VeriFlow: Verifying Network-Wide Invariants in Real Time

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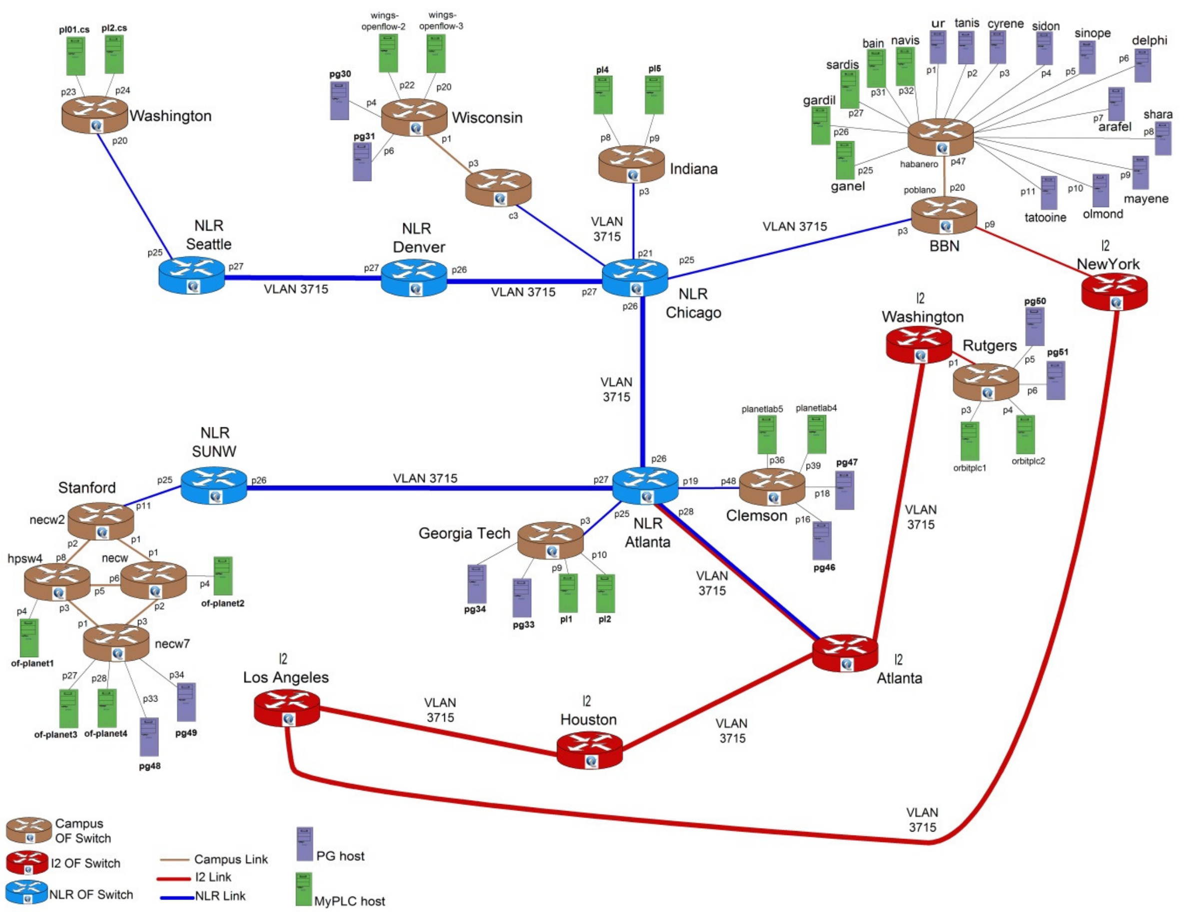
Challenges in Network Debugging

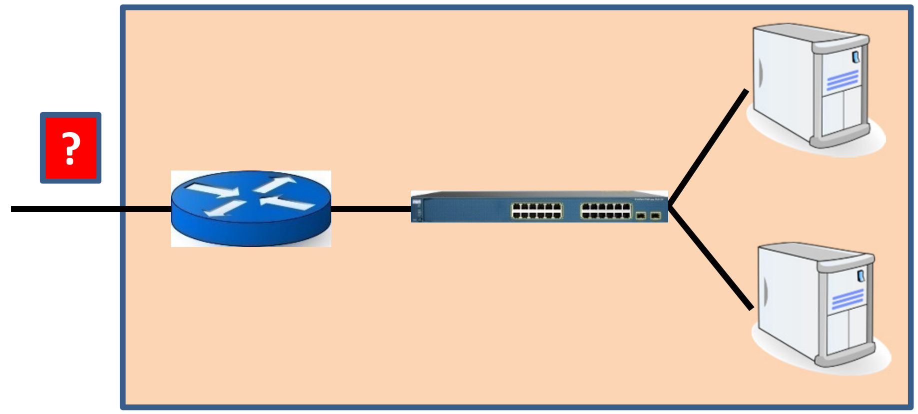


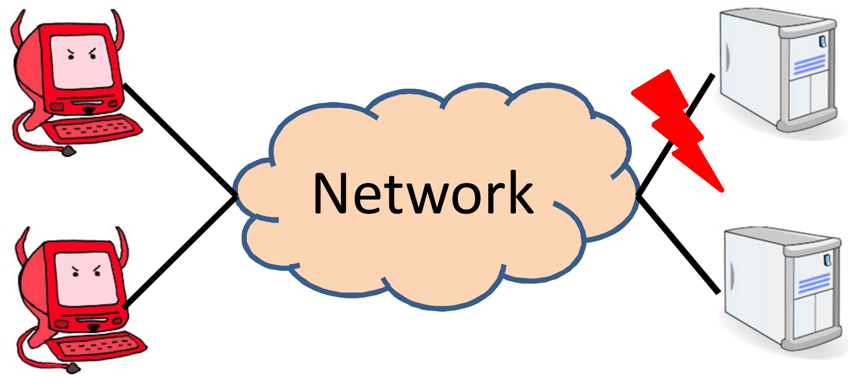
http://groups.geni.net/geni/chrome/site/thumbnails/wiki/TangoGENI/OF-VLAN3715_1000.jpg

- Complex interactions
- Misconfigurations
- Unforeseen bugs
- Difficult to test the entire network state space before deployment

Effects of Network Errors

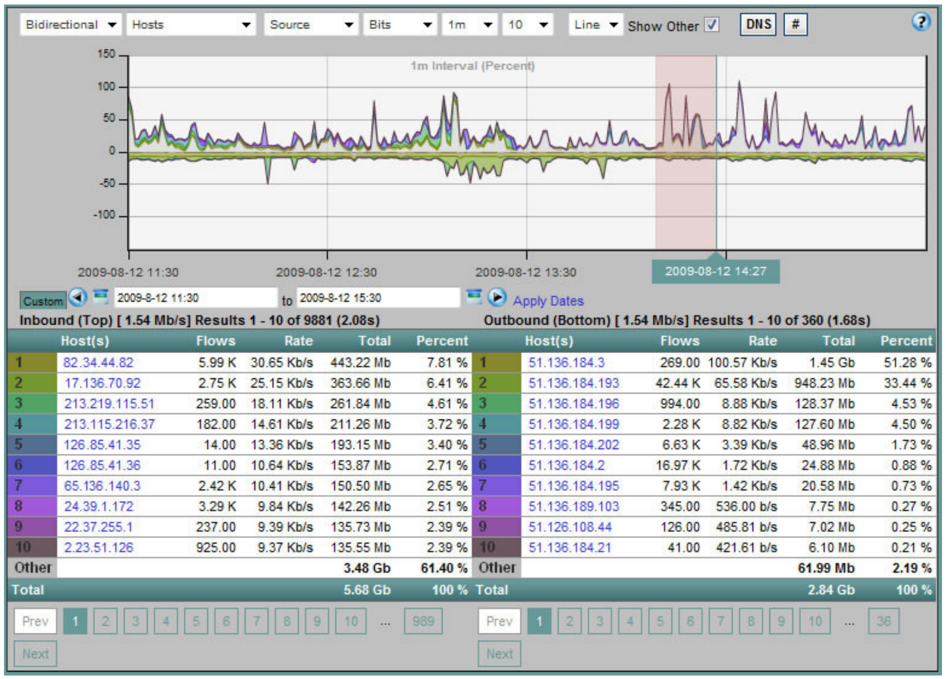
- Allow unauthorized packets to enter a secured zone in a network
- Make services and the infrastructure prone to attacks
- Make critical services unavailable
- Affect network performance





