VERIFLOW

Network Verification: From Algorithms to the Real World

Wenxuan Zhou
Veriflow & UIUC

A simple idea about complexity…

Networks are so complex it's hard to know they're doing the right thing.

Let's automate.

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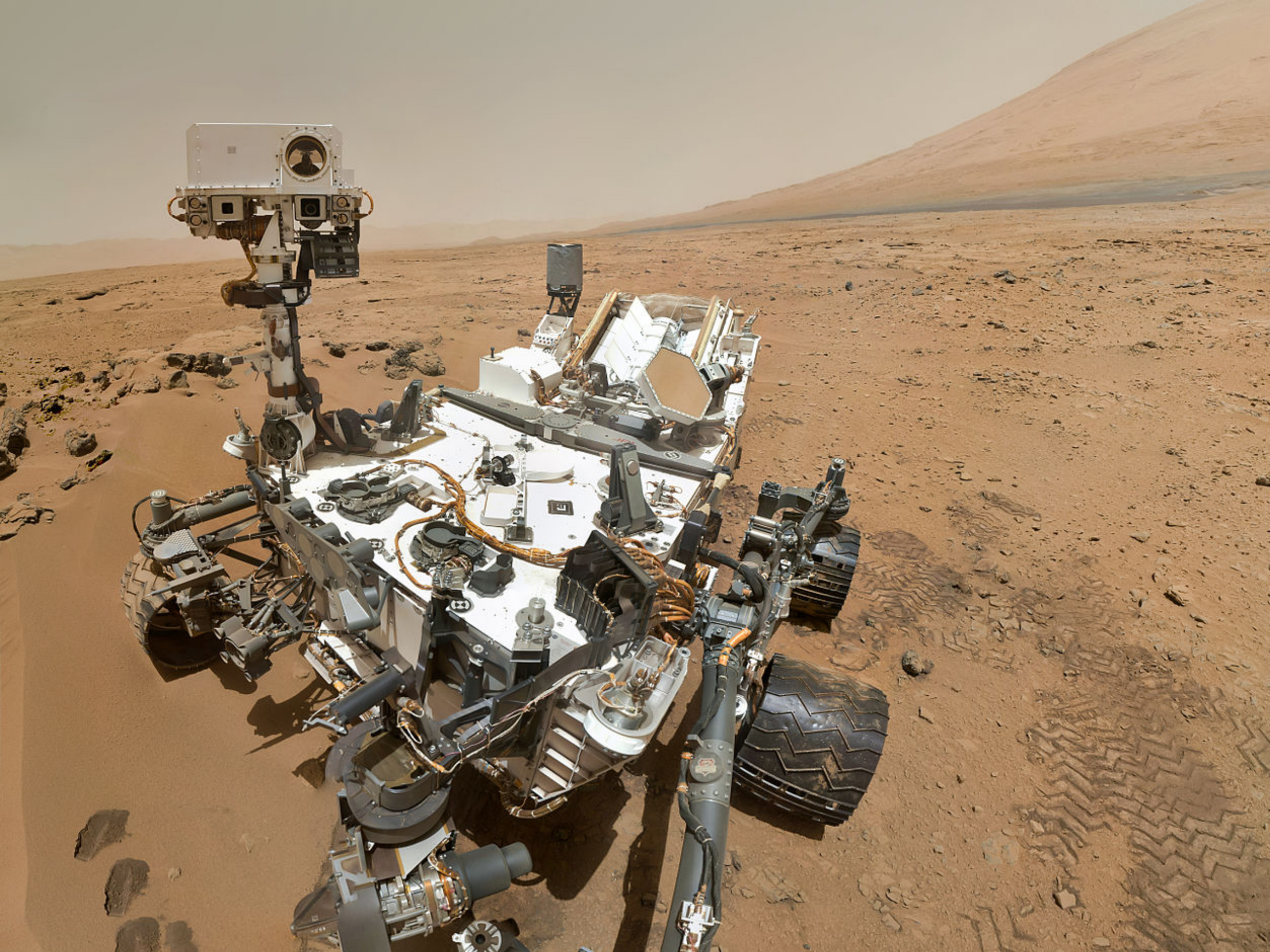
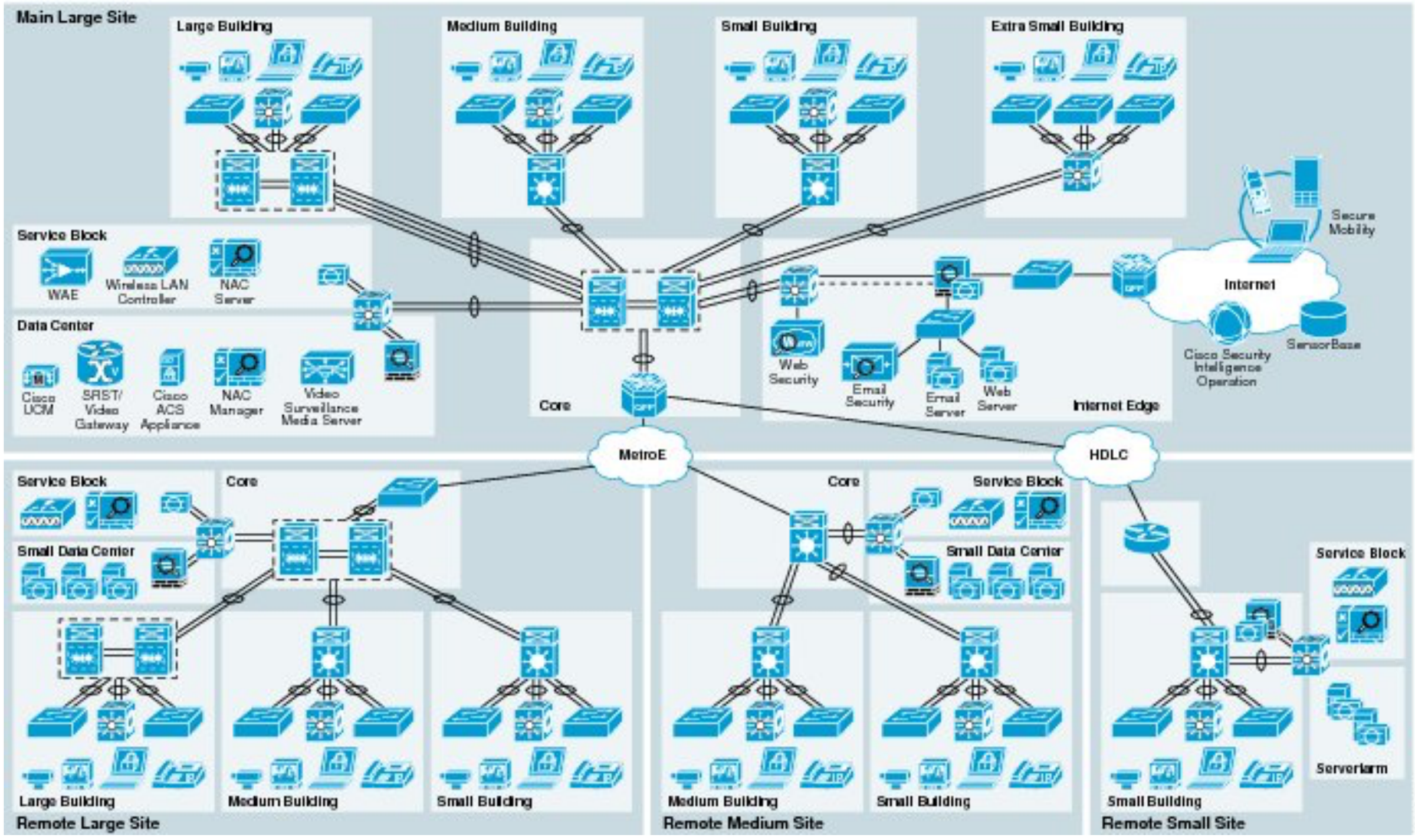


NETWORKING BACKGROUND

Inside a typical enterprise network



Source: http://www.cisco.com/c/en/us/td/docs/solutions/Enterprise/Medium_Enterprise_Design_Profile/MEDP/chap5.html

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Configs use many protocols & features

Layer 1 protocols (physical layer)

USB Physical layer

Ethernet physical layer including 10 BASE T, 100 BASE T,100 BASE TX,100 BASE FX, 1000 BASE T and other variants

varieties of 802.11 Wi-Fi physical layers

DSL

List of protocols commonly encountered by CCNAs
https://learningnetwork.cisco.com/docs/DOC-25649

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Configs use many protocols & features

MPLS Multi-protocol label switching
NAT Network Address translation
OSPF Open Shortest Path First
VRRP Virtual Router Redundancy Protocol

Layer 4 (transport layer or Host-to-Host layer)

AH
TCP
UDP

Layer 5 (session layer or application layer in DoD)

NetBIOS File sharing and name resolution protocol -the basis of file sharing in windows
NFS Network File System

Layer 7 (application layer)

BitTorrent
BGP
DNS
DHCP
FTP
HTTP
HTTPS
IRC
NTP
POP3
RTP
SSH
SMTP
SNMP
Telnet
TFTP
URL

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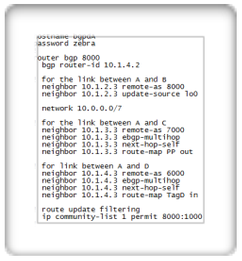
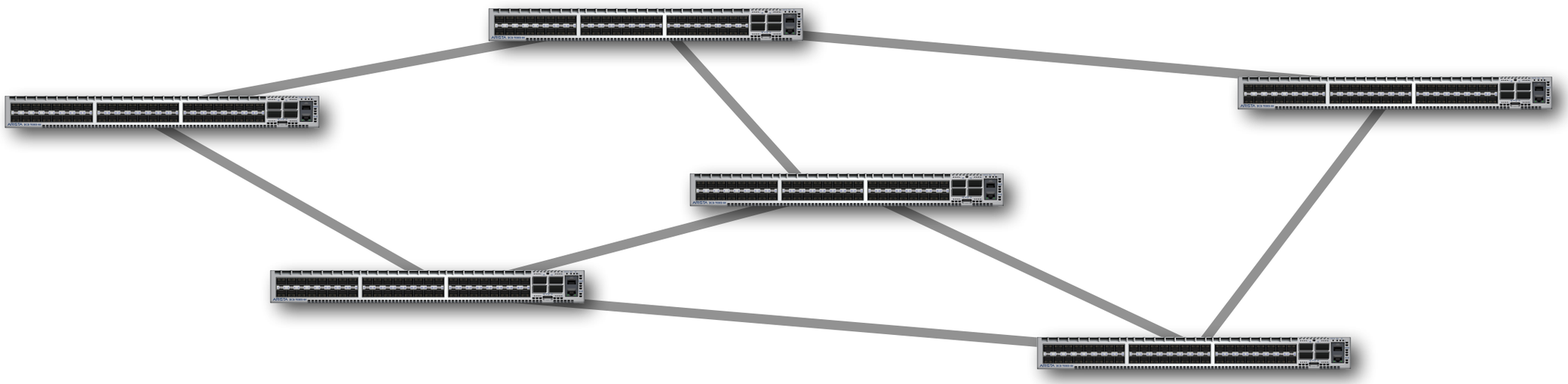
Distributed route computation





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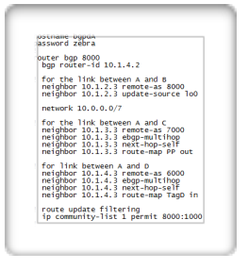
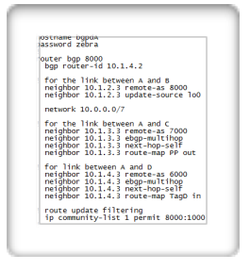
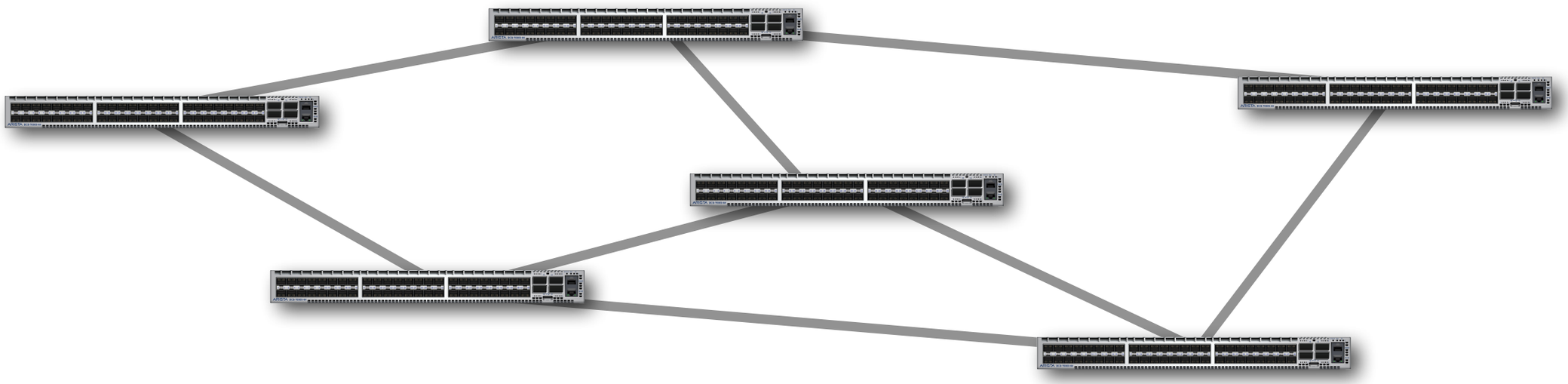
Distributed route computation







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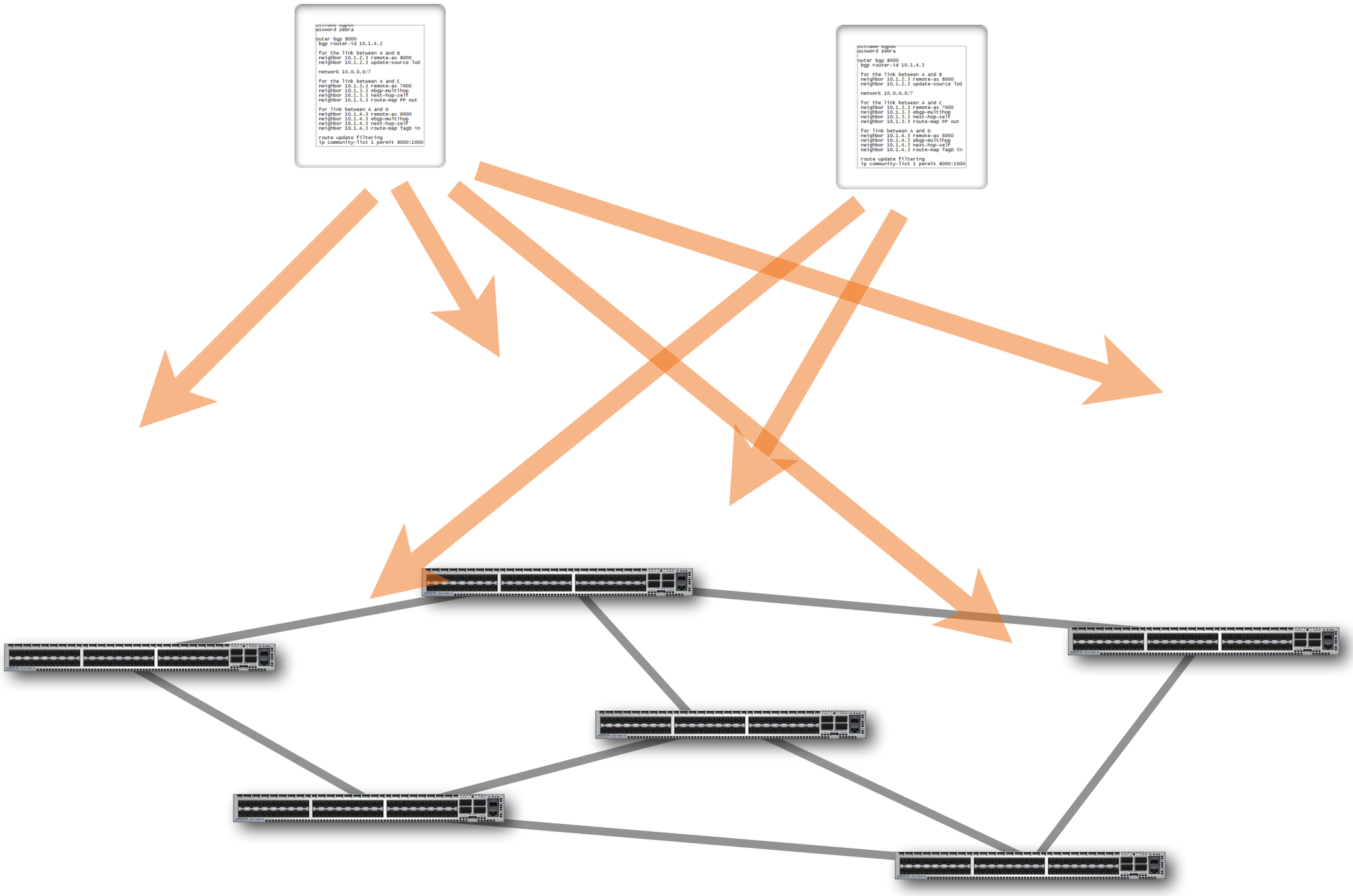

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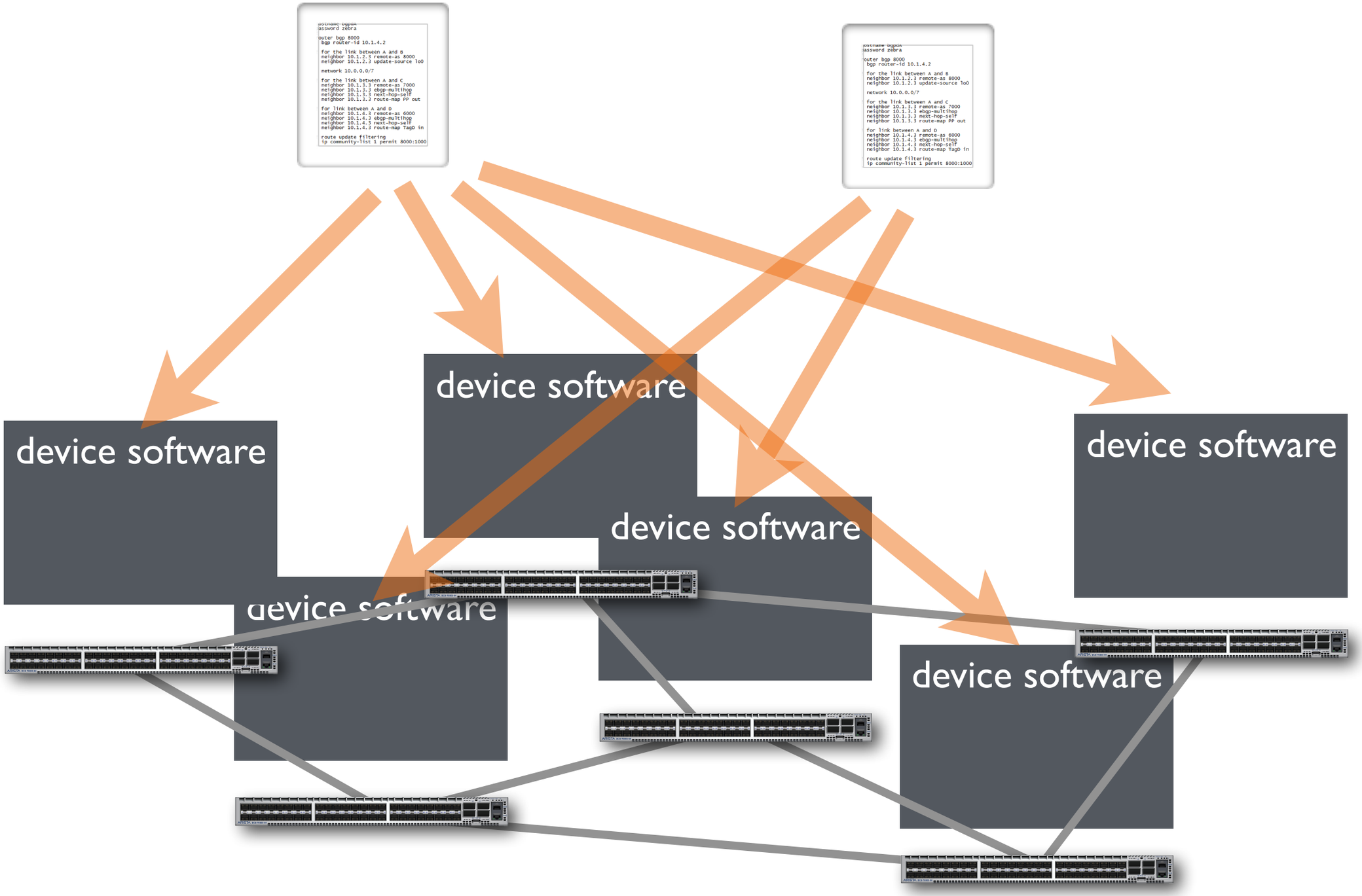
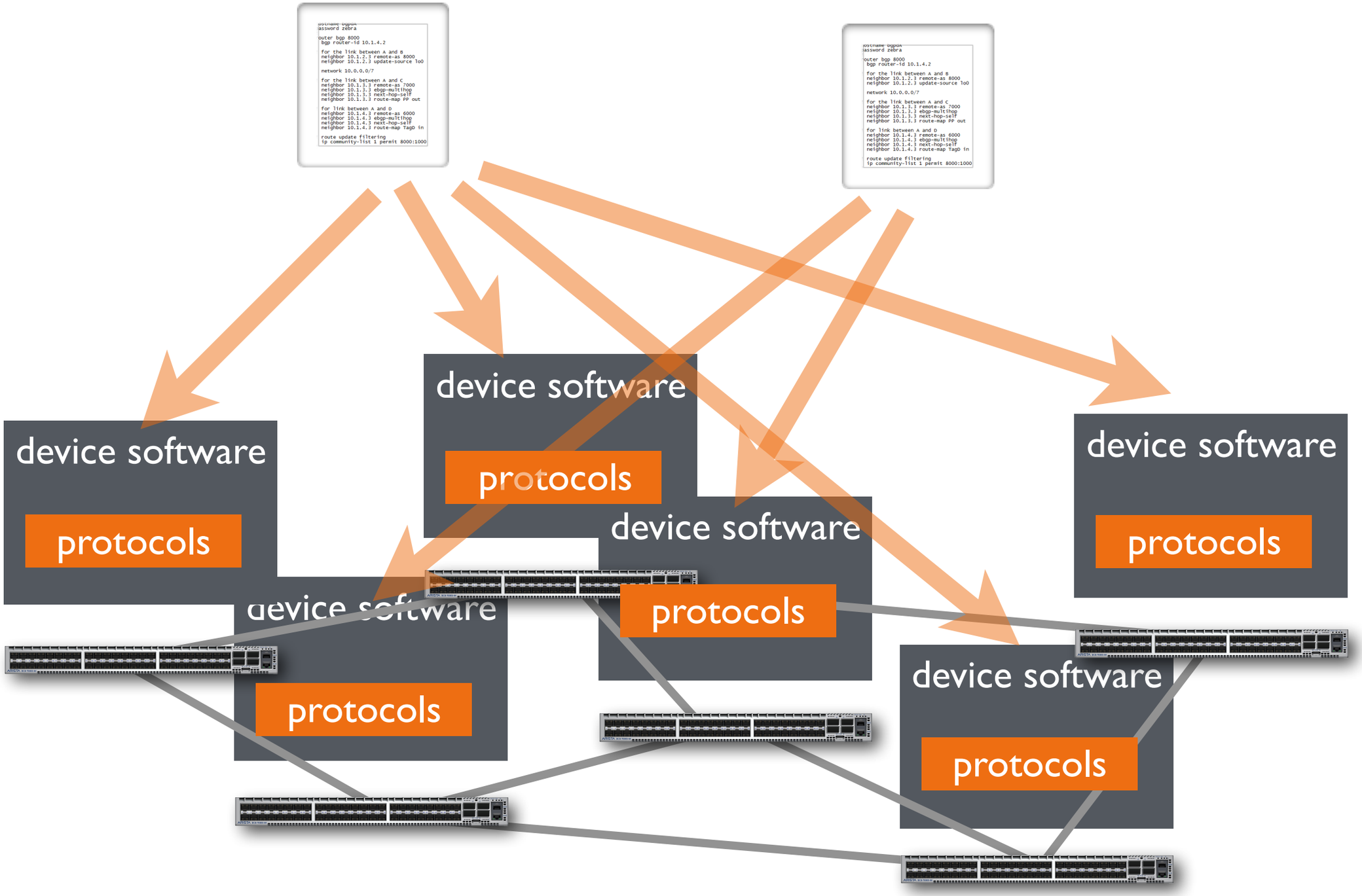


Distributed route computation



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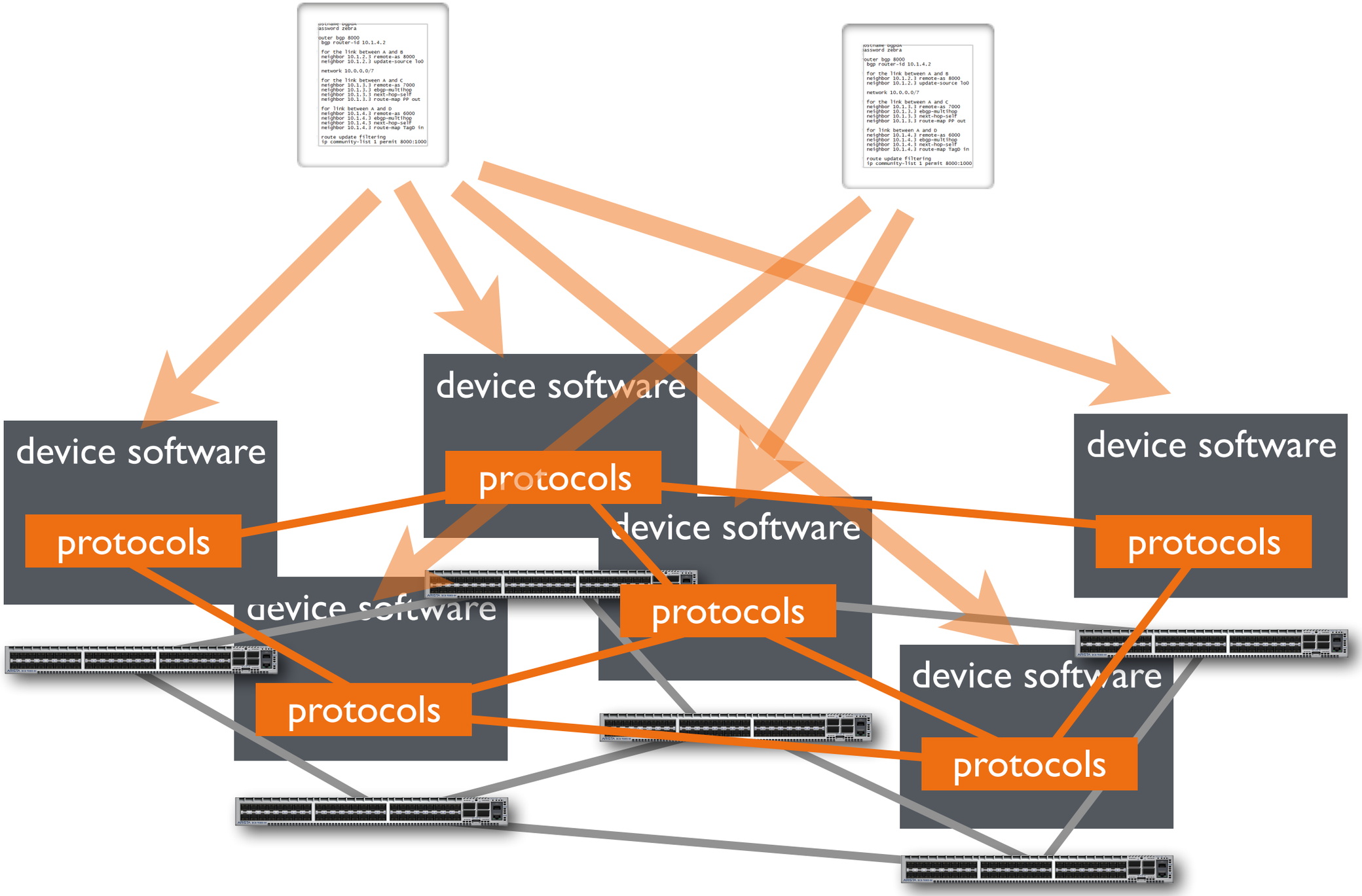

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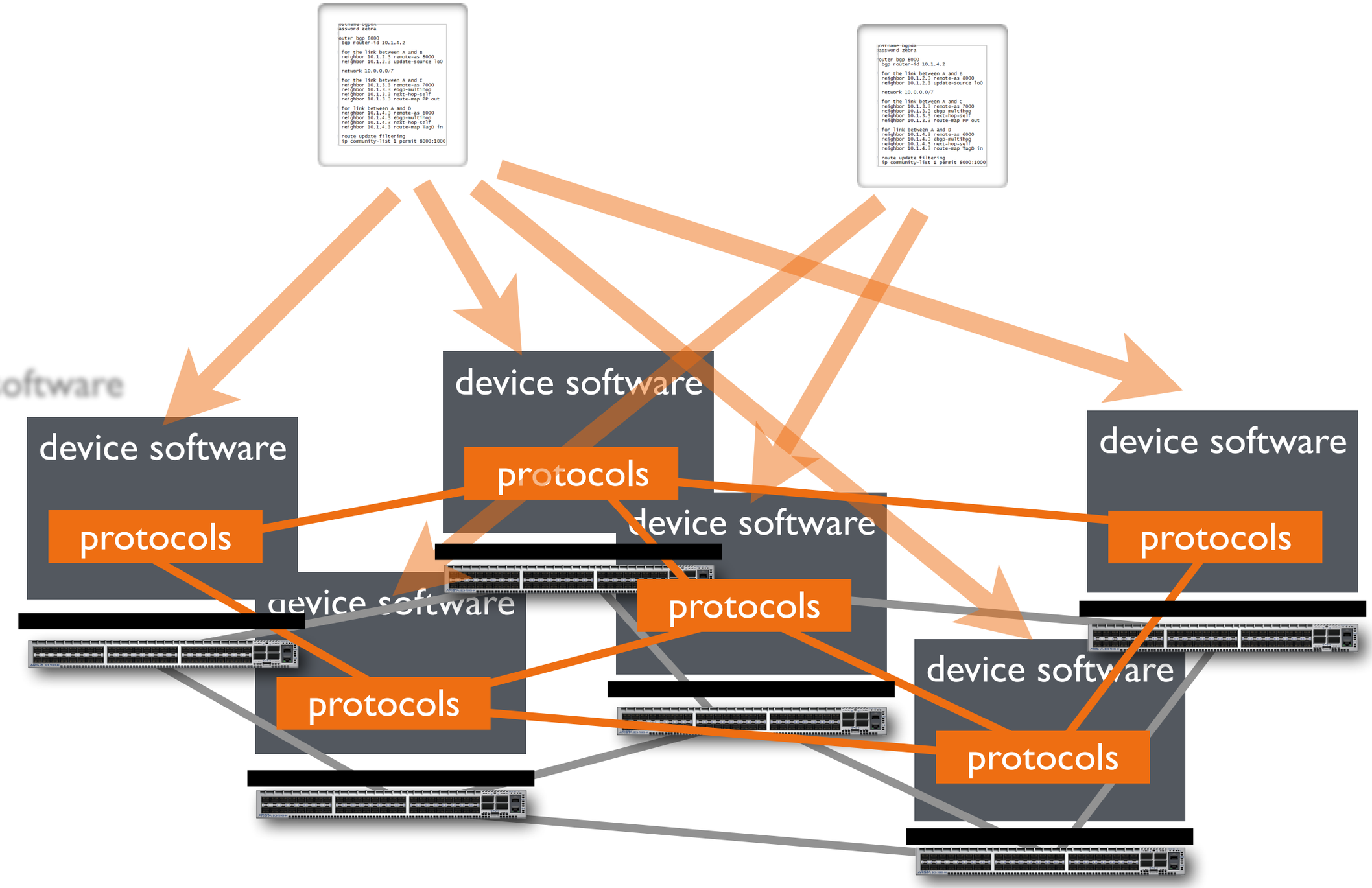
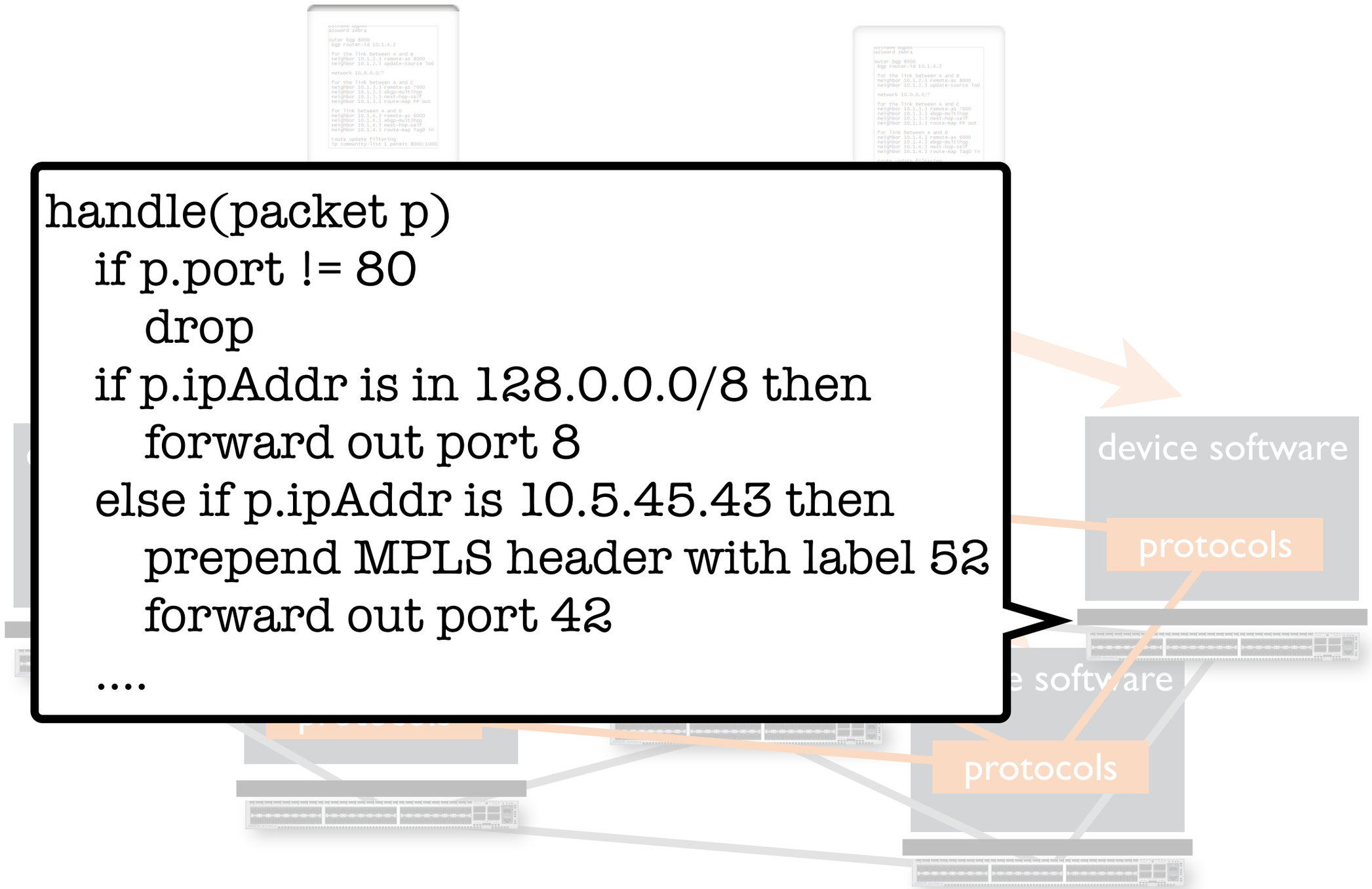


Result: data plane state

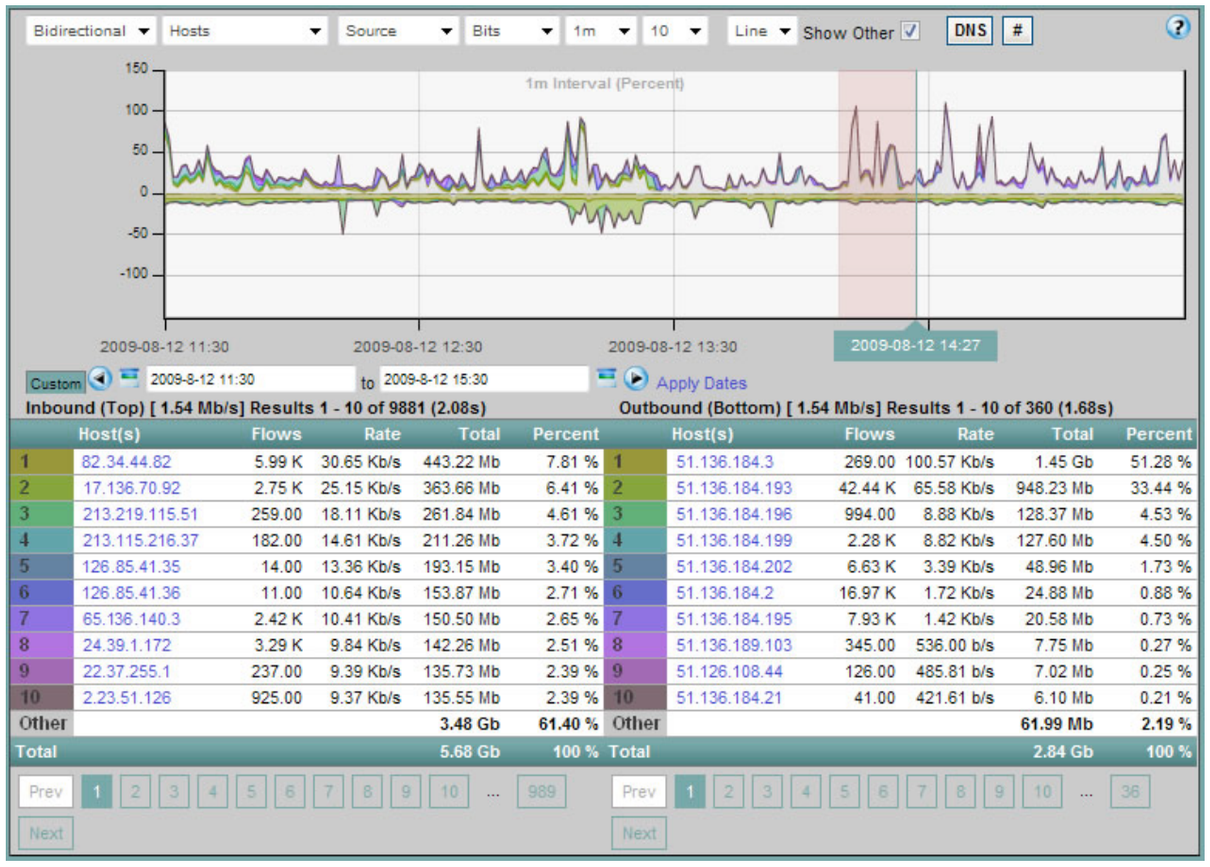
```
handle(packet p)
    if p.port != 80
        drop
    if p.ipAddr is in 128.0.0.0/8 then
        forward out port 8
    else if p.ipAddr is 10.5.45.43 then
        prepend MPLS header with label 52
        forward out port 42
    ....
```



Ensuring correct operations today

Manual spot-checking (pings, traceroutes)

Monitoring of events & flows



	Host(s)	Flows	Rate	Total	Percent
1	82.34.44.82	5.99 K	30.65 Kb/s	443.22 Mb	7.81 %
2	17.136.70.92	2.75 K	25.15 Kb/s	363.66 Mb	6.41 %
3	213.219.115.51	259.00	18.11 Kb/s	261.84 Mb	4.61 %
4	213.115.216.37	182.00	14.61 Kb/s	211.26 Mb	3.72 %
5	126.85.41.35	14.00	13.36 Kb/s	193.15 Mb	3.40 %
6	126.85.41.36	11.00	10.64 Kb/s	153.87 Mb	2.71 %
7	65.136.140.3	2.42 K	10.41 Kb/s	150.50 Mb	2.65 %
8	24.39.1.172	3.29 K	9.84 Kb/s	142.26 Mb	2.51 %
9	22.37.255.1	237.00	9.39 Kb/s	135.73 Mb	2.39 %
10	2.23.51.126	925.00	9.37 Kb/s	135.55 Mb	2.39 %
Other				3.48 Gb	61.40 %
Total				5.68 Gb	100 %

	Host(s)	Flows	Rate	Total	Percent
1	51.136.184.3	269.00	100.57 Kb/s	1.45 Gb	51.28 %
2	51.136.184.193	42.44 K	65.58 Kb/s	948.23 Mb	33.44 %
3	51.136.184.196	994.00	8.88 Kb/s	128.37 Mb	4.53 %
4	51.136.184.199	2.28 K	8.82 Kb/s	127.60 Mb	4.50 %
5	51.136.184.202	6.63 K	3.39 Kb/s	48.96 Mb	1.73 %
6	51.136.184.2	16.97 K	1.72 Kb/s	24.88 Mb	0.88 %
7	51.136.184.195	7.93 K	1.42 Kb/s	20.58 Mb	0.73 %
8	51.136.189.103	345.00	536.00 b/s	7.75 Mb	0.27 %
9	51.126.108.44	126.00	485.81 b/s	7.02 Mb	0.25 %
10	51.136.184.21	41.00	421.61 b/s	6.10 Mb	0.21 %
Other				61.99 Mb	2.19 %
Total				2.84 Gb	100 %

Screenshot from Scrutinizer NetFlow & sFlow analyzer, snmp.co.uk/scrutinizer/

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Networks are complex

– Survey of network operators
[Kim, Reich, Gupta, Shahbaz, Feamster, Clark, USENIX NSDI 2015]

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89%
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Networks are complex

89%
of operators never sure that config changes are bug-free

82%
concerned that changes would cause problems with existing functionality

– Survey of network operators
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The process of proving whether an **abstraction** of the network satisfies intended network-wide **properties**.

