APKeep: Realtime Verification for Real Networks

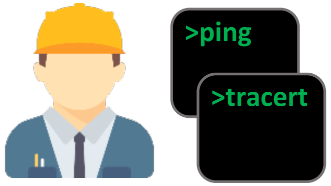
Peng Zhang[*], Xu Liu[*], Hongkun Yang[+], Ning Kang[*], Zhengchang Gu[*], Hao Li[*]

[*] Xi'an Jiaotong University, [+]Google

Background

Network outages are common

human misconfiguration, software bugs, etc.



Post-effect troubleshooting is slow

manually find the root cause after outages using simple tools

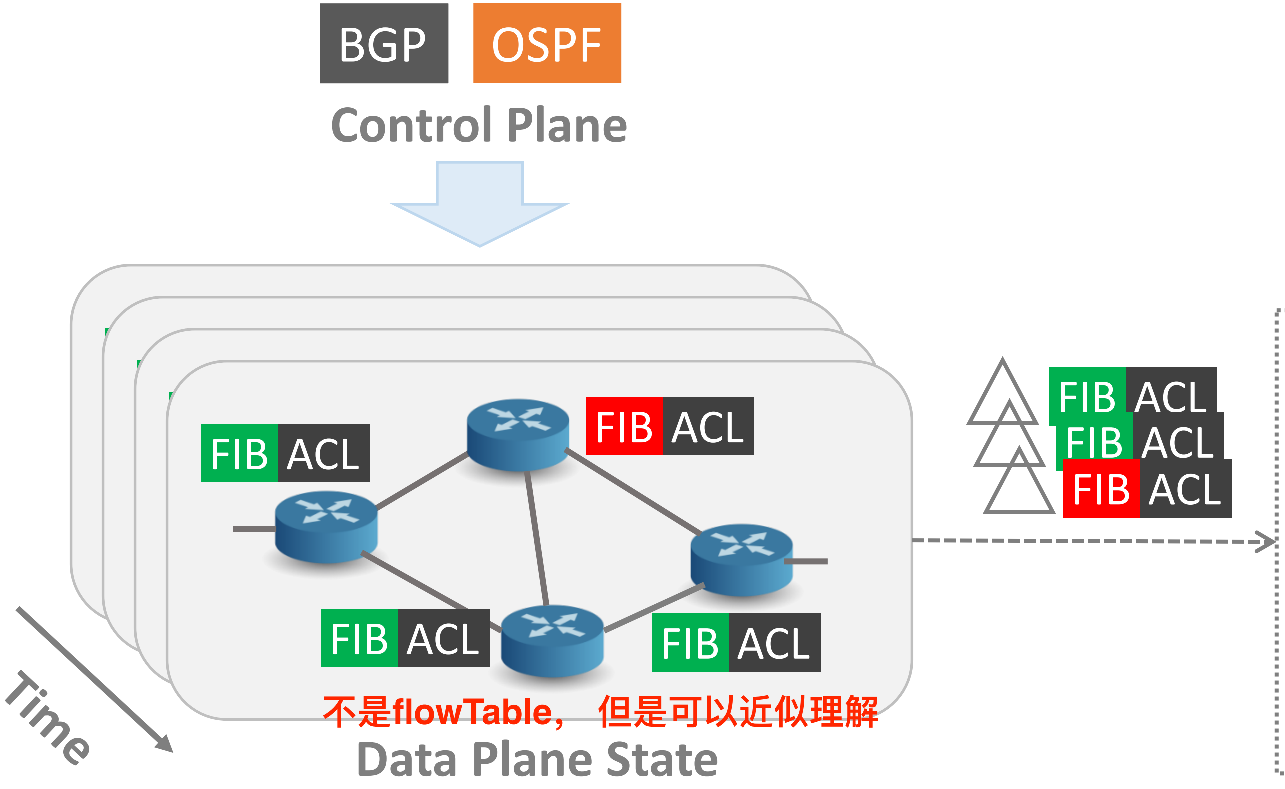
The cost can be quite expensive

service down for hours/days, heavy loss of revenue

Network Verification

automatically check network correctness with formal methods

Realtime Network Verification



Realtime Network verification

VeriFlow [NSDI’13], NetPlumber [NSDI’13], AP Verifier [ICNP’13], Delta-net[NSDI’17]

Check correctness of data plane state after each update in real time

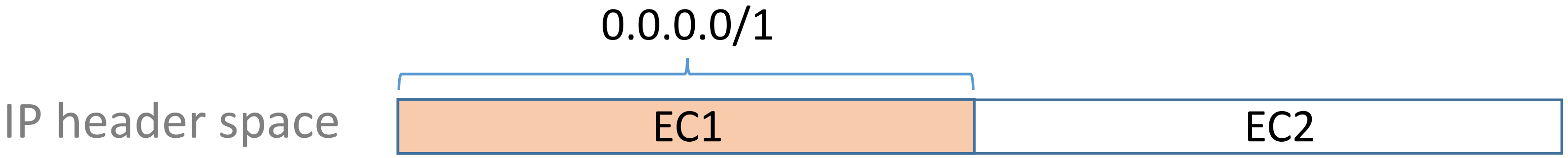
correctness: reachability, no loops, no blackholes, isolation, …

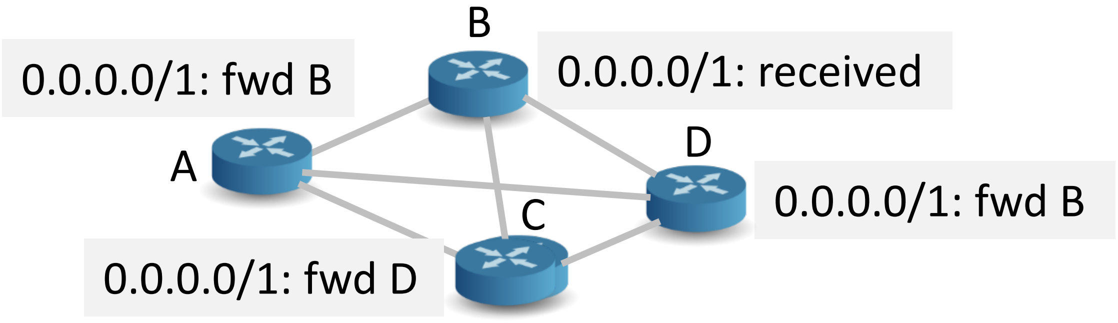
real time: verify each update in small amount of time (<1ms)

Preliminary to Realtime Network Verification

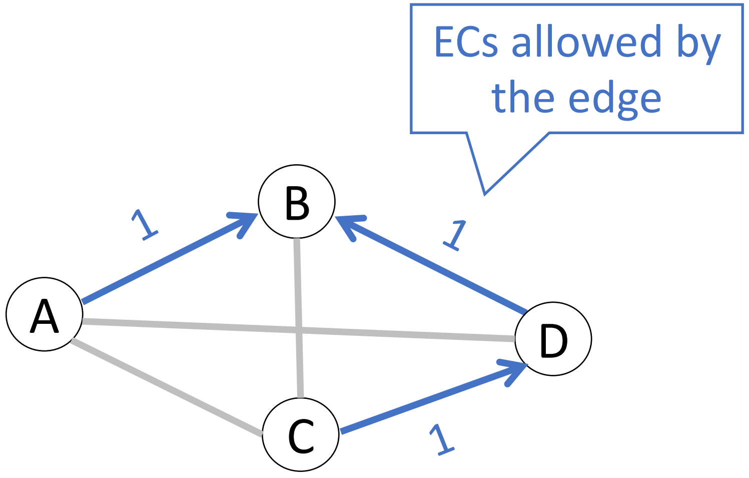
Equivalence Class (EC): a set of packets with the same forwarding behavior

等价类





Data plane state



Network model

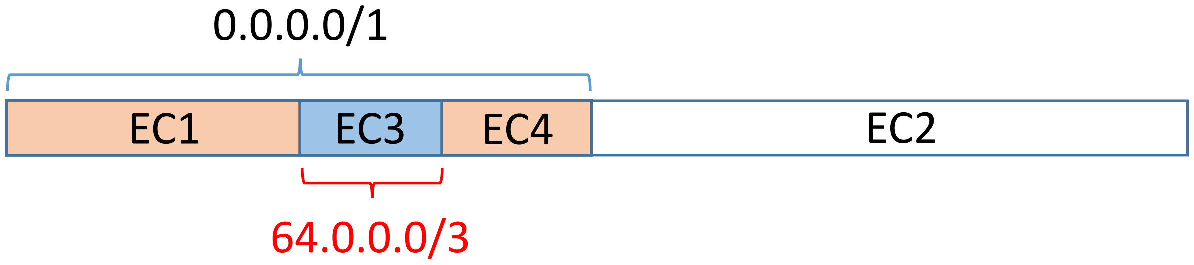
Preliminary to Realtime Network Verification

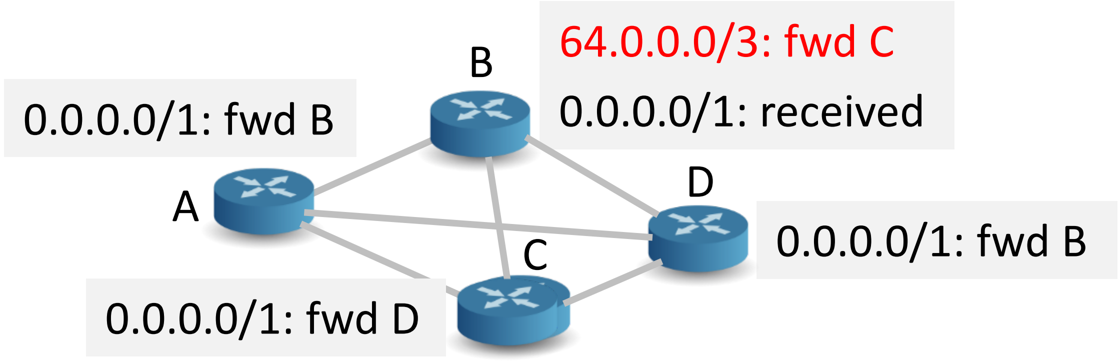
Incremental update and verification [VeriFlow, NSDI’13] [AP Verifier, ICNP’13] [Delta-net, NSDI’17]

Update the ECs

增量更新

IP header space





64.0.0.0/3: fwd C

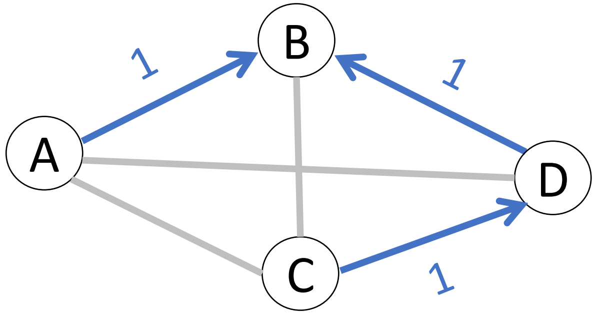
0.0.0.0/1: received

0.0.0.0/1: fwd B

0.0.0.0/1: fwd B

0.0.0.0/1: fwd D

Data plane state



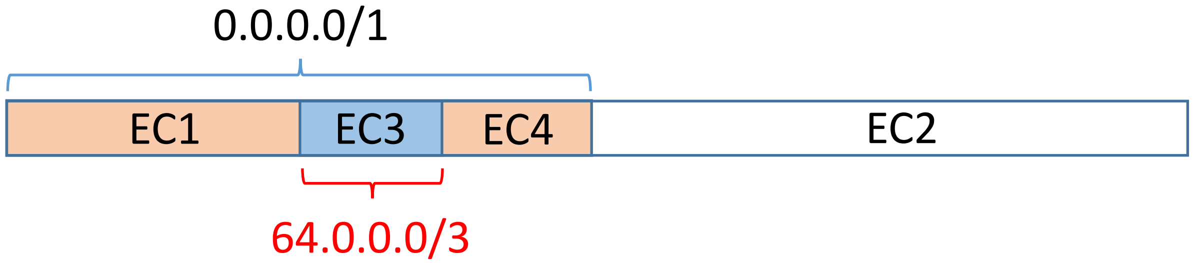
Network model

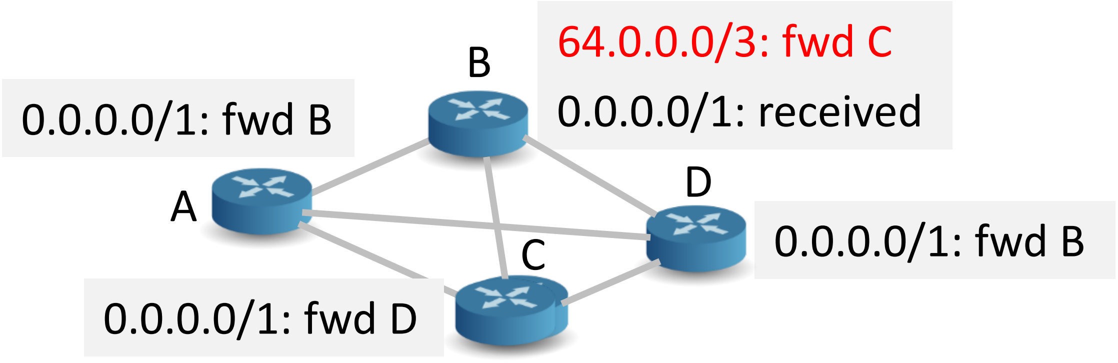
Preliminary to Realtime Network Verification