Network Debugging Techniques

Traffic/Flow Monitoring



Inbound (Top) [1.54 Mb/s] Results 1 - 10 of 9881 (2.08s)

	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 %

Prev 1 2 3 4 5 6 7 8 9 10 ... 989 Next

Outbound (Bottom) [1.54 Mb/s] Results 1 - 10 of 360 (1.68s)

	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 %

Prev 1 2 3 4 5 6 7 8 9 10 ... 36 Next

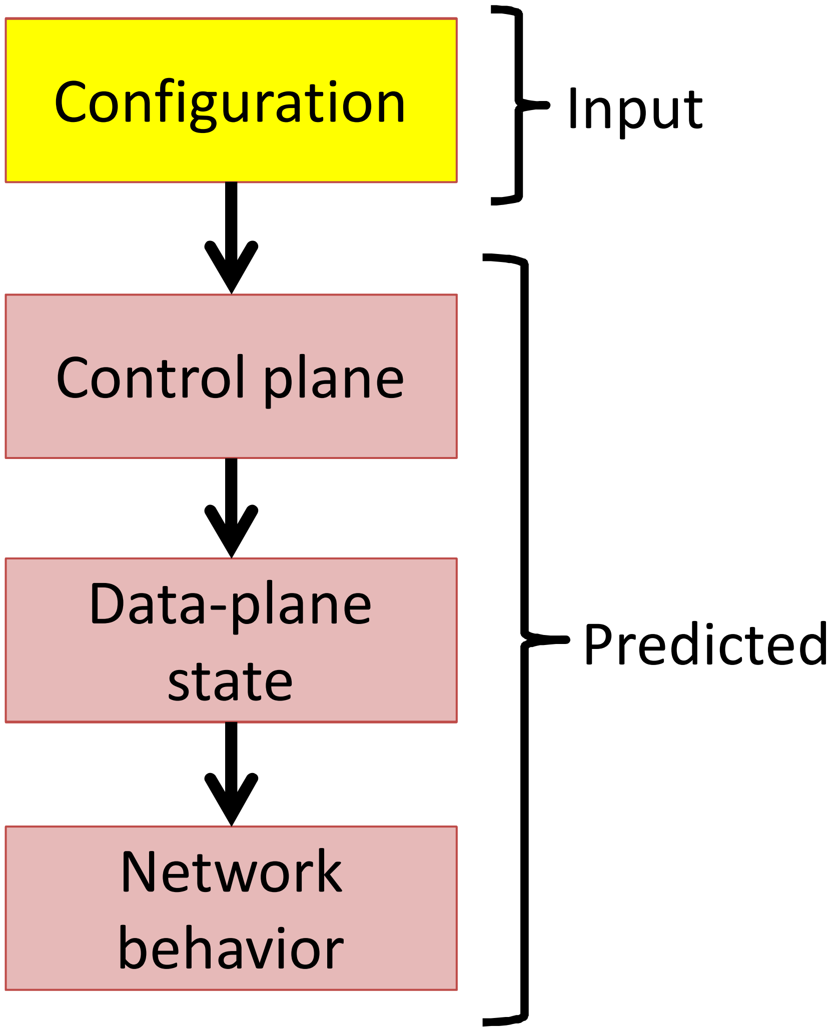
Software using Cisco NetFlow

http://snmp.co.uk/scrutinizer/

Configuration Verification

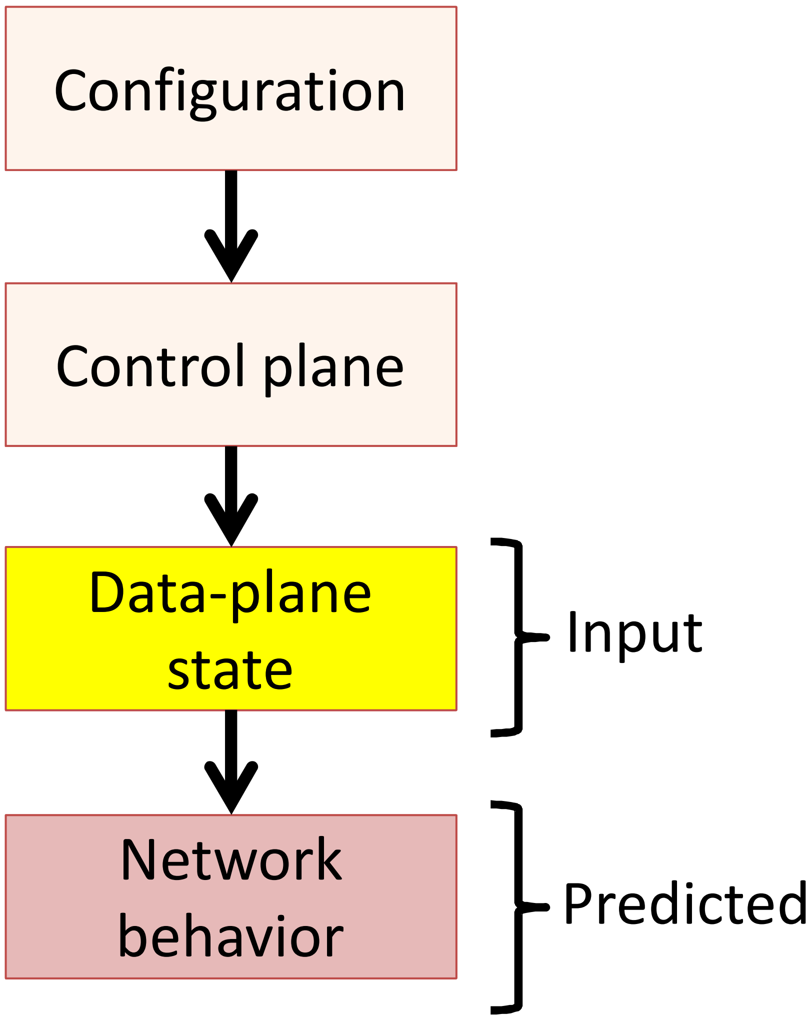
```
hostname bgpdA
password zebra
!
router bgp 8000
  bgp router-id 10.1.4.2

! 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
!
```

Limitations of Configuration Verification



- Prediction is difficult
  - Various configuration languages
  - Dynamic distributed protocols
- Prediction misses implementation bugs in control plane

Our Approach: Data-plane Verification



- Less prediction
- Closer to actual network behavior
- Unified analysis for multiple control-plane protocols
- Can catch control-plane implementation bugs

Data Plane Verification in Action

- FlowChecker [Al-Shaer et al., SafeConfig 2010]
  - Uses BDD-based model checker
- Anteater [Mai et al., SIGCOMM 2011]
  - Uses SAT-based model checking
  - Revealed 23 real bugs in the UIUC campus network
- Header Space Analysis [Kazemian et al., NSDI 2012]
  - Uses set-based custom algorithm
  - Found multiple loops in the Stanford backbone network

Find problems after they occur and (potentially) cause damage

Running time: Several seconds to a few hours

Can we run verification in real time?

