Lecture 12: Network Verification

CS 234 / NetSys 210: Advanced Computer Networks

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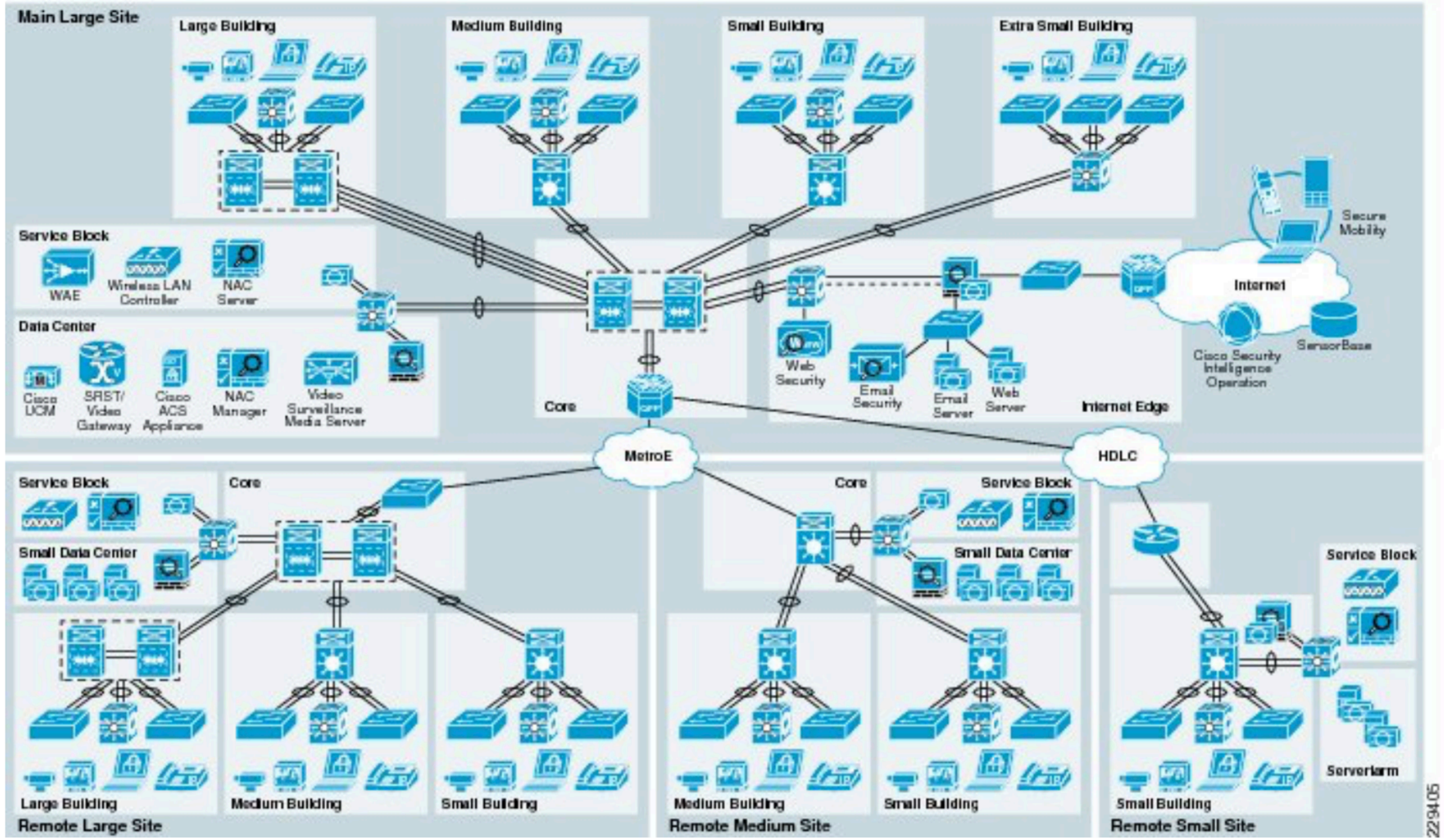
This lecture uses material from Veriflow talk and tutorial by Brighten Godfrey and Santhosh Prabhu, and slides by George Varghese

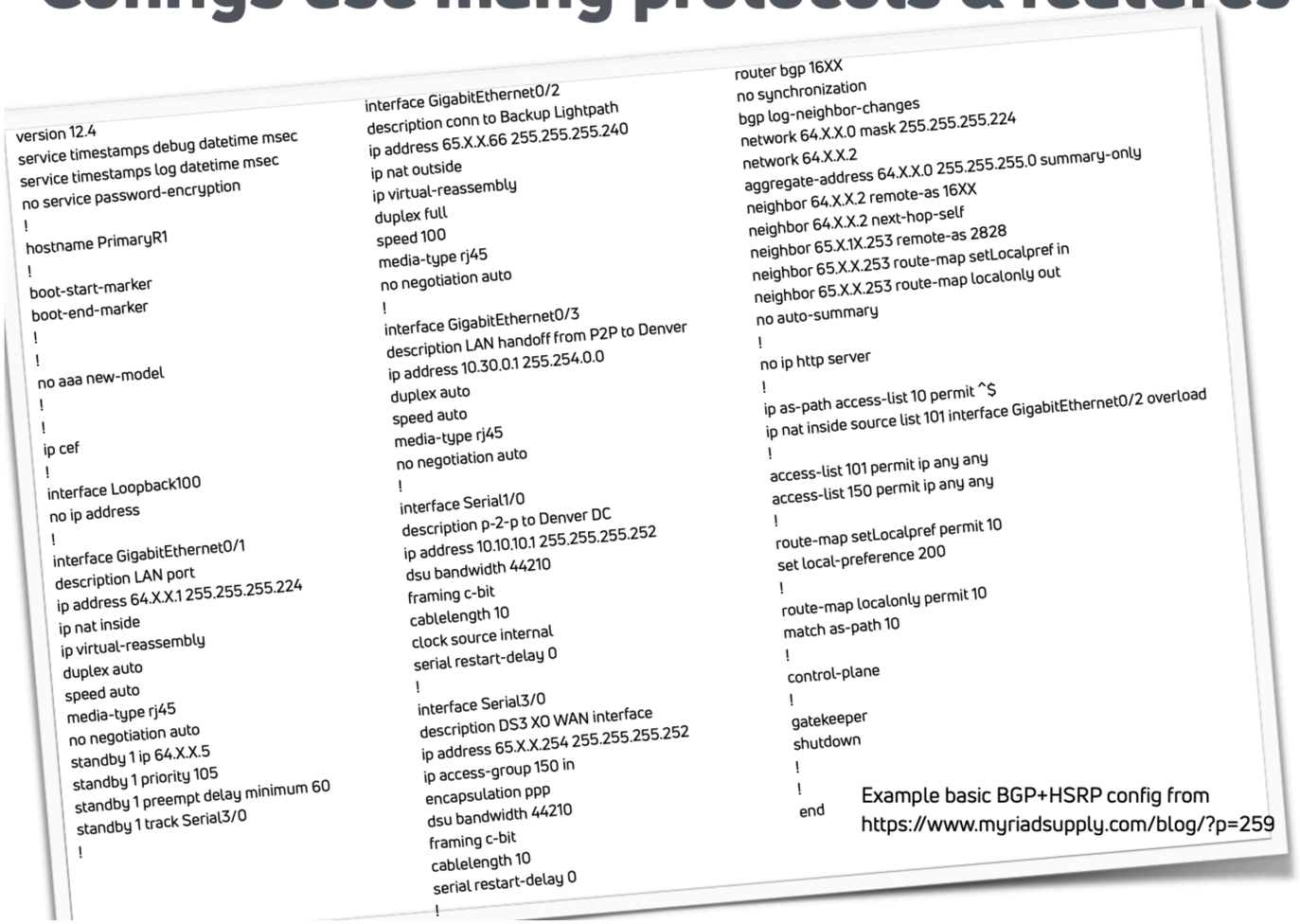
Networks are so complex!