Incremental update and verification [VeriFlow, NSDI’13] [AP Verifier, ICNP’13] [Delta-net, NSDI’17]

Update the ECs >> Update the model

IP header space





64.0.0.0/3: fwd C

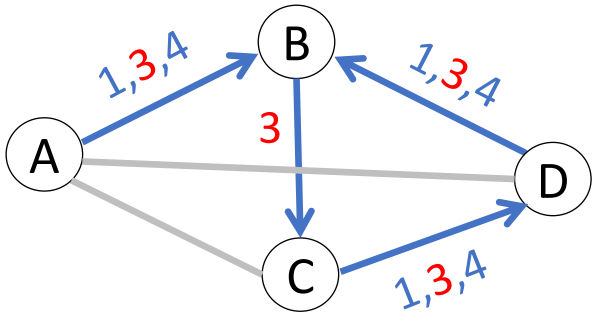
0.0.0.0/1: received

0.0.0.0/1: fwd B

0.0.0.0/1: fwd B

0.0.0.0/1: fwd D

Data plane state

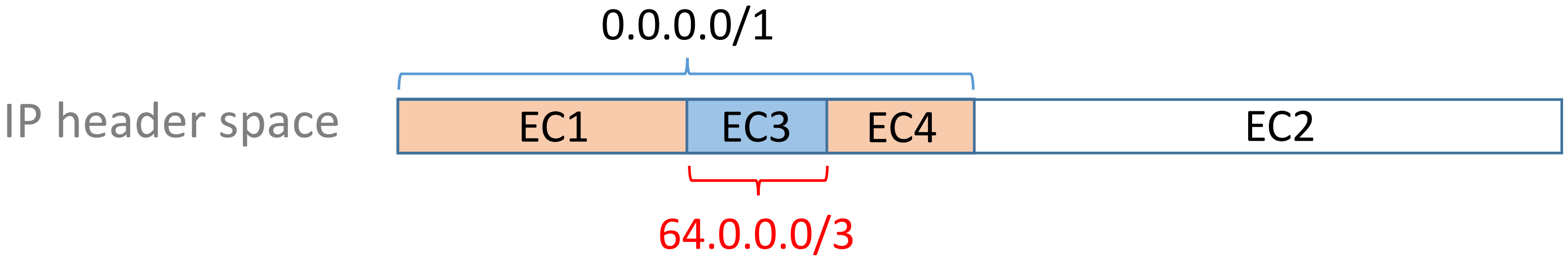


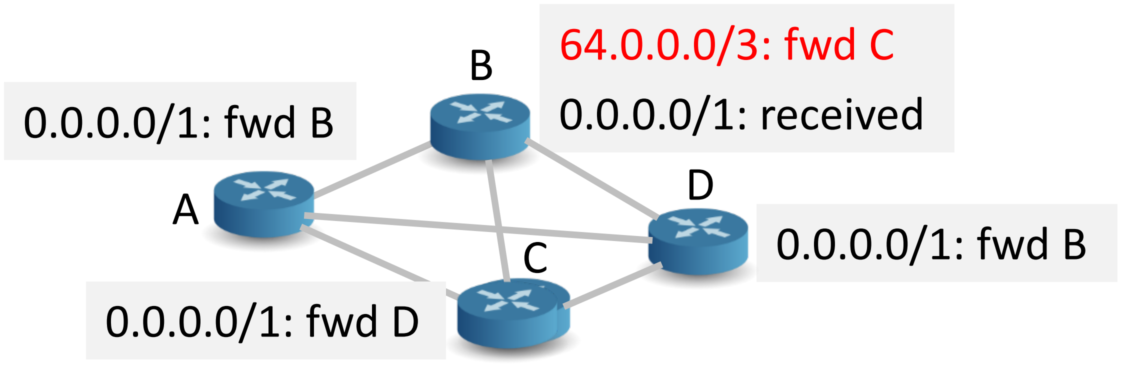
Network model

Preliminary to Realtime Network Verification

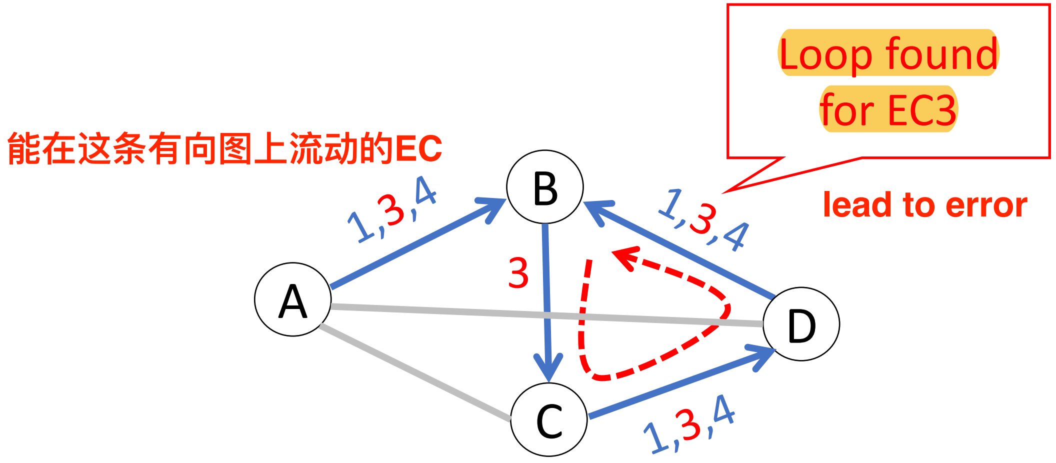
Incremental update and verification [VeriFlow, NSDI'13] [AP Verifier, ICNP'13] [Delta-net, NSDI'17]

Update the ECs >> Update the model >> Check properties



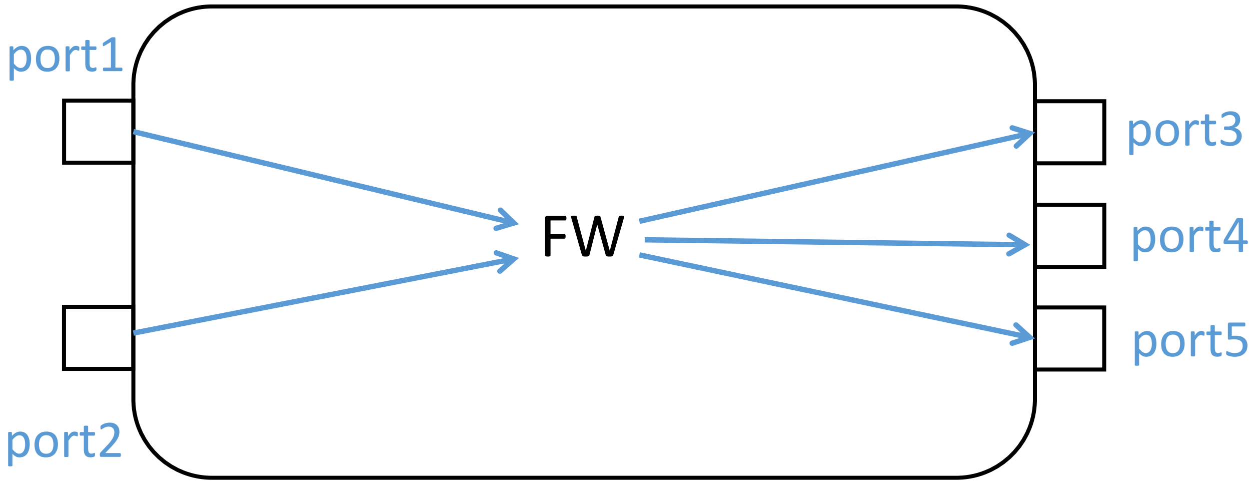


Data plane state



Network model

Realtime Verification for “Real” Networks



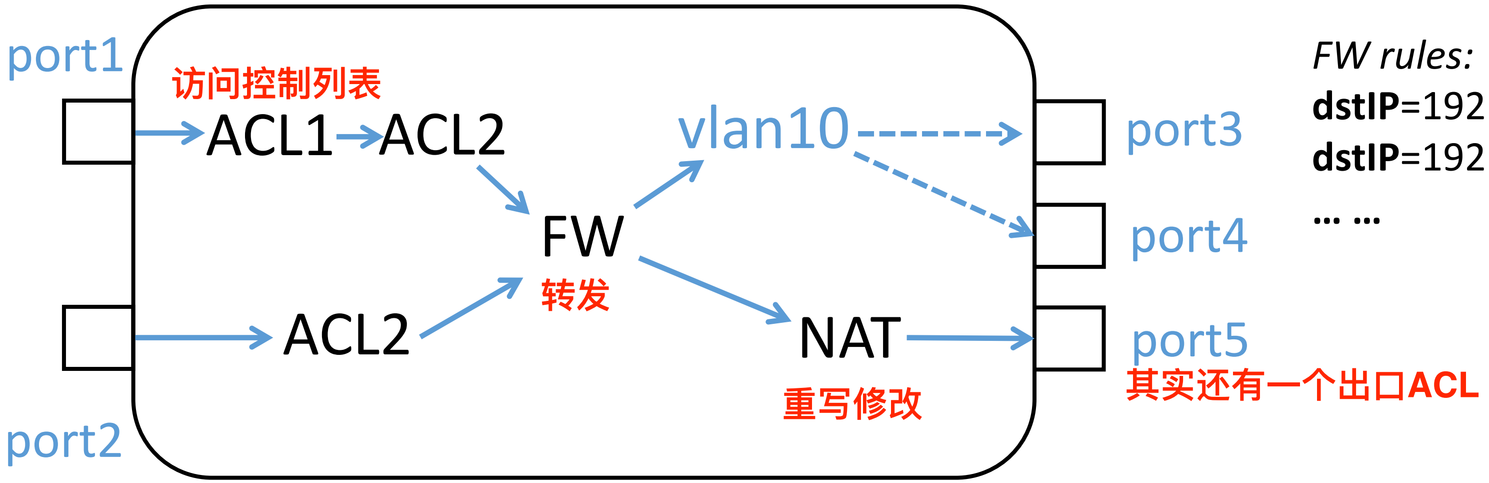
FW rules:

dstIP=192.168.0.0/16 port5

dstIP=192.168.10.0/24 VLAN10

… …

Realtime Verification for “Real” Networks



FW rules:

dstIP=192.168.0.0/16 port5

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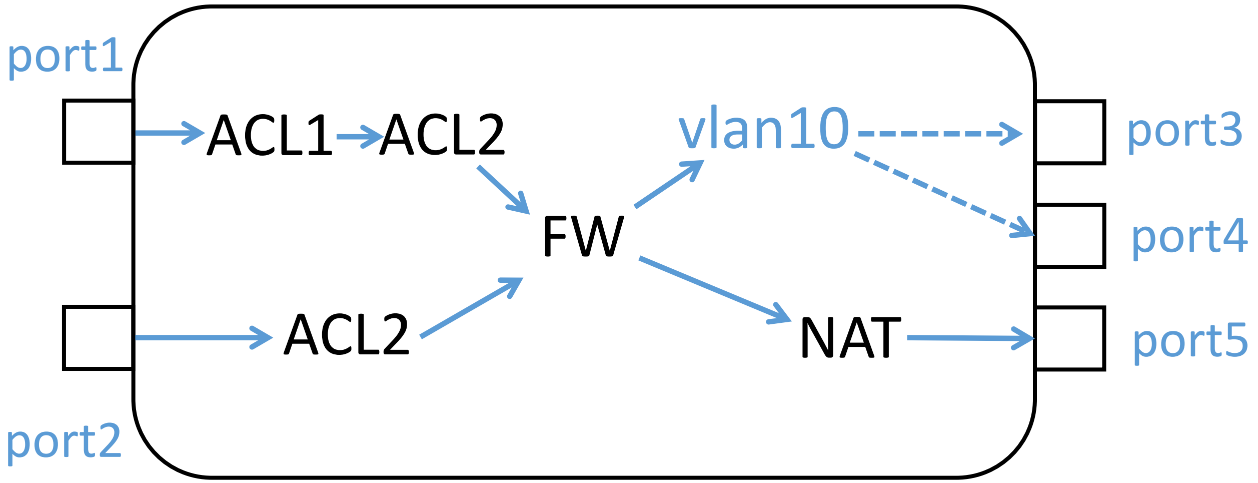
… …

Various functionalities beyond forwarding

- filtering (ACL), rewriting (NAT), traffic policy, …

Requirement 1: Network model should be **expressive** of common functionalities

Realtime Verification for "Real" Networks



FW rules:
dstIP=192.168.0.0/16 port5
dstIP=192.168.10.0/24 VLAN10
… …

ACL1 rules:
dstIP=10.0.0.0/16 **dstPort**=22 permit
dstIP=10.0.1.0/24 **srcIP**=10.0.2.0/24 **dstPort**=80 deny
… …

Various functionalities beyond forwarding

- filtering (ACL), rewriting (NAT), traffic policy, …

Requirement 1: Network model should be **expressive** of common functionalities

Multiple fields other than IP prefix

- 5-tuples used by ACL, traffic policy, NAT, etc.

Requirement 2: Update of ECs should be **scalable** for multi-field rules

Scalability Issue due to Multi-Field Rules

(1) ECs based on Ranges: fast for single-dimensional forwarding rules

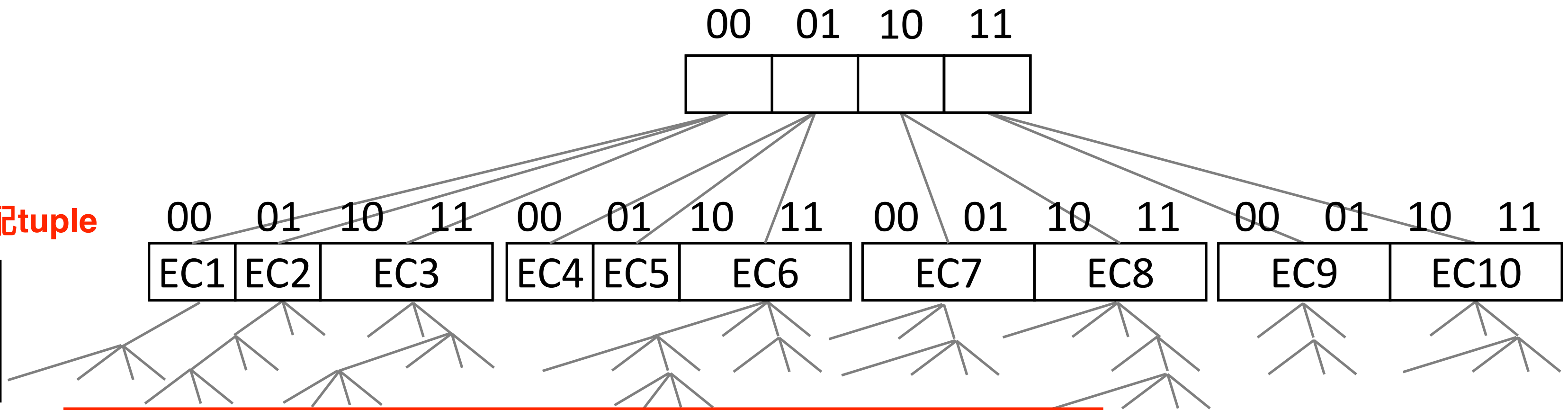
Forwarding rules 为简化，设定IP Addr 2bits

R1. **dstIP**=00: forward port2
R2. **dstIP**=10: forward port2

ACL rules ACL规则：匹配tuple

R3. **dstIP**=0∗, **dstPort**=0: deny
R4. **dstIP**=∗∗, **dstPort**<2: permit

00 | 01



in deltaNet

Network	#fw rules	#acl rules	**# of ECs**
Stanford	3.84×10^3	686	**15,100,968**
Purdue	3.52×10^6	2707	**>104,743,229**

Explosion of ECs

- Memory overflow
- Long verification time

Scalability Issue due to Multi-Field Rules

(2) ECs based on Atomic Predicates [AP Verifier, ICNP’13]: minimum # of ECs

deltaNet是利用匹配规则，所以会导致很多具有相同行为的EC被认为是不同的EC

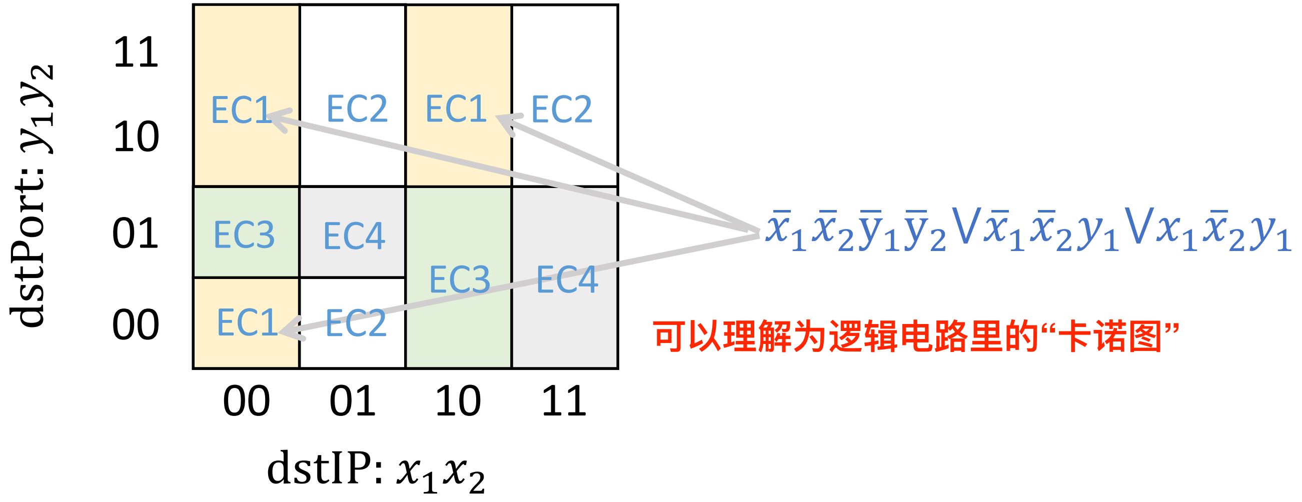
Forwarding rules

R1. **dstIP**=00: forward port2
R2. **dstIP**=10: forward port2

ACL rules

R3. **dstIP**=0∗, **dstPort**=0: deny
R4. **dstIP**=∗∗, **dstPort**<2: permit

在这里例子里，
ECs从10->4



dstPort: $y_1 y_2$	00	01	10	11
11	EC1	EC2	EC1	EC2
10				
01	EC3	EC4	EC3	EC4
00	EC1	EC2		
	dstIP: $x_1 x_2$			

$\bar{x}_1\bar{x}_2\bar{y}_1\bar{y}_2 \vee \bar{x}_1\bar{x}_2 y_1 \vee x_1\bar{x}_2 y_1$

可以理解为逻辑电路里的“卡诺图”

Network	#fw rules	#acl rules	**# of ECs**
Stanford	3.84×10^3	686	**515**
Purdue	3.52×10^6	2707	**4160**

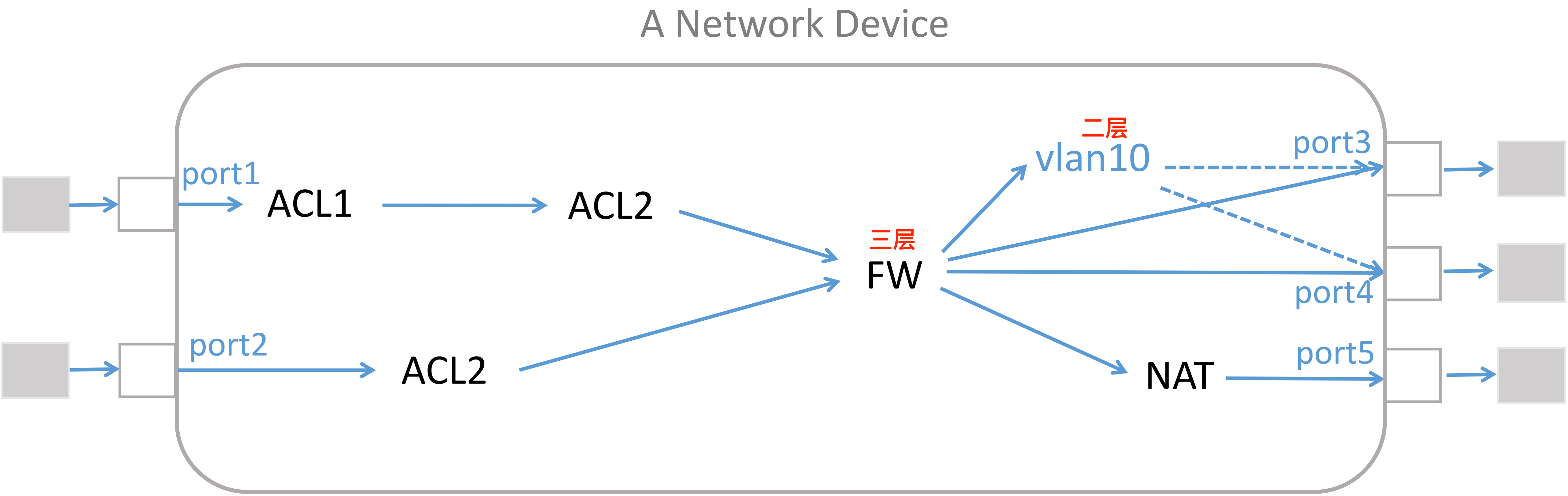
challenging to update atomic predicate fast

- An update potentially affects all atomic predicates
- Checking all atomic predicates is expensive (~10ms)