Checking network-wide invariants in real time as the network evolves

- Need to verify new updates at high speeds
  - Block dangerous changes
  - Provide immediate warning

Challenges in Real-Time Verification

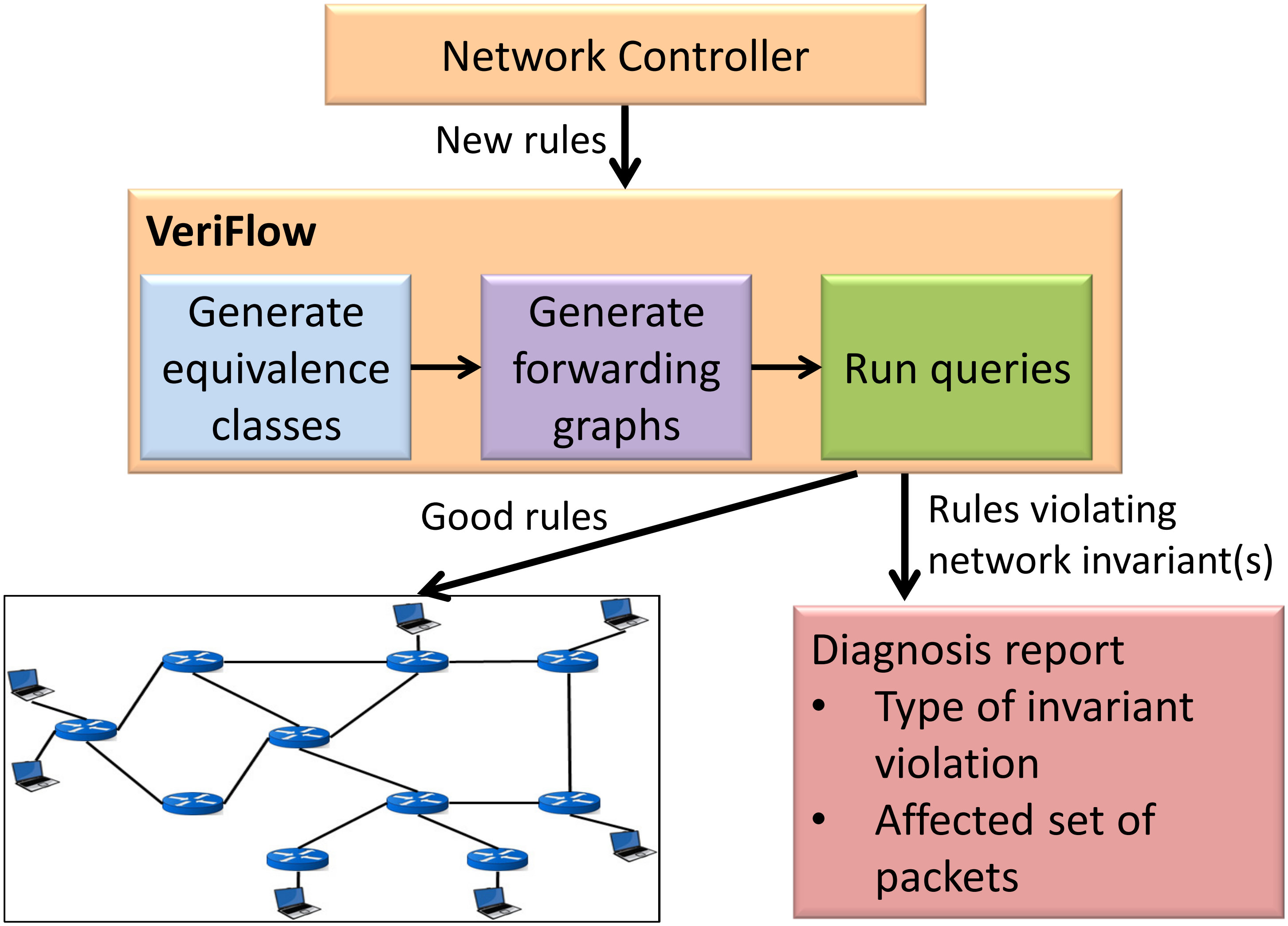
- Challenge 1: Obtaining real-time view of network
  - Solution: Utilize the **centralized** data-plane view available in an **SDN (Software-Defined Network)**
- Challenge 2: Verification speed
  - Solution: Off-the-shelf techniques?

No, too slow!

Our Tool: VeriFlow

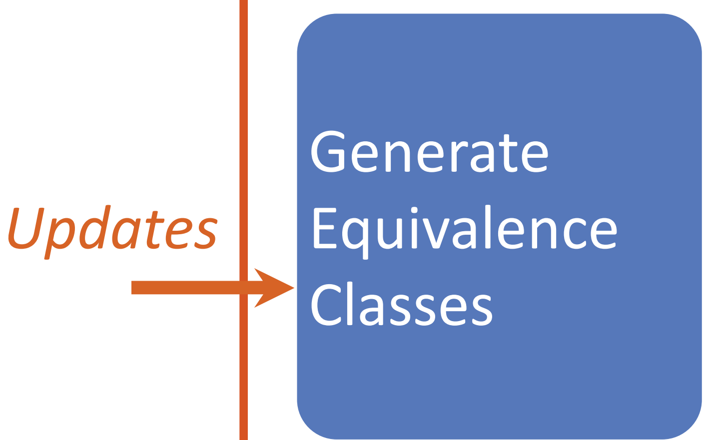
- VeriFlow checks network-wide invariants in **real time** using data-plane state
  - Absence of routing loops and black holes, access control violations, etc.
- VeriFlow functions by
  - Monitoring **dynamic changes** in the network
  - Constructing a **model** of the **network behavior**
  - Using **custom algorithms** to automatically derive whether the network contains errors

