A Hypothesis Testing Framework for Network Security

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Part of the SoS Lablet with

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Work with...

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with

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Haohui Mai

Xuan Zhou

Rachit Agarwal

Sam King

References to papers in this talk

Haohui Mai, Ahmed Khurshid, Rachit Agarwal, Matthew Caesar, P. Brighten Godfrey, and Samuel T. King. **Debugging the Data Plane with Anteater.** ACM SIGCOMM, August 2011.

Ahmed Khurshid, Xuan Zou, Wenxuan Zhou, Matthew Caesar, and P. Brighten Godfrey. **VeriFlow: Verifying Network-Wide Invariants in Real Time.** 10th USENIX Symposium on Networked Systems Design and Implementation (NSDI), April 2013.

Wenxuan Zhou, Dong Jin, Jason Croft, Matthew Caesar, and P. Brighten Godfrey. **Enforcing Customizable Consistency Properties in Software-Defined Networks.** 12th USENIX Symposium on Networked Systems Design and Implementation (NSDI), April 2015.

Anduo Wang, Brighten Godfrey, and Matthew Caesar. **Ravel: Orchestrating Software-Defined Networks.** Demo in SOSR'15.

Background:
Network Verification

Networks are complex

89%

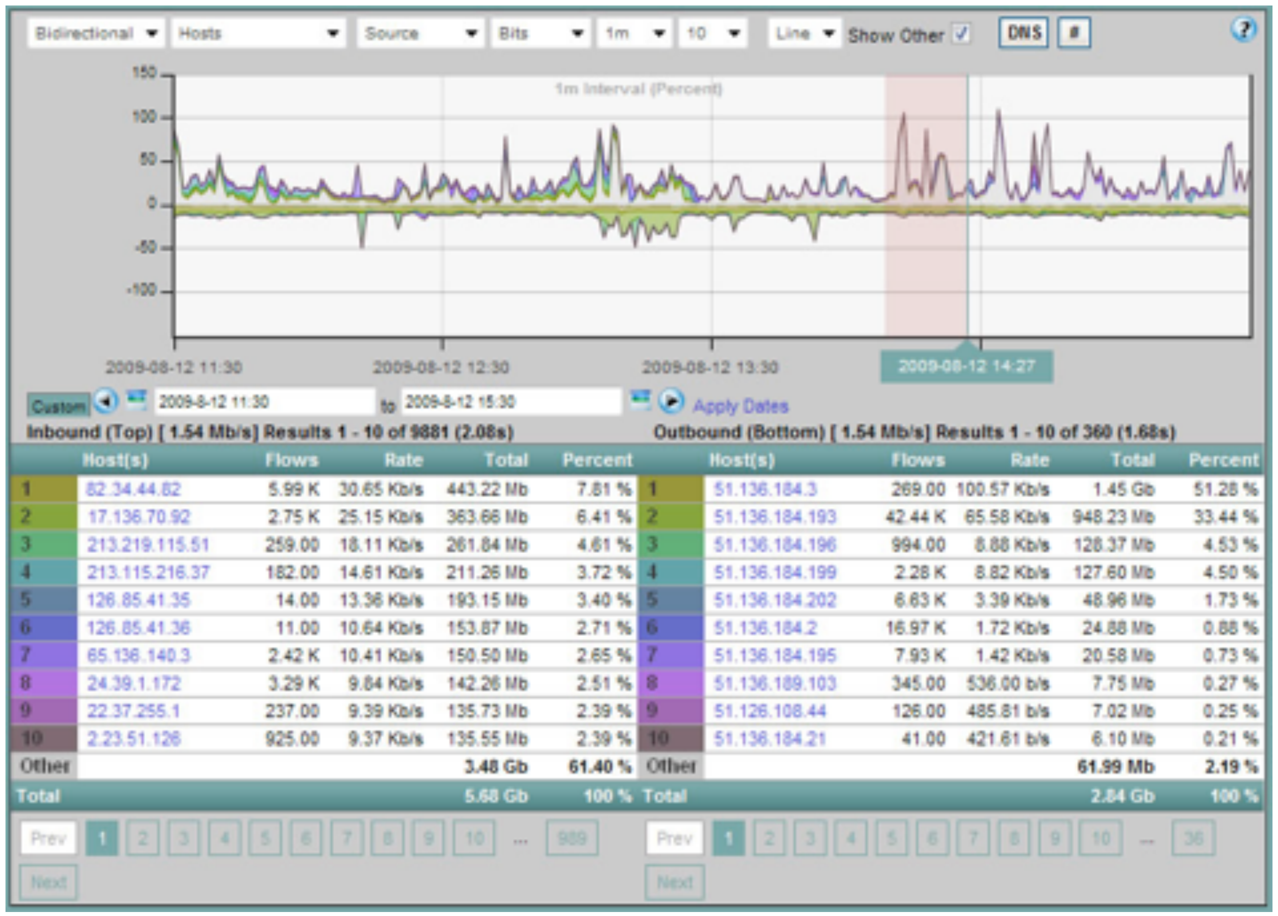
of operators never sure that config changes are bug-free

82%

concerned that changes would cause problems with existing functionality

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

Understanding your network




```
hostname bgpdA
password zebra
!
router bgp 8000
  bgp router-id 10.1.4.2

! for the link between A and B
  neighbor 10.1.2.3 remote-as 8000
  neighbor 10.1.2.3 update-source lo0

  network 10.0.0.0/7

! for the link between A and C
  neighbor 10.1.3.3 remote-as 7000
  neighbor 10.1.3.3 ebgp-multihop
  neighbor 10.1.3.3 next-hop-self
  neighbor 10.1.3.3 route-map PP out

! for link between A and D
  neighbor 10.1.4.3 remote-as 6000
  neighbor 10.1.4.3 ebgp-multihop
  neighbor 10.1.4.3 next-hop-self
  neighbor 10.1.4.3 route-map TagD in

! route update filtering
  ip community-list 1 permit 8000:1000
!
```

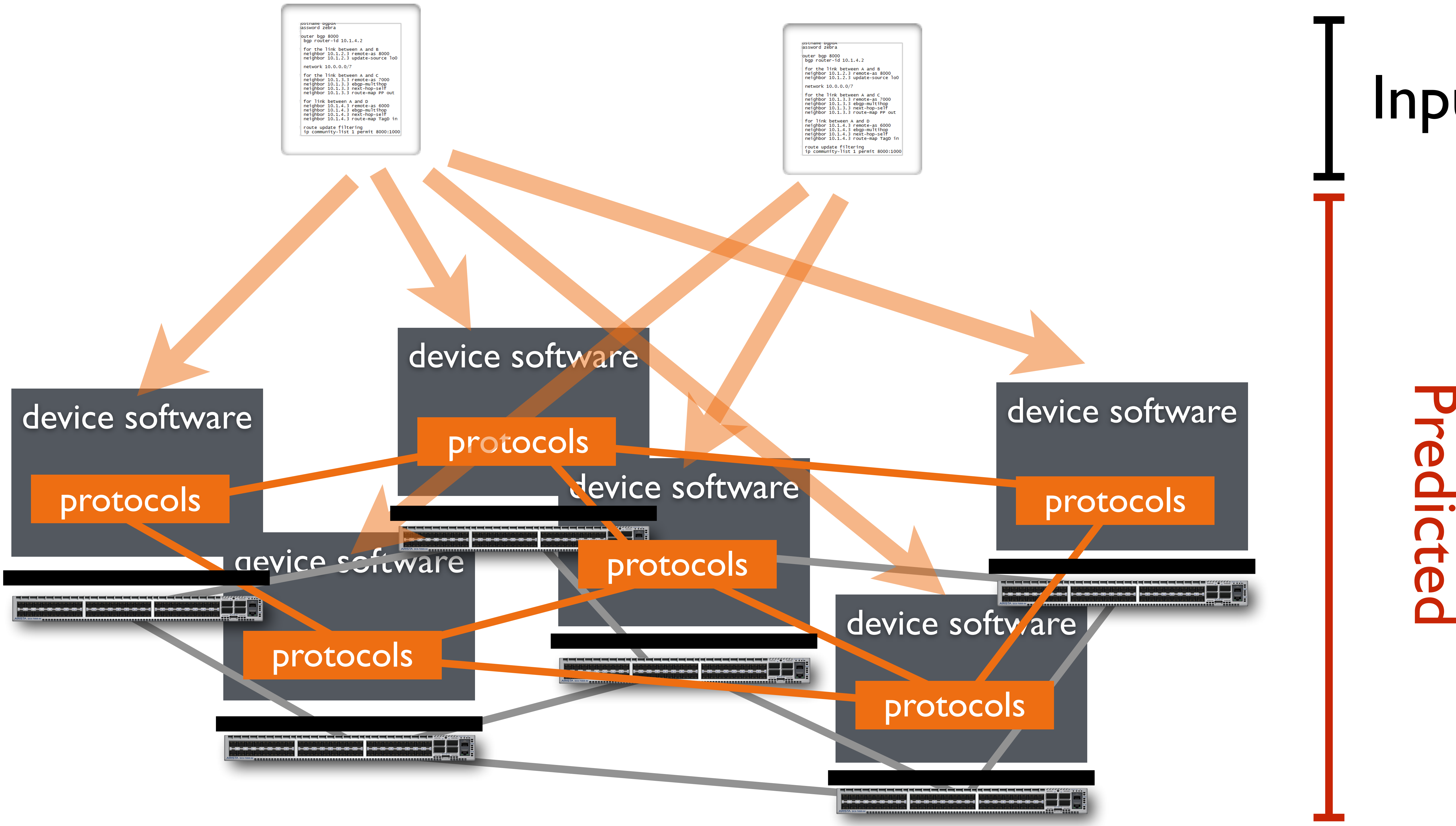
Flow monitoring

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

Configuration verification

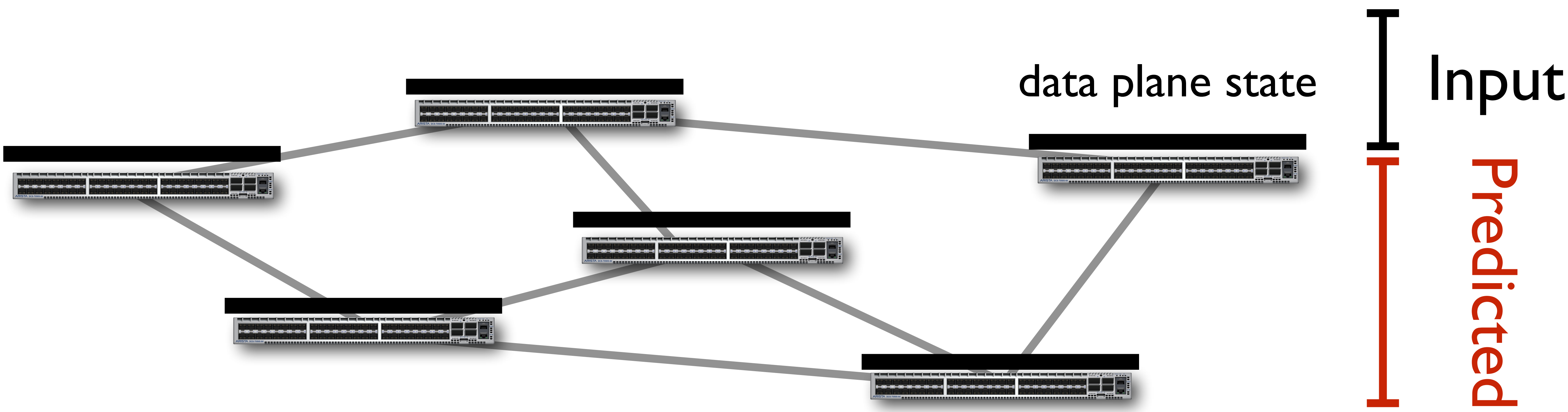
e.g.: RCC for BGP [Feamster & Balakrishnan, NSDI'05]