APKeep

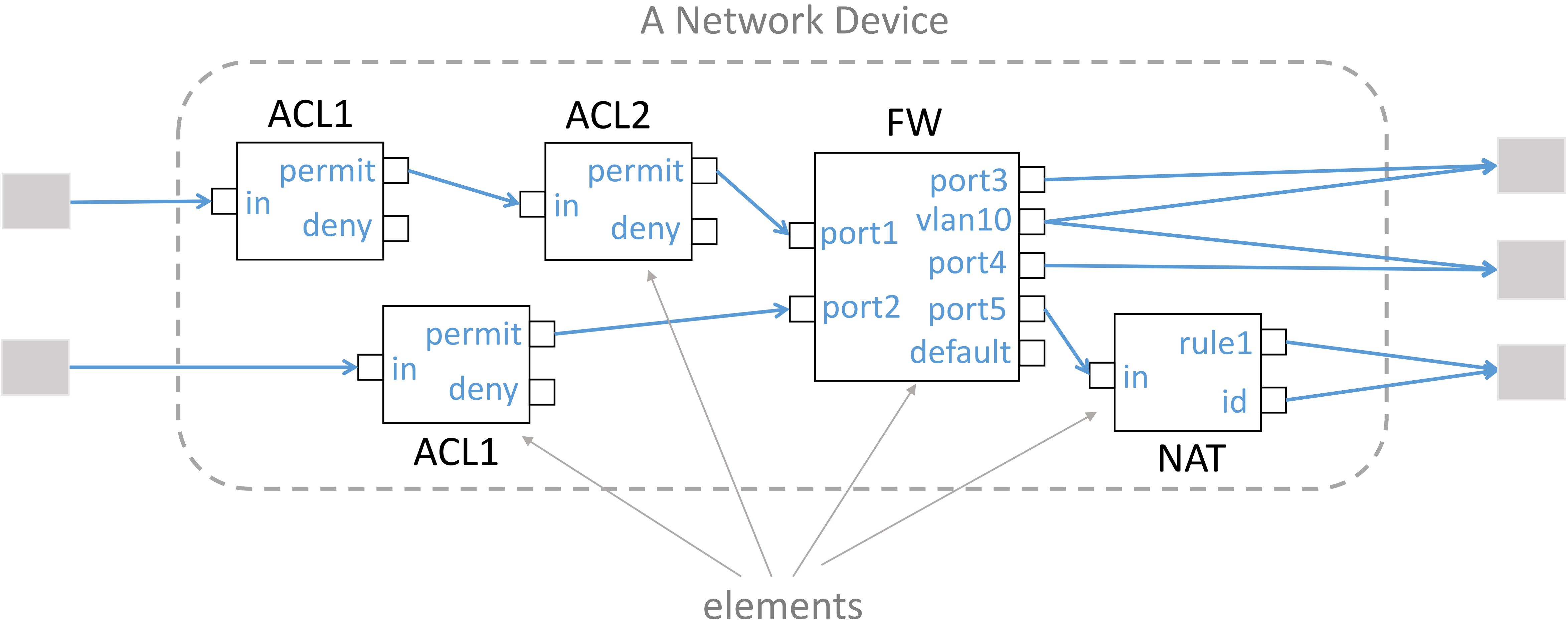
- Modular Network Model
- Scalable Update of ECs

The Modular Network Model



The Modular Network Model

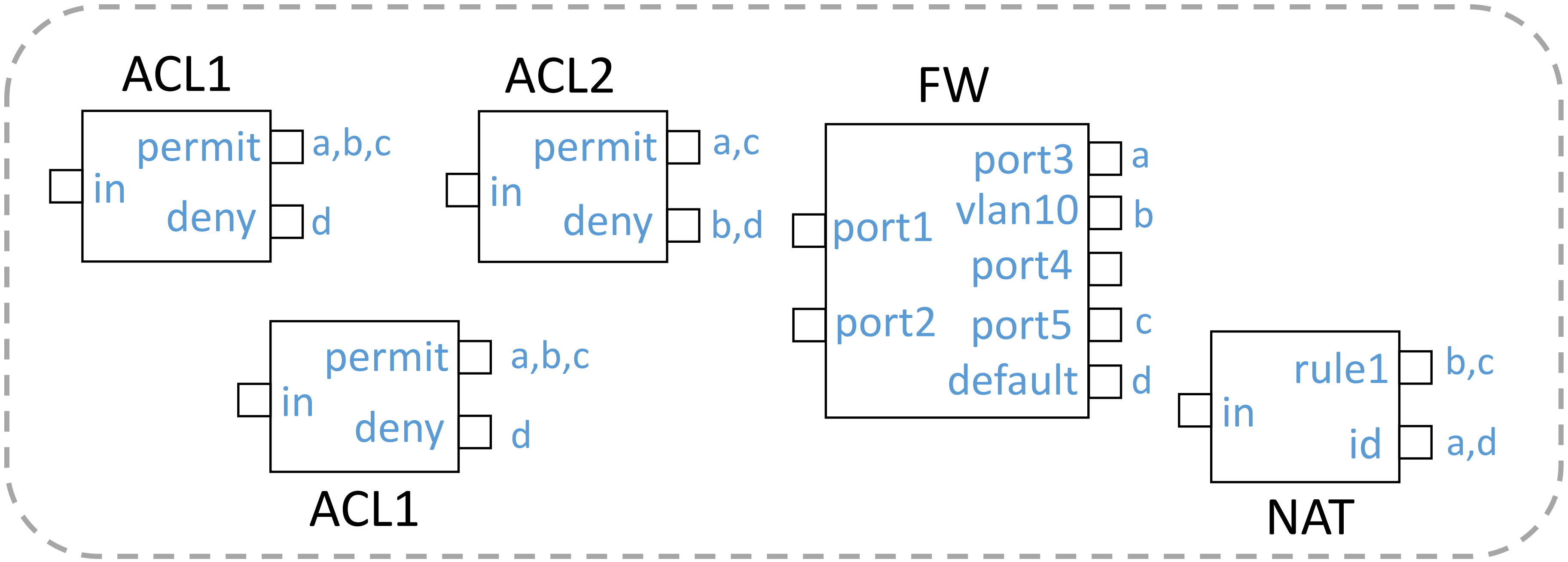
将这些“物理意义上设备内部的table”理解成device



APKeep

- Modular Network Model
- Scalable Update of ECs

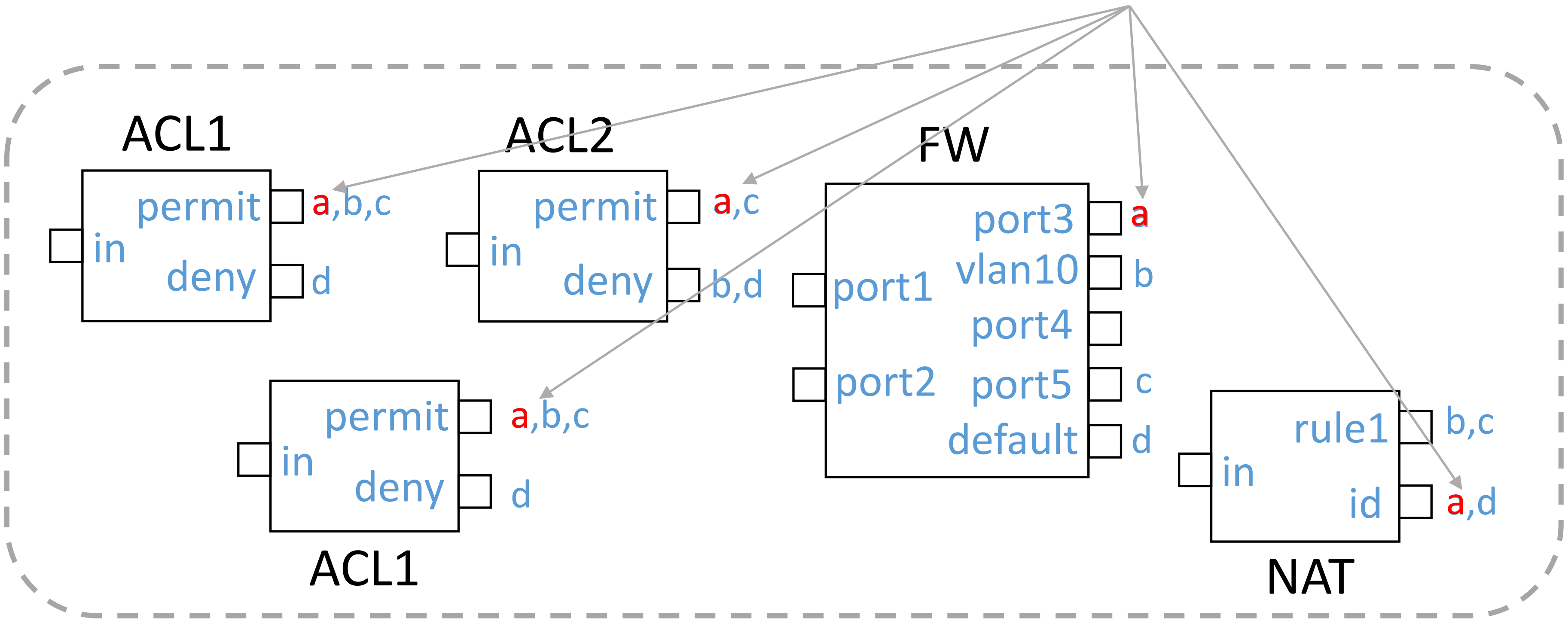
Equivalence Class in Modular Network Model



The model supports general representation of EC

Equivalence Class in Modular Network Model

predicate a: dstIP=10.0.0.0/16 Λ dstPort !=22



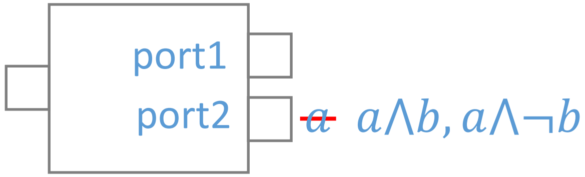
The model supports general representation of EC

Fast Update of Minimum Number of ECs

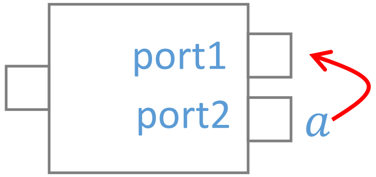
快速增量叠加

APKeep **fast** updates **the minimum number** of ECs **(atomic predicates)** with three operations