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

Complex configurations

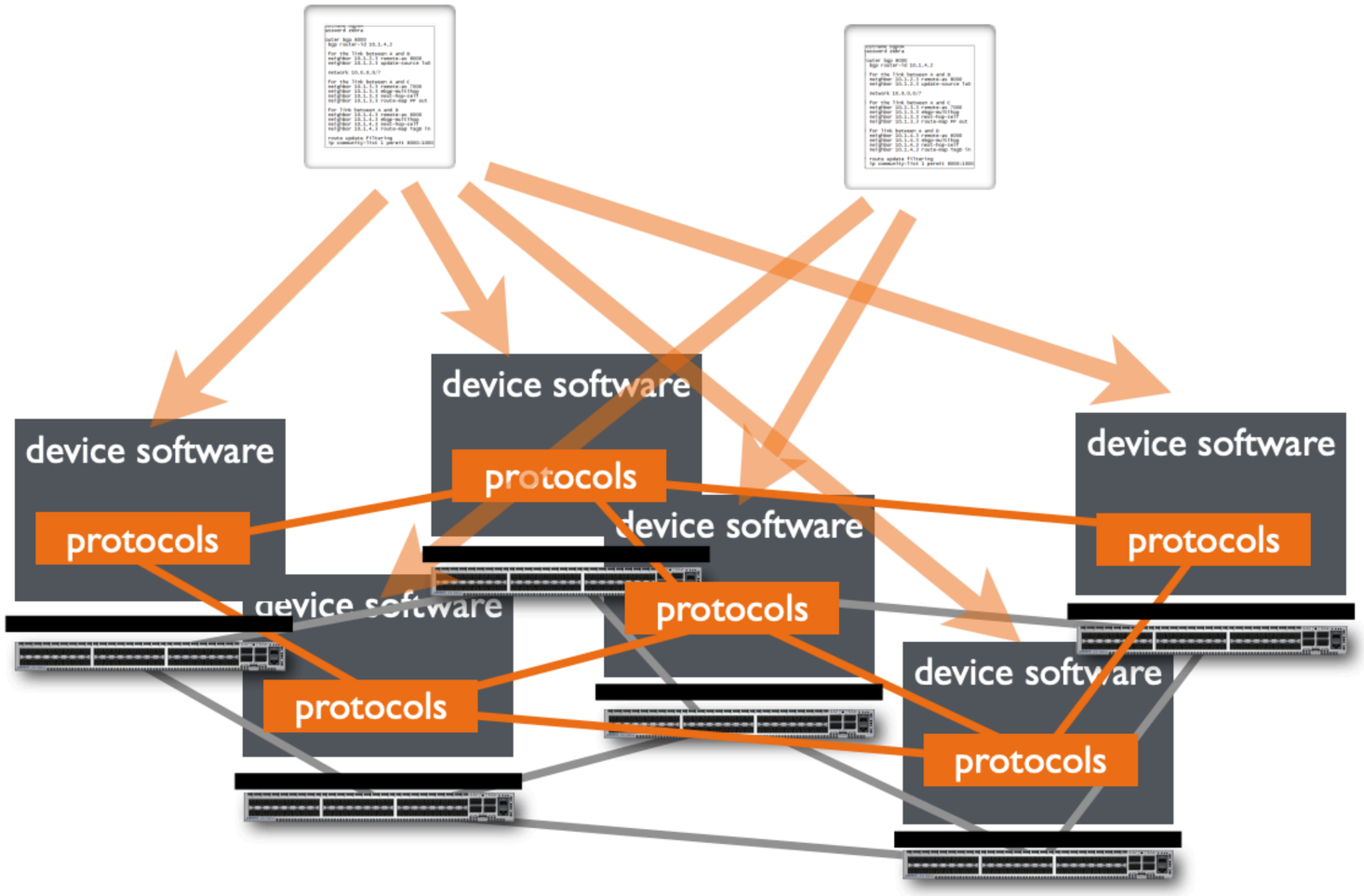
Configs use many protocols & features



```
version 12.4
service timestamps debug datetime msec
service timestamps log datetime msec
no service password-encryption
!
hostname PrimaryR1
!
boot-start-marker
boot-end-marker
!
!
no aaa new-model
!
!
ip cef
!
interface Loopback100
no ip address
!
interface GigabitEthernet0/1
description LAN port
ip address 64.X.X.1 255.255.255.224
ip nat inside
ip virtual-reassembly
duplex auto
speed auto
media-type rj45
no negotiation auto
standby 1 ip 64.X.X.5
standby 1 priority 105
standby 1 preempt delay minimum 60
standby 1 track Serial3/0
!
interface GigabitEthernet0/2
description conn to Backup Lightpath
ip address 65.X.X.66 255.255.255.240
ip nat outside
ip virtual-reassembly
duplex full
speed 100
media-type rj45
no negotiation auto
!
interface GigabitEthernet0/3
description LAN handoff from P2P to Denver
ip address 10.30.0.1 255.254.0.0
duplex auto
speed auto
media-type rj45
no negotiation auto
!
interface Serial1/0
description p-2-p to Denver DC
ip address 10.10.10.1 255.255.255.252
dsu bandwidth 44210
framing c-bit
cablelength 10
clock source internal
serial restart-delay 0
!
interface Serial3/0
description DS3 XO WAN interface
ip address 65.X.X.254 255.255.255.252
ip access-group 150 in
encapsulation ppp
dsu bandwidth 44210
framing c-bit
cablelength 10
serial restart-delay 0
!
router bgp 16XX
no synchronization
bgp log-neighbor-changes
network 64.X.X.0 mask 255.255.255.224
network 64.X.X.2
aggregate-address 64.X.X.0 255.255.255.0 summary-only
neighbor 64.X.X.2 remote-as 16XX
neighbor 64.X.X.2 next-hop-self
neighbor 65.X.1X.253 remote-as 2828
neighbor 65.X.X.253 route-map setLocalpref in
neighbor 65.X.X.253 route-map localonly out
no auto-summary
!
no ip http server
!
ip as-path access-list 10 permit ^$
ip nat inside source list 101 interface GigabitEthernet0/2 overload
!
access-list 101 permit ip any any
access-list 150 permit ip any any
!
route-map setLocalpref permit 10
set local-preference 200
!
route-map localonly permit 10
match as-path 10
!
control-plane
!
gatekeeper
shutdown
!
!
end
```

Example basic BGP+HSRP config from
https://www.myriadsupply.com/blog/?p=259

Distributed Route Computation



Networks are Difficult to Change

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

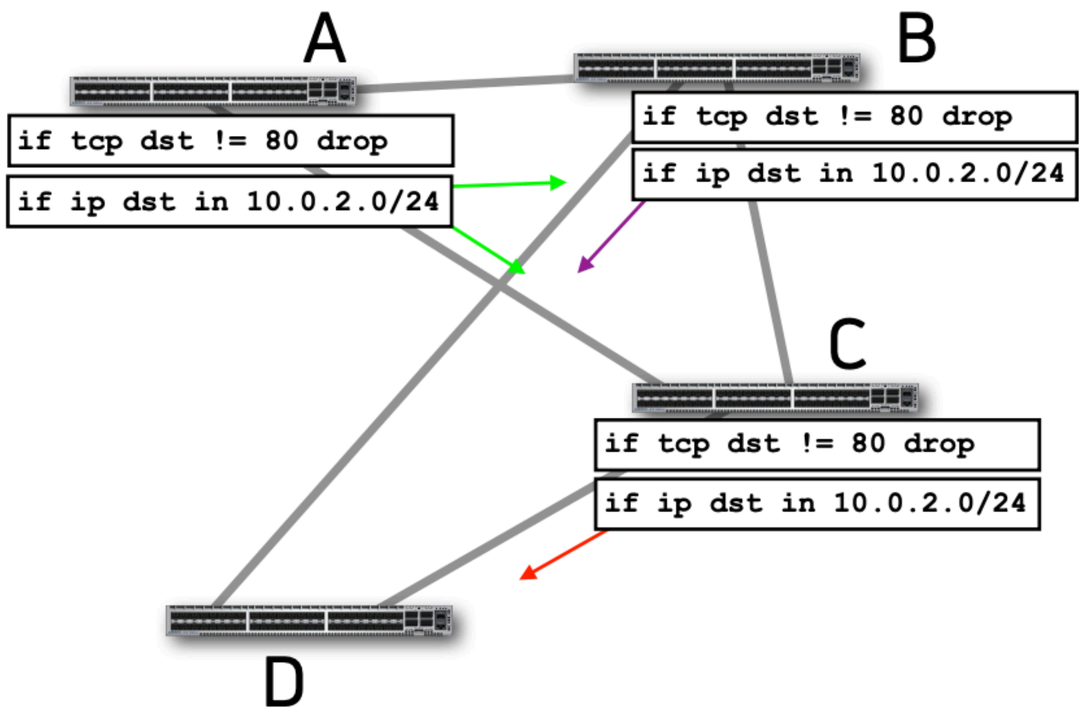
82%
concerned that changes would cause problems with existing functionality

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

Simple Questions are Hard to Answer

- Which packets from A can reach B?
- Is Group X provably isolated from Group Y?
- Is the network causing poor performance or the server? Are QoS settings to blame?
- Why is my backbone utilization poor?
- Is my load balancer distributing evenly?
- Where are there mysterious packet losses?

