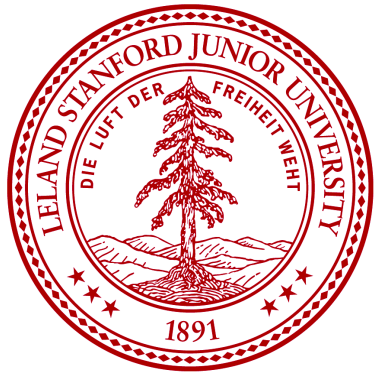

Libra: Divide and Conquer to Verify Forwarding Tables in Huge Networks

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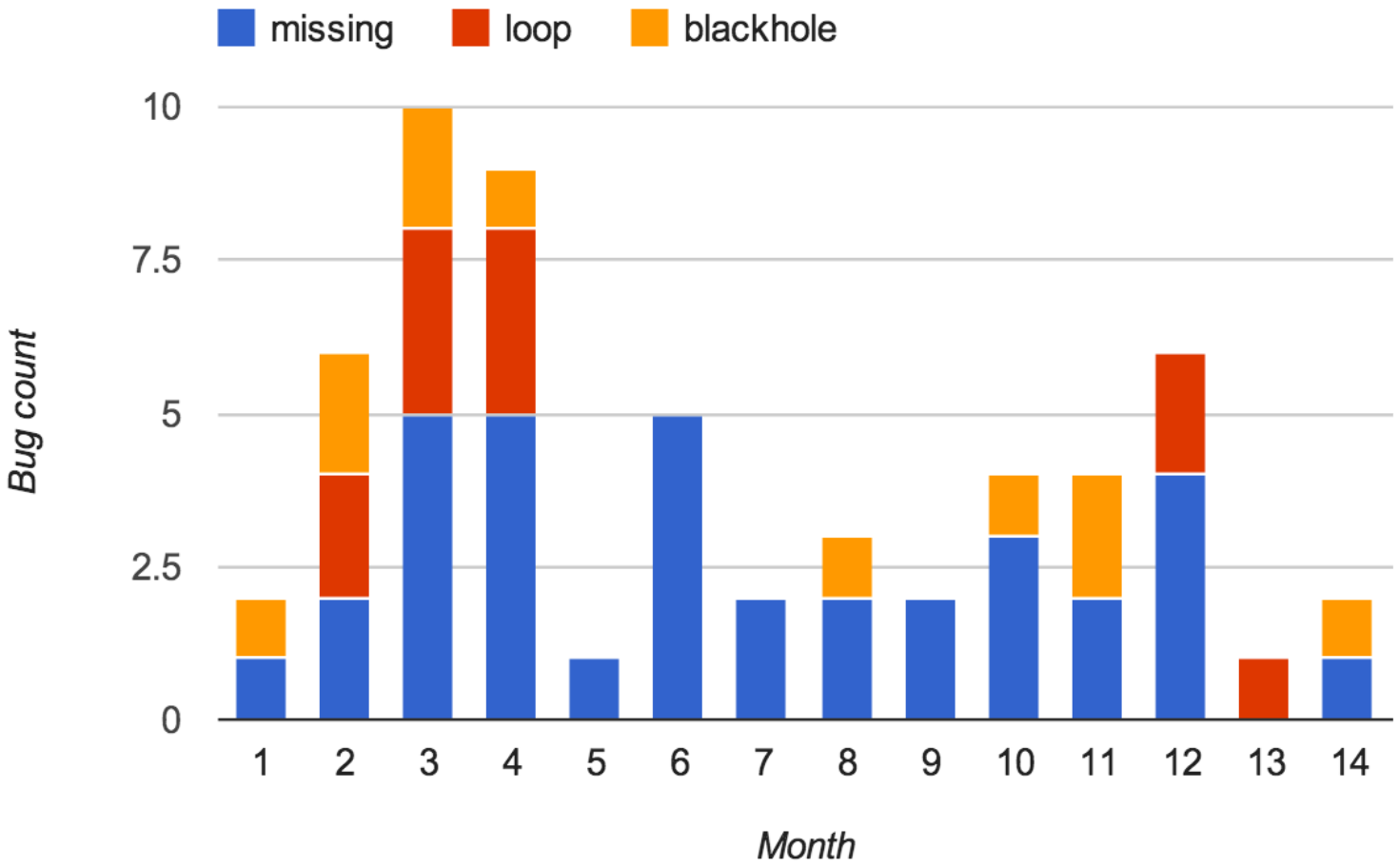
“My dear friend Copperfield,” said Mr. Micawber, “accidents will occur in the best-regulated families.”

-- Charles Dickens


Best Regulated Families: Data Centers
- Homogeneous machines/switches
- Pure IP forwarding
- Few security concerns
- No “silly” human users
- Full control to all devices
Google | google.com/datacenters

Data Plane Tickets in a Google Data Center



Why getting networks right is hard?

Complex interaction

- Between multiple protocols on a switch.
- Between state on different switches.

Multiple uncoordinated writers of state.