Configuration verification



Data plane verification

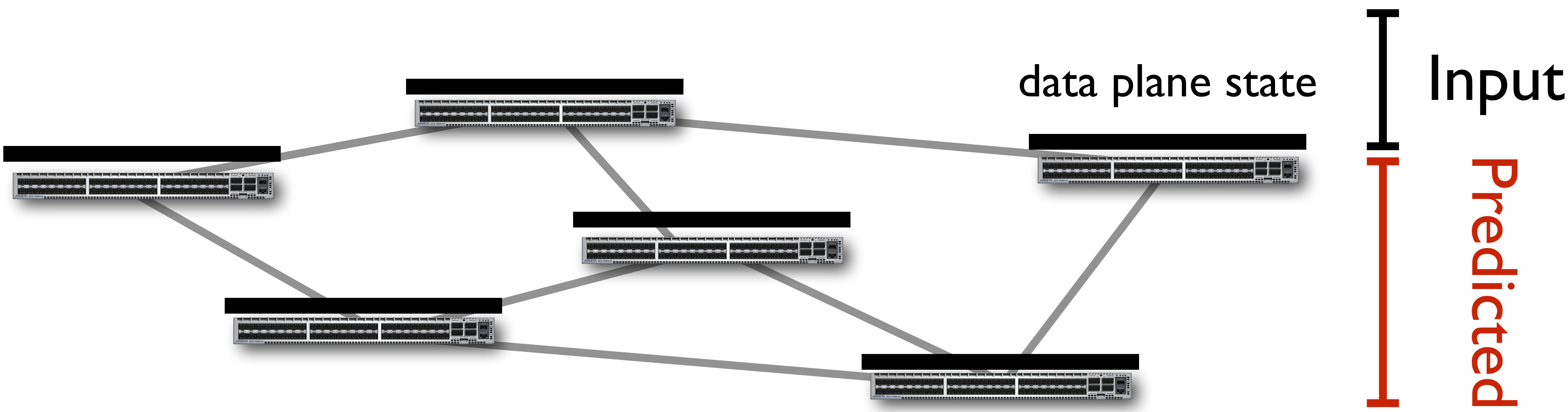
Verify the network
as close as possible to
its actual behavior



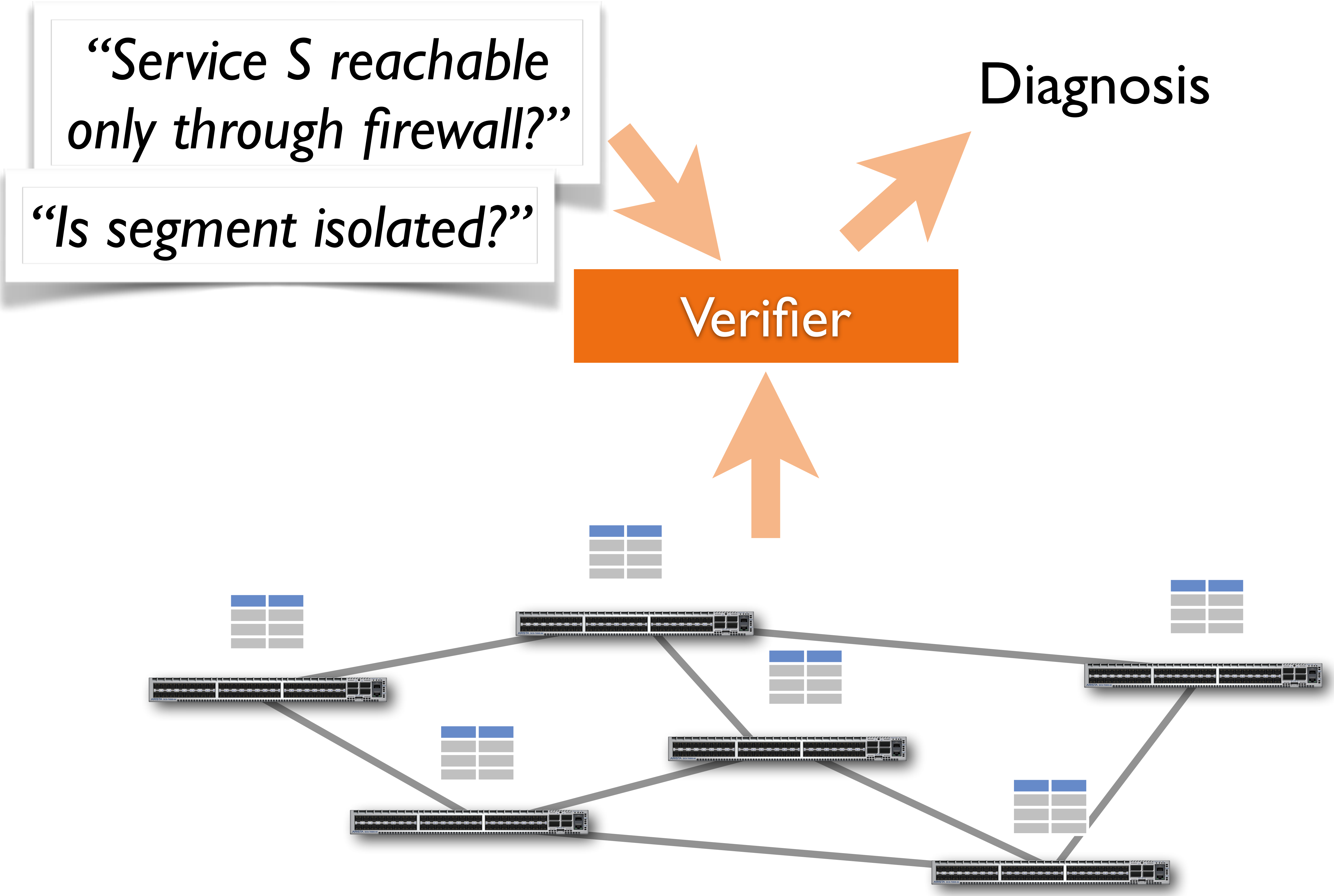
Data plane verification

Verify the network
as close as possible to
its actual behavior

- (Checks current snapshot)
- Insensitive to control protocols
- Accurate model



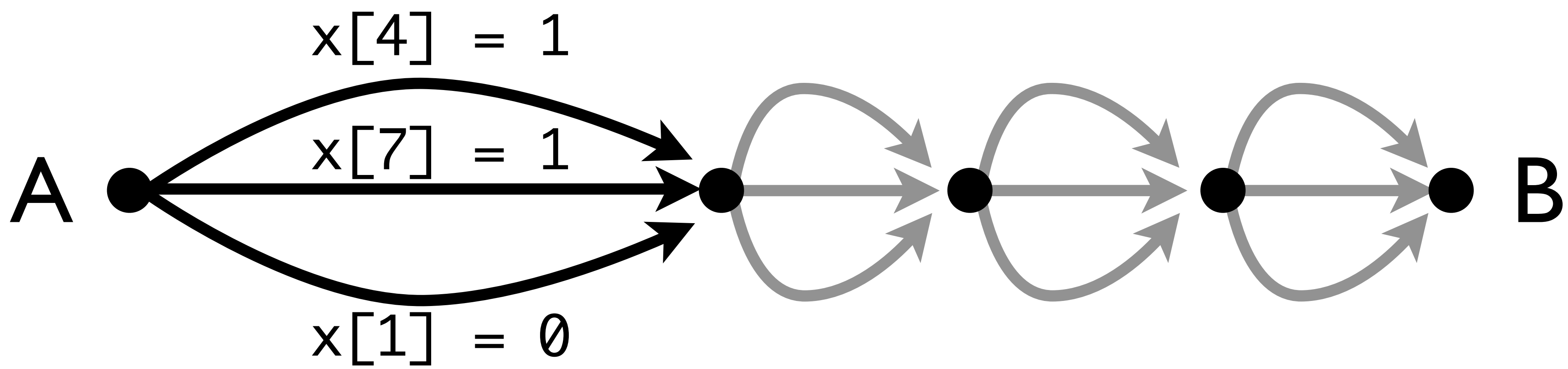
Architecture



Building It

Verification is nontrivial

Packet: `x[0] x[1] x[2] … x[n]`



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

NP-complete!

Anteater's solution

Express data plane and invariants as SAT

- ...up to some max # hops

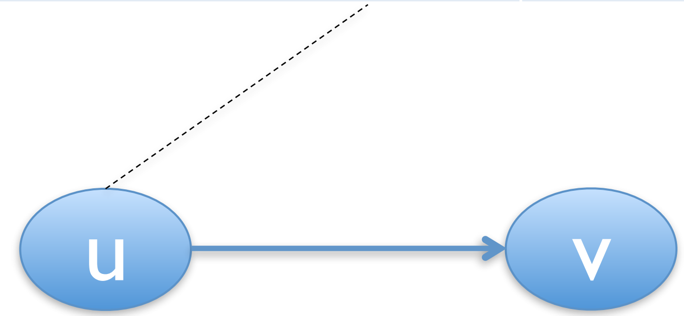
Check with off-the-shelf SAT solver (Boolector)

Data plane as boolean functions

Define P(u, v) as the expression for packets traveling from u to v

- A packet can flow over (u, v) *if and only if* it satisfies P(u, v)