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“No packet should fall into a loop.”

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"Host A should be connected to host B."

"Host A should not be able to reach service B on any server."

"No packet should fall into a loop."

"All packets should follow shortest paths."

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- Configuration
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- Packet processing

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Network Verification

The process of proving whether an **abstraction** of the network satisfies intended network-wide **properties**.

Configuration	Configuration verification
Control software	Controller verification & verifiable control languages
Data plane state	Data plane verification
Packet processing	Software switch verification

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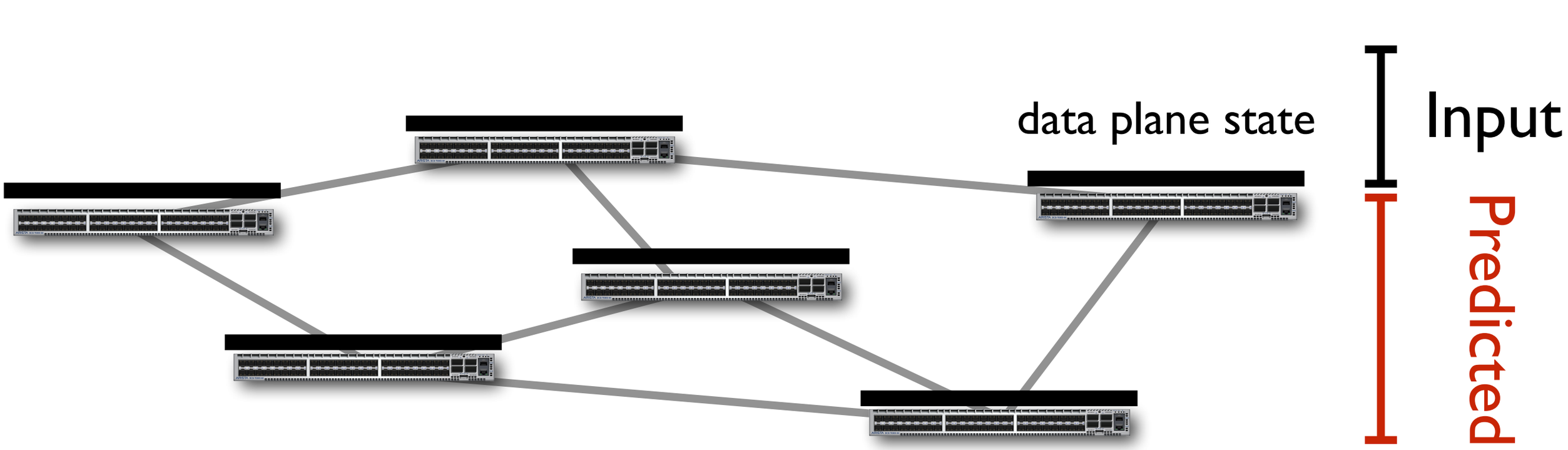
Data plane verification



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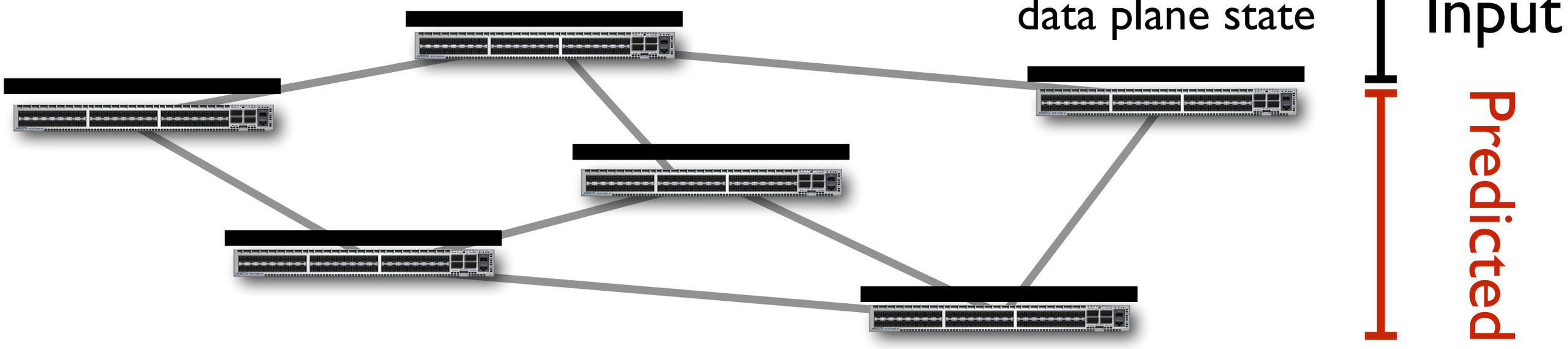
Data plane verification

Verify the network
as close as possible
to its actual
behavior



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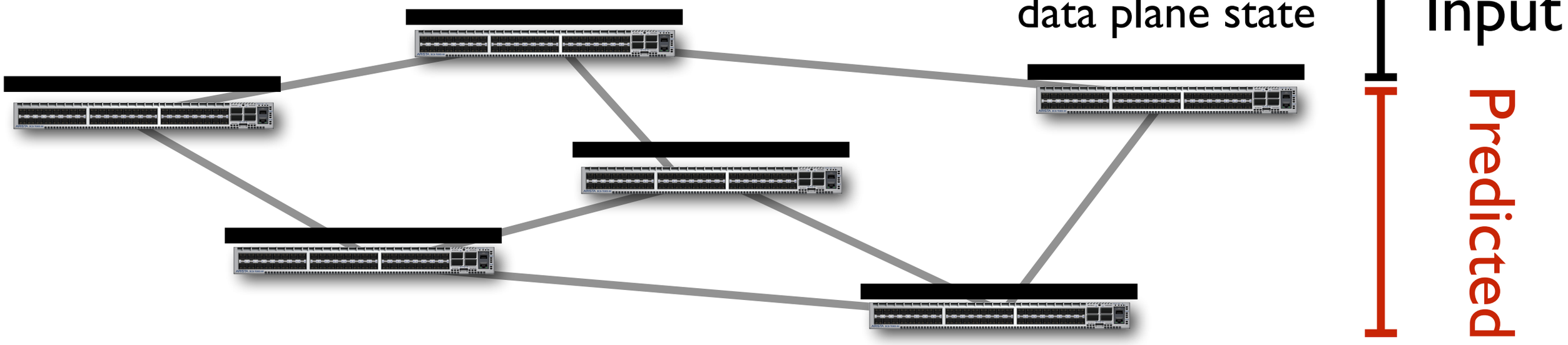
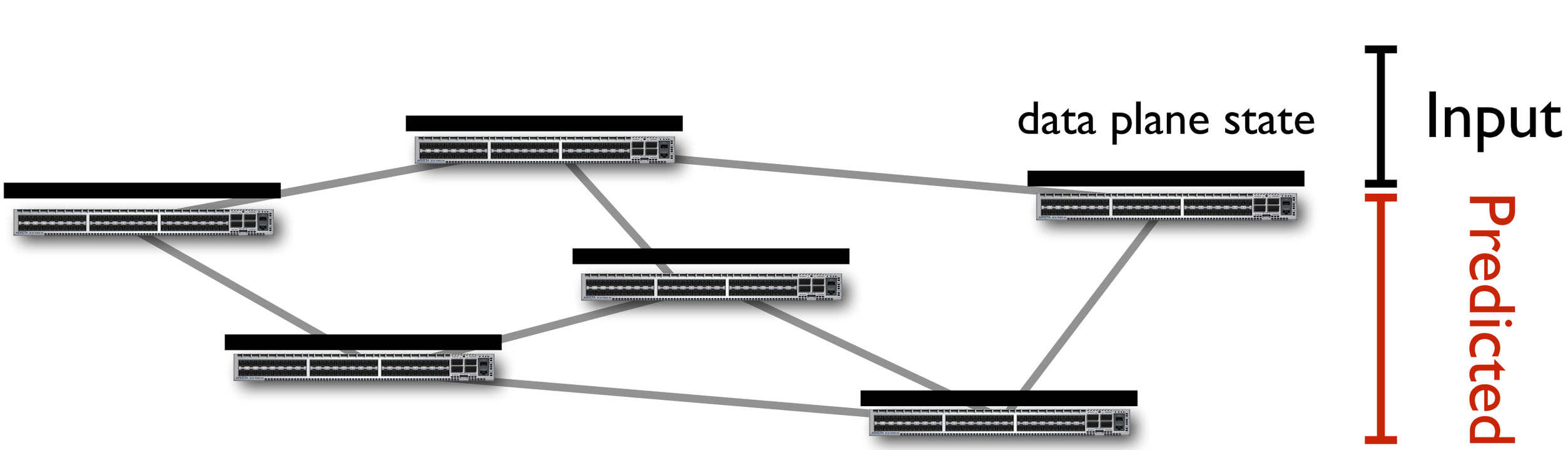


Data plane verification

Verify the network as close as possible to its actual behavior

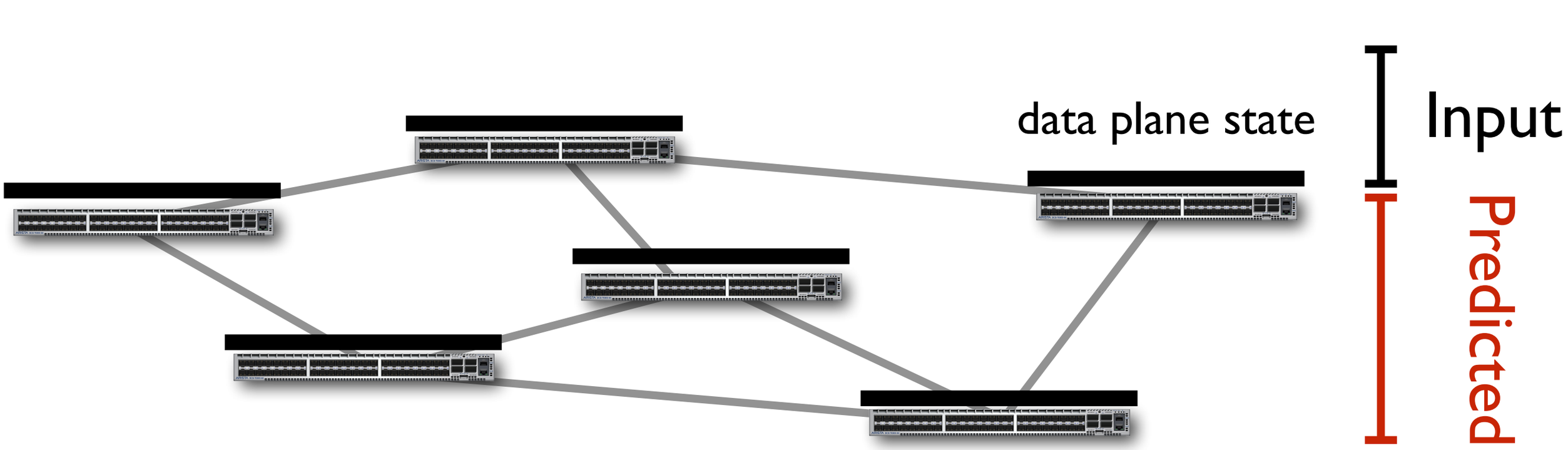
- Insensitive to control protocols



Data plane verification

Verify the network as close as possible to its actual behavior

- Insensitive to control protocols
- Accurate model



Data plane verification

Verify the network as close as possible to its actual behavior

- Insensitive to control protocols
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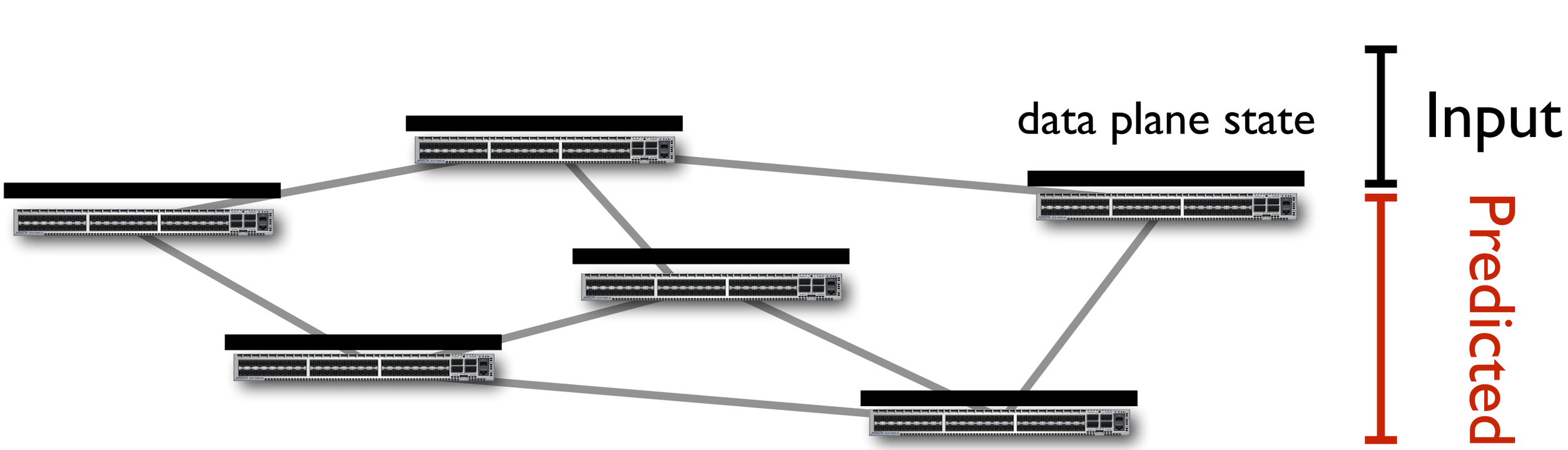
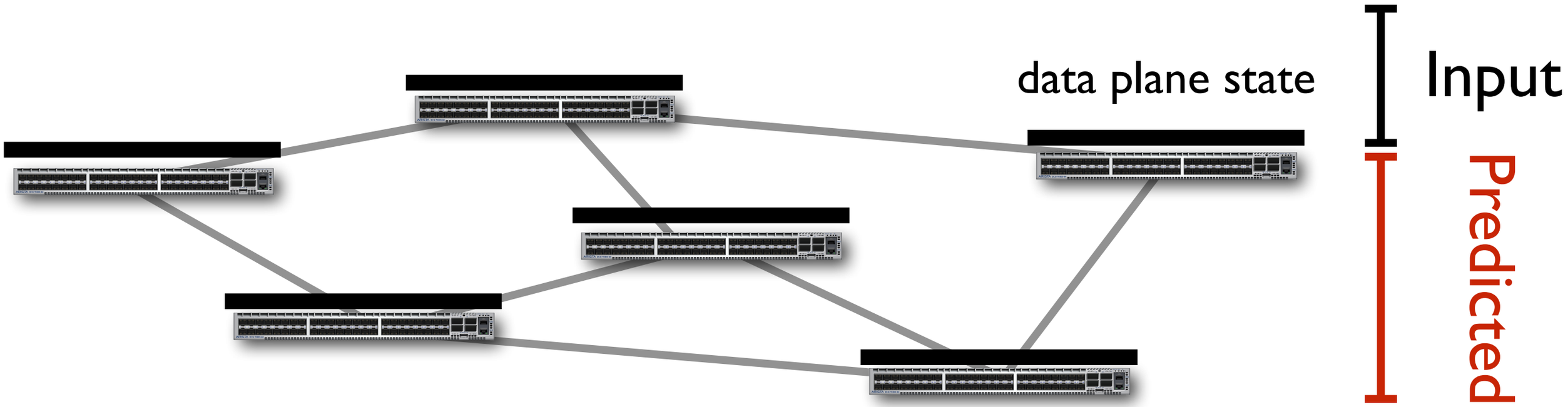
- *Checks current snapshot*



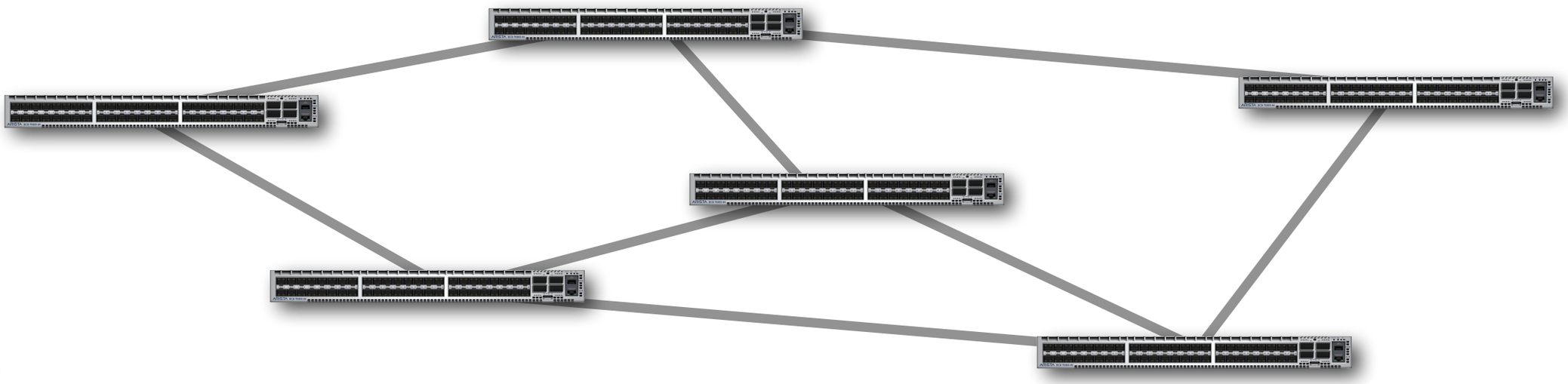
Data plane verification

Verify the network as close as possible to its actual behavior

- Insensitive to control protocols
- Accurate model
- *Checks current snapshot*
  - but can be foundation for config verification



Data plane verification architecture



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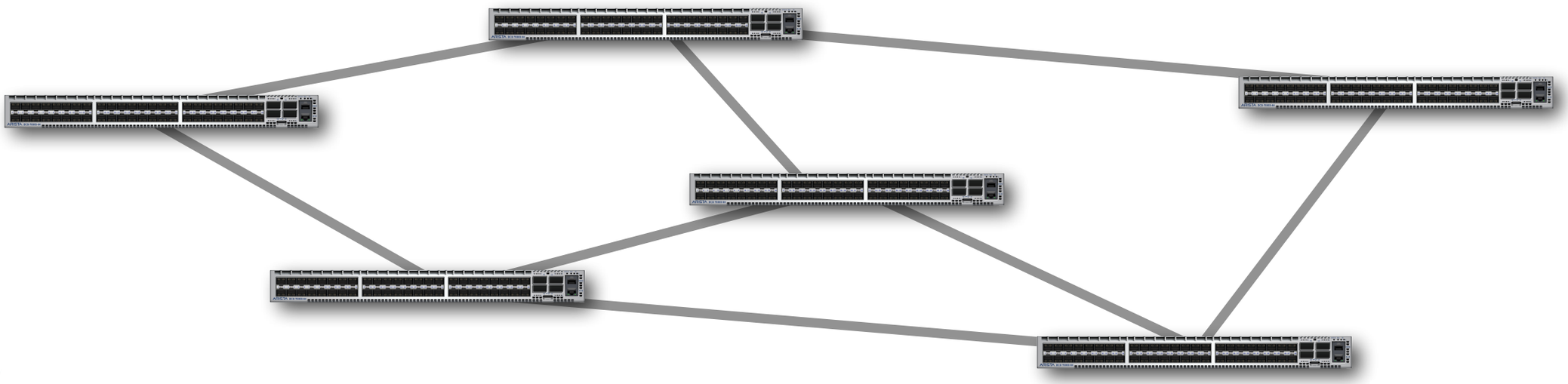
Data plane verification architecture

Verifier



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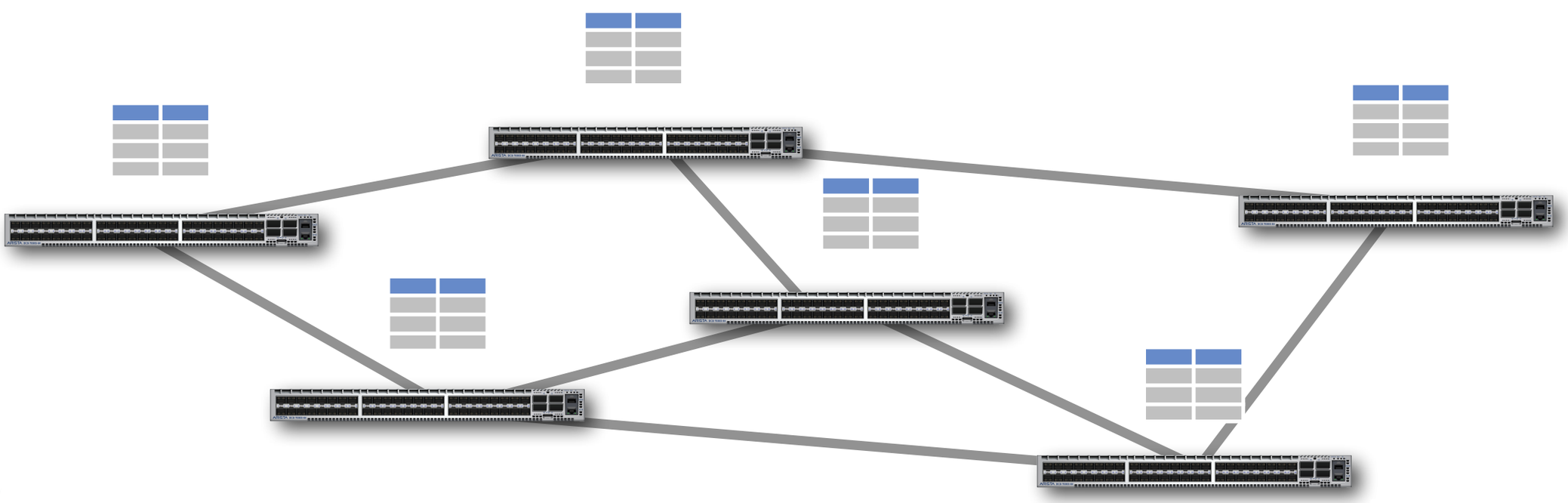

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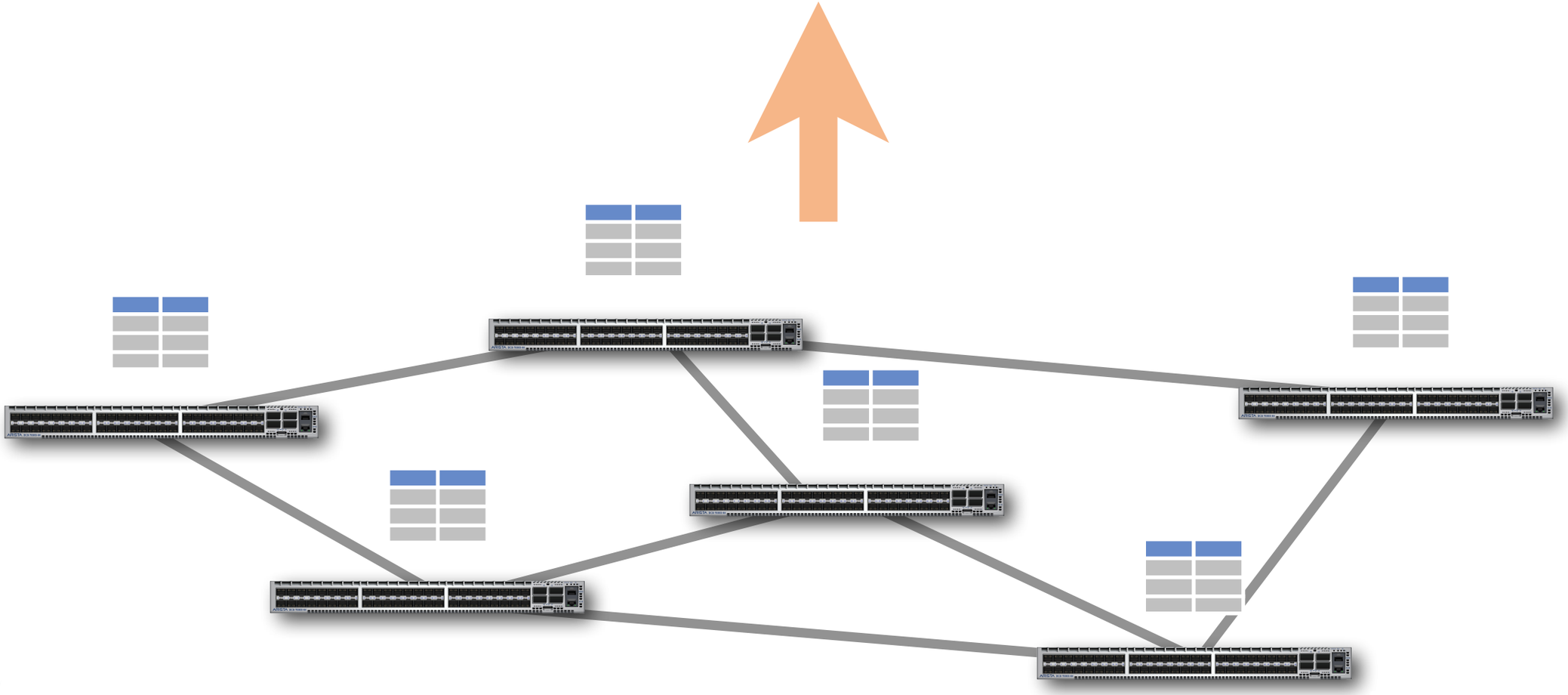

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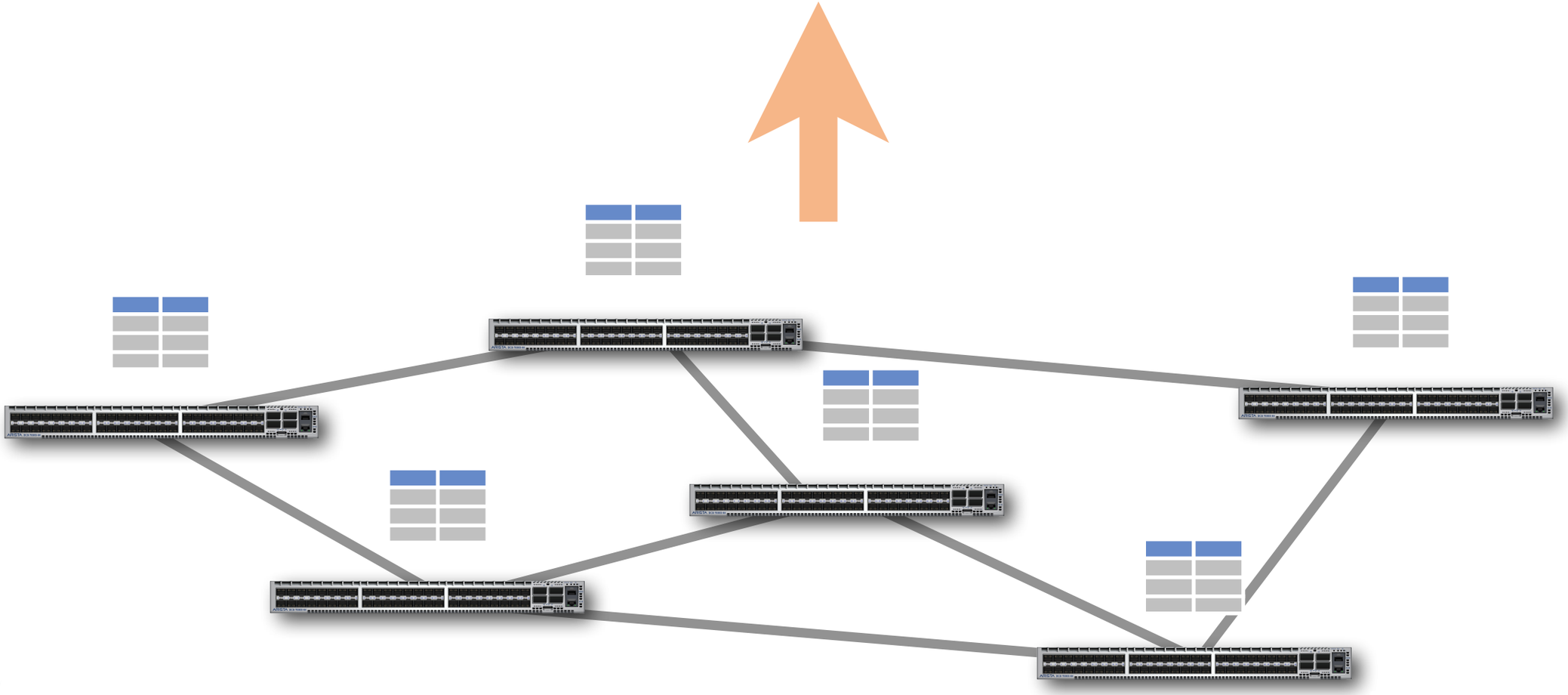
Data plane verification architecture

"Can any packet starting at A reach B?"

Verifier



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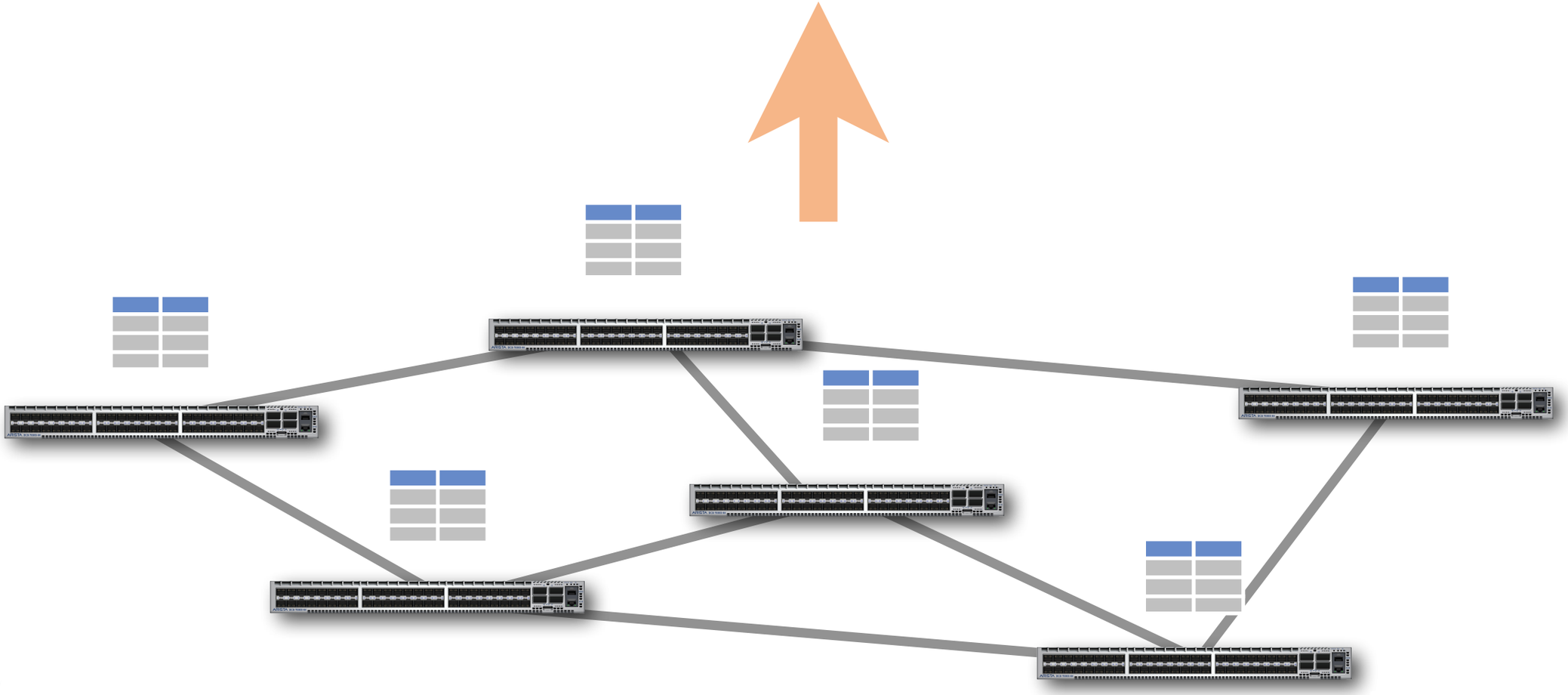
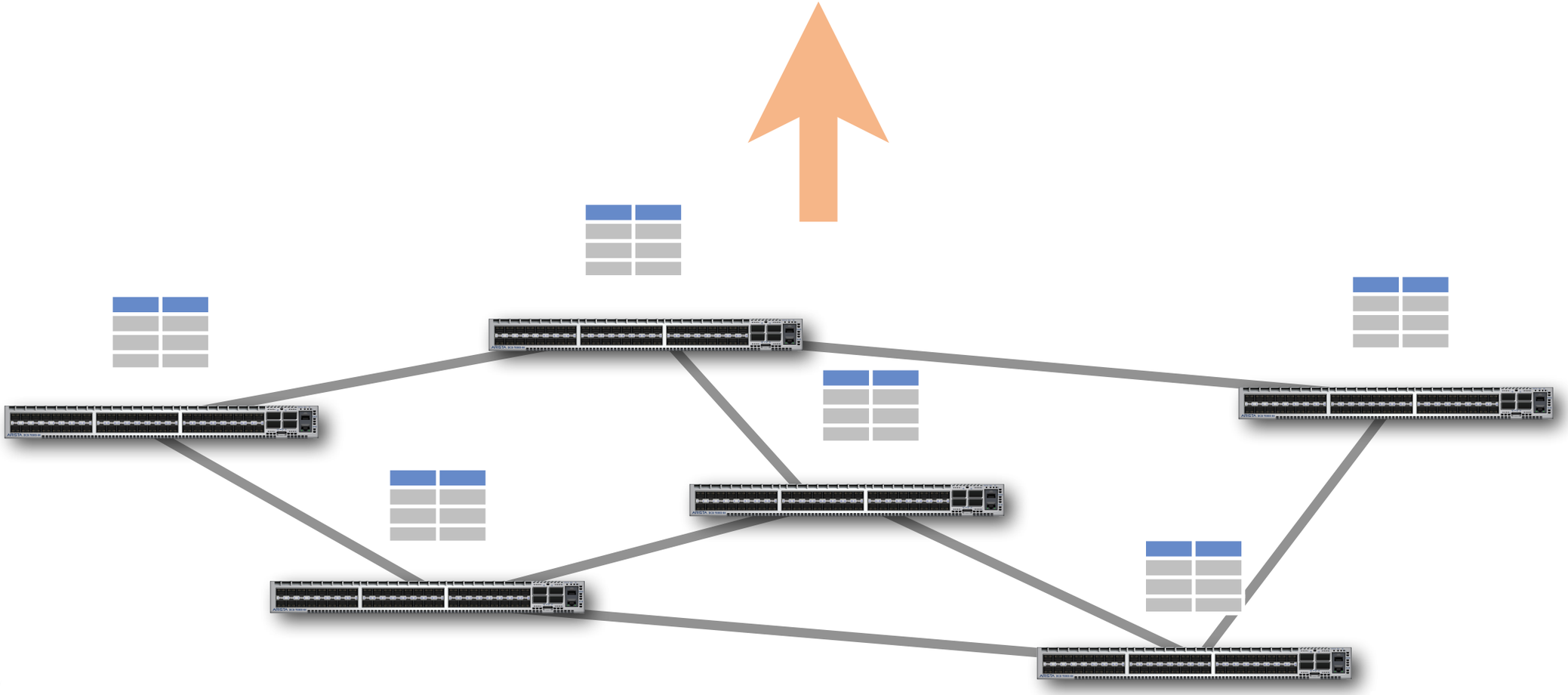


Data plane verification architecture

"Can any packet starting at A reach B?"

