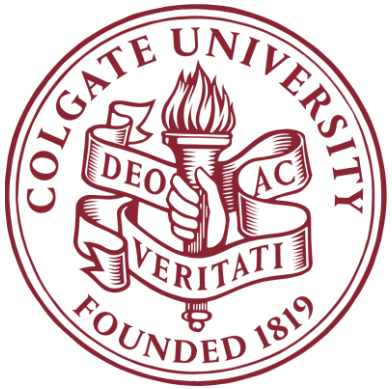
Expresso: Comprehensively Reasoning About External Routes Using Symbolic Simulation

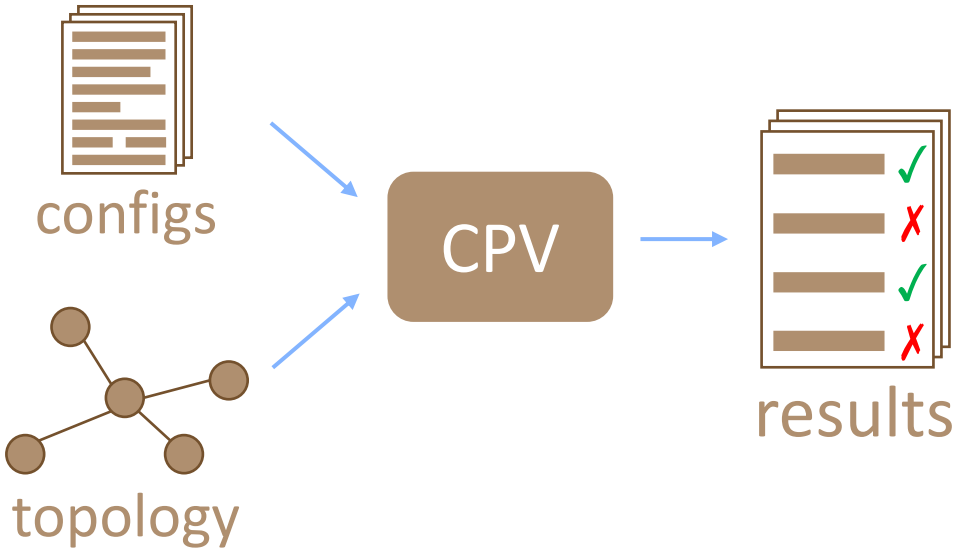
Dan Wang, Peng Zhang

Aaron Gember-Jacobson

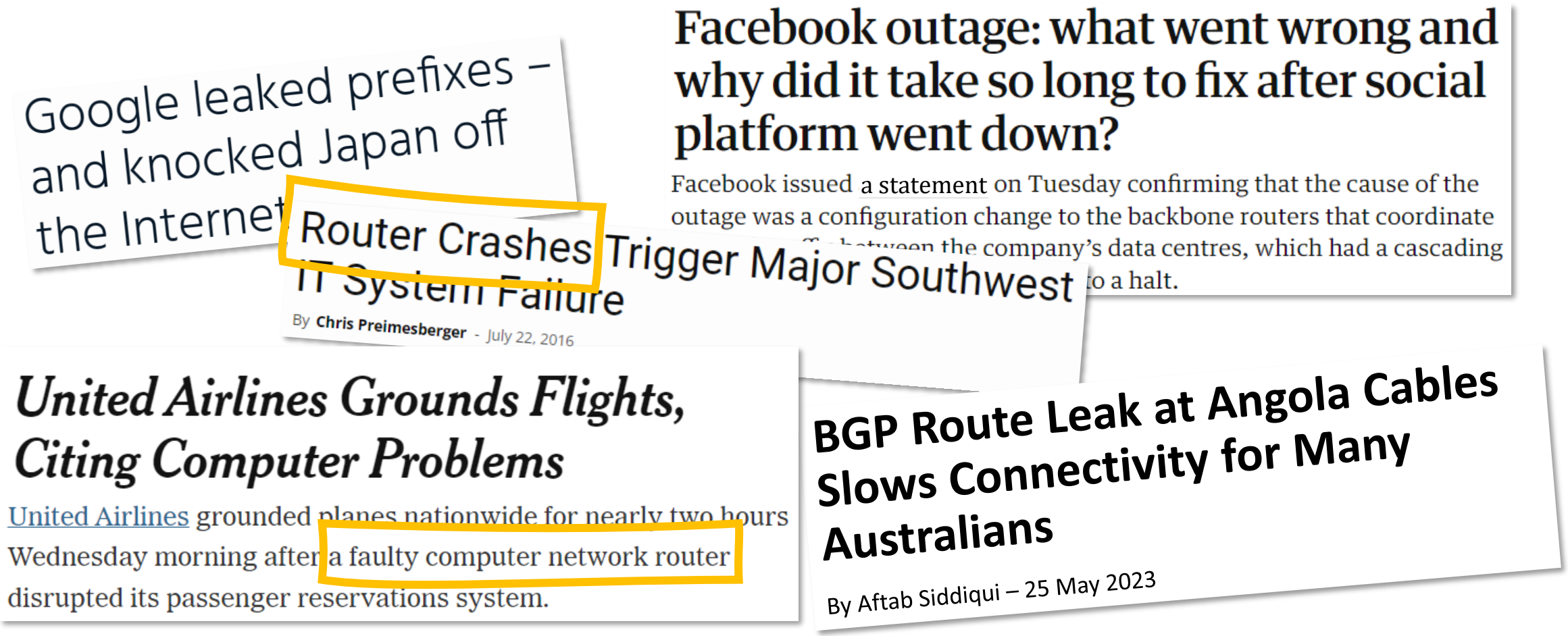


Network Outages are Common and Costly

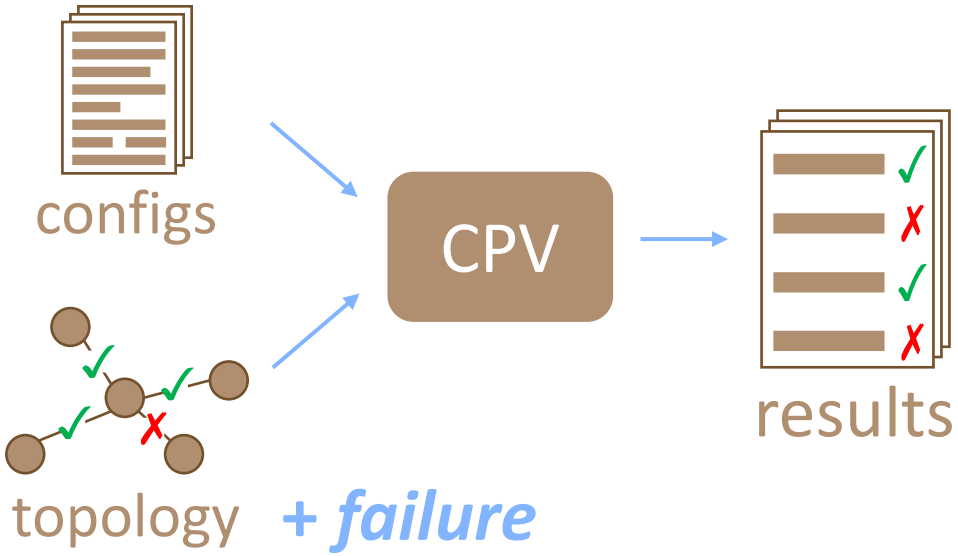
Control Plane Verifiers (CPVs)



Req #1: Reasoning About Failures



CPV #1: Reasoning About Failures



Minesweeper[3]
Hoyan[6]
SRE[7]
……

Req #2: Reasoning About Config Updates

Google leaked prefixes – and knocked Japan off the Internet

Router Crashes Trig IT System Failure

By **Chris Preimesberger** - July 22, 2016