Network Correctness (a.k.a Intent)



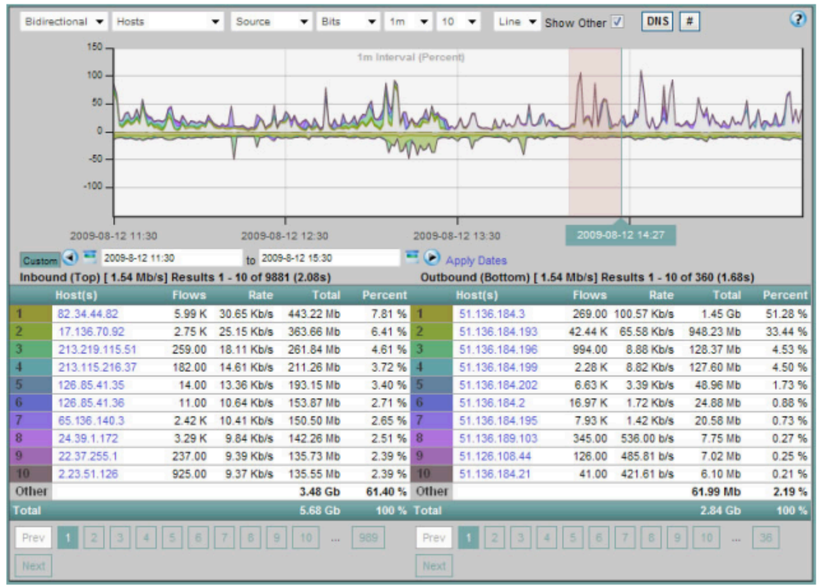
Intent Checklist

- ☑ All packets should follow the shortest paths
- ☑ There should not be any loops
- ☑ There should be multiple paths between A and D
- ☑ HTTP Packets in the subnet 10.0.2.0/24 should reach D
- ☑ External networks attached to A should be isolated from D except via HTTP

Ensuring Correct Operations Before Network Verification

Manual spot-checking (pings, traceroutes)

Monitoring of events & flows

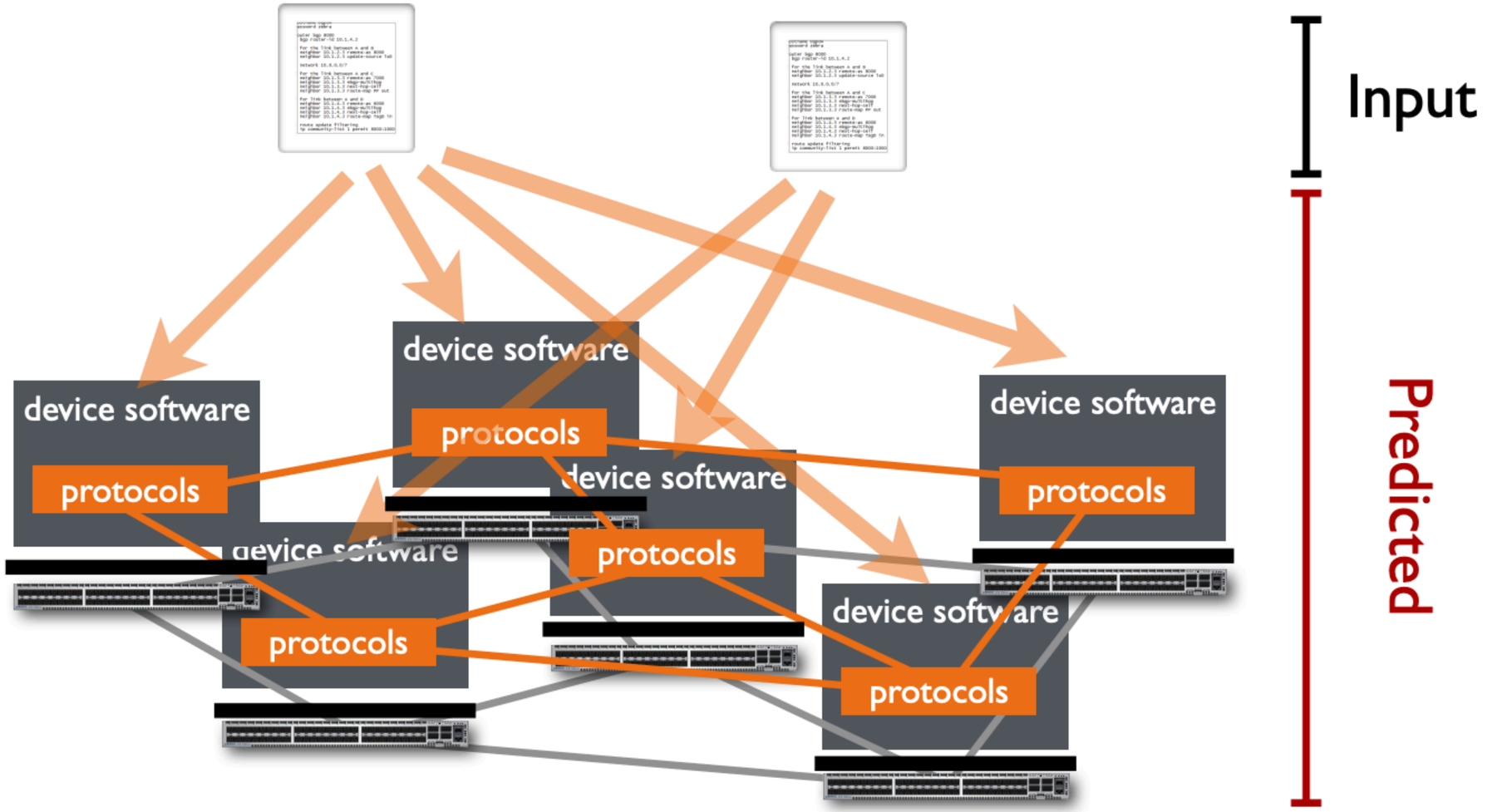


Screenshot from Scrutinizer NetFlow & sFlow analyzer, snmp.co.uk/scrutinizer/

Network Verification

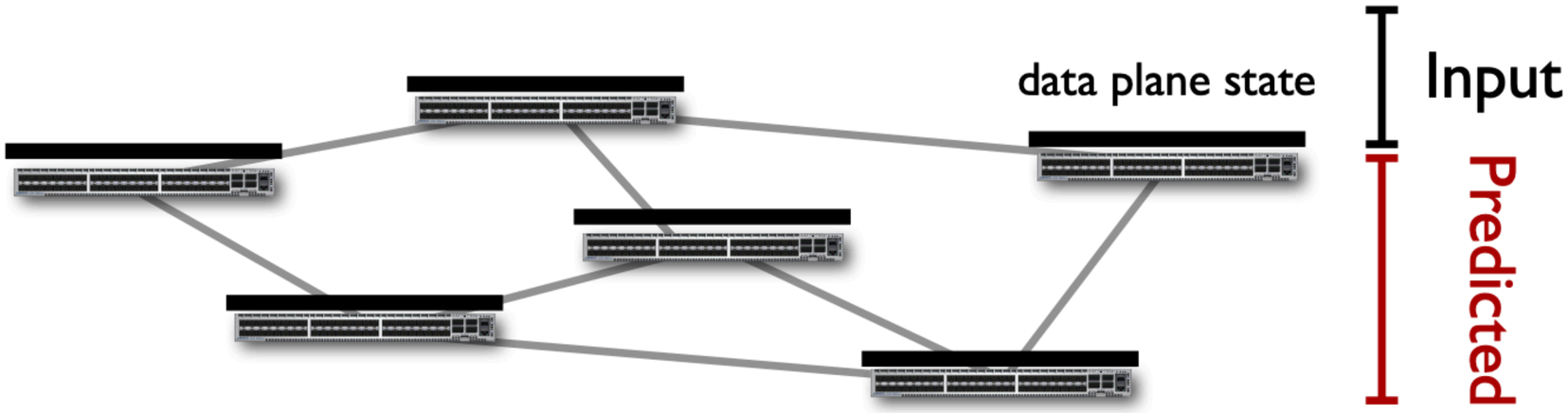
The process of proving whether an **abstraction** of the network satisfies the network-wide intent.