Diagnosis

Verifier



A little calculation…

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theoretical packets

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$$= 2^{(\#\text{header bits})} \times \#\text{injection points}$$

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theoretical packets

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$= 2^{(18 \text{ byte ethernet} + 20 \text{ byte IPv4})} \times 10{,}000 \text{ ports}$

$= 3.25 \times 10^{95}$ possible packets

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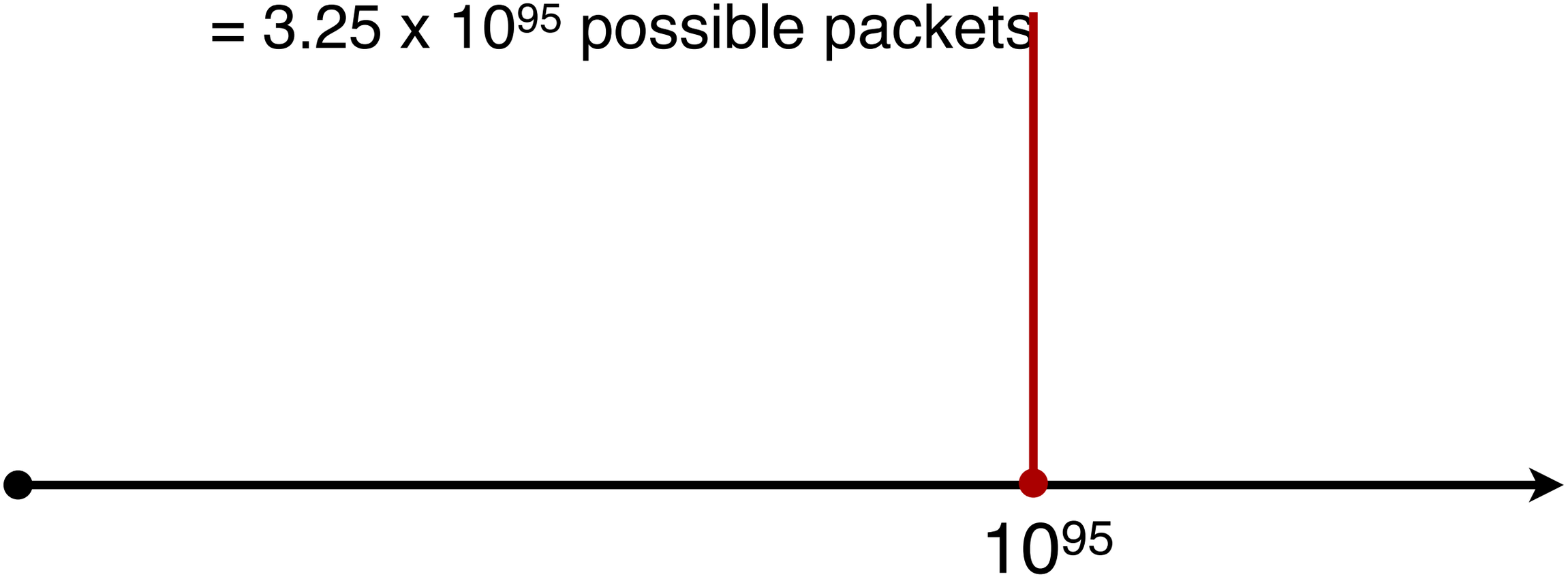

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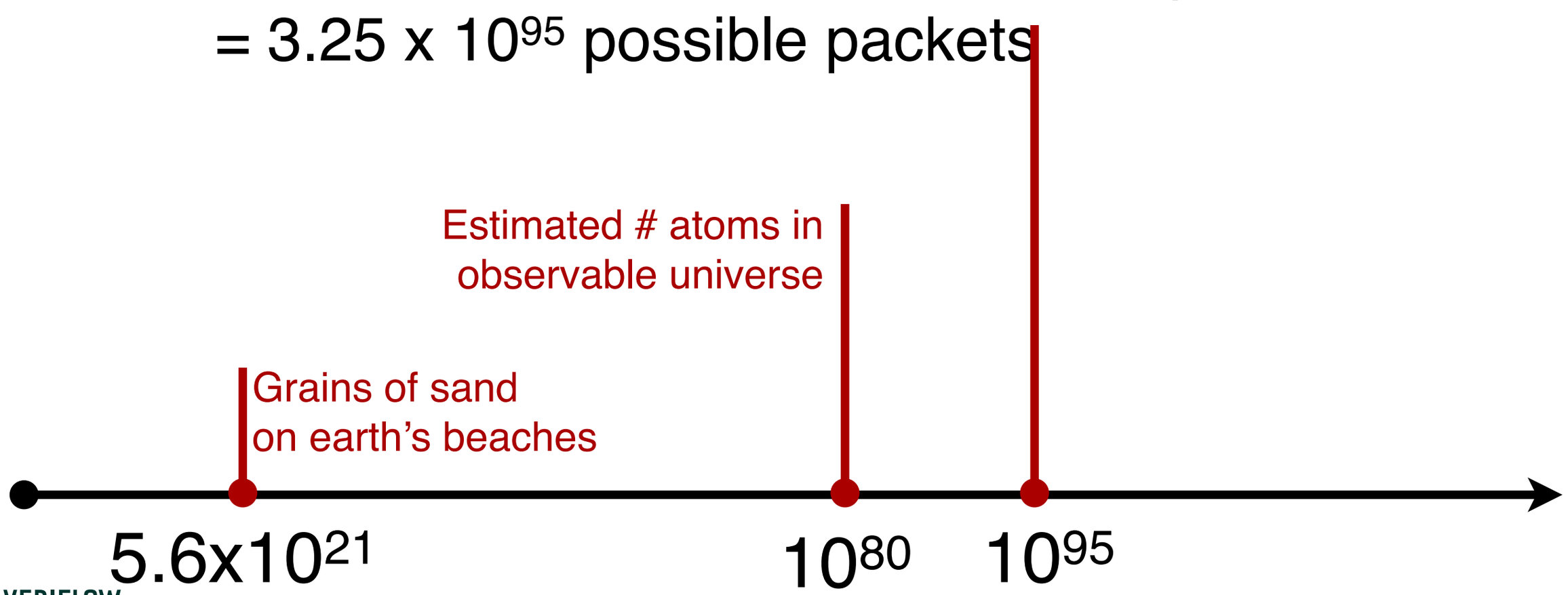

A-to-B query with bitmask

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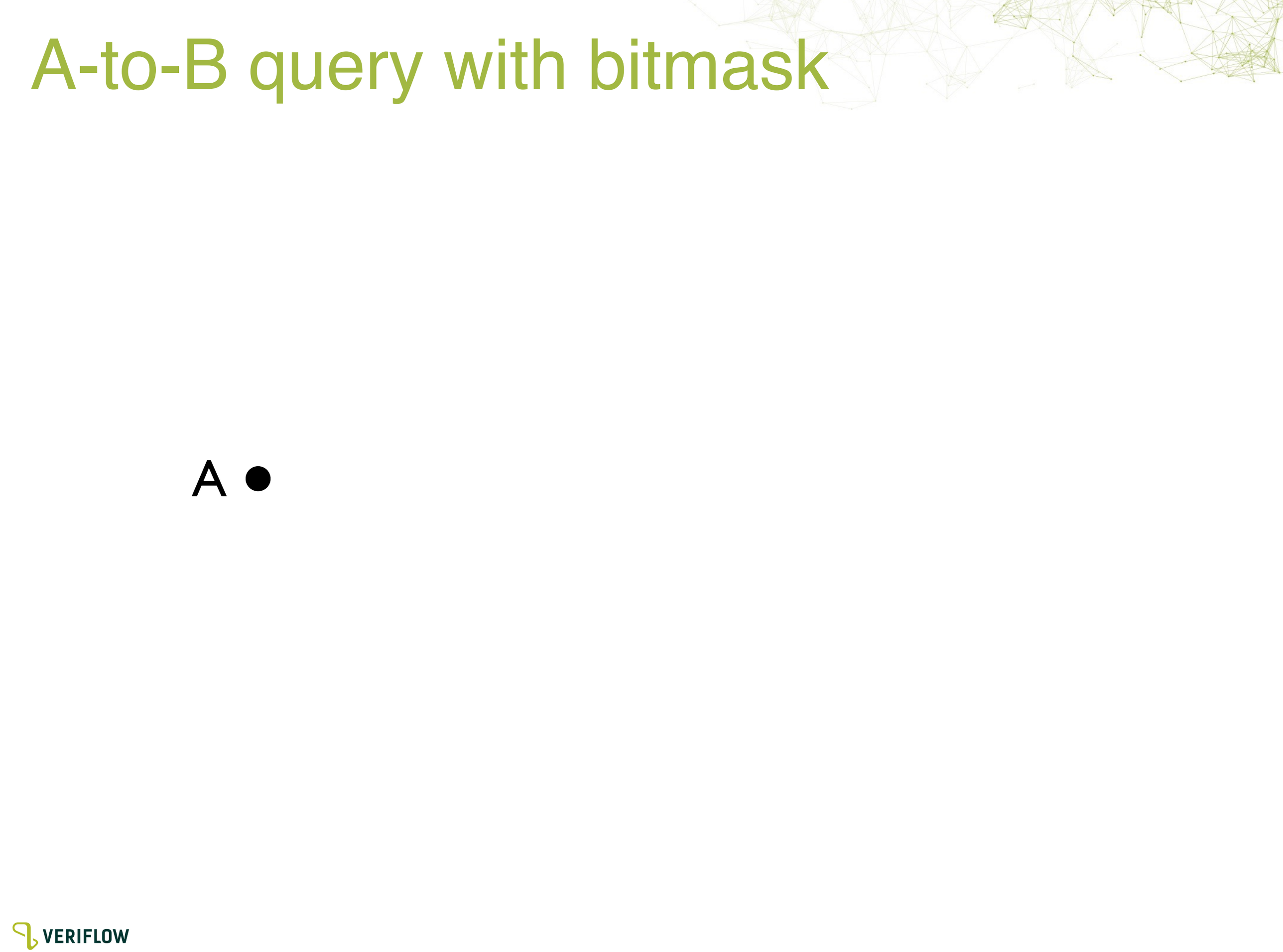

A-to-B query with bitmask

A ● ● B

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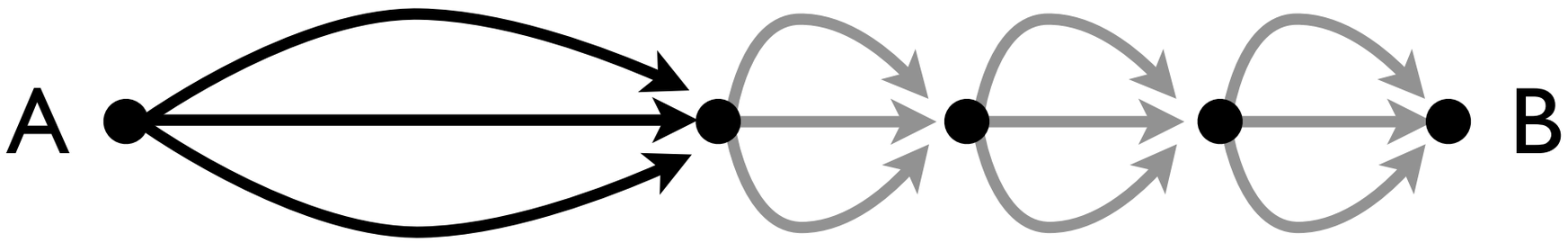
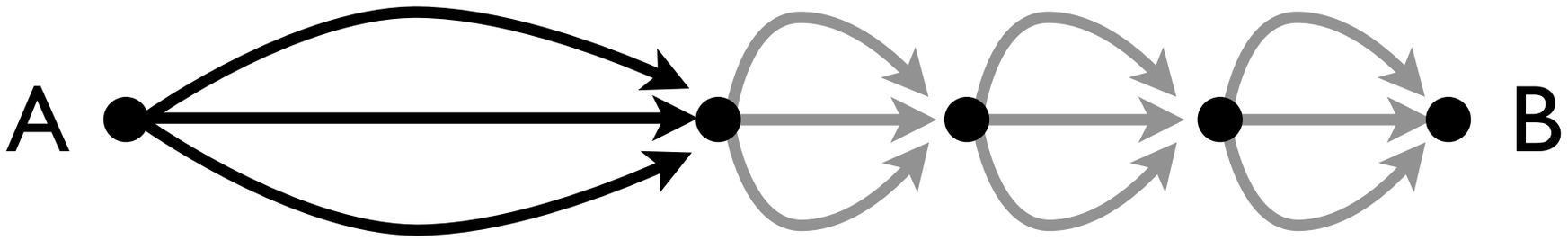


A-to-B query with bitmask

Packet: `x[0] x[1] x[2] … x[n]`



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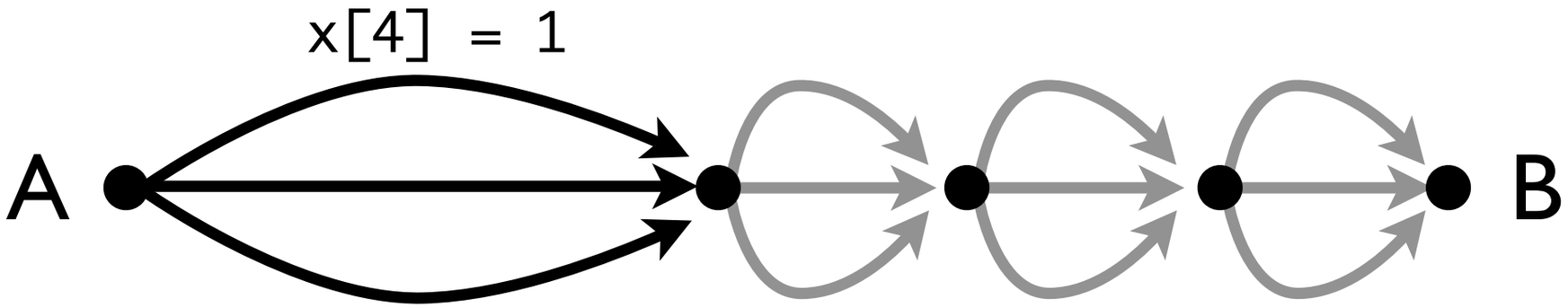

A-to-B query with bitmask

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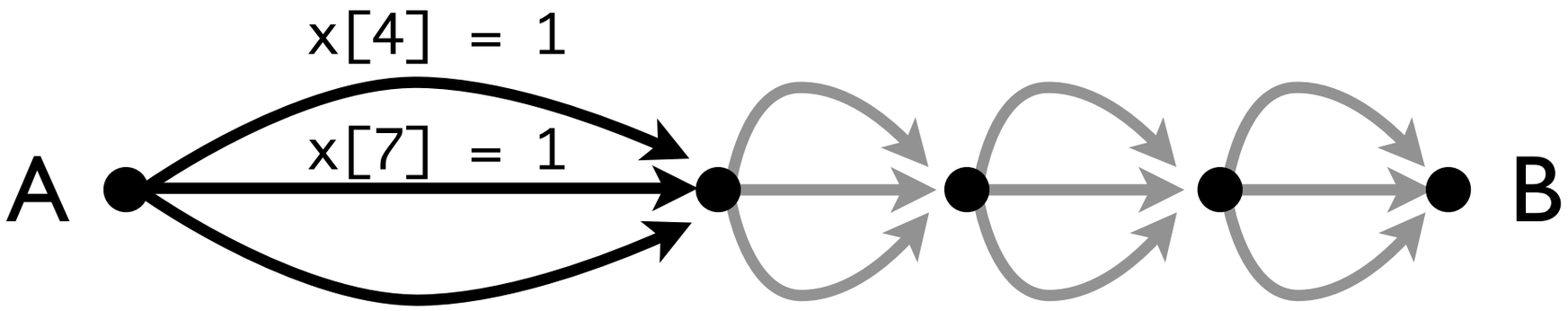

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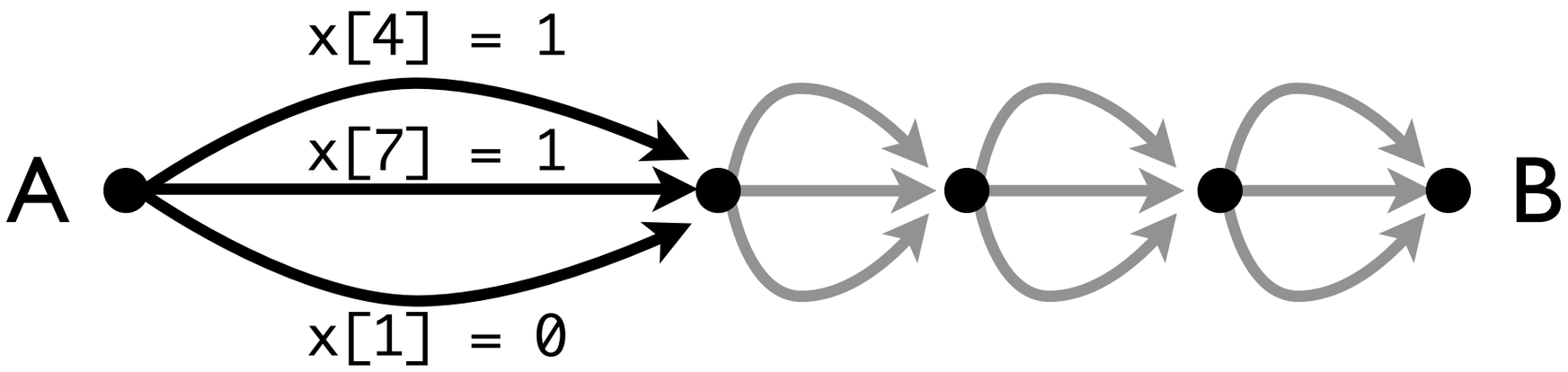

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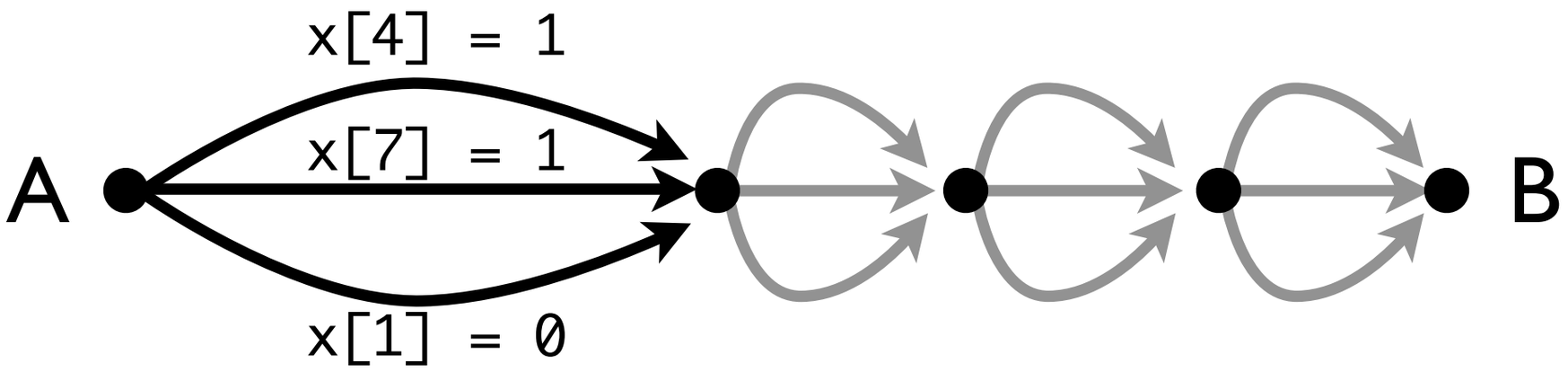

$$(x_4 \vee x_7 \vee \bar{x_1}) \wedge (\ldots) \wedge (\ldots) \wedge (\ldots)$$

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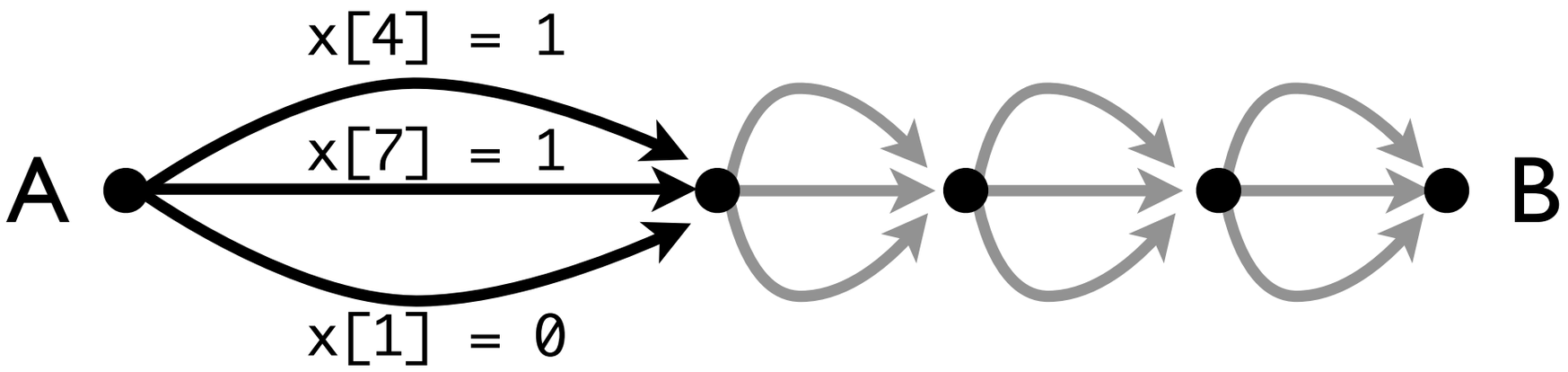


$$(x_4 \vee x_7 \vee \bar{x_1}) \wedge (\ldots) \wedge (\ldots) \wedge (\ldots)$$

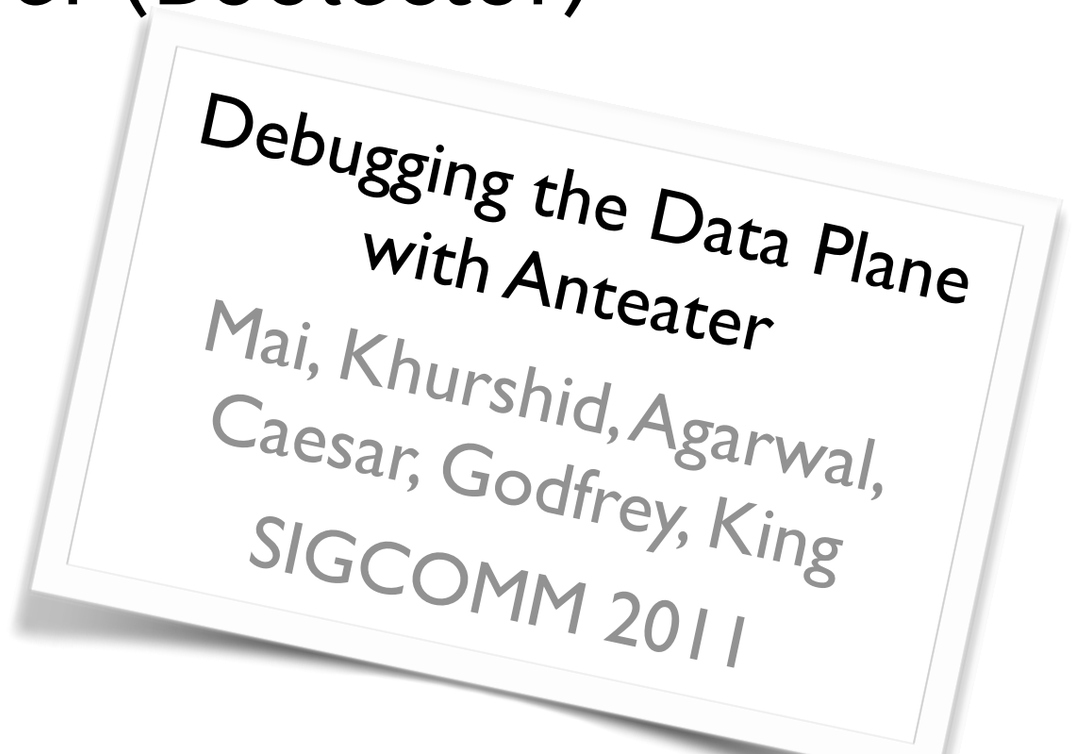
NP-complete!

Anteater's solution

Express data plane and invariants as SAT

- …up to some max # hops
- Dynamic programming to deal with exponential number of paths
- Model packet transformations with vector of packet "versions" & constraints across versions

Check with off-the-shelf SAT solver (Boolector)



Experiences with real network

Evaluated Anteater with operational network

- ~178 routers supporting >70,000 machines
- Predominantly OSPF, also uses BGP and static routing
- 1,627 FIB entries per router (mean)
- State collected using operator's SNMP scripts

Revealed 23 violations of 3 invariants in 2 hours

	Loop	Packet loss	Consistency
Being fixed	9	0	0
Stale config.	0	13	1
Total alerts	9	17	2

CAN WE VERIFY NETWORKS IN REAL TIME?

VeriFlow: Verifying Network-Wide Invariants in Real Time

Khurshid, Zou, Zhou, Caesar, Godfrey

HotSDN'12 best paper, NSDI'13

Not so simple

Not so simple

Challenge #1: Obtaining real time view

Not so simple

Challenge #1: Obtaining real time view

Challenge #2: Verify quickly

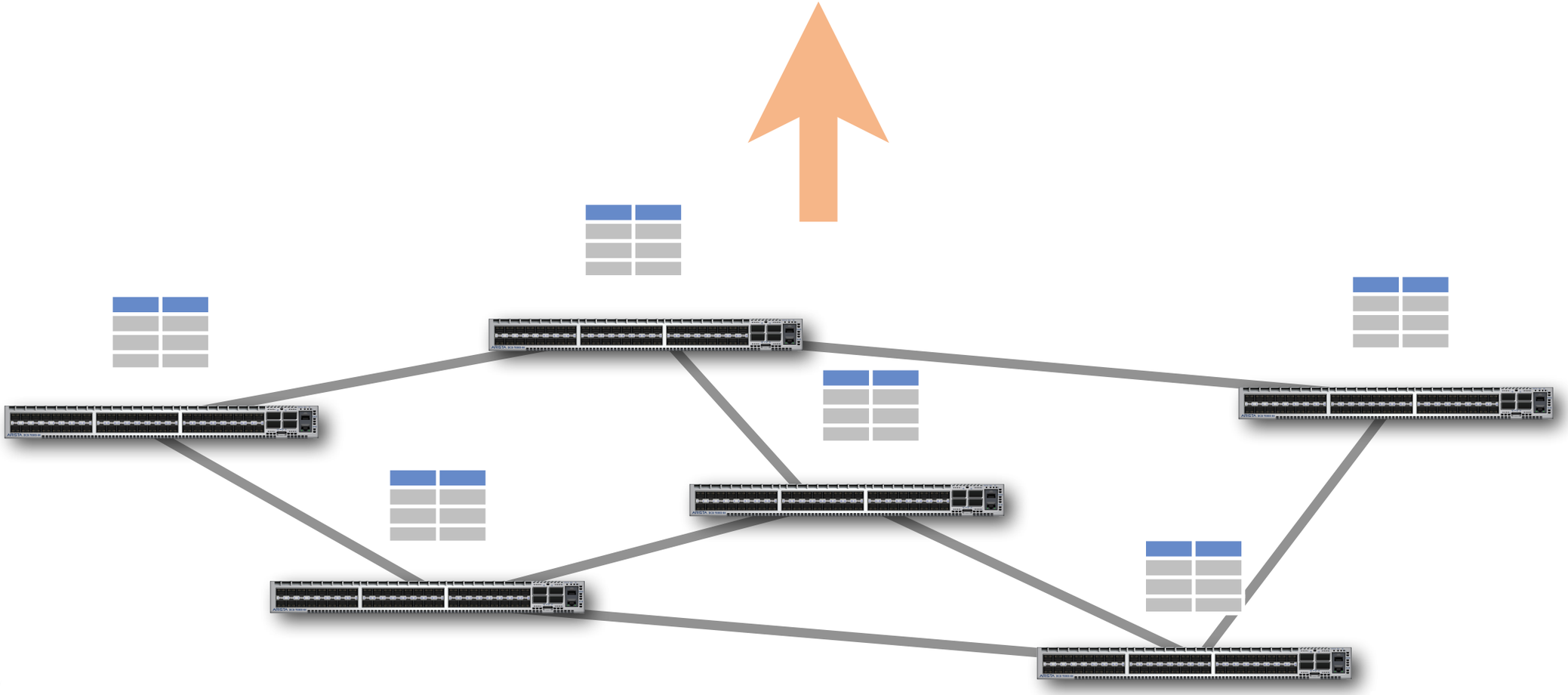
Architecture

"Service S reachable only through firewall?"

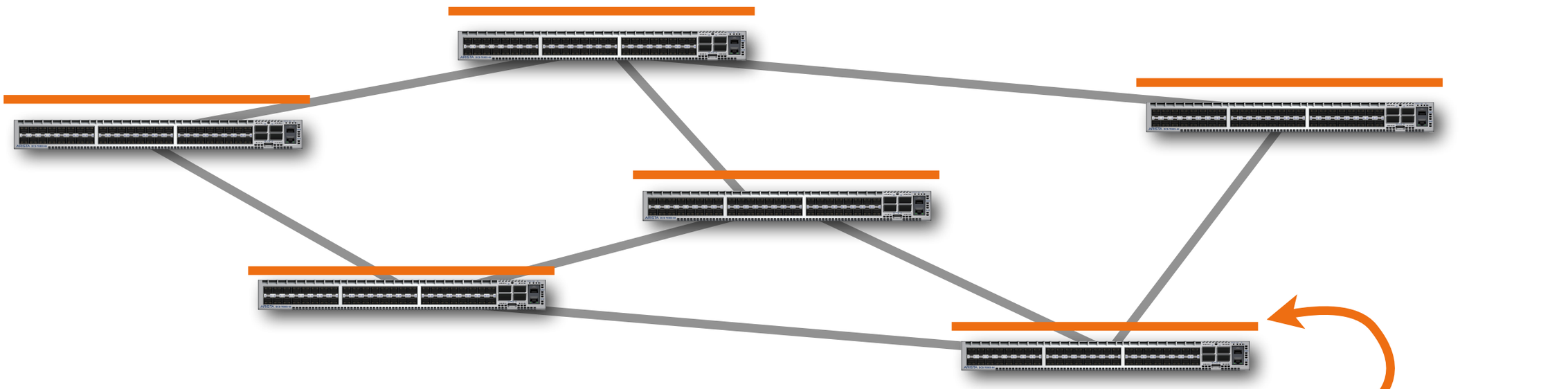
"Is segment isolated?"

Verifier

Diagnosis



VeriFlow [NSDI'13] architecture



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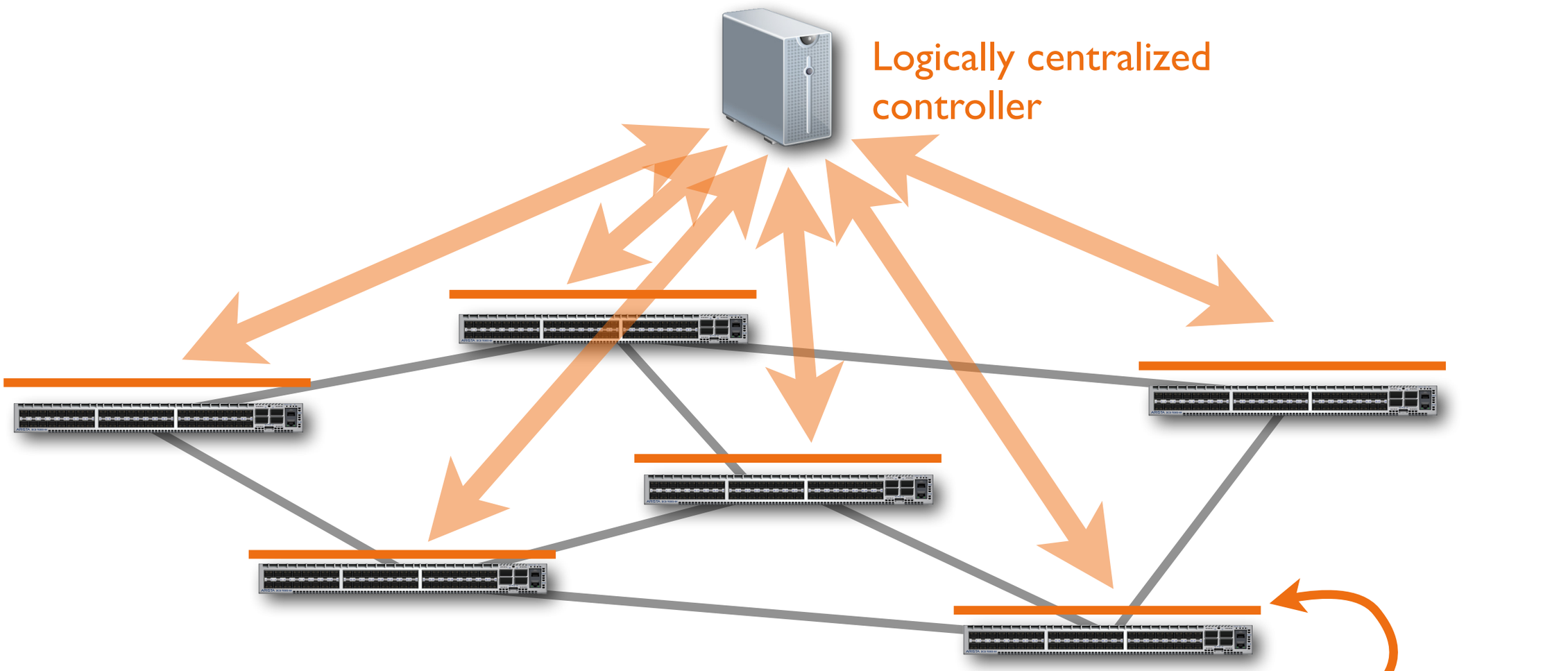

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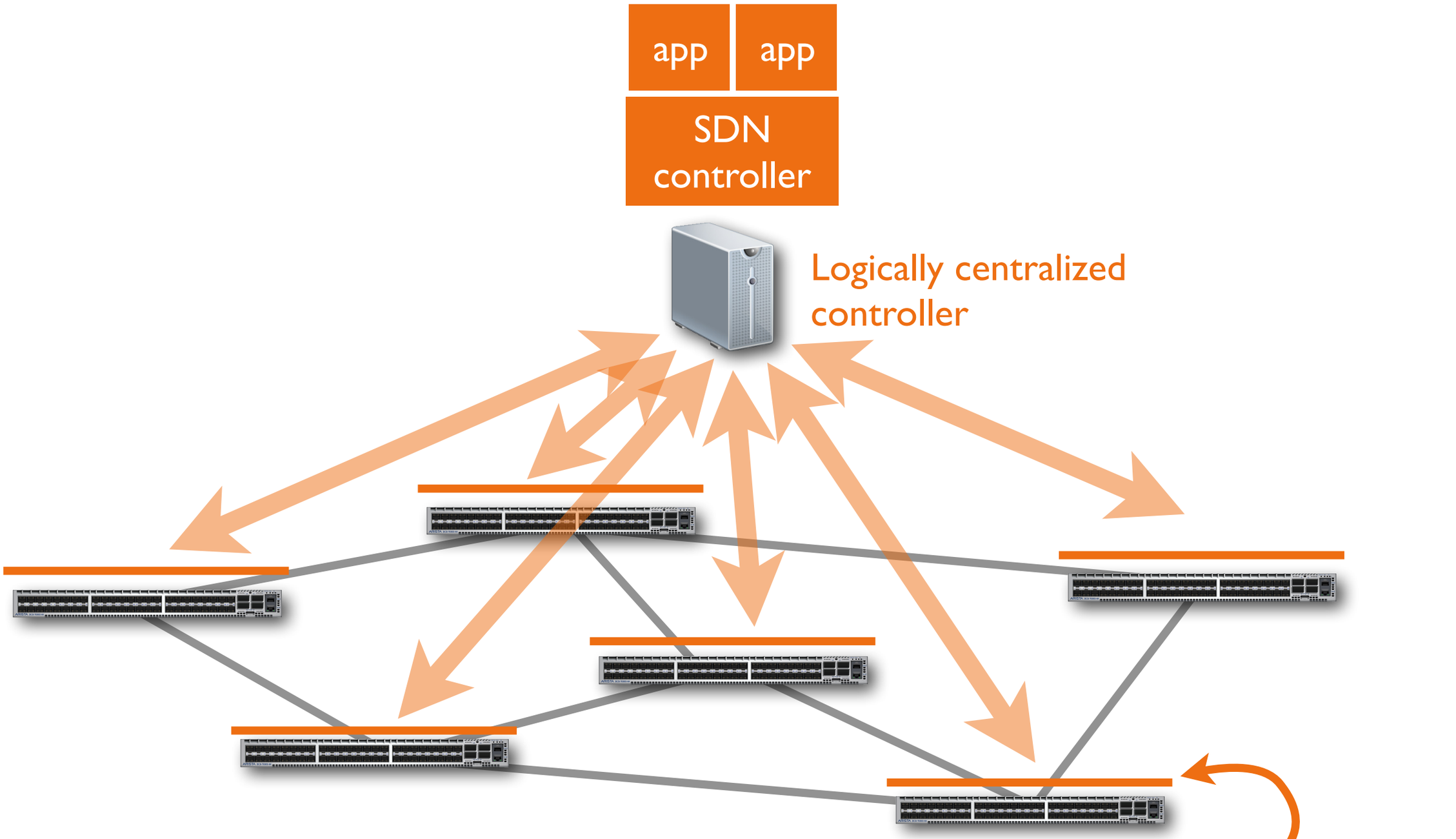

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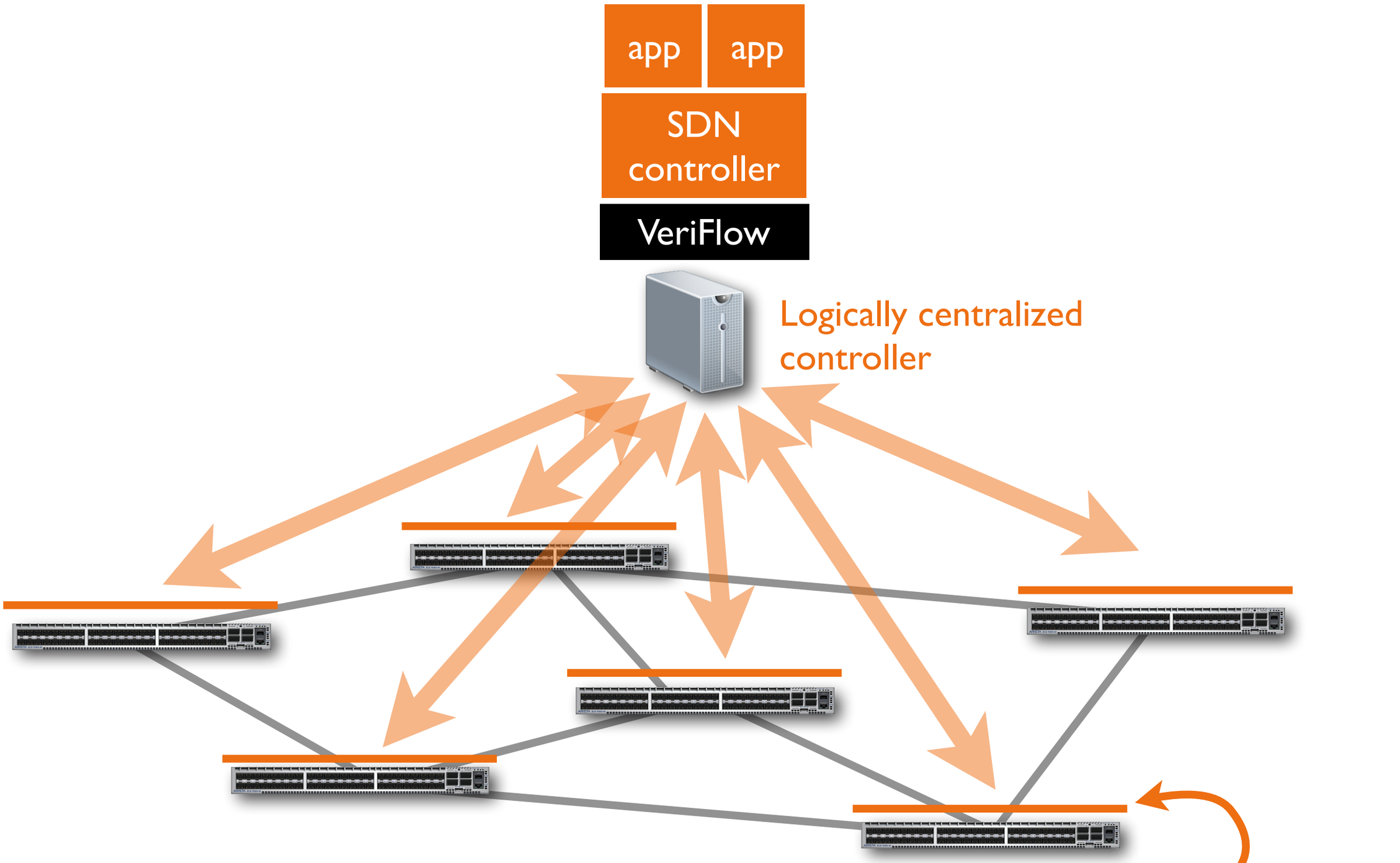

Verifying invariants quickly

Overview:

1. Limit the search space
2. Represent forwarding behaviors using graphs
3. Run Light-weight graph-based algorithm to check *reachability properties*

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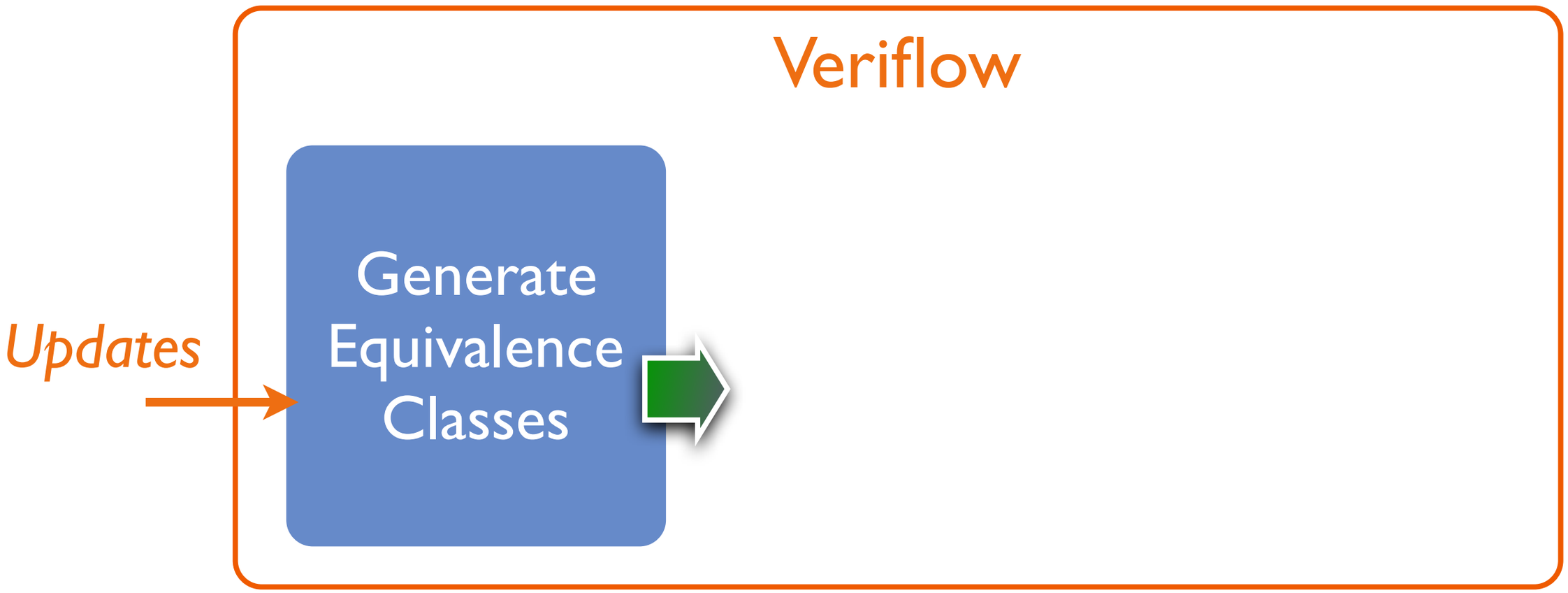