Facebook outage: what went wrong and why did it take so long to fix after social platform went down?

Facebook issued a statement on Tuesday confirming that the cause of the outage was a configuration change to the backbone routers that coordinate network traffic between the company's data centres, which had a cascading effect, bringing all Facebook services to a halt.

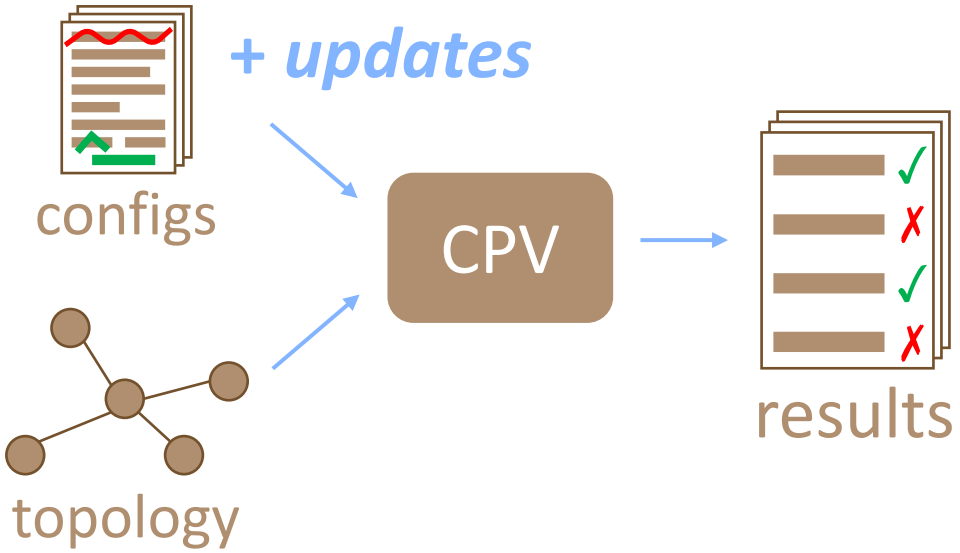
United Airlines Grounds Flights, Citing Computer Problems

United Airlines grounded planes nationwide for nearly two hours Wednesday morning after a faulty computer network router disrupted its passenger reservations system.