Operators cannot…

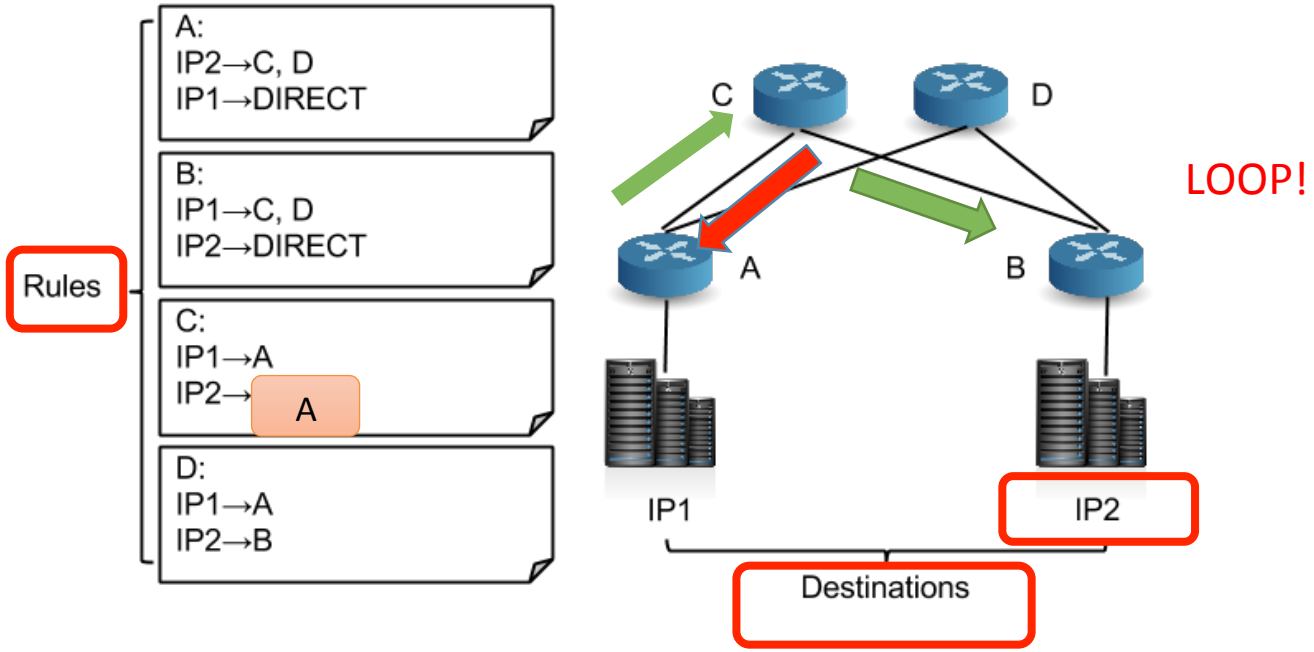
- Observe all state.
- Control all state.

One solution: Static Data Plane Verification

Static Data Plane Verification

Goal: Verifying data plane's logical correctness

- Example failures: loops, blackholes, partitions
- Inputs: destinations, rules, topology
- Independent of control plane

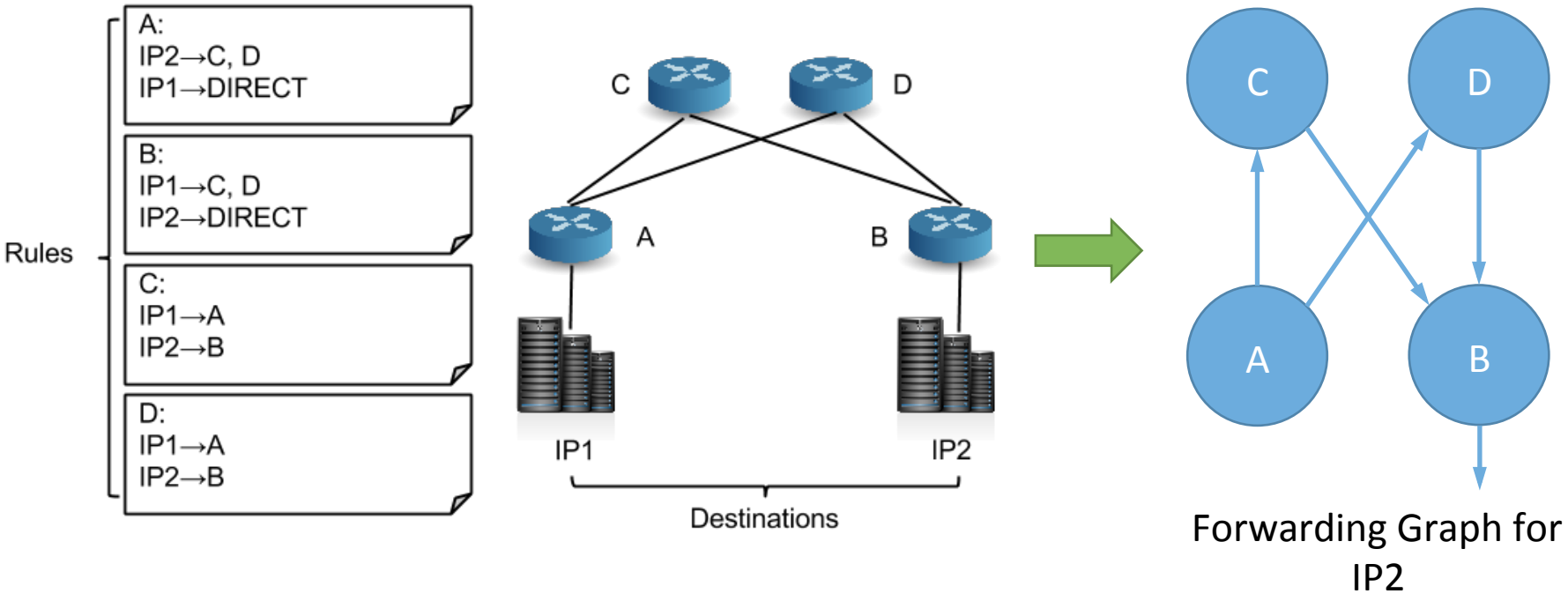


Two Challenges of Data Plane Verification in Data Centers

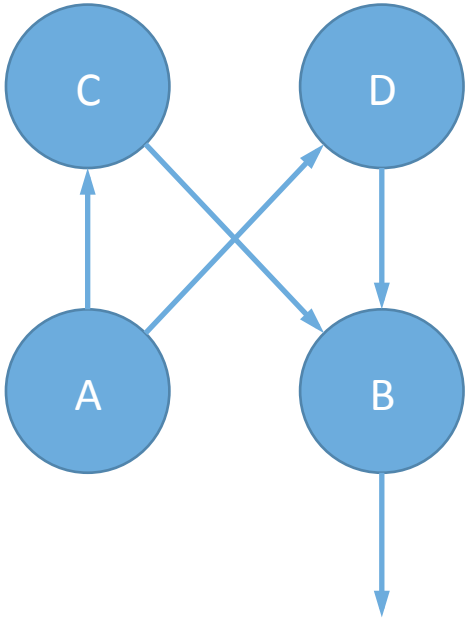
- Constant Rule Changes
  - Link up/down, route recalculation, new policy, etc.
  - Careless snapshot of forwarding tables may result in false positives

