Data Plane Verification and Anteater

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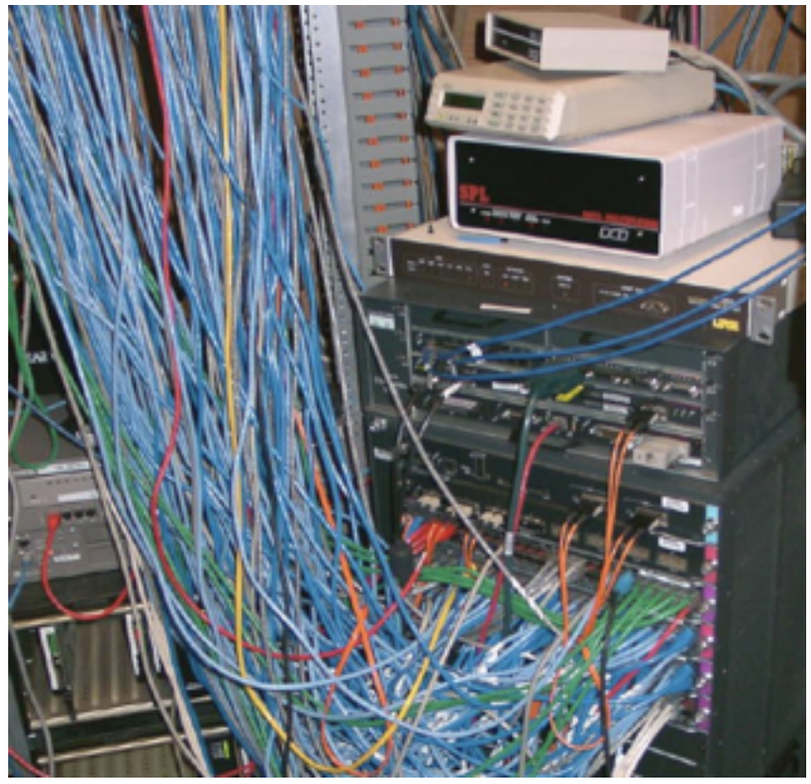
Data Plane Verification

Managing networks is challenging

Production networks are complex

- Security policies
- Traffic engineering
- Legacy devices
- Protocol inter-dependencies
- …



- Even well-managed networks have downtime & security vulnerabilities
- Few good tools to ensure all networking components working together correctly

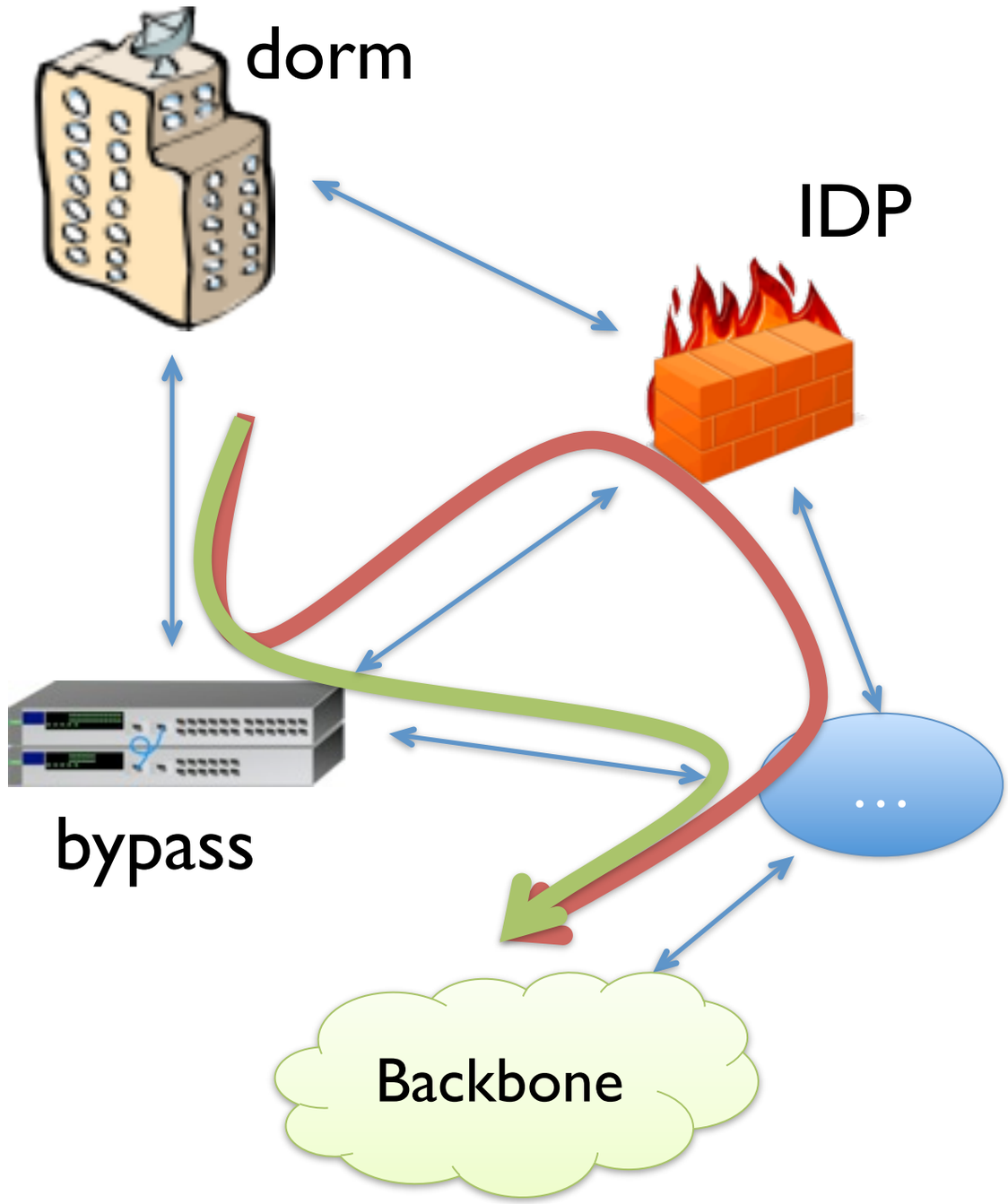
A real example from UIUC

Previously, an intrusion detection and prevention (IDP) device inspected all traffic to/from dorms