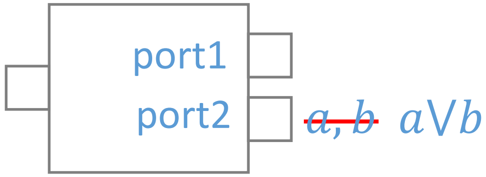
Split a predicate*



Transfer a predicate

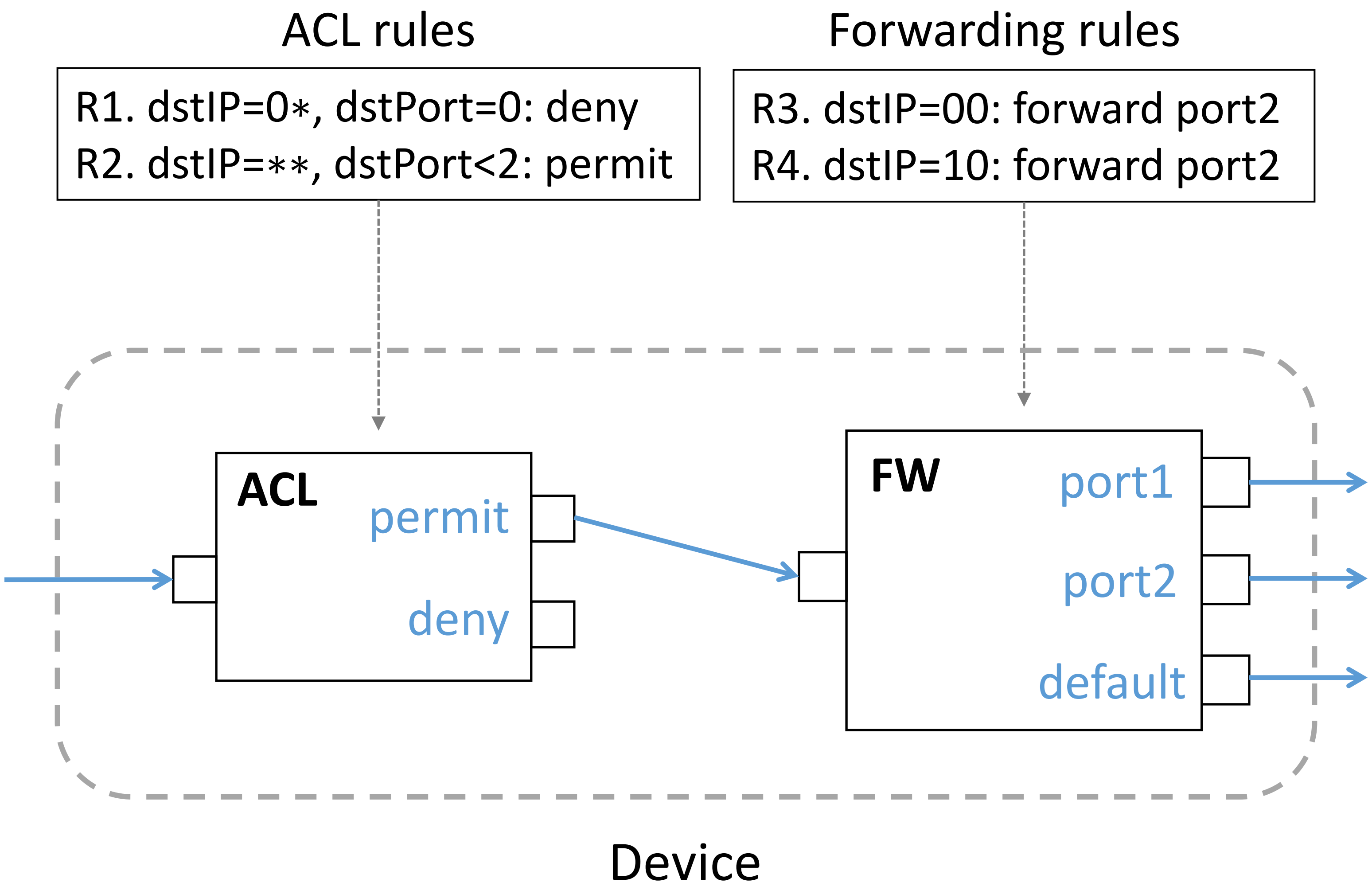


Merge predicates



*Inspired by AP Verifier to compute atomic predicates

Example



ACL rules

R1. dstIP=0∗, dstPort=0: deny

R2. dstIP=∗∗, dstPort<2: permit

Forwarding rules

R3. dstIP=00: forward port2

R4. dstIP=10: forward port2

ACL

permit

deny

FW

port1

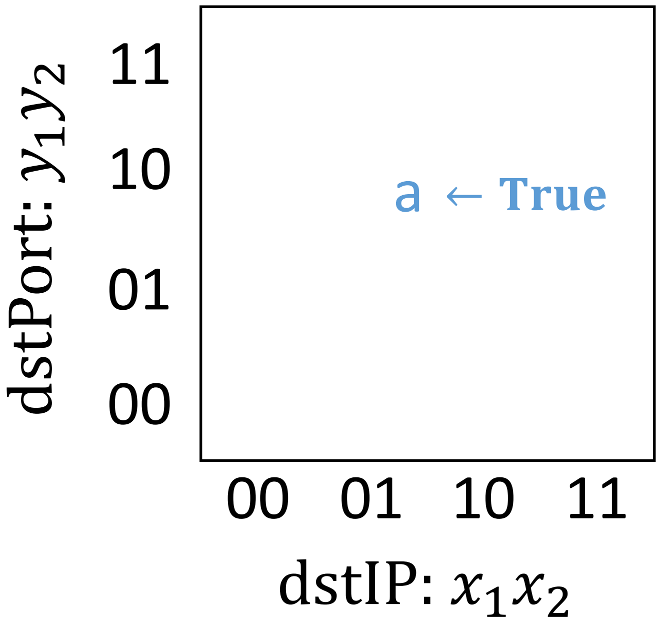
port2

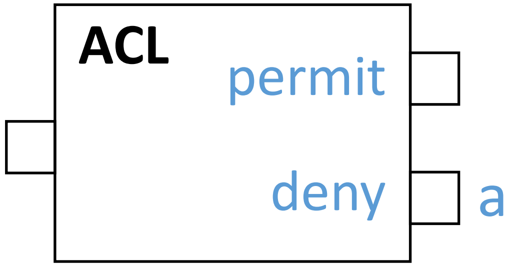
default

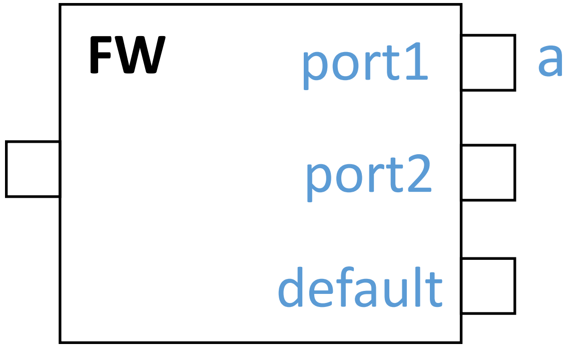
Device

Initial State without Rules

True在这里表示全集





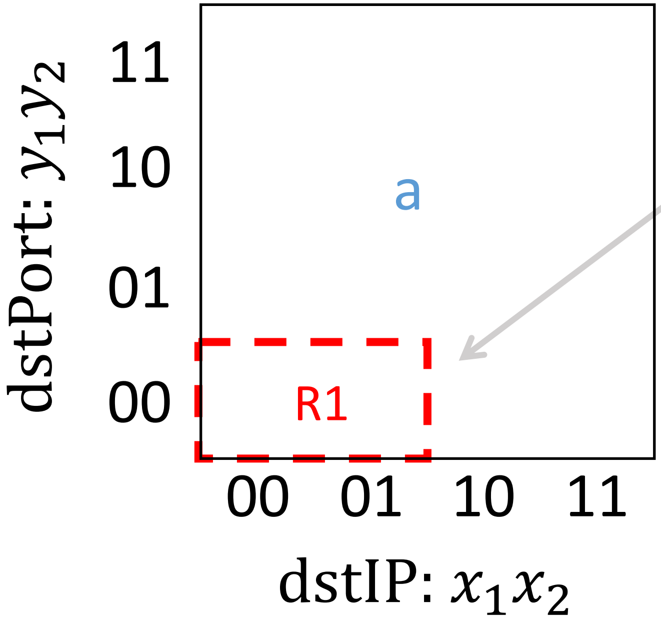


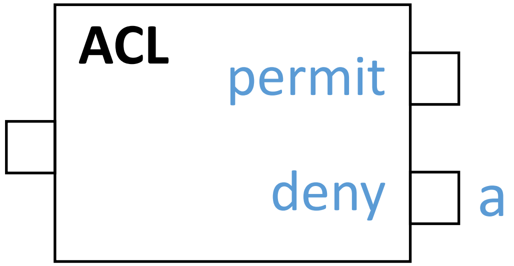
Initial State without Rules

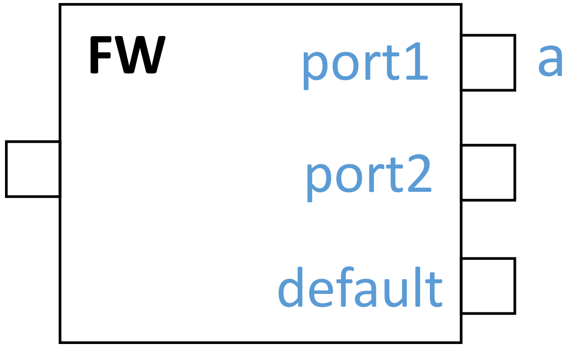
ACL rules

R1. dstIP=0∗, dstPort=0: deny

No behavior change: no need to update



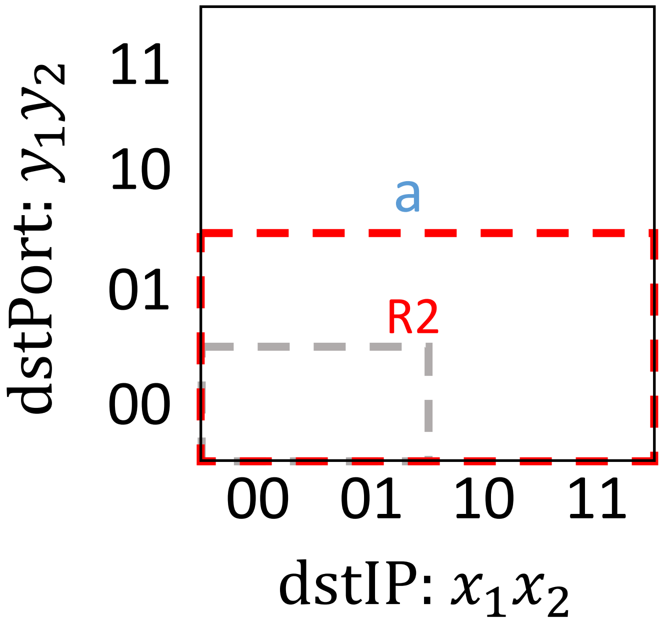




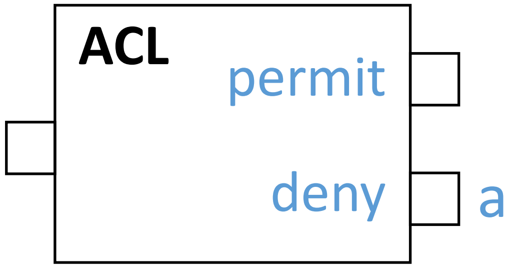
Splitting and Transferring Predicates

