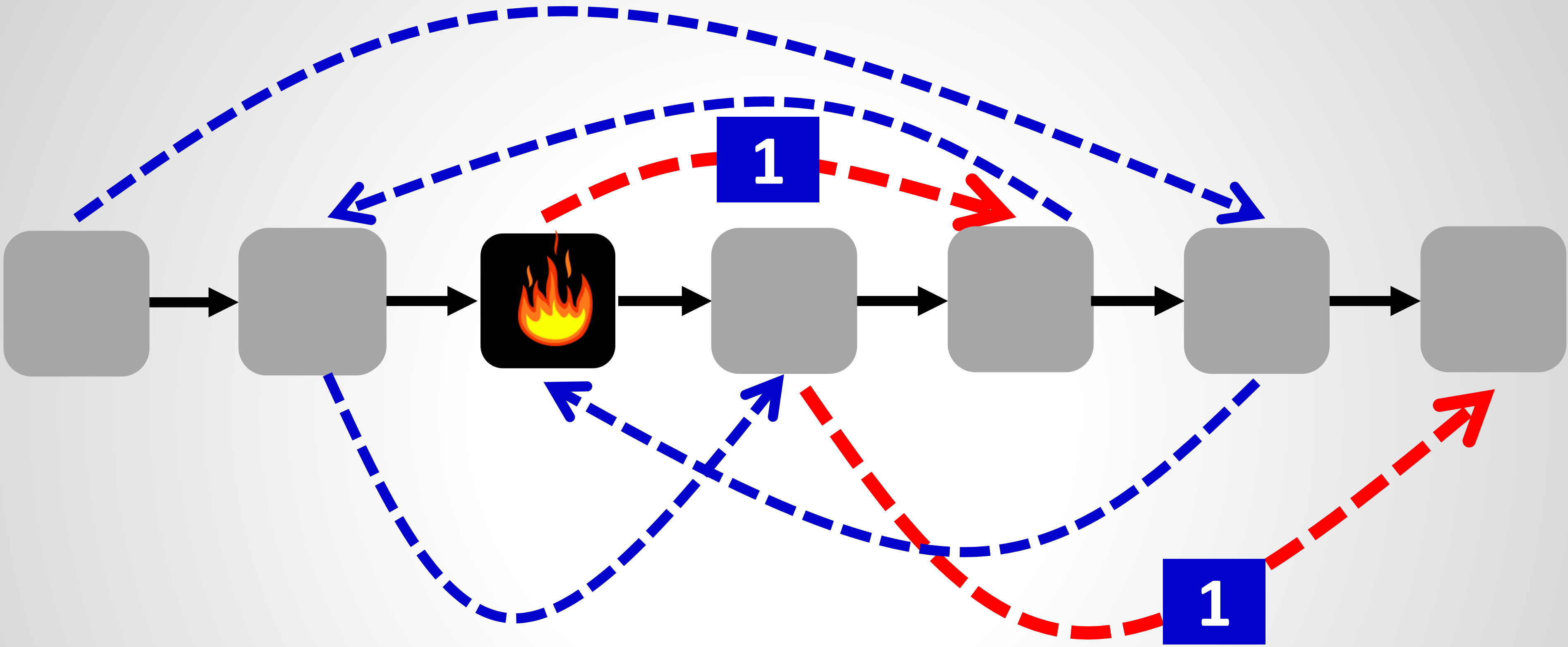

- ❑ Update any of the 2 backward edges? LF ☹

# Back to the start: What if…. also this one?!

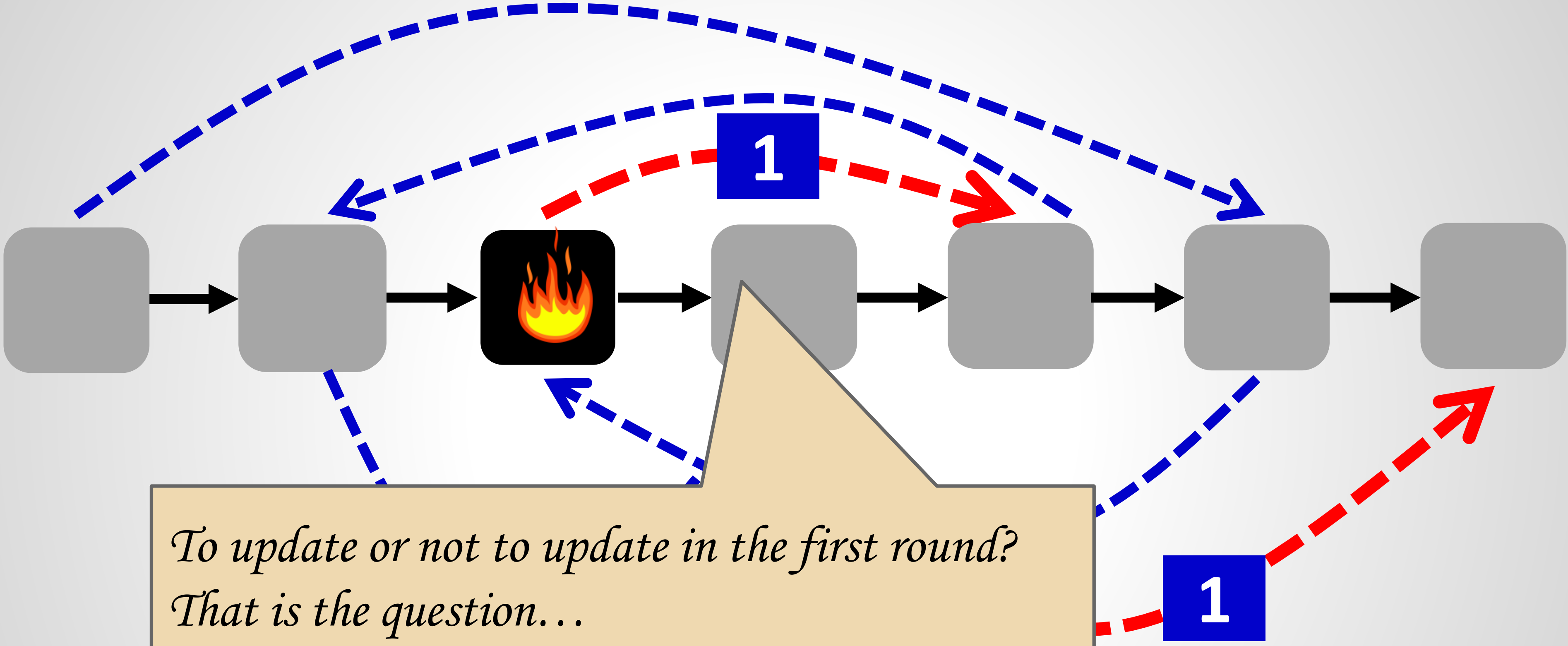



- ❑ Update any of the 2 backward edges? LF ☹
- ❑ Update any of the 2 other forward edges? WPE ☹
- ❑ What about a combination? Nope…

# Back to the start: What if…. also this one?!

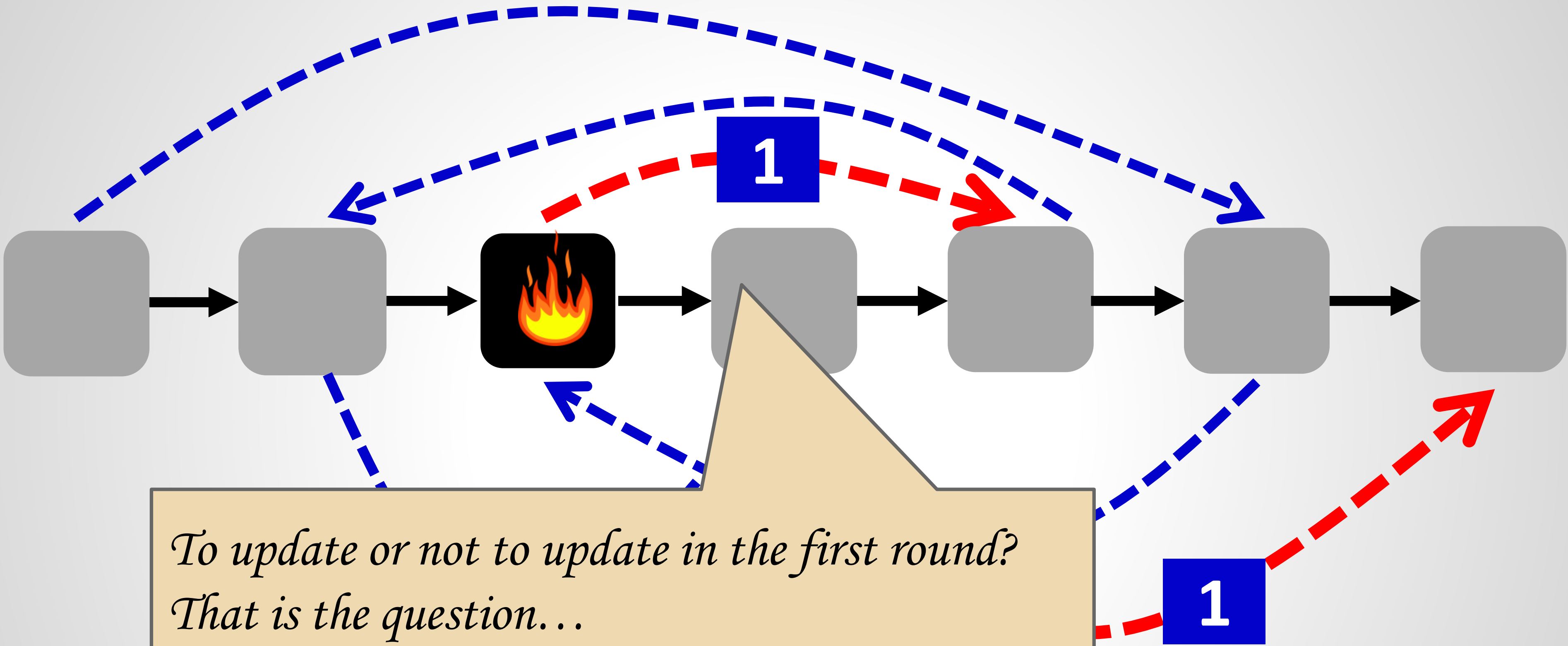


# Back to the start: What if…. also this one?!




*To update or not to update in the first round?*
*That is the question…*
… which leads to NP-hardness!

# Back to the start: What if…. also this one?!




*To update or not to update in the first round?*
*That is the question…*
… which leads to NP-hardness!

[Transiently Secure Network Updates]
Arne Ludwig, Szymon Dudycz, Matthias Rost, and Stefan Schmid.
42nd ACM **SIGMETRICS**, Antibes Juan-les-Pins, France, June 2016.

**Let us focus on loop-freedom only: always possible in *n* rounds! (How?) But how to minimize rounds?**

# Example: Optimal 2-Round Update Schedules

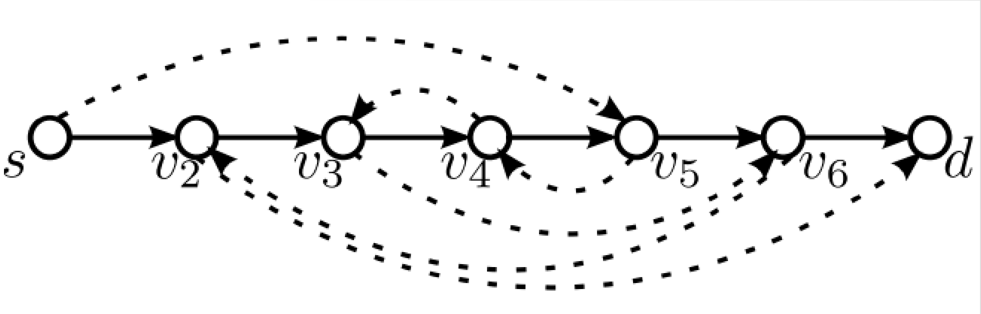
# Example: Optimal 2-Round Update Schedules

Clear: in Round 1 (R1), I can only update „forward“ links!

What about last round? Observe: Update schedule read backward (i.e., updating **from new to old policy**), must also be legal! I.e., in last round (R2), I can do all „forward“ edges of old edges wrt to new ones! **Symmetry**!

# Optimal Algorithm for 2-Round Instances: Leveraging Symmetry!

- Classify nodes/edges with **2-letter code**:
  - F•, B•: Does (dashed) new edge point forward or backward wrt (solid) old path?



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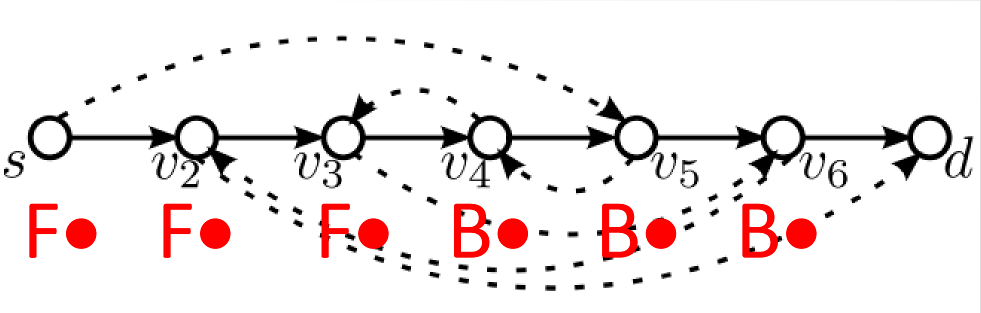
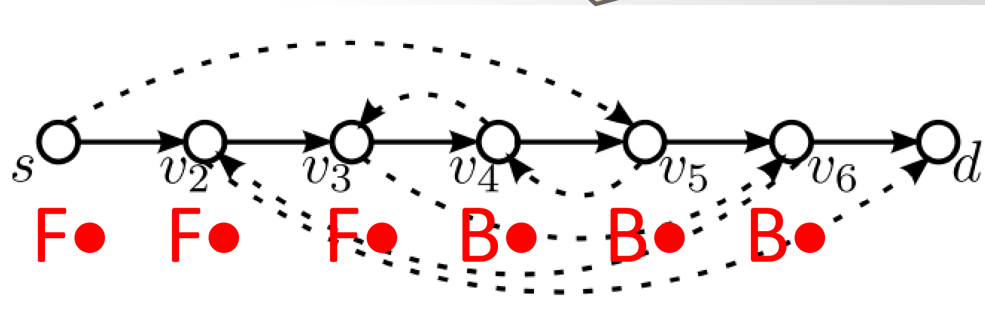


# Optimal Algorithm for 2-Round Instances: Leveraging Symmetry!

Old policy from left to right!

- Classify nodes/edg
  - F•, B•: Does (dashed) new edge point forward or backward wrt (solid) old path?