- Large Scale
  - 10,000s of switches, 1,000,000s of rules
  - How to finish the verification within a reasonable time?

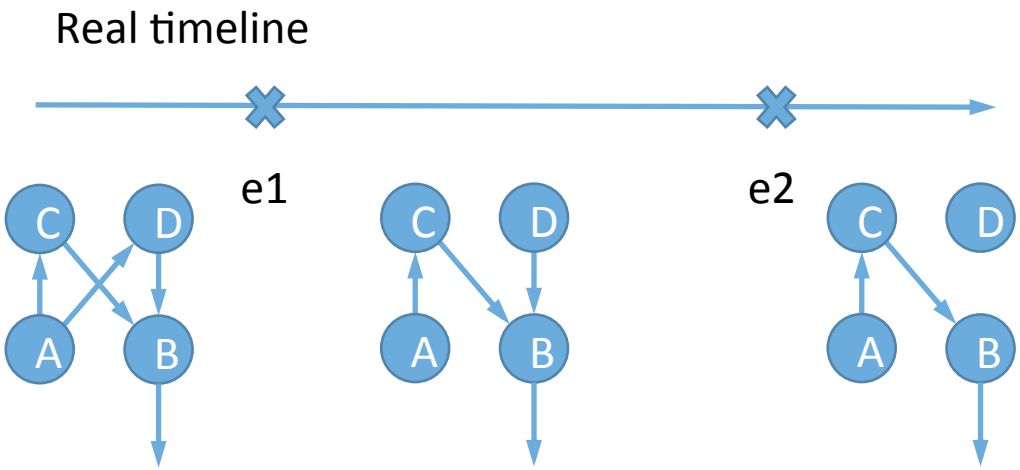
Forwarding Graph



The Snapshot Problem



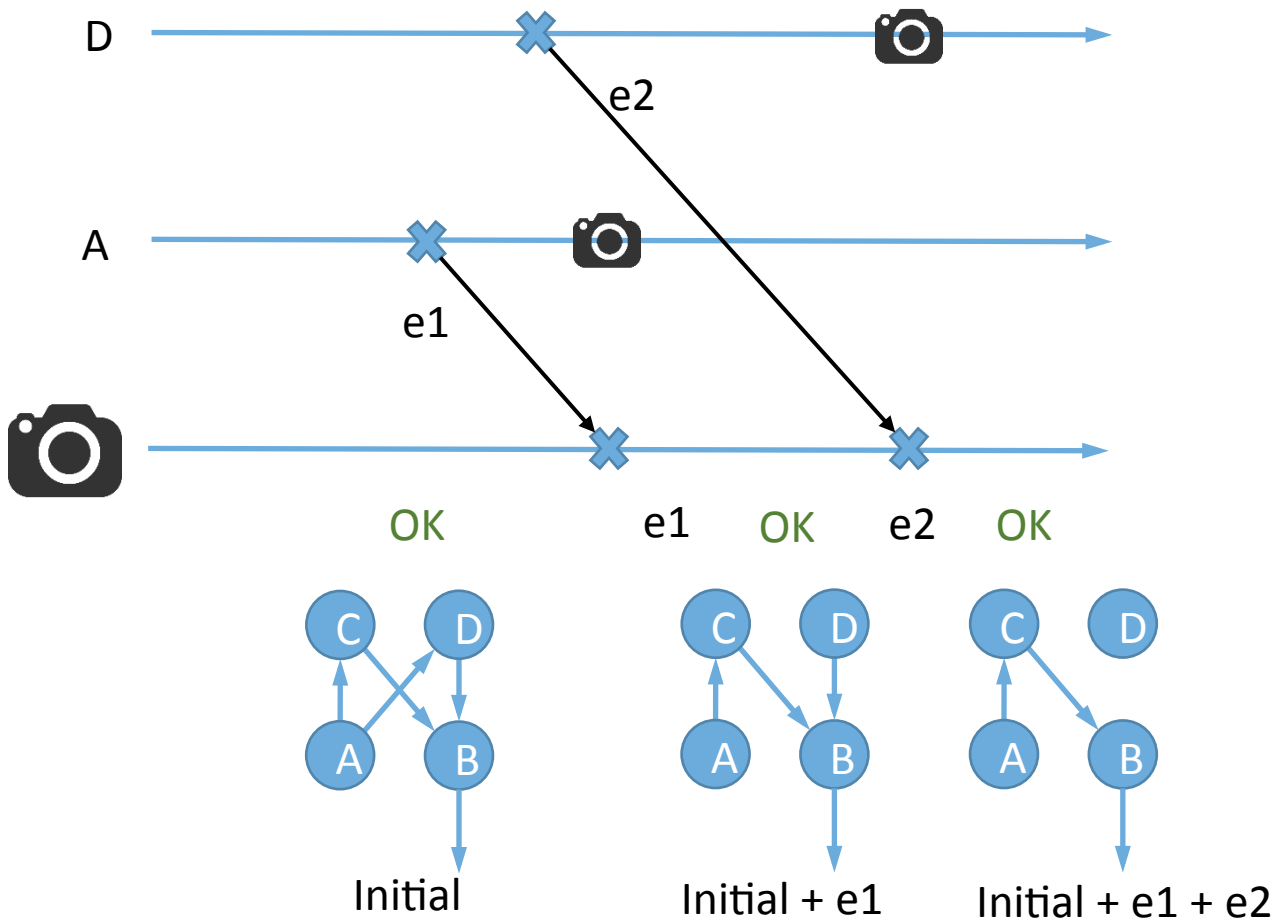
e1) A deletes rule A→D
e2) D deletes rule D→B