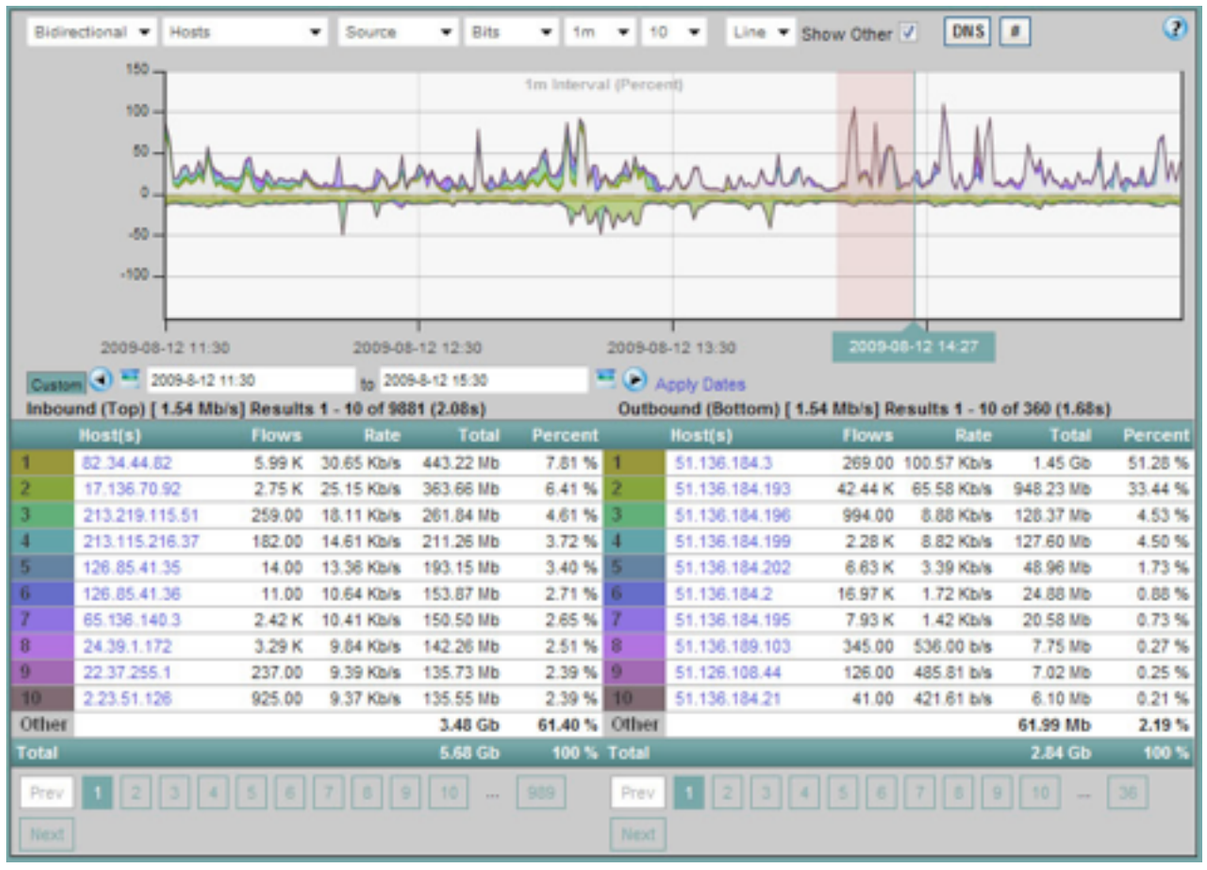
IDP couldn't handle load; added bypass

- IDP only inspected traffic between dorm and campus
- Seemingly simple changes

How do you know if it worked?



Understanding your network



	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 %

Flow monitoring

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

```
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
!
```

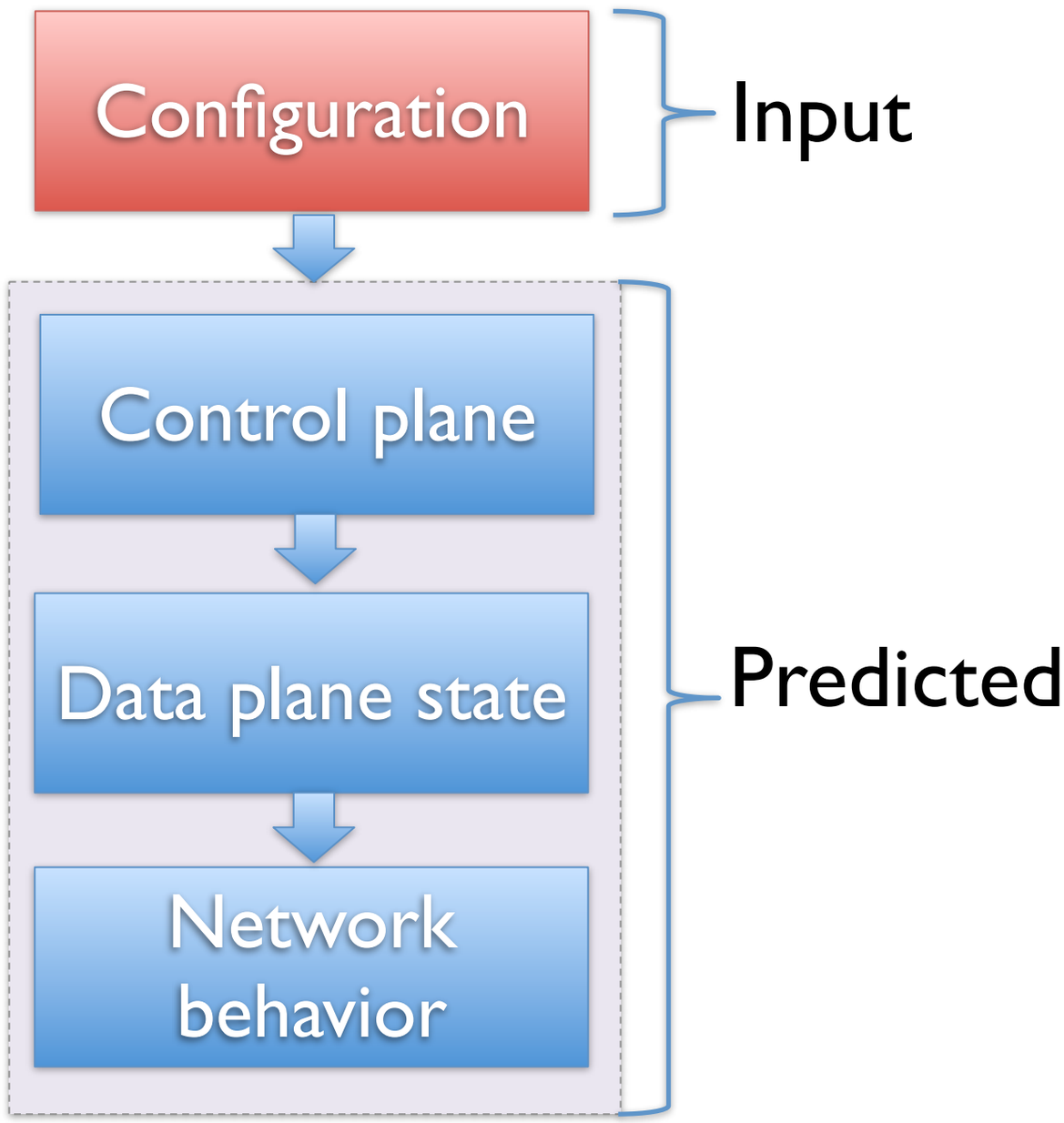
Configuration verification

Past approach: Config. verification

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

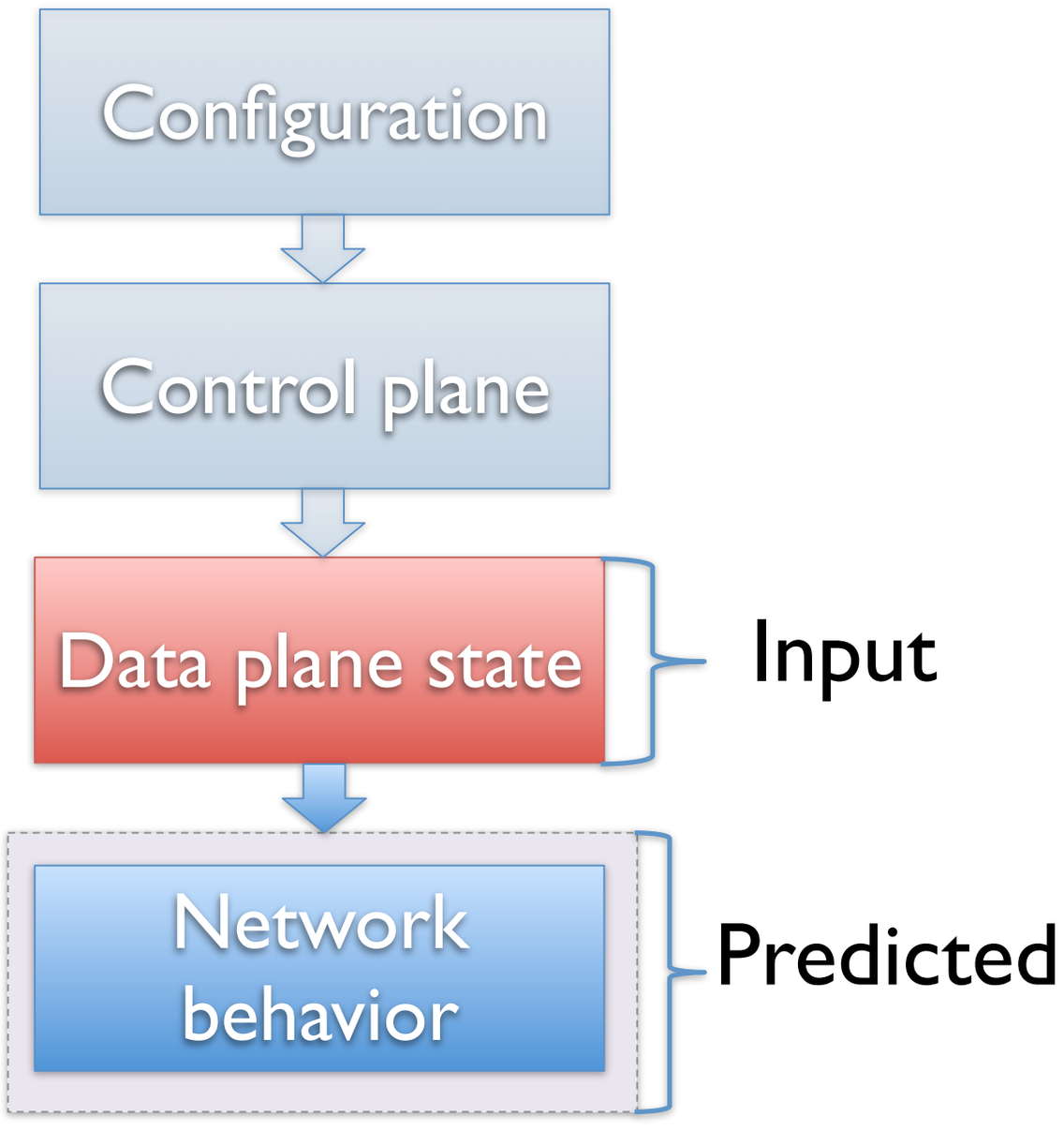
Margrave for firewalls [Nelson, Barratt, Dougherty, Fisler, Krishnamurthi, LISA'10]