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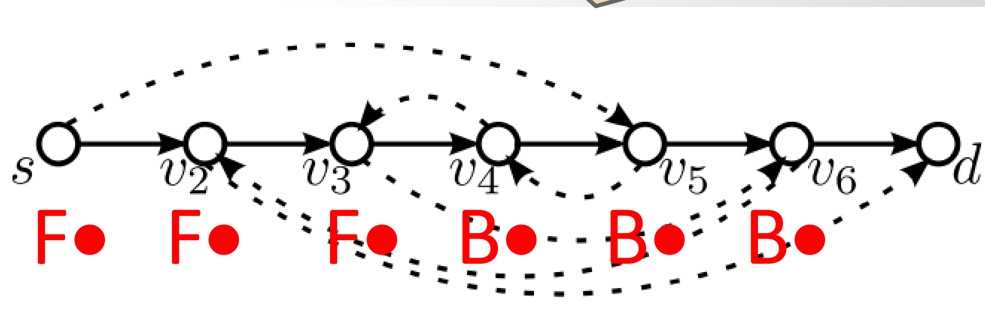


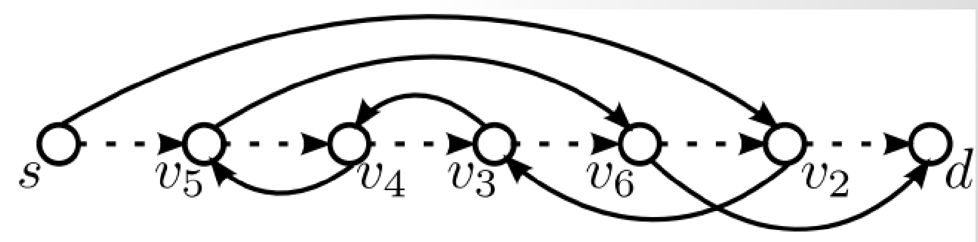


New policy from left to right!

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- Classify nodes/edg

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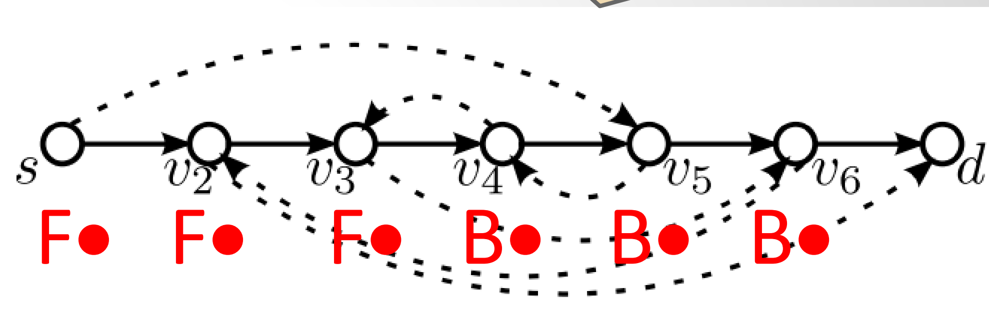
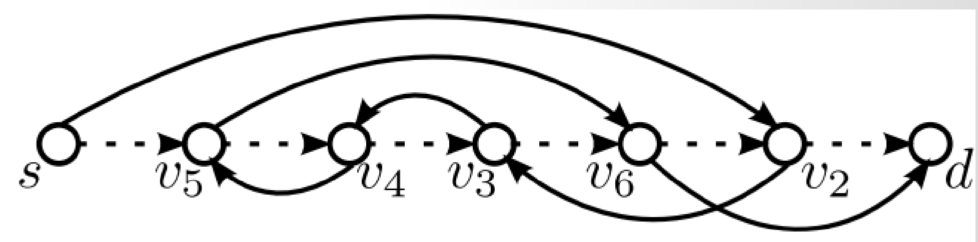



  - •F, •B: Does the (solid) old edge point forward or backward wrt (dashed) new path?

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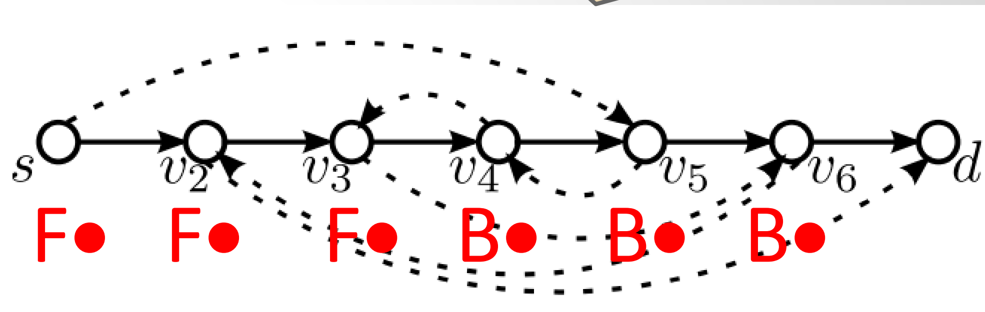


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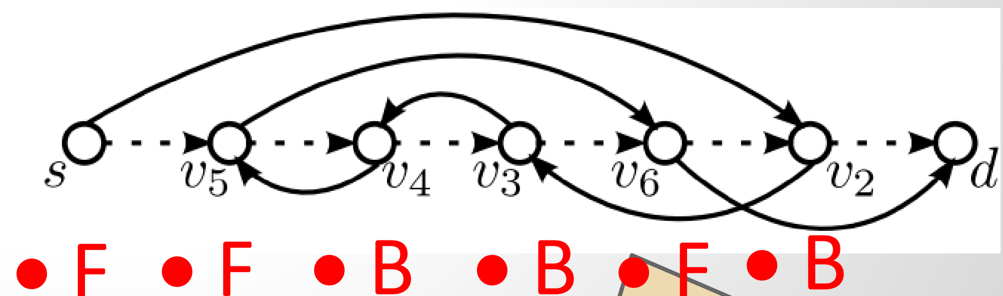
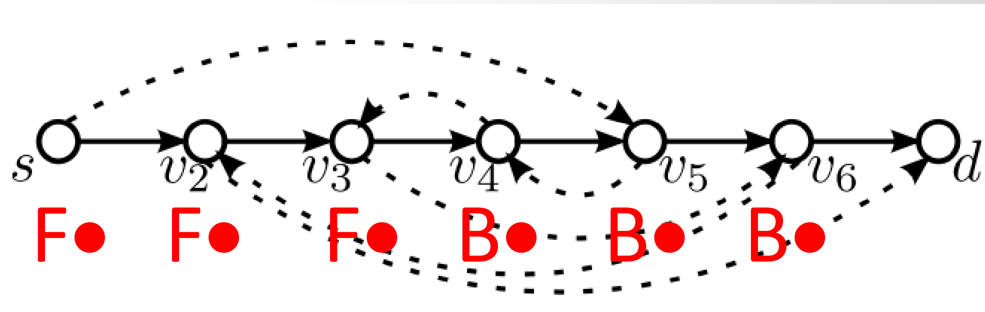



New policy from left to right!

# Optimal Algorithm for 2-Round Instances: ...ging Symmetry!

**Insight 1:** In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

- ...es with 2-letter code:
  - F•, B•: Does (dashed) new edge point forward or backward wrt (solid) old path?

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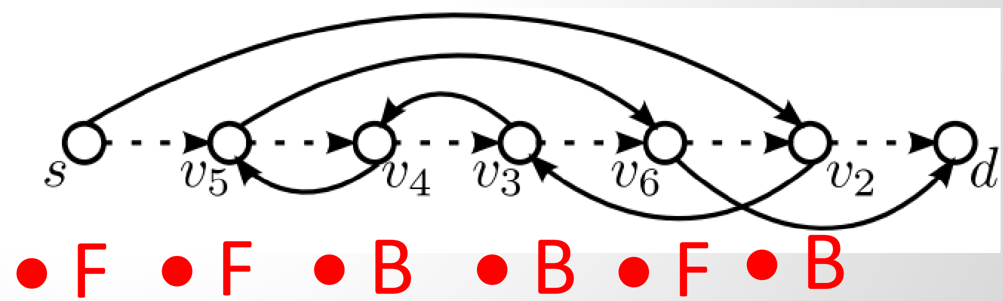


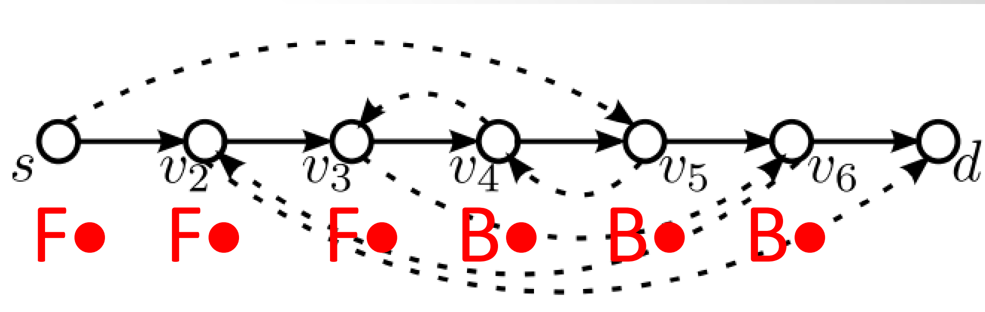
# Optimal Algorithm for 2-Round Instances: ...ging Symmetry!

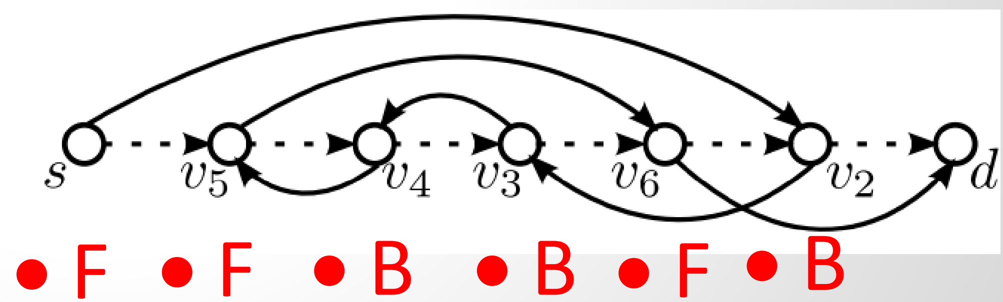
**Insight 1:** In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

...es with 2-letter code:

**Insight 2:** Valid schedules are reversible! A valid schedule from old to new *read backward* is a valid schedule for new to old!

old edge point forward or backward wrt (dashed) new path?



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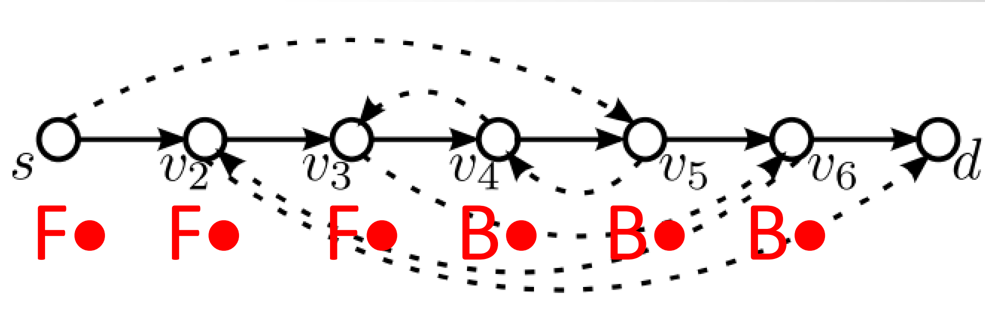
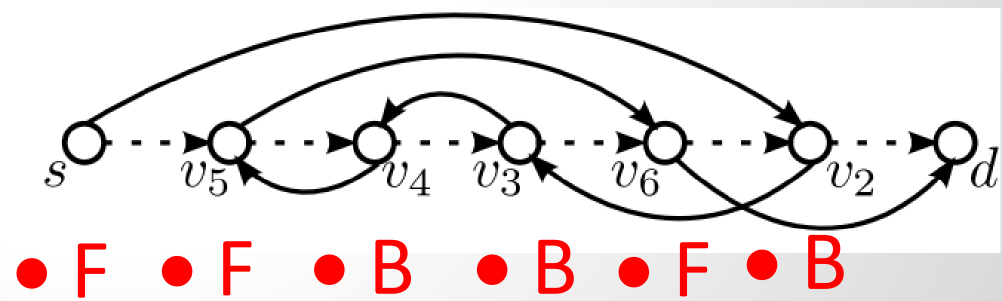



**Insight 3:** Hence in the last round, I can safely update all forwarding (•F) edges! For sure loopfree.



# Optimal Algorithm for 2-Round Instances: ...ging Symmetry!

...es with 2-letter code:

**<u>Insight 1:</u>** In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

**<u>Insight 2:</u>** Valid schedules are reversible! A valid schedule from old to new *read backward* is a valid schedule for new to old!

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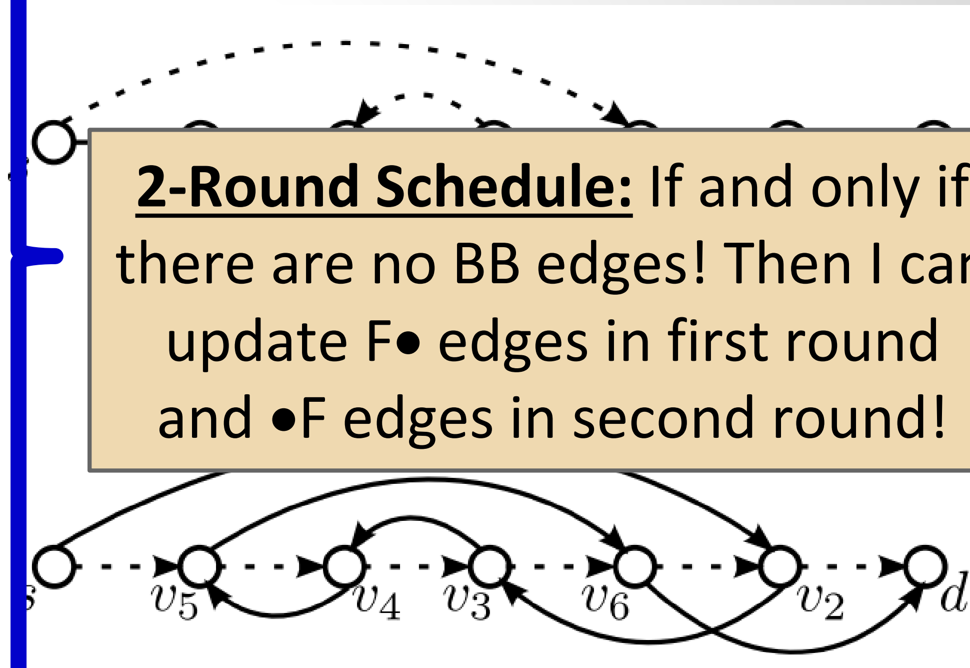



**<u>2-Round Schedule:</u>** If and only if there are no BB edges! Then I can update F• edges in first round and •F edges in second round!