BGP Route Leak at Angola Cables Slows Connectivity for Many Australians

By Aftab Siddiqui – 25 May 2023

CPV #2: Reasoning About Config Updates



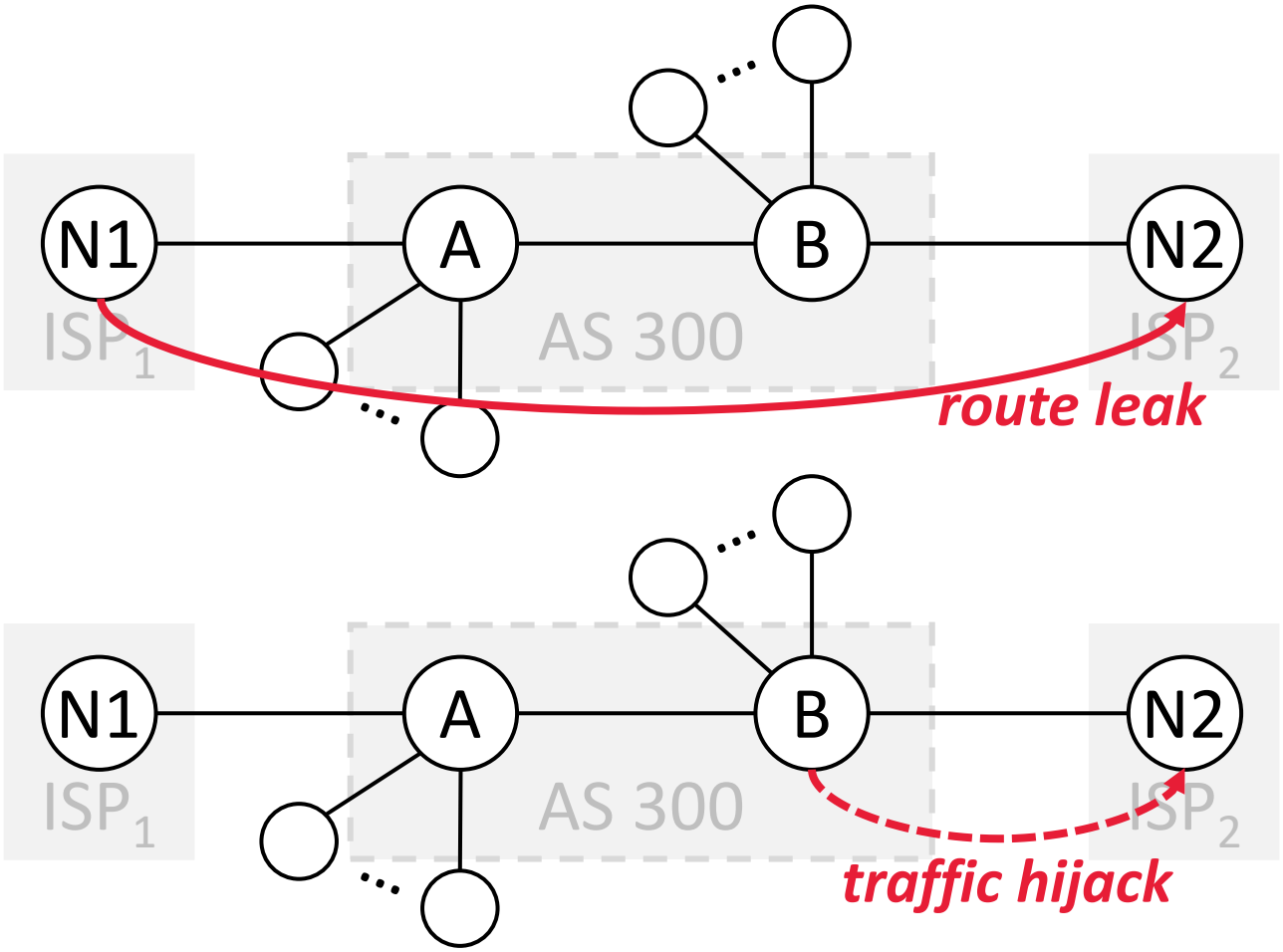
DNA[8]

JinJing[13]