VeriFlow Operation

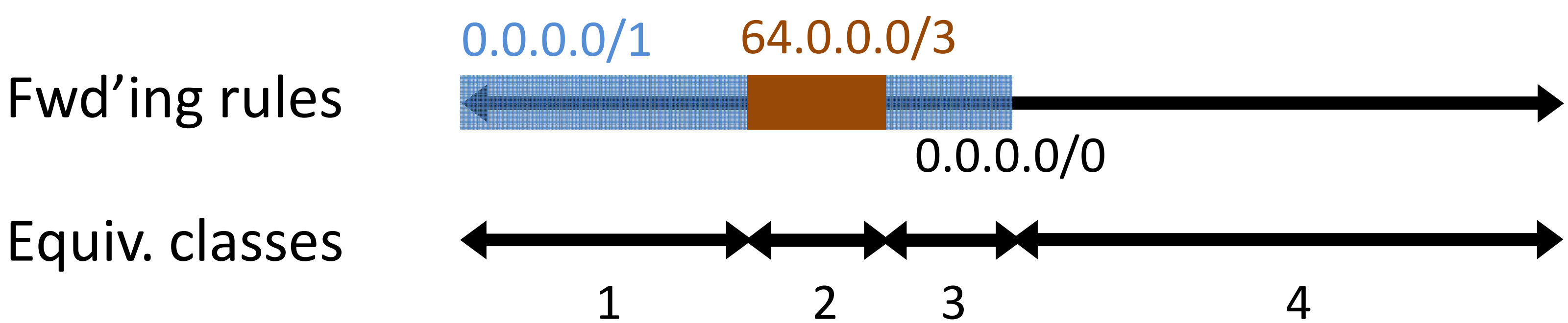


1. Limit the Search Space

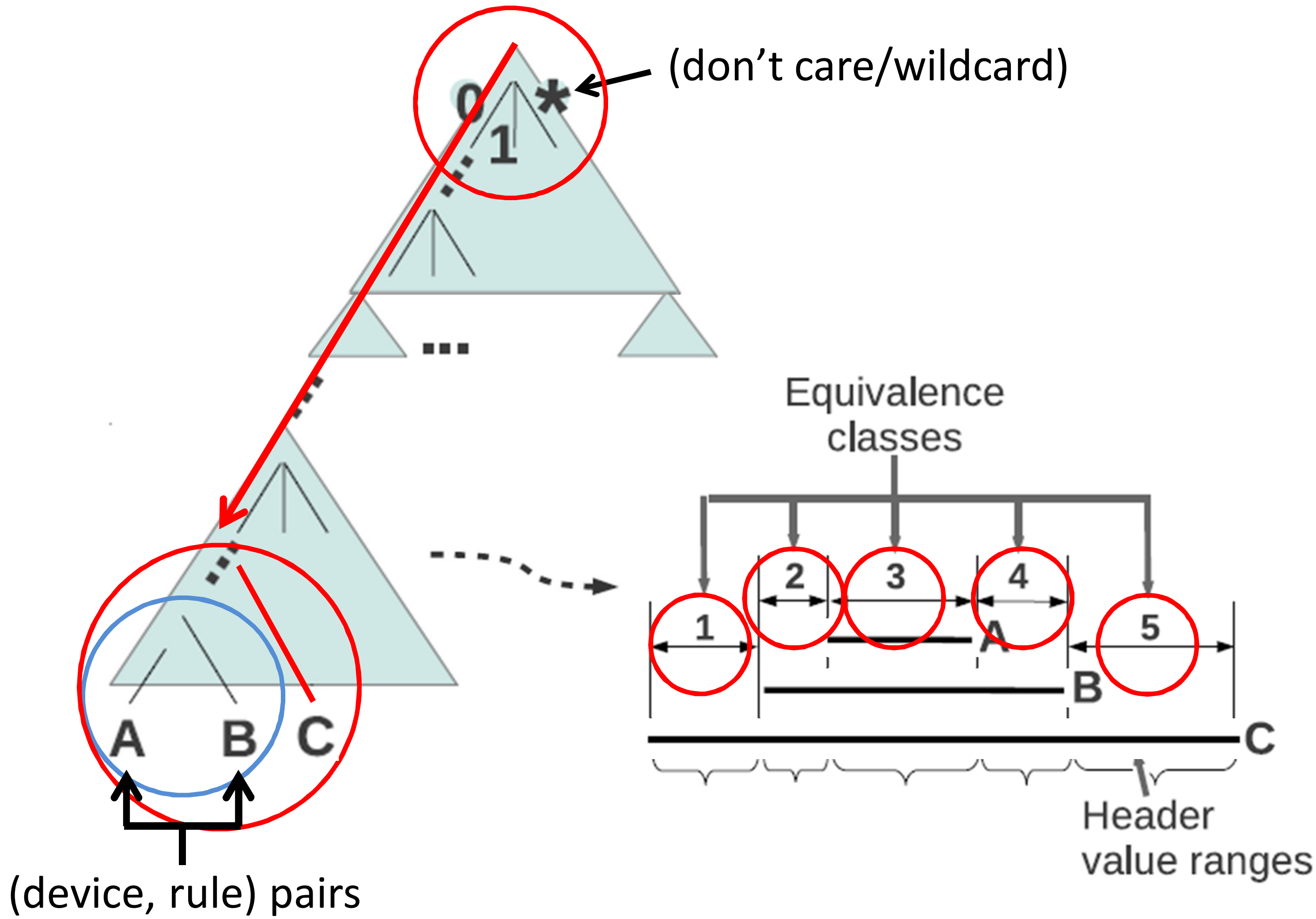
VeriFlow



Equivalence class: Packets experiencing the same forwarding actions throughout the network.



Computing Equivalence Classes

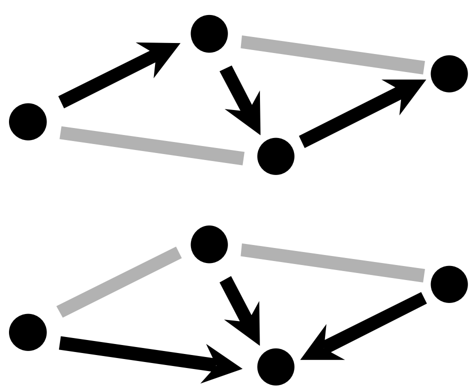


2. Represent Forwarding Behavior

VeriFlow

Updates → Generate Equivalence Classes → Generate Forwarding Graphs

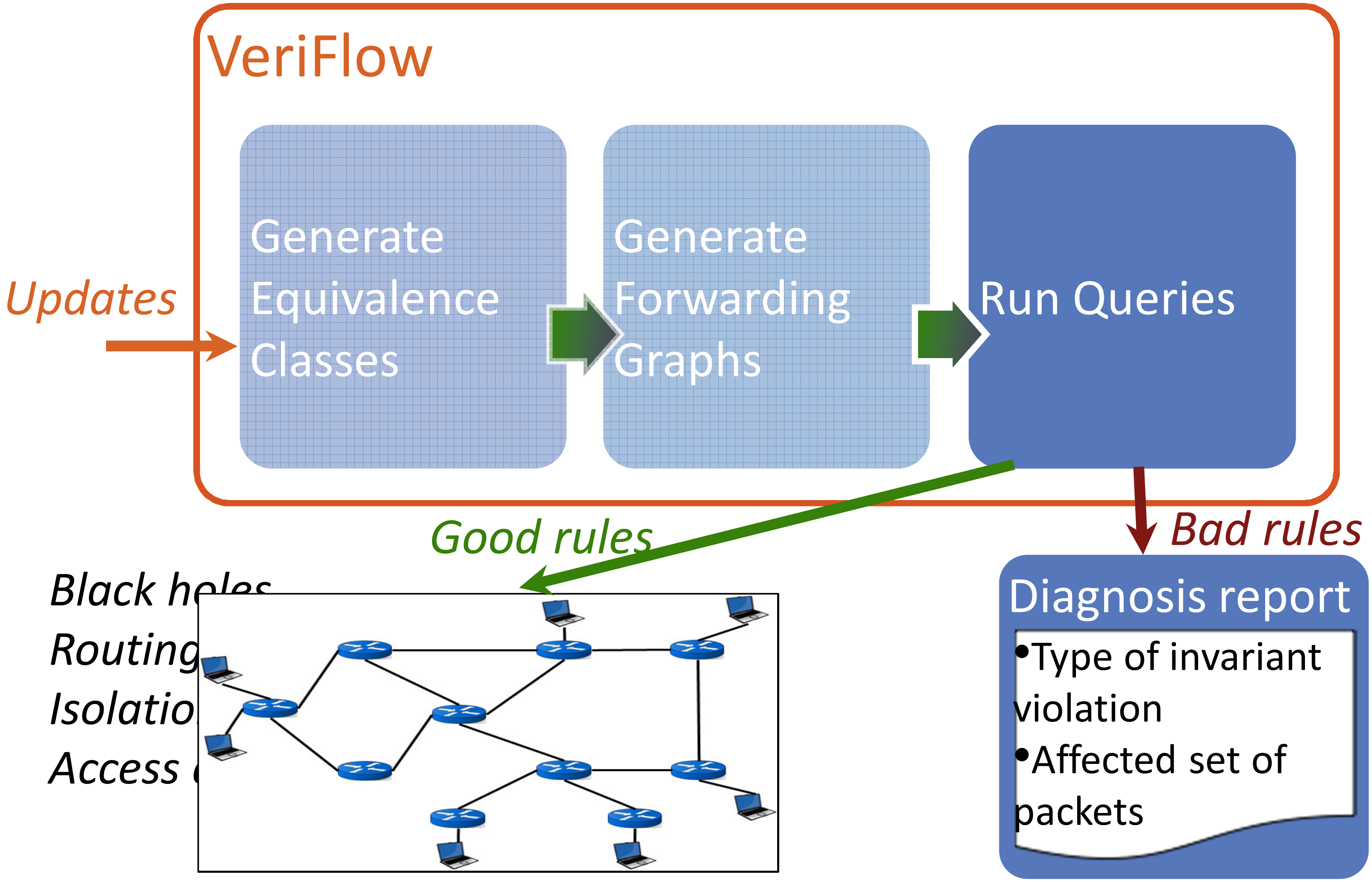
Equivalence Class 1



Equivalence Class 2

All the info to answer queries!