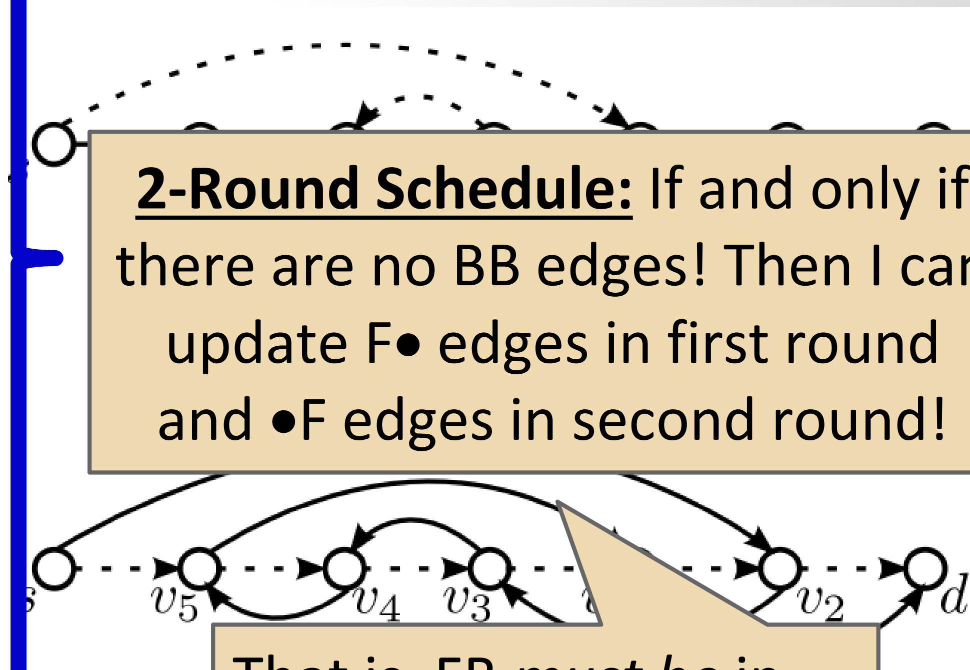
# Optimal Algorithm for 2-Round Instances: ...ging Symmetry!

...es with 2-letter code:

**<u>Insight 1:</u>** In the 1st round, I can safely update all forwarding (F•) edges! For sure loopfree.

**<u>Insight 2:</u>** Valid schedules are reversible! A valid schedule from old to new *read backward* is a valid schedule for new to old!

**<u>Insight 3:</u>** Hence in the last round, I can safely update all forwarding (•F) edges! For sure loopfree.

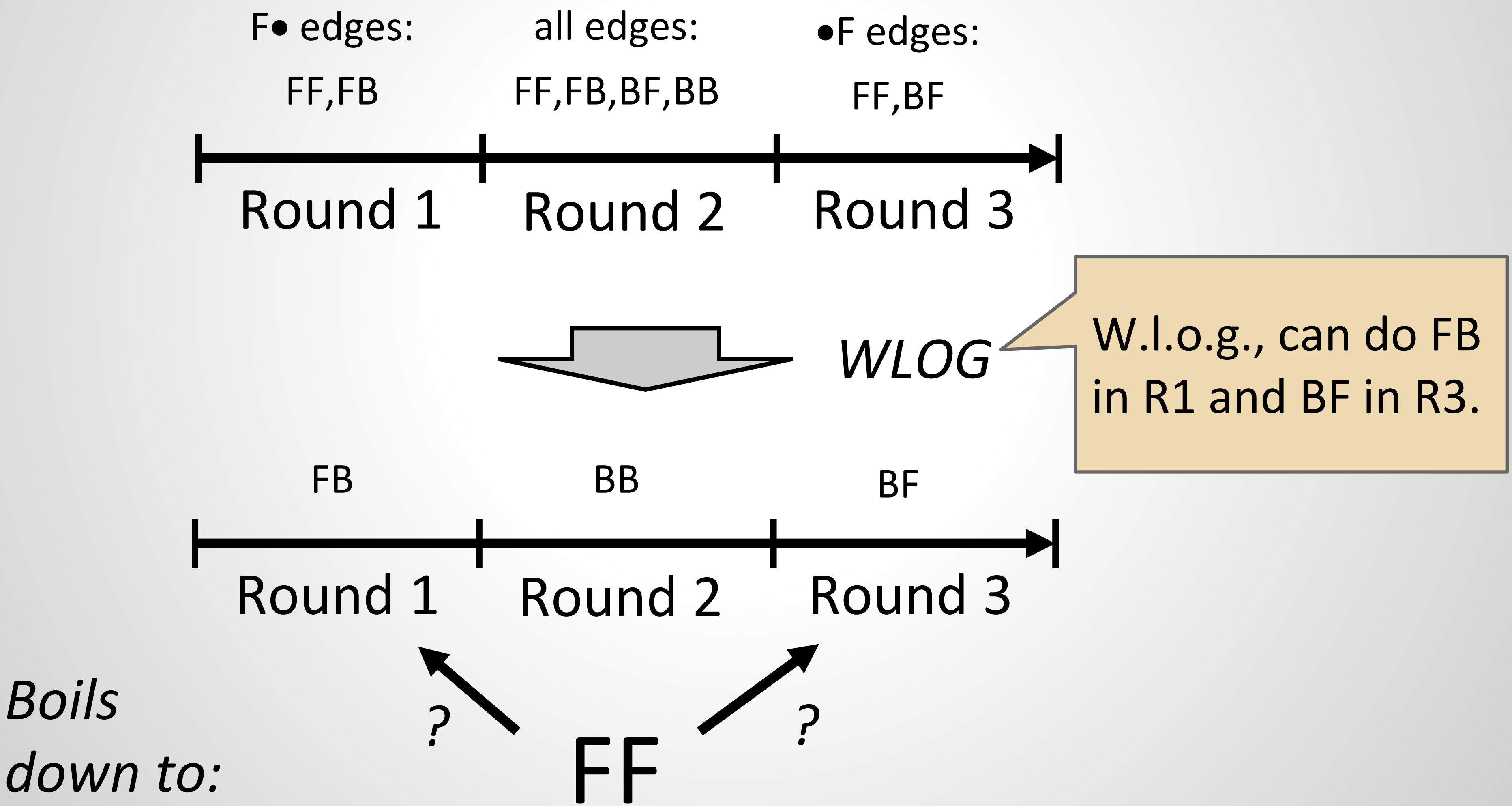



**<u>2-Round Schedule:</u>** If and only if there are no BB edges! Then I can update F• edges in first round and •F edges in second round!

That is, FB *must be* in first round, BF *must be* in second round, and FF are *flexible*!

# Intuition Why 3 Rounds Are Hard

- Structure of a 3-round schedule:



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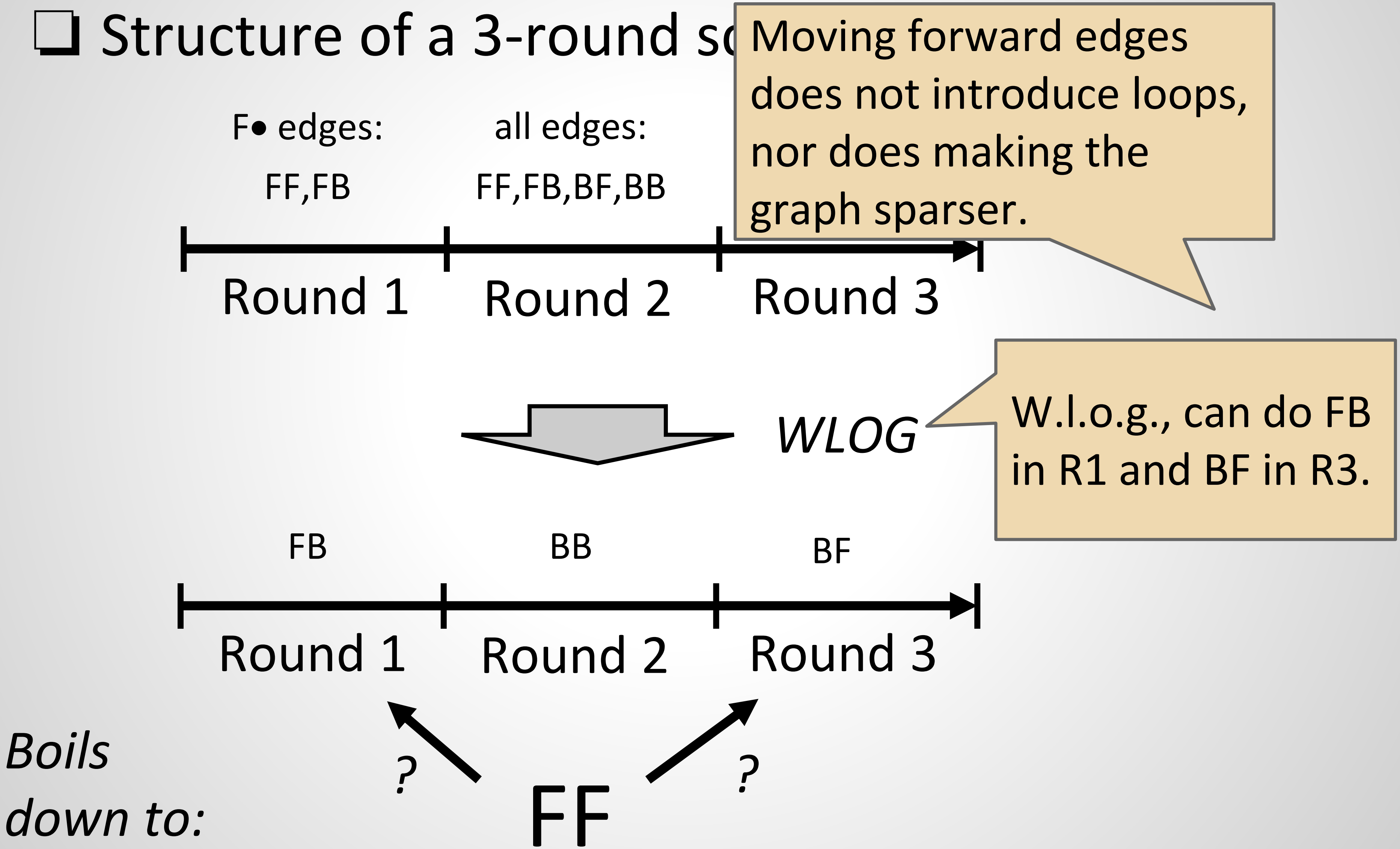
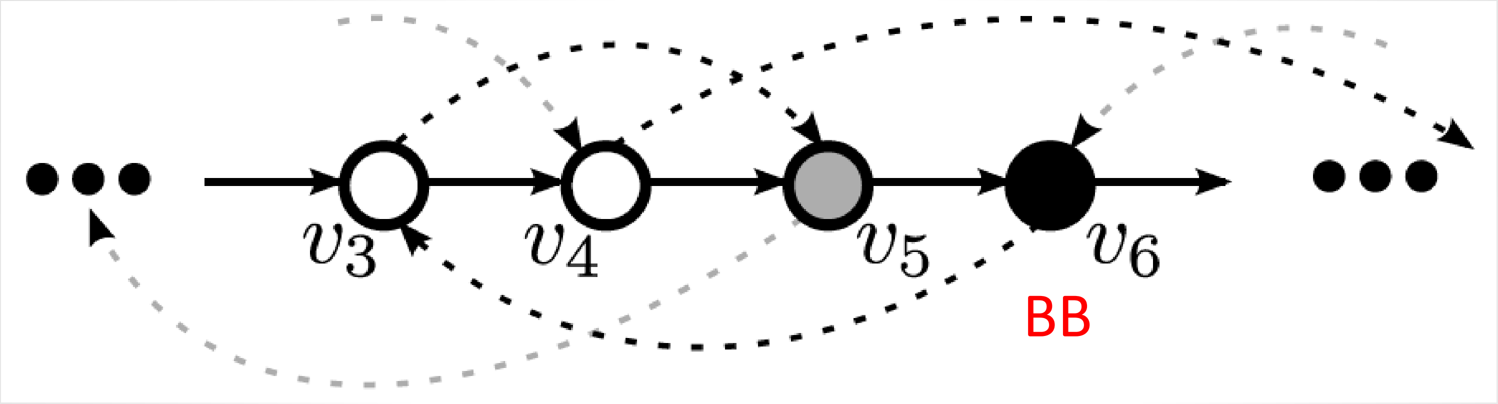


# Intuition Why 3 Rounds Are Hard

A hard decision problem: when to update FF?




- We know: BB node $v_6$ can only be updated in R2
- When to update FF nodes to make enable update BB in R2?

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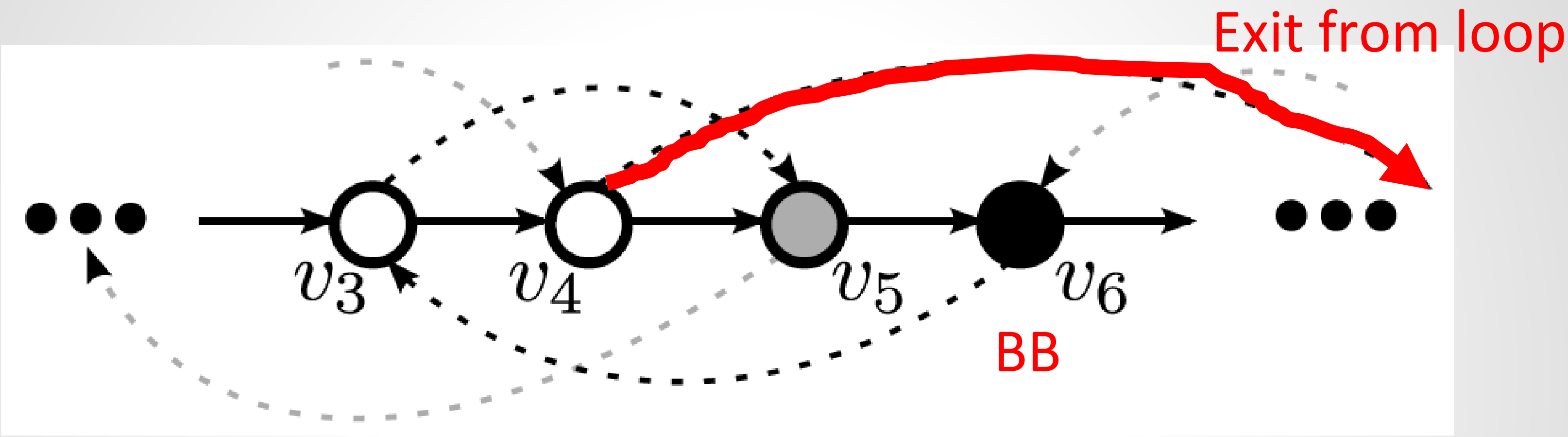
A hard decision problem: when to update FF?