Destination	Action
10.1.1.0/24	Fwd to v



$P(u, v) = dst\_ip \in 10.1.1.0/24$

Reachability as SAT solving

Goal: reachability from u to w

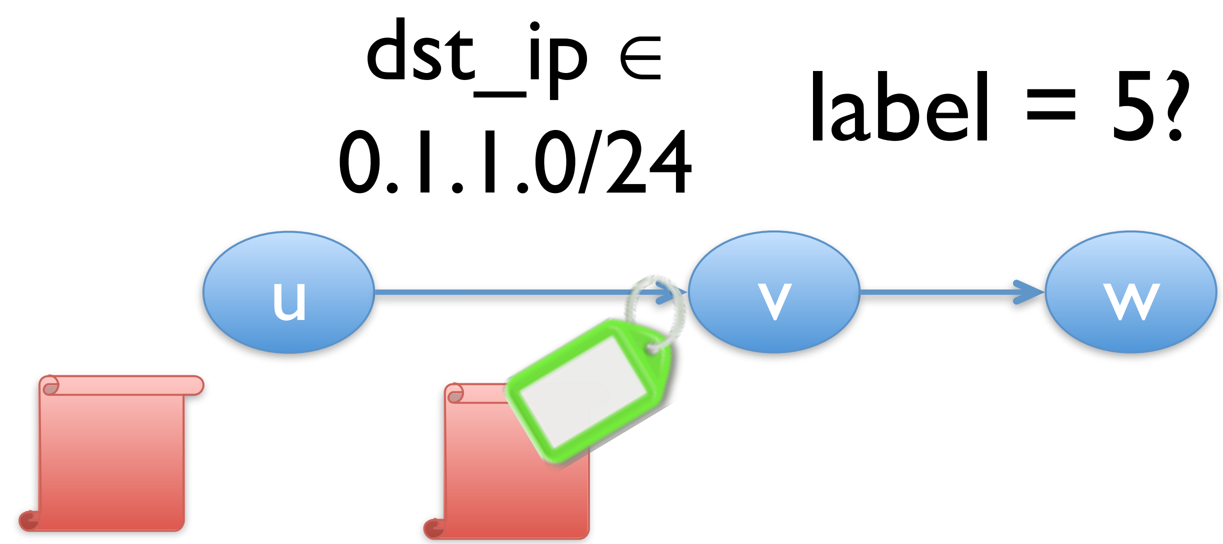
==

$C = (P(u, v) \wedge P(v,w))$ is satisfiable

- SAT solver determines the satisfiability of C
- Problem: exponentially many paths
  - Solution: Dynamic programming (a.k.a. loop unrolling)
  - Intermediate variables: "Can reach *x* in *k* hops?"
  - Similar to [Xie, Zhan, Maltz, Zhang, Greenberg, Hjalmtysson, Rexford, INFOCOM'05]

Packet transformation

Essential to model MPLS, QoS, NAT, etc.



- Model the history of packets: vector over time
- Packet transformation ⇒ boolean constraints over adjacent packet versions

$$(p_i.dst\_ip \in 0.1.1.0/24) \wedge (p_{i+1}.label = 5)$$

More generally: $p_{i+1} = f(p_i)$

Experience with an operational network

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 bugs with 3 invariants in 2 hours

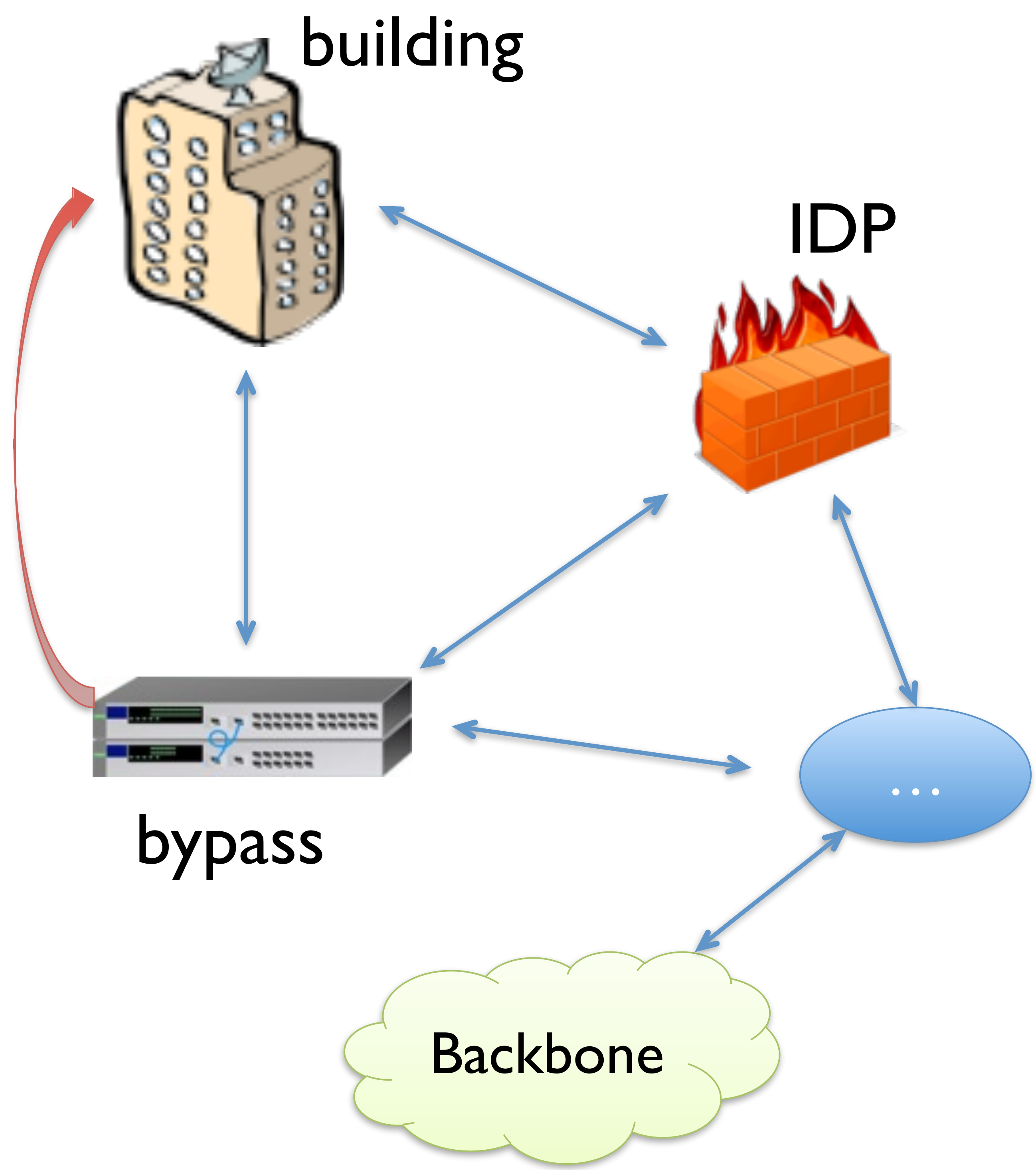
	Loop	Packet loss	Consistency
Being fixed	9	0	0
Stale config.	0	13	1
Total alerts	9	17	2

Forwarding loops

IDP was overloaded, operator introduced bypass

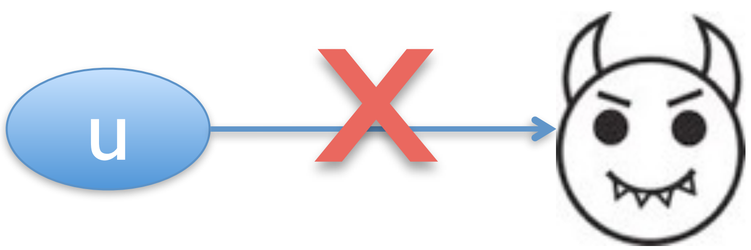
Bypass routed campus traffic to IDP through static routes

Introduced 9 loops



Bugs found by other invariants

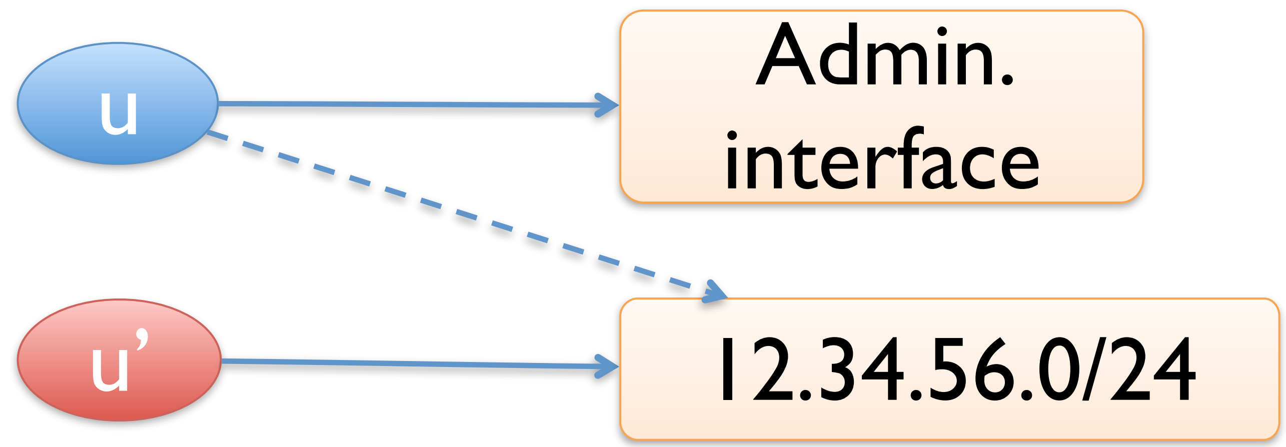
Packet loss



- Blocking compromised machines at IP level
- Stale configuration

  From Sep, 2008

Consistency



- One router exposed web admin interface in FIB
- Different policy on private IP address range

Can we verify networks
in real time?