Configuration Verification



Data Plane Verification

Verify the network
as close as possible
to its actual behavior

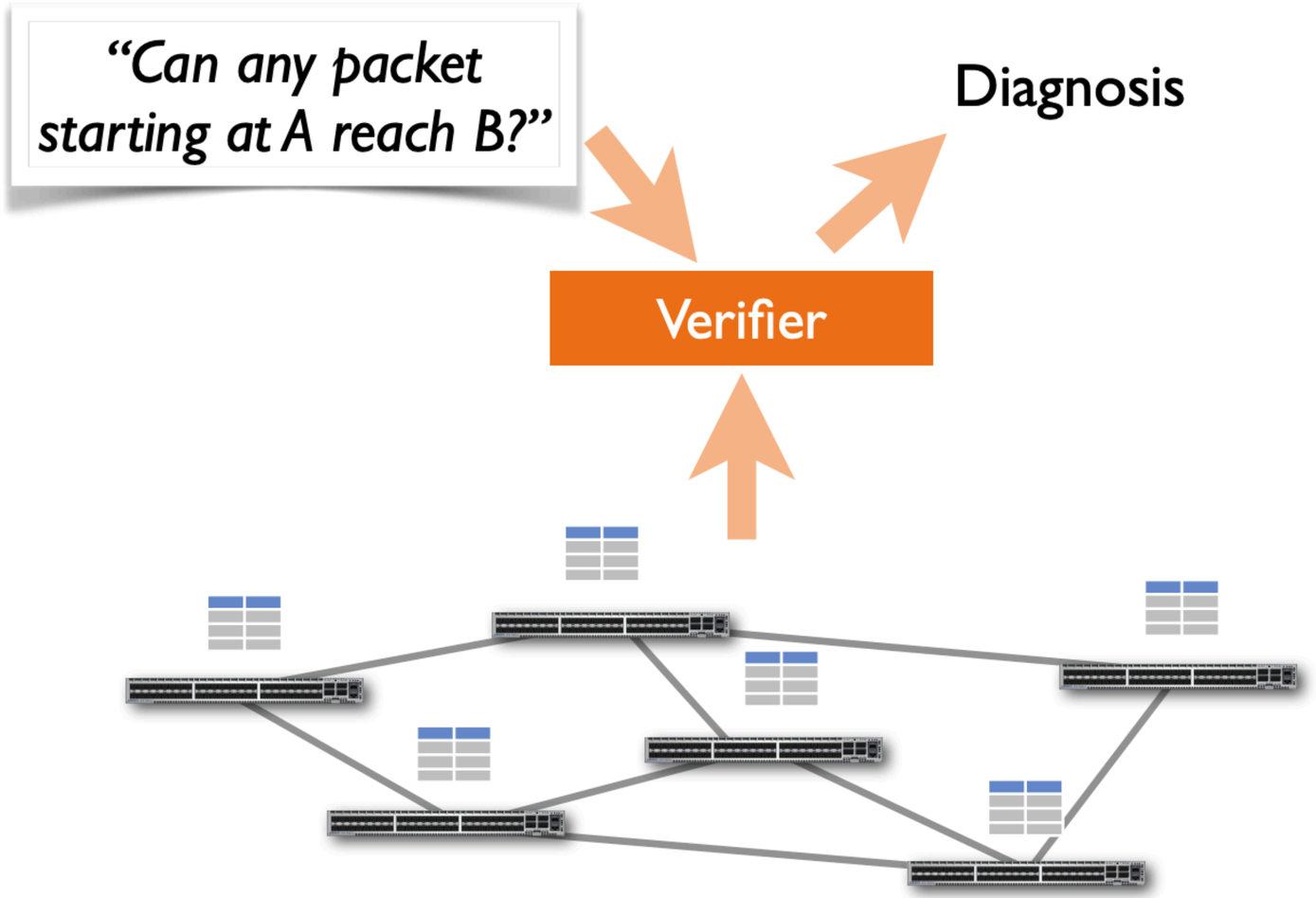


Data Plane Verification

Data Plane Verification Benefits

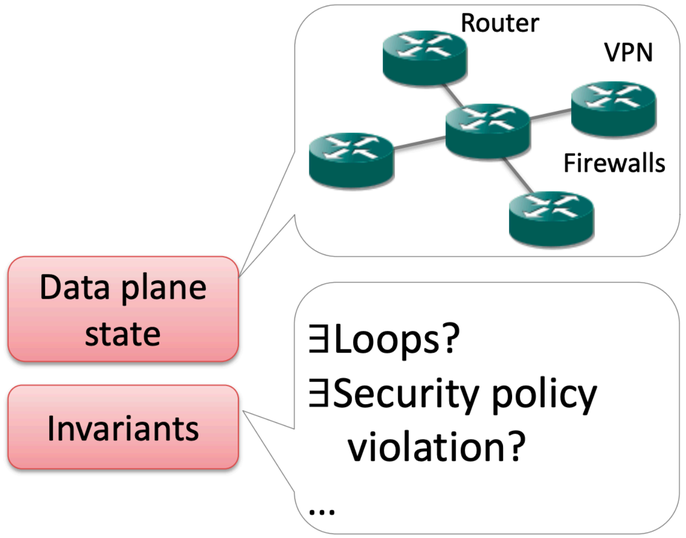
- Insensitive to control protocols
- Accurate model
- Checks current snapshot

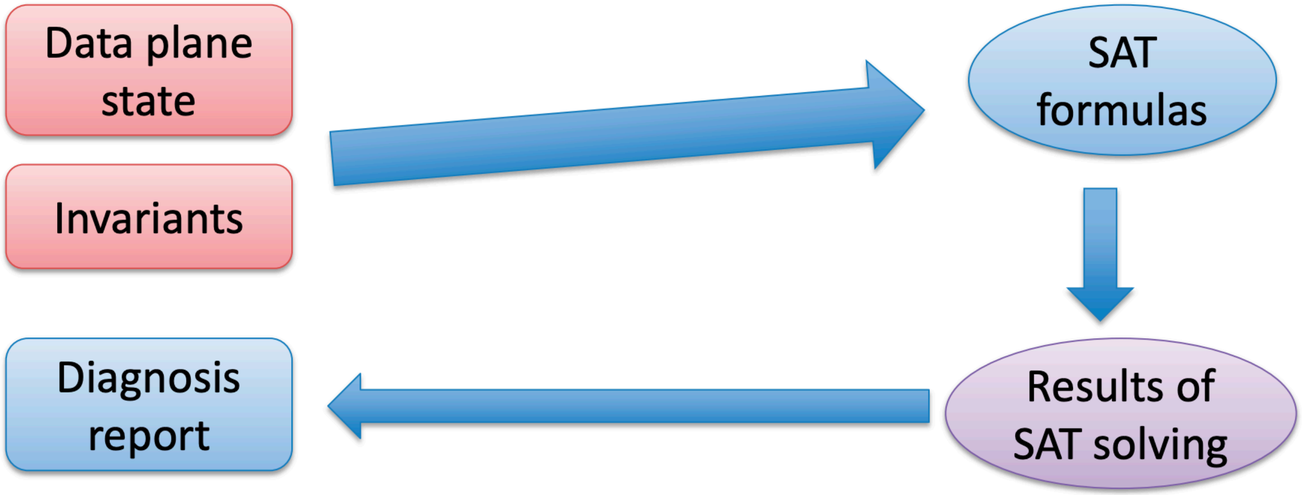
Data Plane Verification Architecture



Debugging the Data Plane with Anteater [SIGCOMM'11]