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- E.g, updating FF-node $v_4$ in R1 allows to update BB $v_6$ in R2

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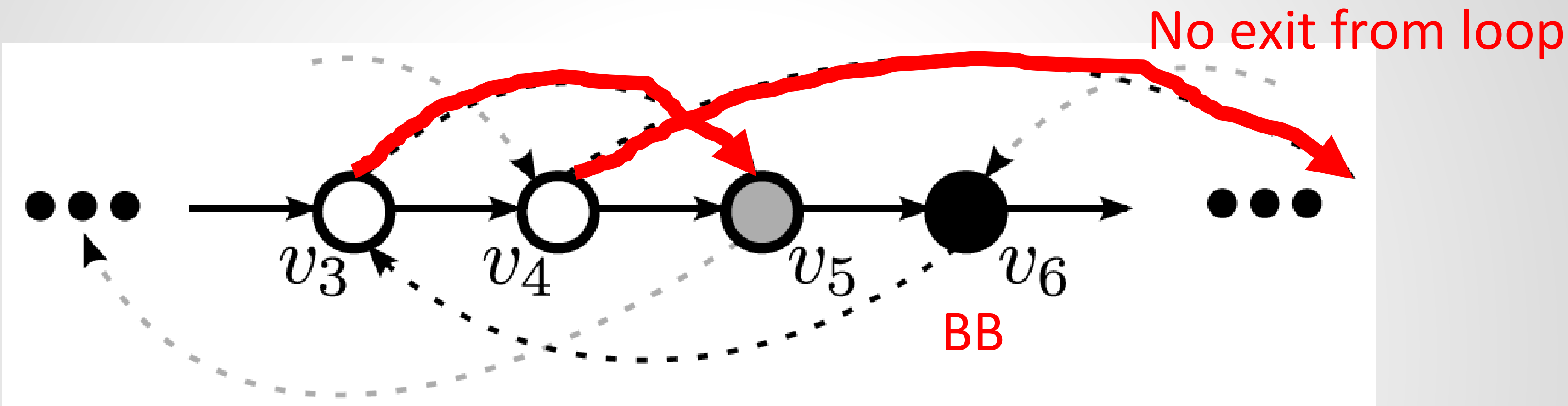


- ❑ We know: BB node $v_6$ can only be updated in R2
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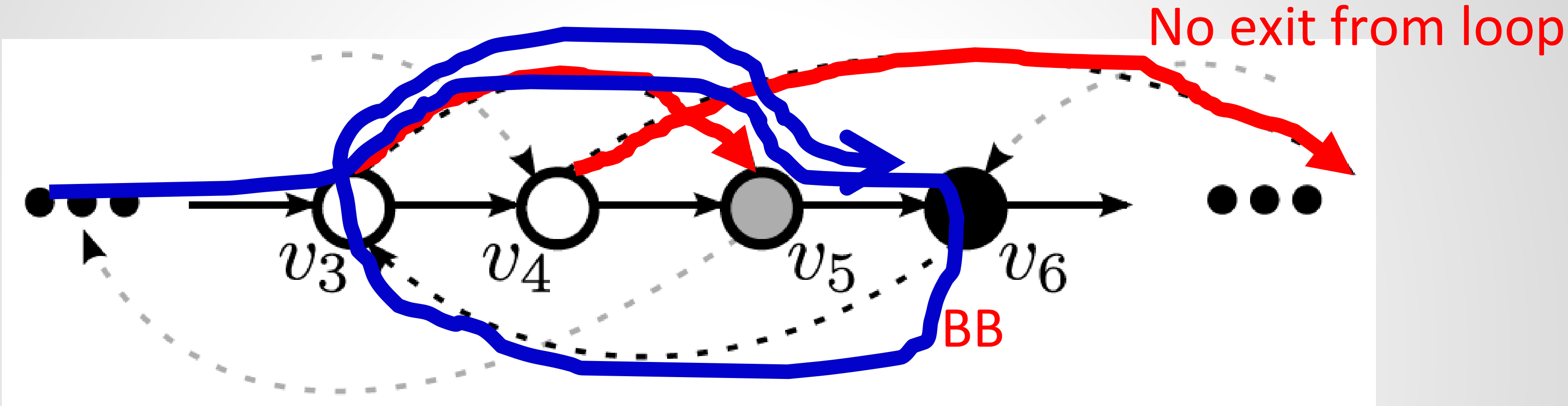


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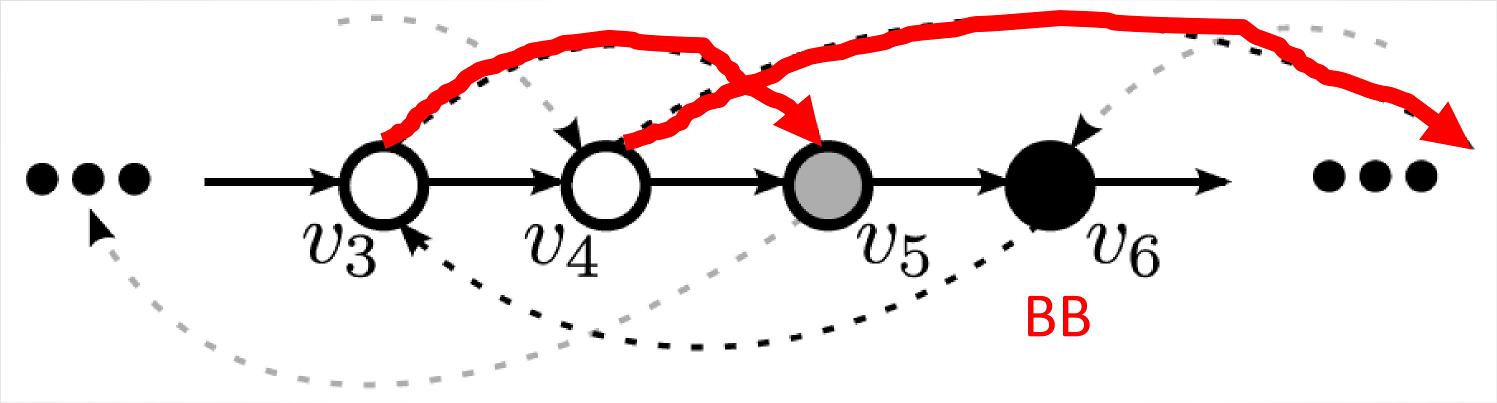


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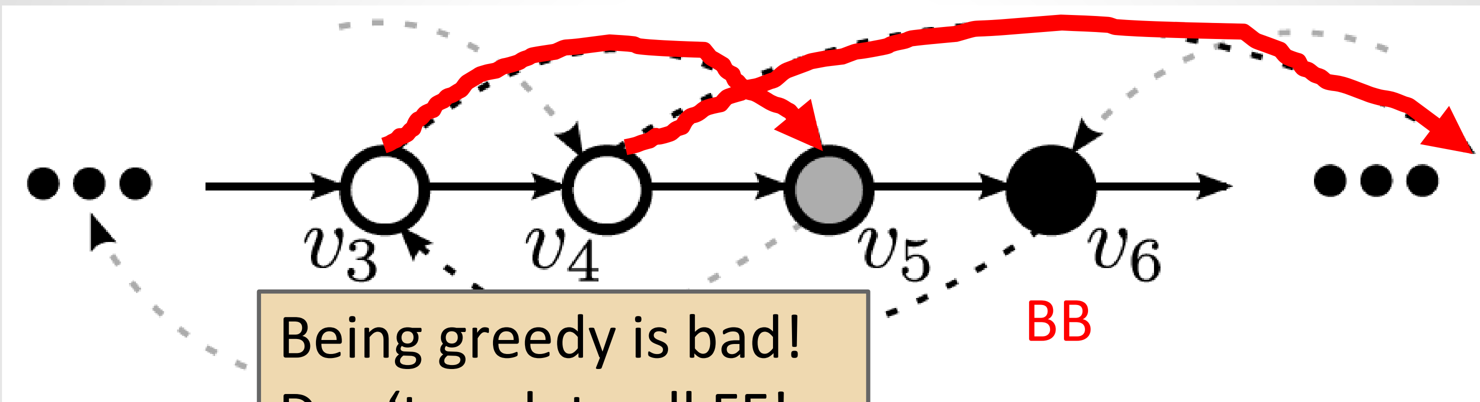
- E.g, updating FF-node $v_4$ in R1 allows to update BB $v_6$ in R2
- But only if FF-node $v_3$ is not updated as well in R1: potential loop
- Smells like a gadget: which FF nodes to update when is hard!

# Intuition Why 3 Rounds Are Hard

A hard decision problem: when to update FF?



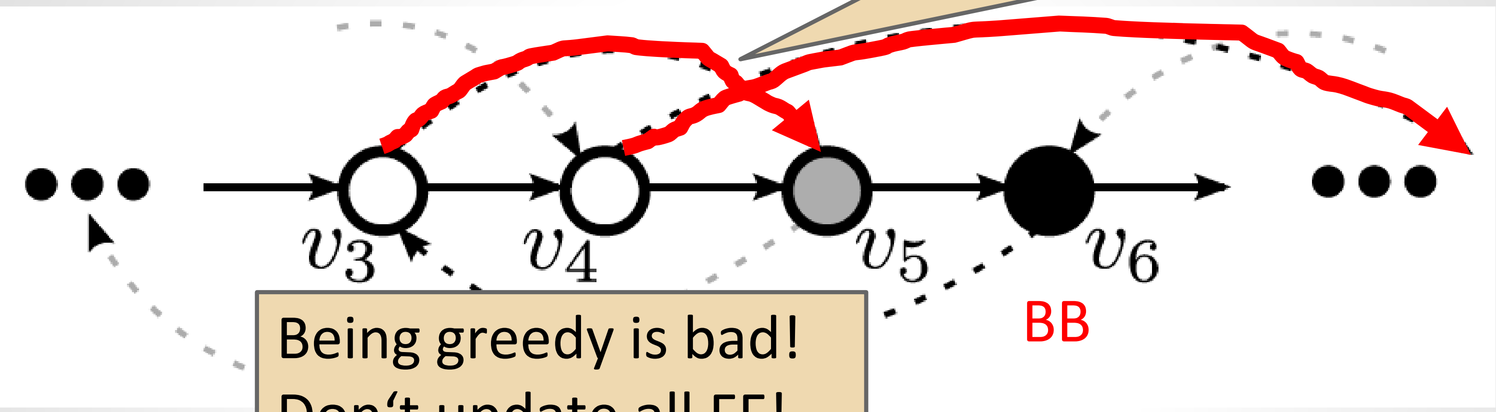

Being greedy is bad!
Don't update all FF!

- We know: [illegible] node $v_6$ can only be updated in R2
- When to update FF nodes to make enable update BB in R2
- E.g, updating FF-node $v_4$ in R1 allows to update BB $v_6$ in R2
- But only if FF-node $v_3$ is not updated as well in R1: potential loop
- Smells like a gadget: which FF nodes to update when is hard!

# Intuition Why 3

Devil lies in details: original paths must also be valid!
I.e., to prove that such a configuration can be reached.

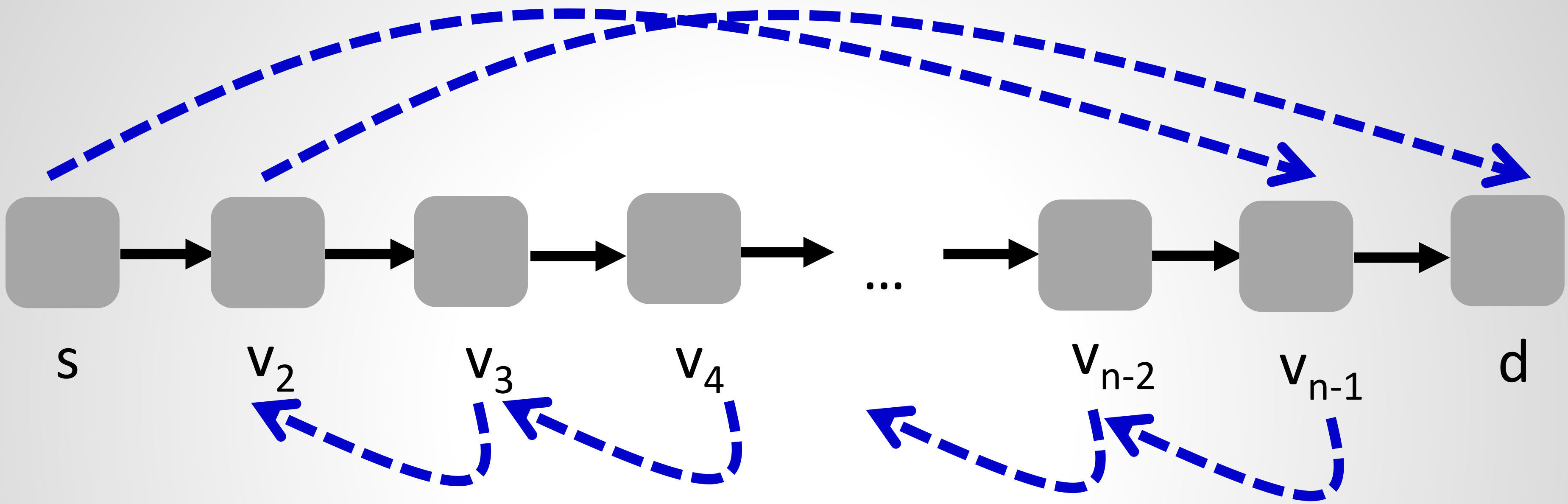
A hard decision problem:



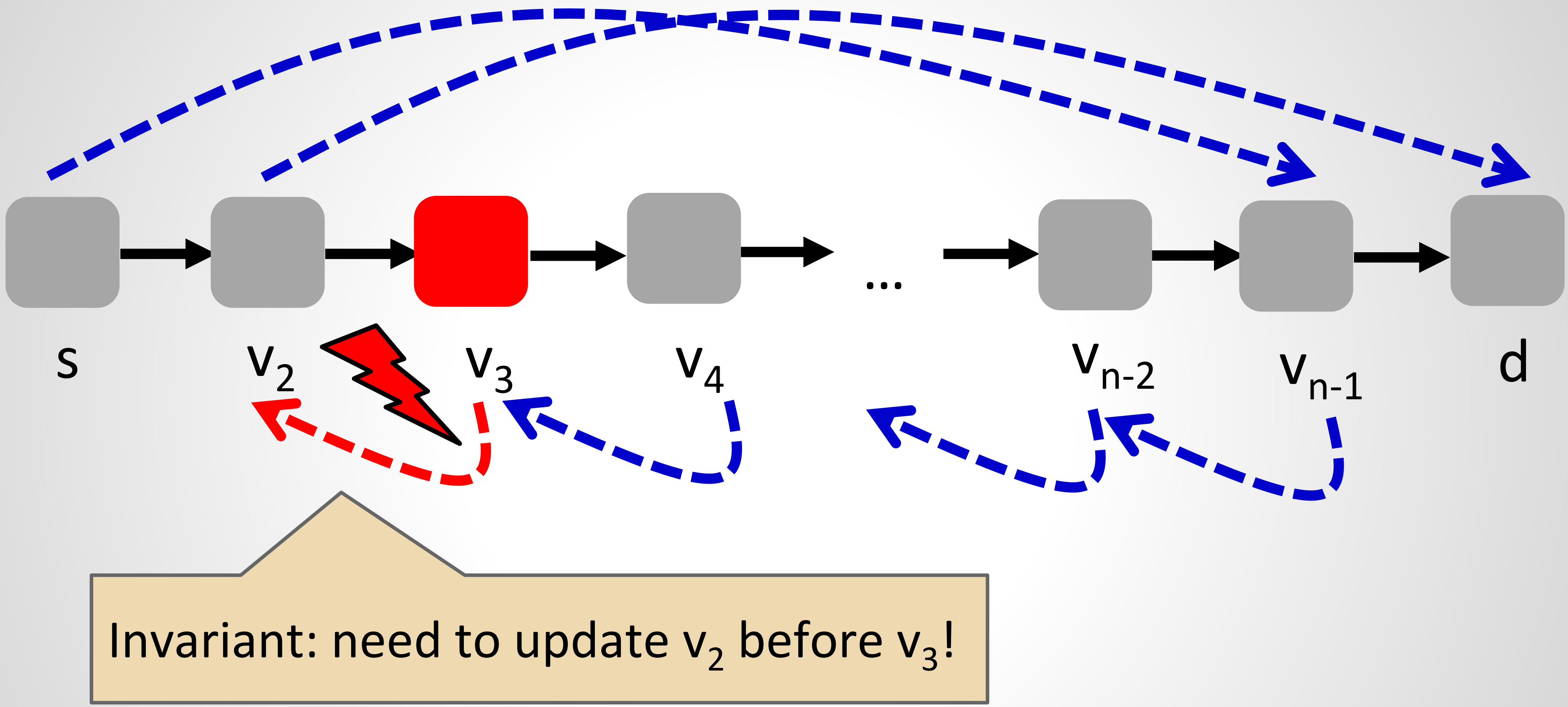

Being greedy is bad!
Don‘t update all FF!

- We know: [...]ode $v_6$ can only be updated in R2
- When to update FF nodes to make enable update BB in R2
- E.g, updating FF-node $v_4$ in R1 allows to update BB $v_6$ in R2
- But only if FF-node $v_3$ is not updated as well in R1: potential loop
- Smells like a gadget: which FF nodes to update when is hard!

# It's Good to Relax: How to update LF?



# LF Updates Can Take Many Rounds!



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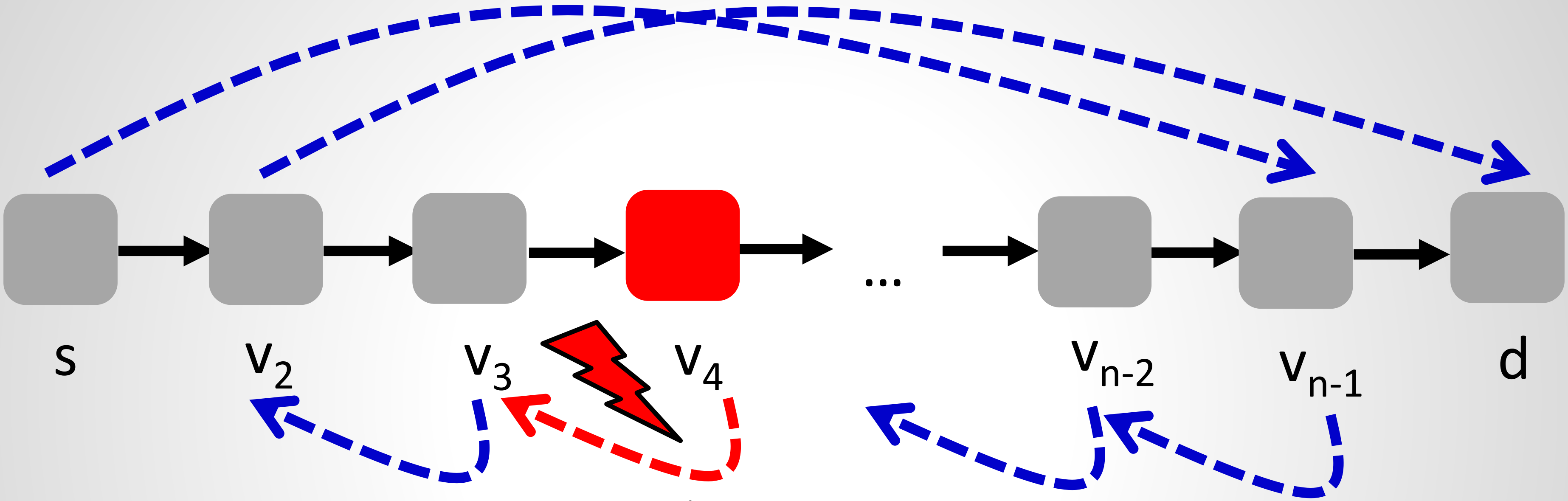
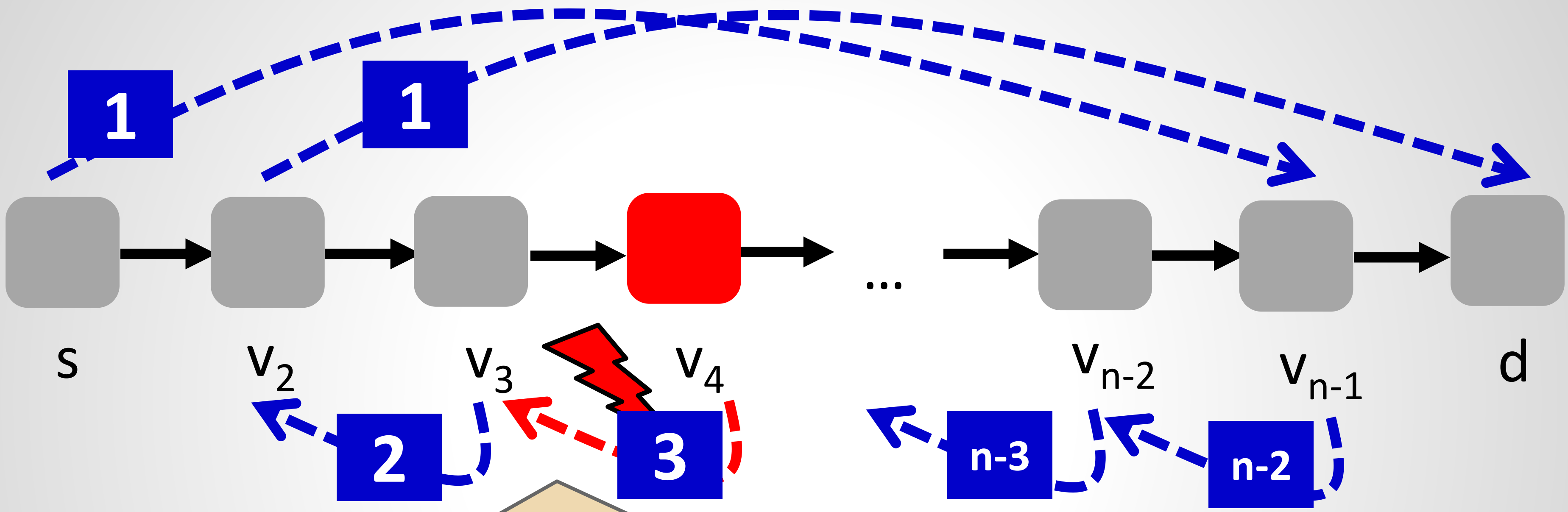



Invariant: need to update $v_3$ before $v_4$!

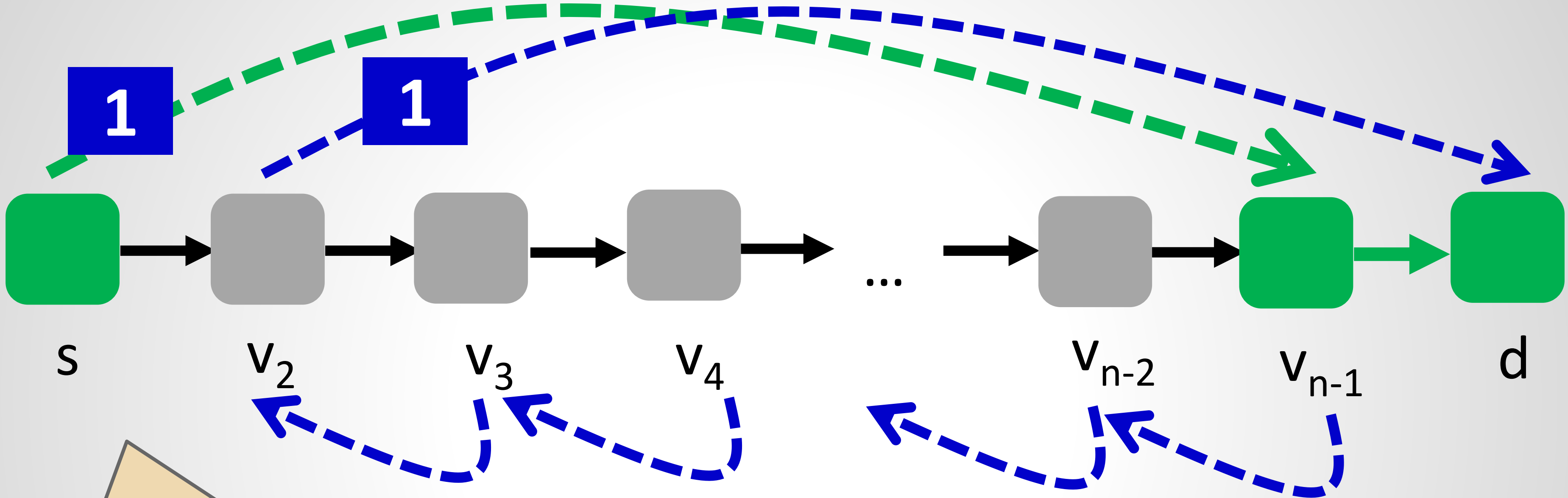
# LF Updates Can Take Many Rounds!




Induction: need to update $v_{i-1}$ before $v_i$ (before $v_{i+1}$ etc.)!

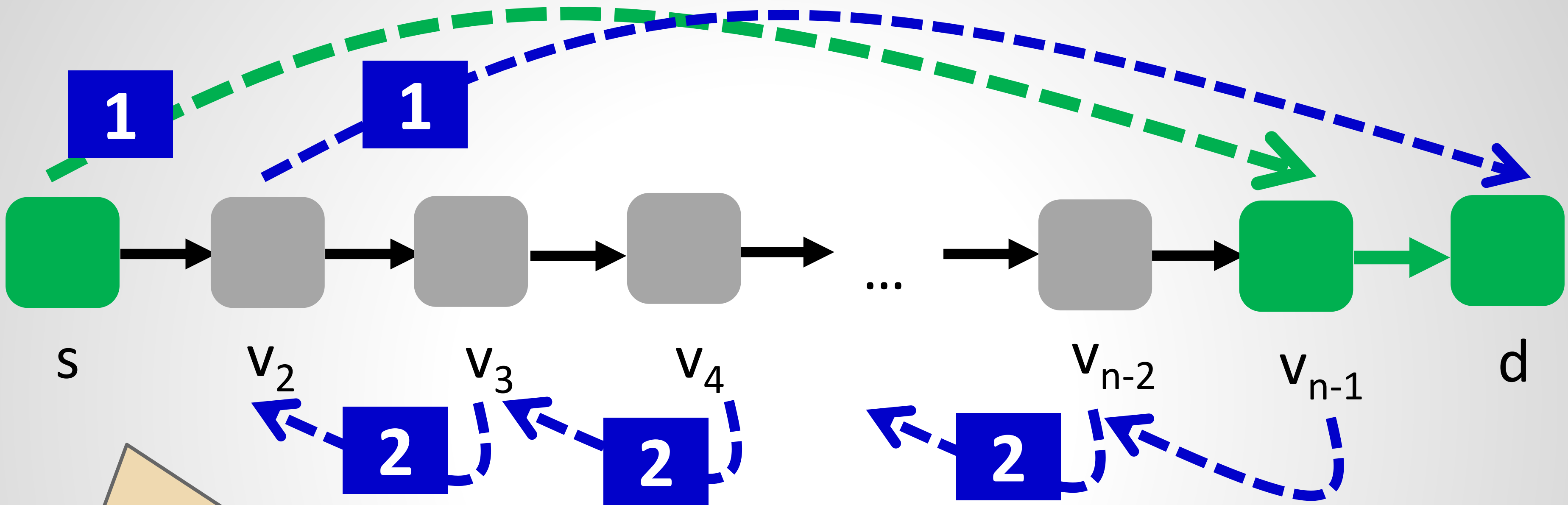
$\Omega$(n) rounds?! In principle, yes…: Need a path back out before updating backward edge!

# It is good to relax!




But: If s has been updated, nodes not on (s,d)-path!