The Snapshot Problem

e1) A deletes rule A→D

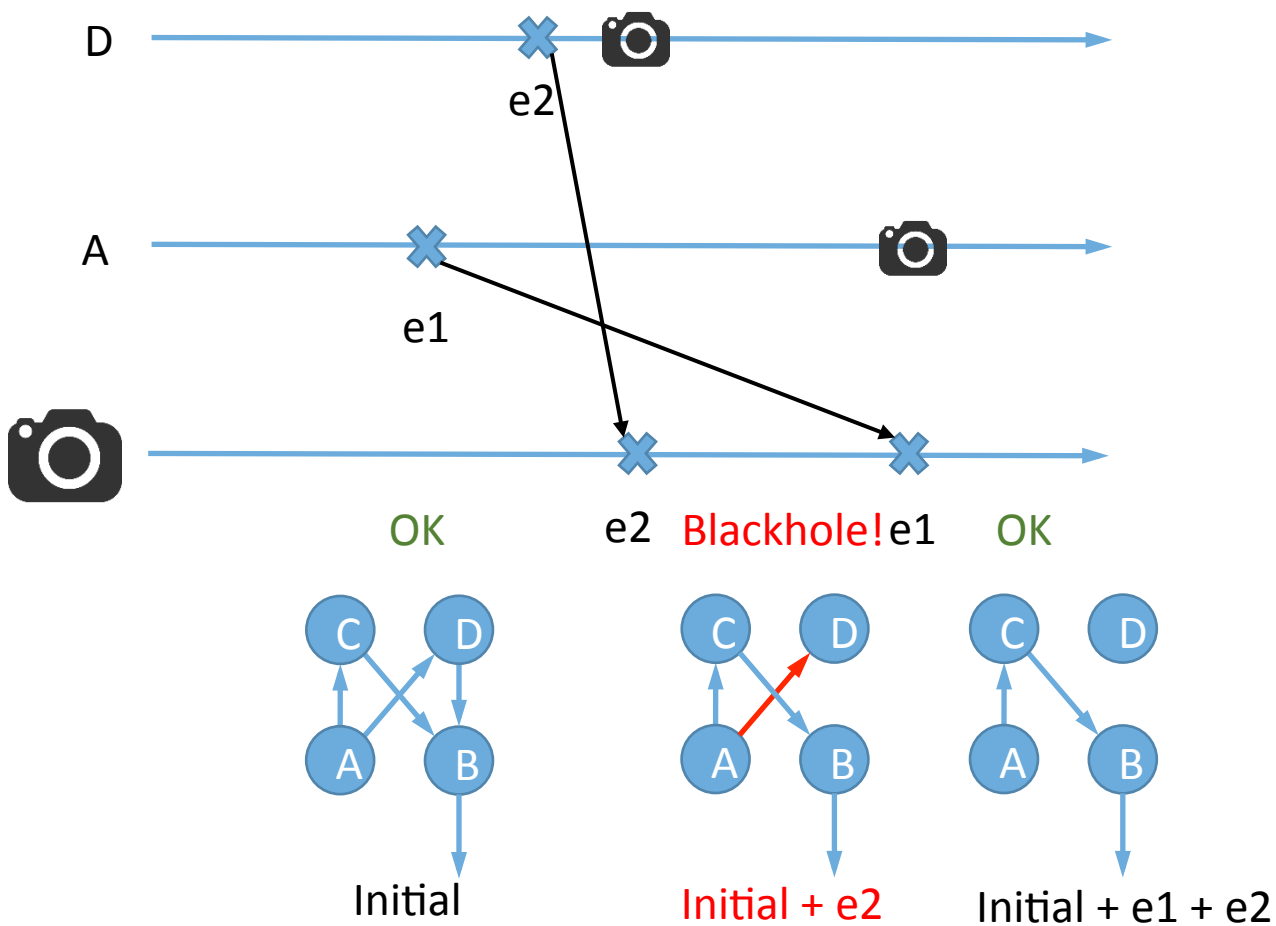
e2) D deletes rule D→B



The Snapshot Problem

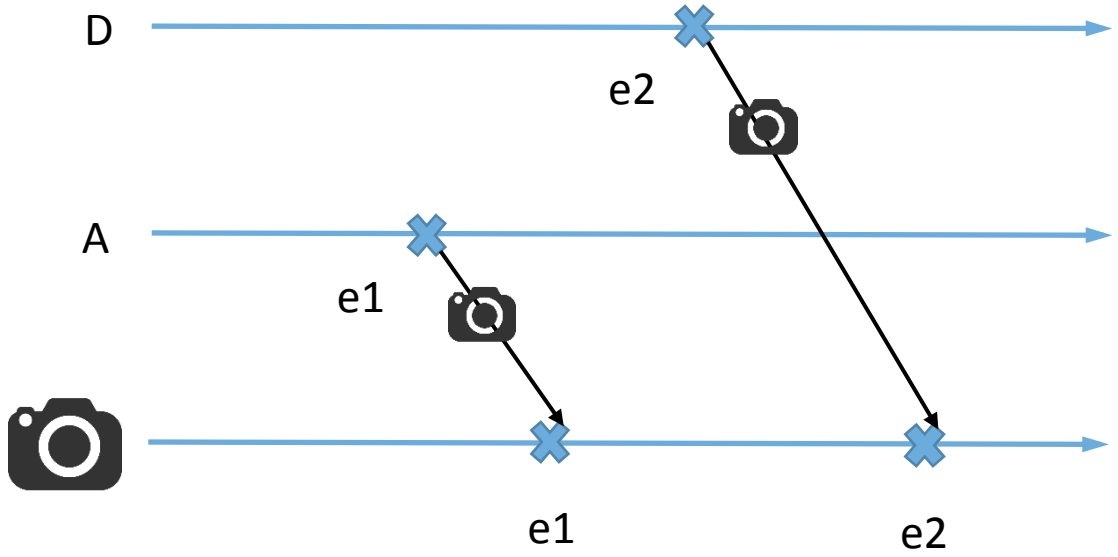
e1) A deletes rule A→D

e2) D deletes rule D→B



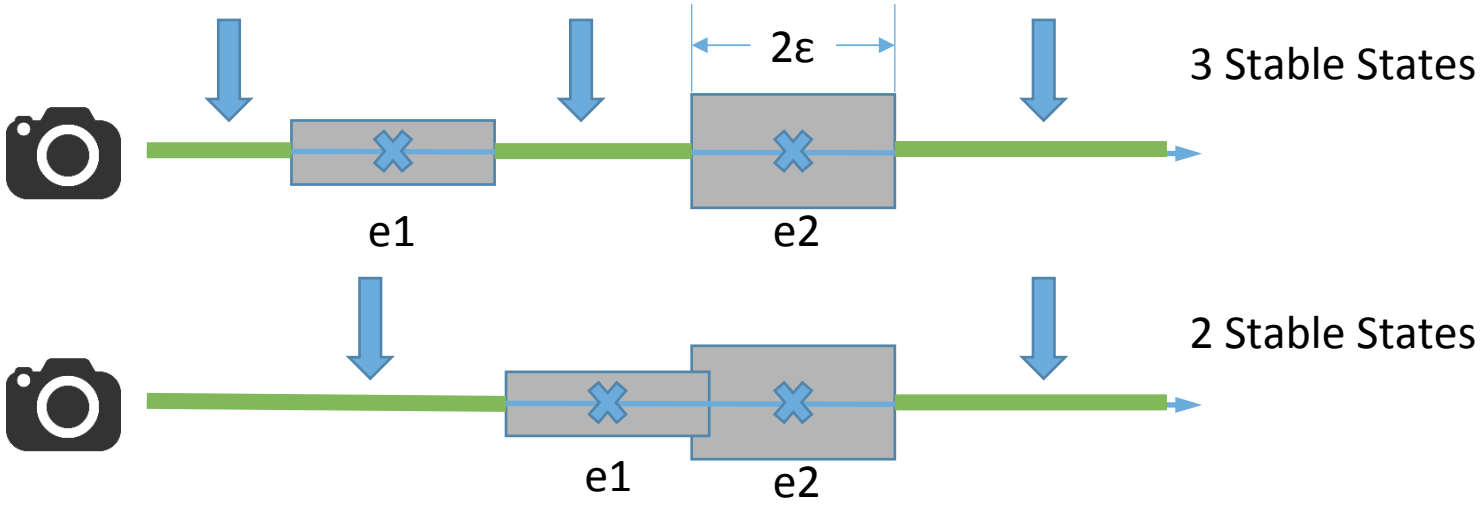
The Stable Snapshot

- Problem: Cannot take a global snapshot simultaneously
  - Otherwise, we will know either (initial), (initial+e1), or (initial +e1+e2) but never (initial+e2)
  - But this is a physical limitation..
- Solution: Record events (rule updates), not states (forwarding tables)



The Stable Snapshot

- Problem: Lack of true Global Clock for timestamps
- Solution: Leverage imperfect global clock – NTP
  - NTP has precision of ε = 1-100ms: Every event is bounded by 2ε
  - Only consider a snapshot when it's stable



Will networks ever be stable?

Example: Bursty rule updates in a production Google DC

- 28,445 events in 24 hours
- 95% of events happen within 400ms of each other