3. Run Query to Check Invariants



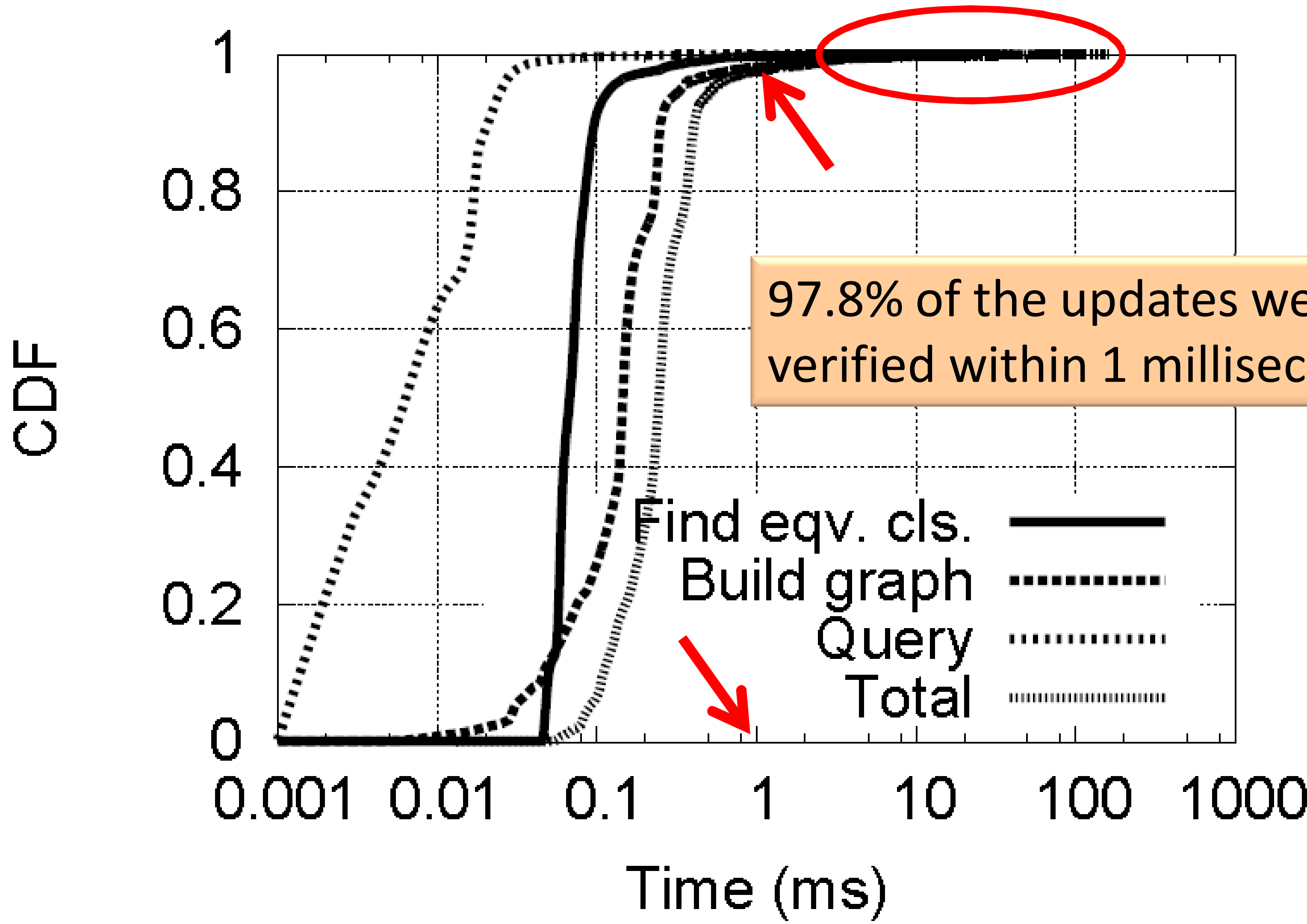
API to write custom invariants

- VeriFlow provides a set of functions to write custom query algorithms
  - Gives access to the affected set of equivalence classes and their forwarding graphs
  - Verification becomes a standard graph traversal algorithm
- Can be used to
  - Check forwarding behavior of specific packet sets
  - Verify effects of potential changes

Experiment

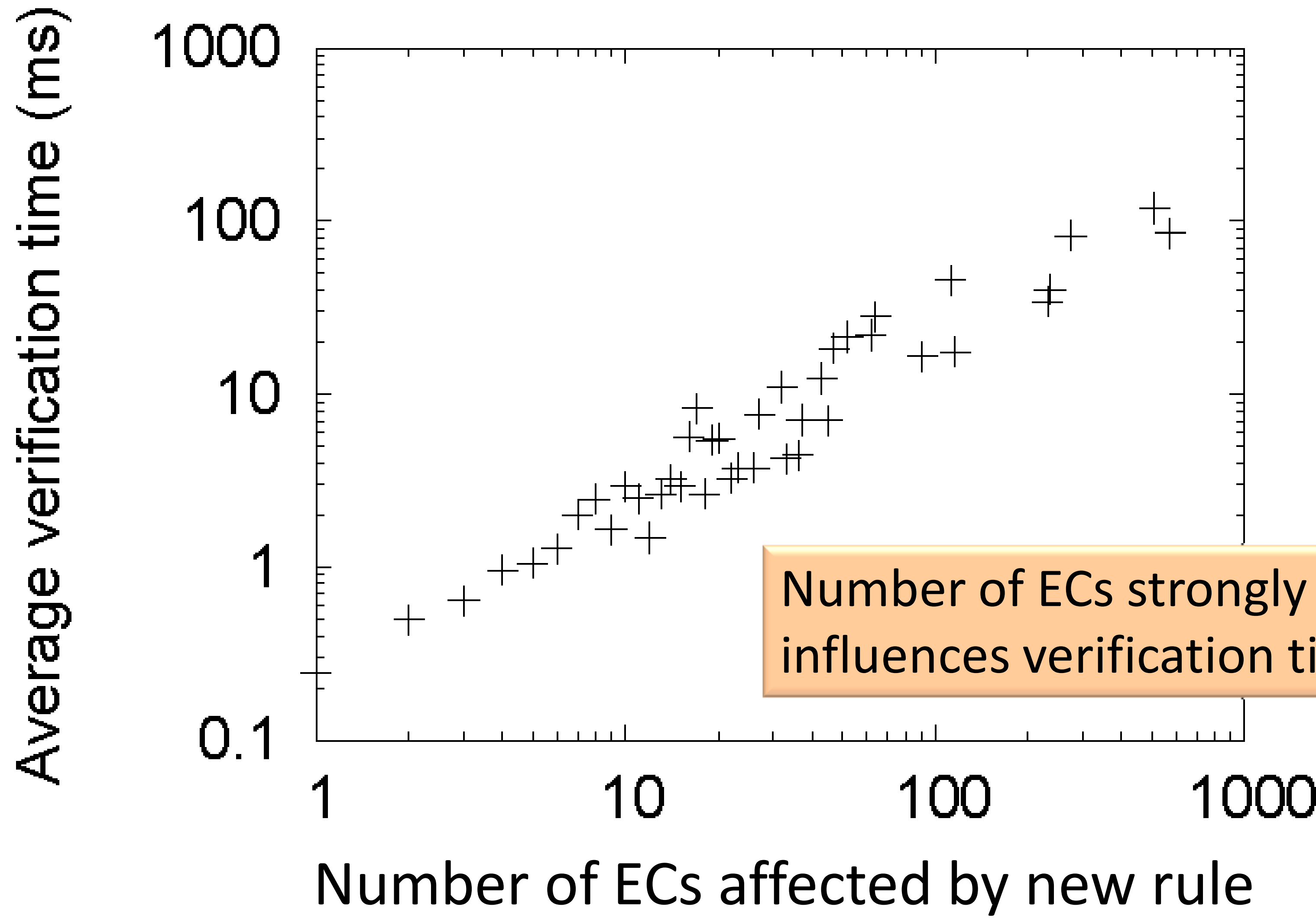
- Simulated an IP network using a Rocketfuel topology
  - 172 routers
- Replayed Route Views BGP traces
  - 5 million RIB entries
  - 90K BGP updates
- Checked for loops and black holes
- Microbenchmarked each phase of VeriFlow's operation