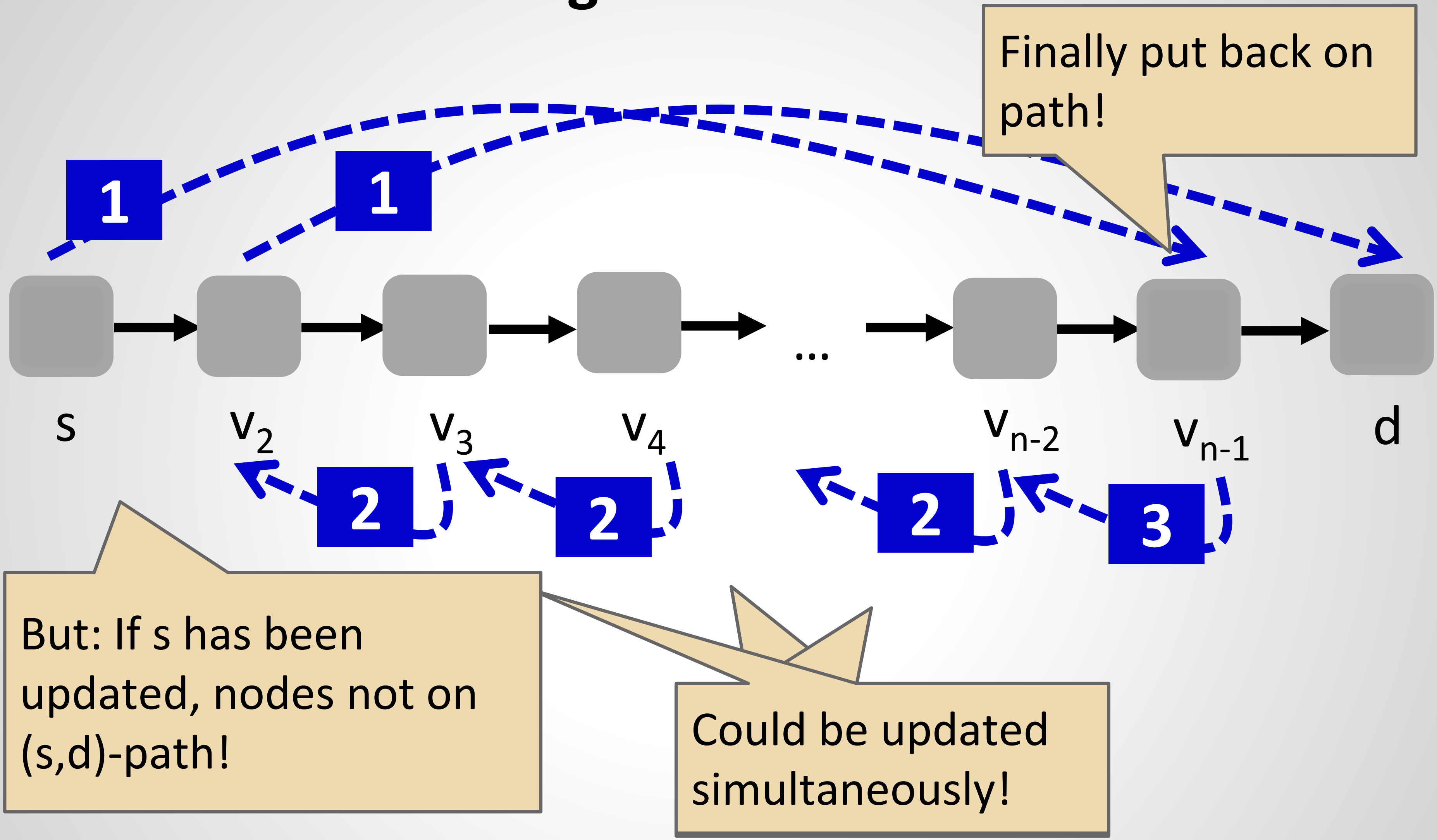
# It is good to relax!




But: If s has been updated, nodes not on (s,d)-path!

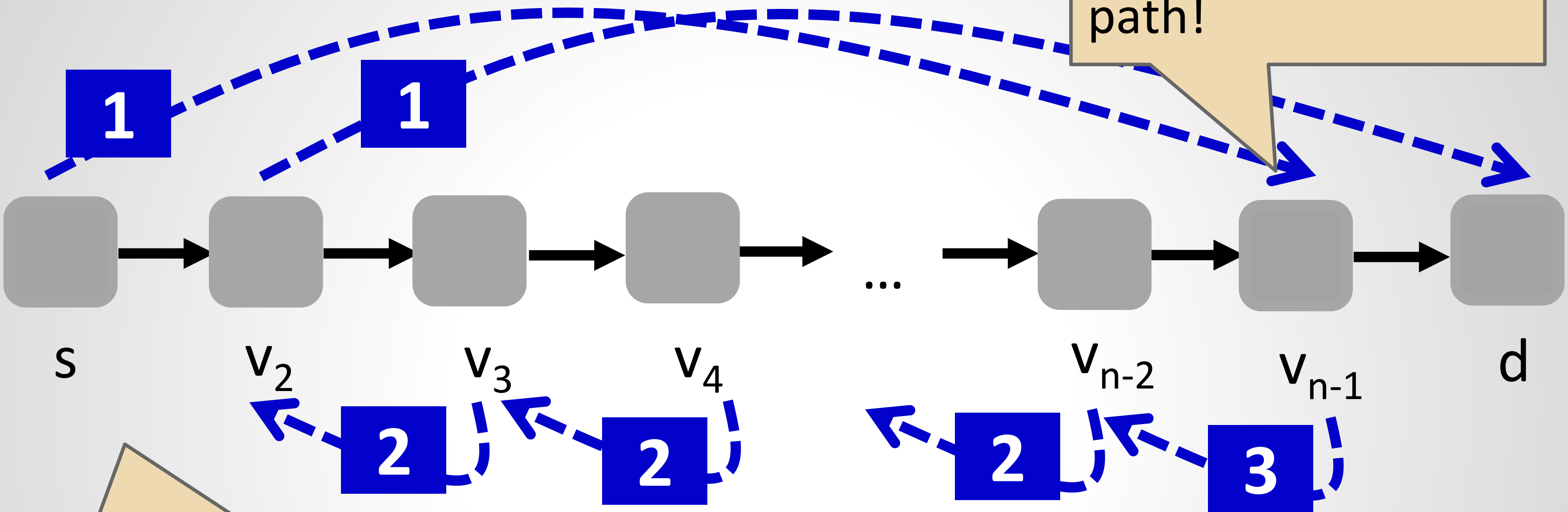
Could be updated simultaneously!

# It is good to relax!



# It is good to relax!

Finally put back on path!

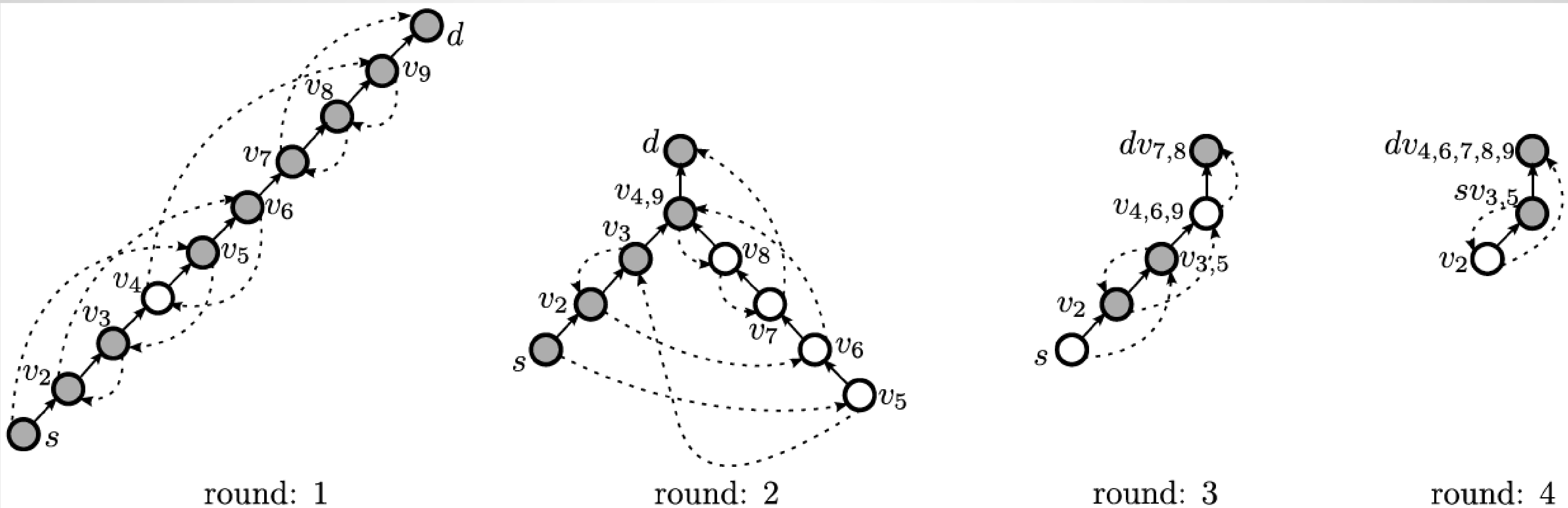



But: If s has been updated, nodes not on (s,d)-path!

Could be updated simultaneously!

**3 rounds only!**

# A log(n)-time Algorithm: *Peacock* in Action




Shortcut Prune Shortcut Prune

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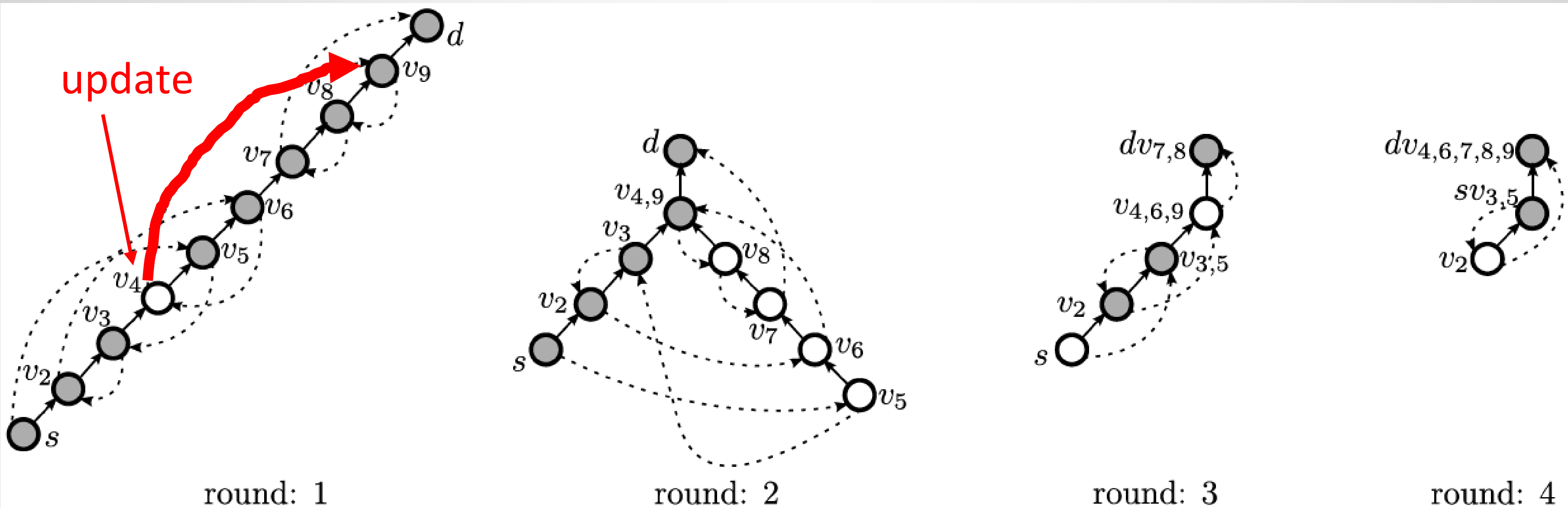



Shortcut

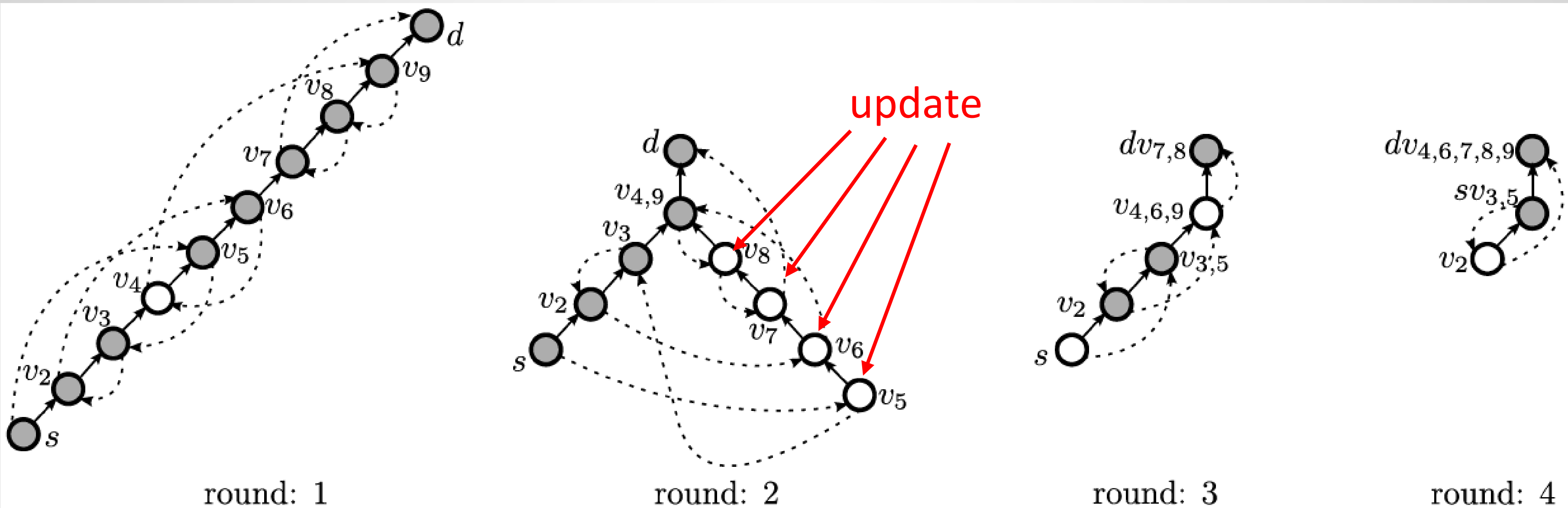
Prune

Shortcut

Prune

Greedily choose far-reaching (independent) forward edges.