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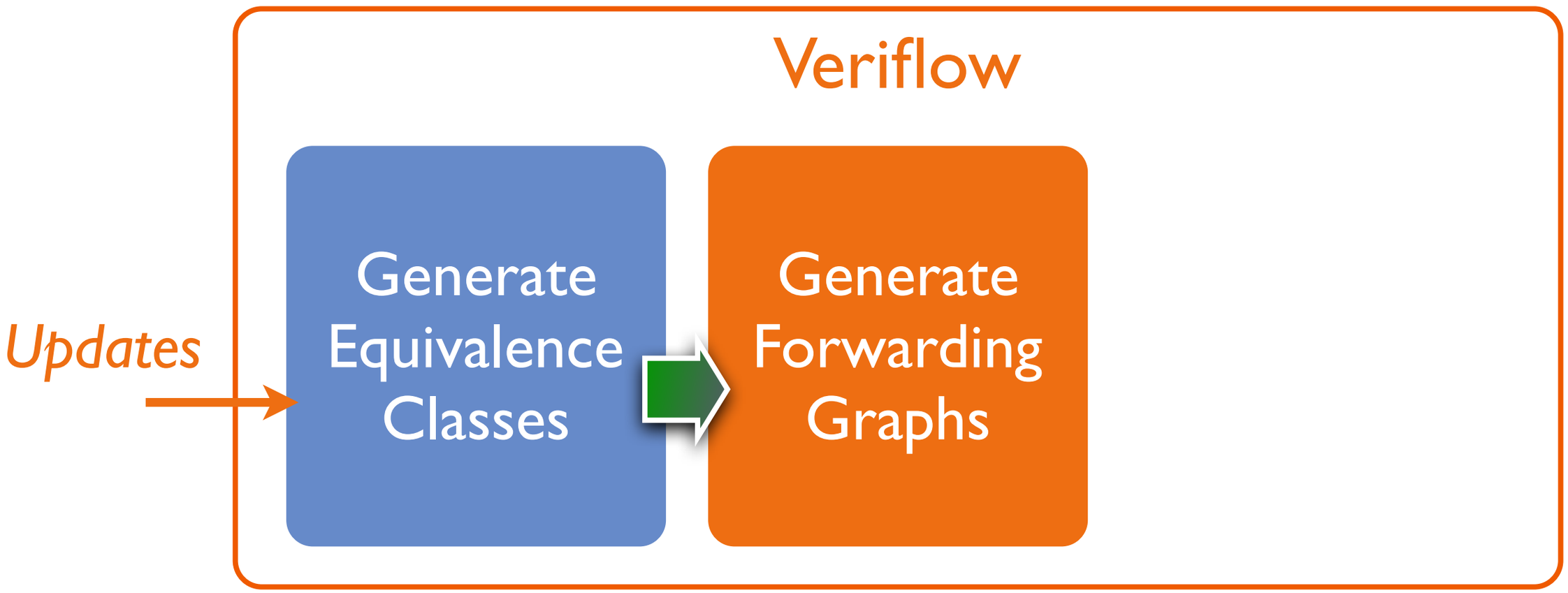

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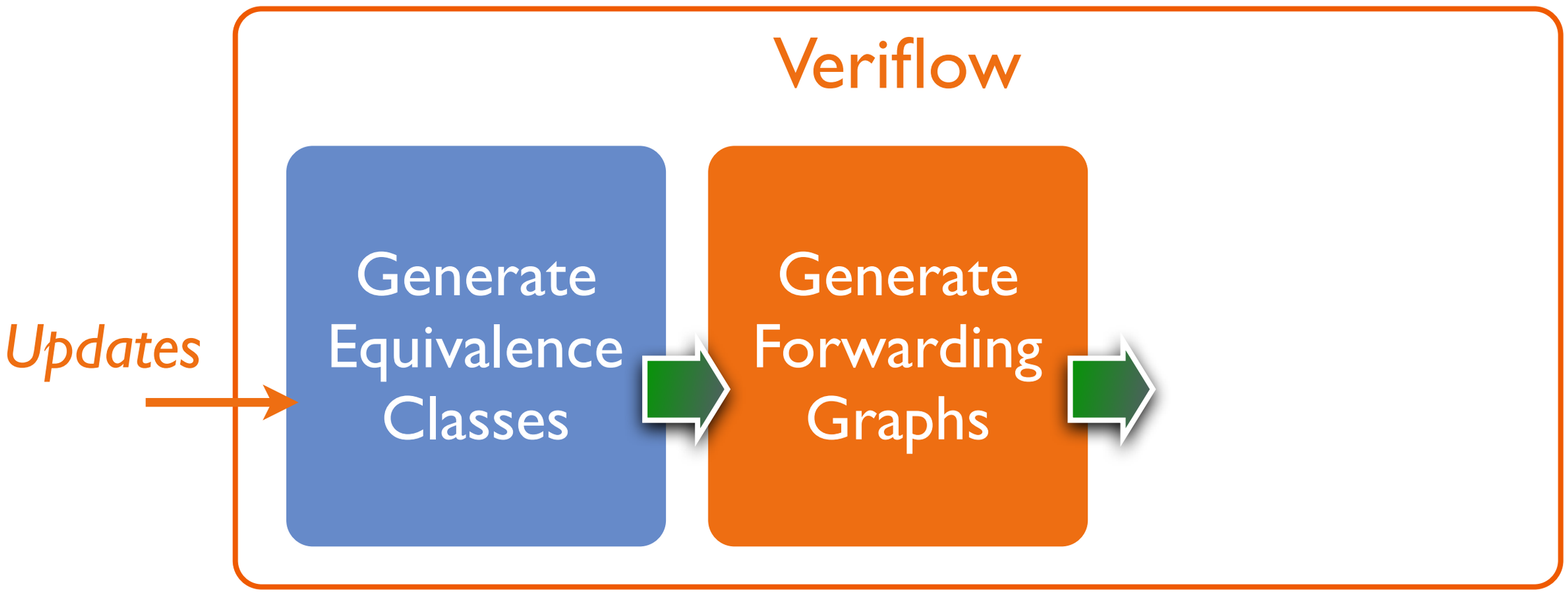

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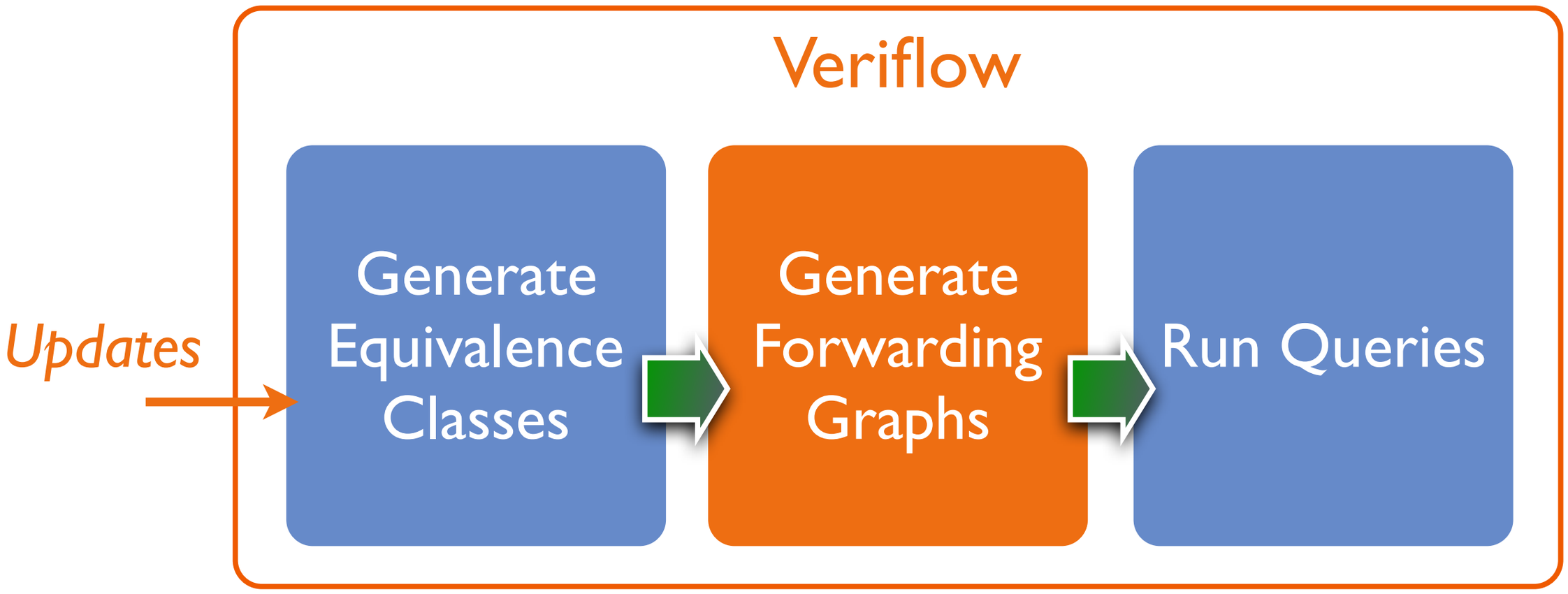

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MODELING DYNAMIC NETWORKS

Enforcing Customizable Consistency Properties in Software-Defined Networks

Zhou, Jin, Croft, Caesar, Godfrey

NSDI 2015

Timing uncertainty

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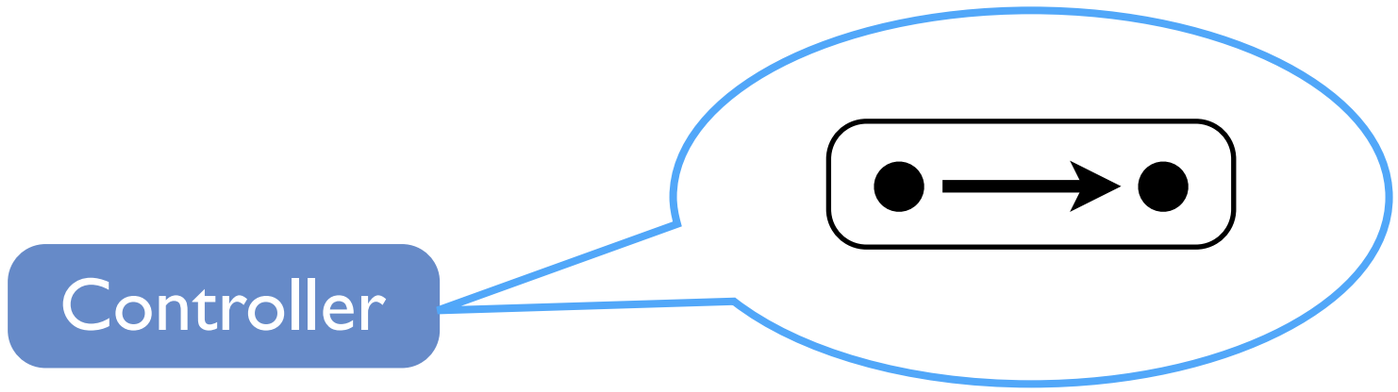

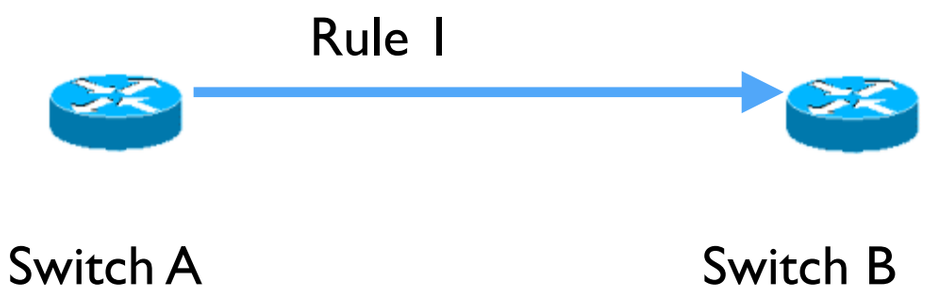

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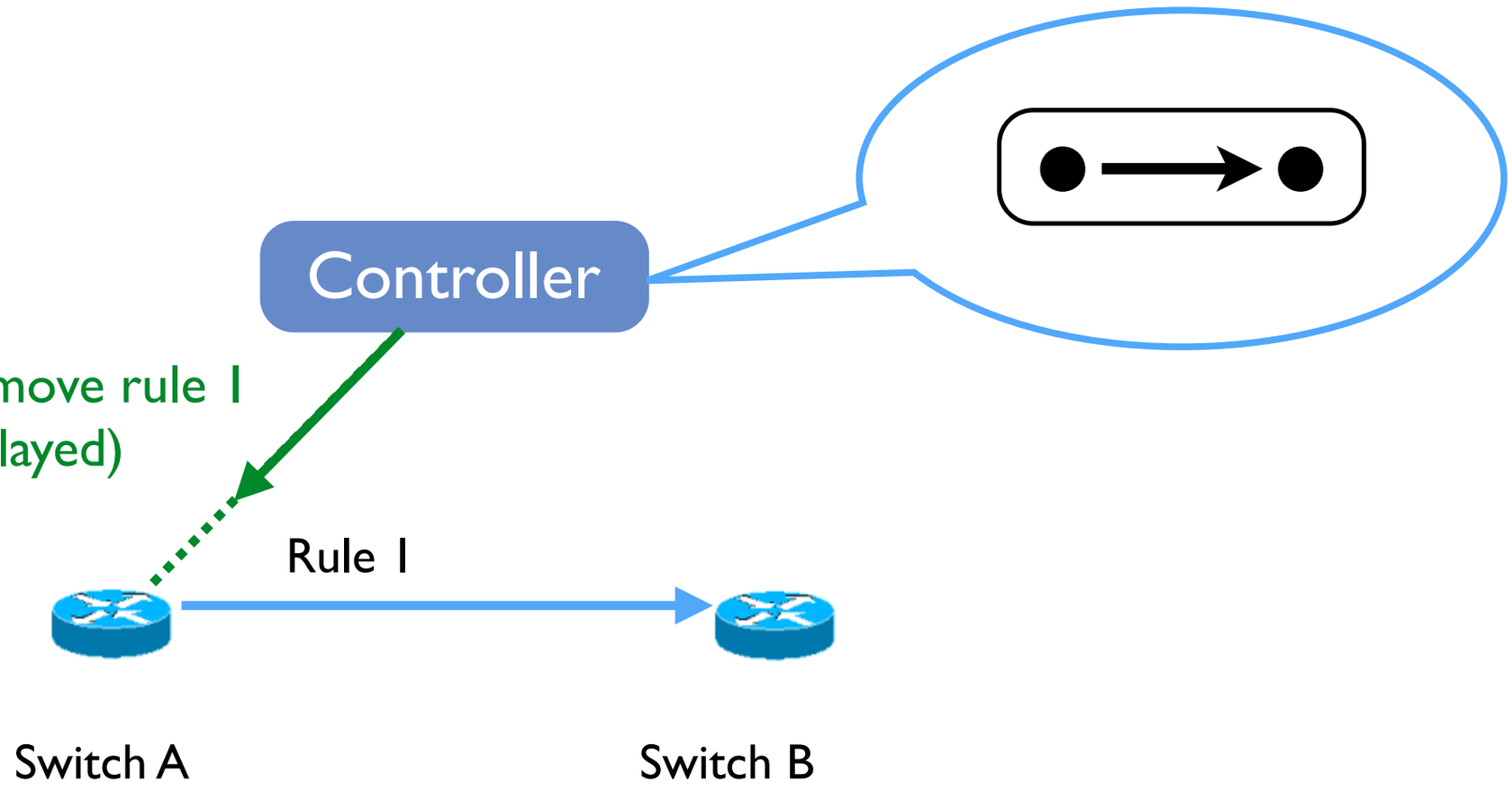

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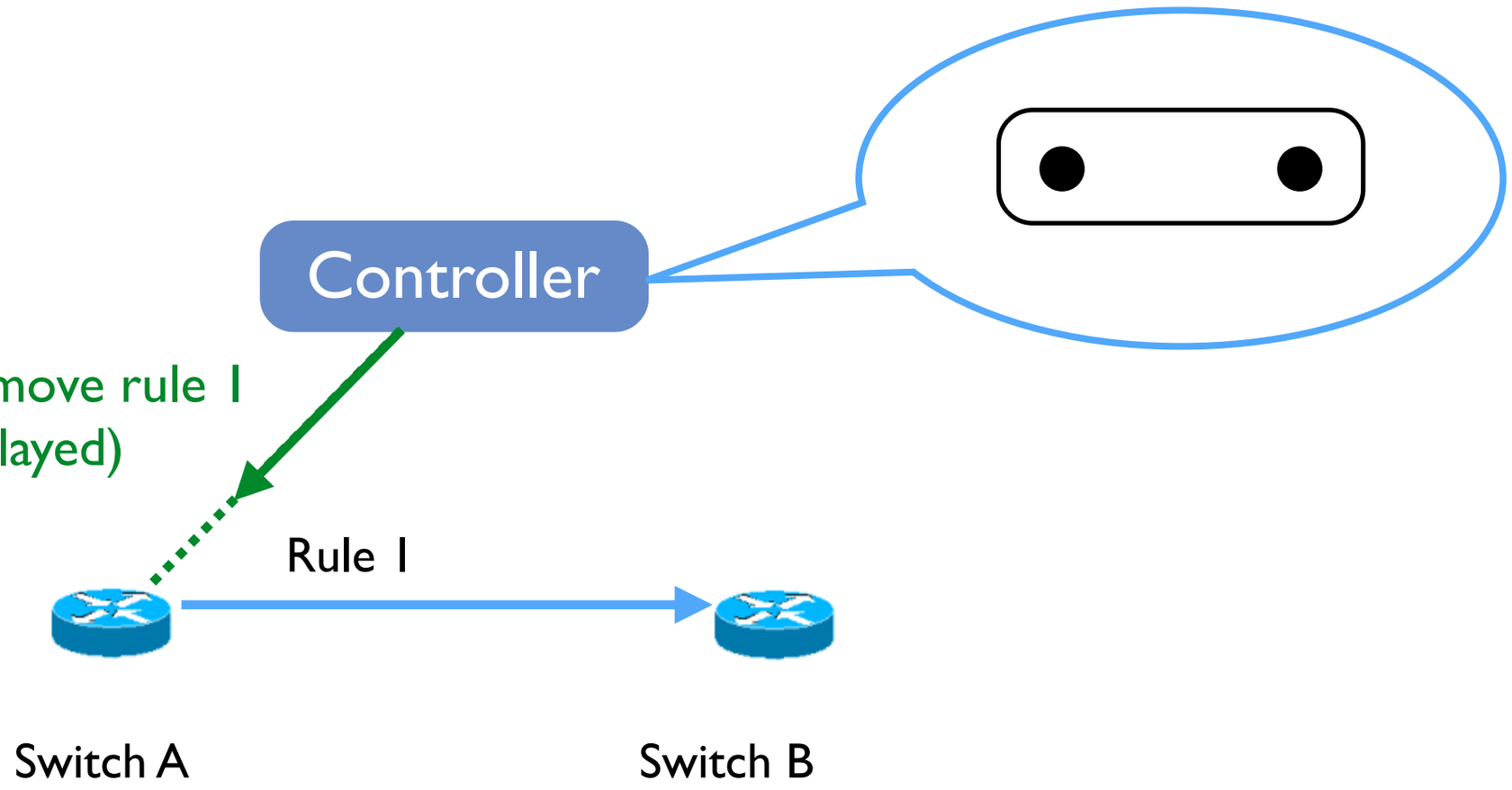

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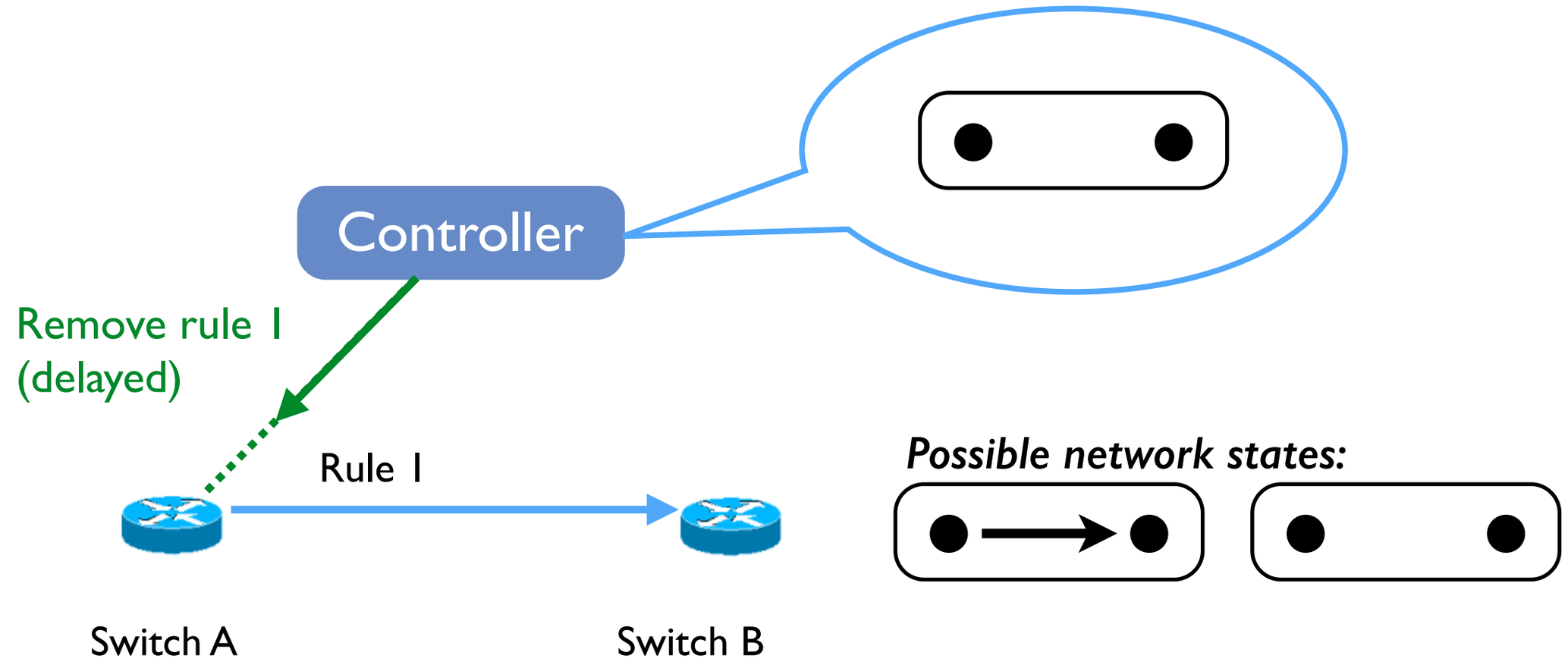

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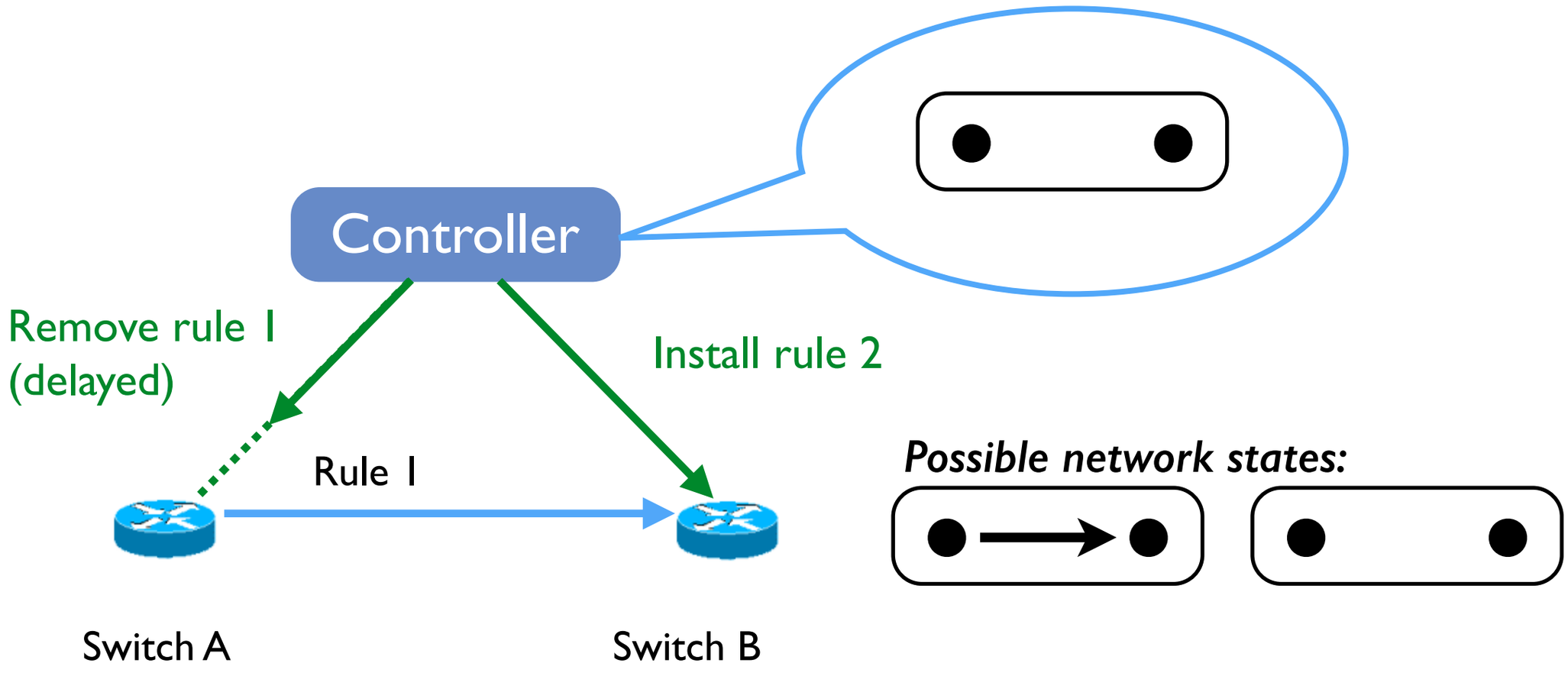

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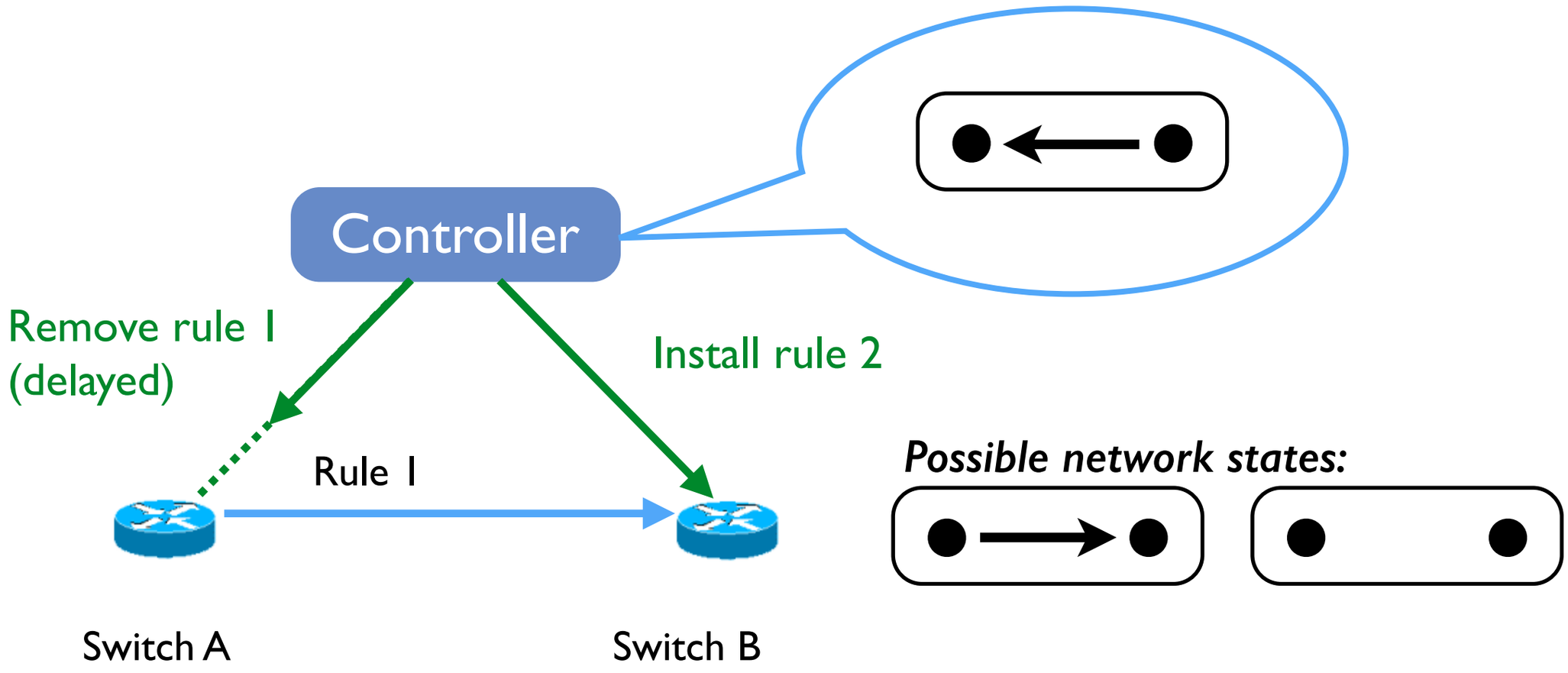

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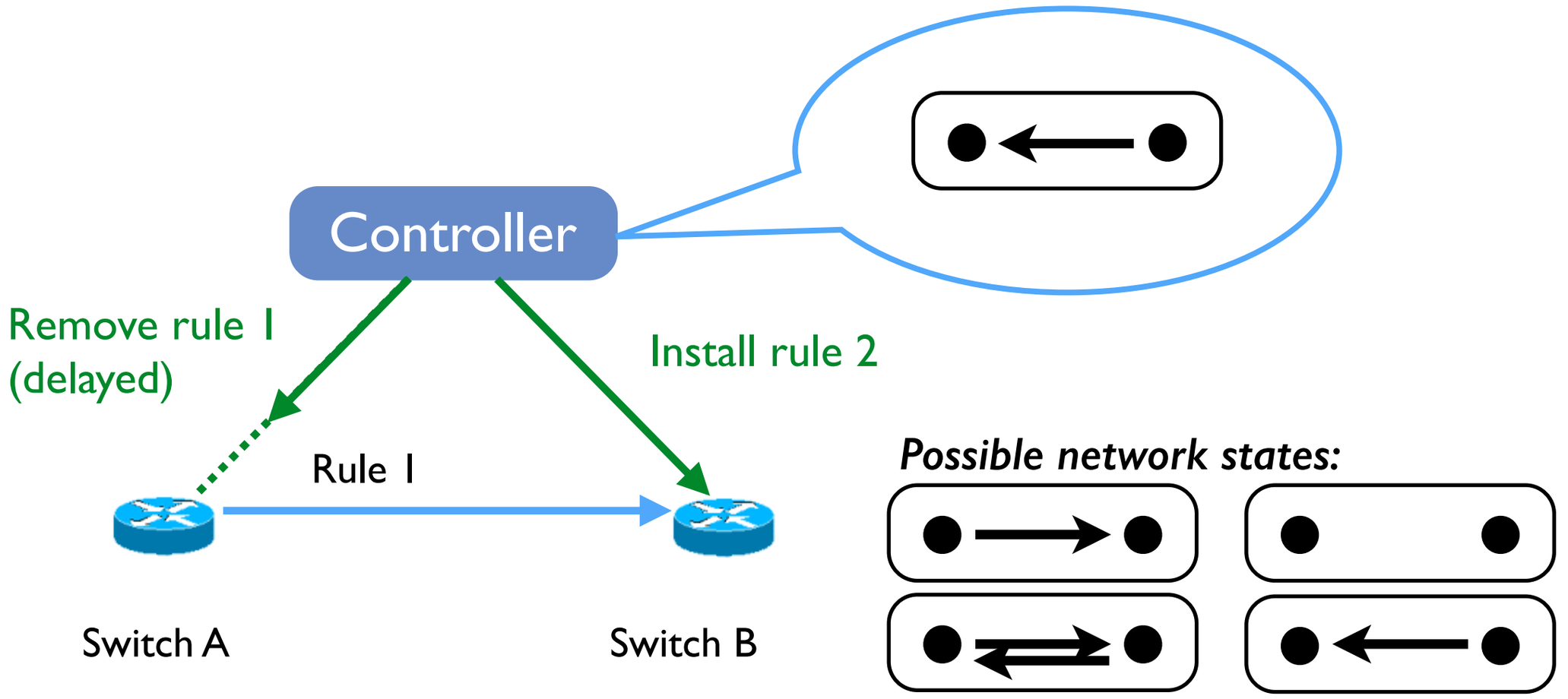

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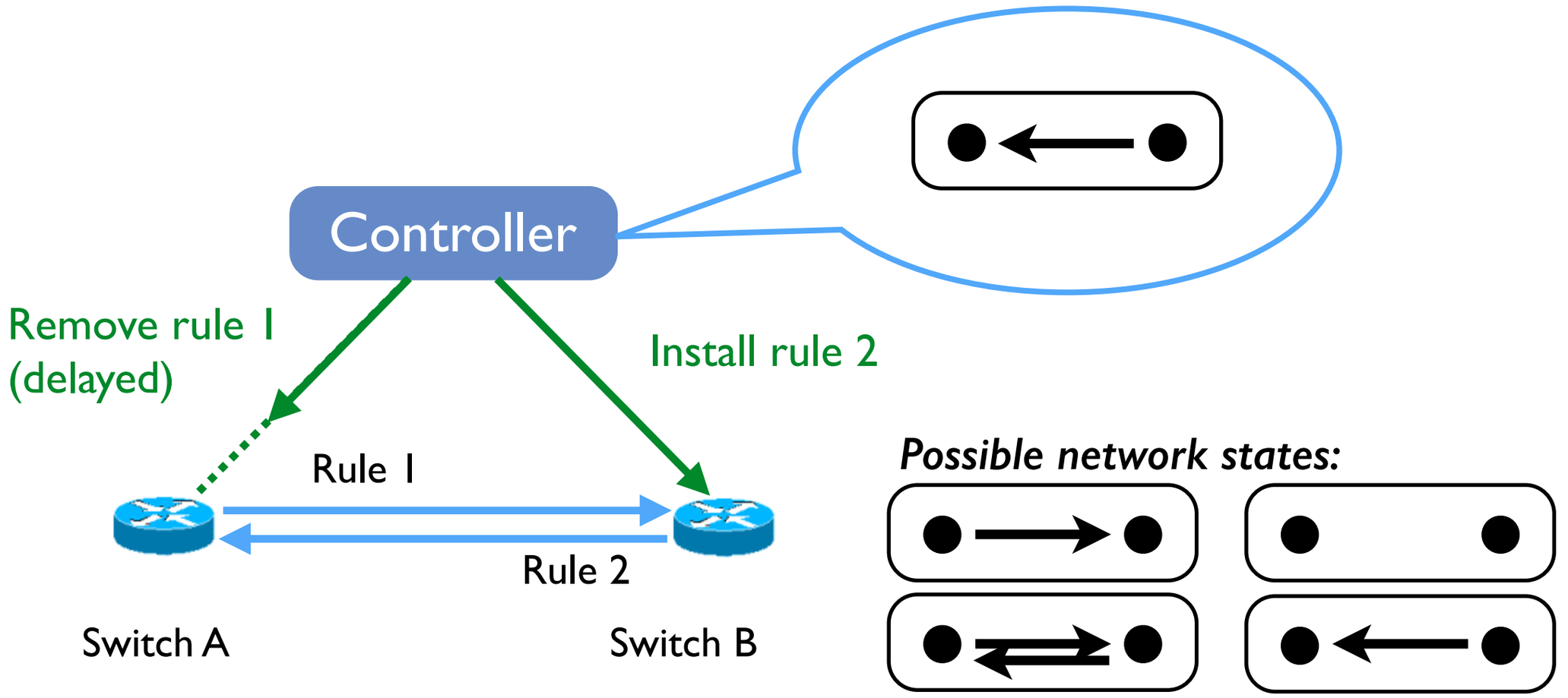

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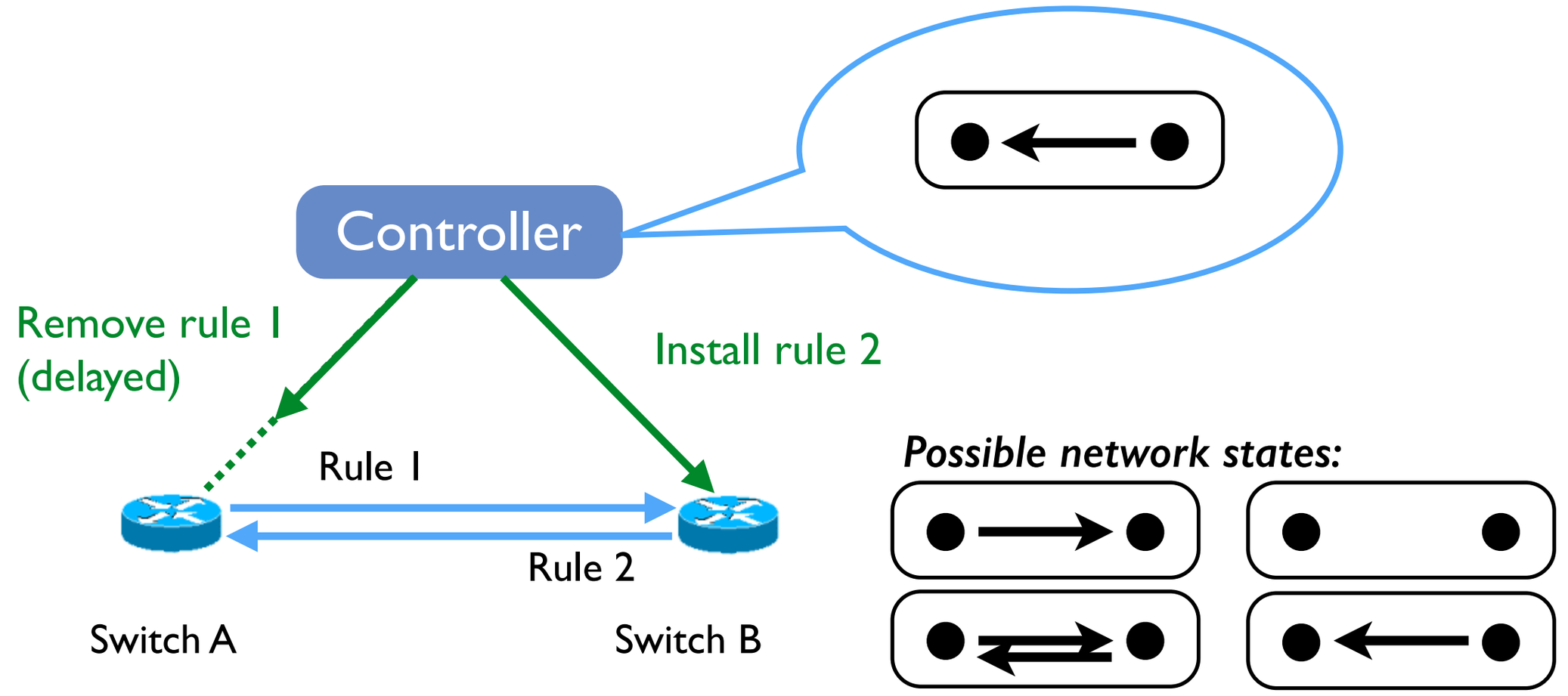

One solution: "consistent updates"

[Reitblatt, Foster, Rexford, Schlesinger, Walker, "Abstractions for Network Update", SIGCOMM 2012]