UCLA+MSR [in progress...]



Data plane verification

Our approach: Verify the network as close as possible to its actual behavior



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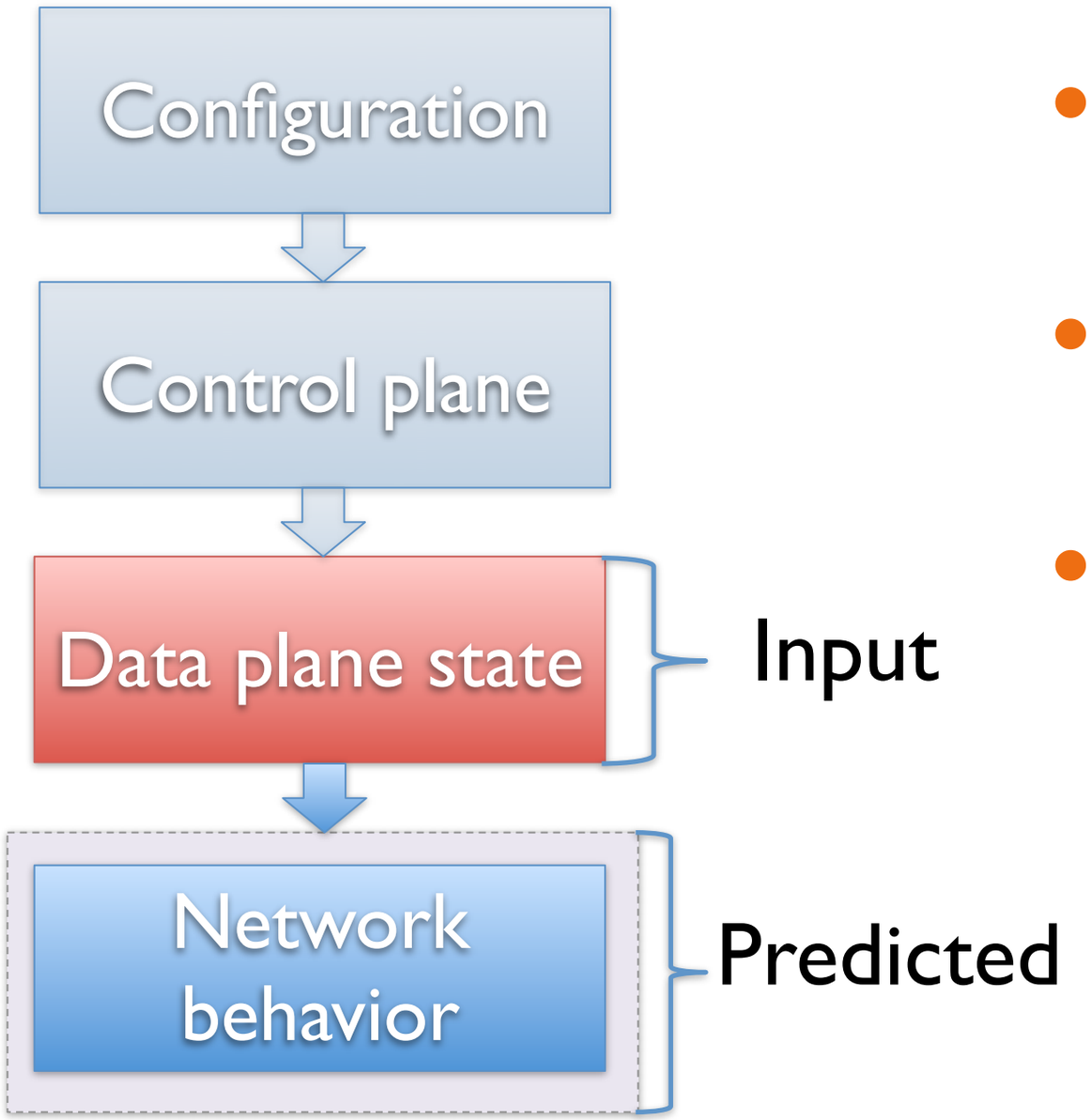
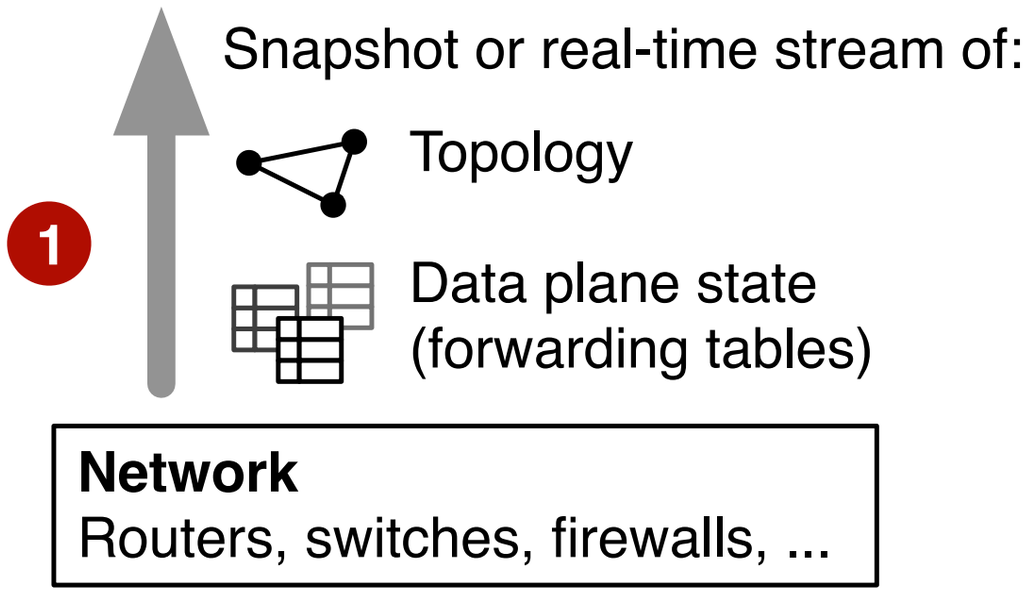
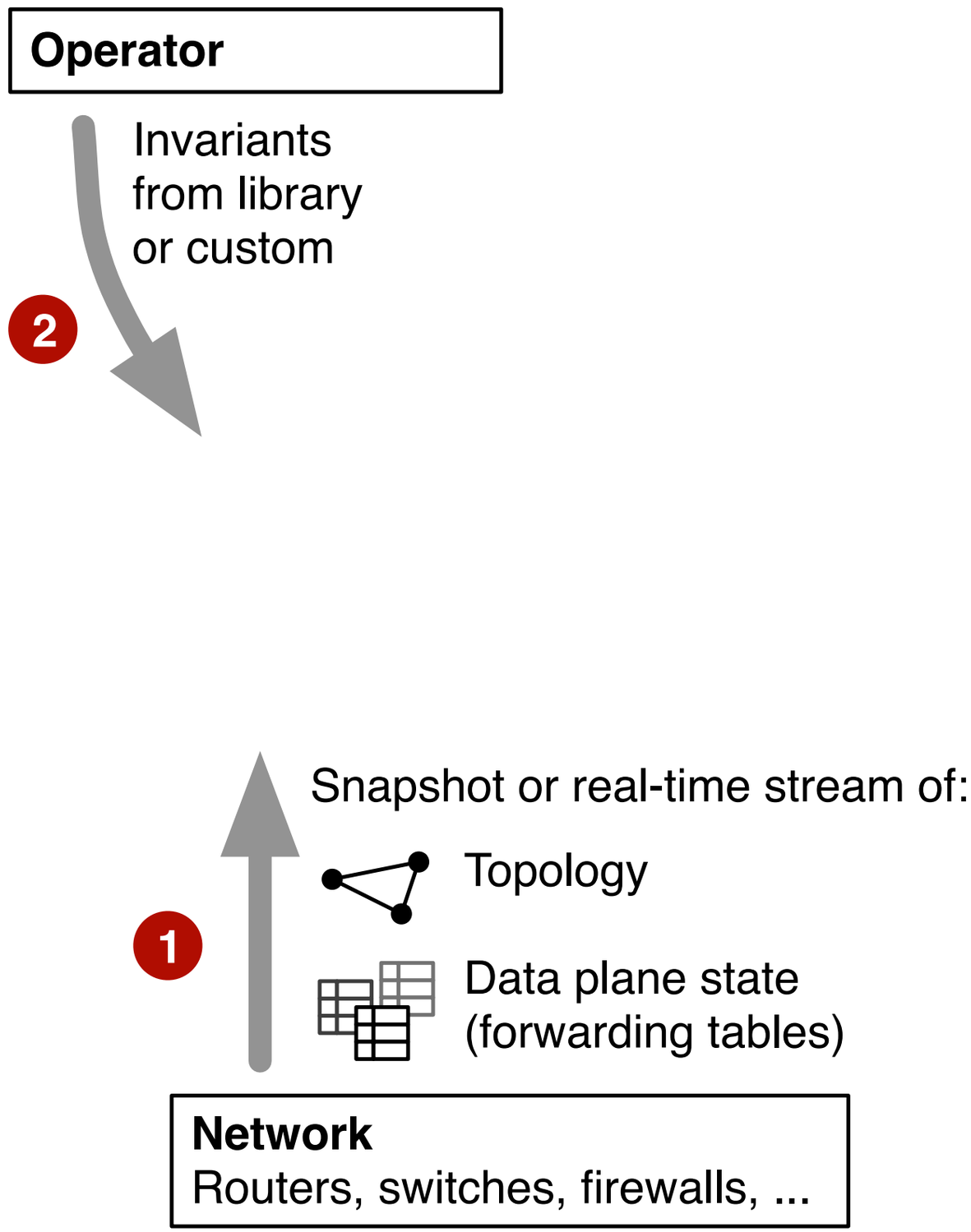