# A log(n)-time Algorithm: *Peacock* in Action




Shortcut

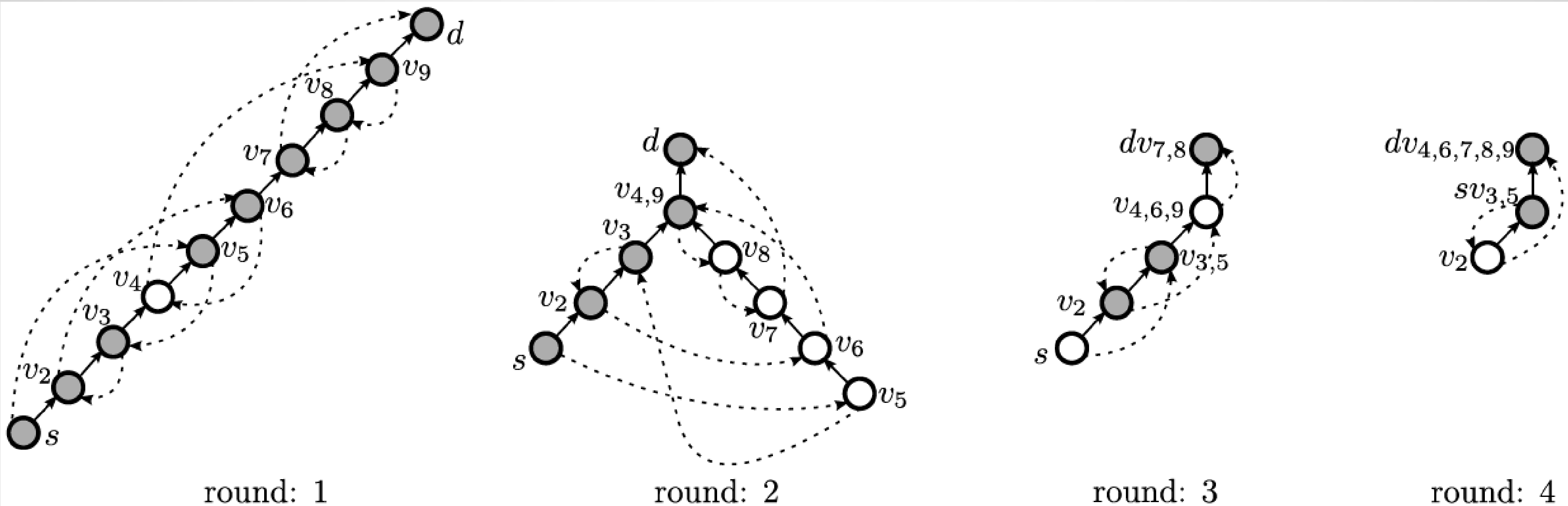
Prune

Shortcut

Prune

R1 generated many nodes in branches which can be updated simultaneously!

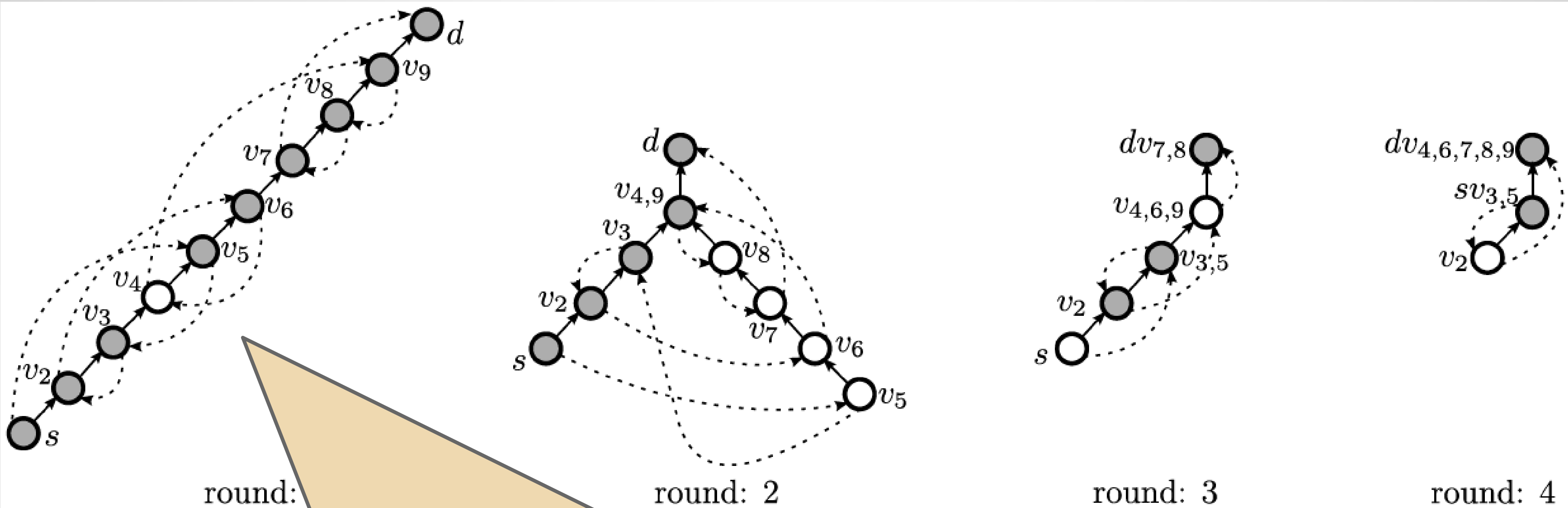
# A log(n)-time Algorithm: *Peacock* in Action




Shortcut Prune Shortcut Prune

Line re-established!
(all merged with a node on the s-d-path)

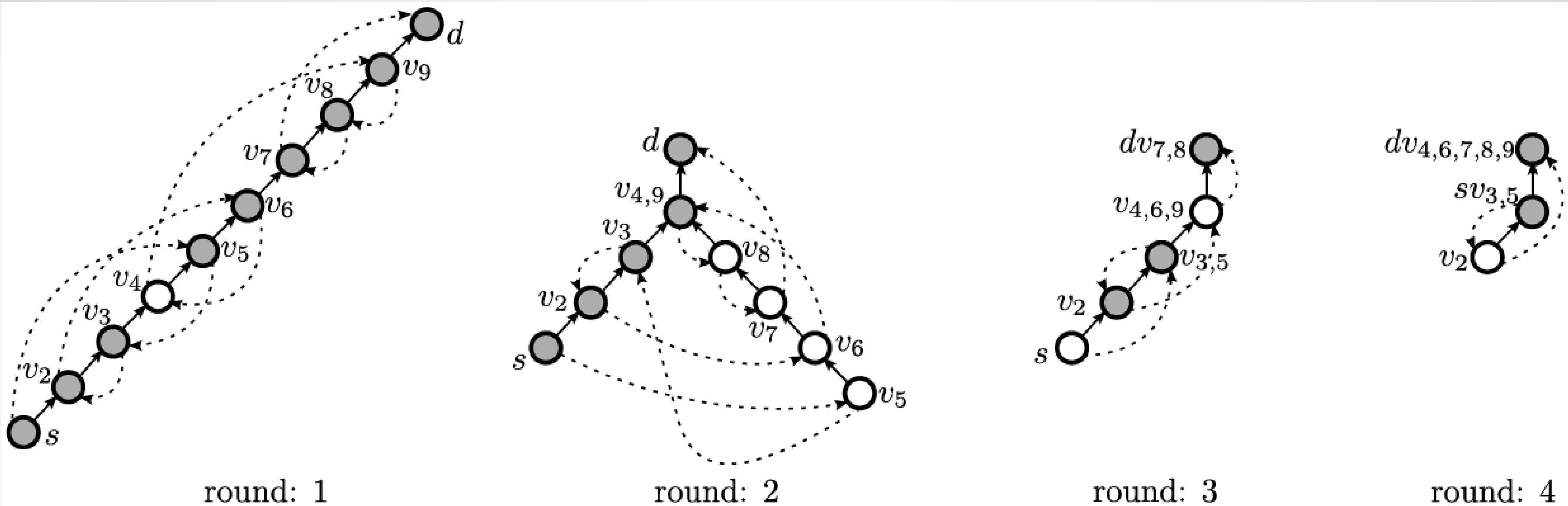
# A log(n)-time Algorithm: *Peacock* in Action




Peacock orders nodes wrt to distance: edge of length x **can block** at most 2 edges of length x, so distance 2x.

Prune

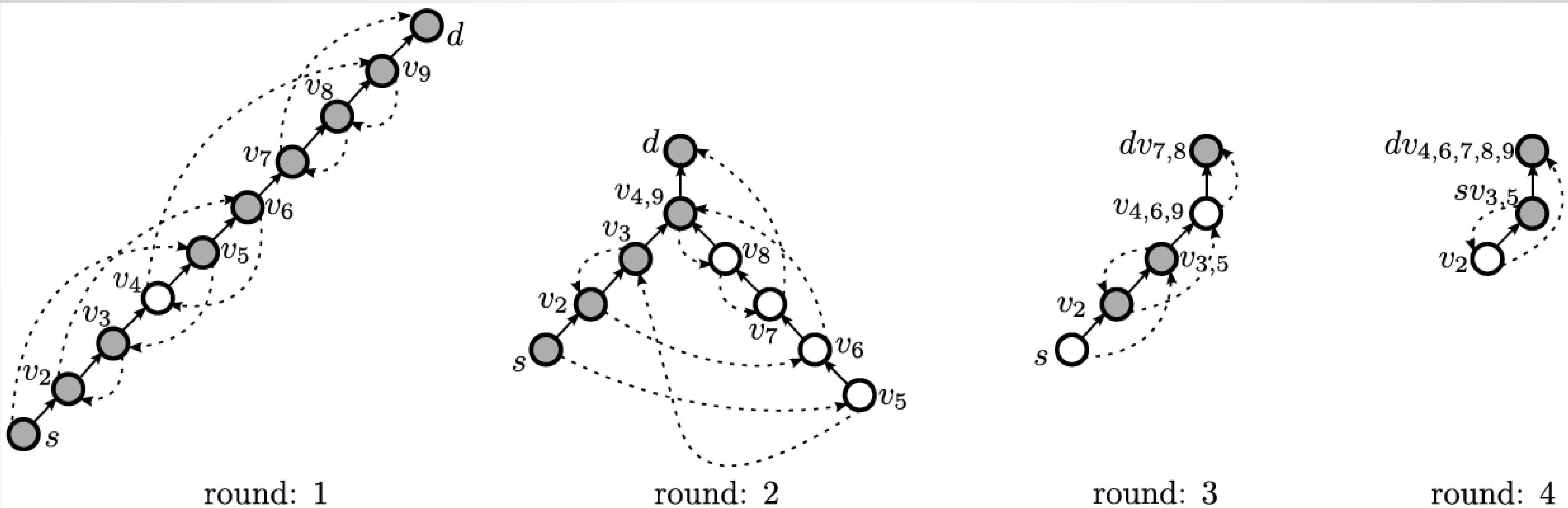
# A log(n)-time Algorithm: *Peacock* in Action




Shortcut Prune Shortcut Prune

At least 1/3 of nodes merged in each round pair (shorter s-d path): logarithmic runtime!

# A log(n)-time Algorithm: *Peacock* in Action

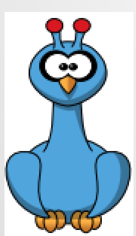


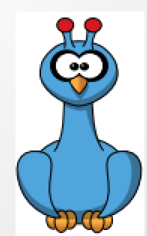

Shortcut

Prune

Shortcut

Prune





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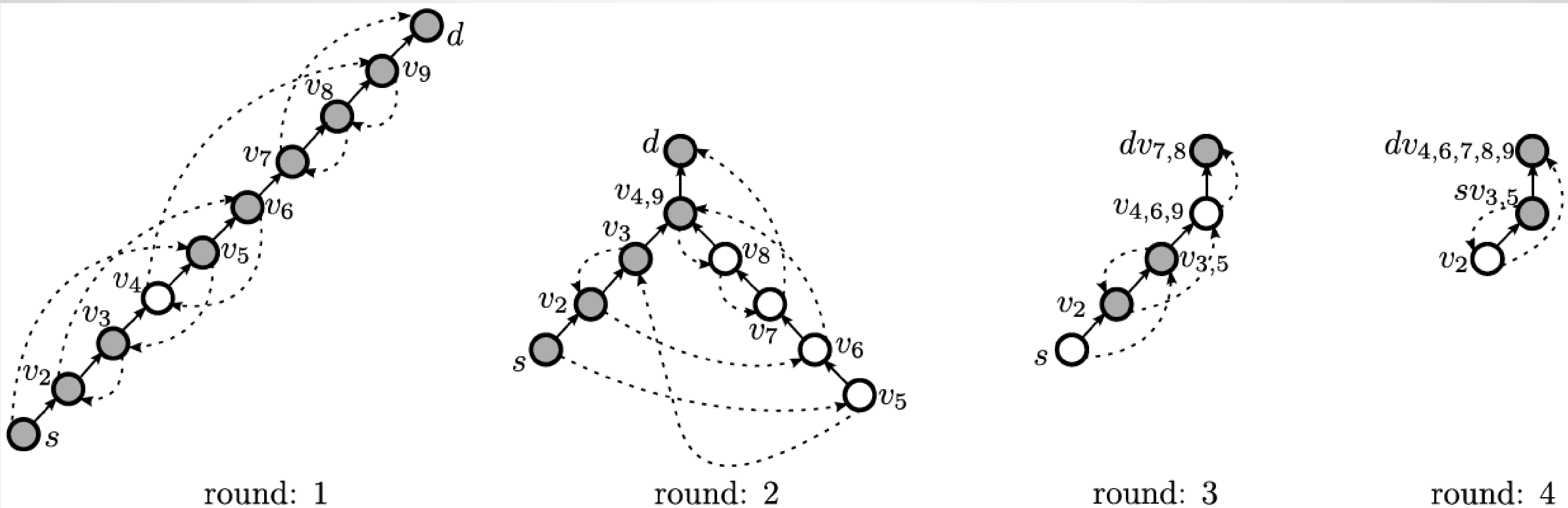
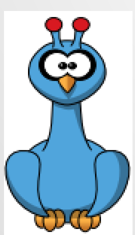
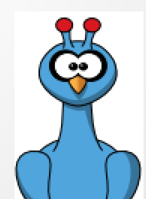
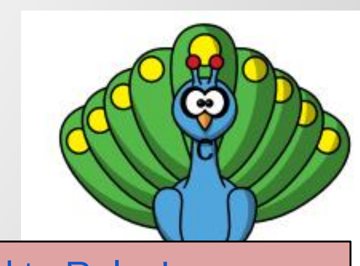



Shortcut | Prune | Shortcut | Prune



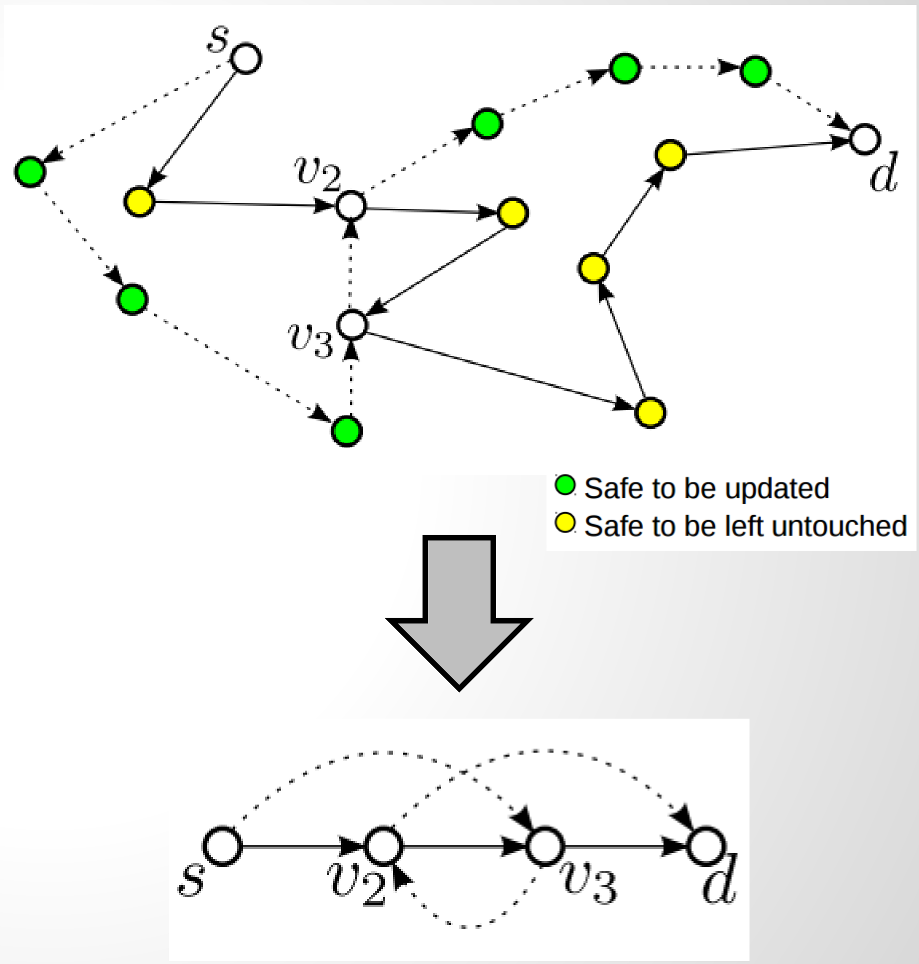




[Scheduling Loop-free Network Updates: It's Good to Relax!]()
Arne Ludwig, Jan Marcinkowski, and Stefan Schmid.
ACM Symposium on Principles of Distributed Computing (**PODC**), Donostia-San Sebastian, Spain, July 2015.