Uncertainty-aware verification

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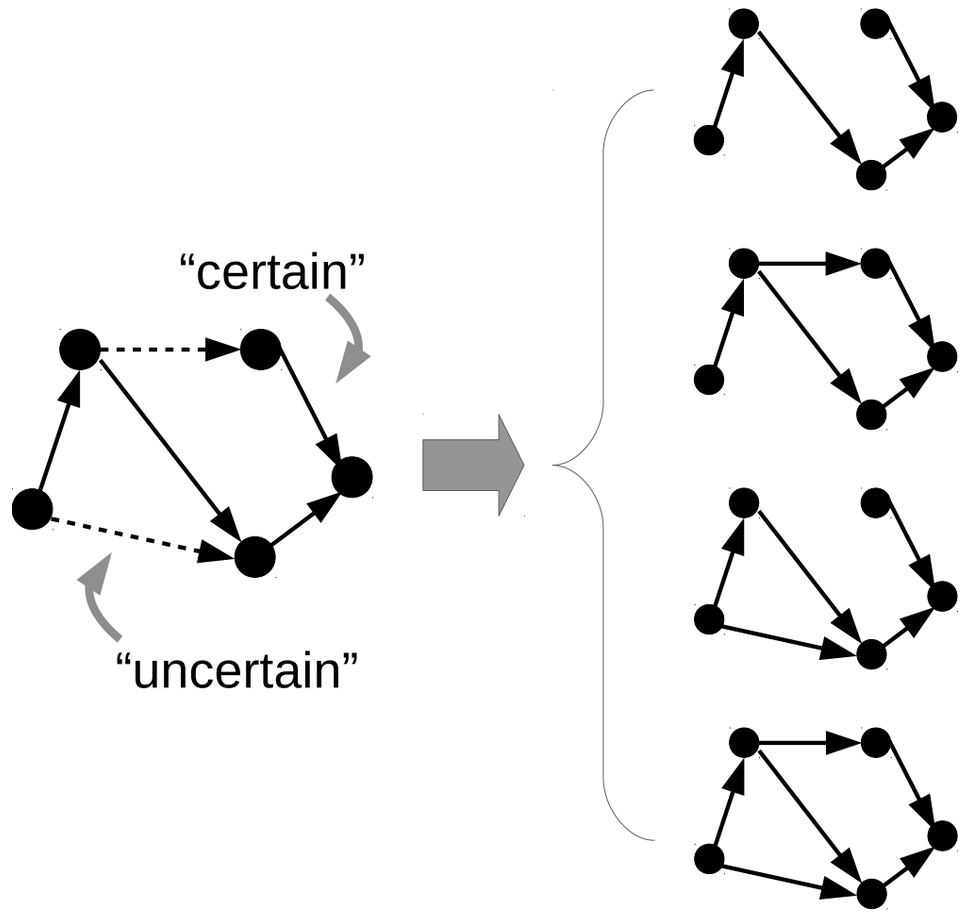
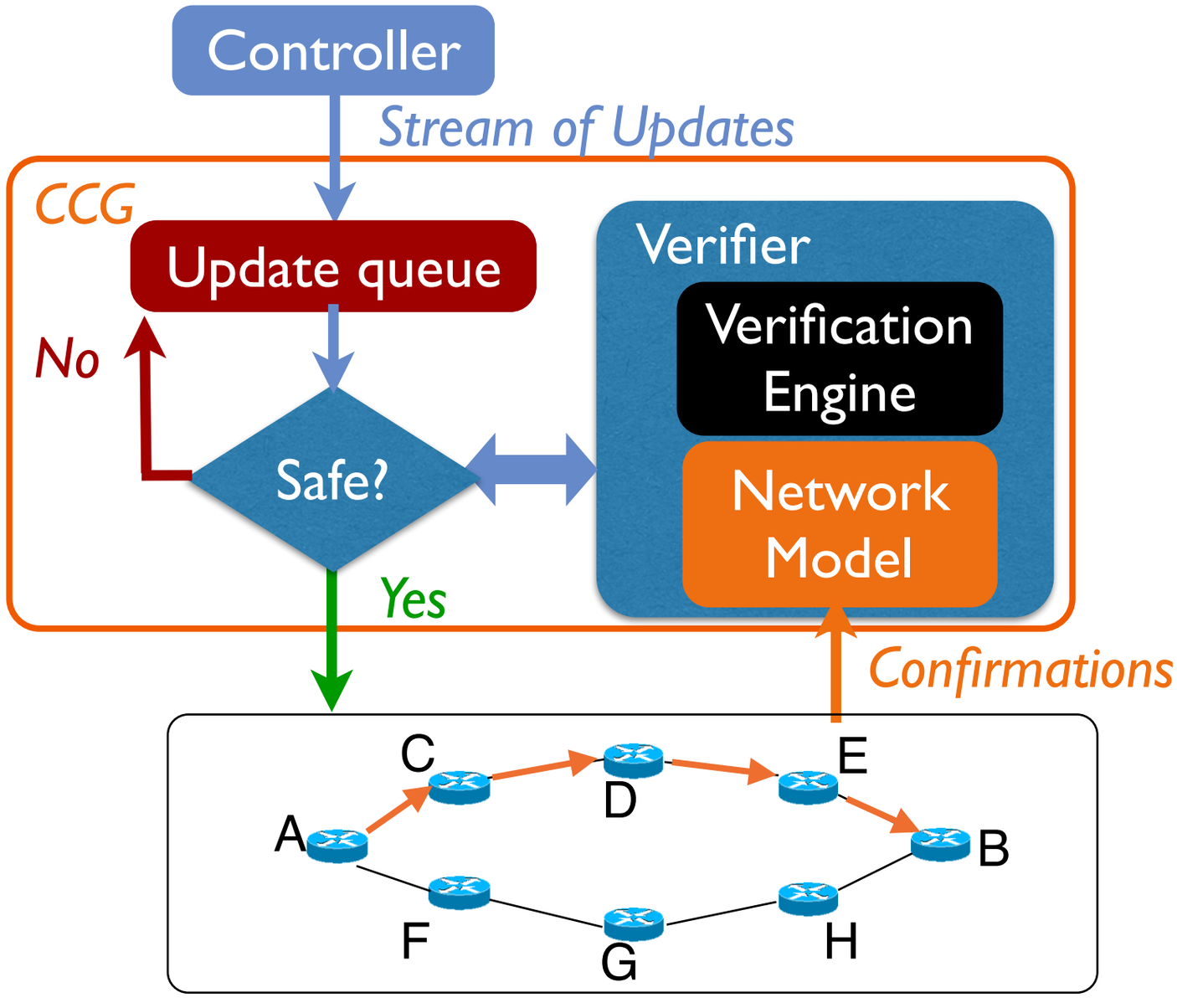


Update synthesis via verification



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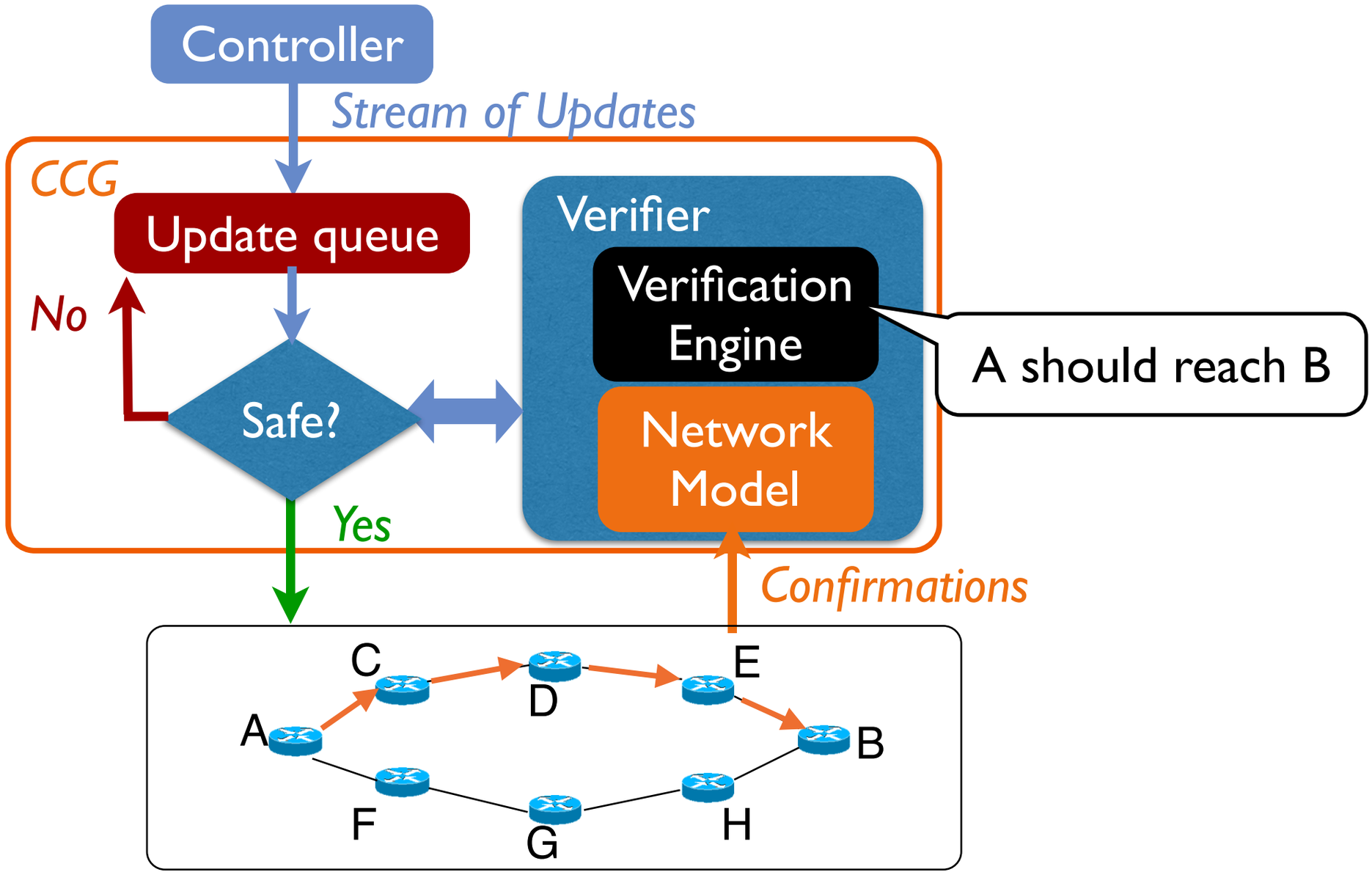

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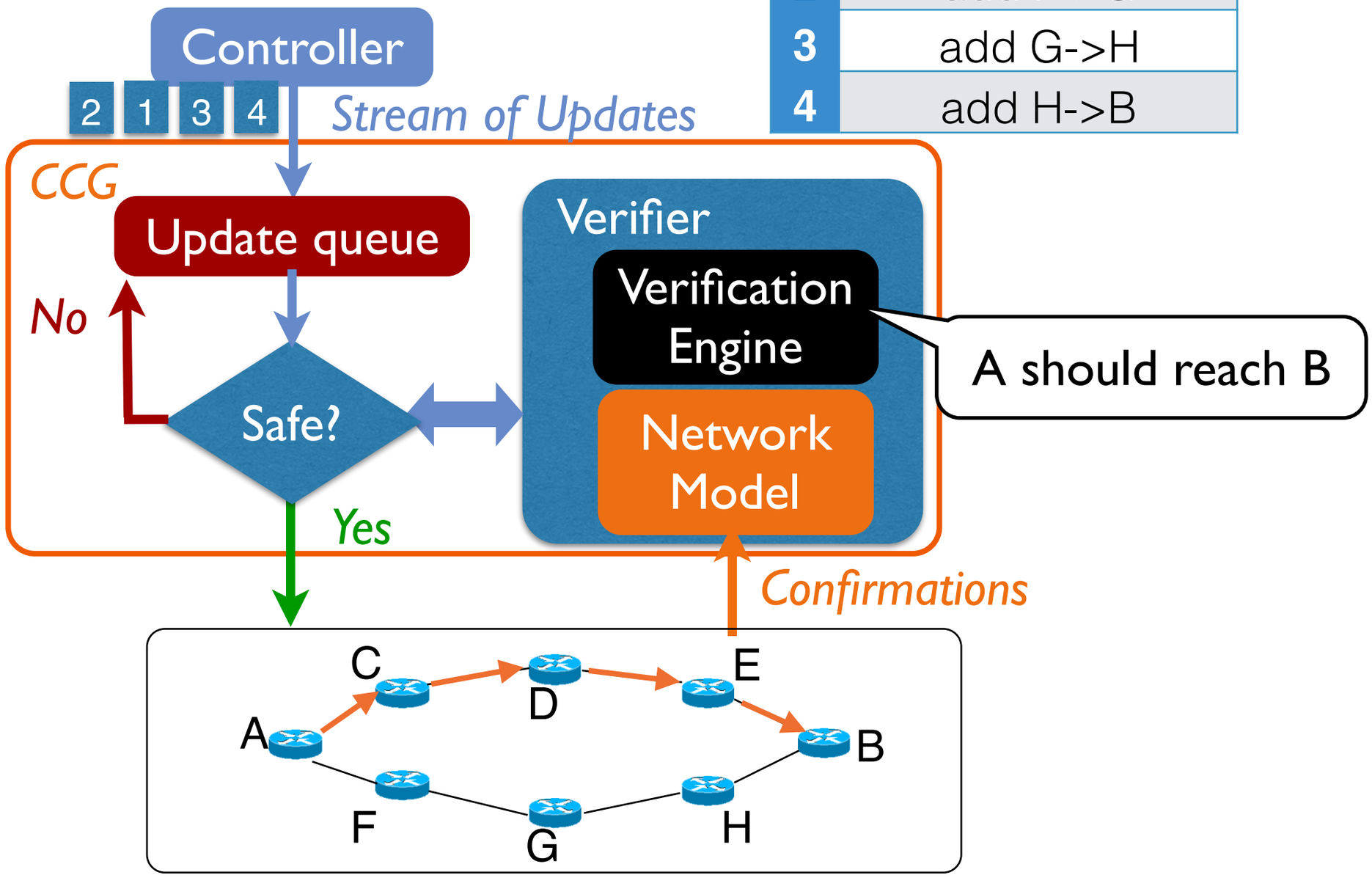

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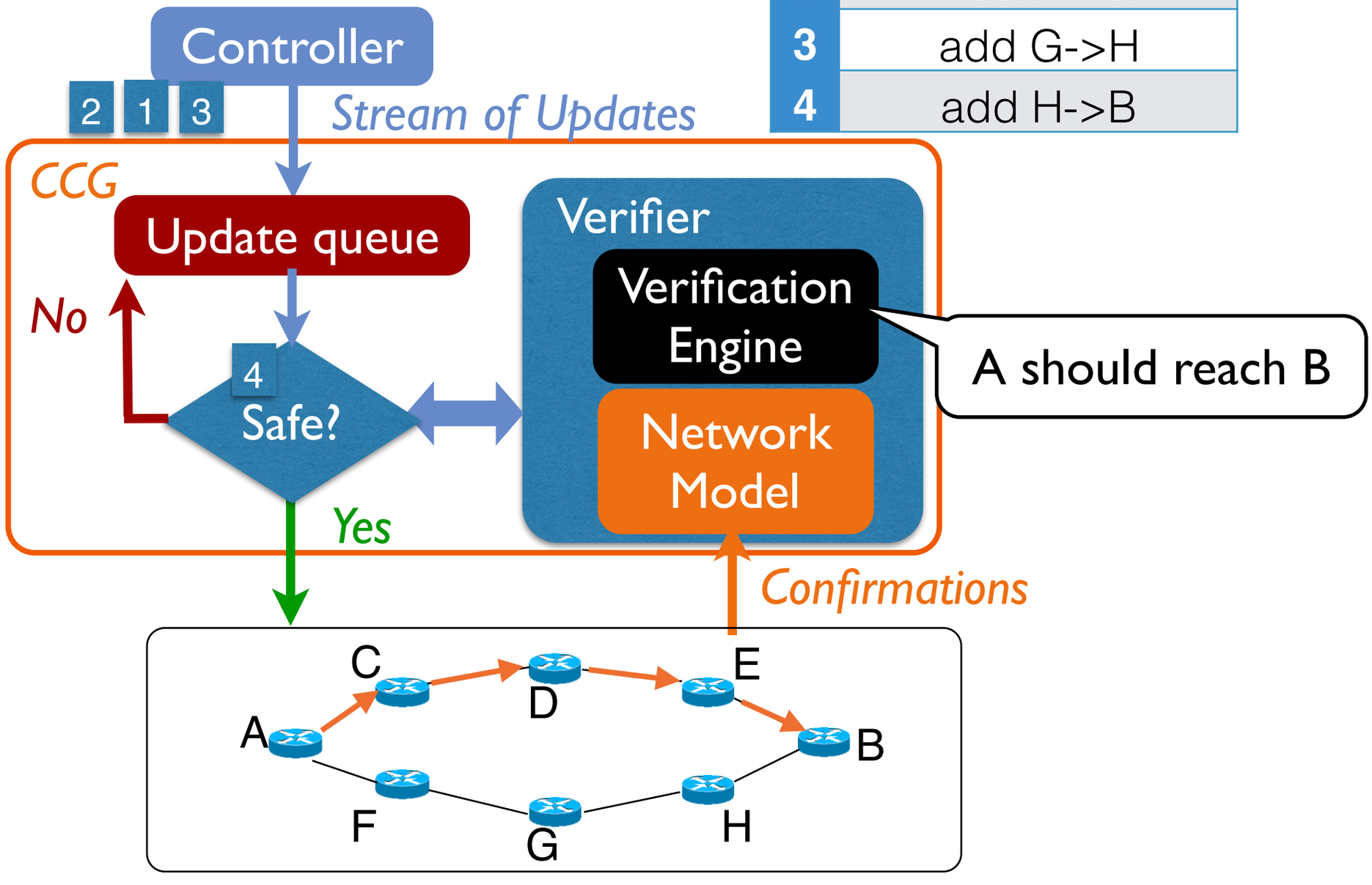

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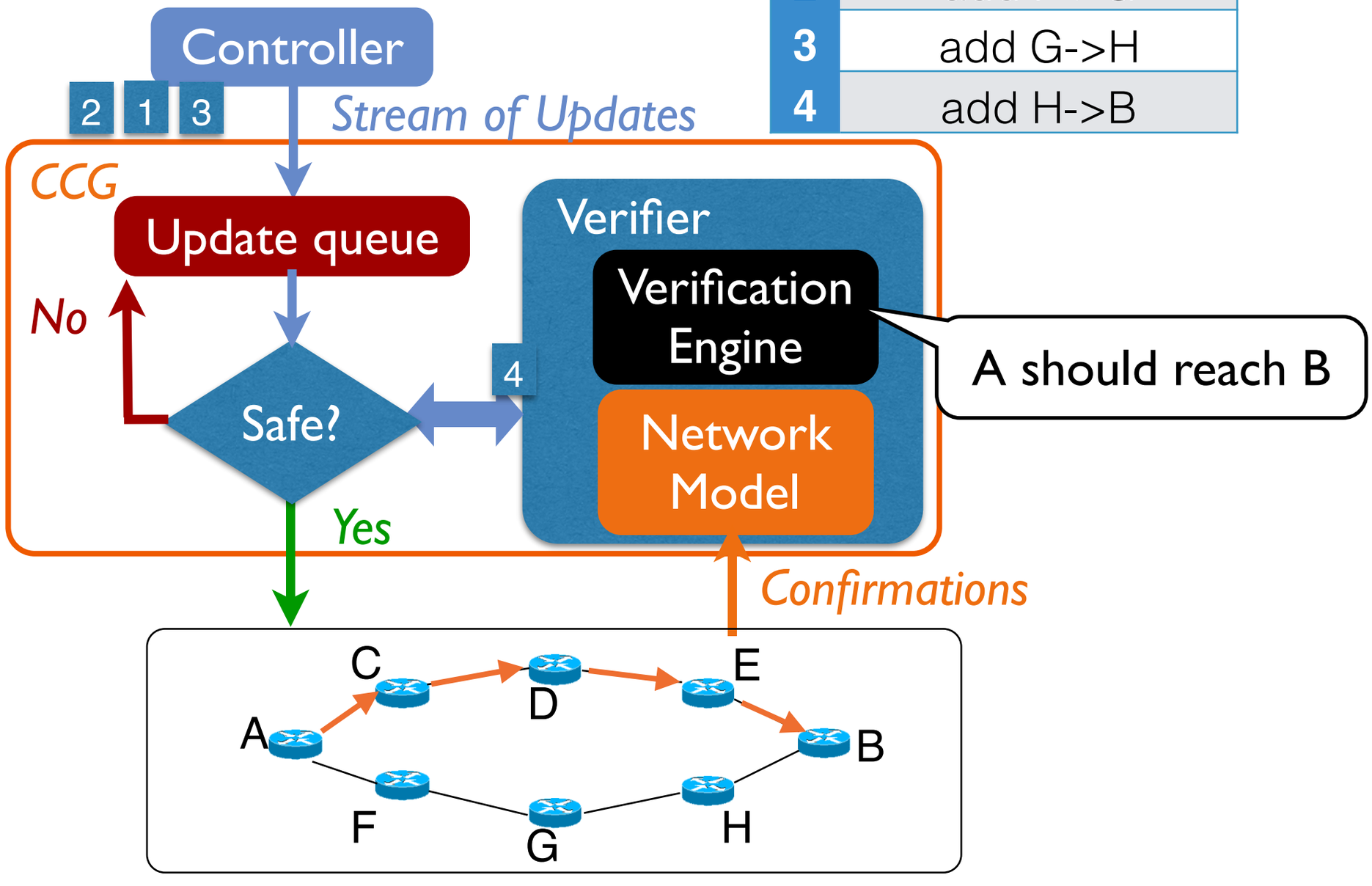

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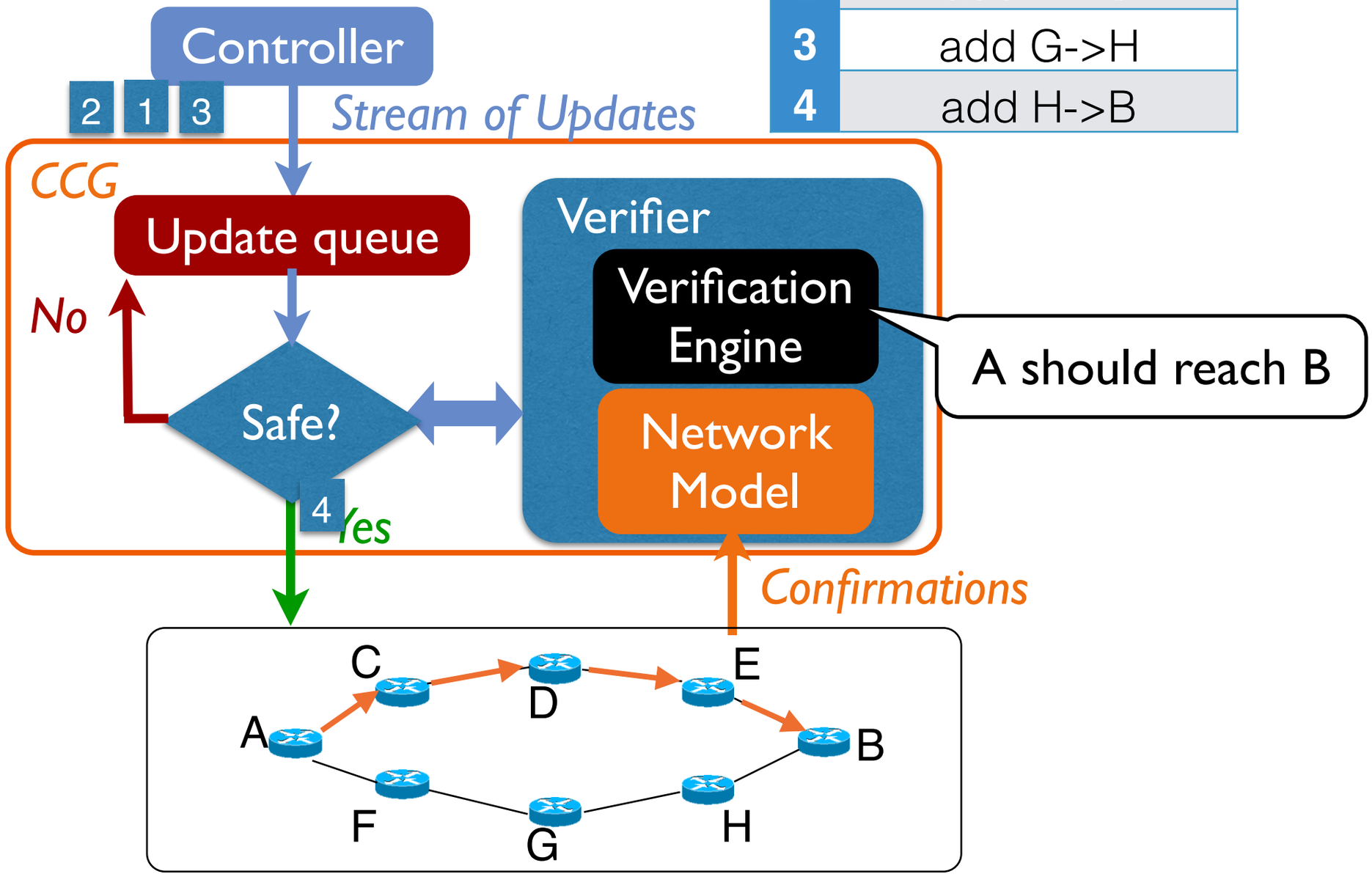

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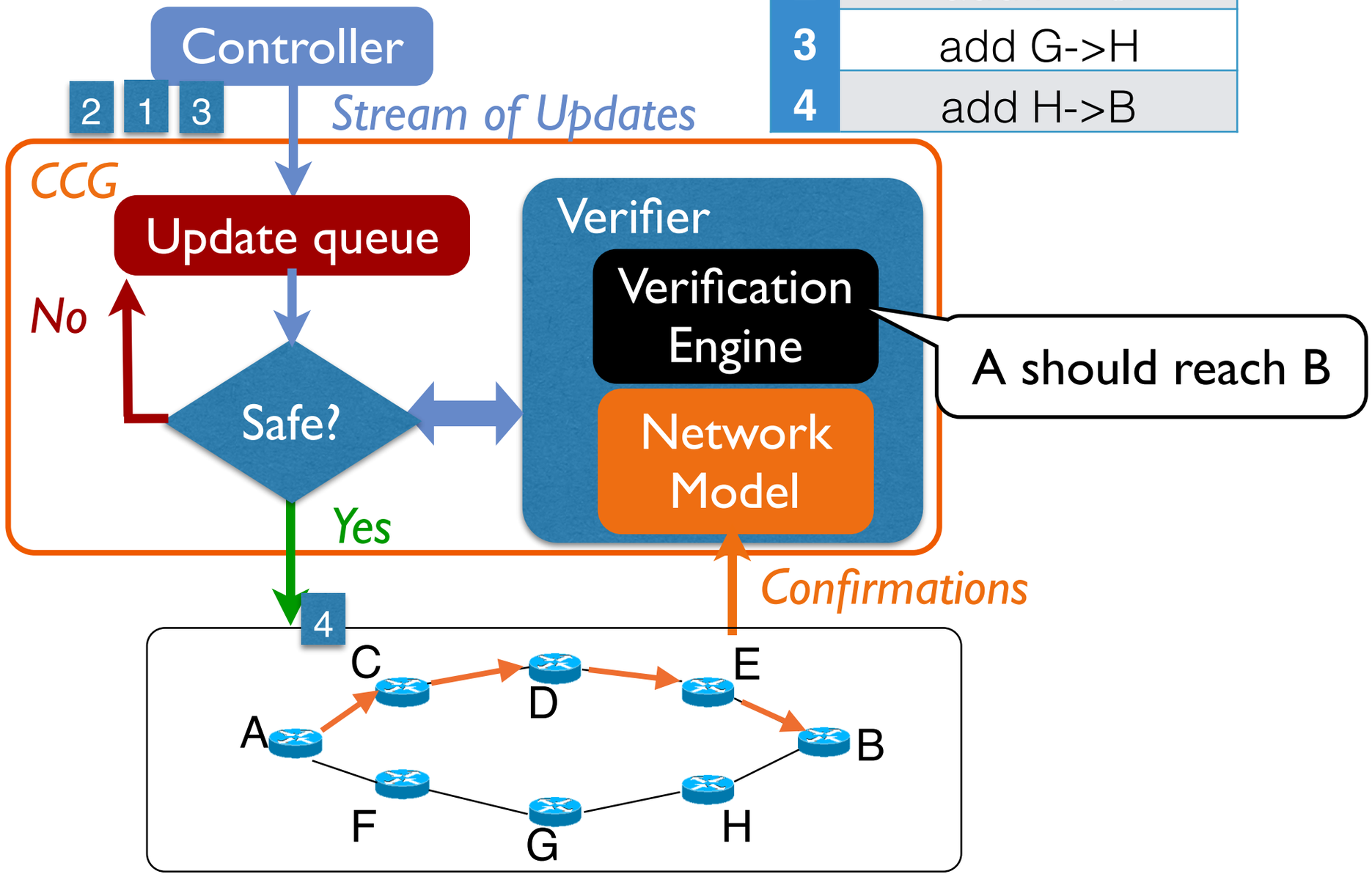

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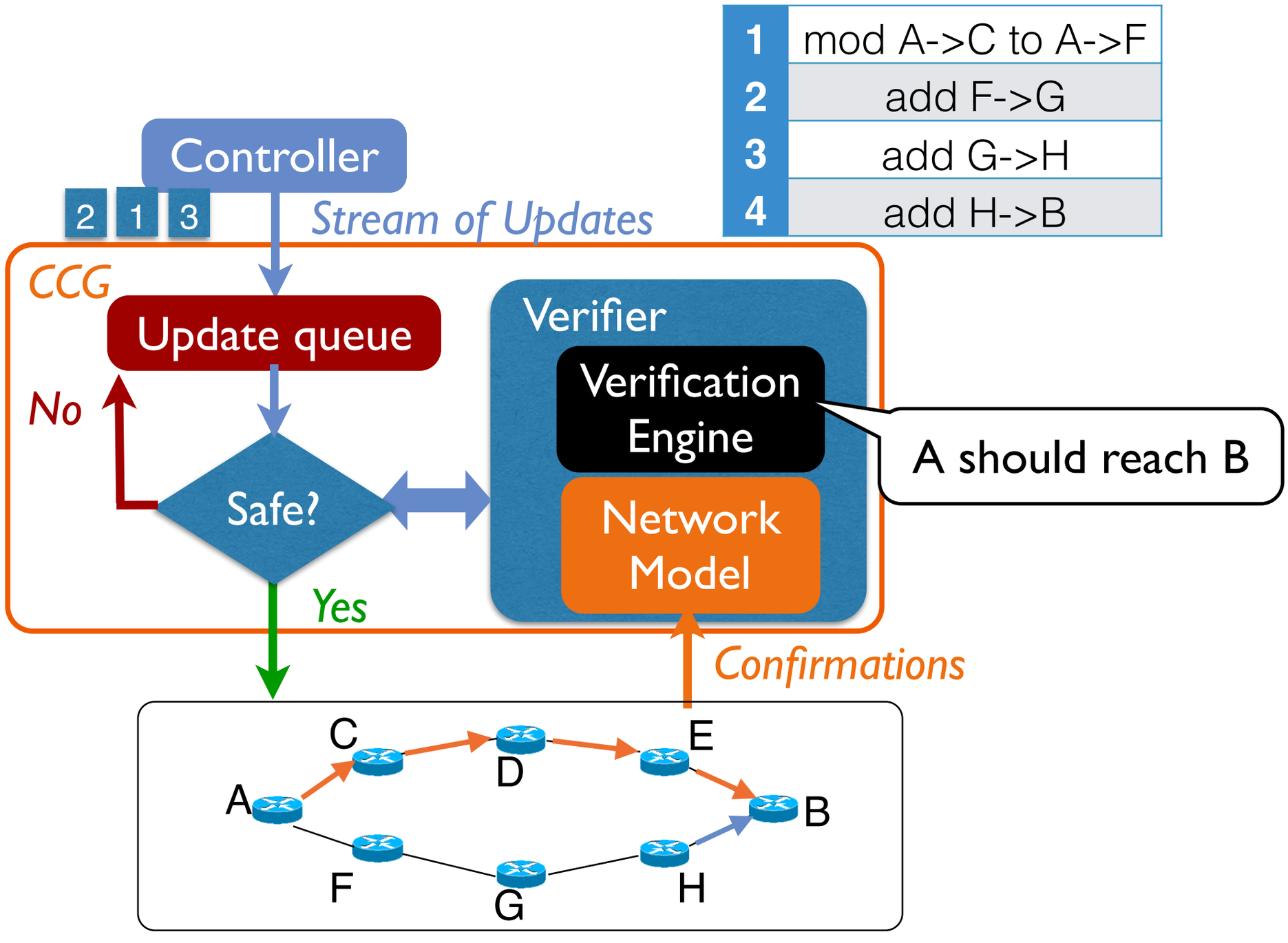

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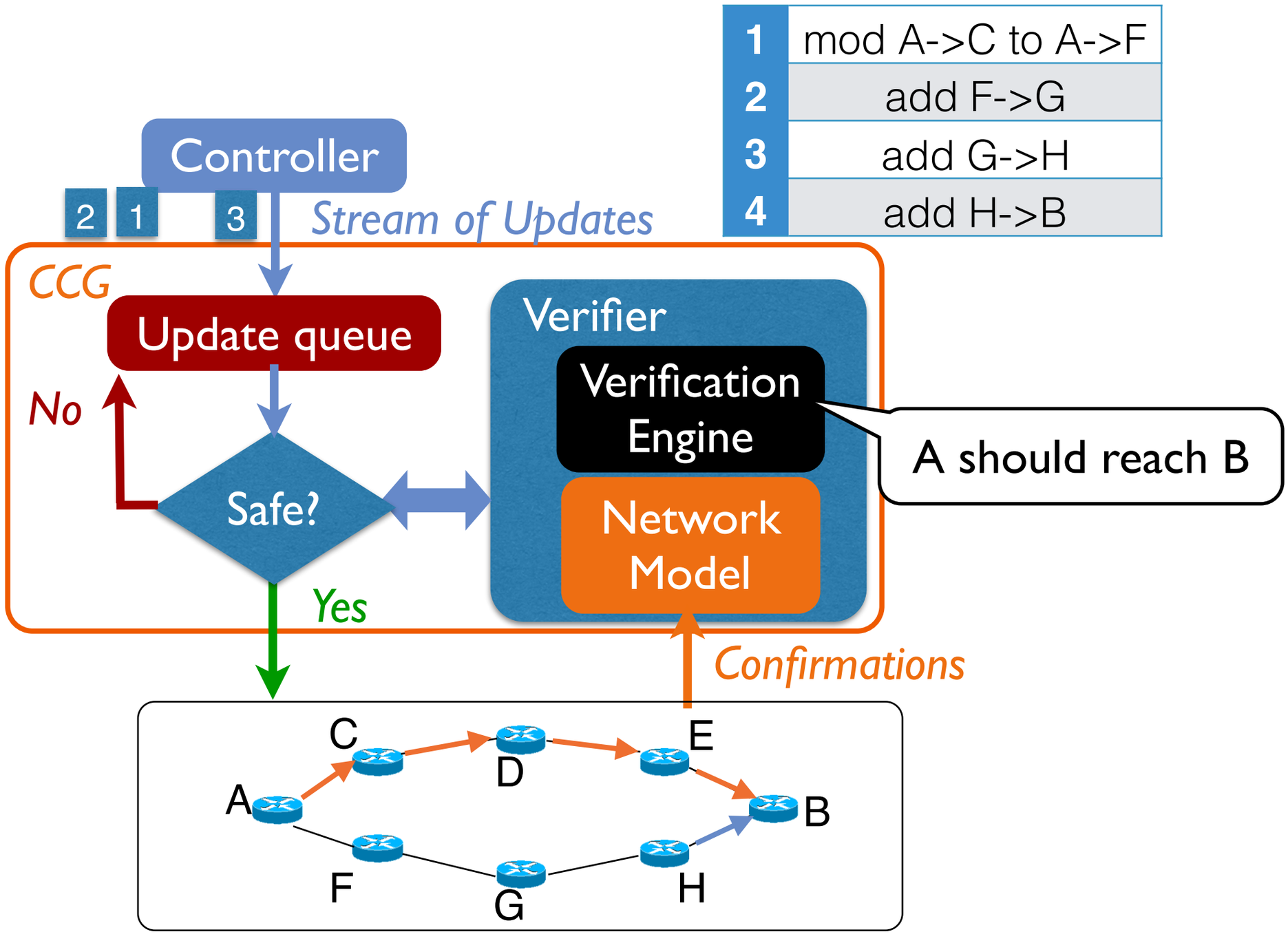

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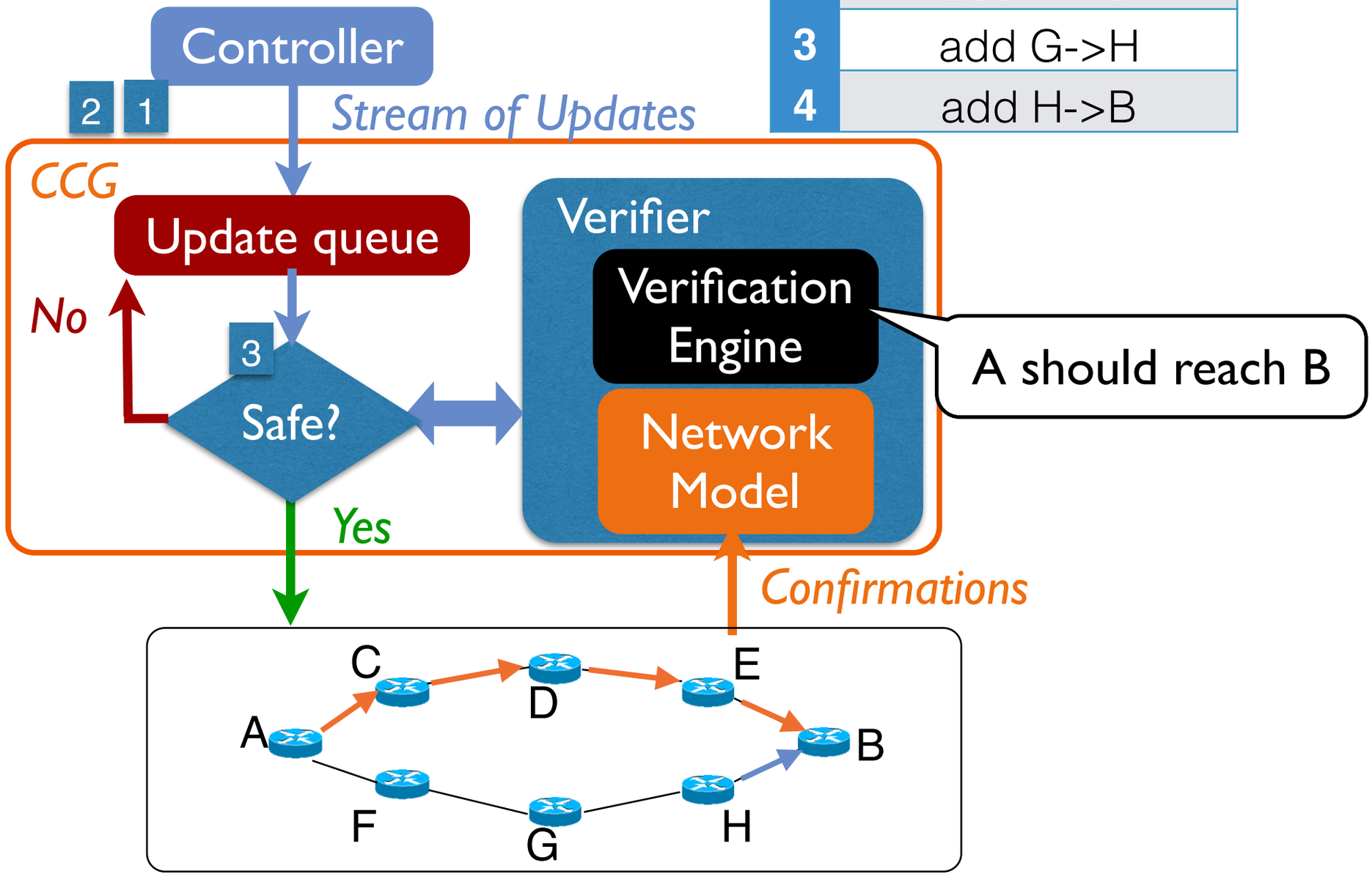