- Simpler, unified analysis across control protocols
- Catch bugs in control software
- Checks current snapshot

Architecture overview



Architecture overview



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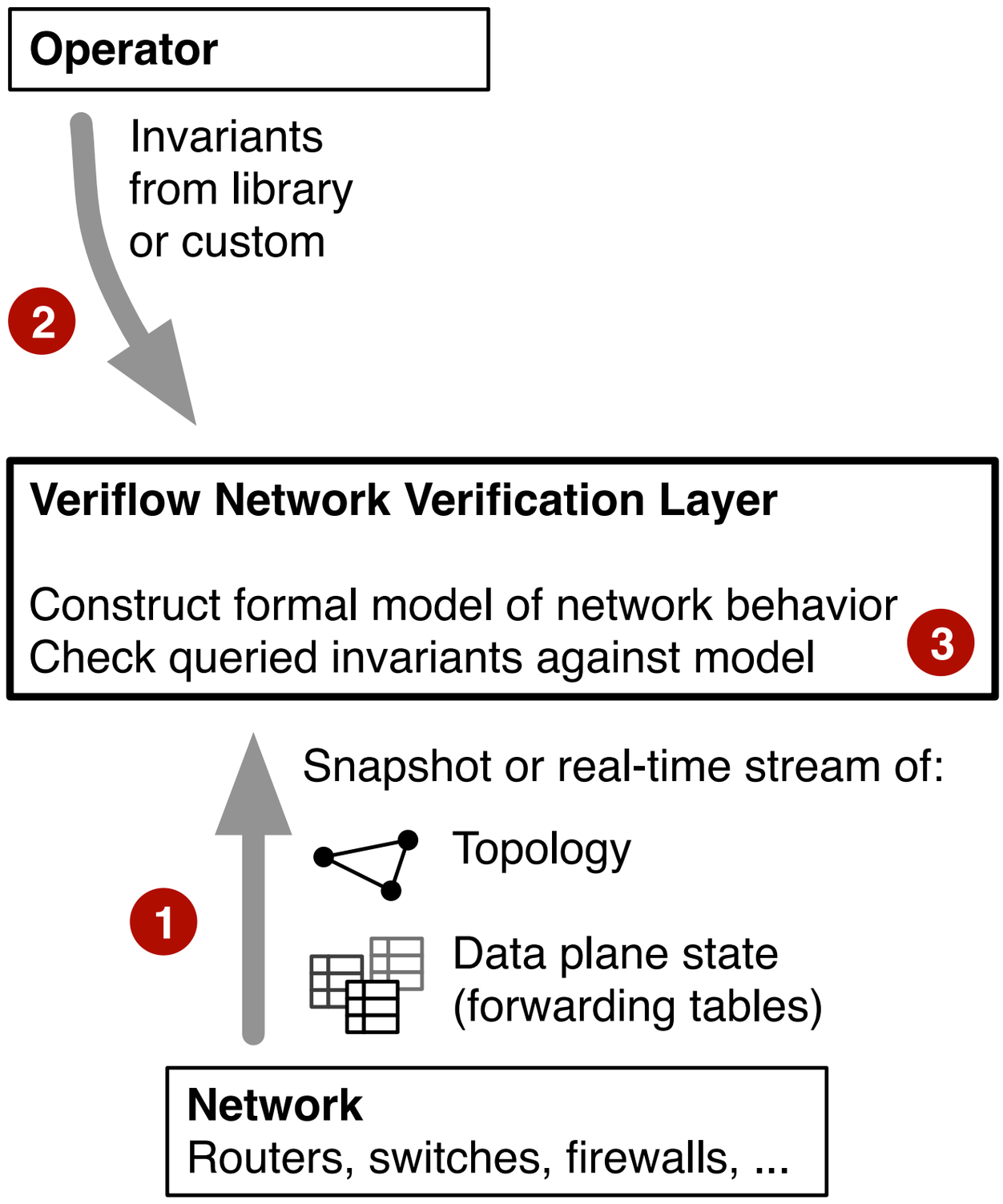
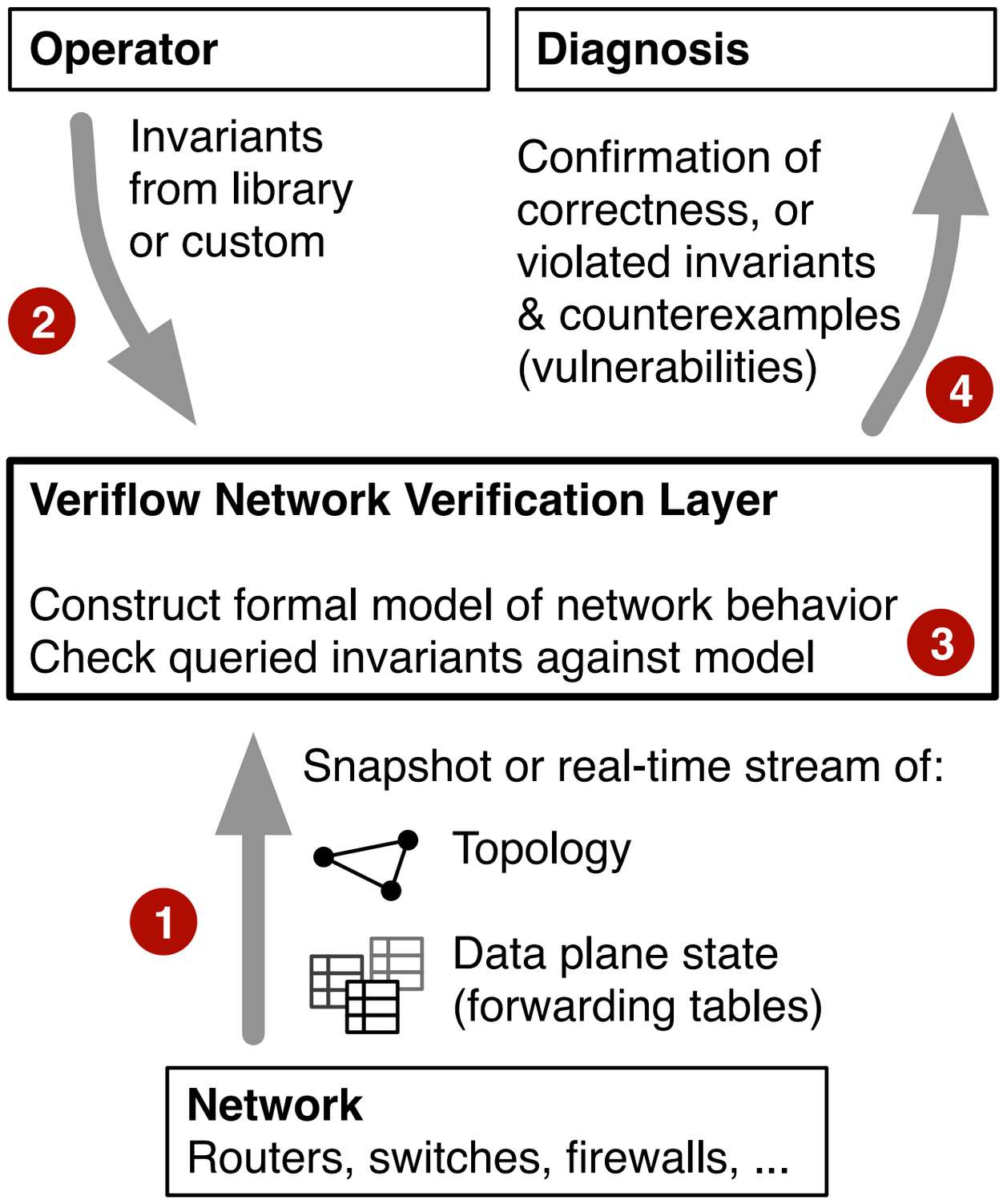