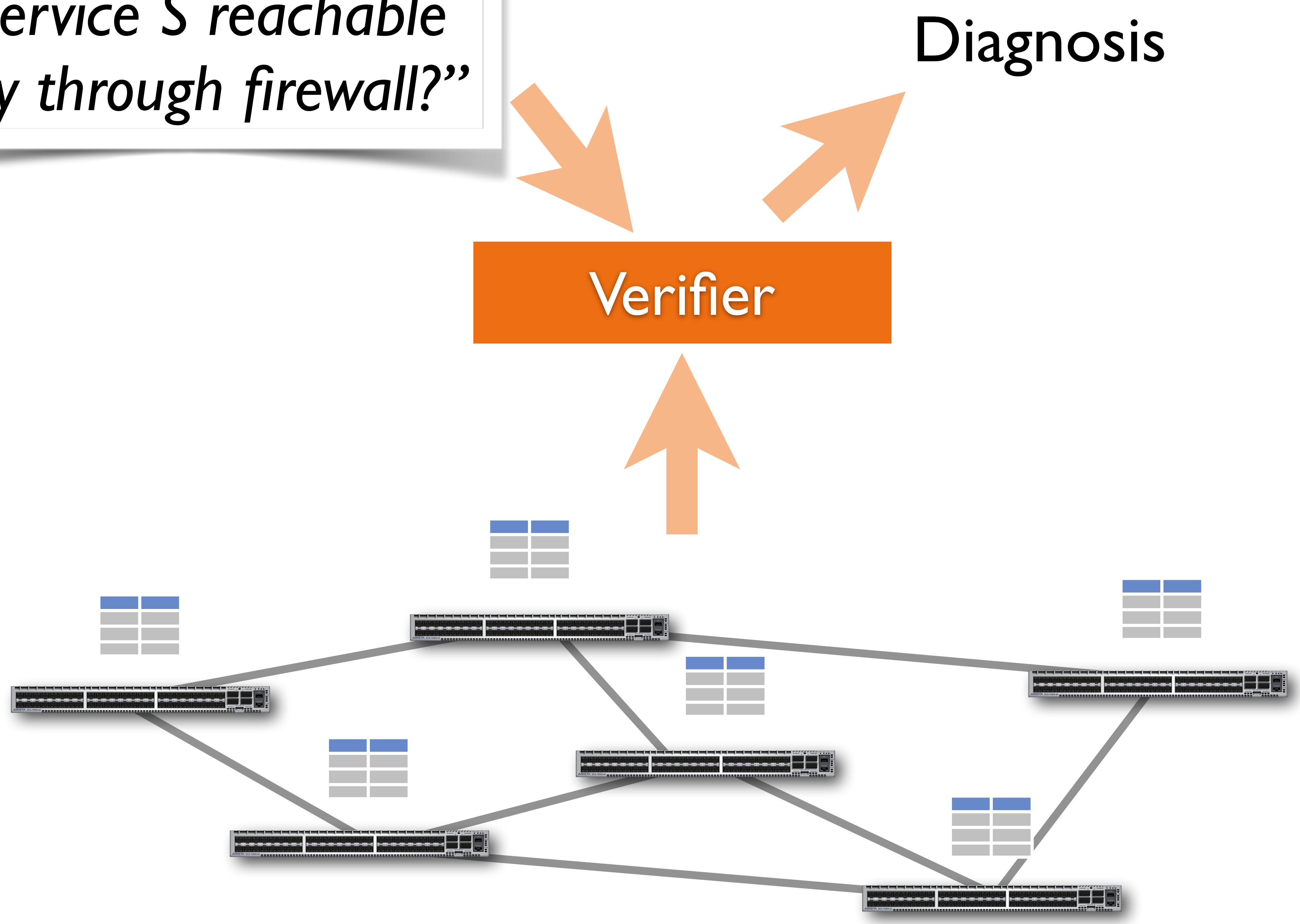
Not so simple

Challenge #1: Obtaining real time view of network

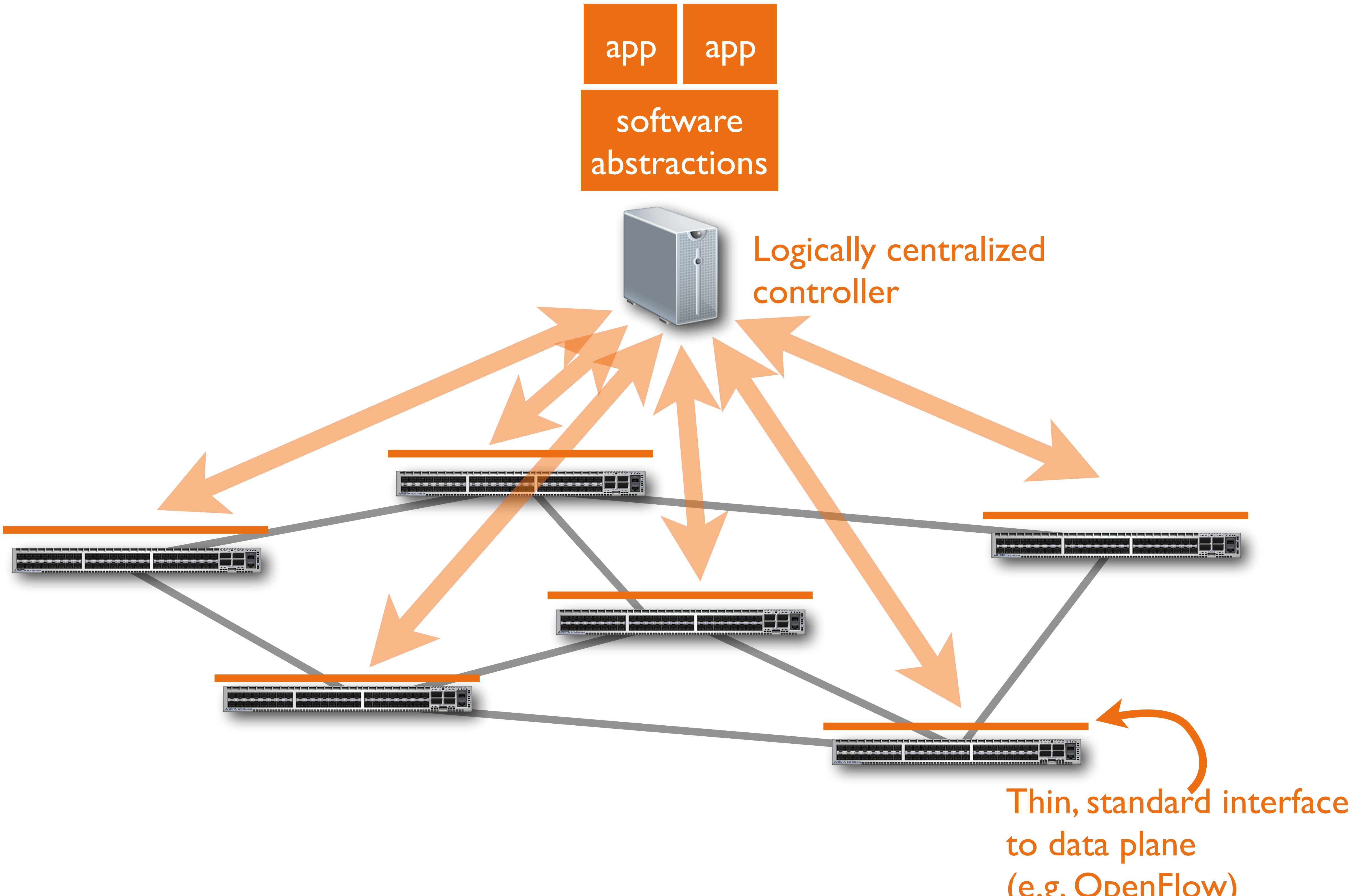
Challenge #2: Verification speed

Architecture

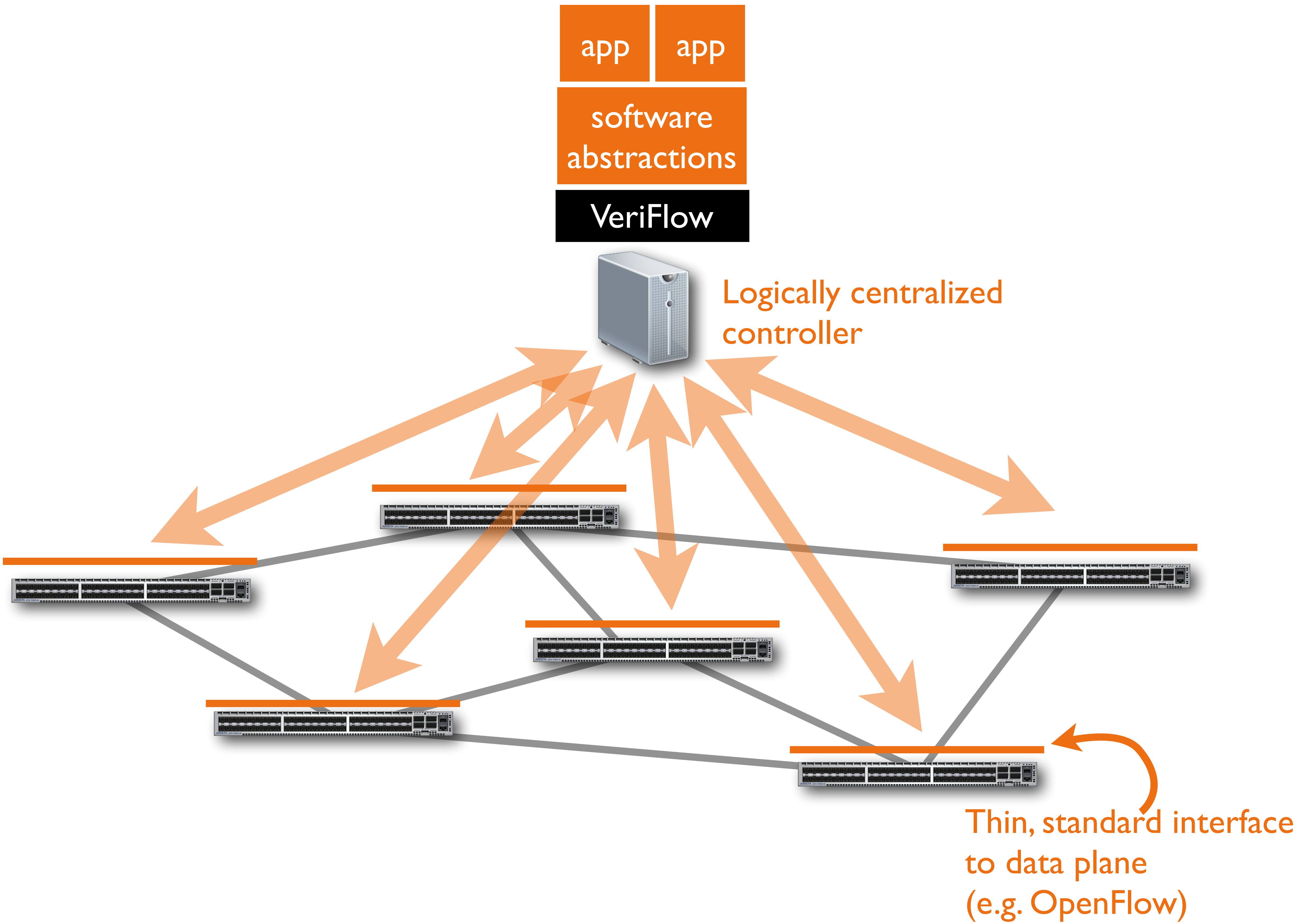
"Service S reachable only through firewall?"