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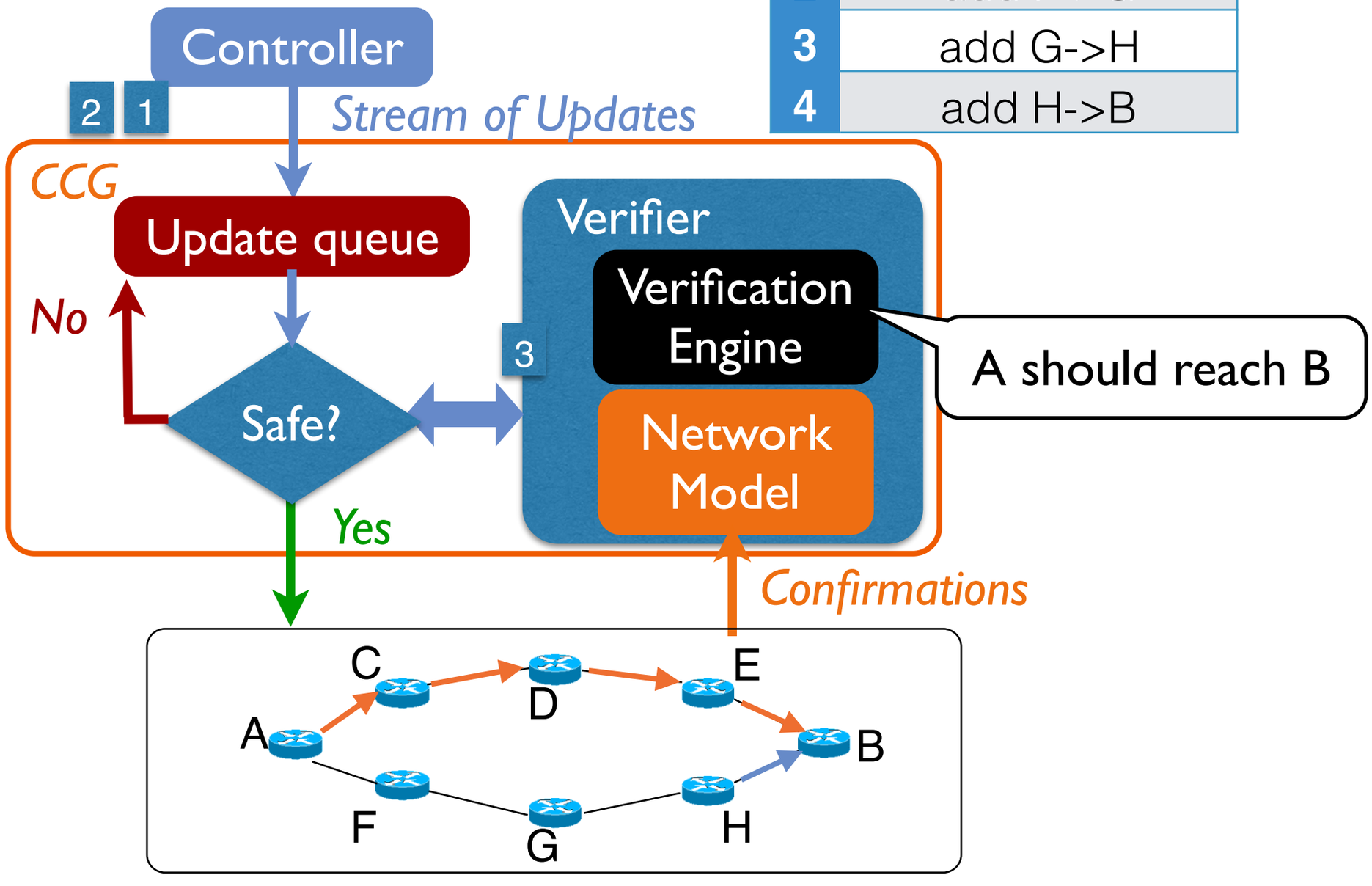

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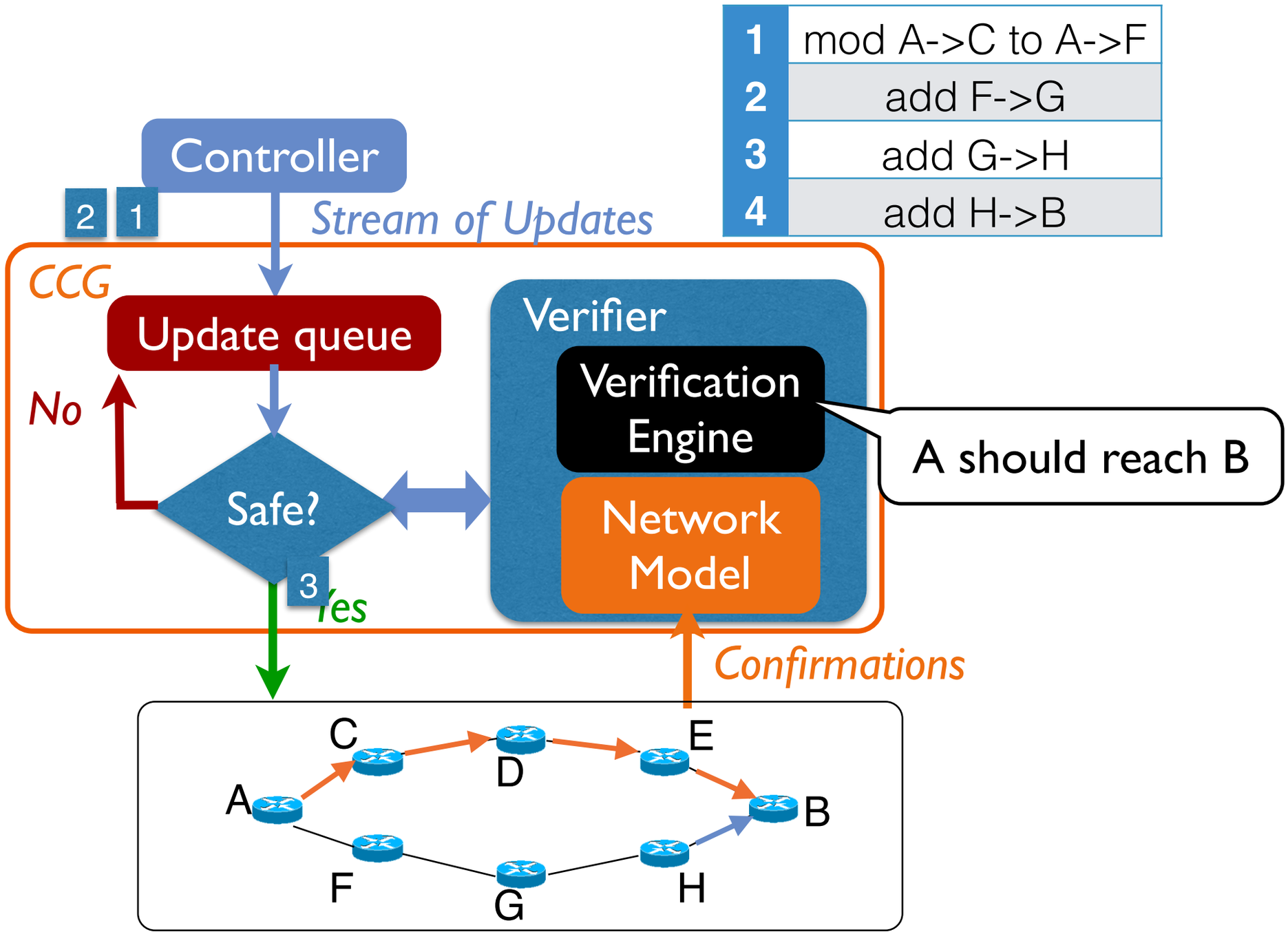

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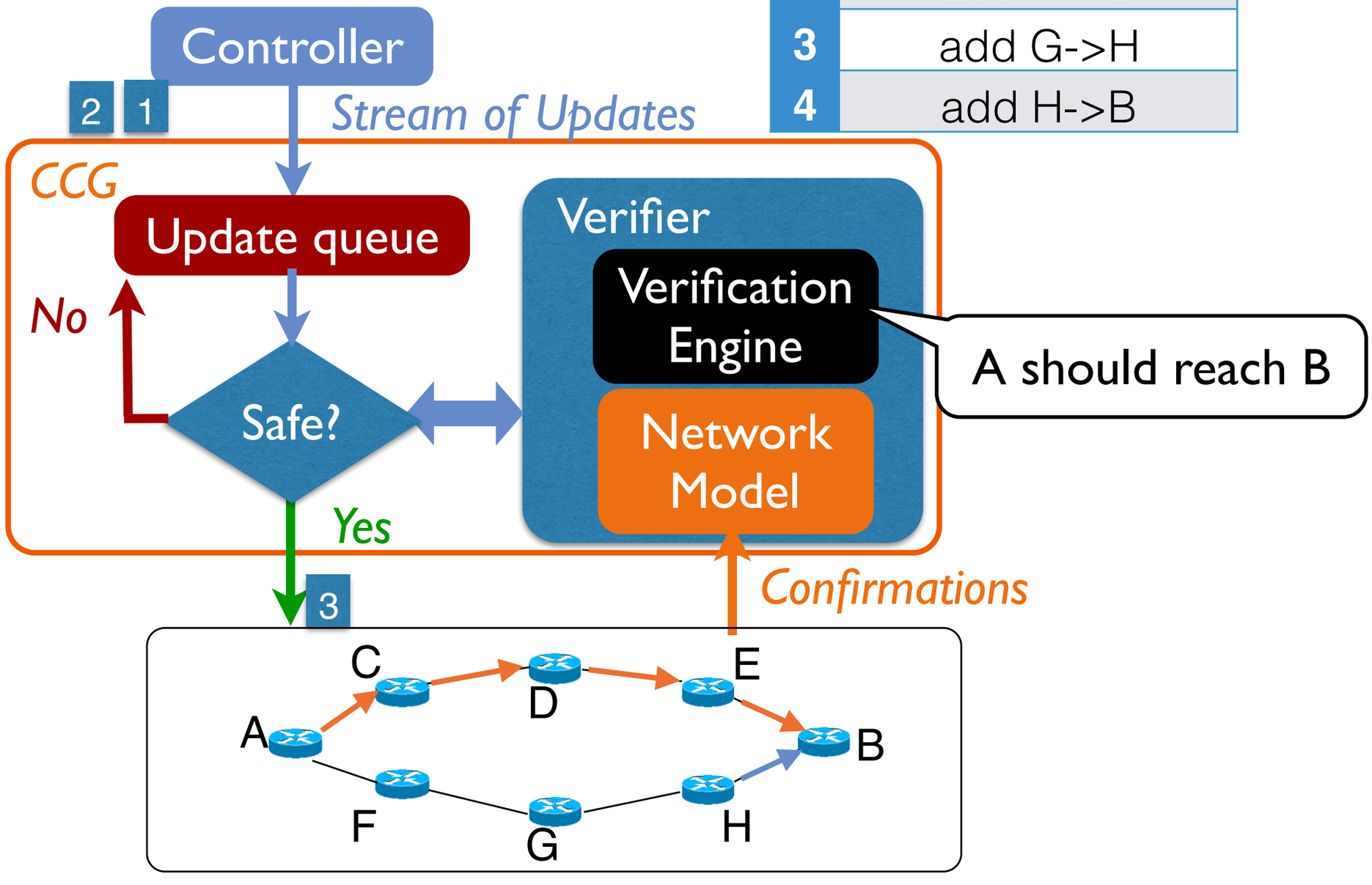

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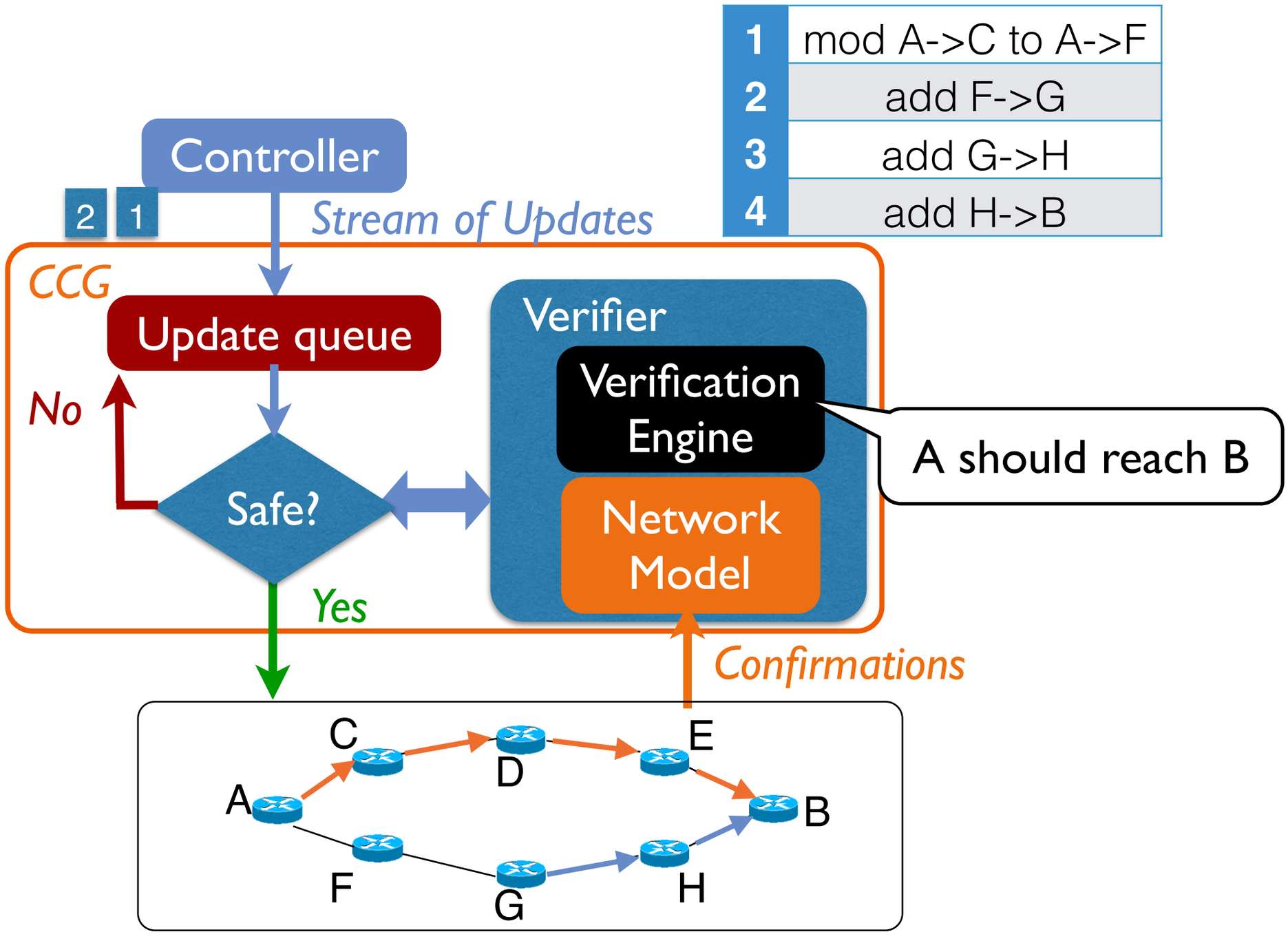

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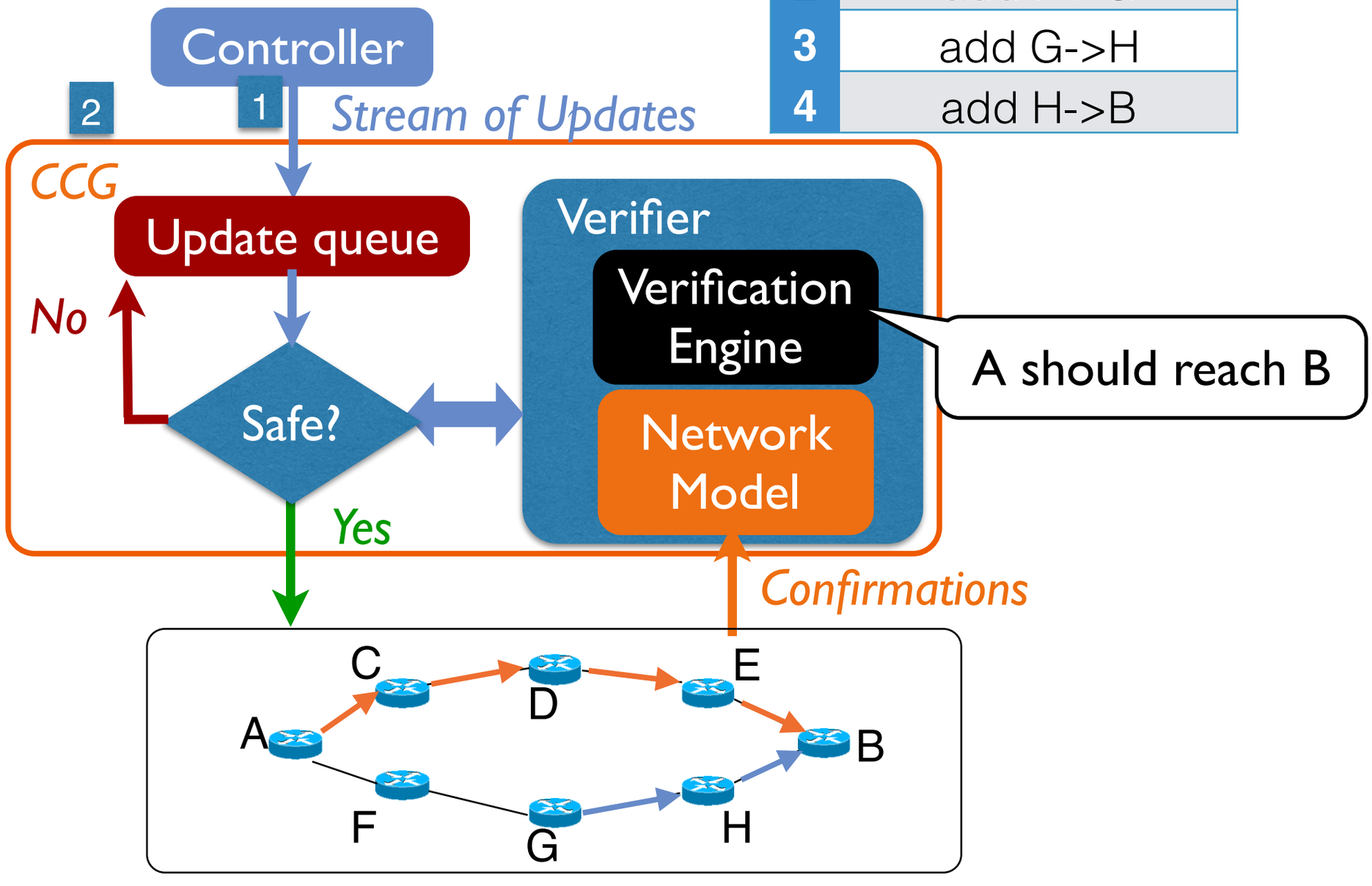

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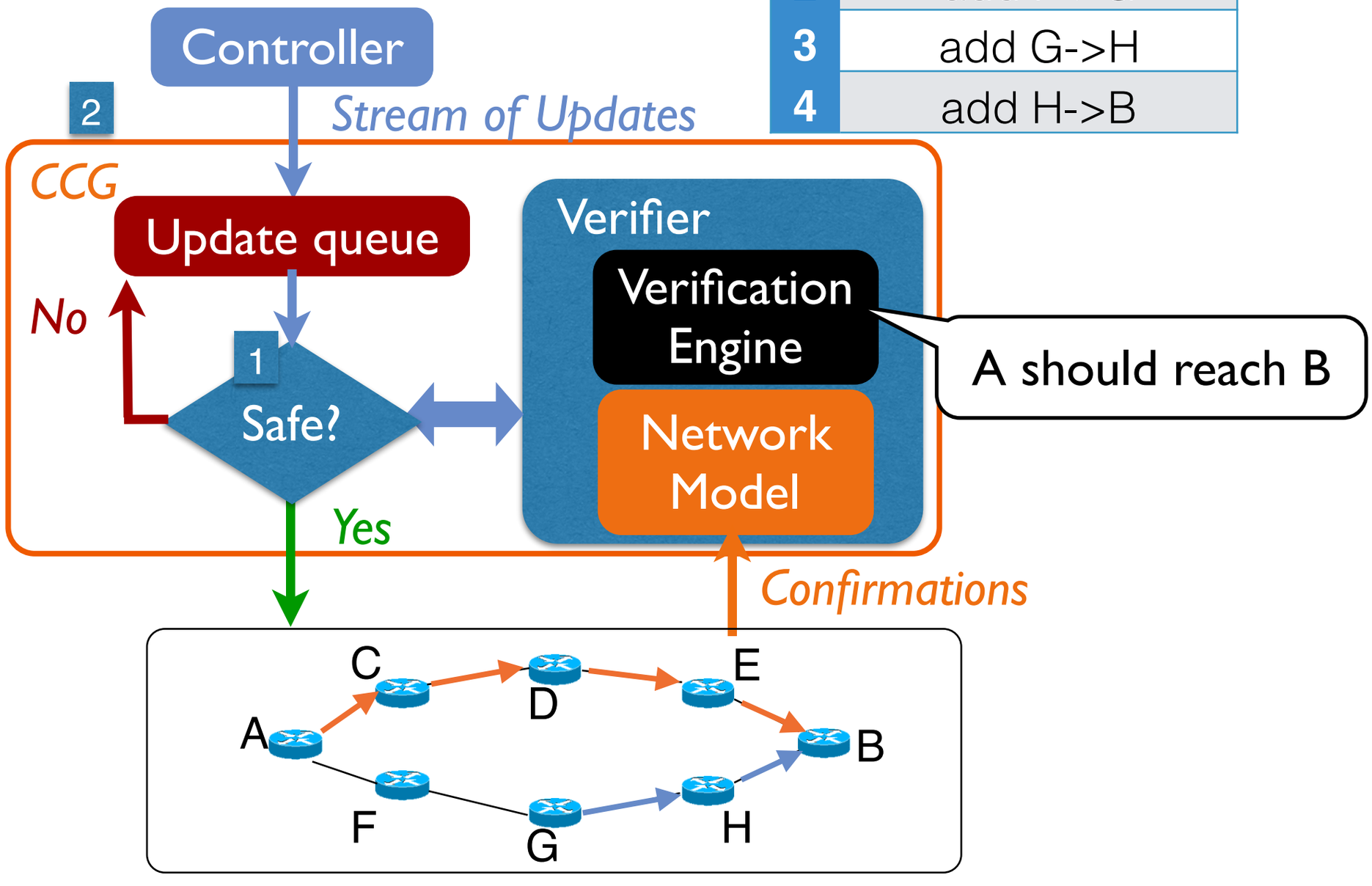

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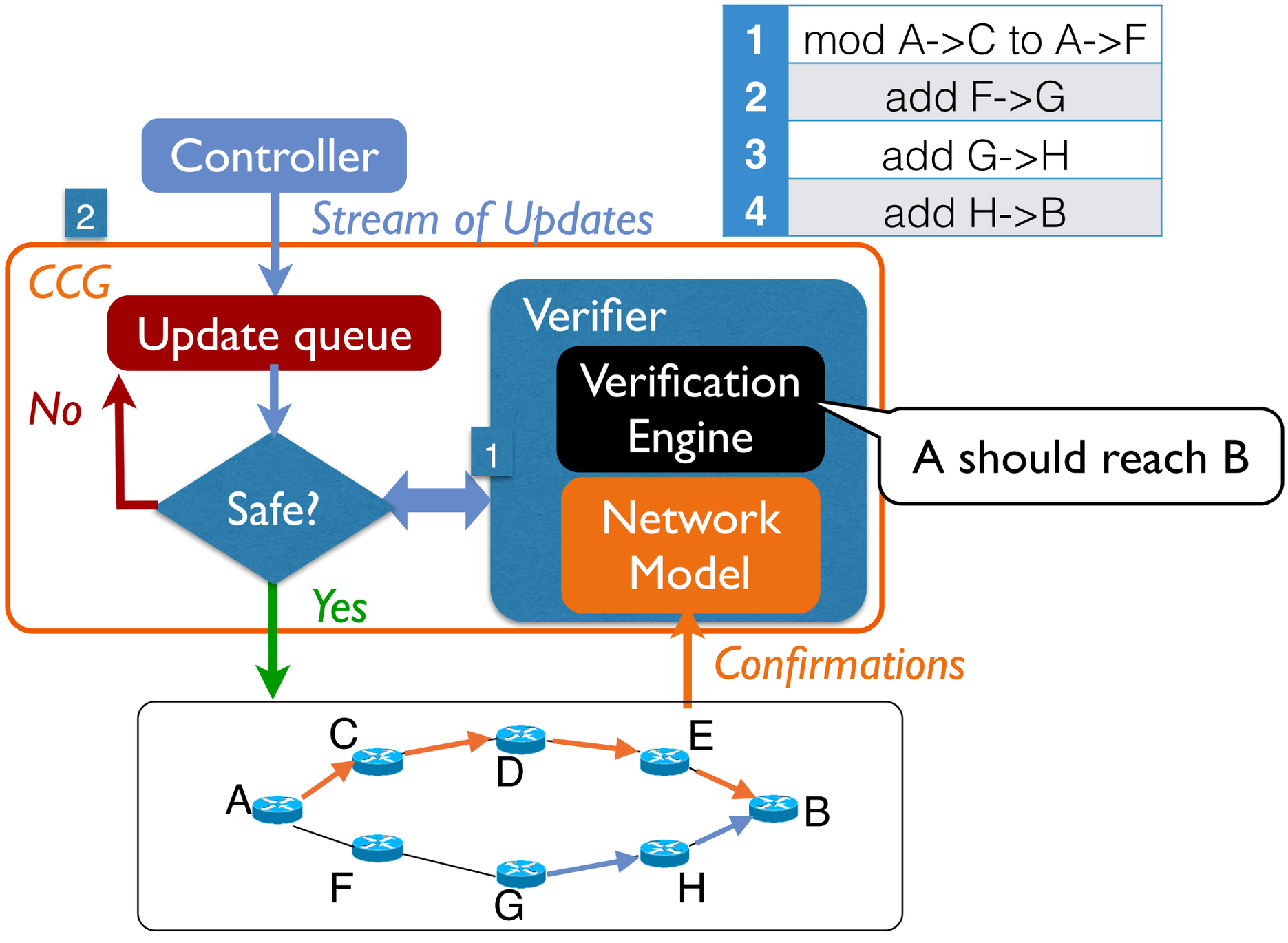

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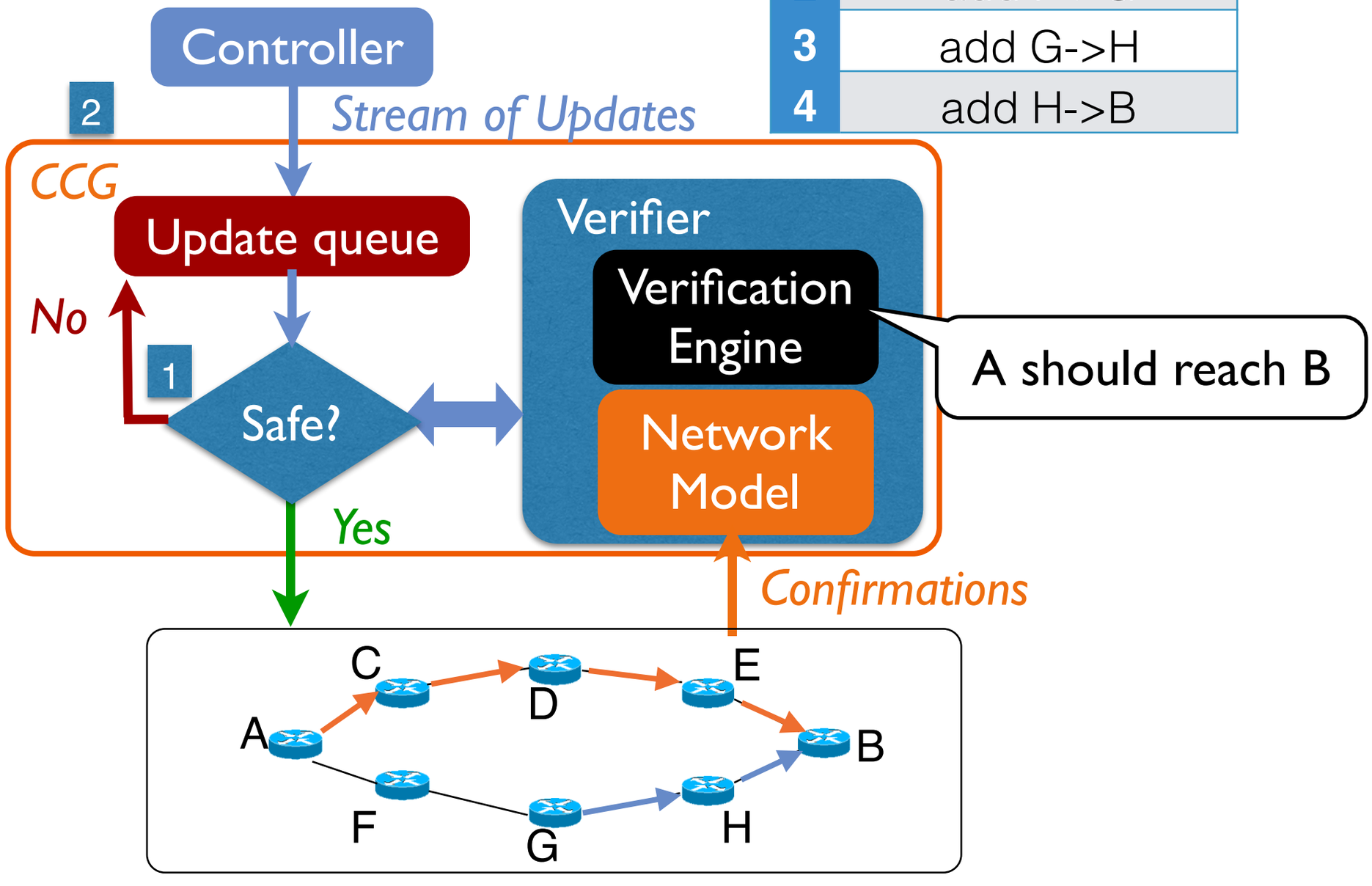

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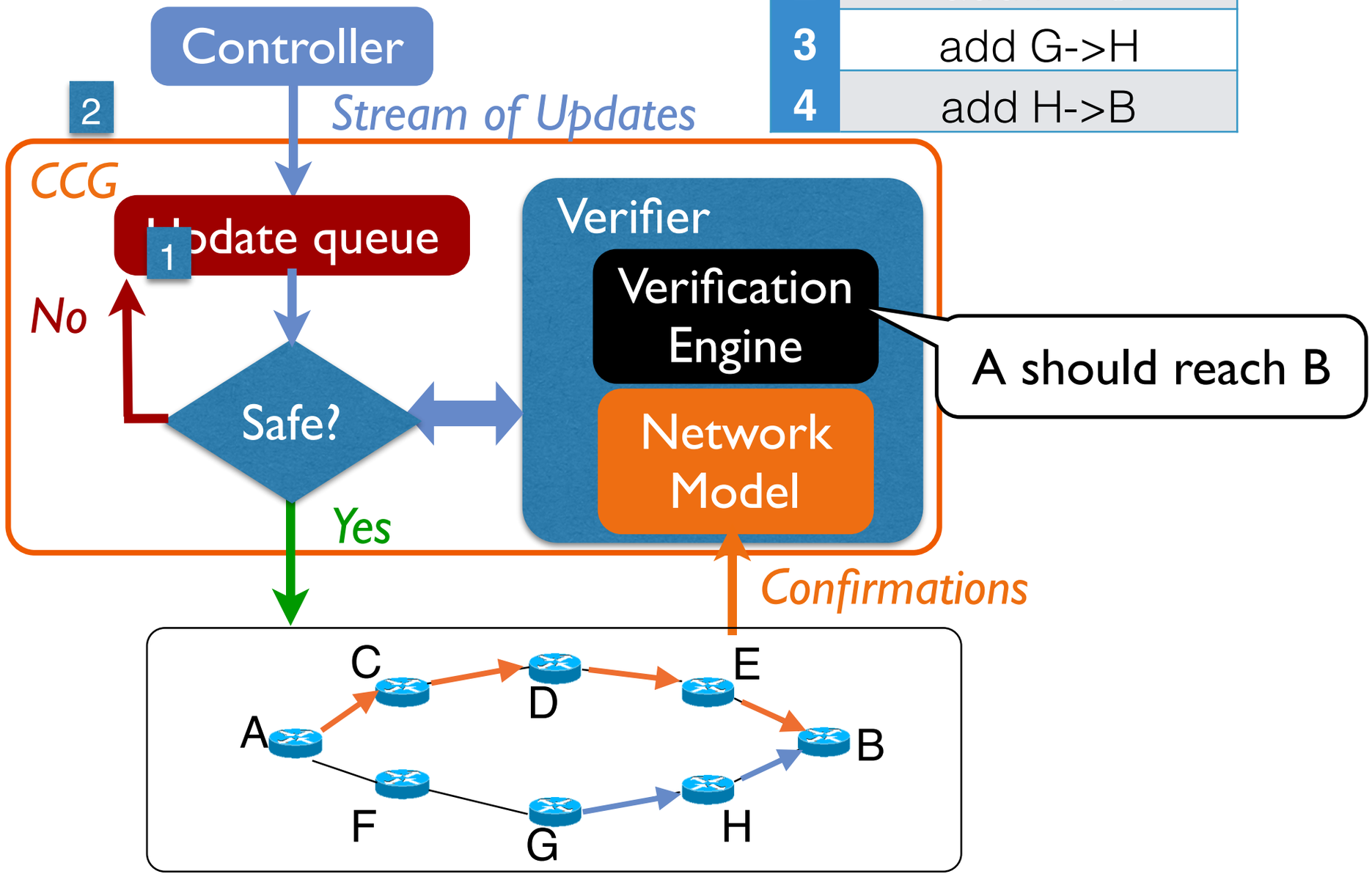

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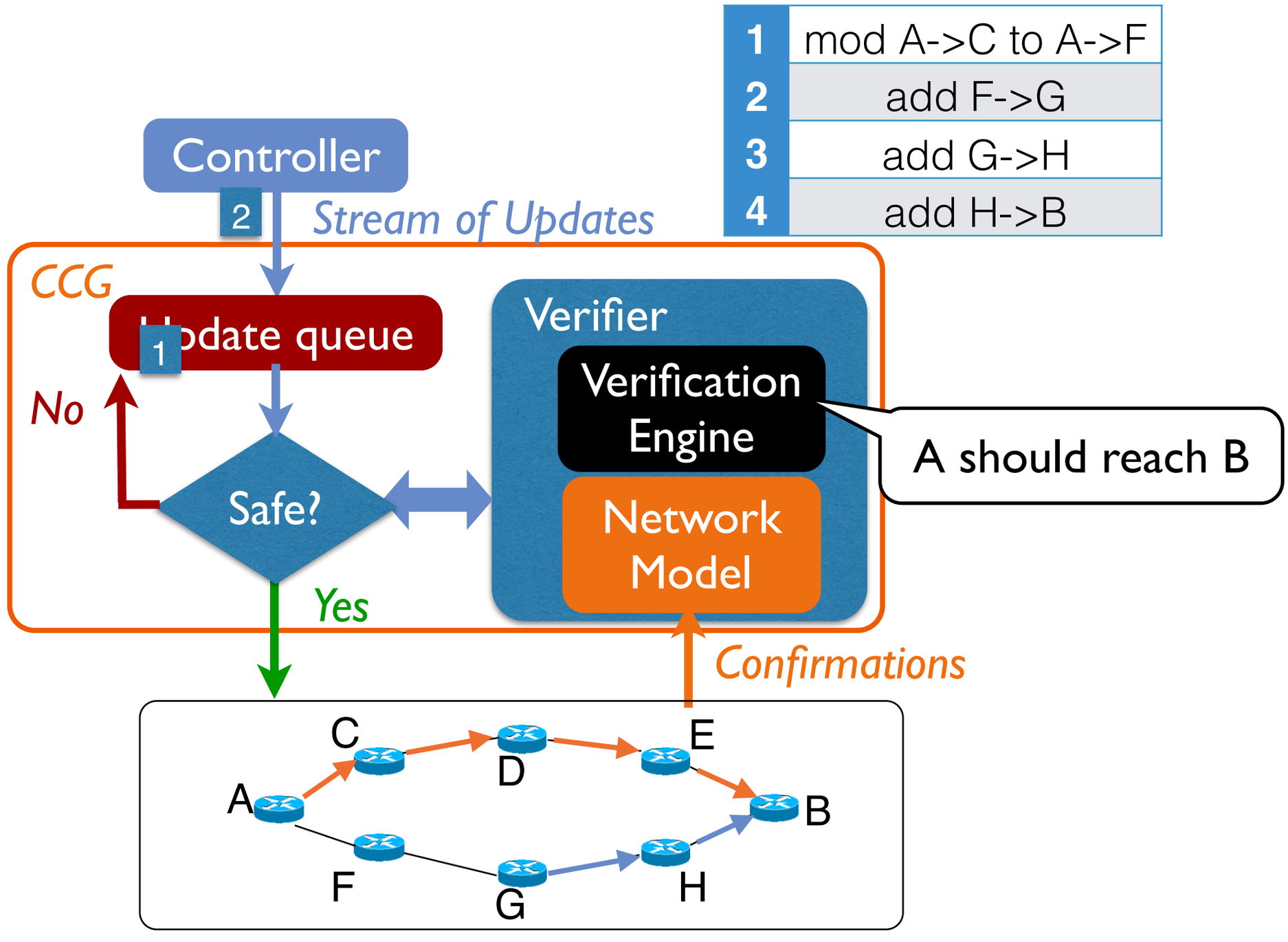

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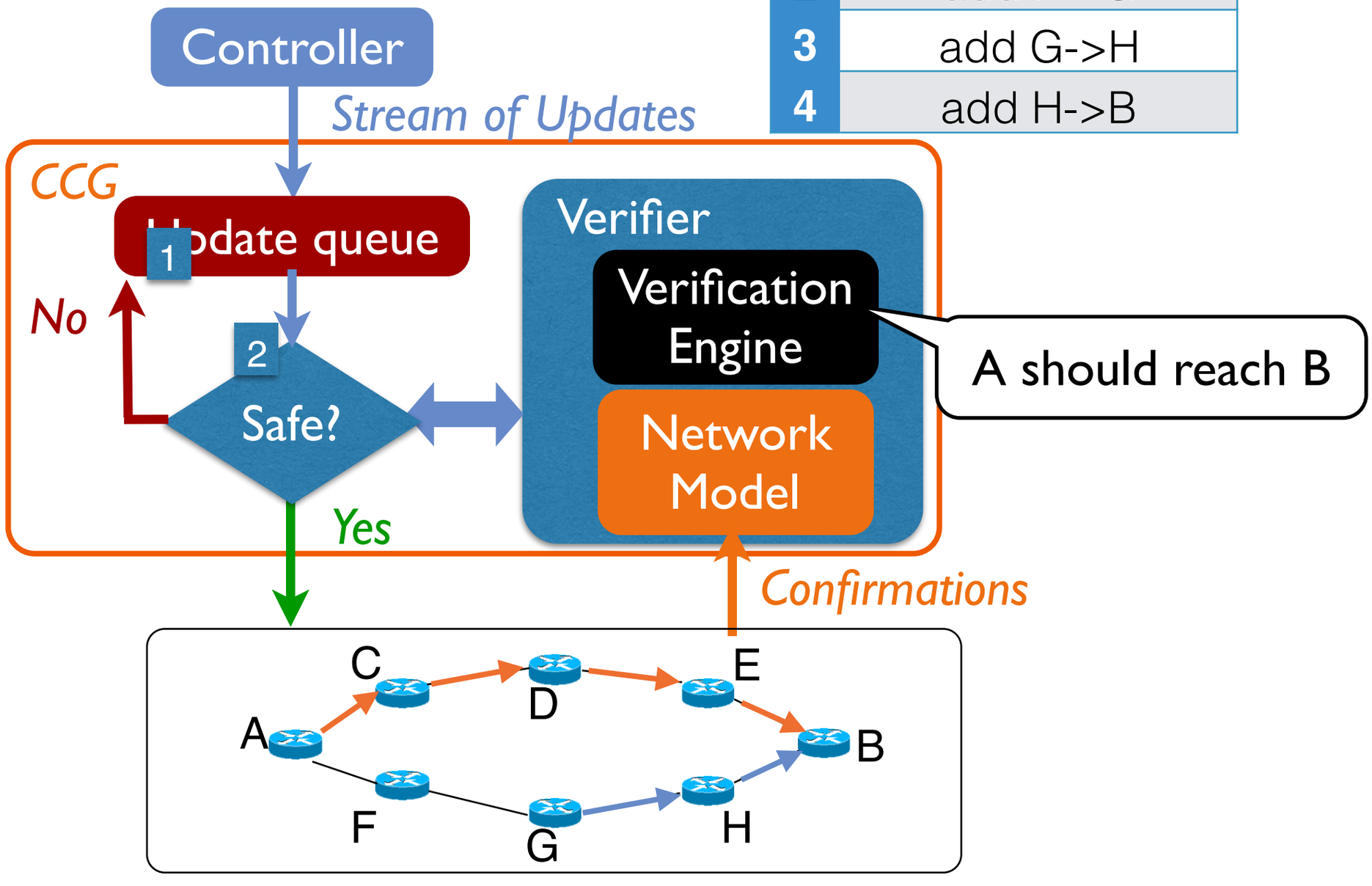