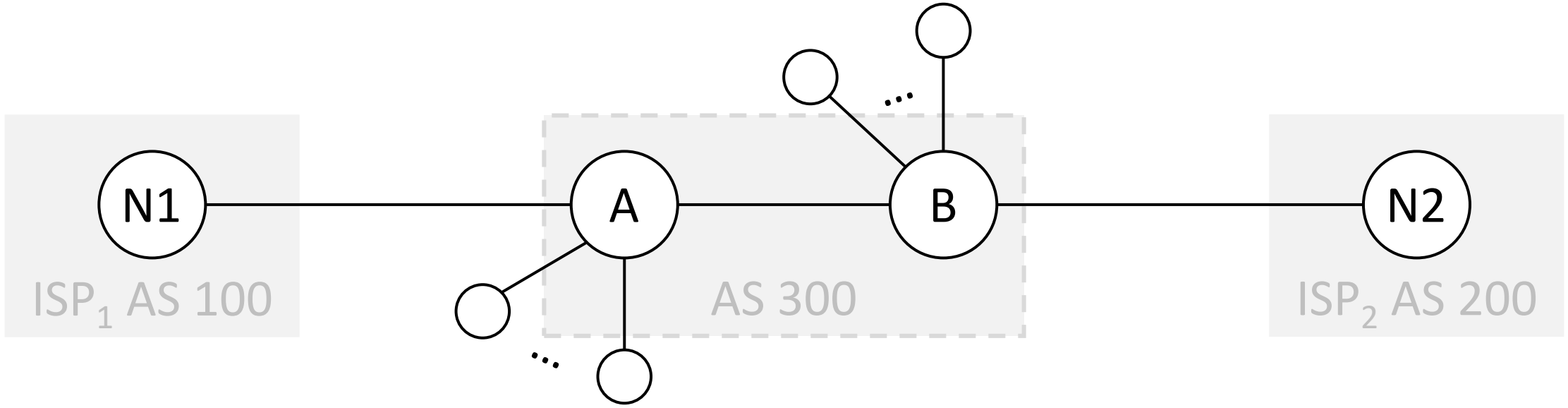
……

Req #3: Reasoning About External Routes

Reasoning About External Route is Important



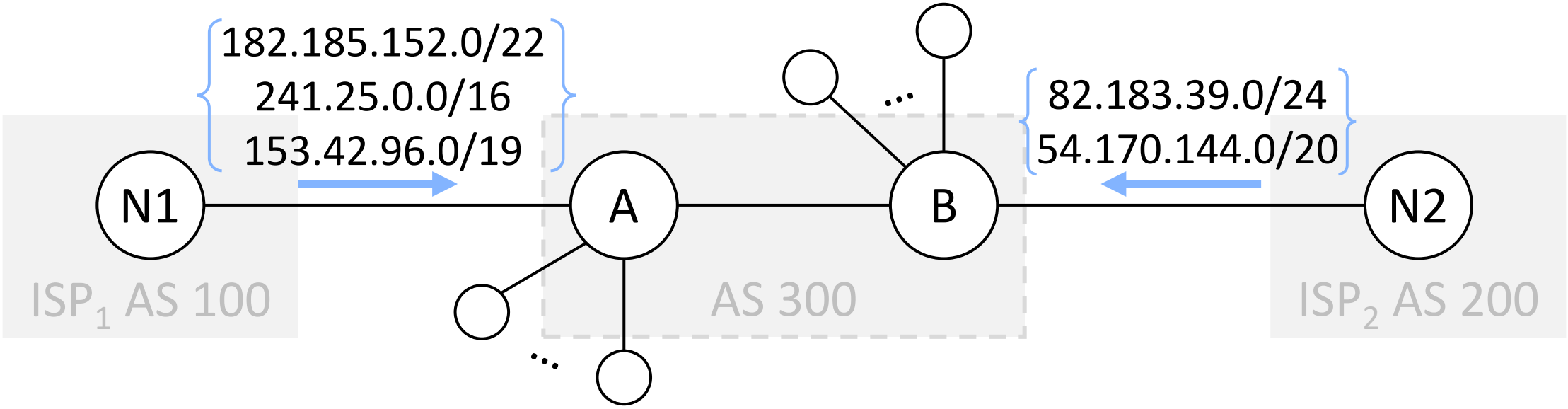
Space of External Route is Colossal



$$\#Prefix = 2^{33} - 1$$

0.0.0.0/0
0.0.0.0/1
128.0.0.0/1
……
255.255.255.255/32

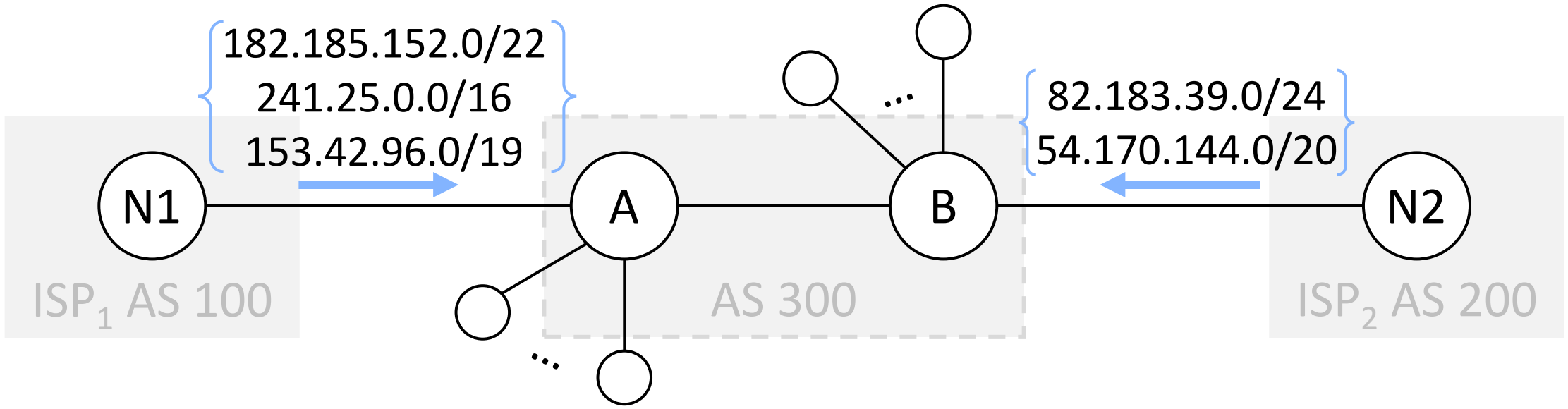
Space of External Route is Colossal



$\#Prefix = 2^{33} - 1$

0.0.0.0/0
0.0.0.0/1
128.0.0.0/1
……
255.255.255.255/32

Space of External Route is Colossal

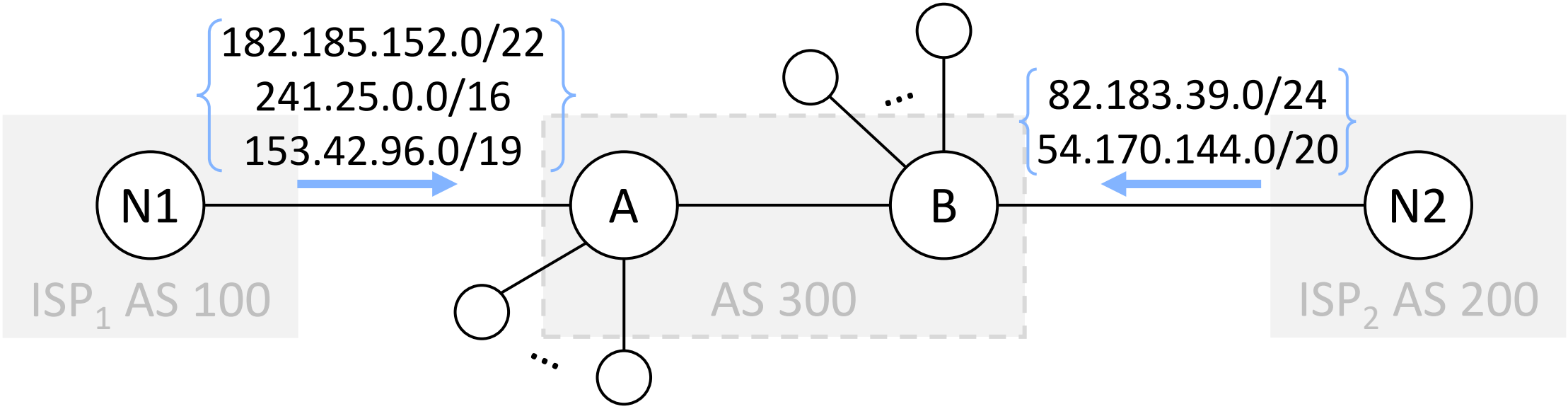