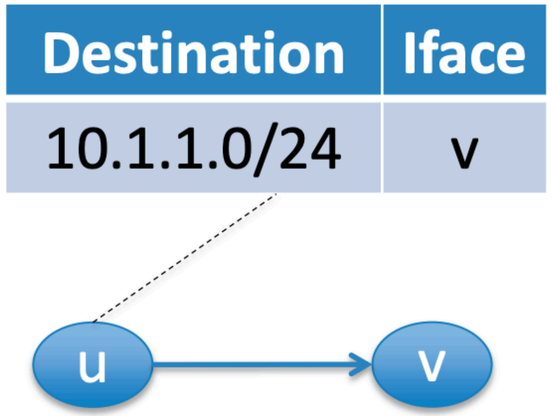
- Express data plane and invariants as SAT
- Check with off-the-shelf SAT solver (Boolector)





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)



P(u, v) = dst_ip ∈10.1.1.0/24

Some Examples

Destination	Iface
10.1.1.0/24	v
Drop port 80 to v	

P(u, v) = dst_ip ∈10.1.1.0/24
∧ dst_port ≠ 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 ∈10.1.1.0/24
∧ dst_ip ∉ 10.1.1.128/25)
∨ dst_ip ∈10.1.2.0/24

Longest prefix matching

Reachability as SAT solving

- Goal: reachability from u to w

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

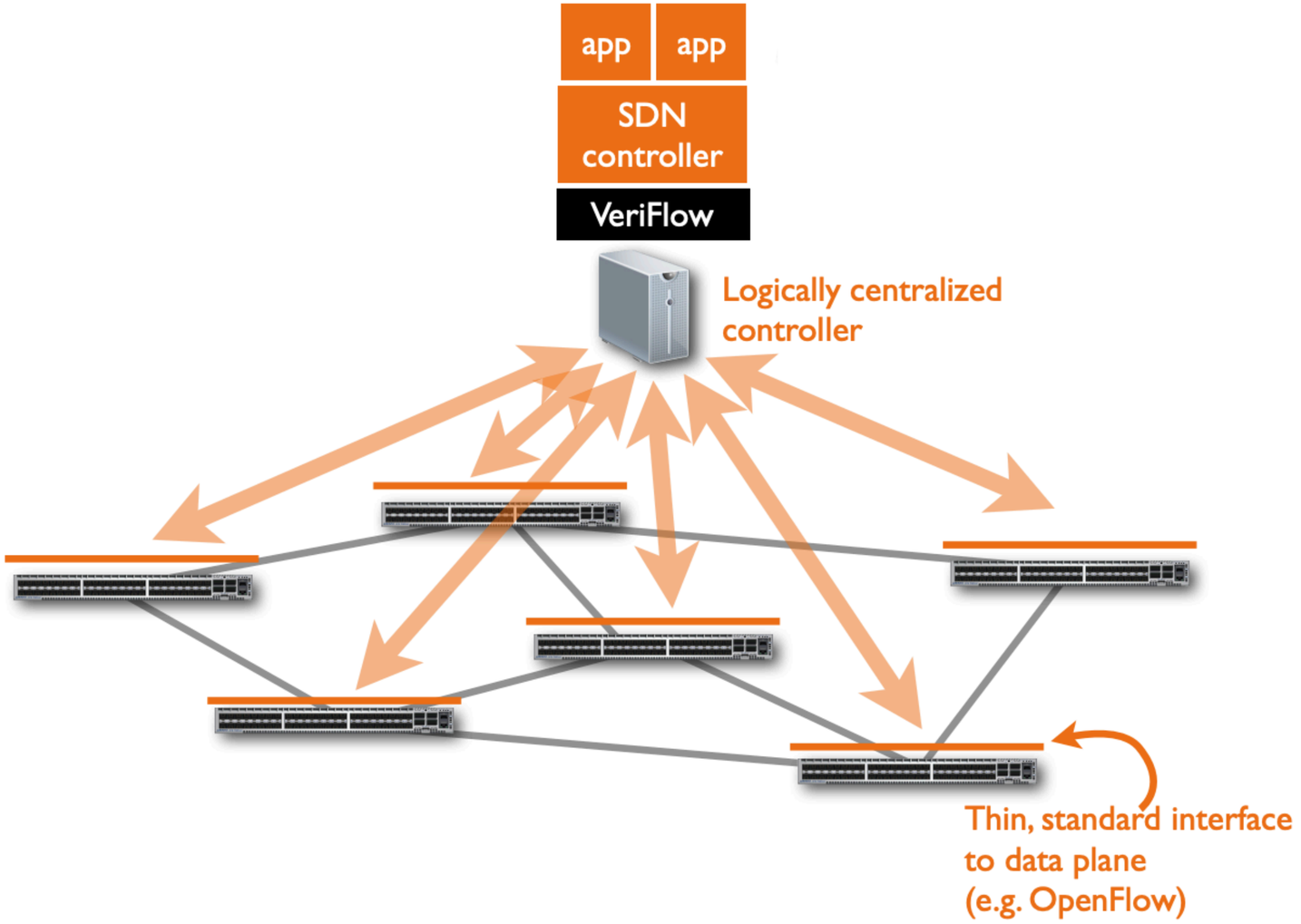
- SAT solver determines the satisfiability of C

Anteater challenges

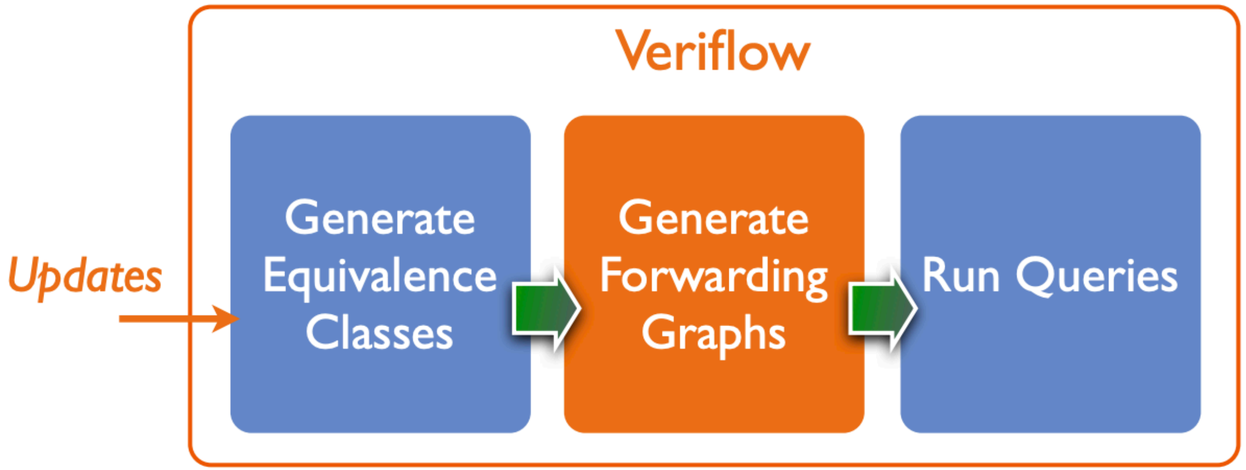
- Challenge #1: Obtaining real time view