# Remark on the Model

Easy to update new nodes which do not appear in old policy. And just keep nodes which are not on new path!



# Loop-Freedom: Summary of Results

- Minimizing the **number of rounds**
  - For 2-round instances: polynomial time
  - For 3-round instances: NP-hard, no approximation known
- Relaxed notion of loop-freedom: O(log n) rounds
  - No approximation known
- Maximizing the **number of updated edges** per round: NP-hard (dual feedback arc set) and bad (large number of rounds)
  - dFASP on simple graphs (out-degree 2 and originates from paths!)
  - Even hard on bounded treewidth?
  - Resulting number of rounds up to $\Omega(n)$ although O(1) possible
- Multiple policies: aggregate updates to given switch!
  - Related to Shortest Common Supersequence Problem

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Being greedy is bad!
And hard ☺

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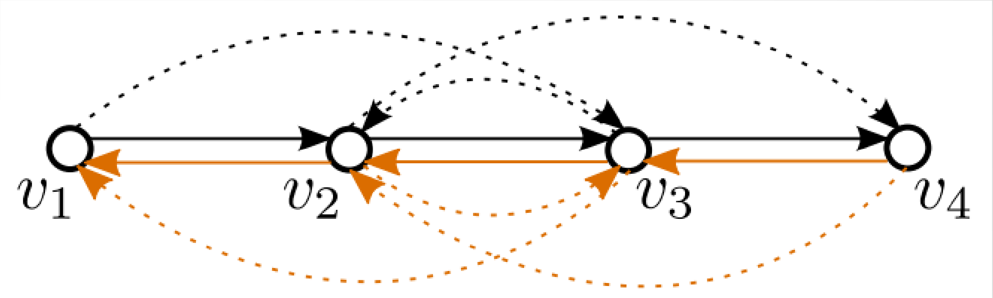
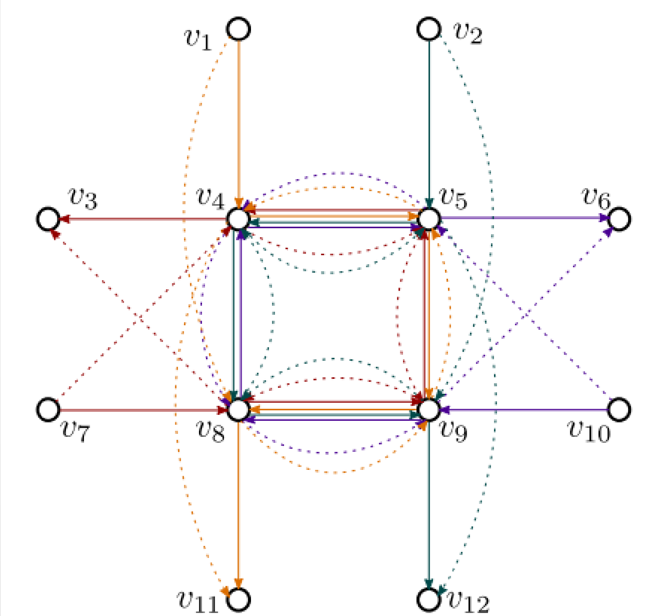
# Extension: Multiple Policies

At least one node needs to be **touched** twice: otherwise at least one flow will have a temporary loop:




Worst case: k policies require k touches!

# Extension: Multiple Policies

At least one node needs
to be **touched** twice:
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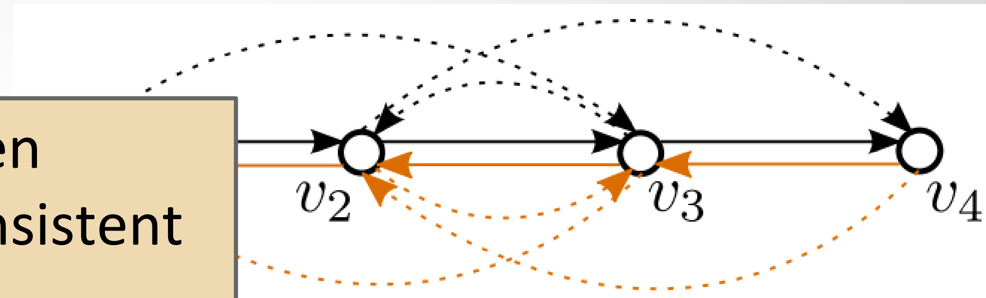
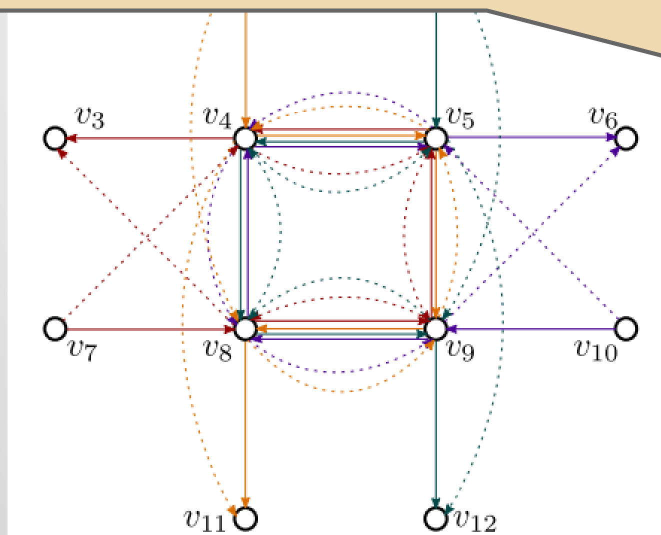



On the positive side: given individual transiently consistent schedules, can optimally combine them using dynamic programming! Independently of the consistency property.

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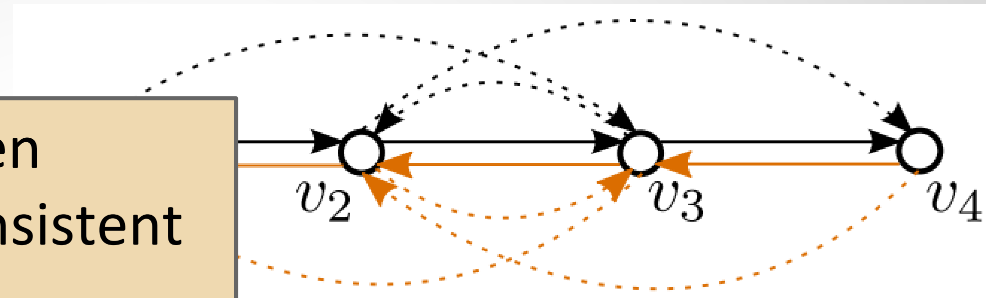


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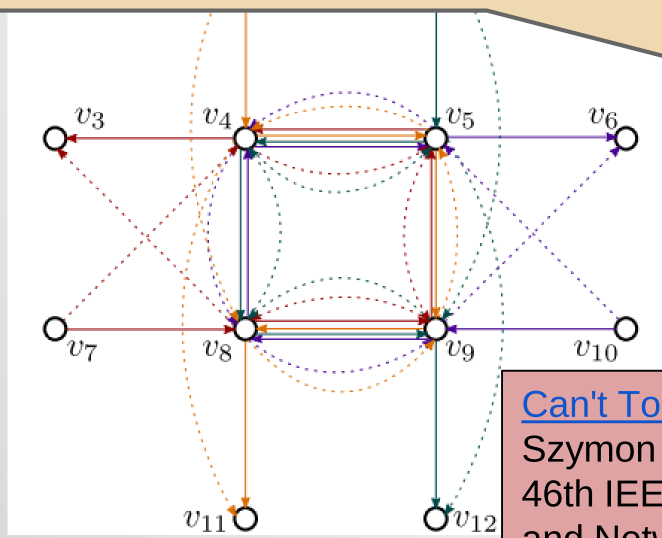



Worst case: k policies require k touches!

[Can't Touch This: Consistent Network Updates for Multiple Policies](#)
Szymon Dudycz, Arne Ludwig, and Stefan Schmid.
46th IEEE/IFIP International Conference on Dependable Systems and Networks (**DSN**), Toulouse, France, June 2016.

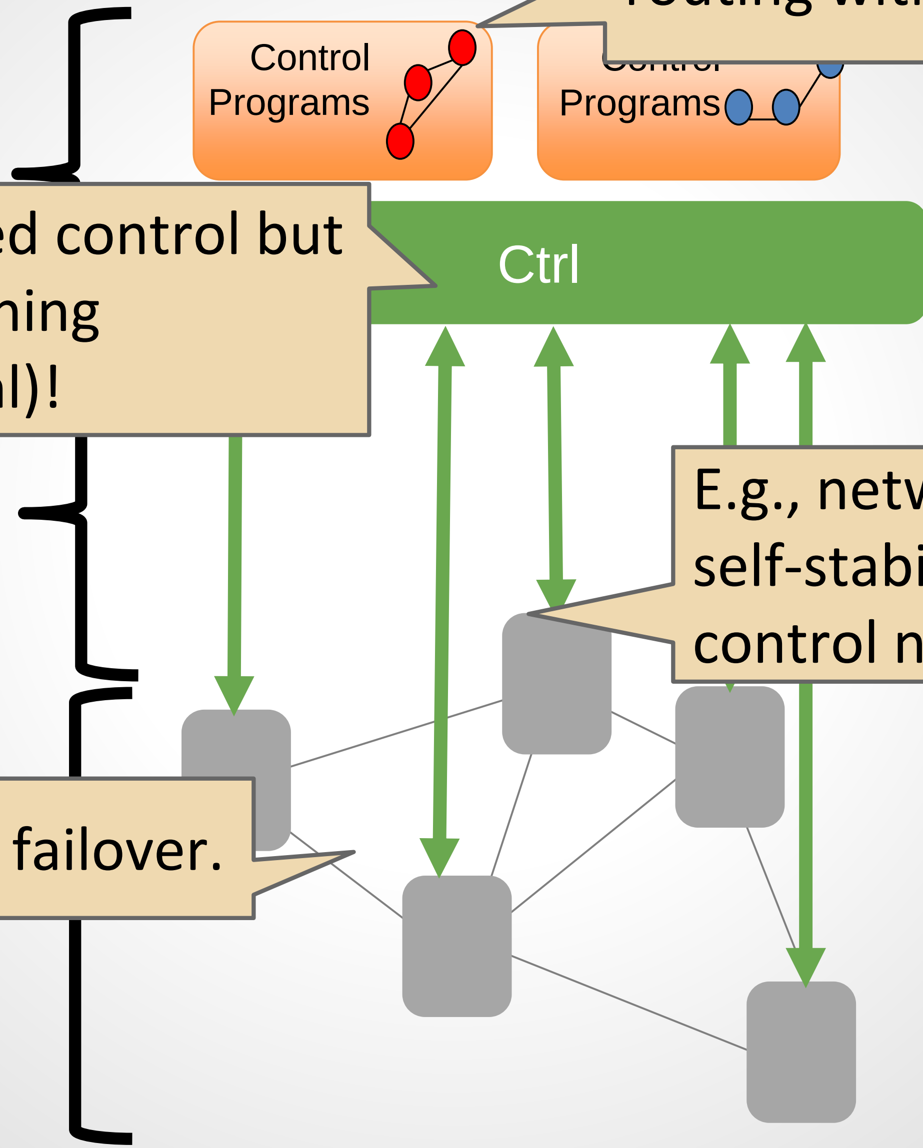
# Conclusio

Applications and

C

... *and regarding*
*inter-connect!*

Da




E.g., admission control and routing with waypoints.

E.g., distributed control but also MAC learning (Jen@Dagstuhl)!

E.g., network updates or self-stabilizing in-band control network.

E.g., robust failover.

# Own References


[Can't Touch This: Consistent Network Updates for Multiple Policies]
Szymon Dudycz, Arne Ludwig, and Stefan Schmid.
46th IEEE/IFIP International Conference on Dependable Systems and Networks (**DSN**), Toulouse, France, June 2016.

[Transiently Secure Network Updates]
Arne Ludwig, Szymon Dudycz, Matthias Rost, and Stefan Schmid.
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[Scheduling Loop-free Network Updates: It's Good to Relax!]
Arne Ludwig, Jan Marcinkowski, and Stefan Schmid.
ACM Symposium on Principles of Distributed Computing (**PODC**), Donostia-San Sebastian, Spain, July 2015.

[Medieval: Towards A Self-Stabilizing, Plug & Play, In-Band SDN Control Network] (Demo Paper)
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[A Distributed and Robust SDN Control Plane for Transactional Network Updates]
Marco Canini, Petr Kuznetsov, Dan Levin, and Stefan Schmid.
34th IEEE Conference on Computer Communications (**INFOCOM**), Hong Kong, April 2015.

[Good Network Updates for Bad Packets: Waypoint Enforcement Beyond Destination-Based Routing Policies]
Arne Ludwig, Matthias Rost, Damien Foucard, and Stefan Schmid.
13th ACM Workshop on Hot Topics in Networks (**HotNets**), Los Angeles, California, USA, October 2014.

[Provable Data Plane Connectivity with Local Fast Failover: Introducing OpenFlow Graph Algorithms]
Michael Borokhovich, Liron Schiff, and Stefan Schmid.
ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking (**HotSDN**), Chicago, Illinois, USA, August 2014.