$\#Prefix = 2^{33} - 1$

$\#Prefix\text{-}set = 2^{2^{33}-1}$

0.0.0.0/0
0.0.0.0/1
128.0.0.0/1
……
255.255.255.255/32

Space of External Route is Colossal



$\#Prefix = 2^{33} - 1$

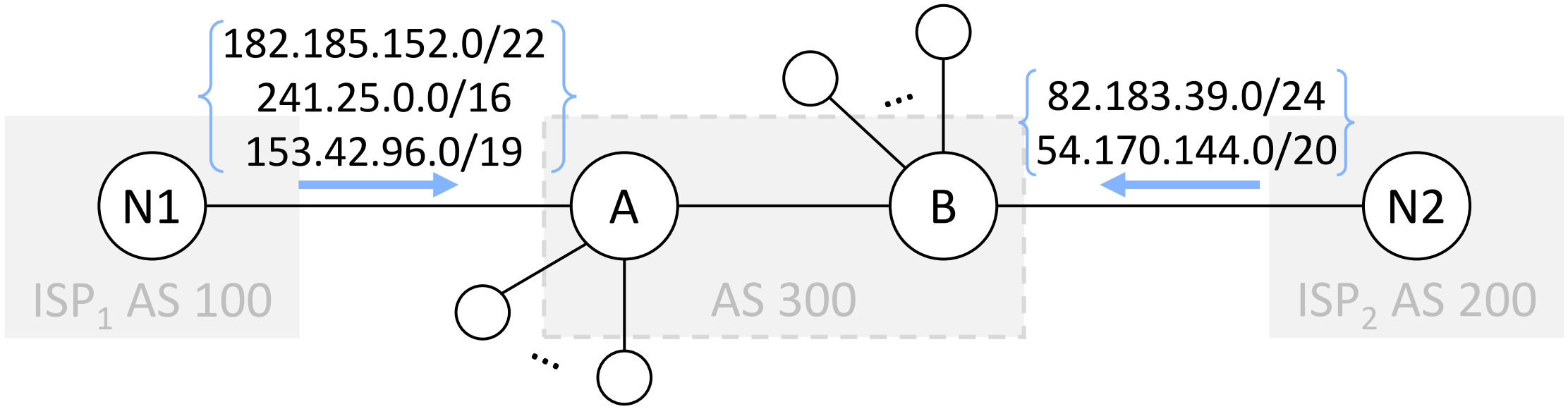
$\#Prefix\text{-}set = 2^{2^{33}-1}$

0.0.0.0/0
0.0.0.0/1
128.0.0.0/1
……
255.255.255.255/32

$Space\ size = 2^{(2^{33}-1)\times m}$

m: #Neighbor

Space of External Route is Colossal

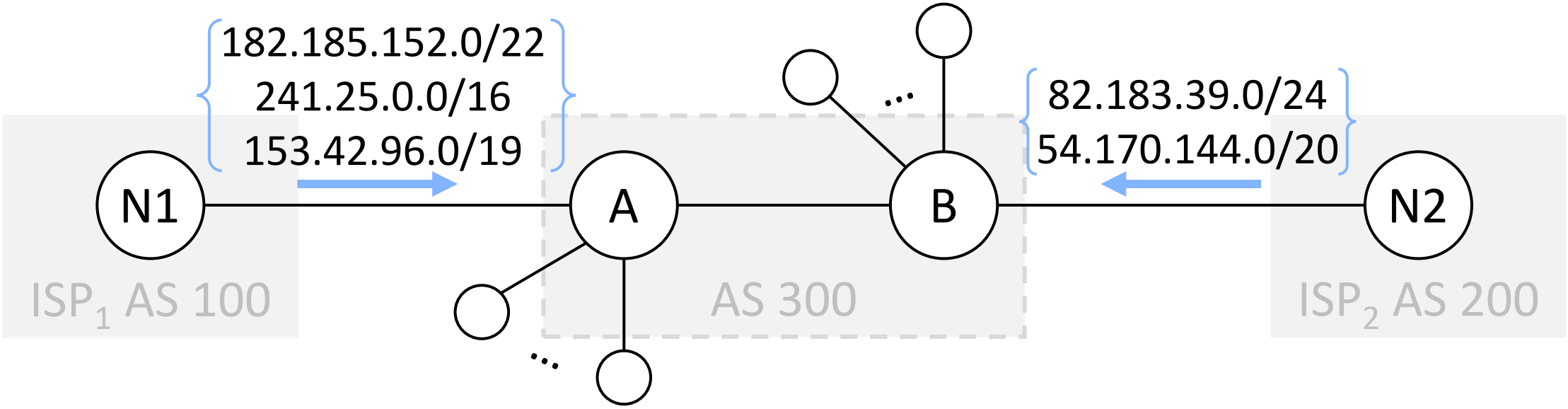


How to handle such a colossal space?

$$\text{Space size} = 2^{(2^{33}-1)\times m}$$