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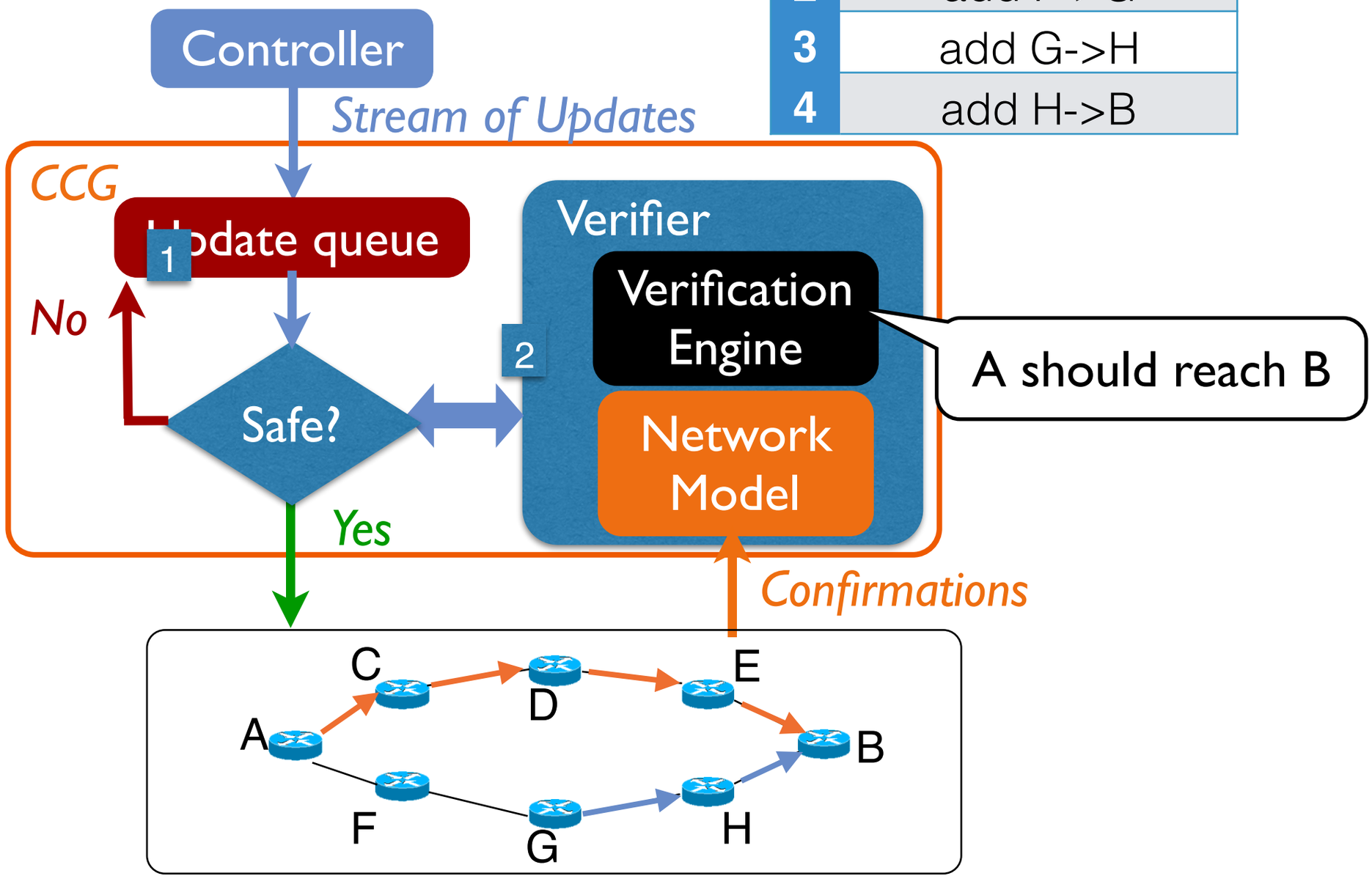

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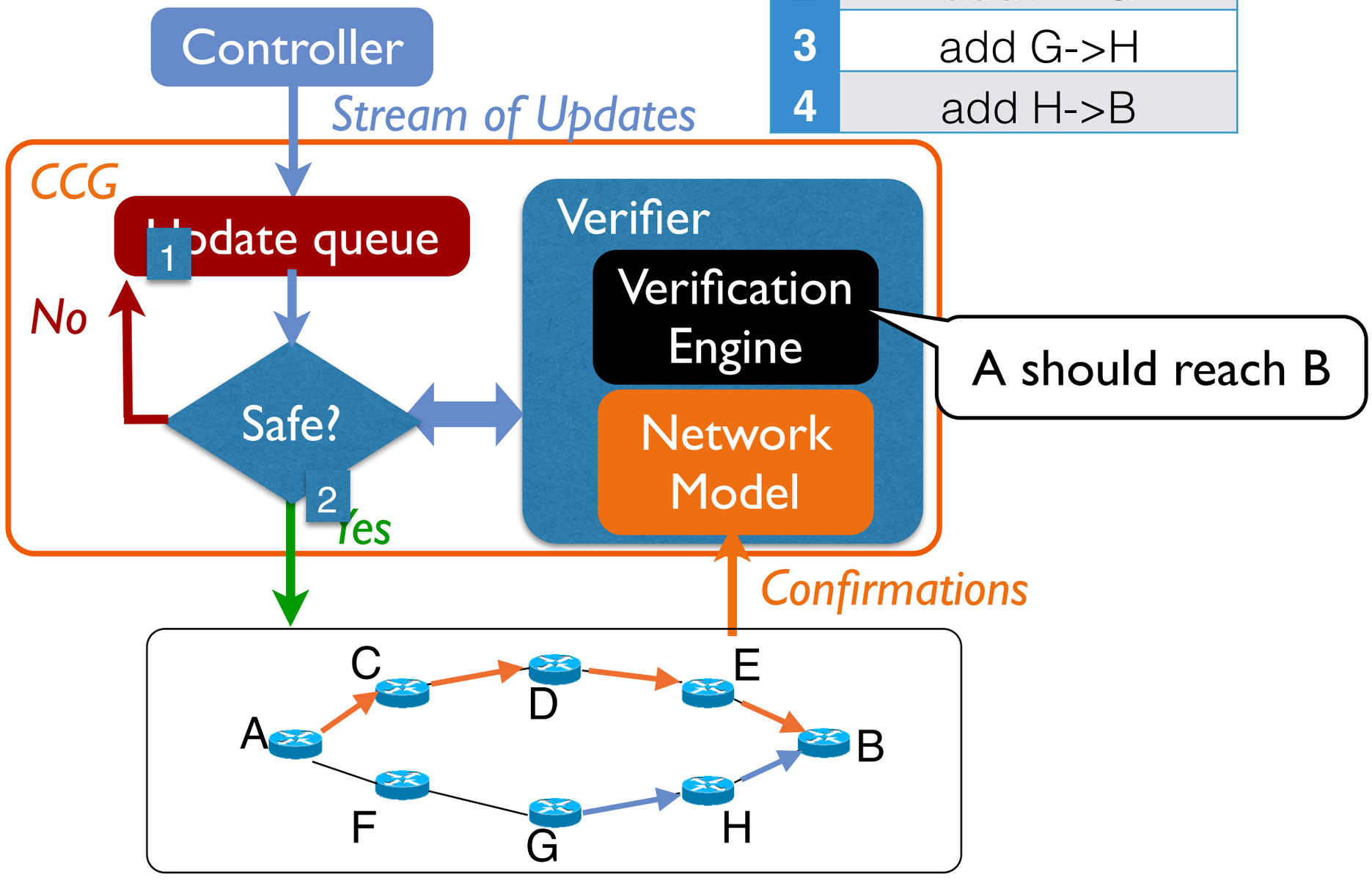

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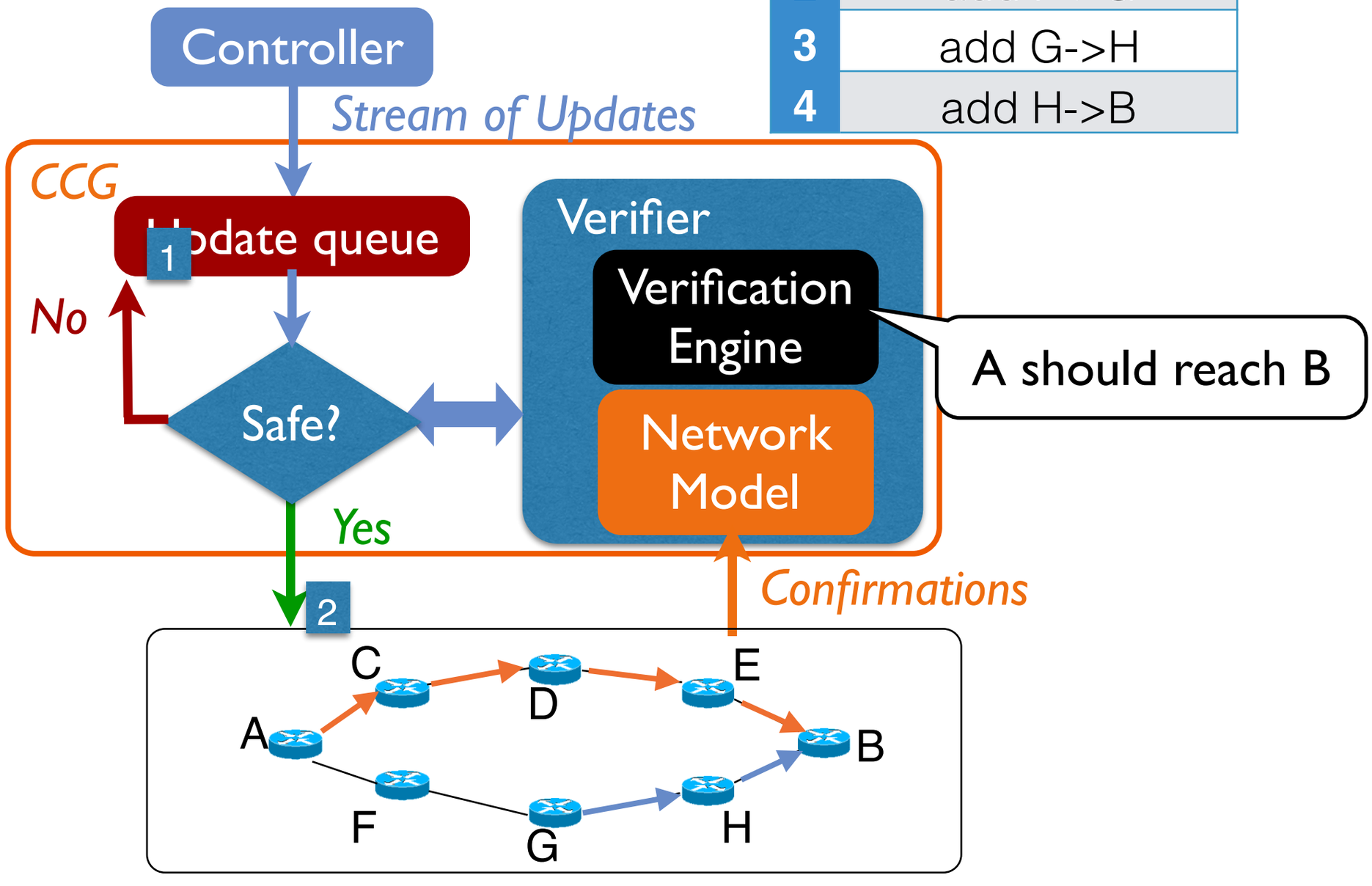

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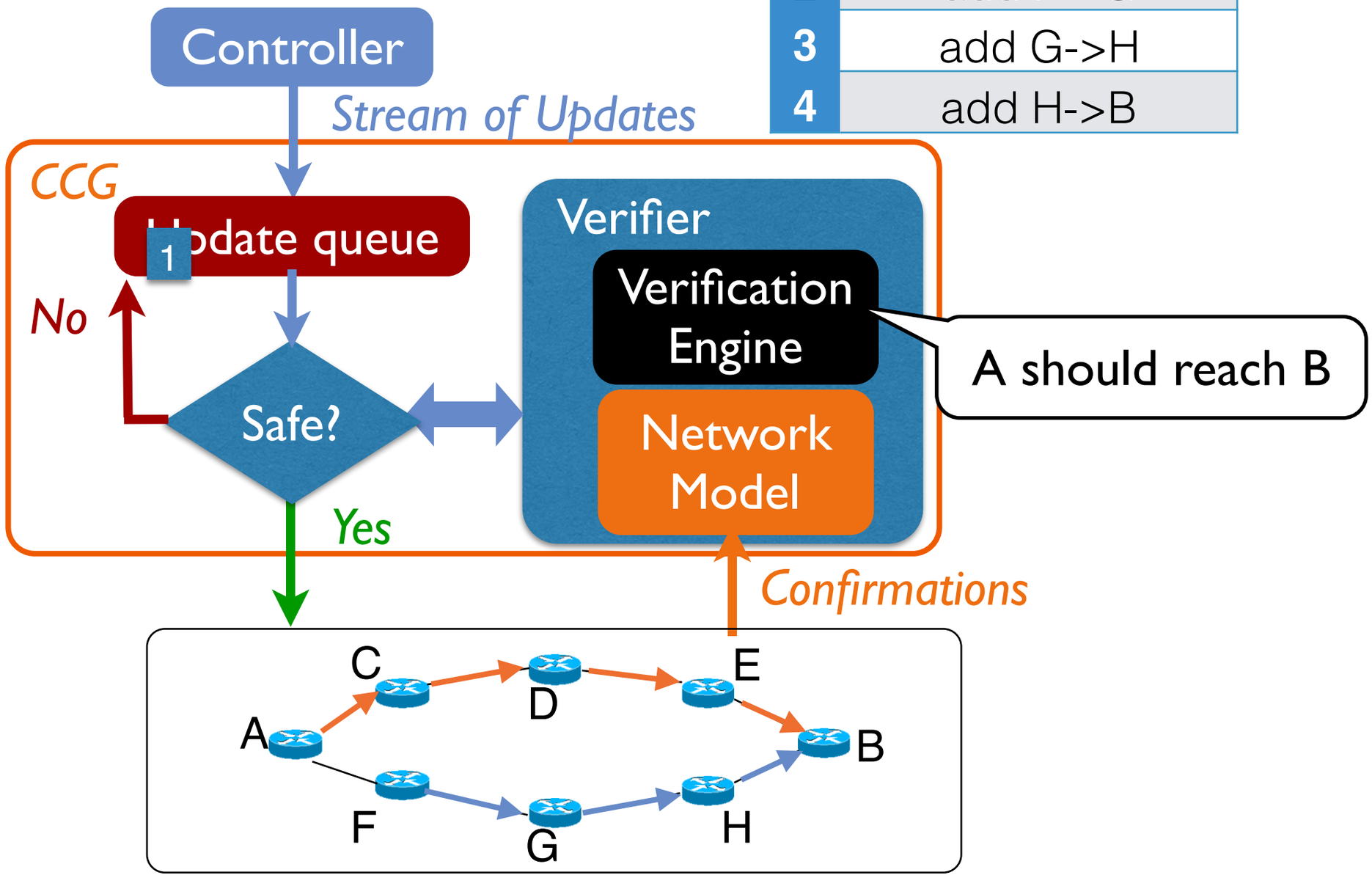

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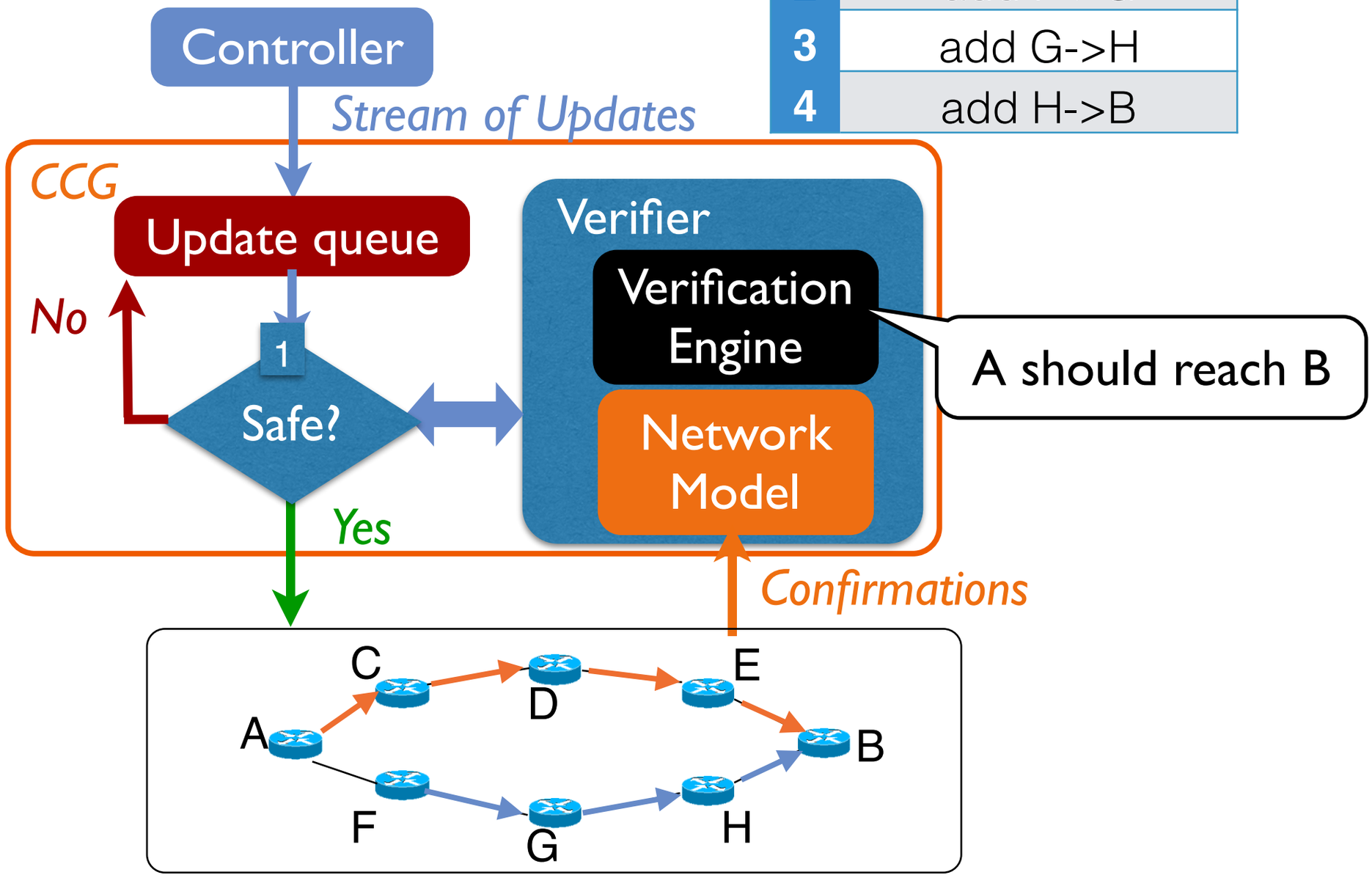

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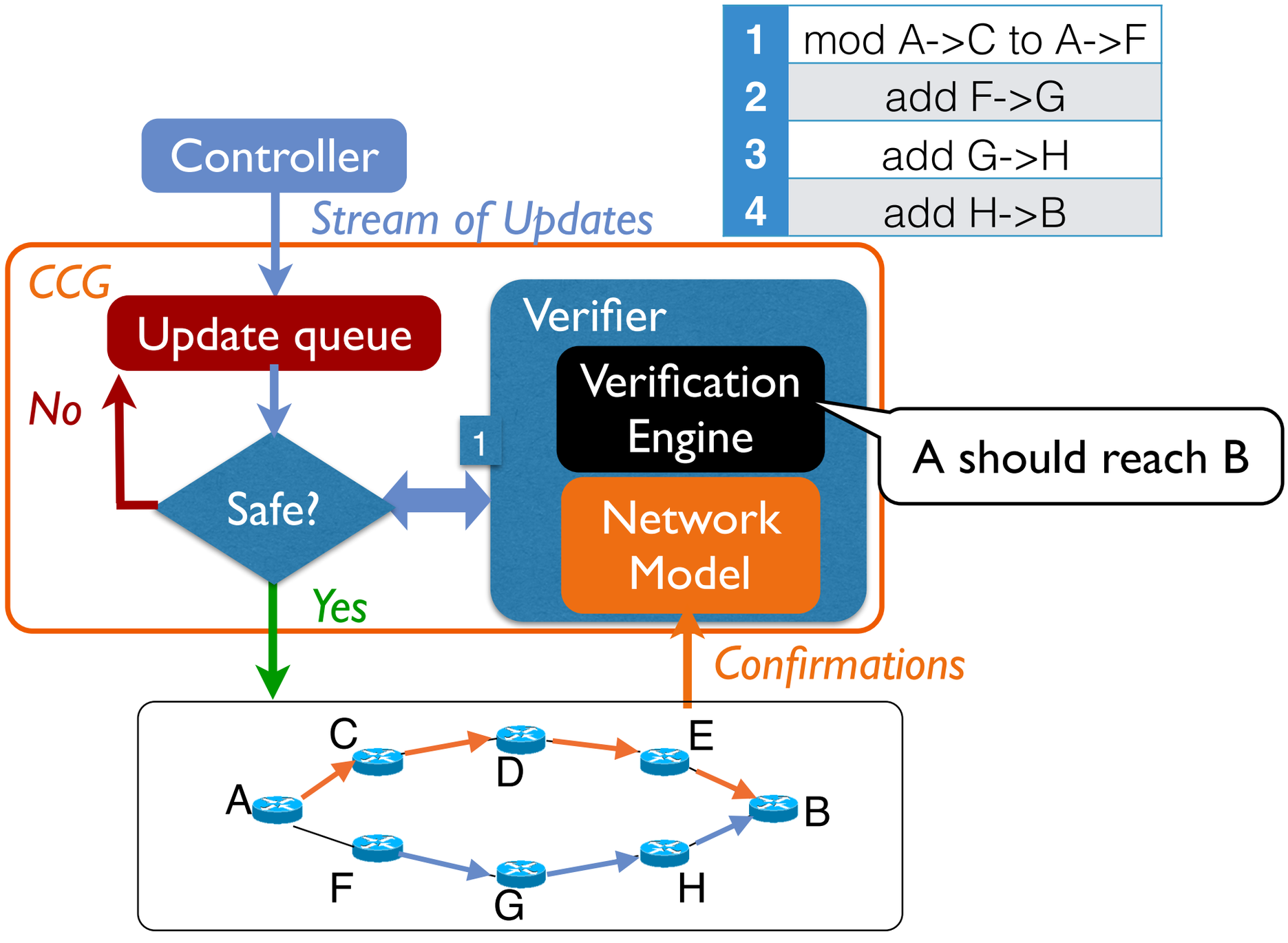

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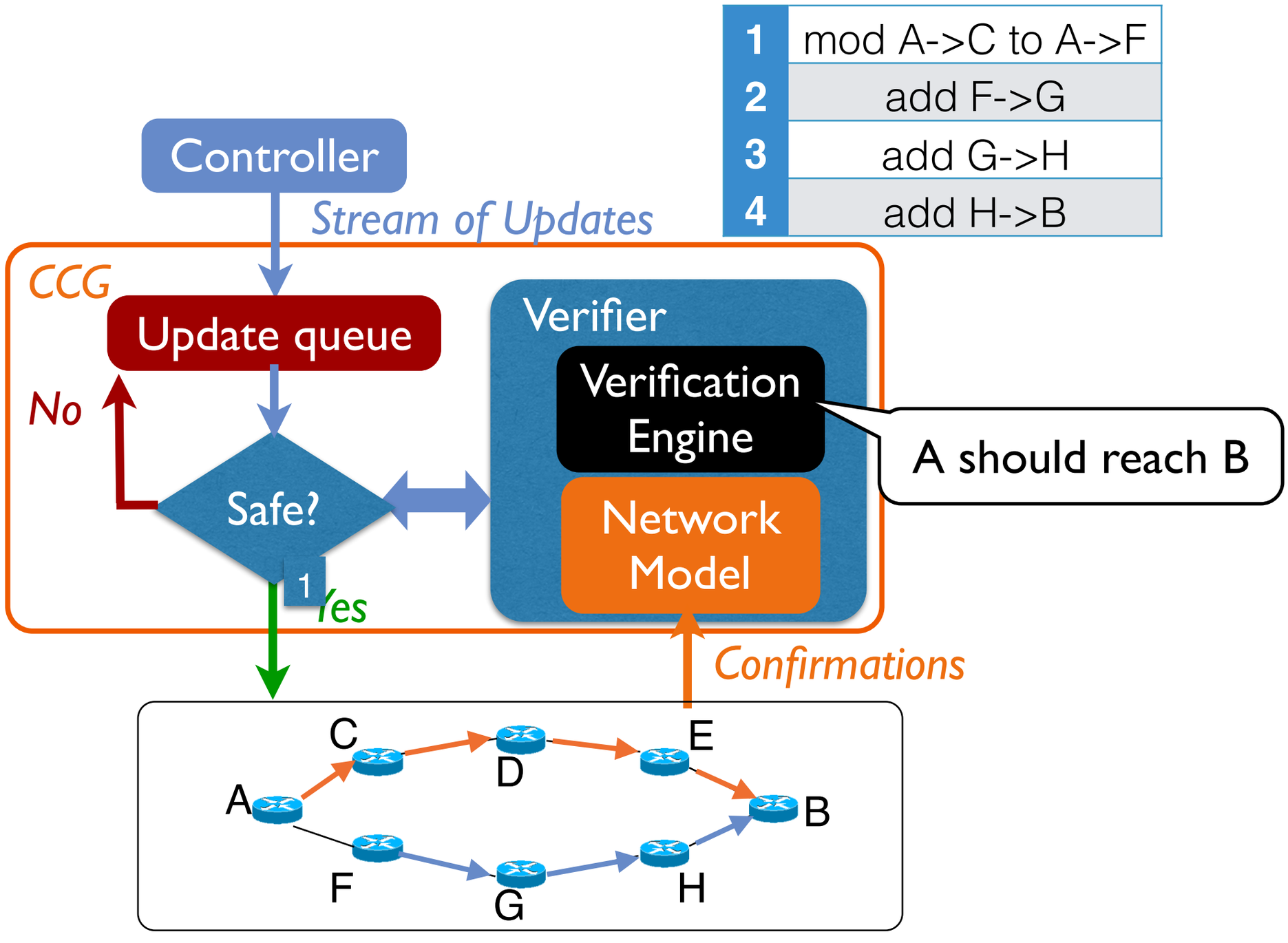

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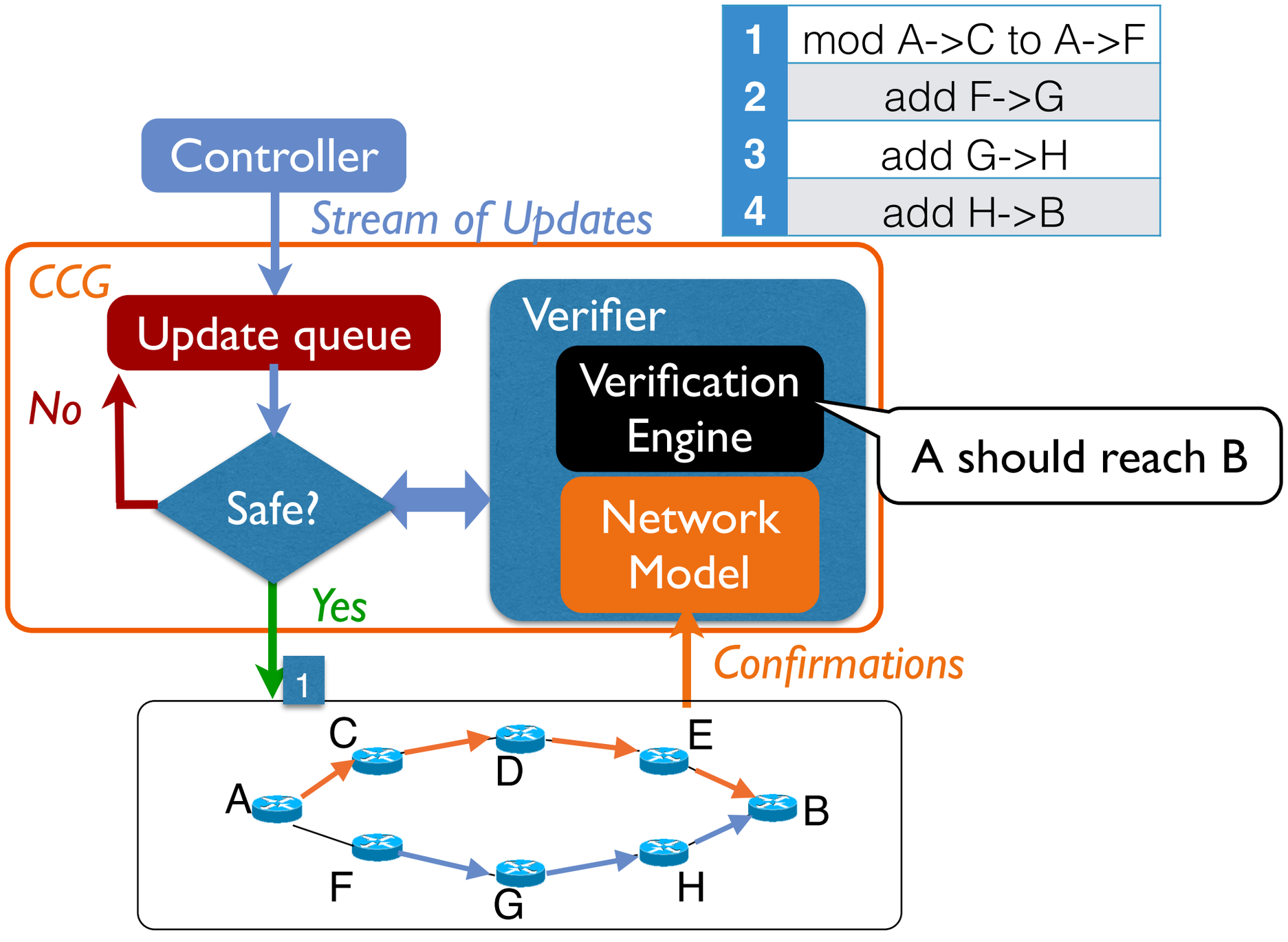

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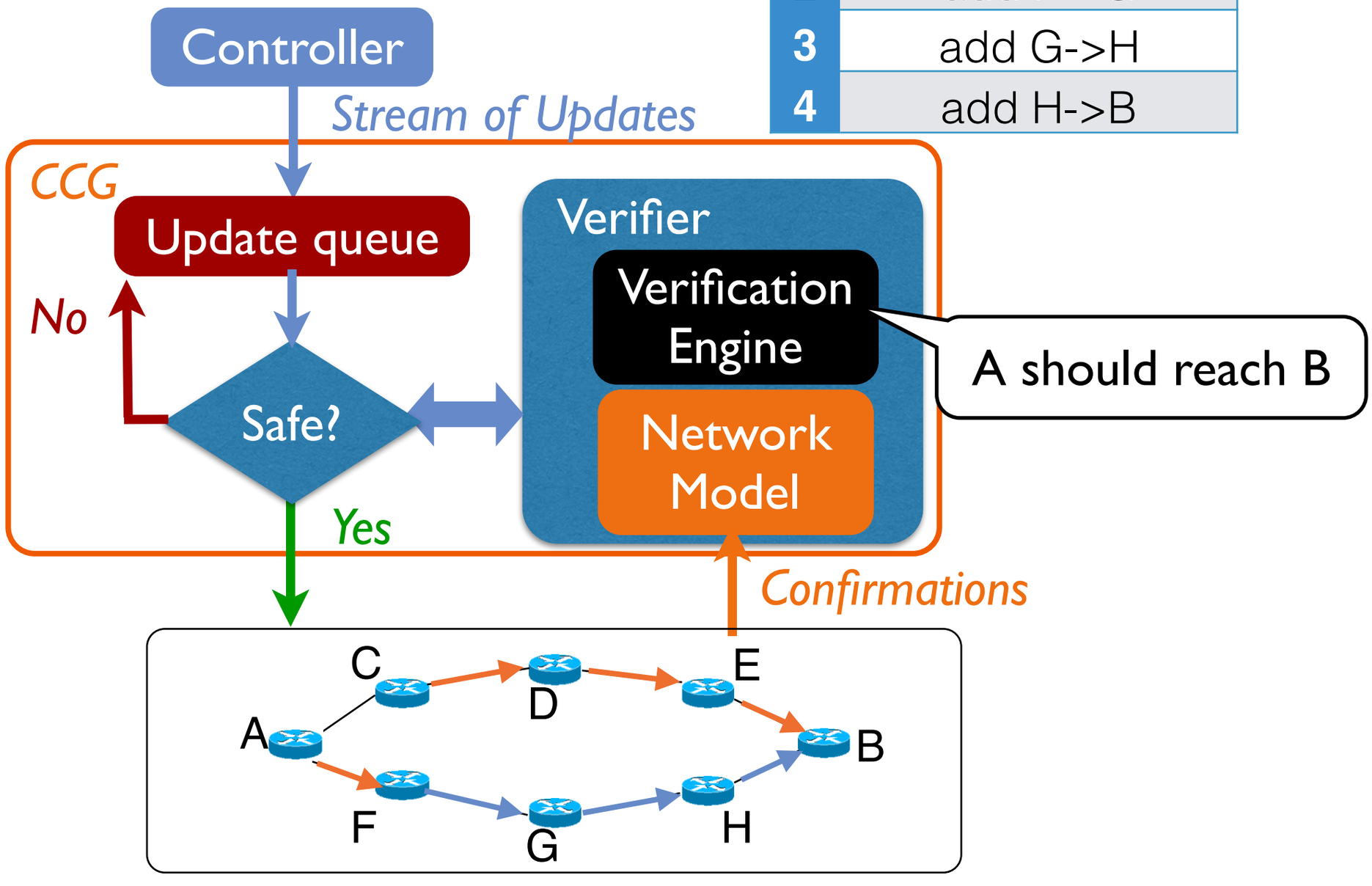

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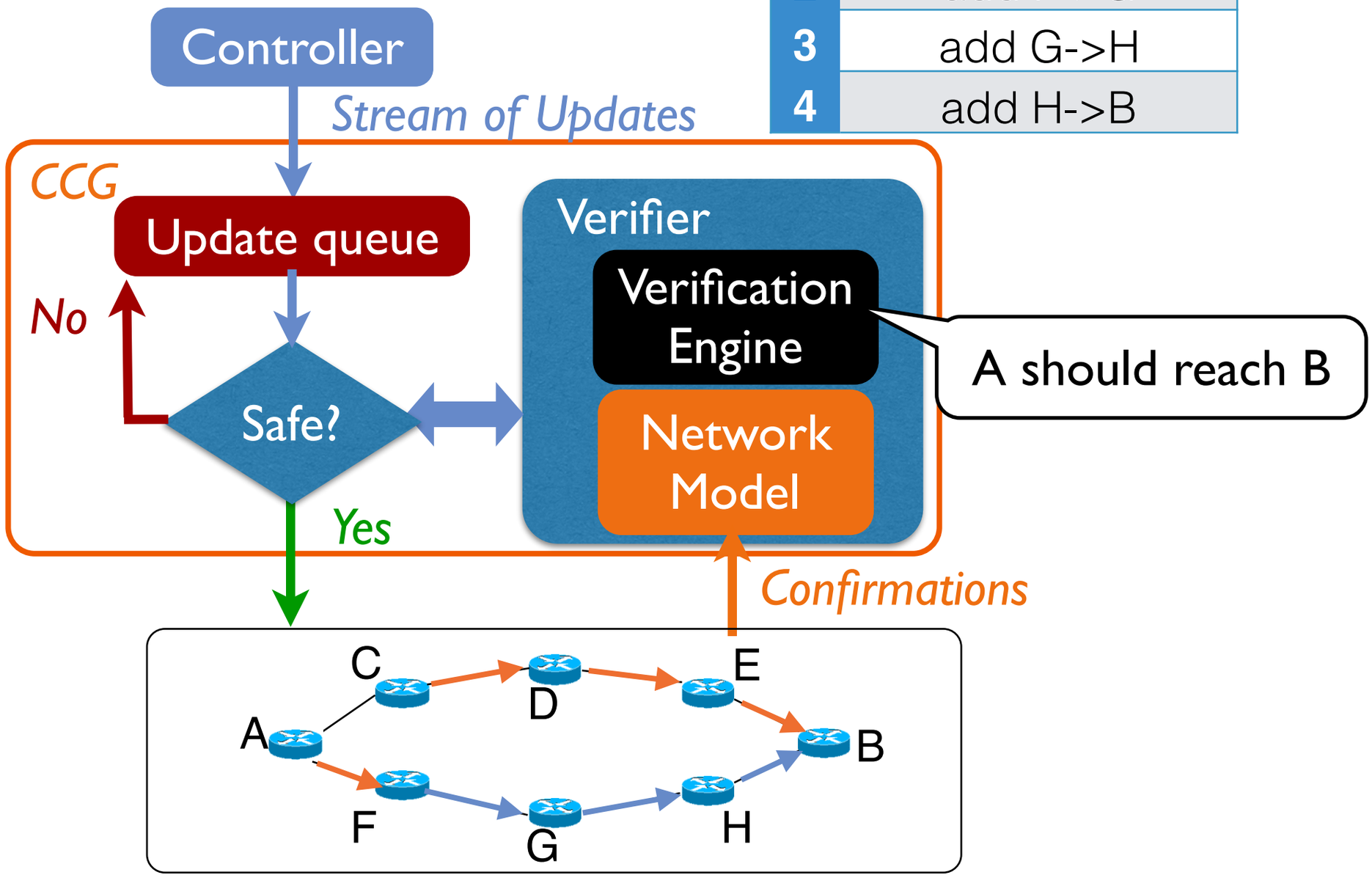

Enforcing dynamic correctness with heuristically maximized parallelism

VERIFICATION IN THE REAL WORLD:

WHAT DID WE LEARN?

Industry efforts

Three startups pursuing general-purpose network verification for enterprises

Special purpose efforts

- Hyperscale clouds
- Major network device manufacturer

Gartner grouping verification in “intent-based networking” category

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What have we learned?