- 99.9% of time the network is stable ("silent")
  - Assuming ε = 100ms

How about transient states?

- We can report "potential" problems
- Network operators may not care anyway

Two Challenges of Data Plane Verification in Data Centers

Constant Data Plane Changes

- Link up/down, route recalculation, new policy, etc.
- Bad snapshot may result in false positives
- Solution: Stable Snapshots

Large Scale

- 10,000s of switches, 1,000,000s of rules
- How to finish the verification within a reasonable time?

Scalable Verification

Naïve Static Checker:

- Load all rules in memory
- Pick one destination, pick one ingress port, *simulate*
- Try the next one

Data Center Networks are immense

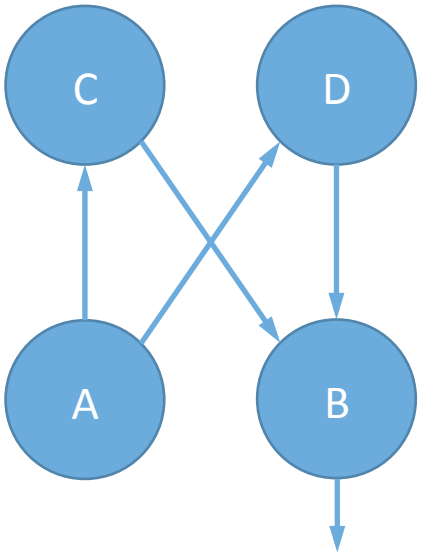
- 10,000 switches x 1,000 rules = 10M rules
- Thousands of destinations

Verification Complexity grows as $O(N^2)$

- N times switches/rules
- N times destinations

Parallelism! – But, how to partition?