Architecture overview



Control software bugs

78 bugs sampled randomly from Bugzilla repository of Quagga (open source software router)

67 could cause data plane effect

- Under heavy load, Quagga 0.96.5 fails to update Linux kernel's routing tables
- In Quagga 0.99.5, a BGP session could remain active after it has been shut down

11 would not affect data plane

- Mgmt. terminal hangs in Quagga 0.96.4 on "show ip bgp"

Q: Where does SDN fit in?

Unified data plane interface

- Helpful, but not absolutely necessary

Centralized control of network

- Critical for real time verification

Our Two Tools

Anteater

- [Mai, Khurshid, Agarwal, Caesar, Godfrey, King, SIGCOMM 2011]
- Offline verification of data plane

Veriflow

- [Khurshid, Zhou, Caesar, Godfrey, HotSDN 2012]
- [Khurshid, Zou, Zhou, Caesar, Godfrey, NSDI 2013]
- Online real-time verification of data plane
- Interoperates with OpenFlow controller

Anteater

Modeling the network is nontrivial

What if only longest prefix match rules on one field?

Modeling the network is nontrivial

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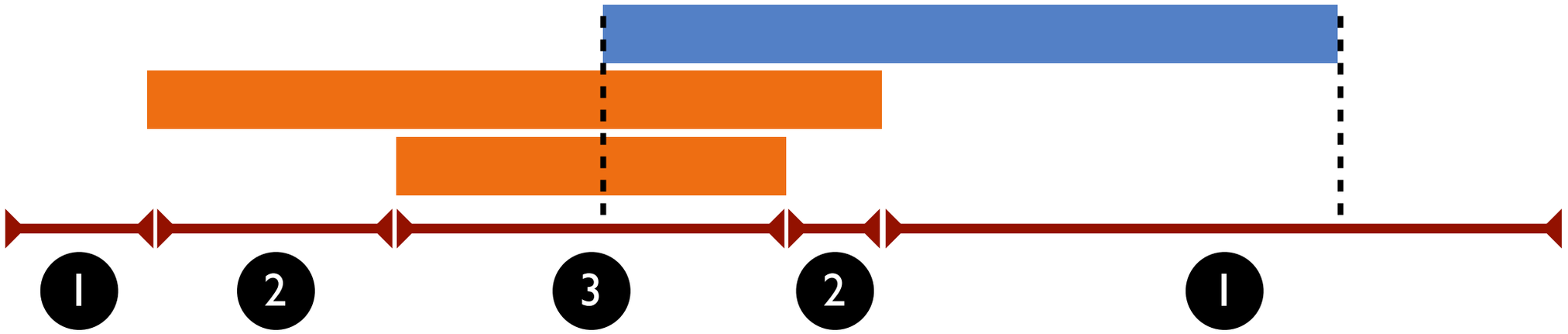

Modeling the network is nontrivial

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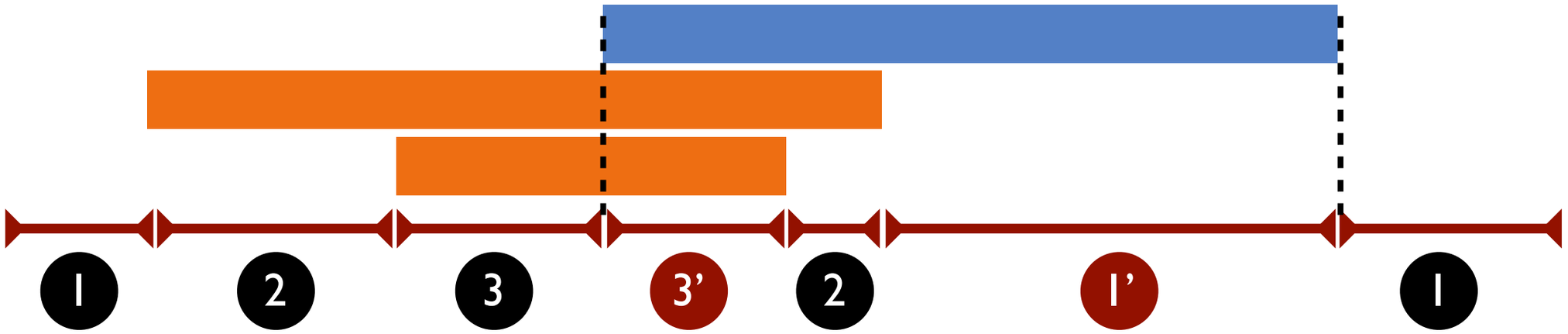


equivalence classes ≤ 2 • #rules

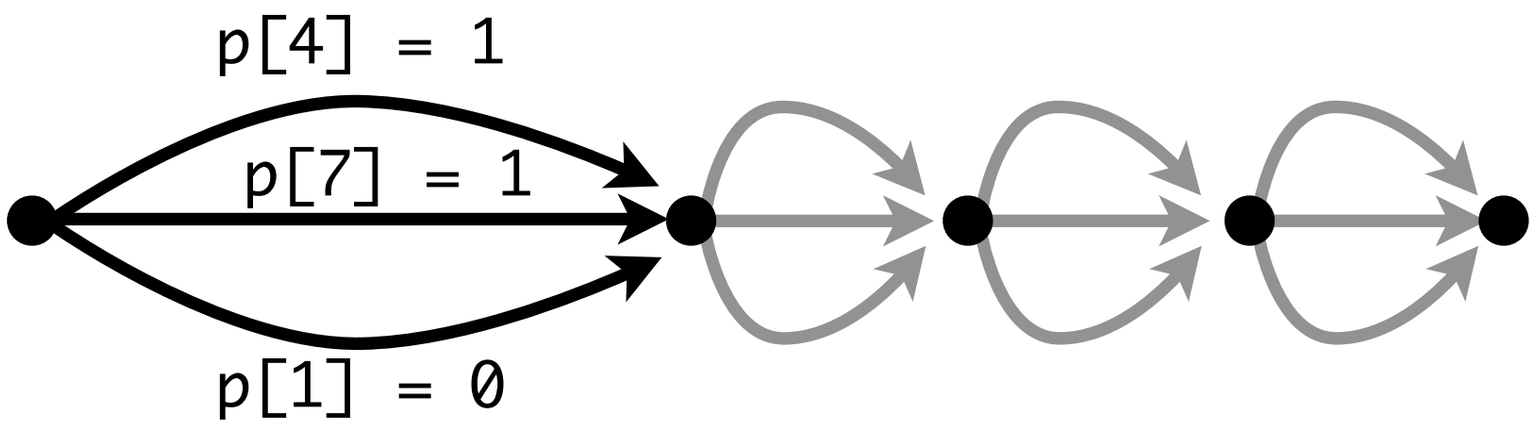
Modeling the network is nontrivial

What if only longest prefix match rules on one field?