#Neighbor

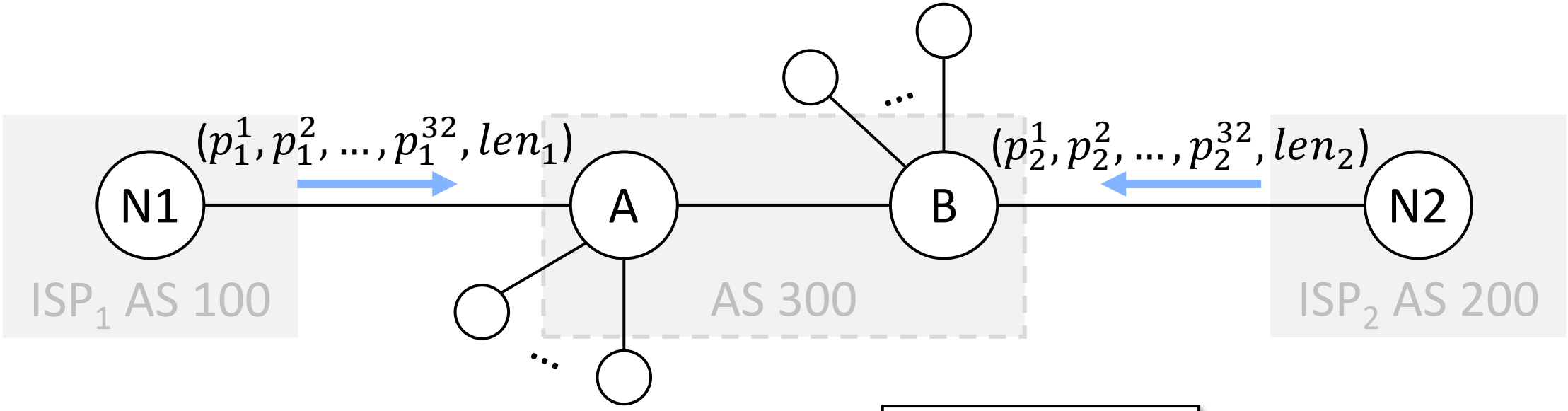
Method #1: Enumerate Concrete External Routes



SRE[7], Hoyan[6], Tiramisu[9], Plankton[10], Shapeshifter[4], ERA[11], Batfish[1]

Enumeration is infeasible

Method #2: Symbolize External Routes with SMT

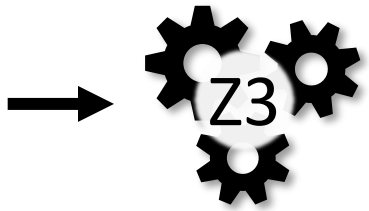


NV[5], Minesweeper[3], Bagpipe[12]

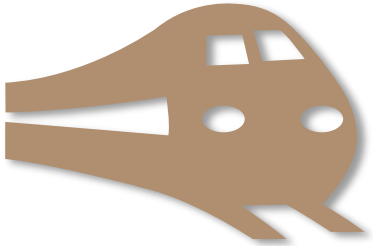
SMT solving is Unscalable

SMT constraints

$p_1^1 = 1, \ldots,$
$len_1 \leq 16,$
$p_2^1 = 0, \ldots,$
$16 \leq len_2 \leq 24,$
$\ldots$