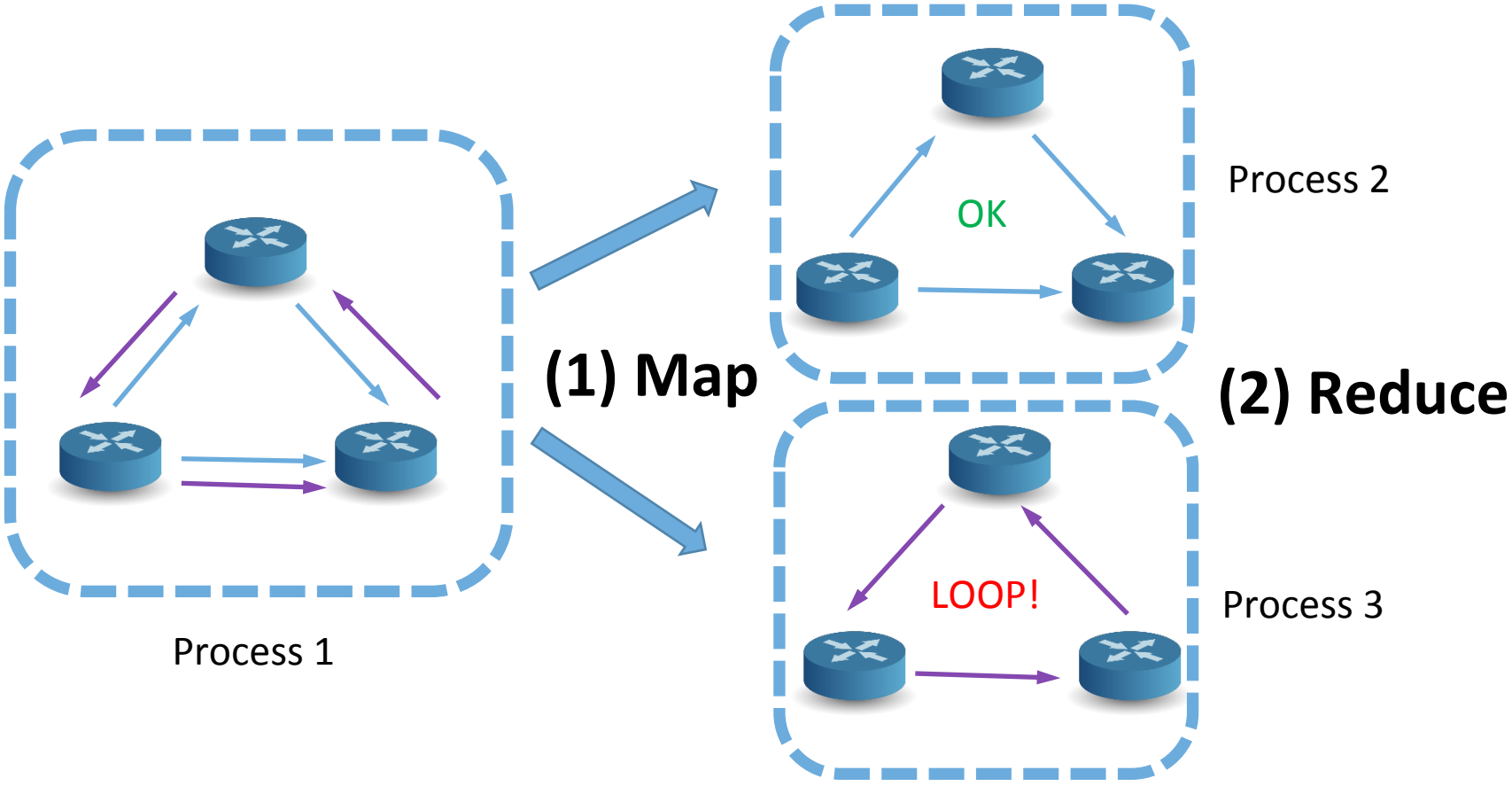
Forwarding Graph



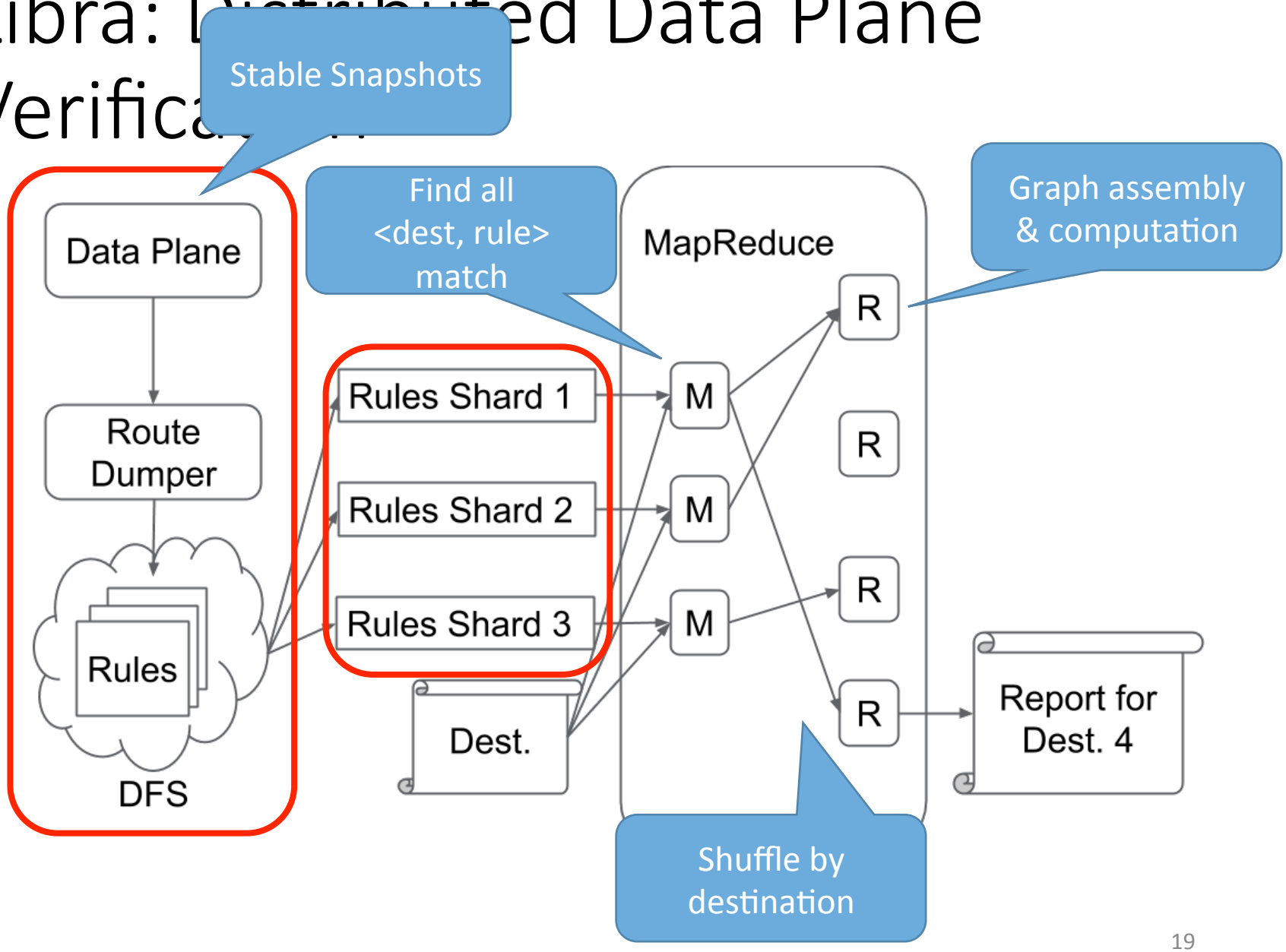
Forwarding Graph for IP2

- Each destination has a forwarding graph
- All data plane abnormalities are graph problems
  - loops, blackholes, partitions
- Forwarding graph size == Physical network size
  - Each physical node is a vertex
- For each graph, only a subset of rules are needed

Divide and Conquer



Libra: Distributed Data Plane Verification



Evaluation: Loop detection

	DCN	DCN-G	INET
Switches	11,260	1,126,001	316
Rules	2,657,422	265,742,626	151,649,486
Destinations	11,136	1,113,600	482,966
Machines	50	20,000*	50
Time/s	57	906	93

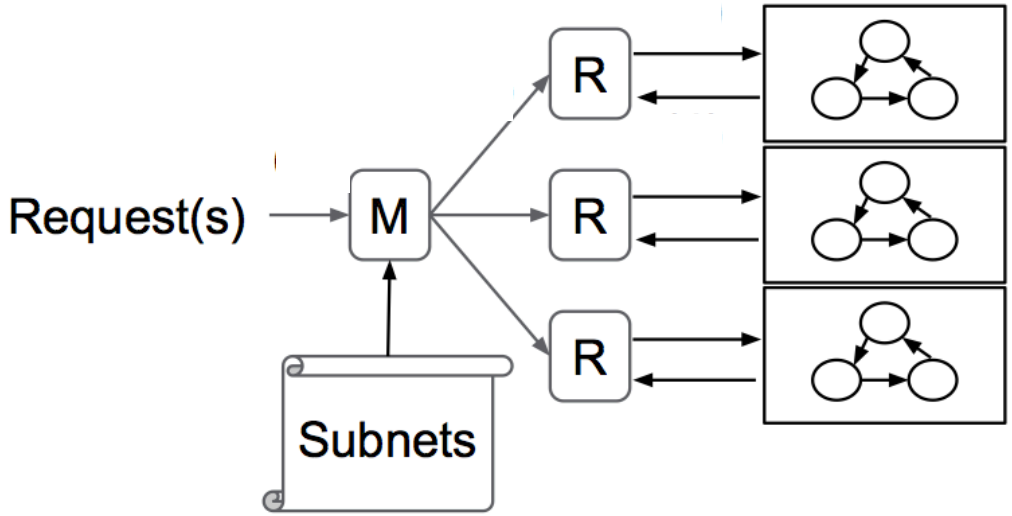
DCN: Google's emulated data center network

DCN-G: 100 DCNs connected in a star topo

INET: 300 Internet routers with full BGP table

*extrapolated

Even Faster: Incremental Updates



	DCN	DCN-G	INET
Map (us)	0.133	0.156	0.158
Reduce (ms)	0.62	1.76	<0.01

Libra: Data Plane Verification at Data Center Scale

- Stable Snapshots
  - Only consider stable states of the data plane
  - Avoid false positives in bad snapshots
- Divide and Conquer
  - Implemented in MapReduce
  - Handles massive scale with parallelism

Thank you!

http://eastzone.github.io/libra/

Acknowledgement: Thanks to our shepherd T.V. Lakshman and anonymous NSDI reviewers for constructive feedbacks.