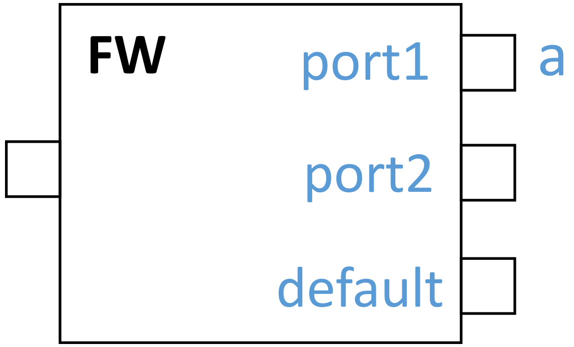
ACL rules

R1. dstIP=0∗, dstPort=0: deny
R2. dstIP=∗∗, dstPort<2: permit



“重叠”等价类之间产生行为冲突





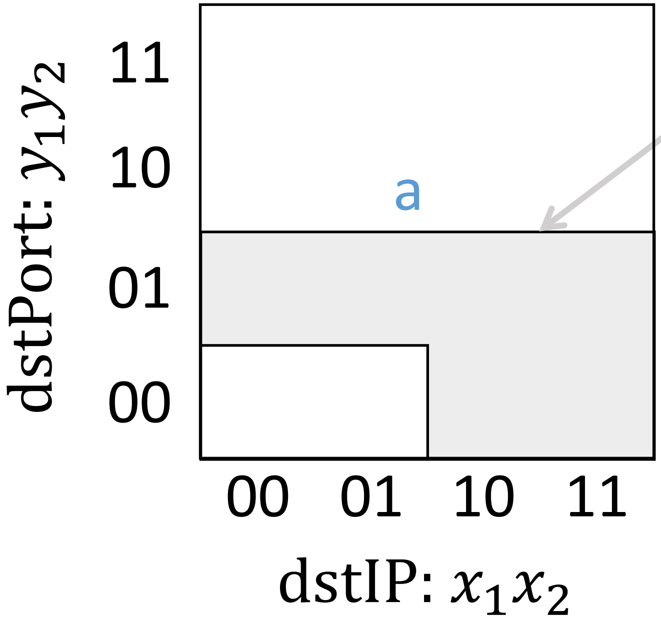
Splitting and Transferring Predicates

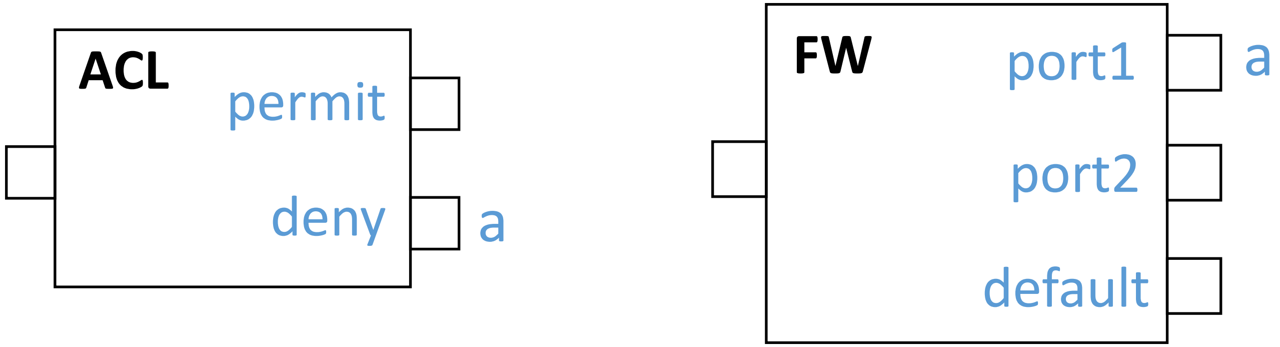
ACL rules

R1. dstIP=0∗, dstPort=0: deny

R2. dstIP=∗∗, dstPort<2: permit

Part of a changes behavior from *deny* to *permit*

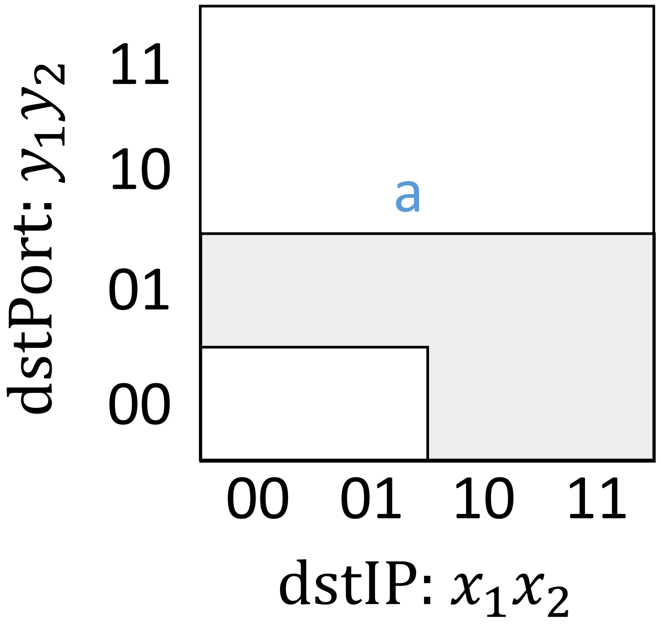


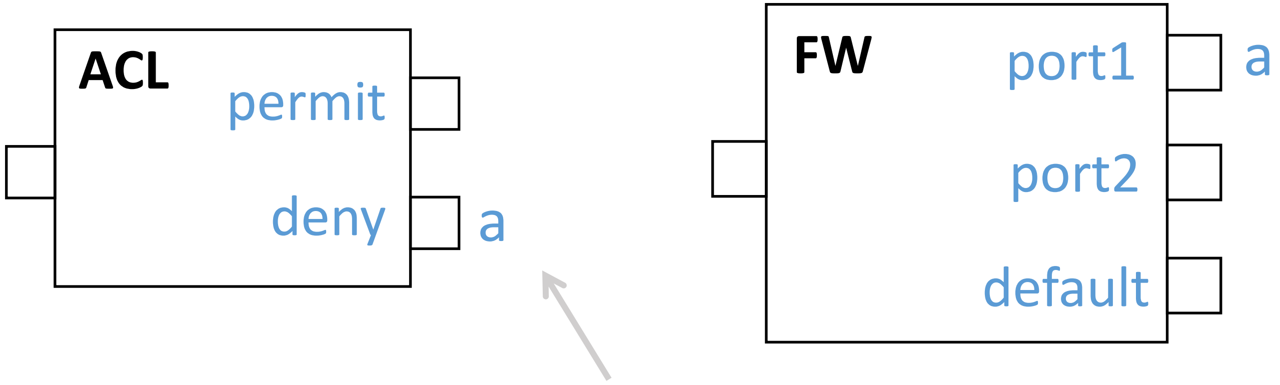


Splitting and Transferring Predicates

ACL rules

R1. dstIP=0*, dstPort=0: deny
R2. dstIP=**, dstPort<2: permit





Transfer part of a
from *deny* to *permit*

Splitting and Transferring Predicates

ACL rules

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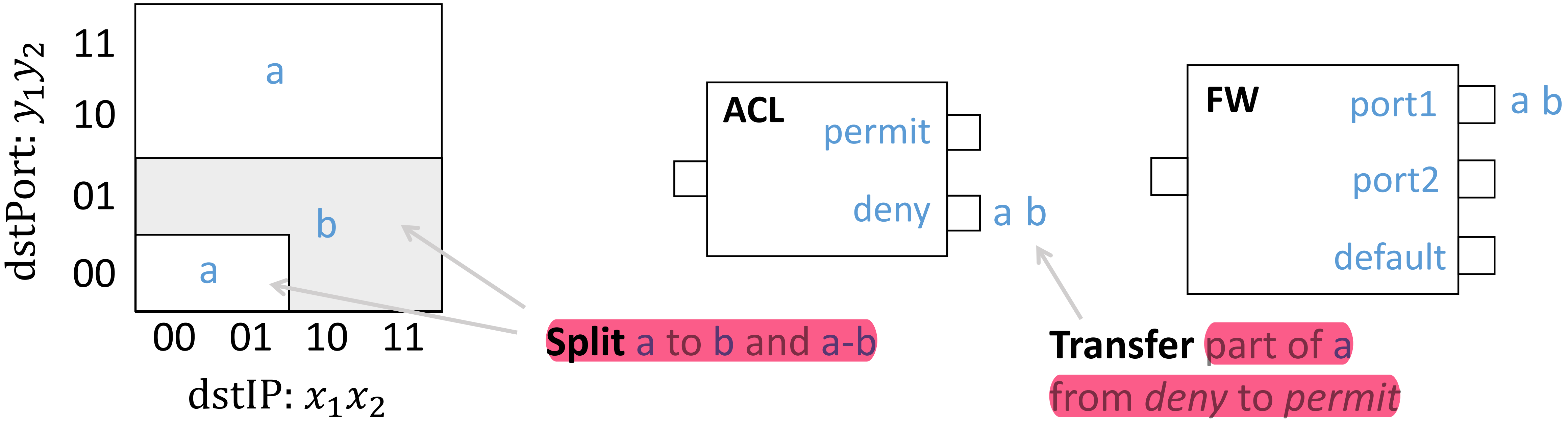


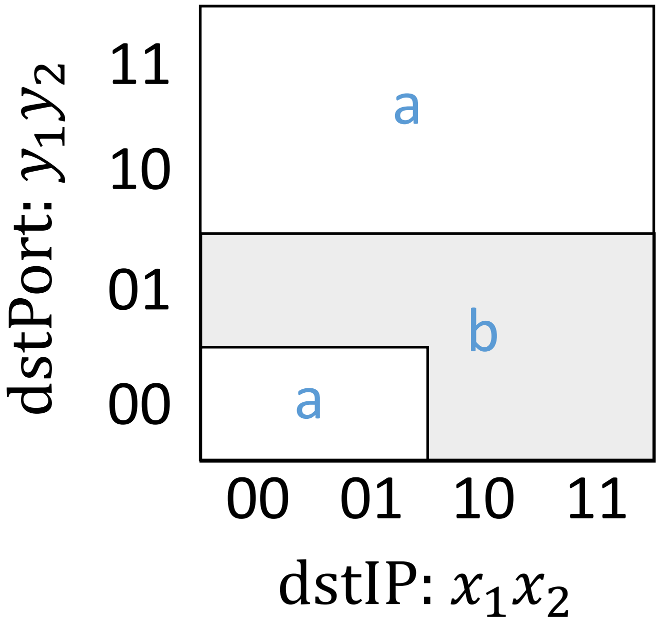
Split a to b and a-b

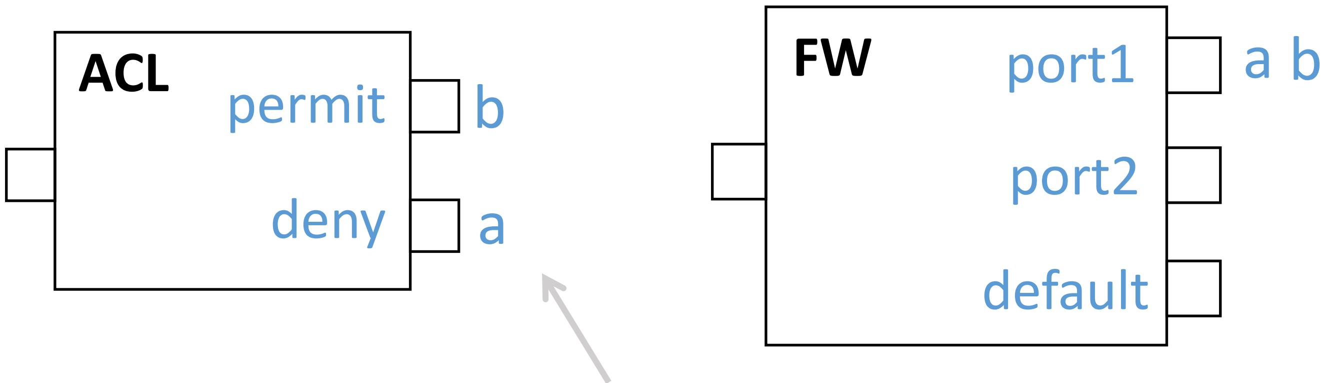
Transfer part of a from *deny* to *permit*