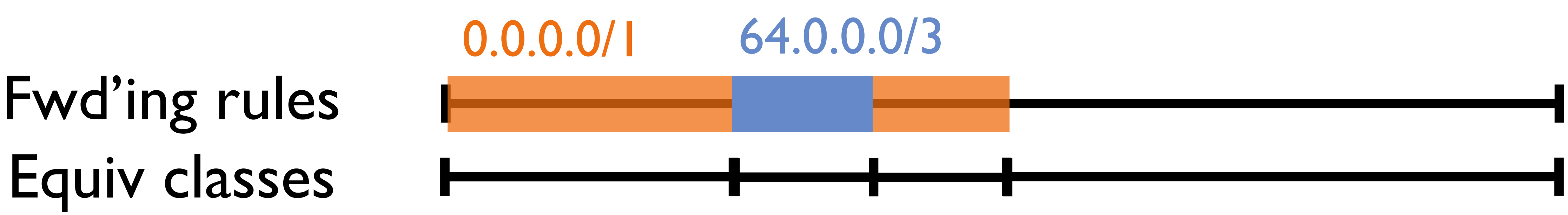
VeriFlow architecture



VeriFlow architecture



Verifying invariants quickly



Find only equivalence classes affected by the update via a multidimensional trie data structure

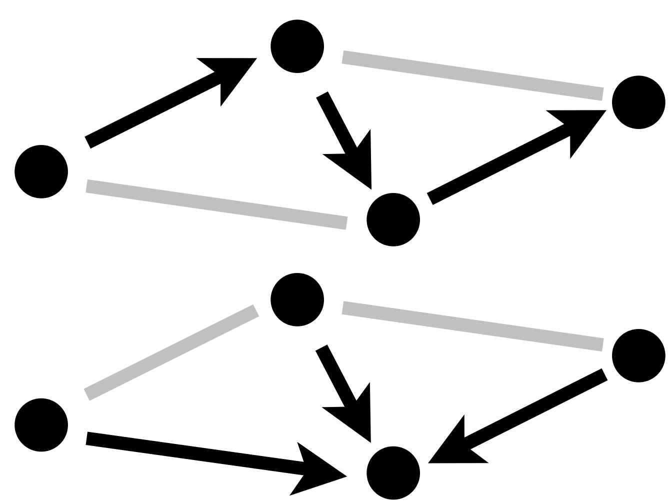
Verifying invariants quickly

Veriflow

Updates

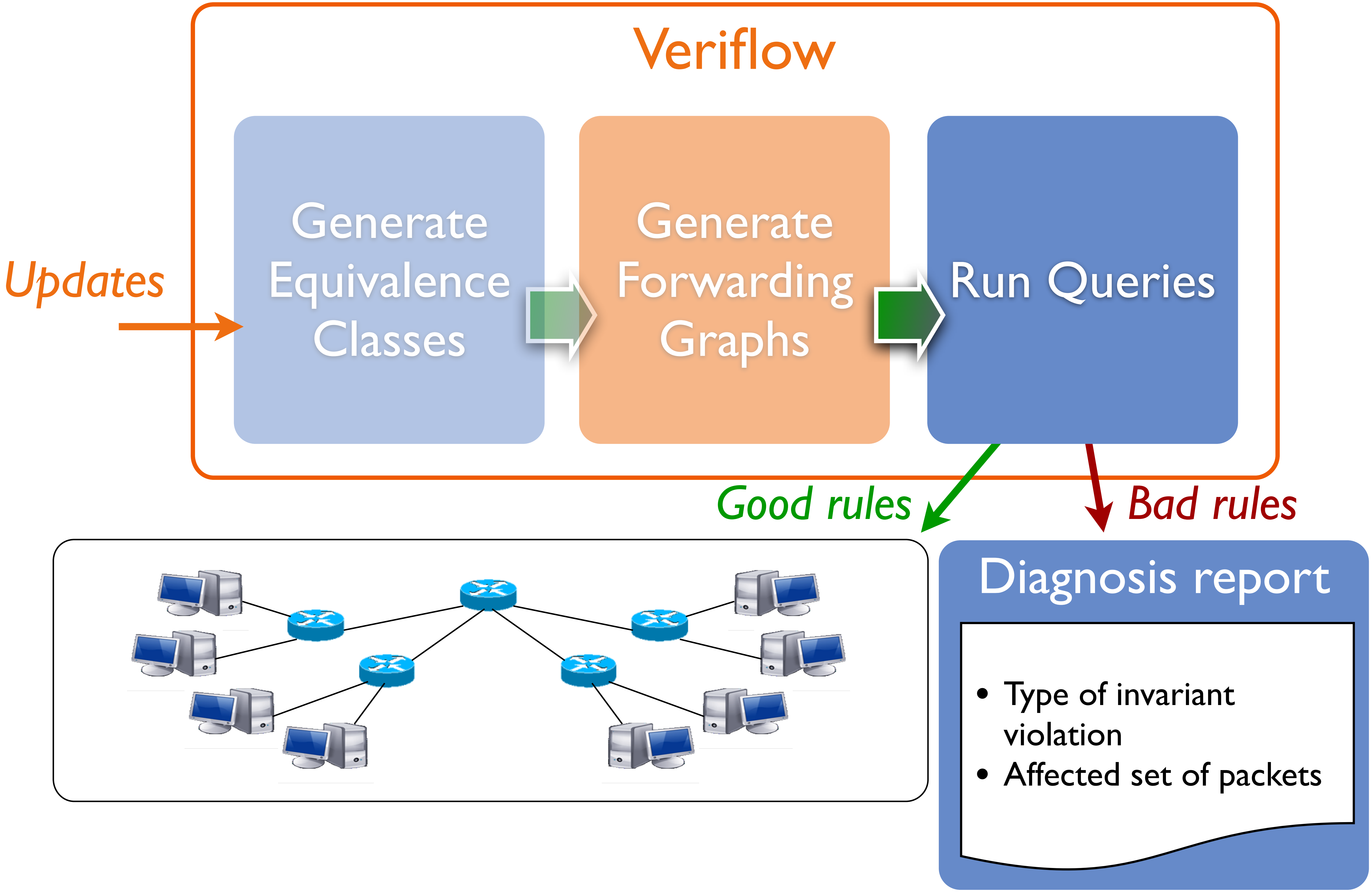
Generate Equivalence Classes

Generate Forwarding Graphs



All the info to answer queries!

Verifying invariants quickly



Evaluation

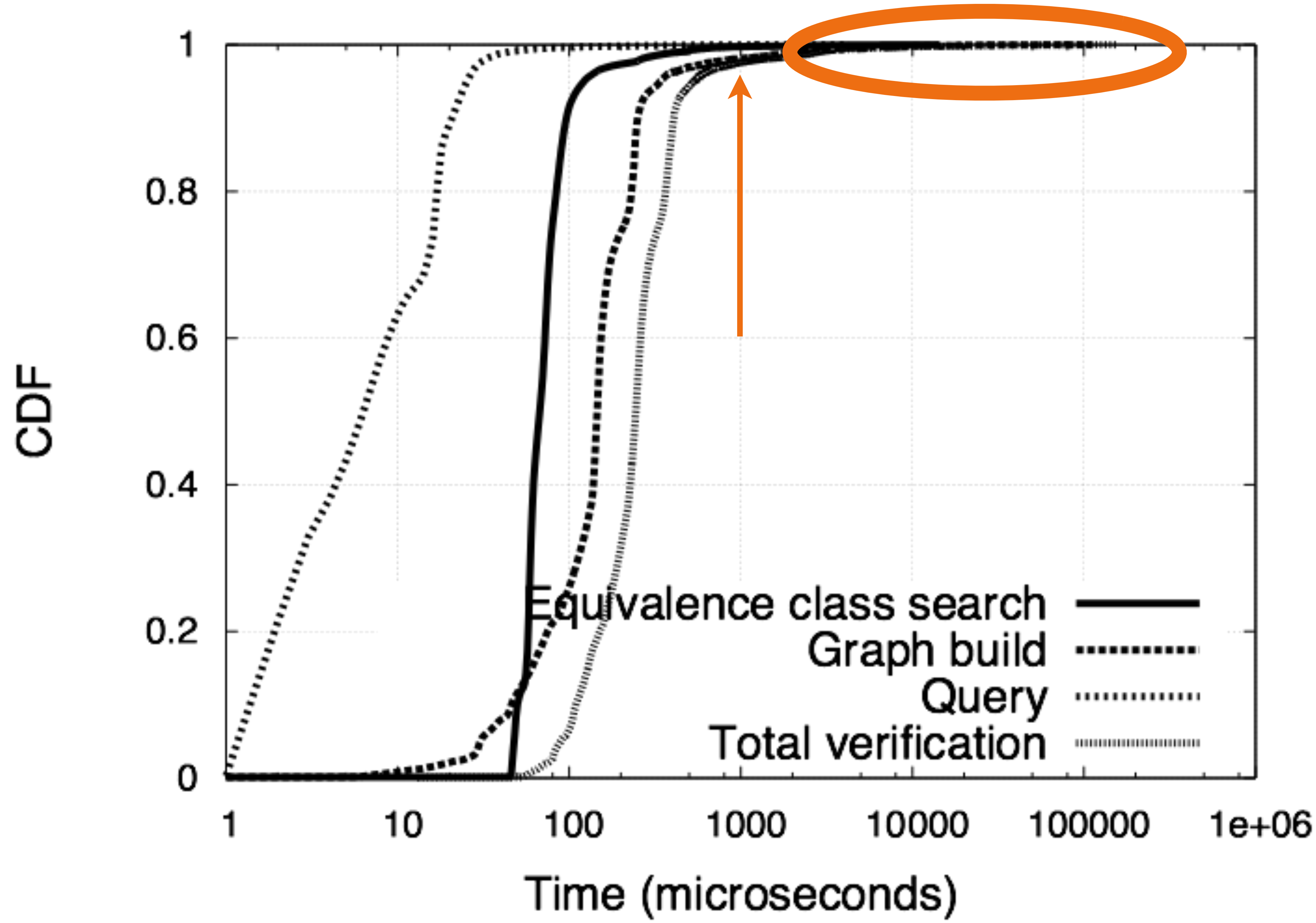
Simulated network

- Real-world BGP routing tables (RIBs) from RouteViews totaling 5 million RIB entries
- Injected into 172-router network (AS 1755 topology)

Measure time to process each forwarding change

- 90,000 updates from Route Views
- Check for loops and black holes

Microbenchmark latency



97.8% of updates verified within 1 ms

Towards a Science of Security:

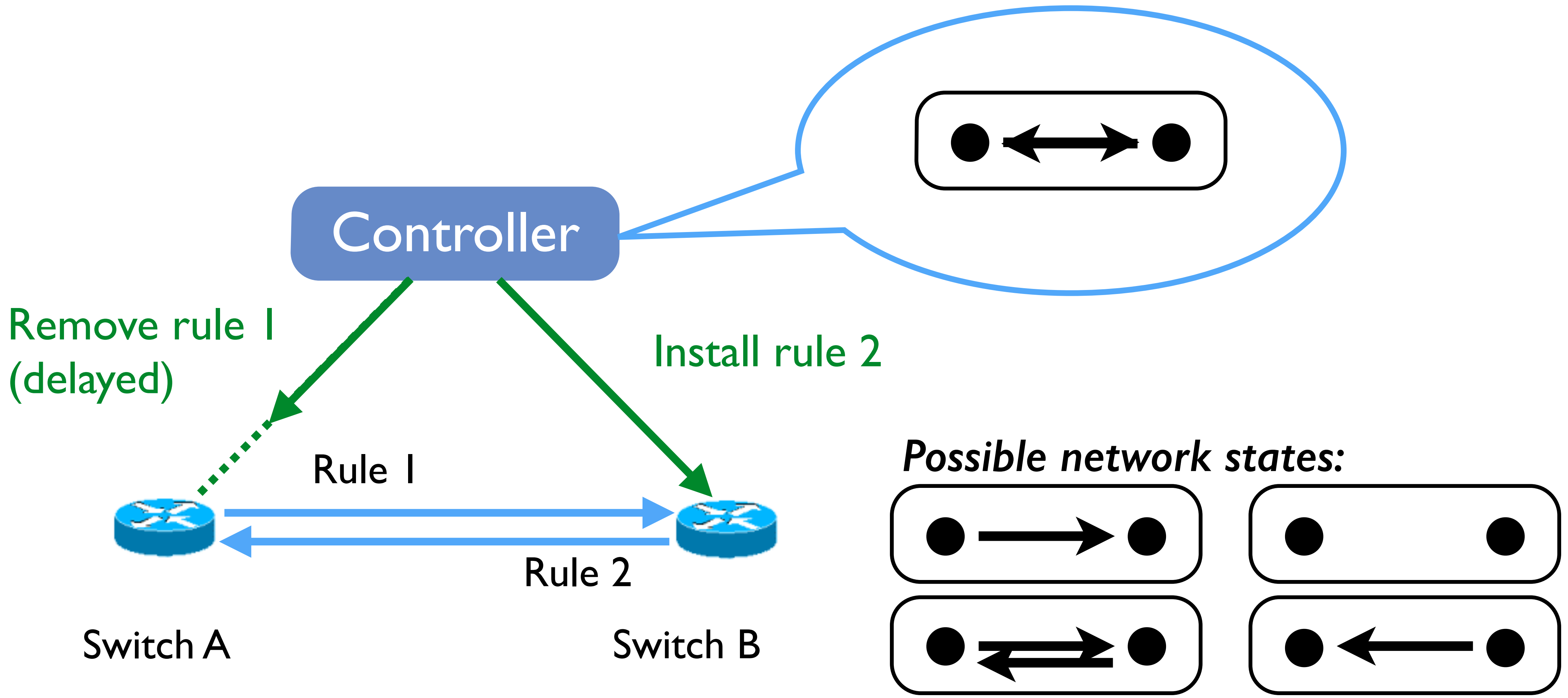
Network Hypothesis Testing

SoS: Network Hypothesis Testing

1. Modeling dynamic networks
2. Networks as databases
3. Provably correct virtual networks

Modeling dynamic networks

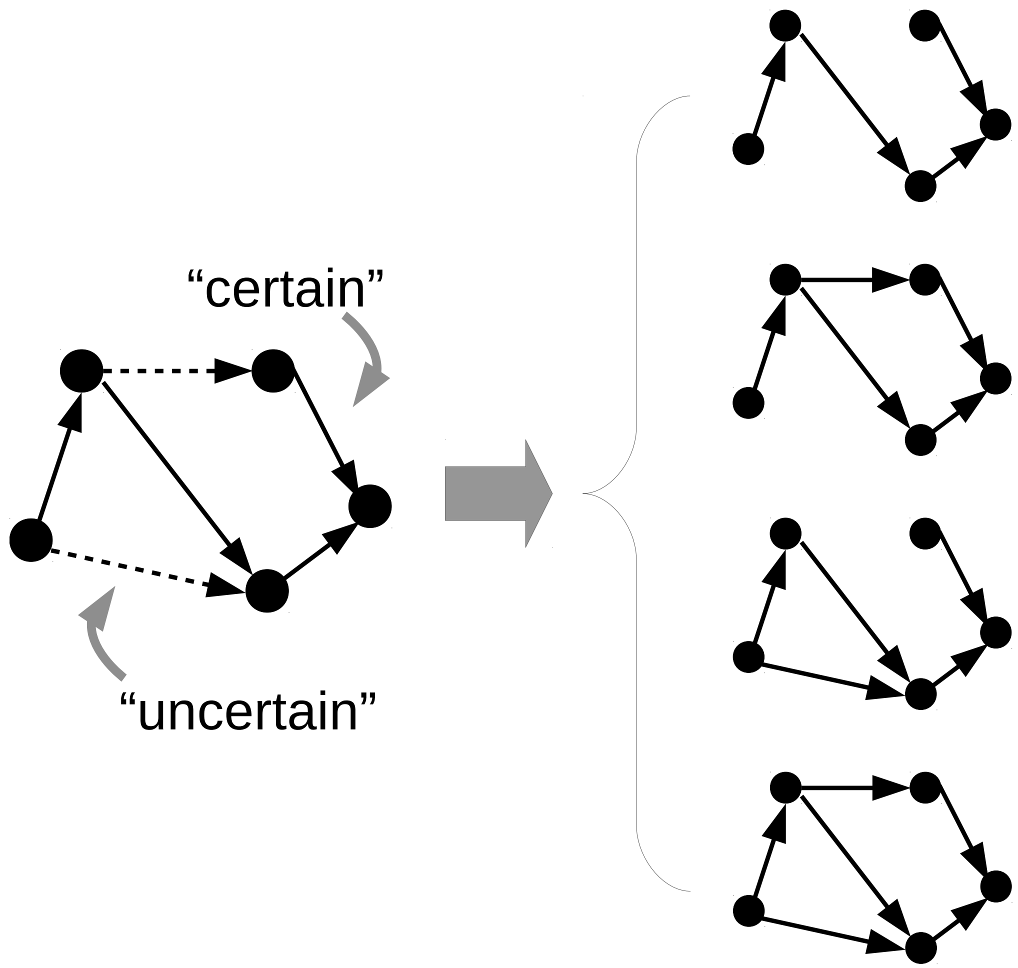
Timing uncertainty



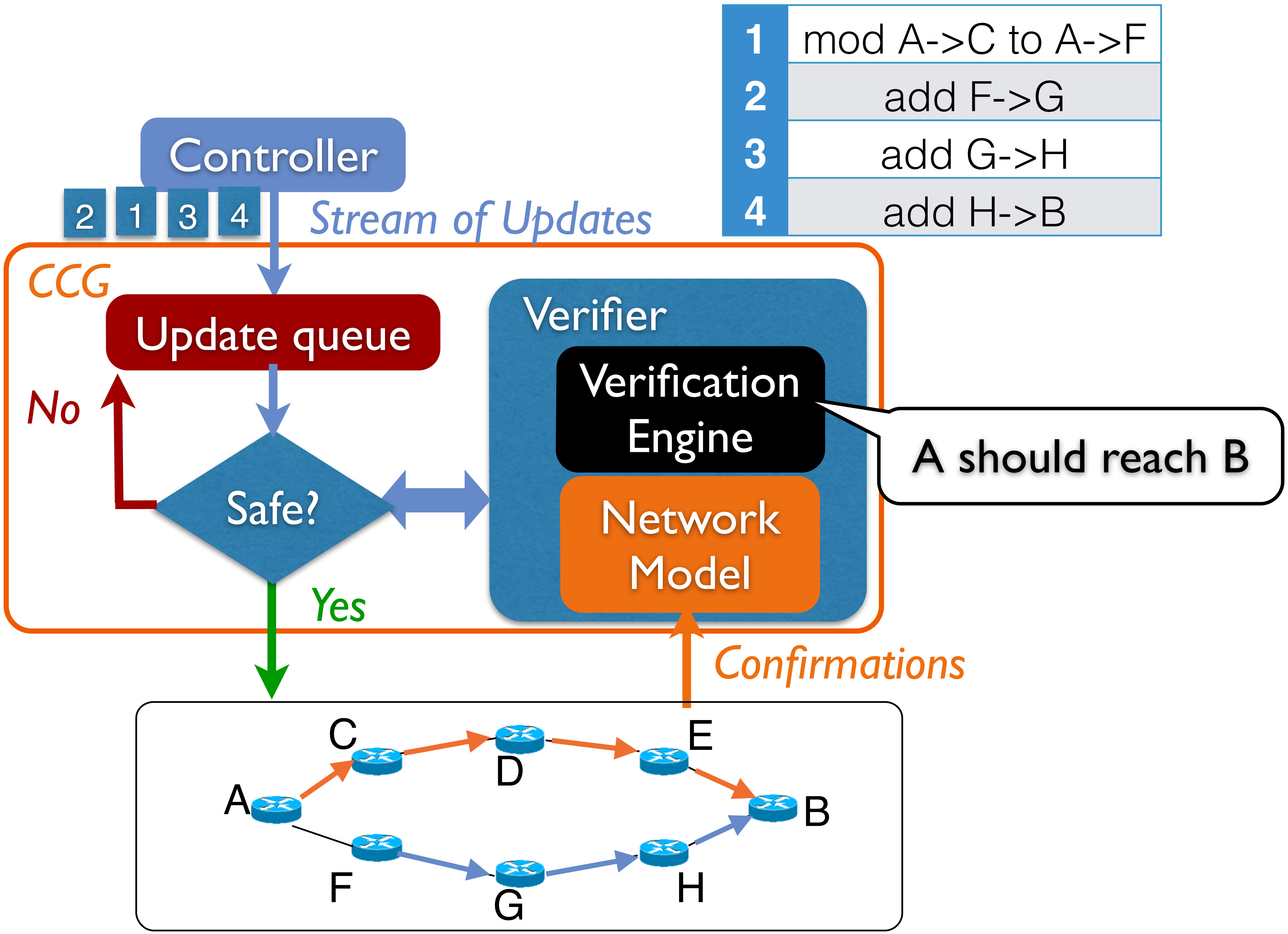
One solution: "consistent updates"

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

Uncertainty-aware verification



Update synthesis via verification



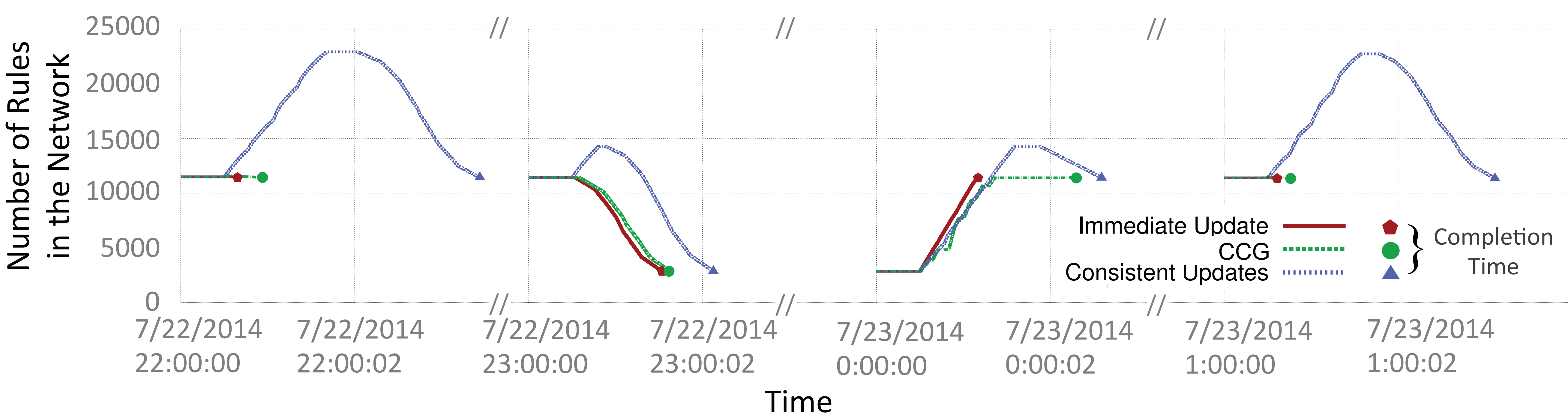
Enforcing dynamic correctness with heuristically maximized parallelism

OK, but…

Can the system "deadlock"?