"Distributed" Longest Prefix Matching

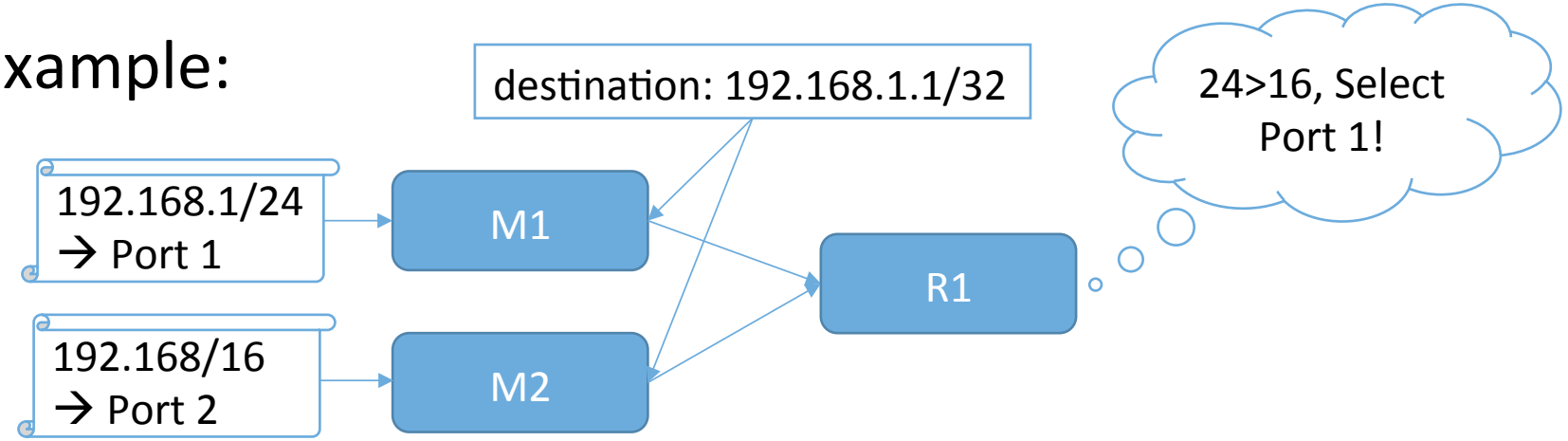
Problem: Relevant rules may be in different shards

- Mappers cannot see each other!

Solution: Defer length comparison to Reduce phase

- Reducer can see everything related to a destination

Example:



Challenge: All-prefix Matching

Problem: In mappers, given a rule, find out *all* matching destinations

- Conventional matching: Given a destination, find out *one* matching rule
- Naïve approach: Linear search, O(*TR*) where *T* = # of destinations, *R* = # of rules

Solution: Use a Trie (prefix Tree)

- Put all destinations in a Trie (once per mapper)
- O(*LR*) where *L*=32 for IPv4
  - Assuming a small number of matching destinations

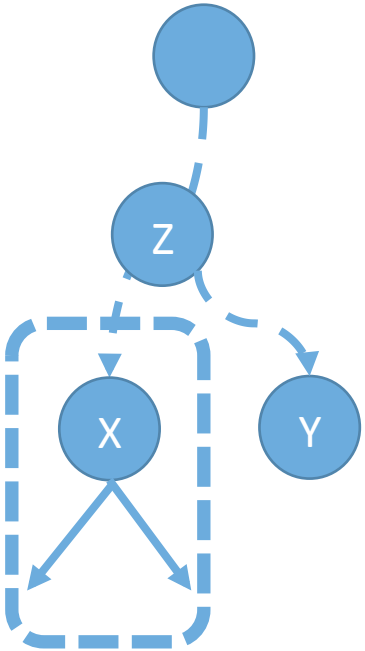
Challenge: All-prefix Matching

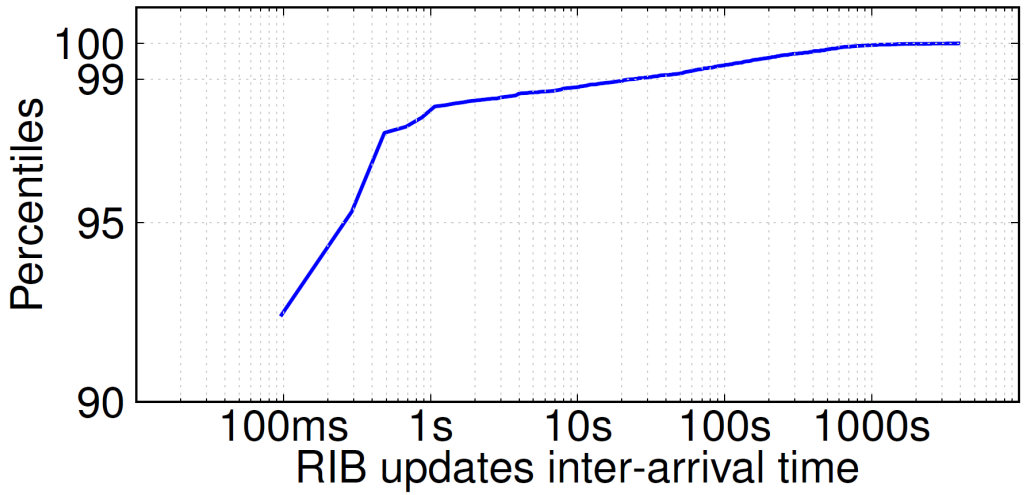
Algorithm:

- Step 1: Find the smallest matching trie node (*X*) that is bigger or equal to the rule (*A*) (lexical order)
- Step 2: Enumerate all *X*'s descendants including *X*.

Proof:

- Assume there is another node *Y* that isn't *X*'s descendant
- *X* and *Y* have common ancestor *Z*, *Z*!=*X* and *Z*!=*Y*
- *Z* matches *A* because both *X* and *Y* match *A*, and
- *Z* is smaller than *X*. Contradiction! QED




100
99
95
90
Percentiles
100ms
1s
10s
100s
1000s
RIB updates inter-arrival time

Who benefits

Network Engineers

- Ensure policy compliance
- Reduce service downtime
- Report specific errors to vendors/Fix bugs

Network Users

- Visibility in networks
- Reduce application diagnosis time
  - Verification OK → Debug application
  - Verification Failed → Engage network engineers