Splitting and Transferring Predicates

ACL rules

R1. dstIP=0∗, dstPort=0: deny
R2. dstIP=∗∗, dstPort<2: permit





Transfer part of a from *deny* to *permit*

Merging Predicates

ACL rules

R1. dstIP=0∗, dstPort=0: deny
R2. dstIP=∗∗, dstPort<2: permit

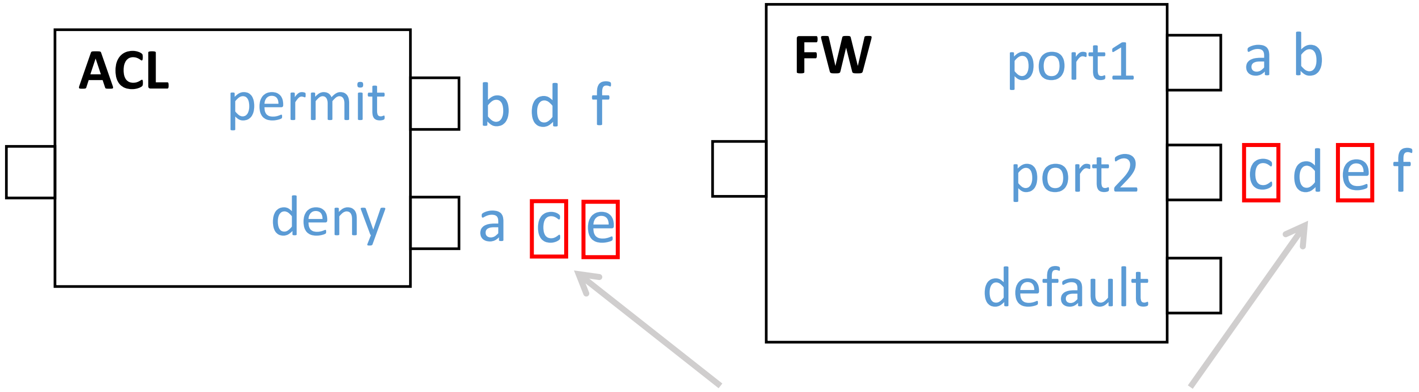
Forwarding rules

R3. dstIP=00: forward port2
R4. dstIP=10: forward port2

dstPort: $y_1 y_2$

	00	01	10	11
11	c	a	e	a
10				
01	d	b	f	b
00	c	a		

dstIP: $x_1 x_2$



此时可以将ce合并成一个更大的EC

c and e have the same forwarding behavior

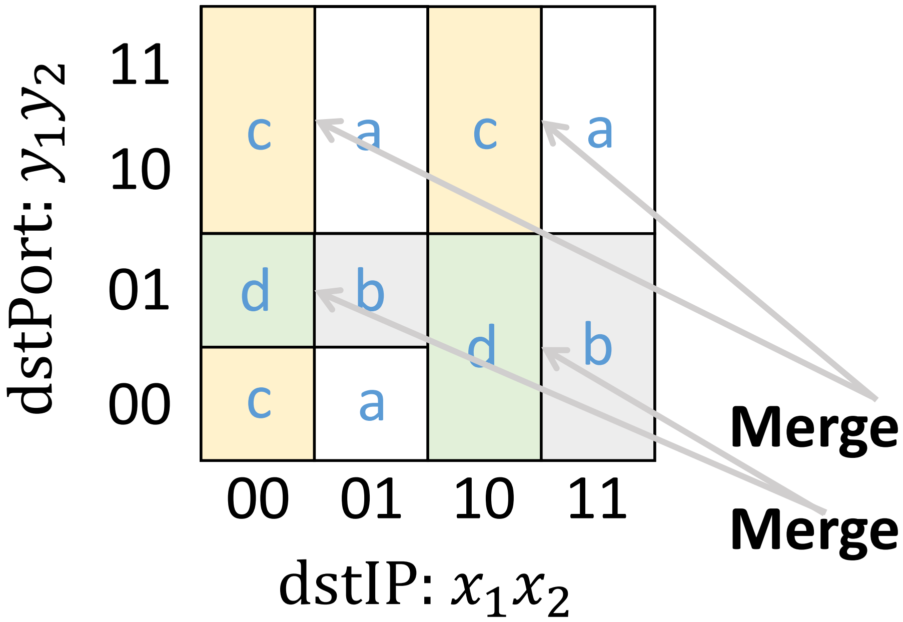
Merging Predicates

ACL rules

R1. dstIP=0∗, dstPort=0: deny
R2. dstIP=∗∗, dstPort<2: permit

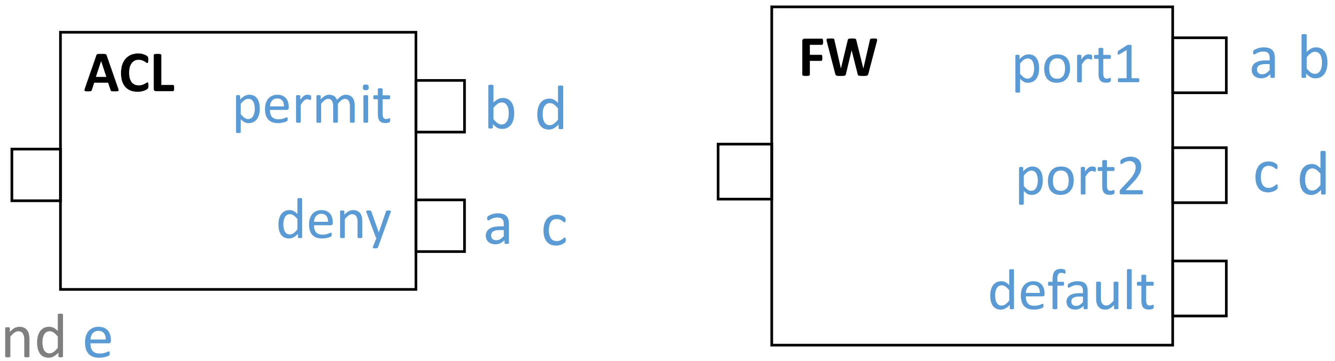
Forwarding rules

R3. dstIP=00: forward port2
R4. dstIP=10: forward port2

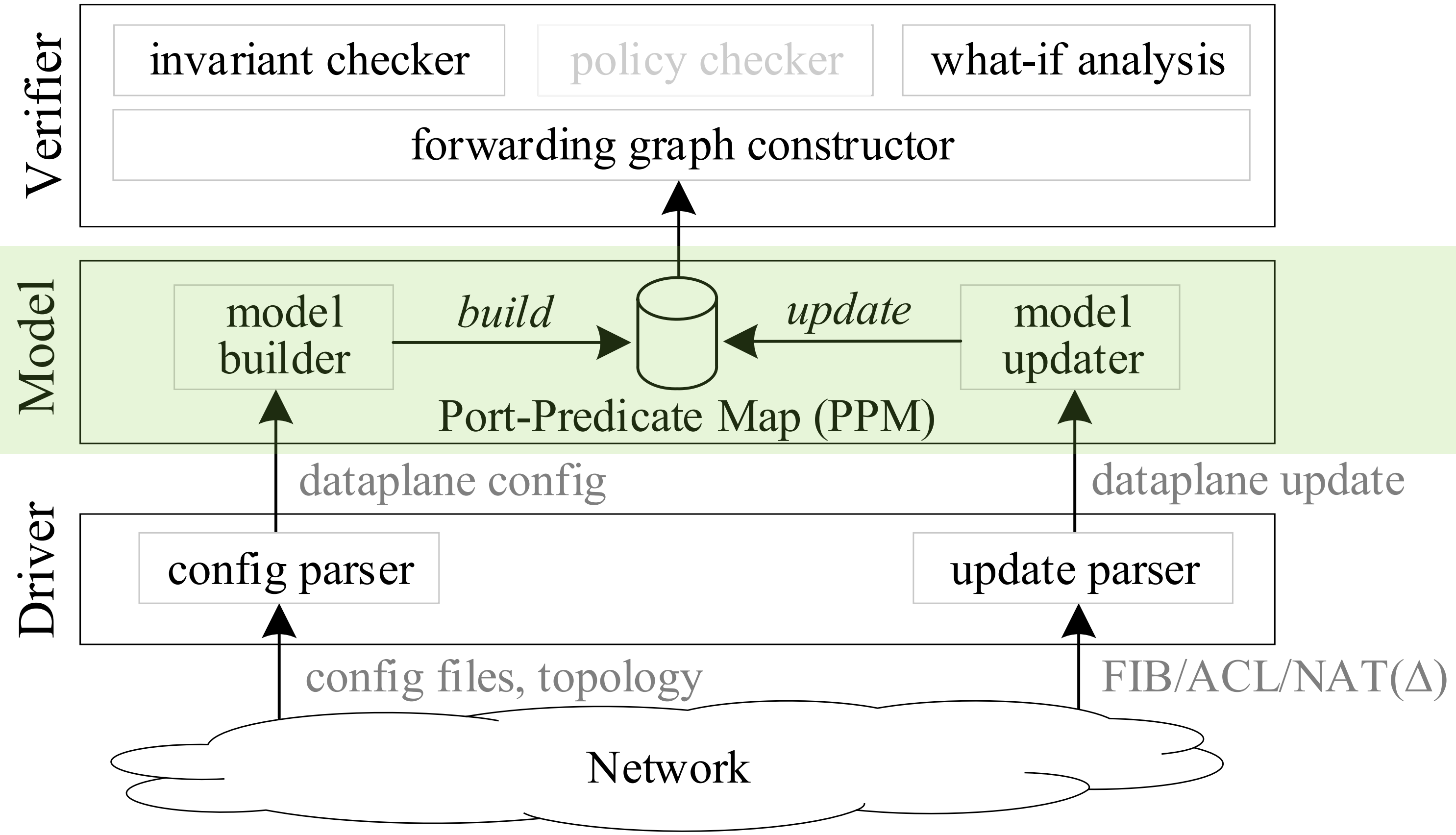


Merge c and e

Merge d and f



System Implementation



Verification applications running on the model (policy checker still under development)

Using **AP Verifier** and **APT** to encode match fields and packet rewriting action with BDD (BDD library: **JDD**)

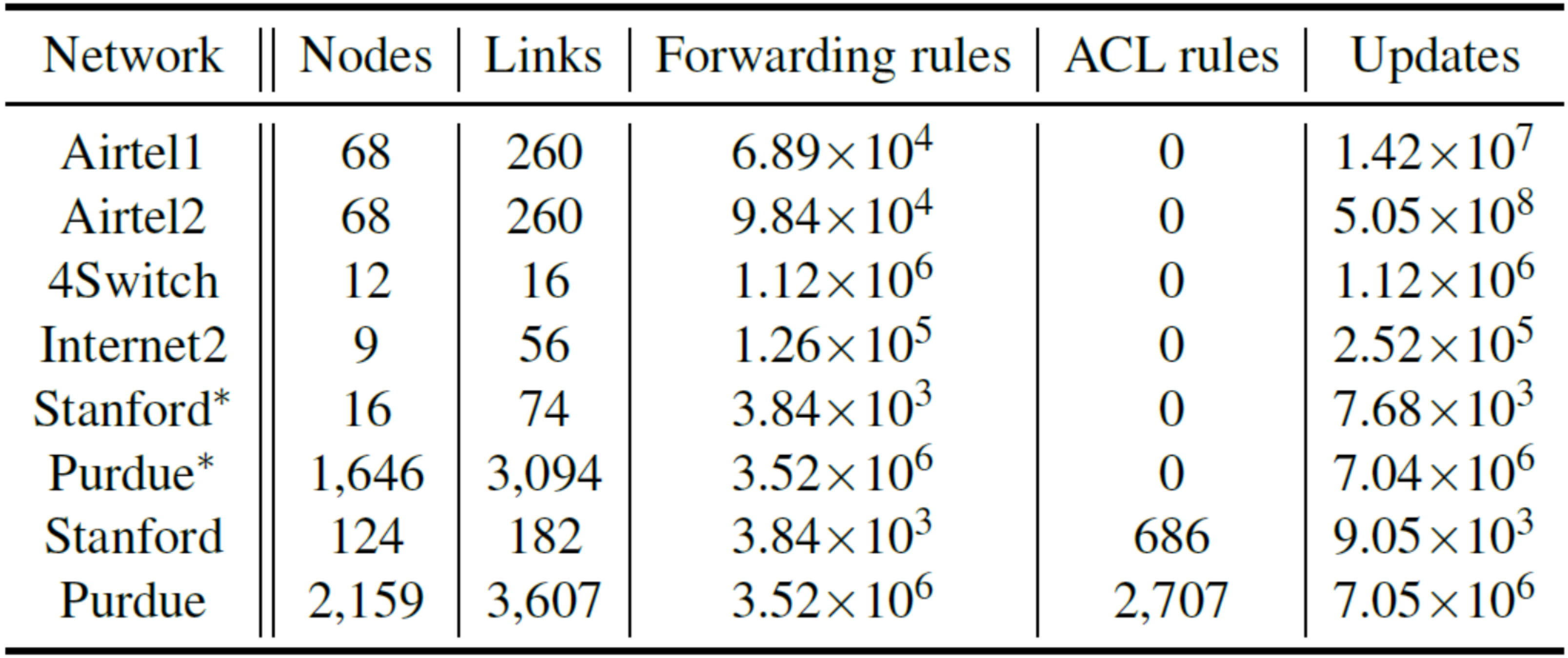
Parsing config files and rule updates into vendor-neutral format

AP Verifier and **APT** are open source, available at:
http://www.cs.utexas.edu/users/lam/NRL/Atomic_Predicates_Verifiers.html

Evaluation – Dataset

8 Datasets from Stanford, Internet2, Purdue, and Delta-net

- 6 datasets with only IP forwarding rules
- 2 datasets with both IP forwarding rules and ACL rules