Performance Result



97.8% of the updates were verified within 1 millisecond

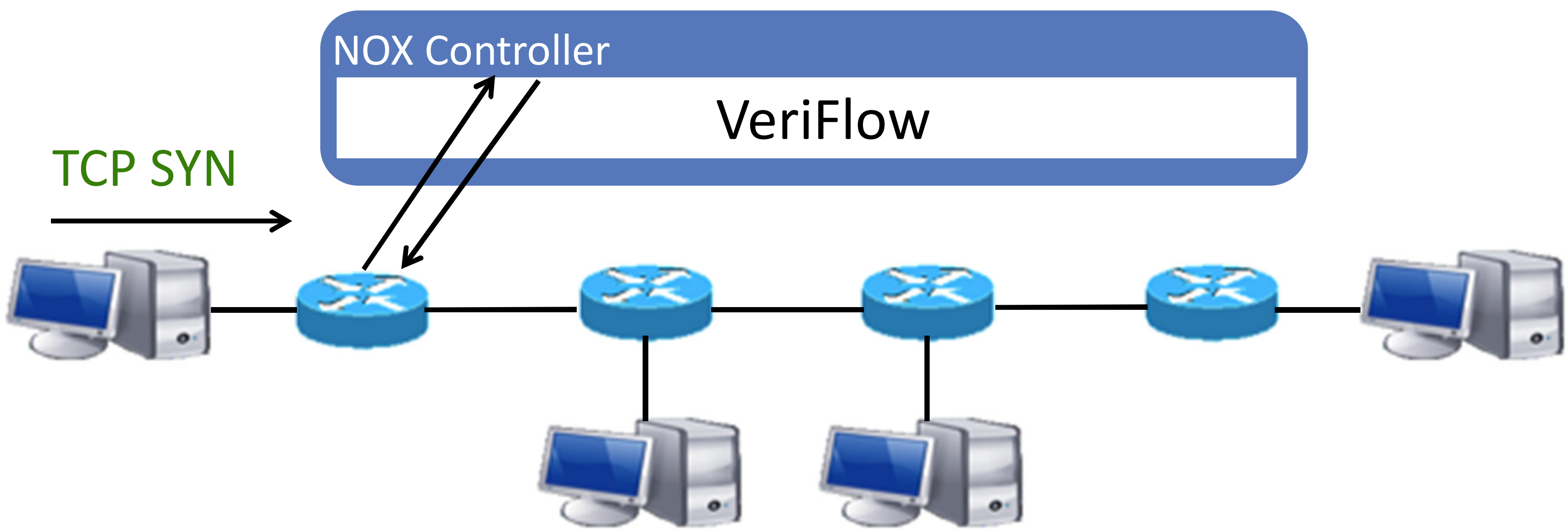
Effect of Equivalence Class Count



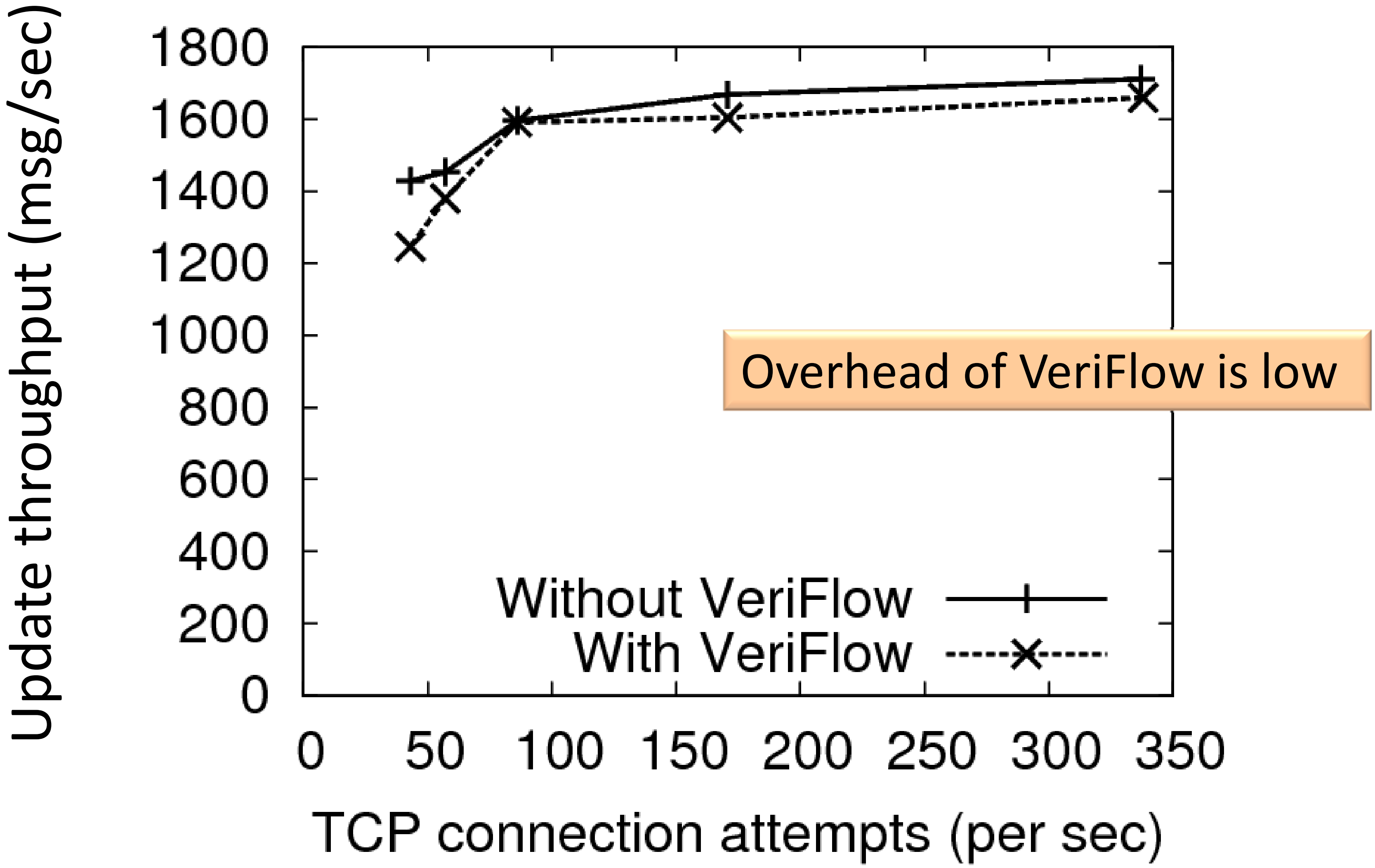
Number of ECs strongly influences verification time

Experiment (cont.)