- Challenge #2: Verify quickly

Real-Time Data Plane Verification: Veriflow

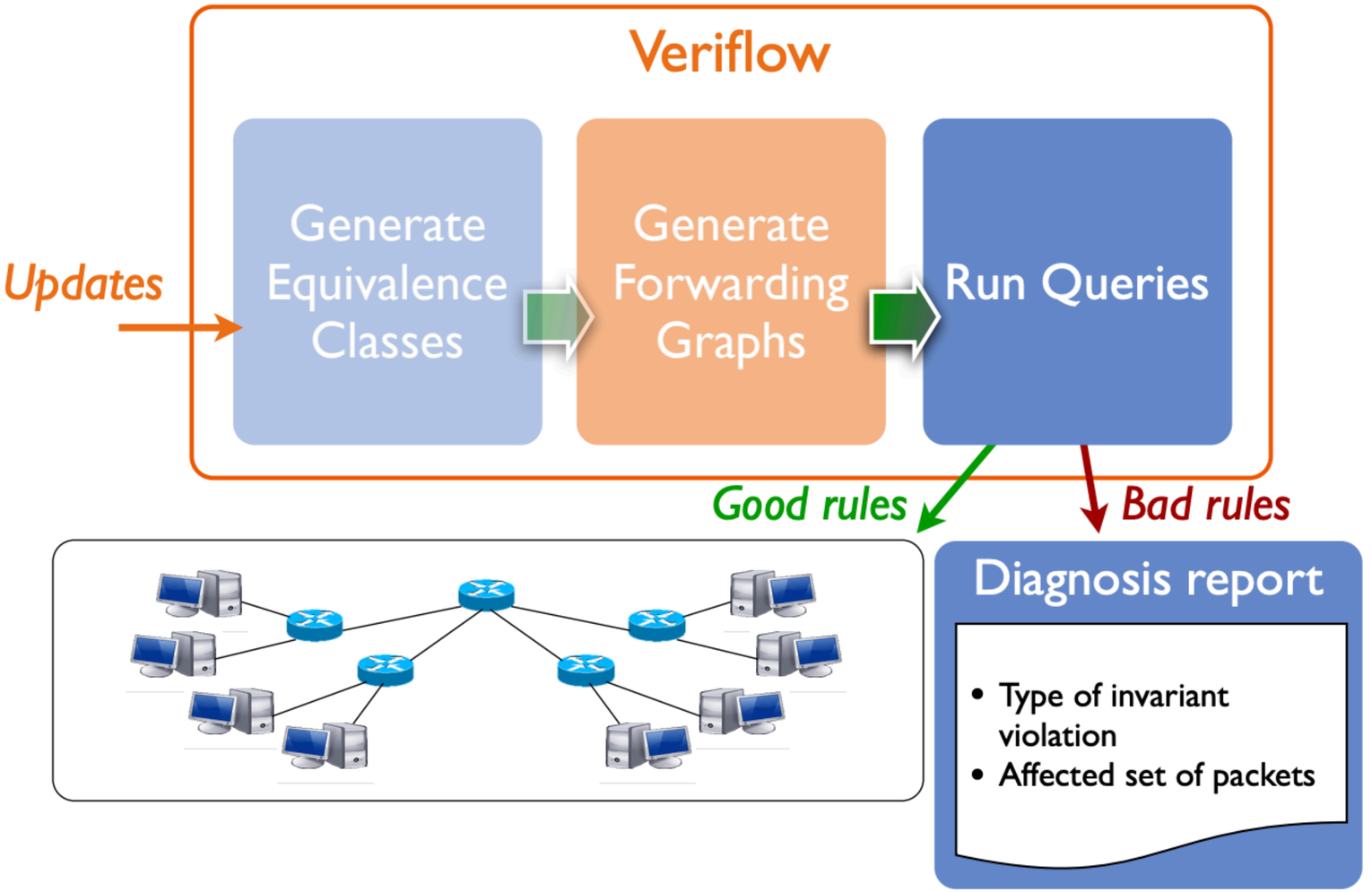


Verifying Invariants Quickly

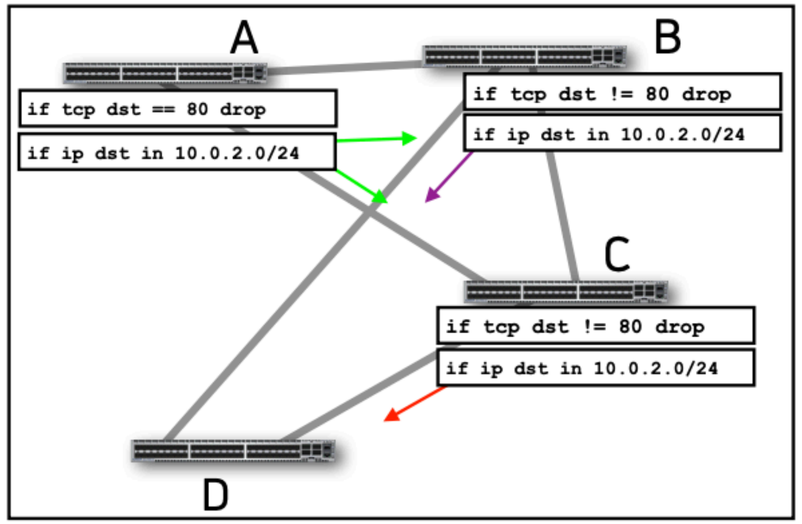


- Limit the search space
- Represent forwarding behaviors using graphs
- Run Light-weight graph-based algorithm to check

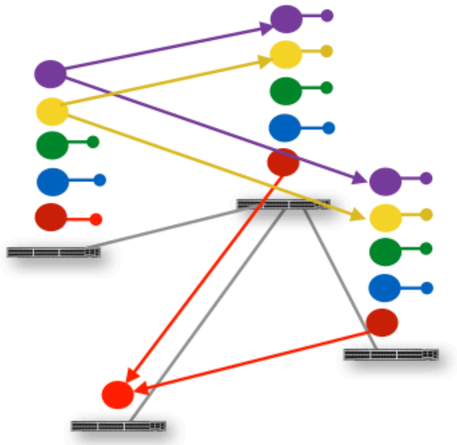
Real-time Verification with Veriflow



Forwarding Graphs



ip dst [0, 167772671], tcp dst [0, 65535]
ip dst [167772672, 167772927], tcp dst [80, 80]
ip dst [167772928, 4294967295], tcp dst [0, 65535]
ip dst [167772672, 167772927], tcp dst [0, 79]
ip dst [167772672, 167772927], tcp dst [81, 65535]

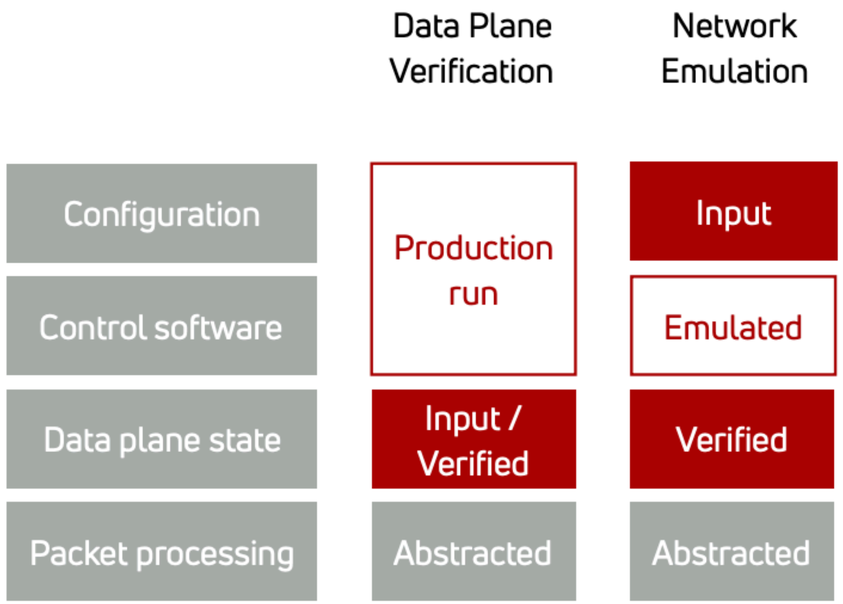


Intent API

- What intents can you check?
  - Anything within data plane state (forwarding rules)...
  - ...that can be verified incrementally
- Veriflow's API enables custom query algorithms
  - Full access to forwarding graph
  - For incremental verification: Gives access to the "diff": forwarding subgraph affected by an update from the SDN controller
  - Verification becomes a standard graph traversal algorithm