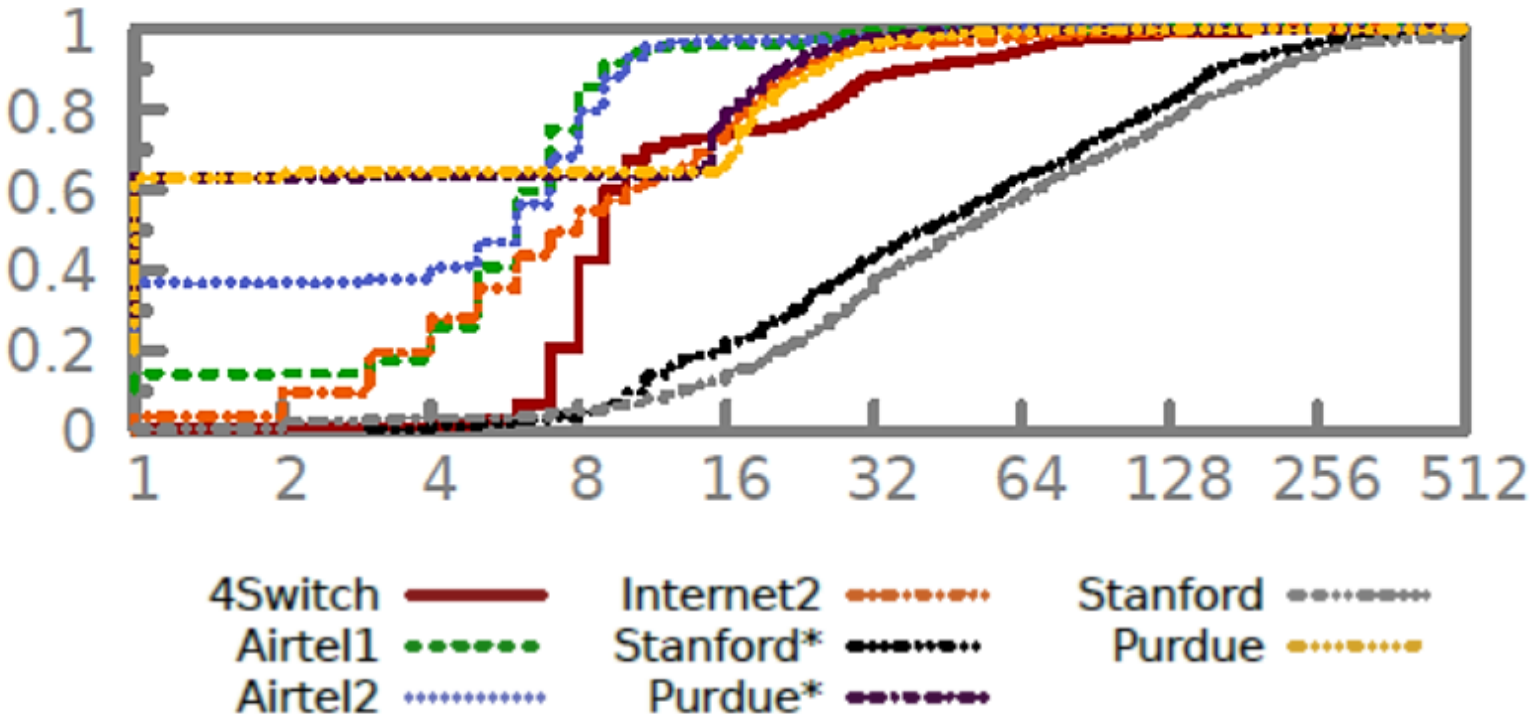


Network	Nodes	Links	Forwarding rules	ACL rules	Updates
Airtel1	68	260	6.89×10^4	0	1.42×10^7
Airtel2	68	260	9.84×10^4	0	5.05×10^8
4Switch	12	16	1.12×10^6	0	1.12×10^6
Internet2	9	56	1.26×10^5	0	2.52×10^5
Stanford*	16	74	3.84×10^3	0	7.68×10^3
Purdue*	1,646	3,094	3.52×10^6	0	7.04×10^6
Stanford	124	182	3.84×10^3	686	9.05×10^3
Purdue	2,159	3,607	3.52×10^6	2,707	7.05×10^6

IP forwarding rules only

IP forwarding rules
+ ACL rules

Evaluation – Verification Speed

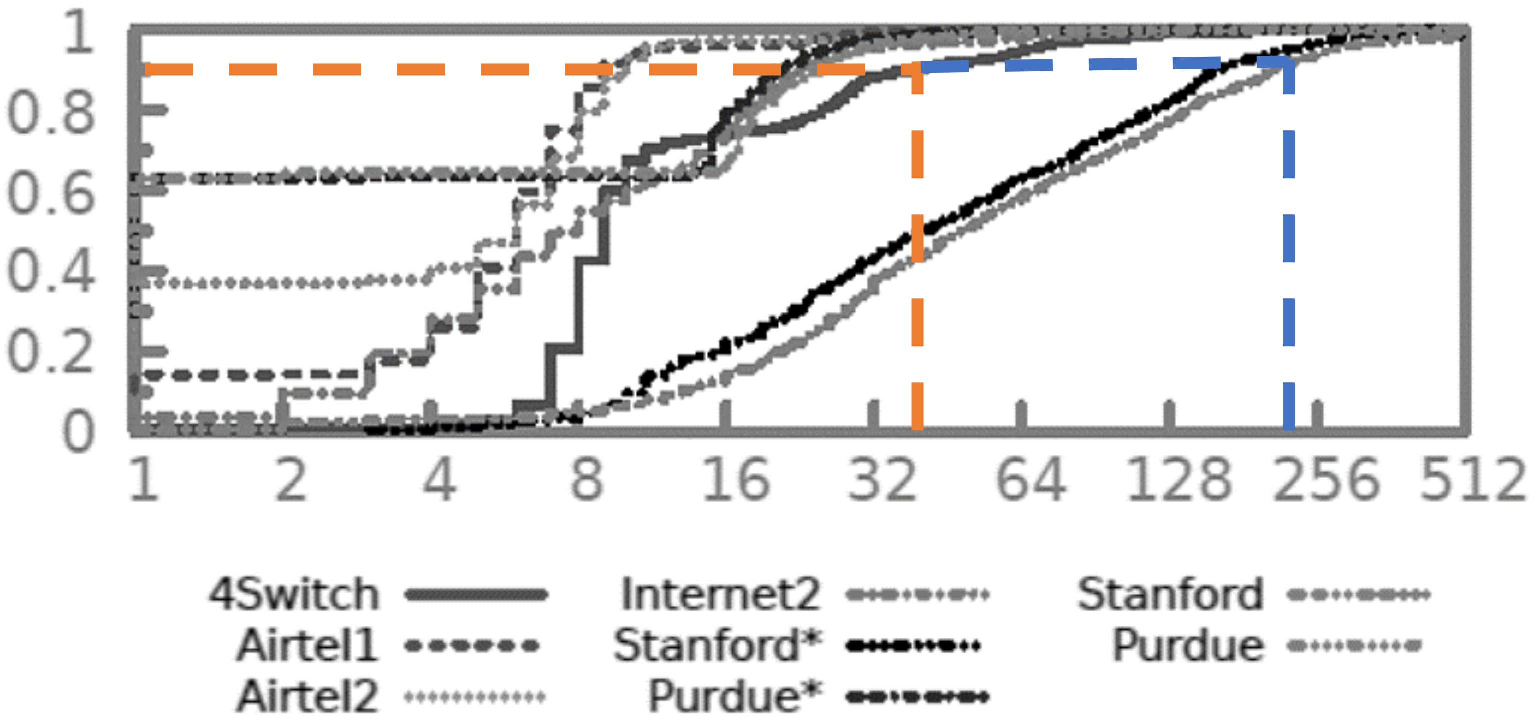


Verification: checking loops after each update. **Setting**: Linux desktop with 3.0GHz Intel Core i5 CPU and 32GB RAM

Evaluation – Verification Speed

IP forwarding only
90%: <50μs

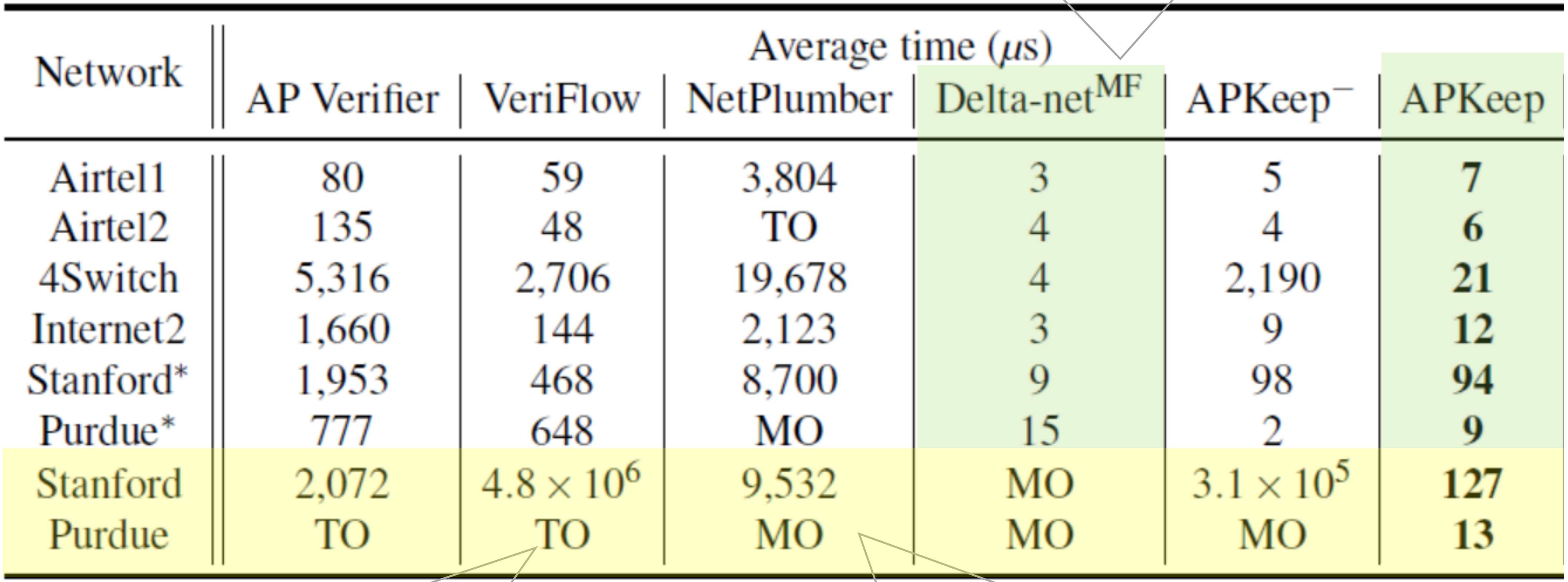
+ ACL
90%: <250μs



Verification: checking loops after each update. **Setting**: Linux desktop with 3.0GHz Intel Core i5 CPU and 32GB RAM

Evaluation – Verification Speed

Our multi-field extension of Delta-net



Network	Average time (μs)					
	AP Verifier	VeriFlow	NetPlumber	Delta-net^{MF}	APKeep^{-}	APKeep
Airtel1	80	59	3,804	3	5	**7**
Airtel2	135	48	TO	4	4	**6**
4Switch	5,316	2,706	19,678	4	2,190	**21**
Internet2	1,660	144	2,123	3	9	**12**
Stanford*	1,953	468	8,700	9	98	**94**
Purdue*	777	648	MO	15	2	**9**
Stanford	2,072	4.8×10^6	9,532	MO	3.1×10^5	**127**
Purdue	TO	TO	MO	MO	MO	**13**

Timeout: >24 hours

Memory overflow: >32GB

Verification: checking loops after each update. **Setting**: Linux desktop with 3.0GHz Intel Core i5 CPU and 32GB RAM

Conclusion

APKeep: checking correctness of data plane with **real** devices in **real** time

- □ Modular network model: expressive and extensible for real network devices
- □ Scalable update of ECs: fast updating the minimum number of ECs (<1ms)

Future work

- □ Checking operator intent beyond reachability
- □ Parallelizing the update of predicates

Thanks for your attention

Peng Zhang
p-zhang@xjtu.edu.cn