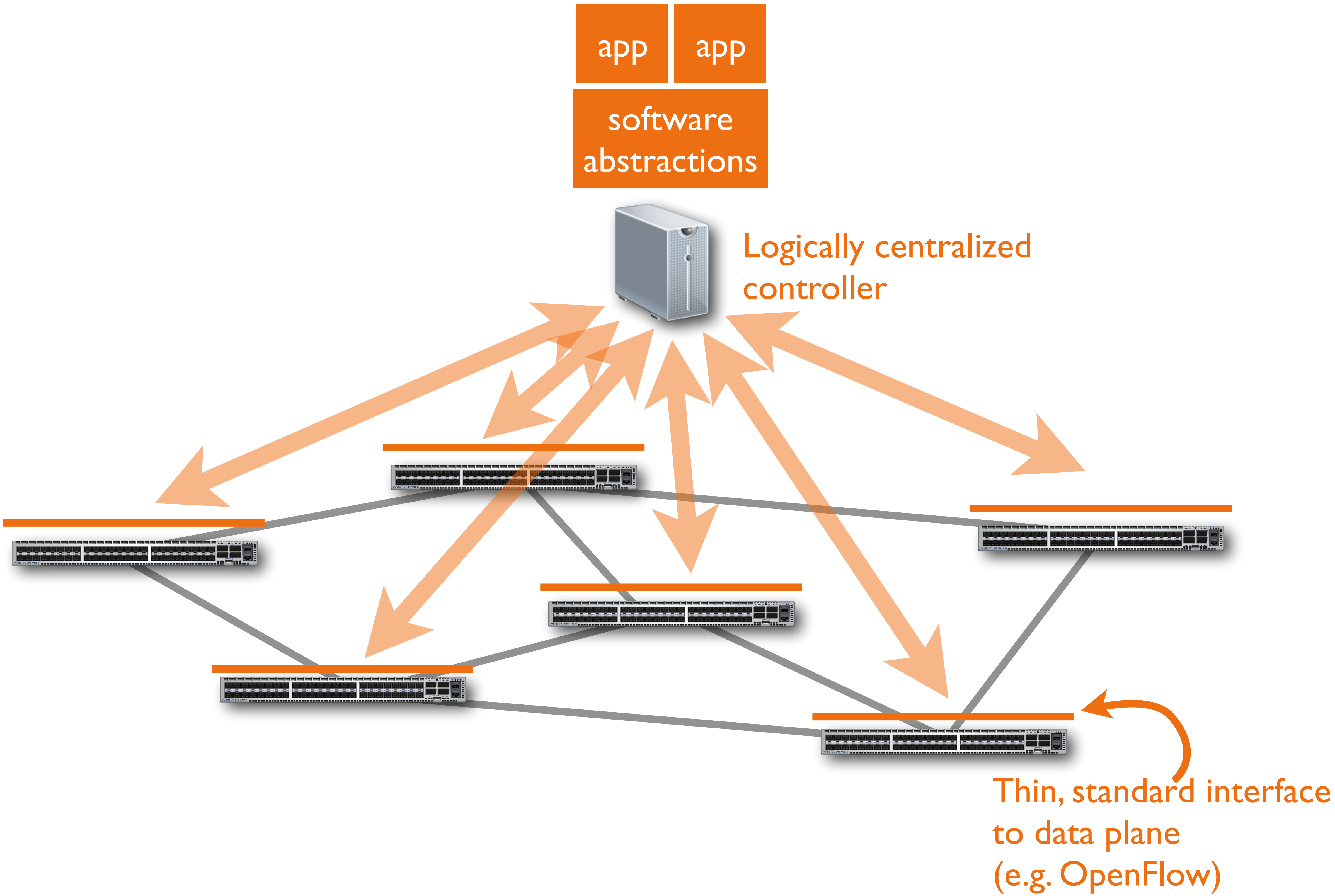
- Proved classes of networks that never deadlock
- Experimentally rare in practice!
- Last resort: heavyweight "fallback" like consistent updates [Reitblatt et al, SIGCOMM 2012]

Is it fast?