Configuration Analysis

Landscape of Approaches



Emulating Production Networks

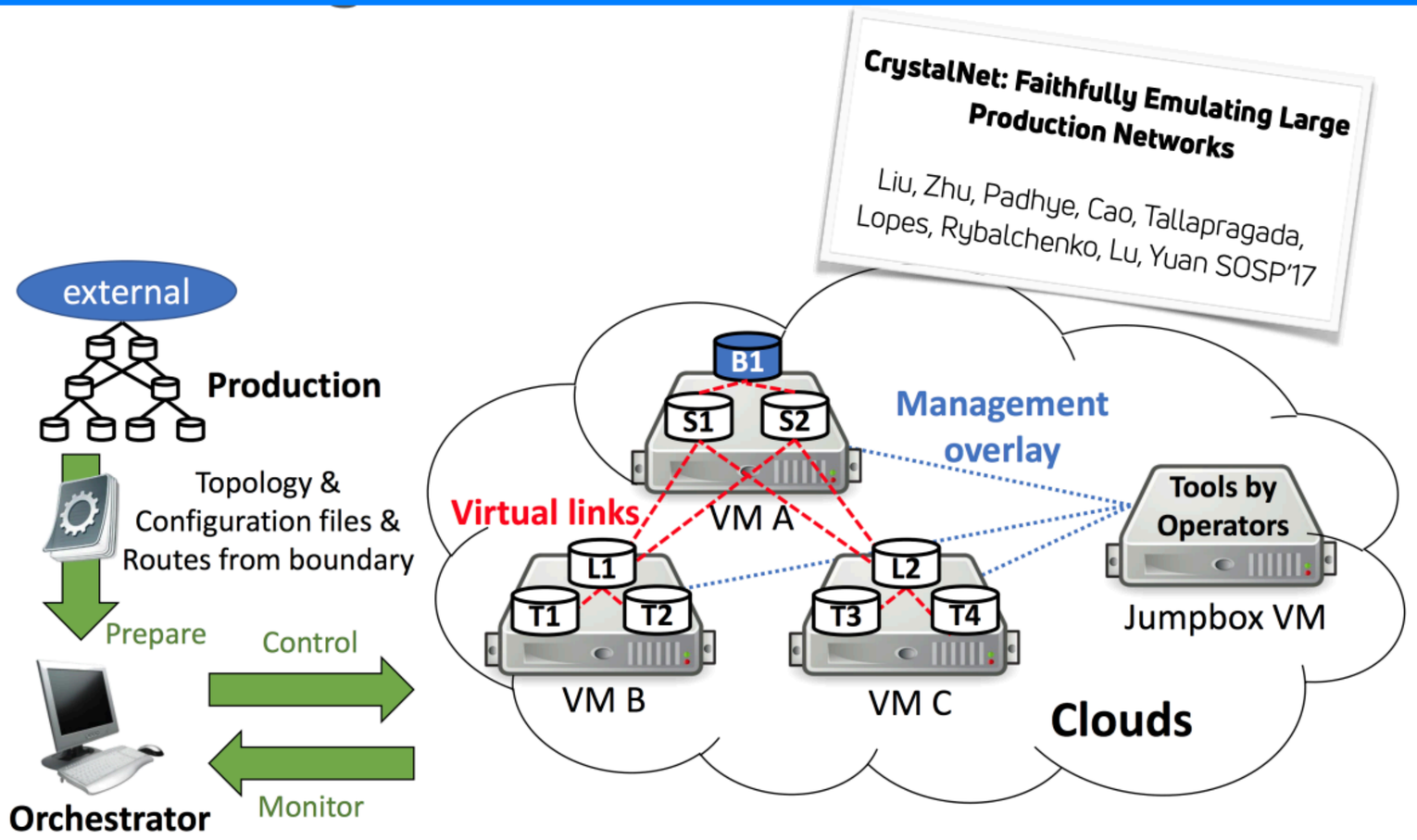
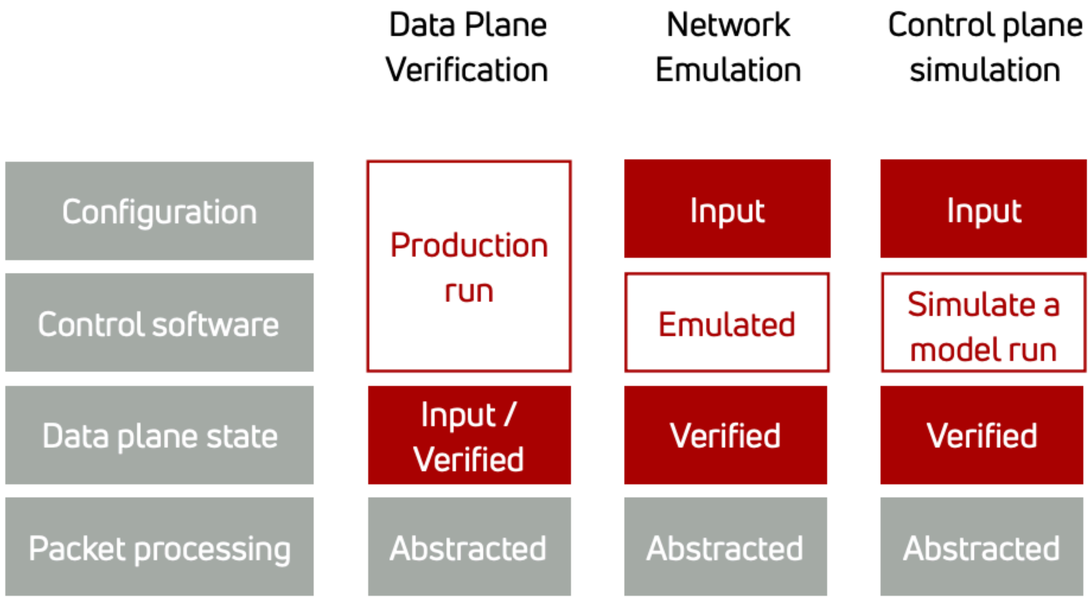