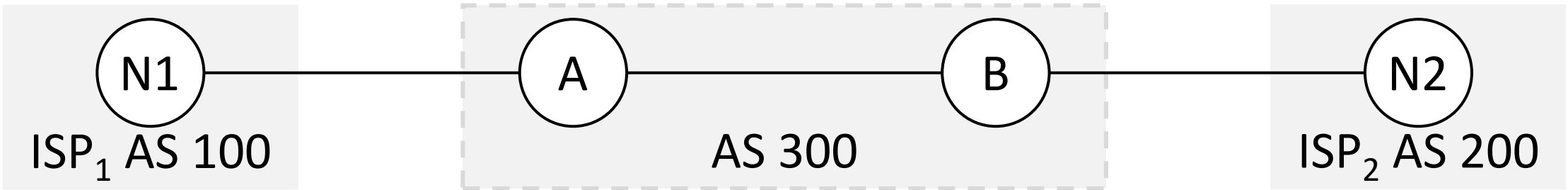
Our Approach: Expresso



Express

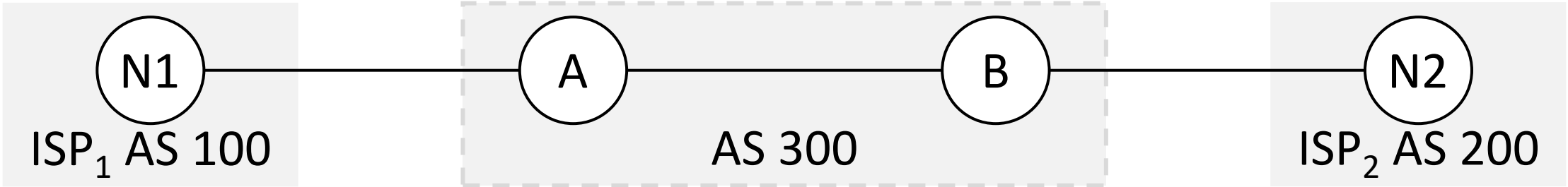
Espresso

Example Network



Example Network

3-bit IP addresses: 110, 010, …
3-bit prefixes: 000/0, 000/1, …, 111/3

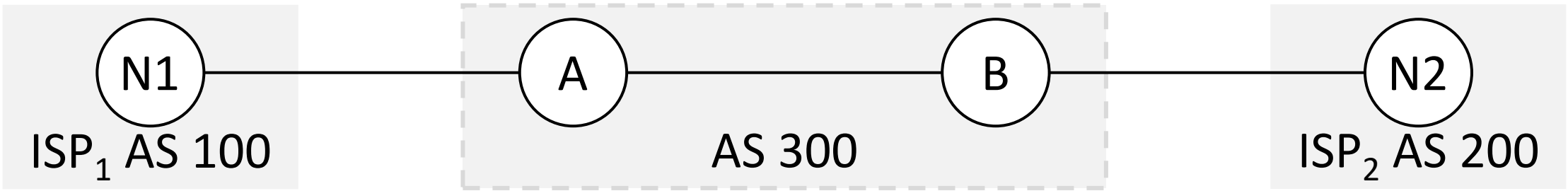


Example Network

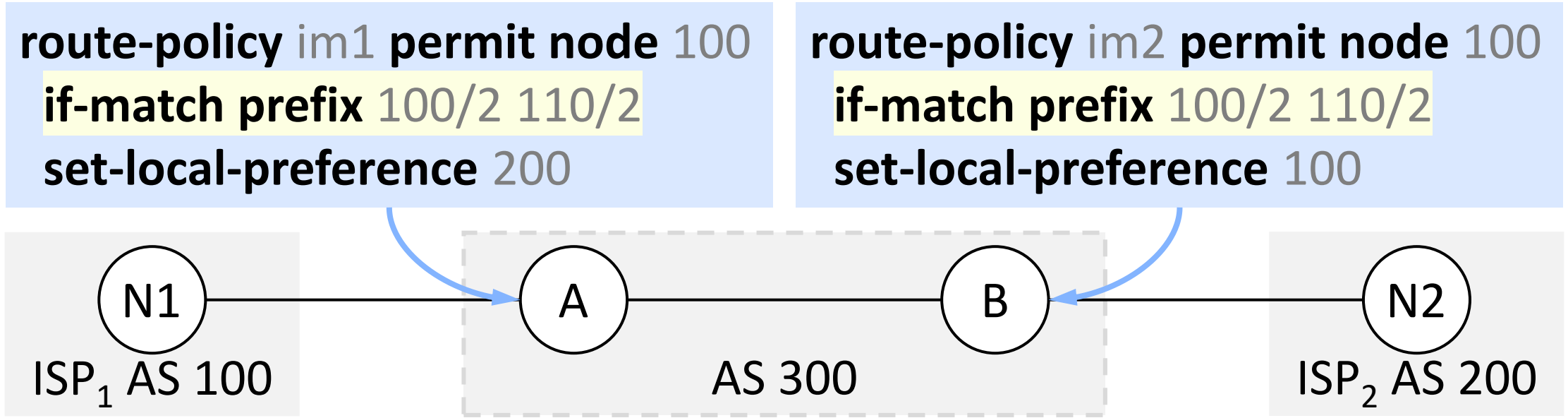
3-bit IP addresses: 110, 010, …

3-bit prefixes: 000/0, 000/1, …, 111/3 → Space size = $2^{15\times2}$