- easy: reachability is polynomial time

Add one-bit packet filters: `"if p[43] = 0 then drop"`

- reachability is NP-complete



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

Modeling the network is nontrivial

What if only longest prefix match rules on one field?

- easy: reachability is polynomial time

Add one-bit packet filters: `"if p[43] = 0 then drop"`

- reachability is NP-complete

Add packet header transformations...

- even harder (depends on assumptions, e.g. packet header length bound)

Anteater's solution

Express data plane and invariants as SAT

- ...up to some max # hops

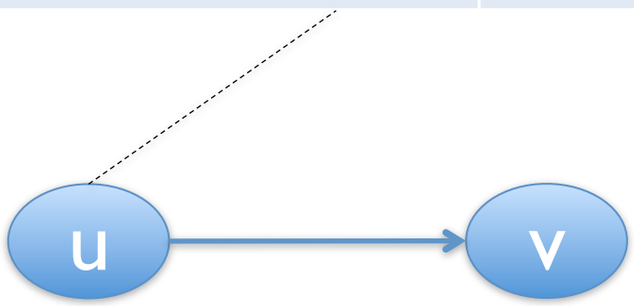
Check with off-the-shelf SAT solver (Boolector)

Data plane as boolean functions

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

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

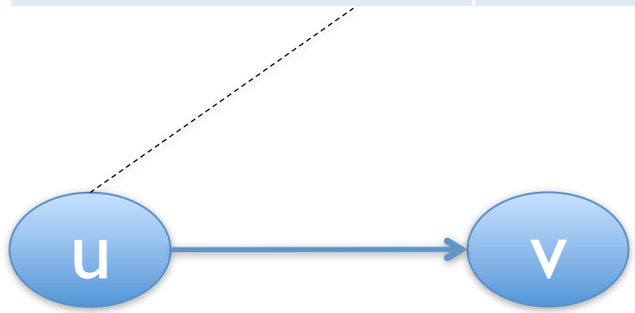
Destination	Iface
10.1.1.0/24	v



P(u, v) = dst_ip ∈10.1.1.0/24

Simpler example

Destination	Iface
0.0.0.0/0	v

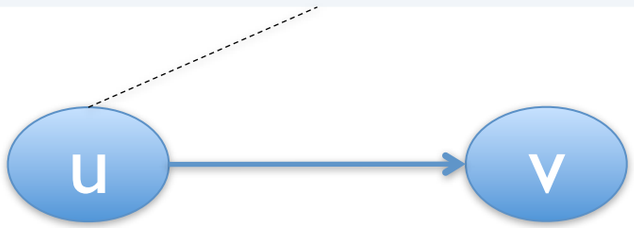


P(u, v) = true

Default routing

Some more examples

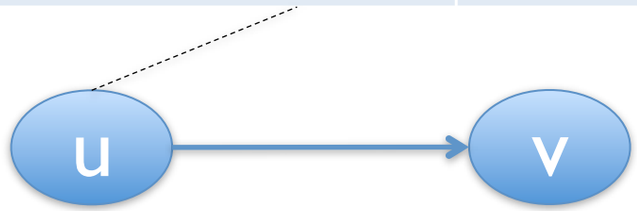
Destination	Iface
10.1.1.0/24	v
Drop port 80 to v	



$P(u, v) = dst\_ip \in 10.1.1.0/24 \wedge dst\_port \neq 80$

Packet filtering

Destination	Iface
10.1.1.0/24	v
10.1.1.128/25	v’
10.1.2.0/24	v



$P(u, v) = (dst\_ip \in 10.1.1.0/24 \wedge dst\_ip \notin 10.1.1.128/25) \vee dst\_ip \in 10.1.2.0/24$

Longest prefix matching

Reachability as SAT solving

Goal: reachability from u to w

C = (P(u, v) ∧ P(v,w)) is satisfiable

⇔∃A packet that makes P(u,v) ∧ P(v,w) true

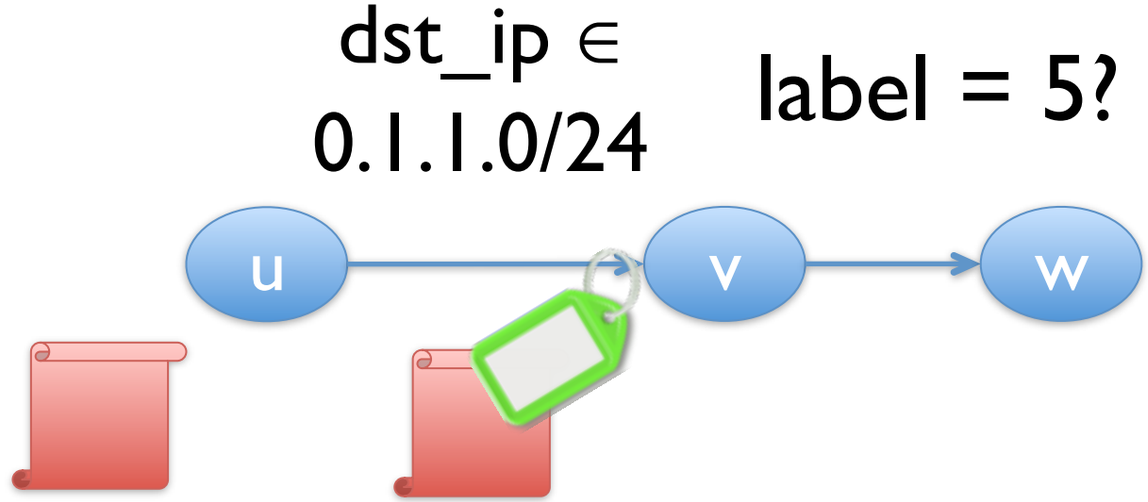
⇔∃A packet that can flow over (u, v) and (v,w)