Image Reproduced from the authors' SOSP '17 paper

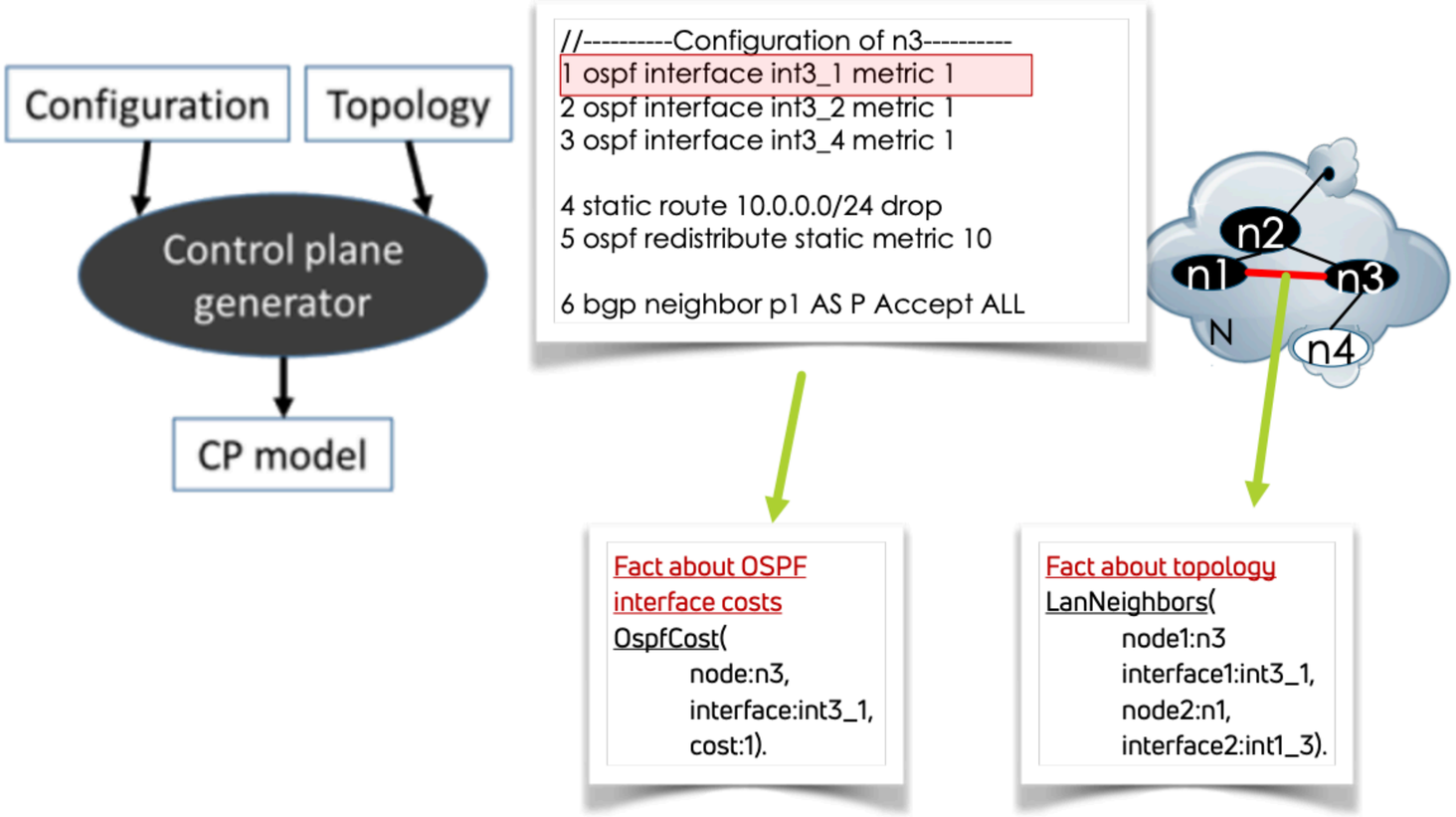
Landscape of Approaches



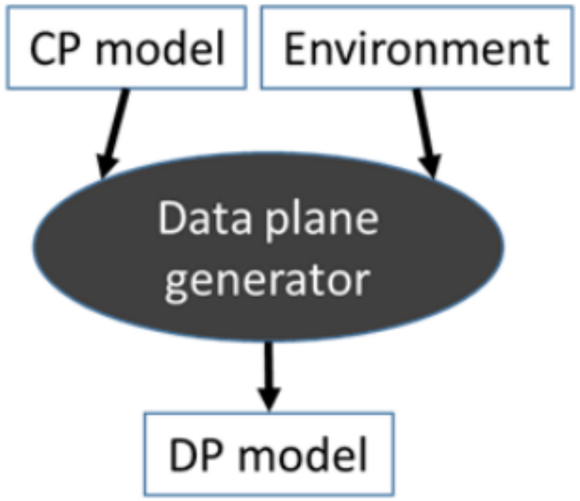
Control Plane Simulation

- Challenges in faithfully deriving the data plane
- Batfish [NSDI'15]
    - Approach: High-fidelity declarative model of control plane
        - Set of relations that expresses the network's control plane computation
        - Provides queryability and provenance for free

Stage 1: Extract control plane model



Stage 2: Compute data plane

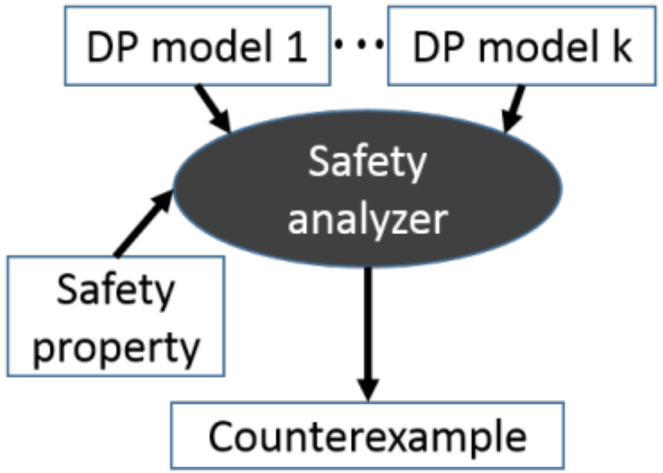



```
OspfExport(
        node=n2,
        network=10.0.0.0/24,
        cost=10,
        type=ospfE2).
```

```
InstalledRoute(route={
        node=n1,
        network=10.0.0.0/24,
        nextHop=n2
        administrativeCost=110,
        protocolCost=10,
        protocol=ospfE2}).
```

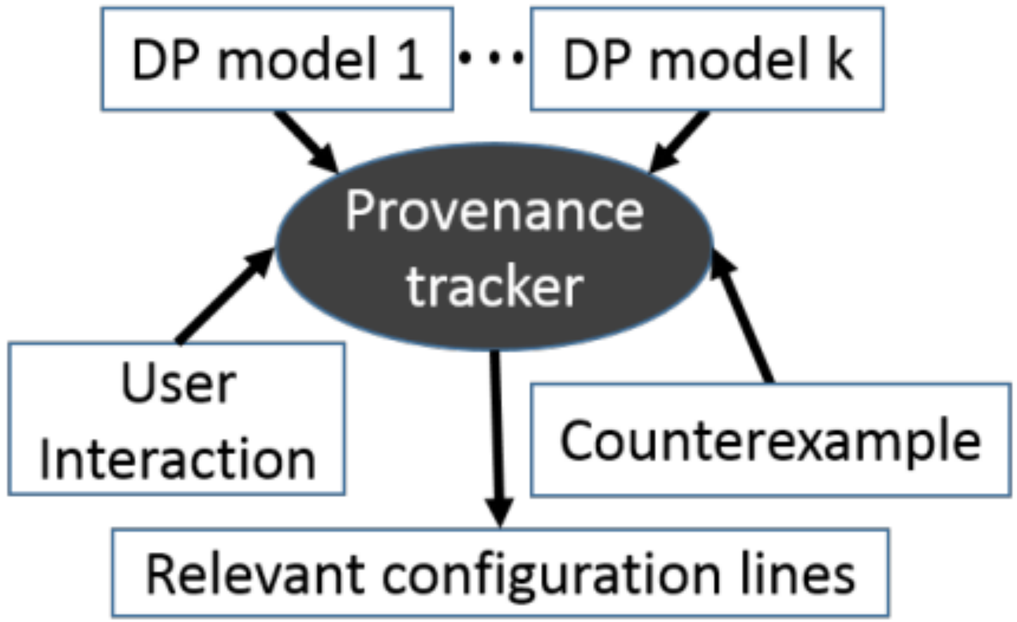
```
Fib(
        node=n1,
        network=10.0.0.0/24,
        egressInterface=int1_2).
```

Stage 3: Data plane analysis



Counterexample of multipath consistency
{
IngressNode=n1,
SrcIp=0.0.0.0,
DstIp=10.0.0.2,
IpProtocol=0
}

Stage 4: Helping Repair



The Research Landscape

Configuration Verification

Configuration

Control software

Data plane state

Packet processing

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]
- ARC [Gember-Jacobson, Viswanathan, Akella, Mahajan SIGCOMM'16]
- ERA [Fayaz, Sharma, Fogel, Mahajan, Millstein, Sekar, Varghese, OSDI'16]
- Minesweeper [Beckett, Gupta, Mahajan, Walker SIGCOMM'17]
- Plankton [Prabhu, Kheradmand, Godfrey, Caesar APNet'17]
- CrystalNet [Liu, Zhu, Padhye, Cao, Tallapragada, Lopes, Rybalchenko, Lu, Yuan SOSP'17]

Control Software Verification

Configuration

Control software

Data plane state

Packet processing

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]

Data Plane Verification

Configuration

Control software

Data plane state

Packet processing

Static

- On static reachability in IP networks [Xie, Zhan, Maltz, Zhang, Greenberg, Hjalmtysson, Rexford, INFOCOM '05]
  - 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]
- DeltaNet [Horn, Kheradmand, Prasad] NSDI'17]

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]

Richer data plane models

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

Packet Processing Verification

Configuration

Control software

Data plane state

Packet processing

Verification of data plane software and data plane languages

- Software Dataplane Verification [Dobrescu, Argyraki, NSDI'14]
- Executable Formal Semantic of P4 and Applications [Kheradmand, Rosu, P4 Workshop'17]
- A Formally Verified NAT [Zaostrovnykh, Pirelli, Pedrosa, Argyraki, Candea, SIGCOMM'17]

Thanks!