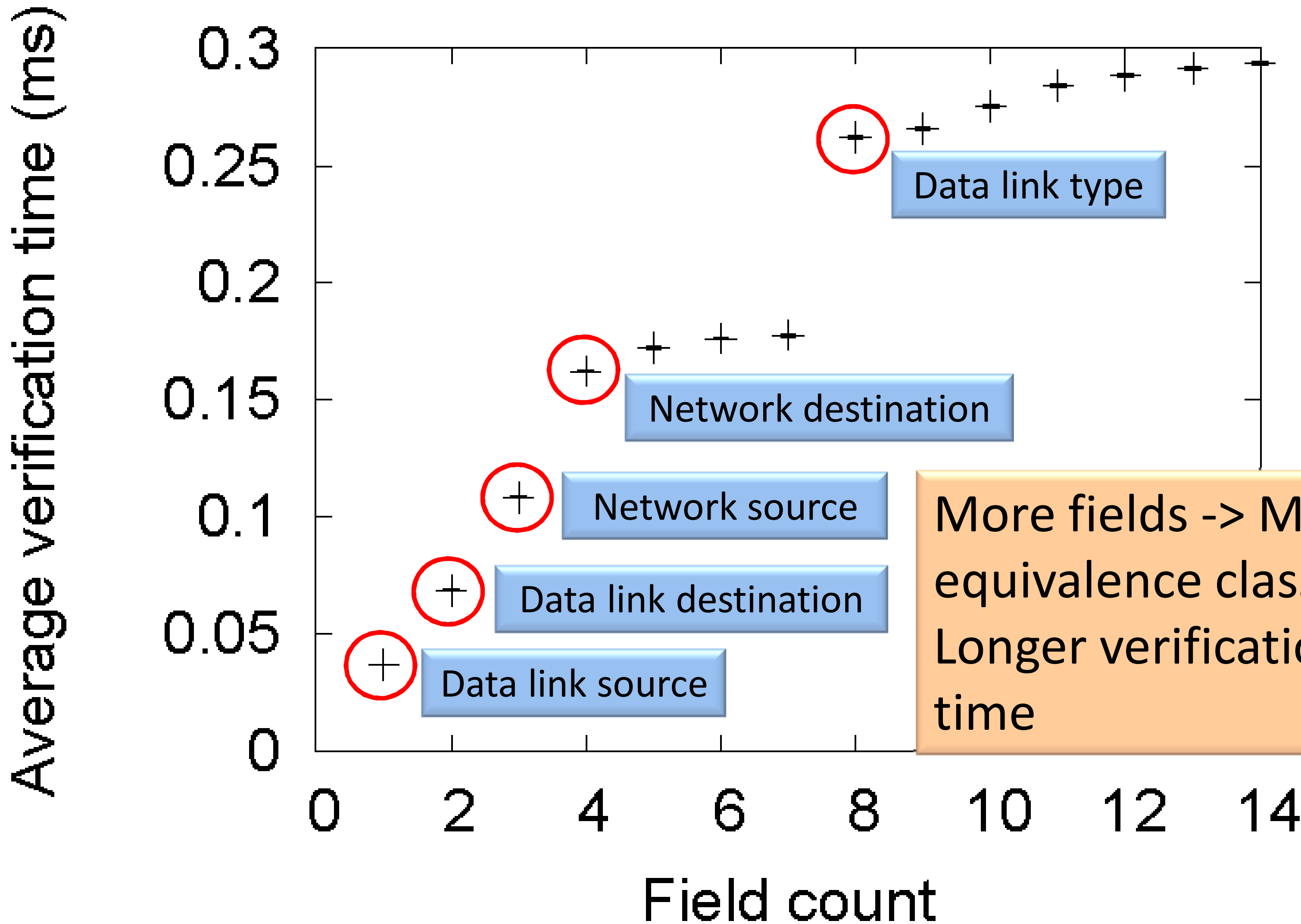
- Mininet OpenFlow network
  - Rocketfuel topology with 172 switches, one host per switch
- NOX controller, learning switch app
- TCP connections between random pairs of hosts



Effect on Flow Table Update Throughput



Effect of Multiple Header Fields



More fields -> More equivalence classes -> Longer verification time

Conclusion

- VeriFlow achieves real-time verification
  - A layer between SDN controller and network devices
  - Handles multiple packet header fields efficiently
  - Runs queries within hundreds of microseconds
  - Exposes an API for writing custom invariants
- Future work
  - Handling packet transformations efficiently
  - Dealing with multiple controllers

Thank you

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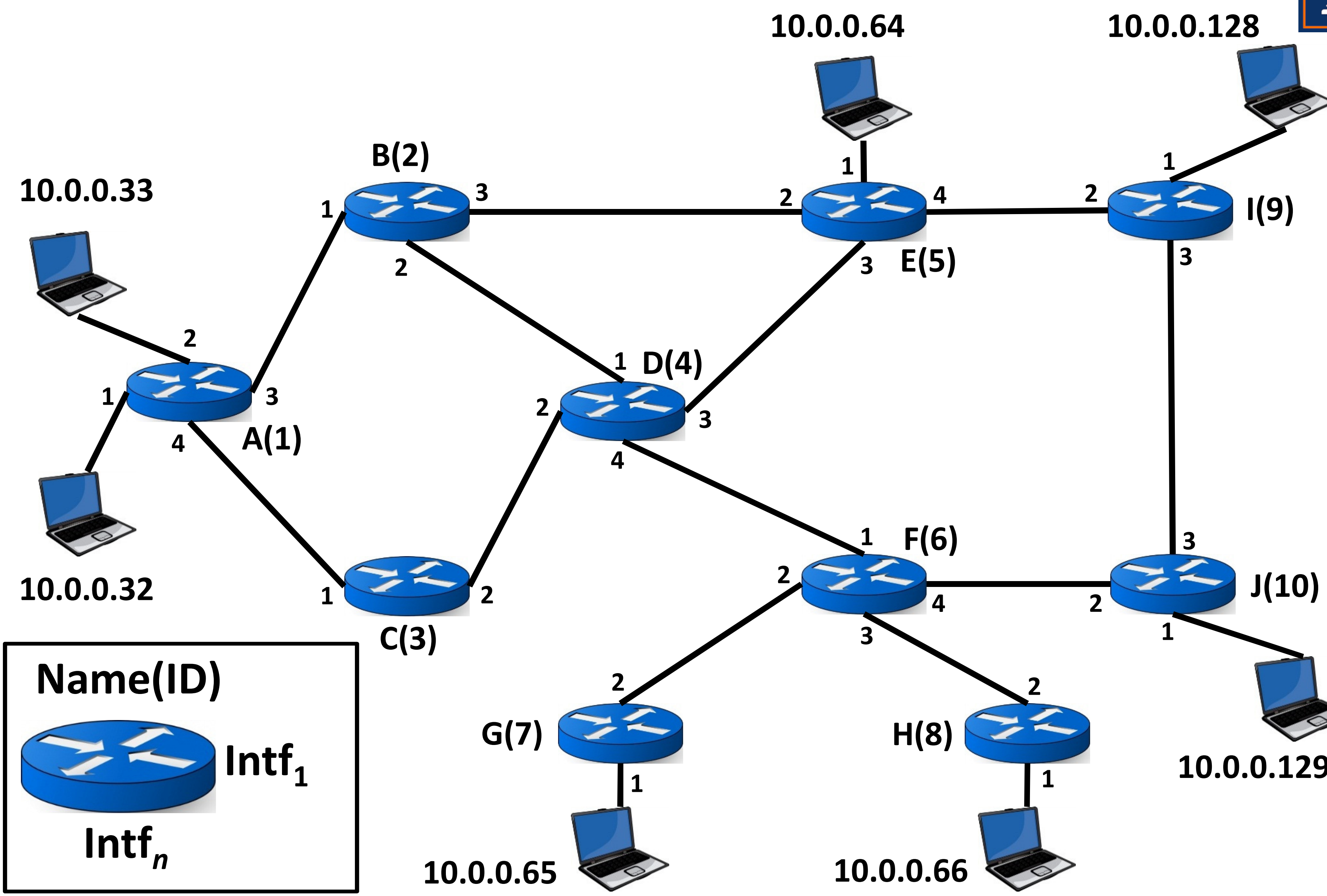
Backup Slides

Related Work

- Header space analysis: Static checking for networks, NSDI 2012
- A NICE way to test OpenFlow applications, NSDI 2012
- Abstractions for network update, SIGCOMM 2012
- Debugging the data plane with Anteater, SIGCOMM 2011
- Can the production network be the testbed?, OSDI 2010
- FlowChecker: Configuration analysis and verification of federated OpenFlow infrastructures, SafeConfig 2010
- Network configuration in a box: Towards end-to-end verification of network reachability and security, ICNP 2009