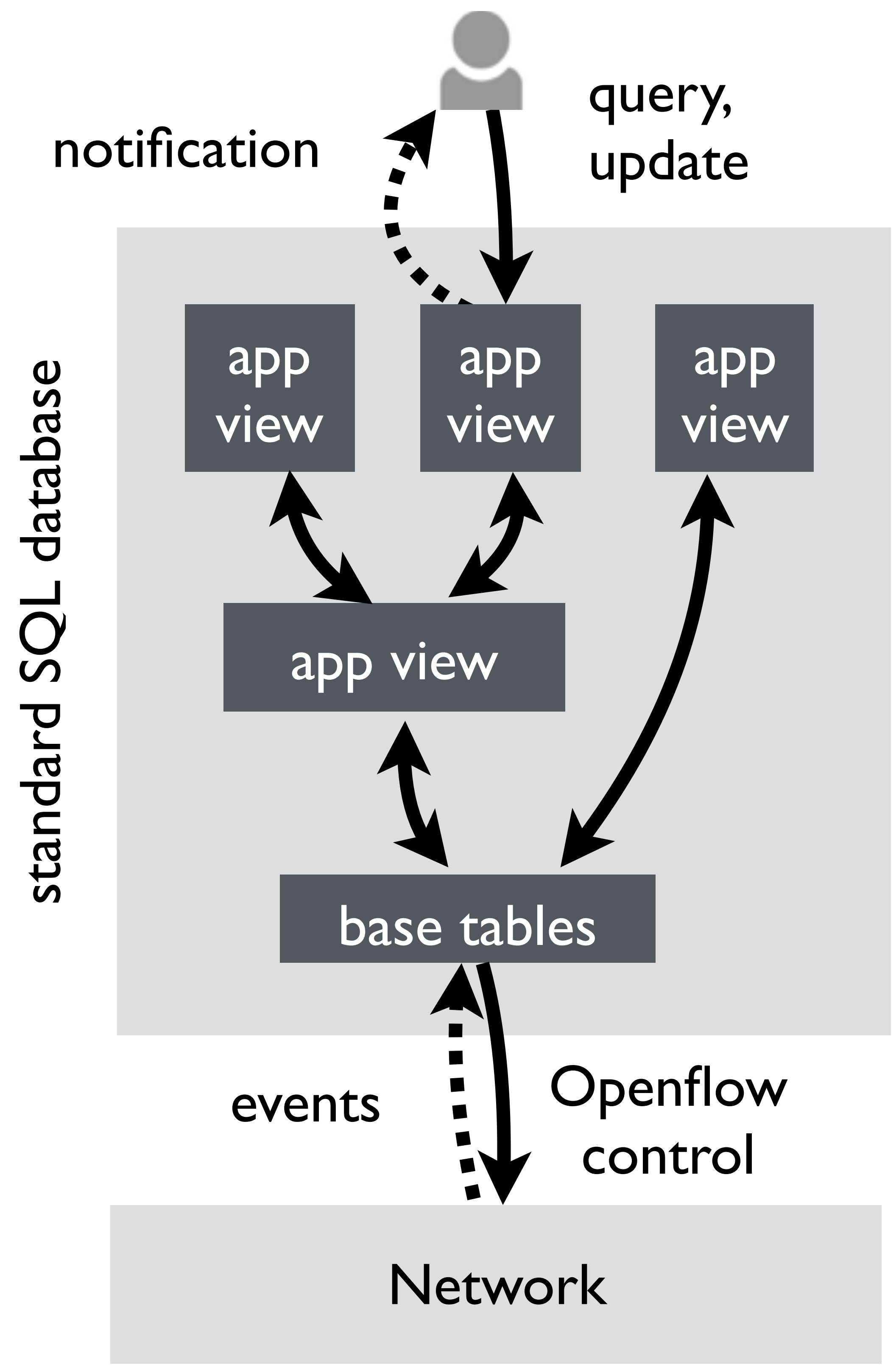


Software-defined Networks as Databases

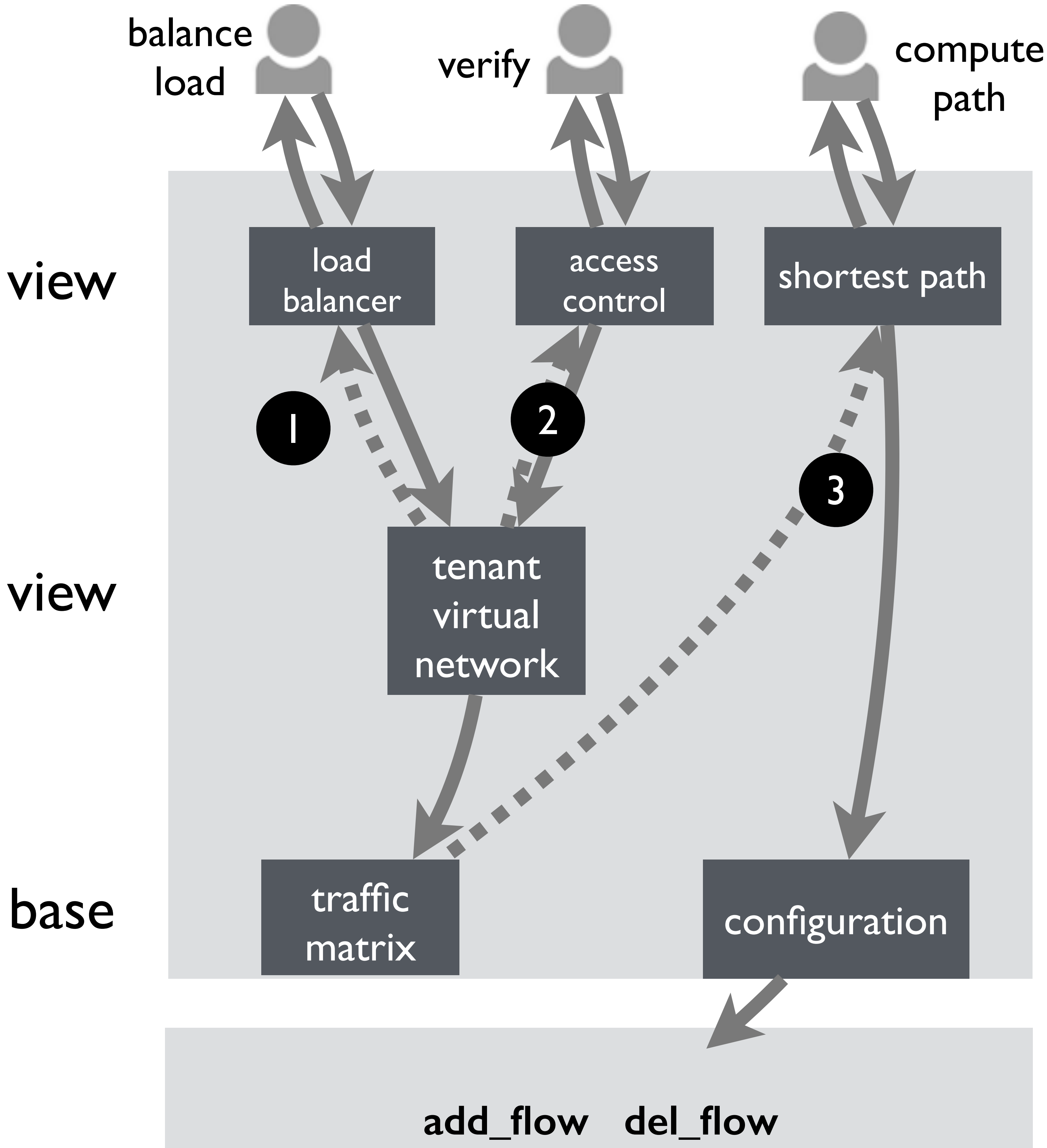
Software-Defined Networks



Ravel: database view of net control



Ravel example



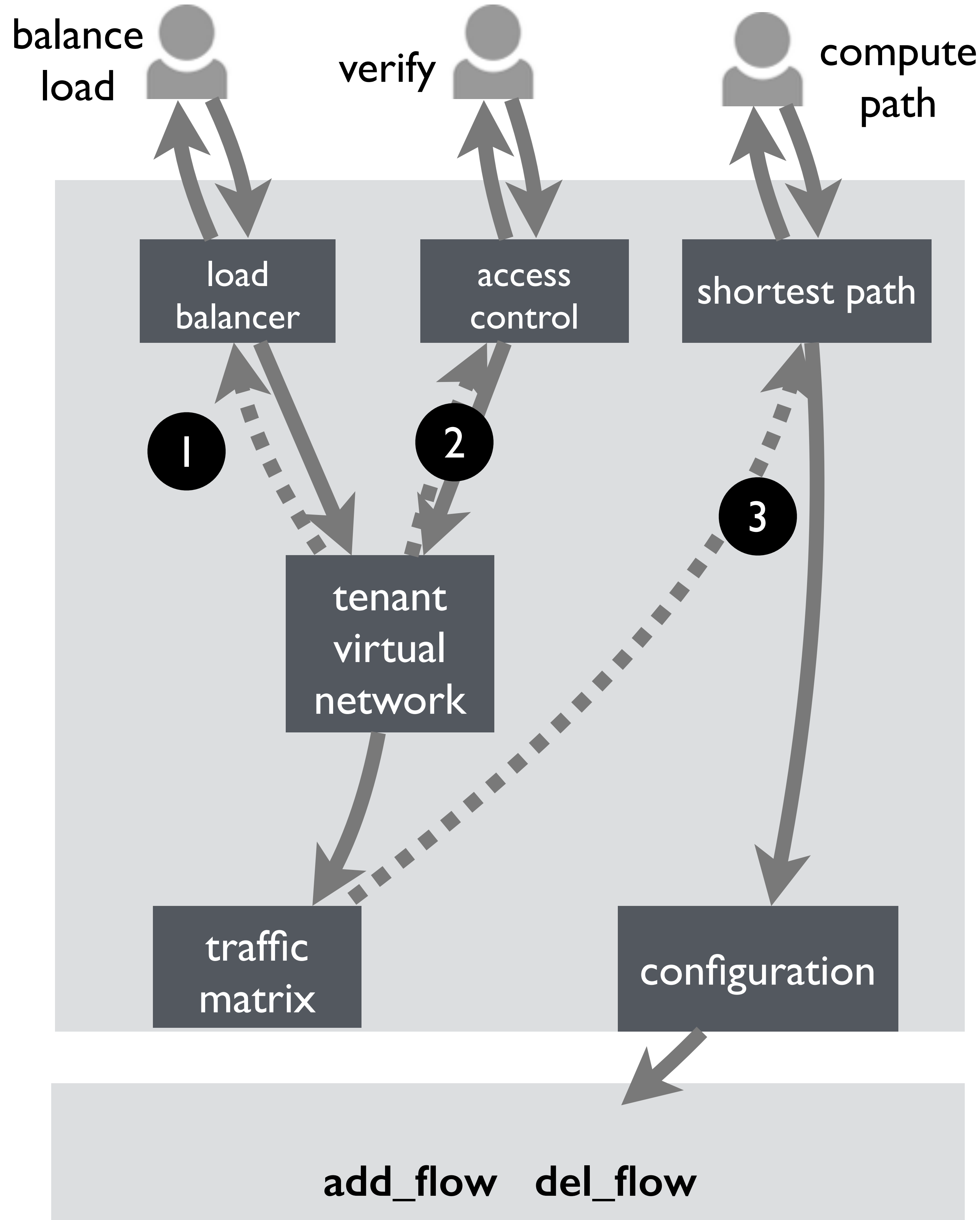
Key benefits

Abstraction via SQL

Orchestration via data-sharing

“Bonus” DB services

- verification, synthesis via view maintenance, update
- transaction processing



Impact of Network Verification

Configuration verification

Configuration verification

- [Al-Shaer2004, Bartal1999, Benson2009, Feamster2005, Yuan2006]

Firewall verification

- Margrave [Nelson, Barratt, Dougherty, Fisler, Krishnamurthi, LISA'10]

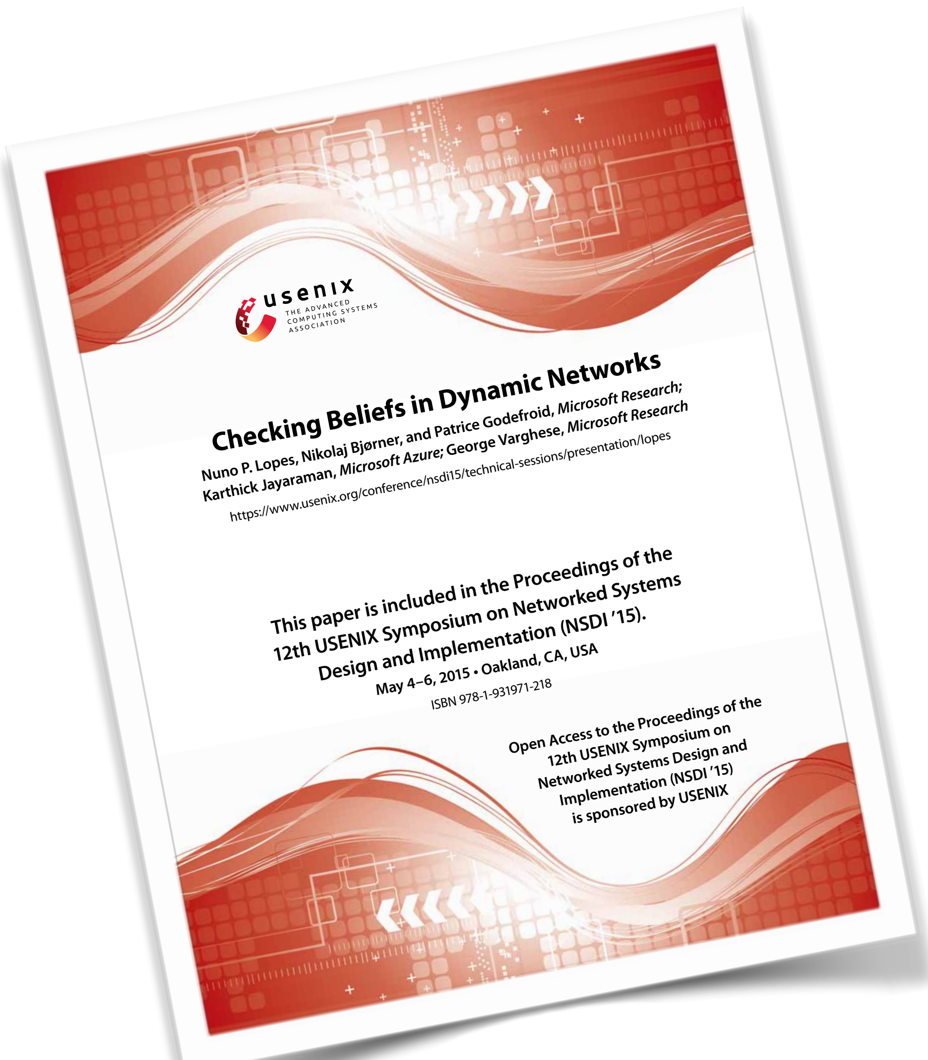
Data plane verification

- Static reachability in IP networks [Xie'05]
- FlowChecker [Al-Shaer, Al-Haj, SafeConfig '10]
- ConfigChecker [Al-Shaer, Al-Saleh, SafeConfig '11]

- Anteater [Mai, Khurshid, Agarwal, Caesar, G., King, SIGCOMM'11]
- VeriFlow [Khurshid, Zou, Zhou, Caesar, G., HotSDN'12, NSDI'13]
- CCG [Zhou, Jin, Croft, Caesar, G., NSDI'15]

- Header Space Analysis [Kazemian, Varghese, and McKeown, NSDI '12]
- NetPlumber [Kazemian, Chang, Zeng, Varghese, McKeown, Whyte, NSDI '13]
- Batfish [Fogel, Fung, Pedrosa, Walraed-Sullivan, Govindan, Mahajan, Millstein, NSDI'15]

DPV in the real world


Checking Beliefs in Dynamic Networks

Nuno P. Lopes, Nikolaj Bjørner, and Patrice Godefroid, *Microsoft Research;*
Karthick Jayaraman, *Microsoft Azure;* George Varghese, *Microsoft Research*

https://www.usenix.org/conference/nsdi15/technical-sessions/presentation/lopes

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veriflow
SYSTEMS

Future research: Richer models

Software pipelines

Stateful Networks

Verifiable SDN Controllers

Higher layer concepts
(roles, people, applications)

Thanks!