VERIFLOW

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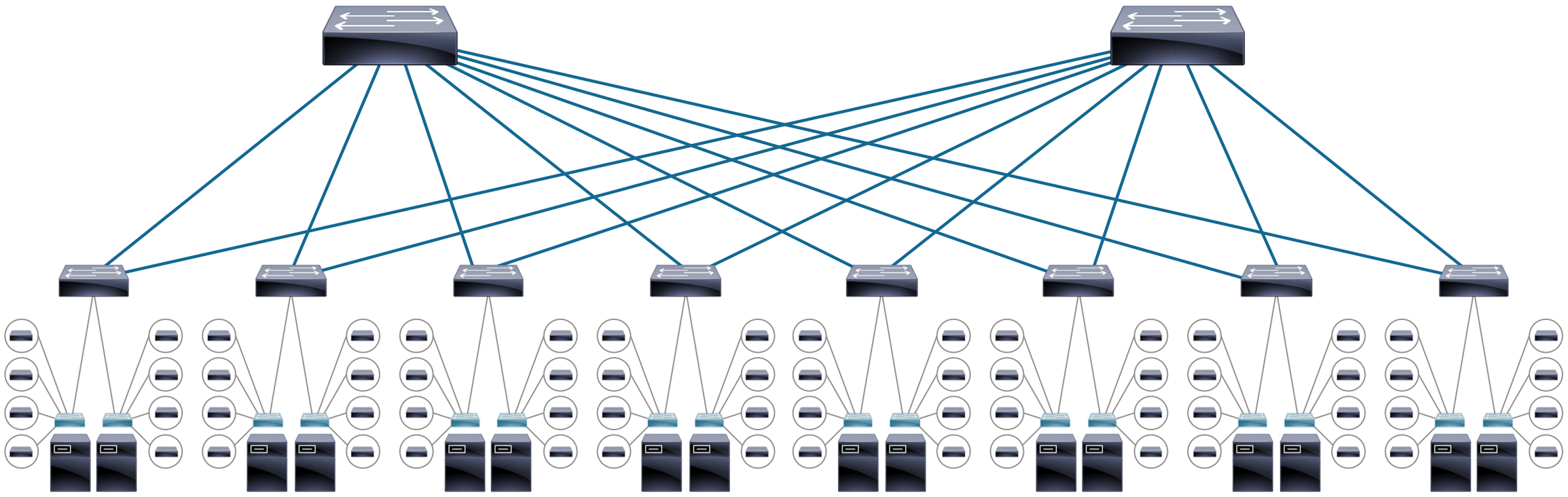

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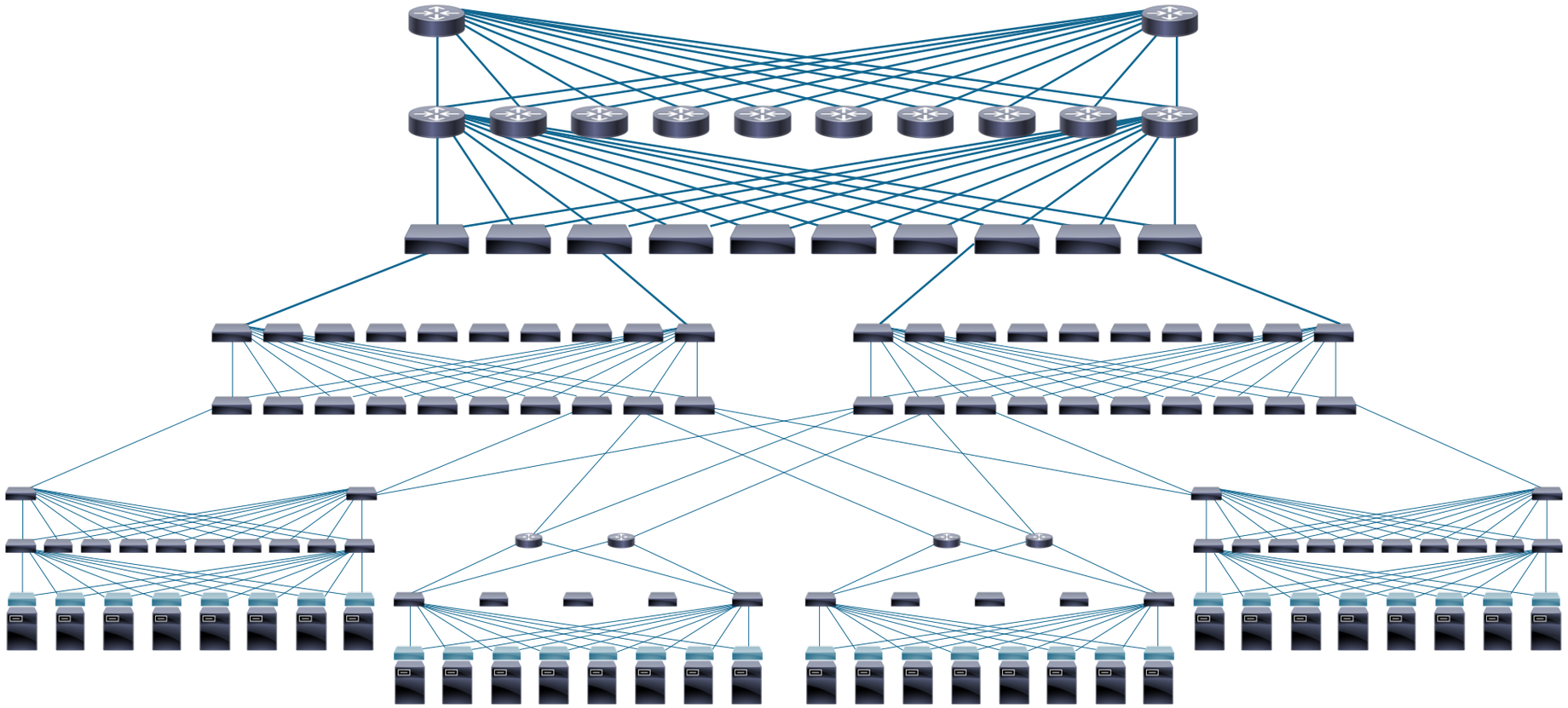

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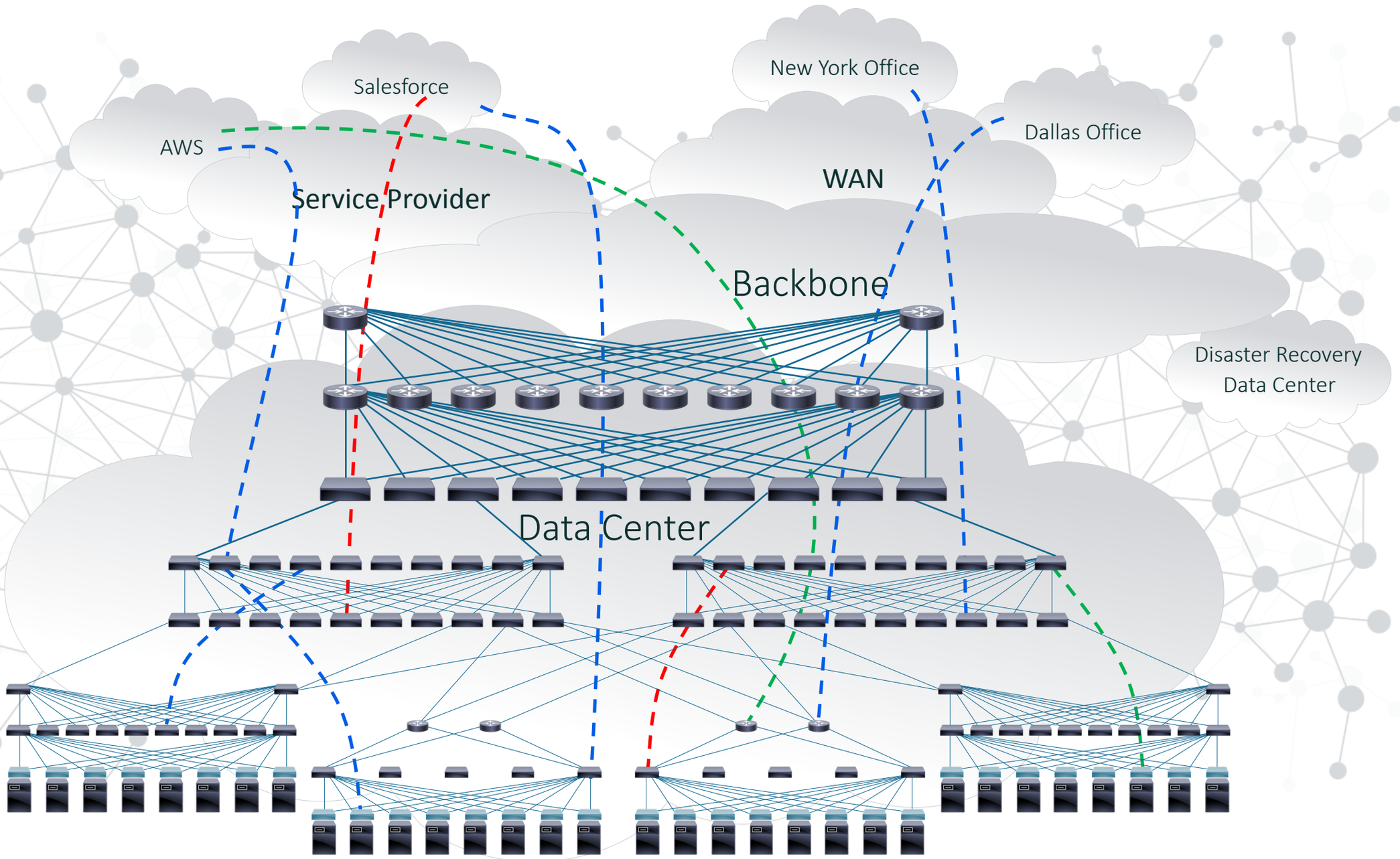

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Network

Complexity

VERIFLOW

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59% say growth in complexity has led to more frequent outages [Dimensional Research]

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Manual Processes

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Manual Processes

69% use manual checks (most common technique) [Dimensional Research]

2. How is it actually useful?

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Availability & Resilience

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Network Segmentation

VERIFLOW

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Availability & Resilience

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Continuous Compliance

VERIFLOW

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Incident Response

VERIFLOW

3. Extracting the abstraction: not easy

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Software verification

```
#include <stdio.h>

int main(int argc, char** argv) {
   if (argv >= 2) {
      printf("Hello world, %s!",
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   }
   return 0;
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- Given program as input
- Assume formal specification of programming language

VERIFLOW

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- Vendor-specific behaviors

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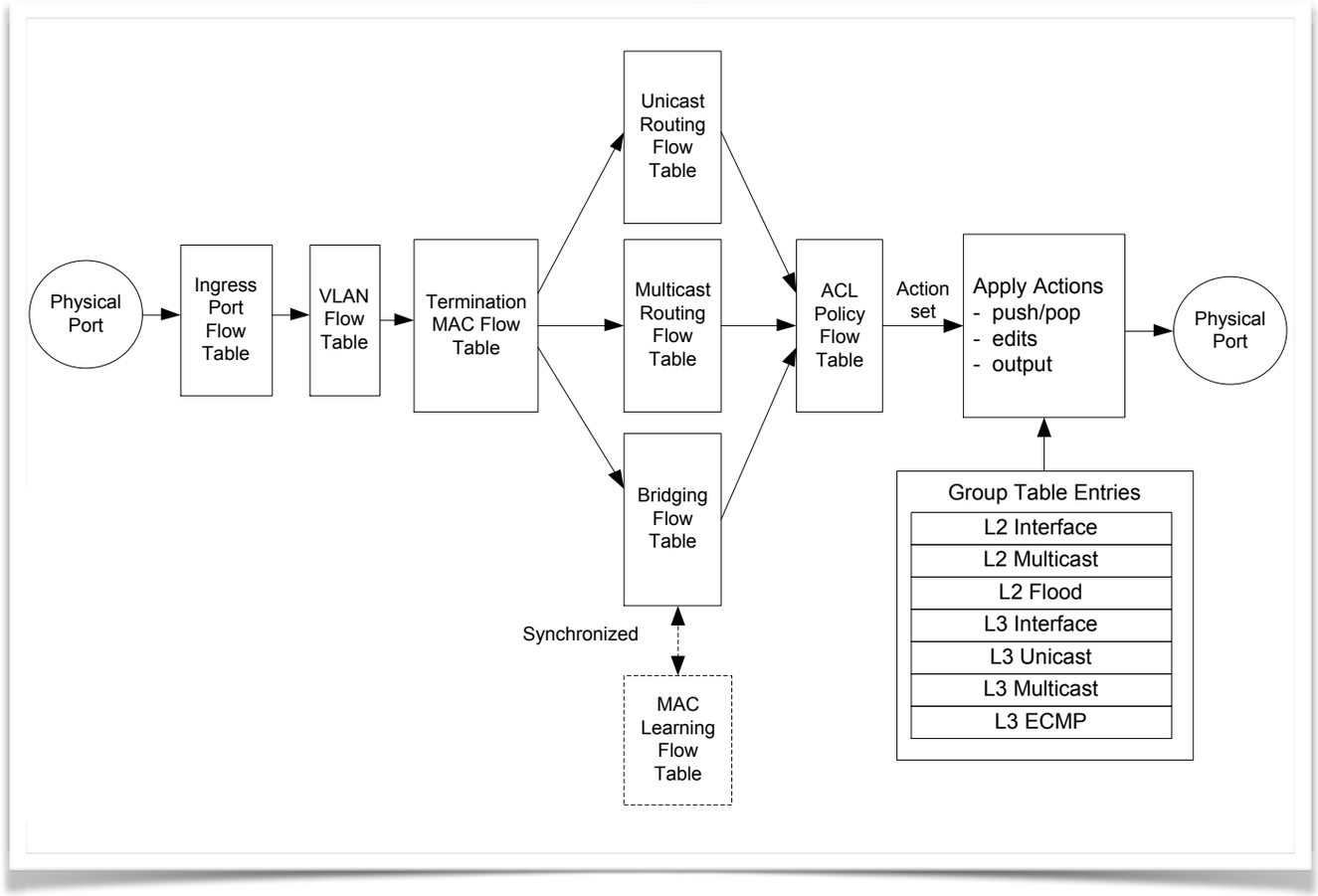

Broadcom’s OF-DPA 1.0 Abstract Switch
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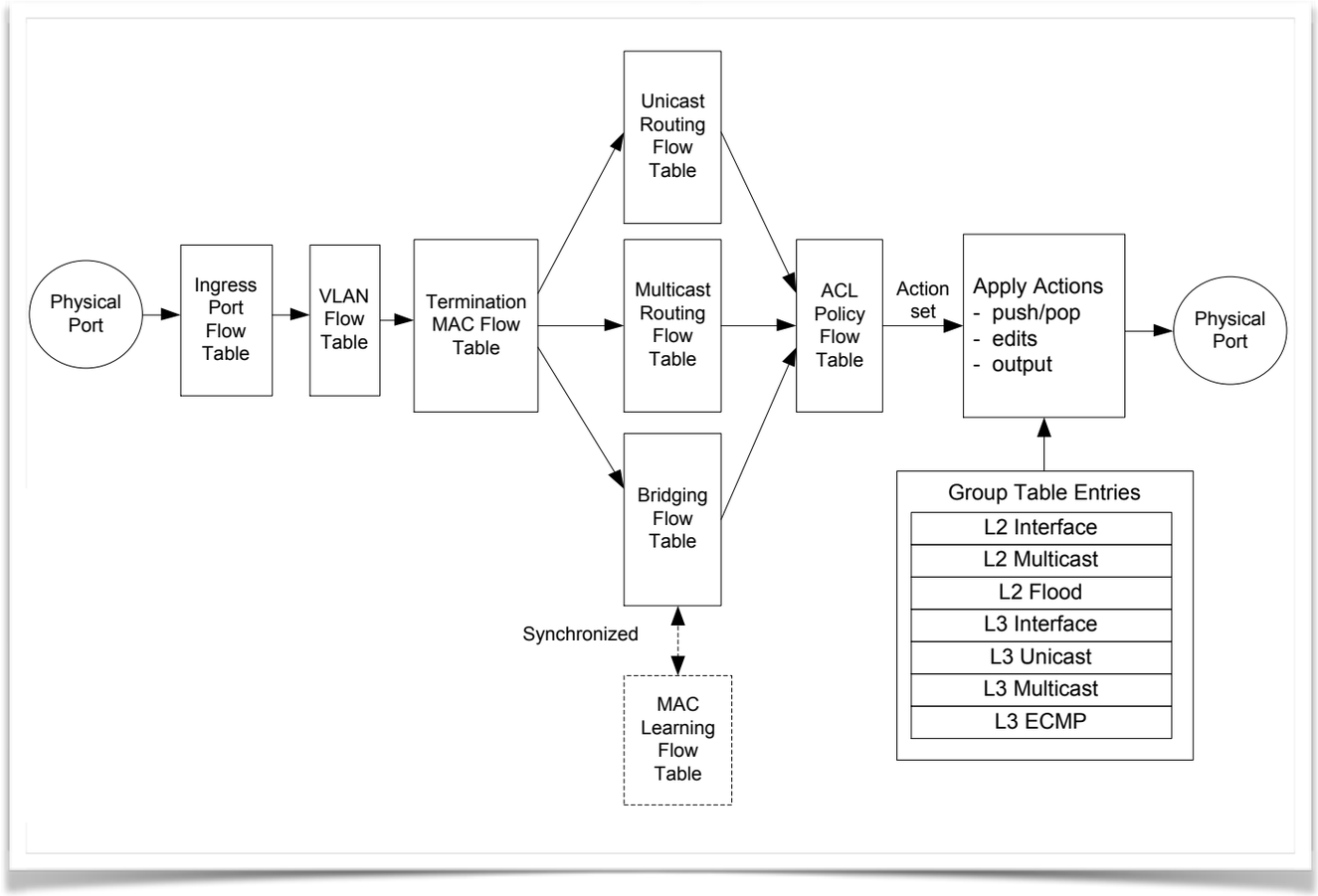

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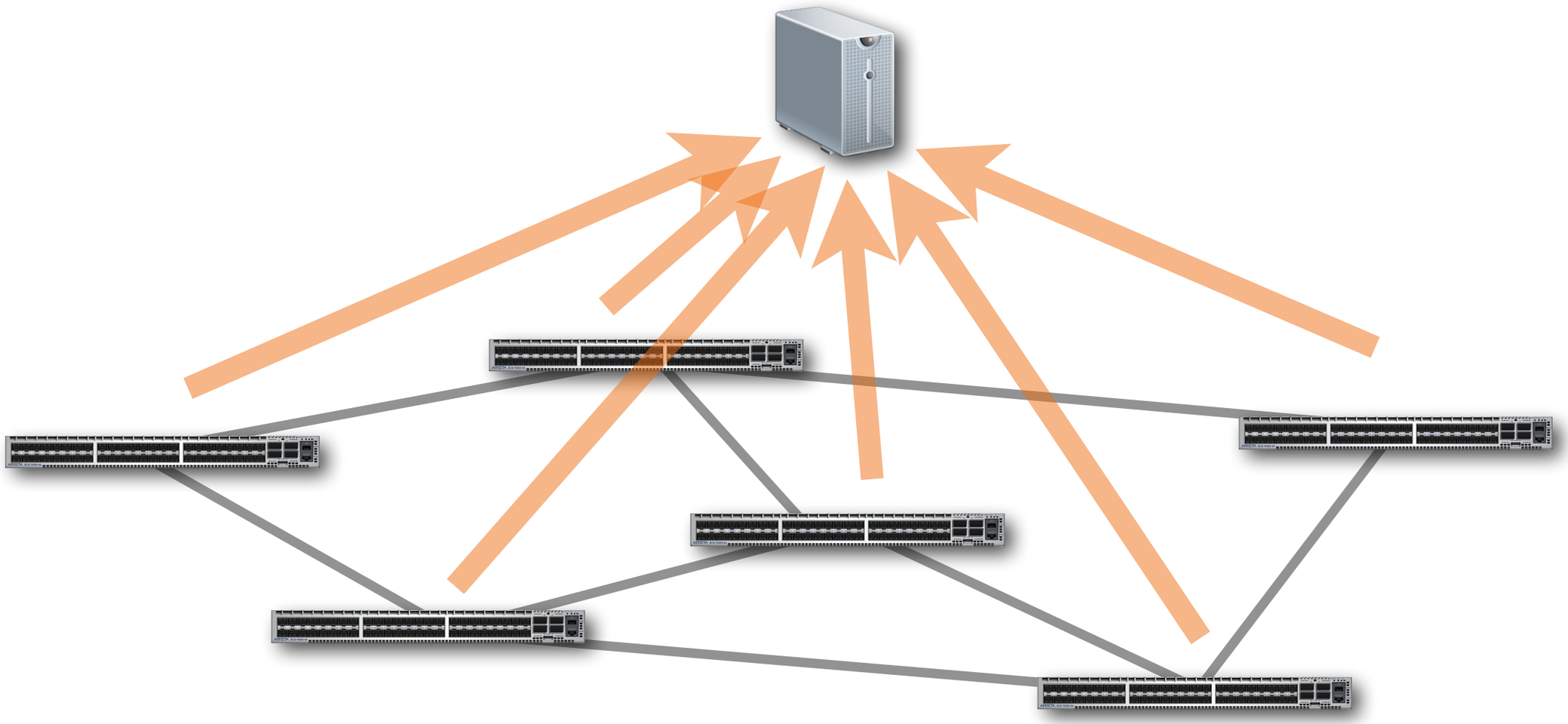
- Some hope: Vendor-specific APIs, OpenConfig

VERIFLOW

4. Model / Verifier separation works

verify

Predictive model
("forwarding graph")



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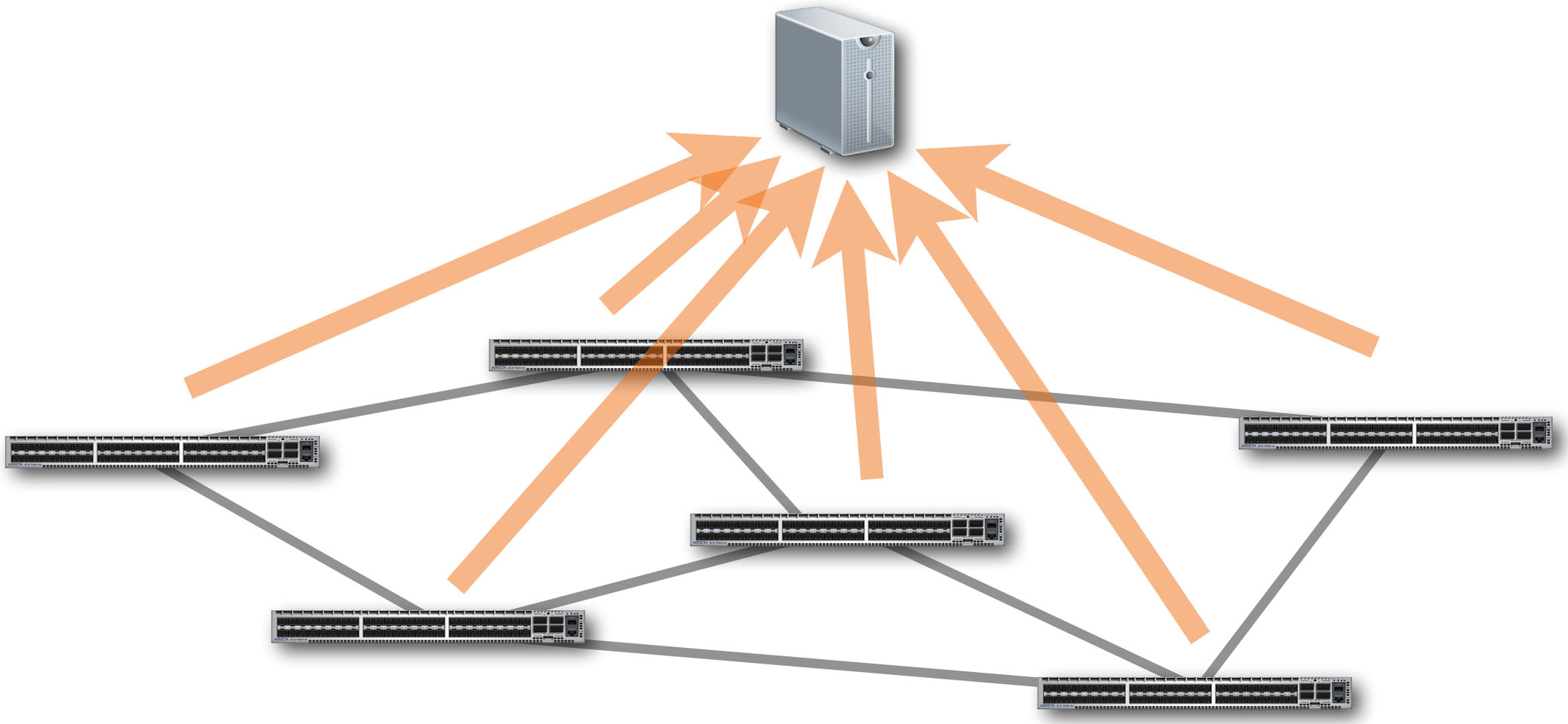

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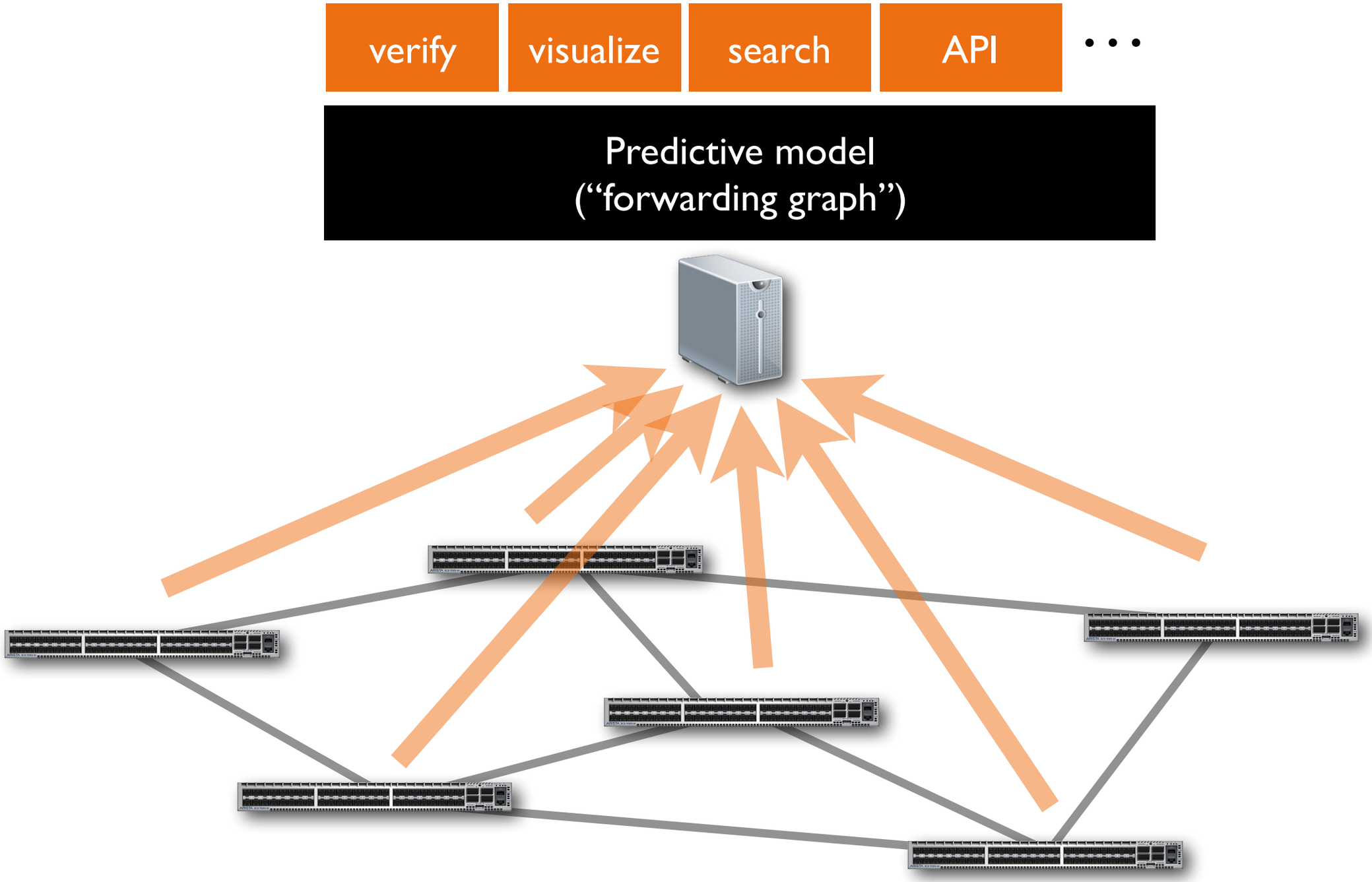

VERIFLOW

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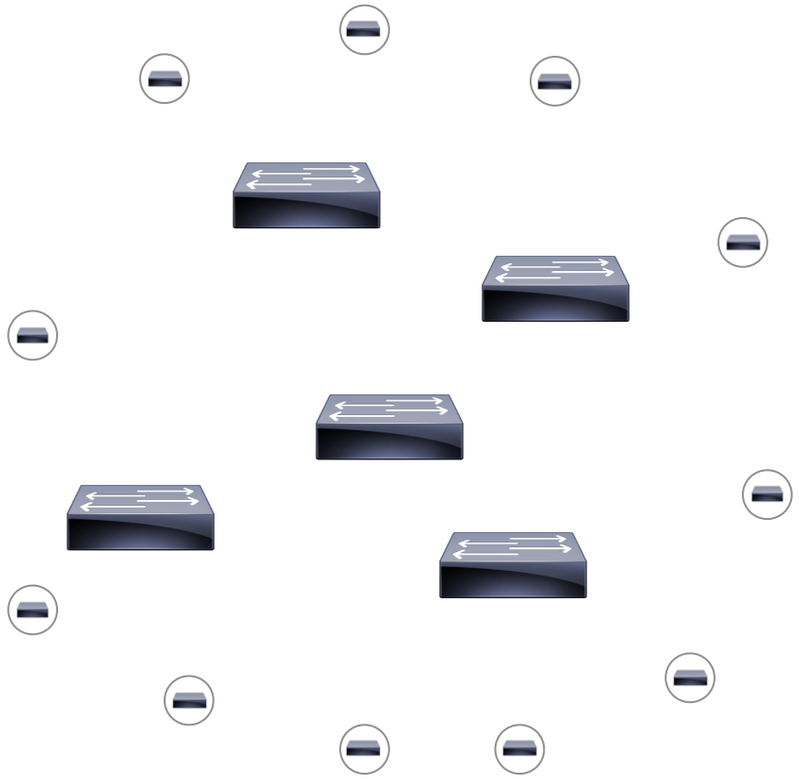

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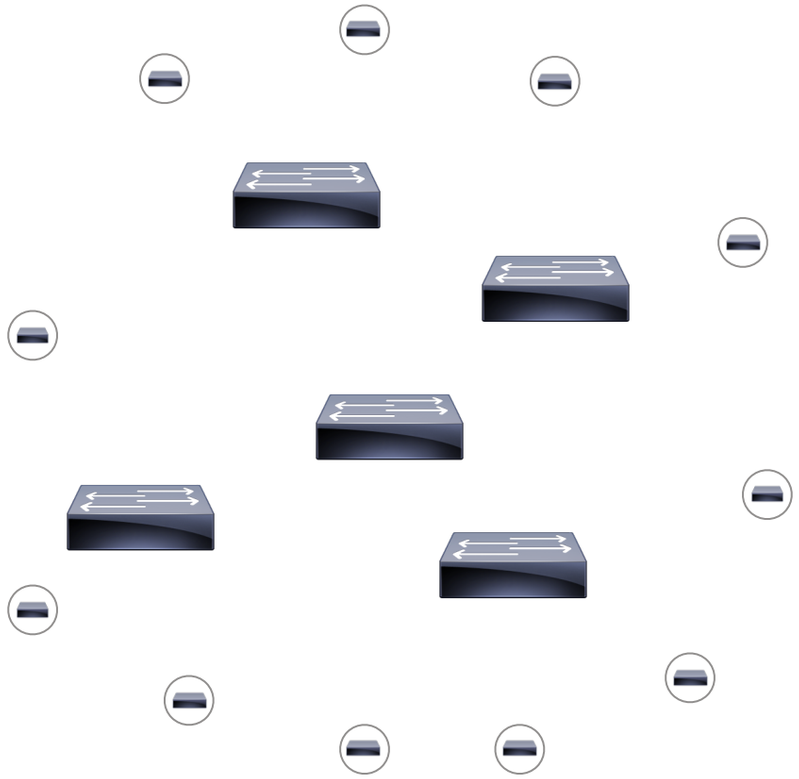

Network as individual devices

Individual config knobs

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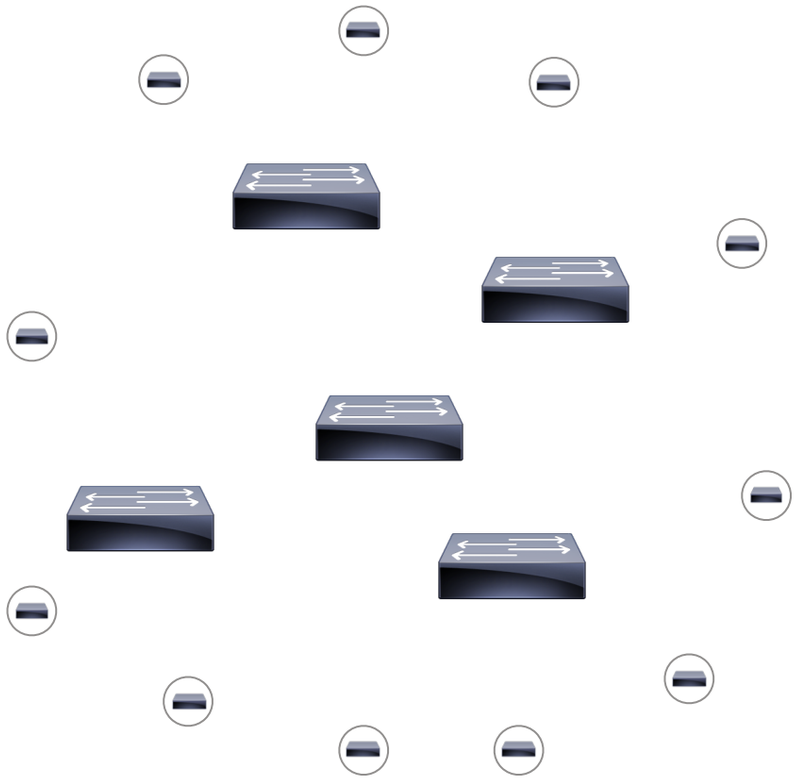

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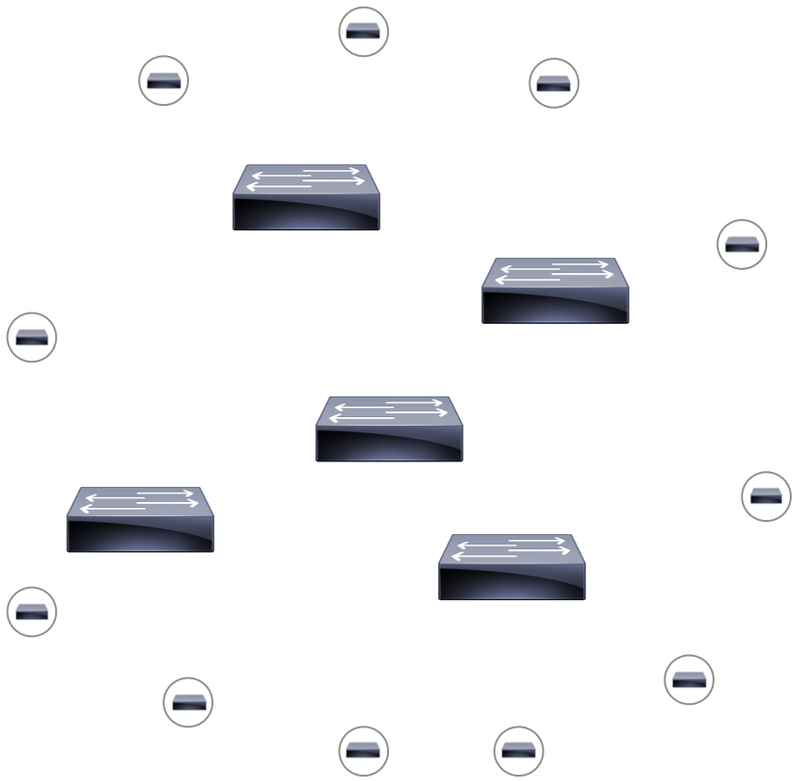

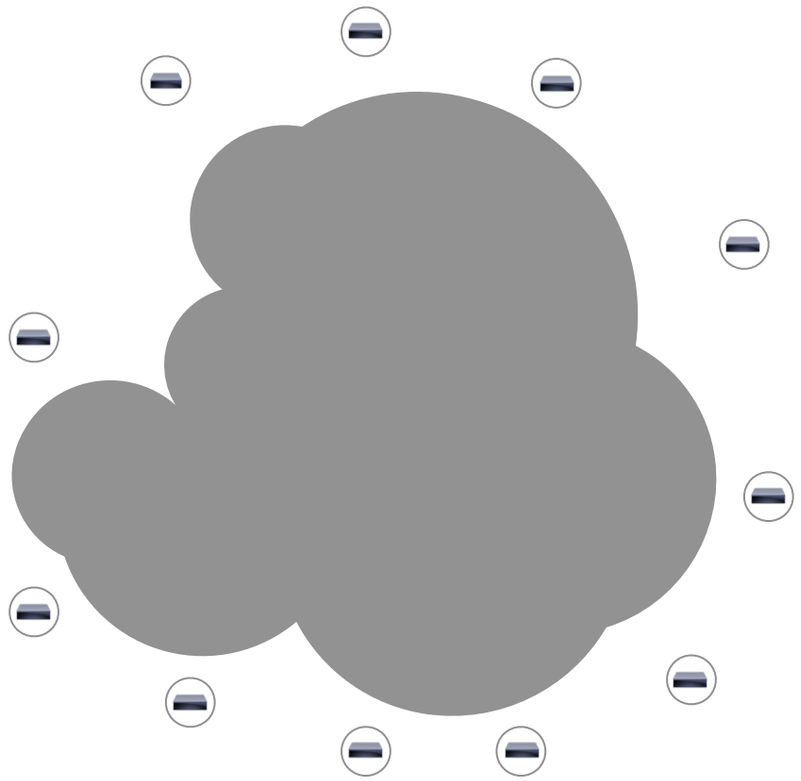

Network as individual devices → Network as one system

Individual config knobs → End-to-end intent

VERIFLOW

Data plane verification

Static

- On static reachability in IP networks [Xie, Zhan, Maltz, Zhang, Greenberg, Hjalmtysson, Rexford, INFOCOM ’05]
  - Essentially early form of data plane verification
  - Computed reachable sets with IP forwarding rules
- FlowChecker [Al-Shaer, Al-Haj, SafeConfig ’10]
- Anteater [Mai, Khurshid, Agarwal, Caesar, G., King, SIGCOMM’11]
- Header Space Analysis [Kazemian, Varghese, and McKeown, NSDI ’12]
- Network-Optimized Datalog (NoD) [Lopes, Bjørner, Godefroid, Jayaraman, Varghese, NSDI 2015]

Real time (incremental)

- VeriFlow [Khurshid, Zou, Zhou, Caesar, G., HotSDN’12, NSDI’13]
- NetPlumber [Kazemian, Chang, Zeng, Varghese, McKeown, Whyte, NSDI ’13]
- CCG [Zhou, Jin, Croft, Caesar, G., NSDI’15]

Data plane verification (cont'd)

Optimizations

- Libra: Divide and Conquer to Verify Forwarding Tables in Huge Networks [Zeng, Zhang, Ye, Google, Jeyakumar, Ju, Liu, McKeown, Vahdat, NSDI'14]
- Atomic Predicates [Yang, Lam, ToN'16]
- ddNF [Bjorner, Juniwal, Mahajan, Seshia, Varghese, HVC'16]

Configuration verification

Configuration verification

- RCC (Detecting BGP config faults w/static analysis)
  [Feamster & Balakrishnan, USENIX ’05]
- ConfigAssure [Narain et al, ’08]
- ConfigChecker [Al-Shaer, Marrero, El-Atawy, ICNP ‘09]
- Batfish [Fogel, Fung, Pedrosa, Walraed-Sullivan, Govindan, Mahajan, Millstein, NSDI’15]
- Bagpipe [Weitz, Woos, Torlak, Ernst, Krishnamurthy, Tatlock, NetPL’16 & OOPSLA’16]

Richer verification

Richer data plane models

- Software Dataplane Verification [Dobrescu, Argyraki, NSDI'14]
- SymNet [Stoenescu, Popovici, Negreanu, Raiciu, SIGCOMM'16]
- Mutable datapaths [Panda, Lahav, Argyraki, Sagiv, Shenker, NSDI'17]

Verifiable controllers & control languages

- NICE [Canini, Venzano, Perešíni, Kostić, Rexford, NSDI'12]
- NetKAT [Anderson, Foster, Guha, Jeannin, Kozen, Schlesinger, Walker, POPL'14]
- Kinetic: Verifiable Dynamic Network Control [Kim, Gupta, Shahbaz, Reich, Feamster, Clark, NSDI'15]

FUTURE RESEARCH DIRECTIONS

FOR VERIFICATION

Research Directions

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1. Pushing the limit towards richer models

    - Software pipelines
    - Verifiable SDN Controllers
    - Stateful networks
    - Higher layer concepts

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2. Moving from verification to remediation

3. Making it easy for users to express intent

VERIFLOW