⇔ u can reach w

- 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

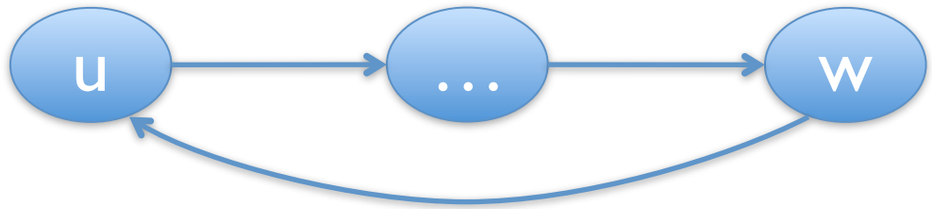
over adjacent packet versions

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

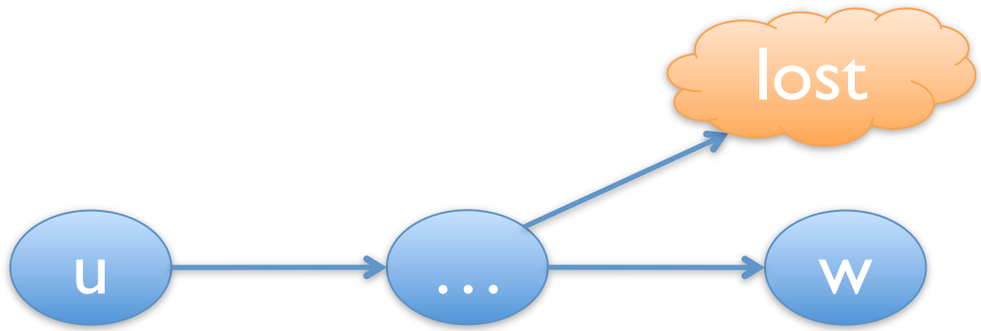
More generally: $p_{i+1} = f(p_i)$

Invariants

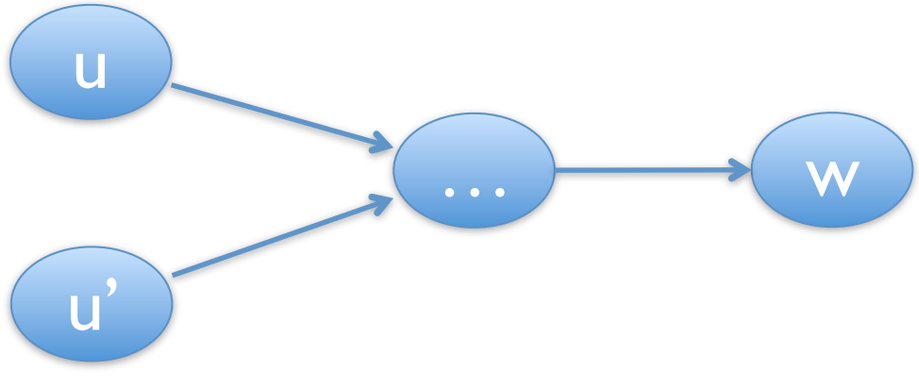
Loop detection



Packet loss (black holes)



Consistency



Experience with the UIUC Network

Experiences with UIUC network

Evaluated Anteater with UIUC campus 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
False pos.	0	4	1
Total alerts	9	17	2

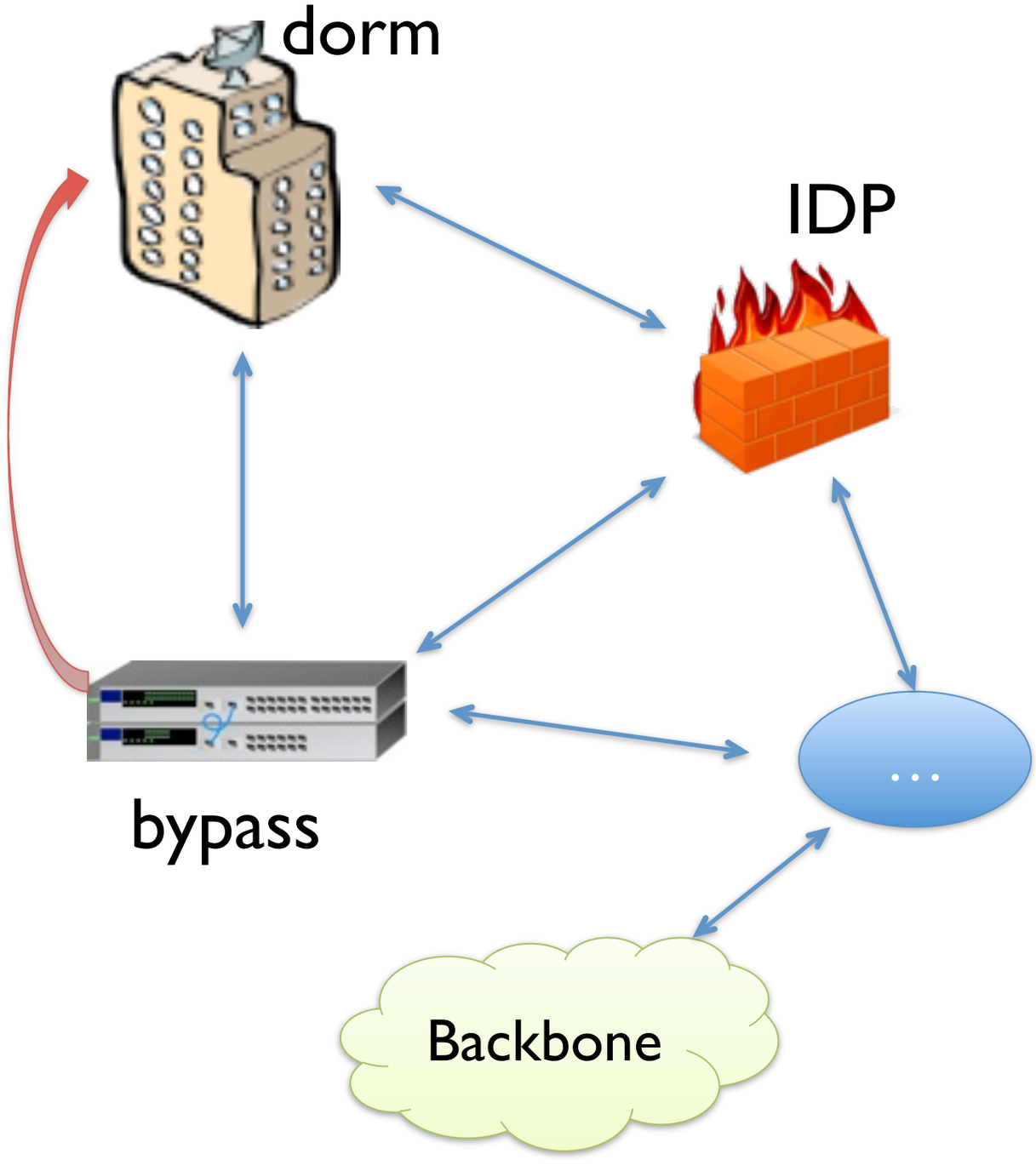
Forwarding loops

IDP was overloaded, operator introduced bypass

- IDP only inspected traffic for campus

bypass routed campus traffic to IDP through static routes

Introduced 9 loops



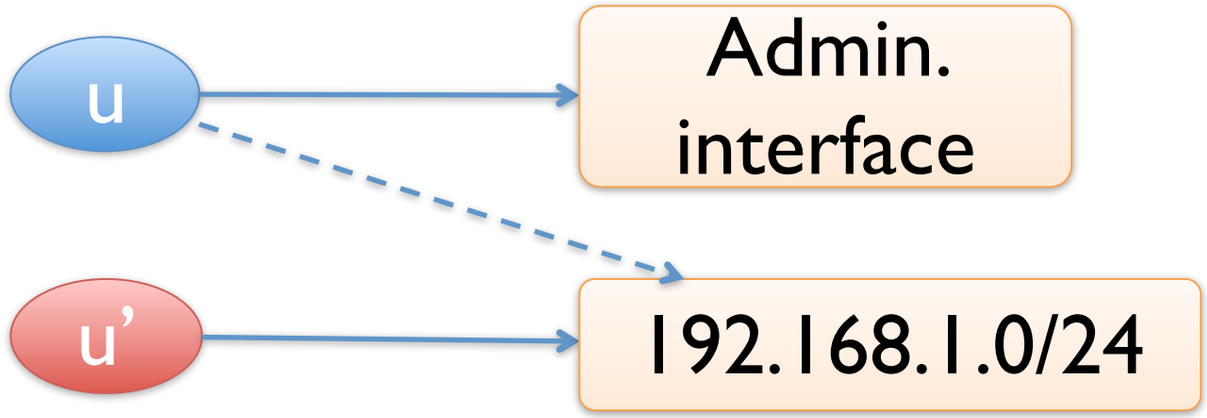
Bugs found by other invariants

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

Refs: Offline Data Plane Verification

Static reachability in IP networks [Bush et al'03, Xie et al'05]

FlowChecker [Al-Shaer, Al-Haj, SafeConfig '10]

ConfigChecker [Al-Shaer, Al-Saleh, SafeConfig '11]