Demo Network


10.0.0.64
10.0.0.128
B(2)
10.0.0.33
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1
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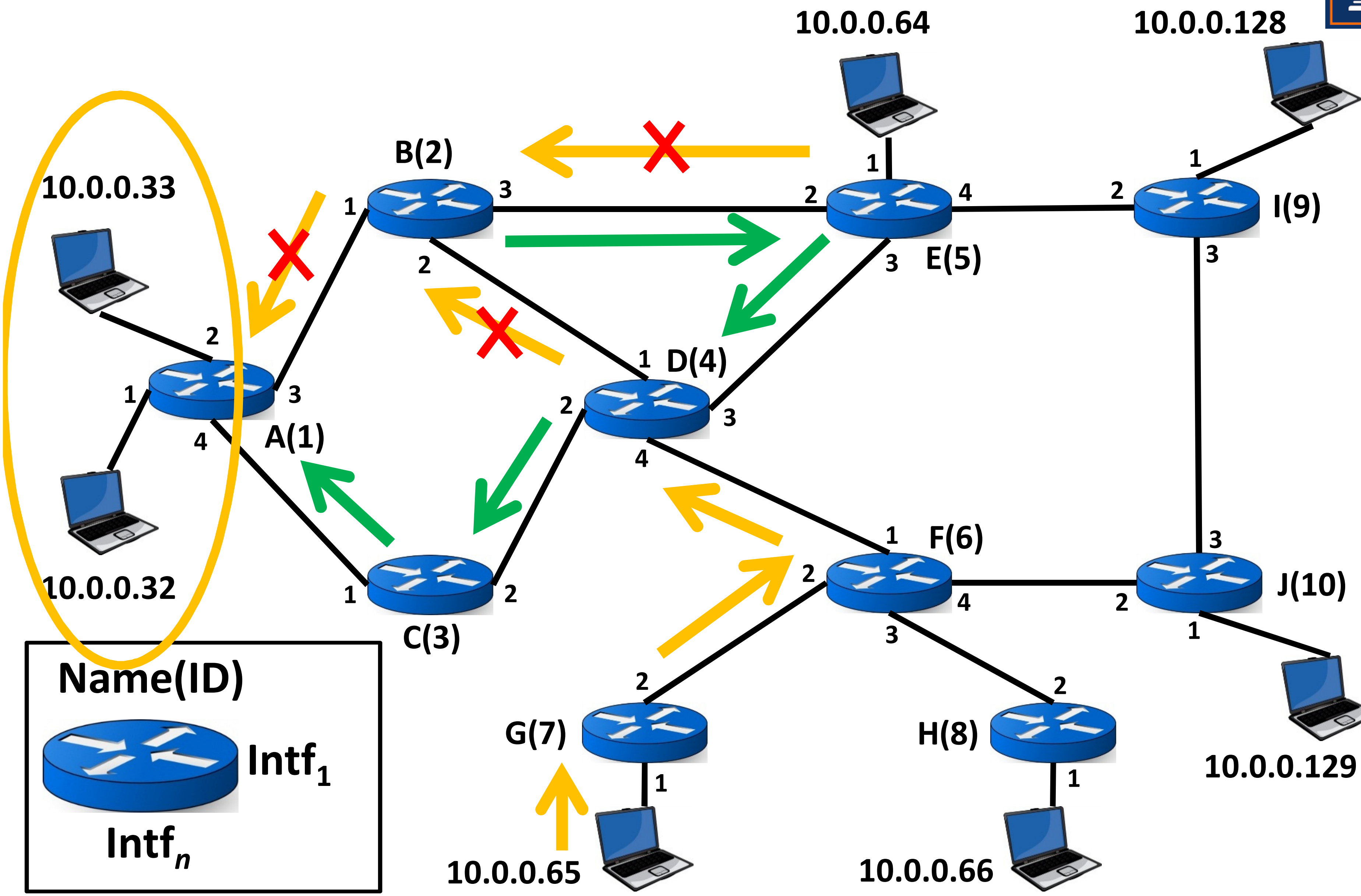
2
1
4
3
E(5)
I(9)
3
2
1
3
A(1)
4
1
D(4)
2
3
4
10.0.0.32
1
2
C(3)
1
F(6)
2
4
3
3
J(10)
2
1
Name(ID)
$Intf_1$
$Intf_n$
2
G(7)
1
2
H(8)
1
10.0.0.129
10.0.0.65
10.0.0.66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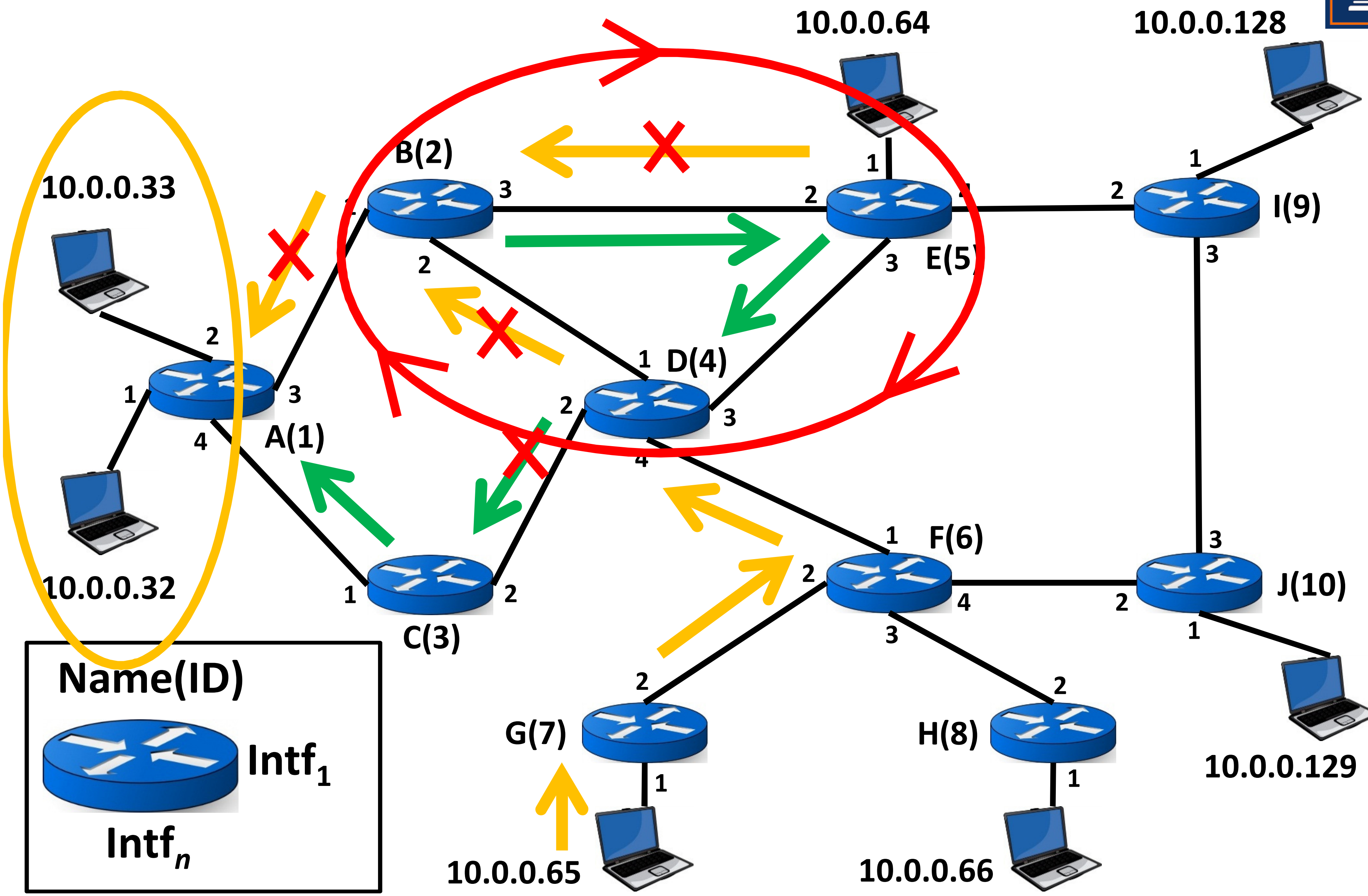
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