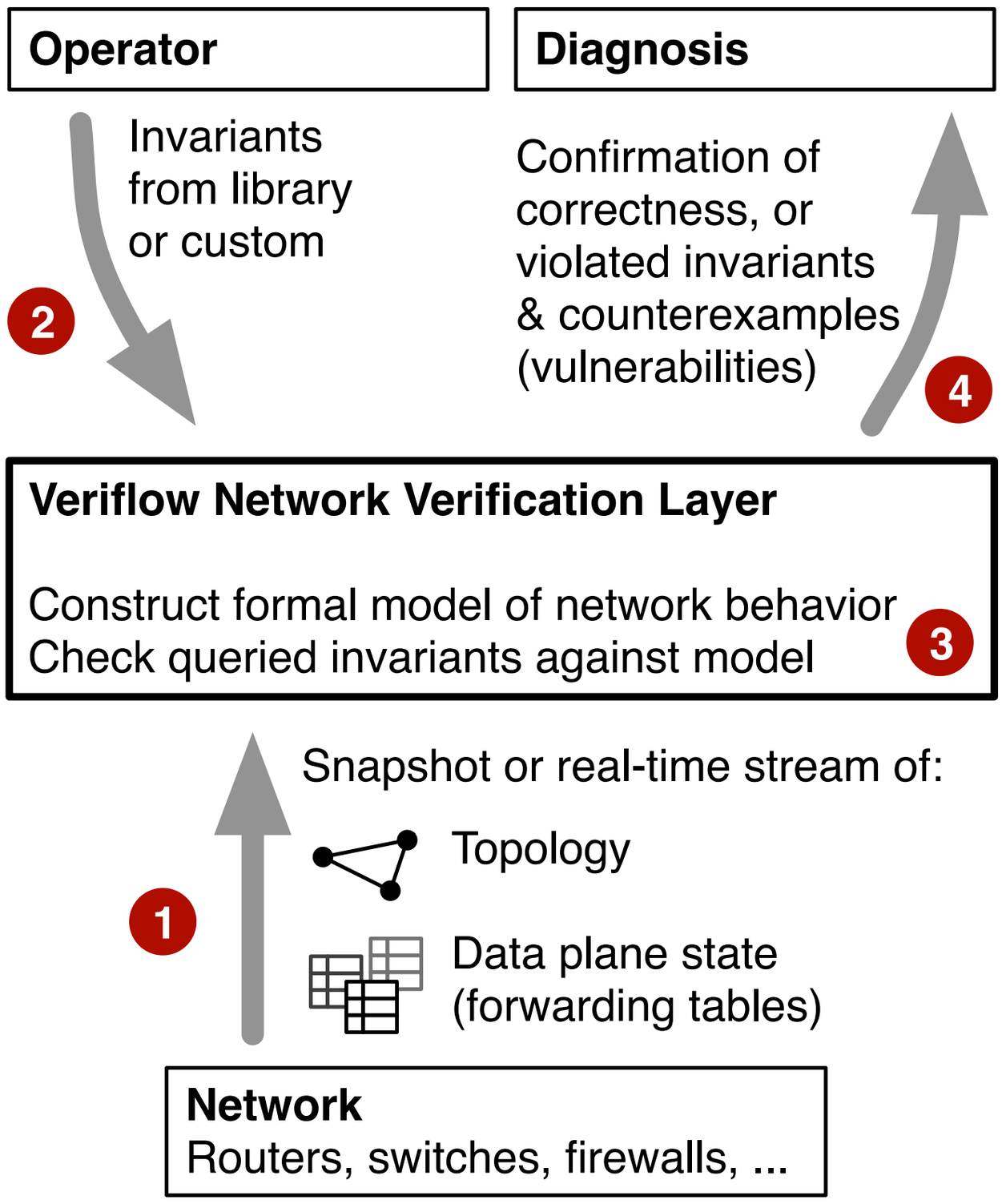
Anteater [SIGCOMM'11] http://code.google.com/p/anteater

Header Space Analysis [Kazemian, Varghese, McKeown, NSDI '12]

Abstractions for Network Update [Reitblatt, Foster, Rexford, Schlesinger, Walker, SIGCOMM'12]

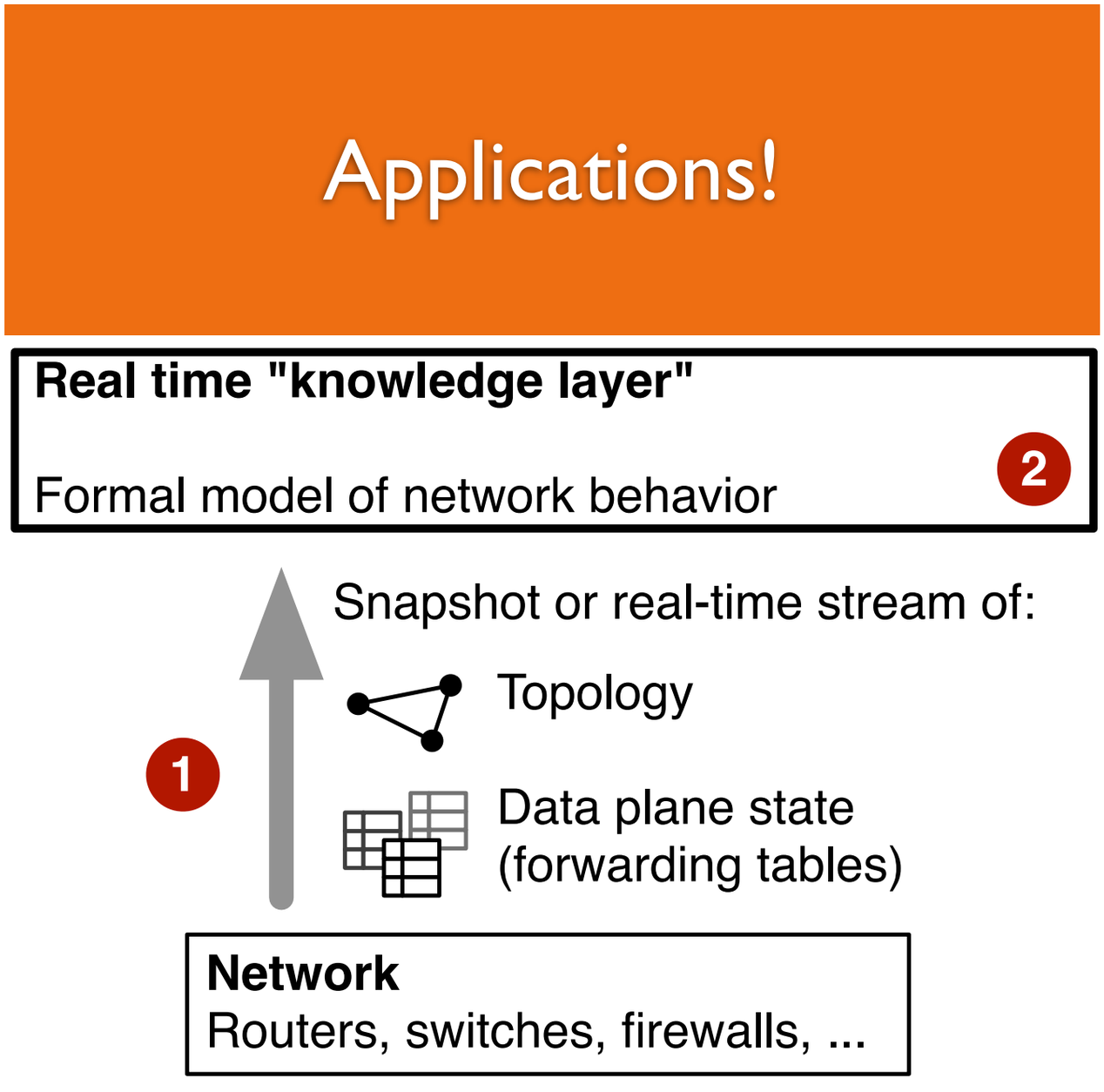
Verification of Computer Switching Networks: An Overview [Shuyun Zhang, Sharad Malik, Rick McGeer]

Looking ahead: An Opportunity



Looking ahead: An Opportunity

Applications!



Data Plane Verification Discussion

1. Expressing policies can be hard. How can we make network verification easy for operators?

2. What apps can we build on top of a real-time understanding of network's behavior?

3. Can DPV be extended to stateful networks?

4. How should DPV connect with policy generation?

5. Can formal methods dramatically improve network reliability?

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