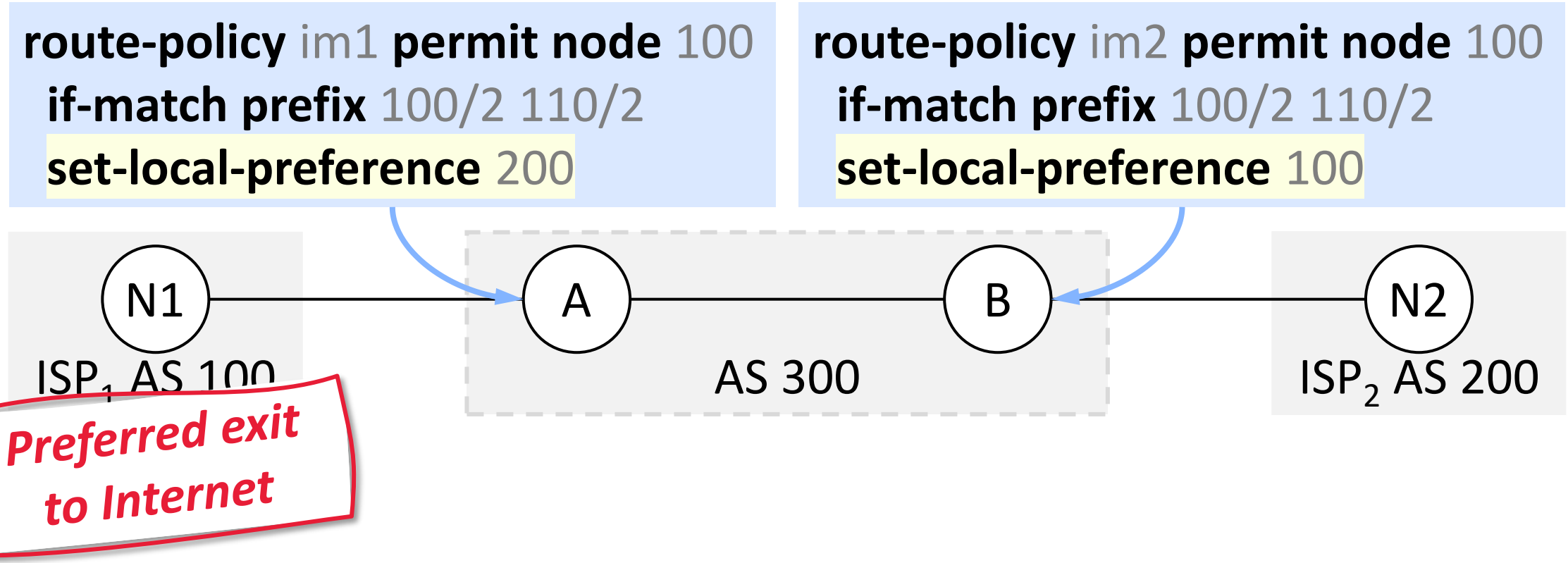
15



Example Network



Example Network



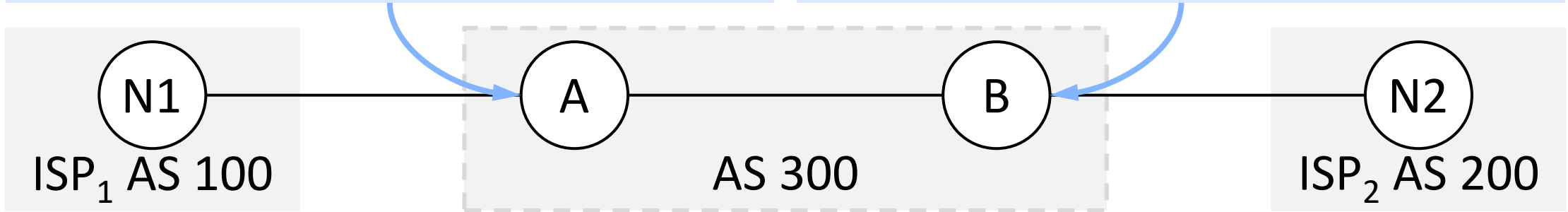
Observation1: Equivalence

Prefix

Equivalence


```
route-policy im1 permit node 100
  if-match prefix 100/2 110/2
  set-local-preference 200
```

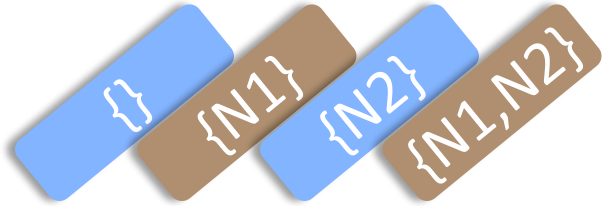
```
route-policy im2 permit node 100
  if-match prefix 100/2 110/2
  set-local-preference 100
```



Observation1: Equivalence

Advertiser

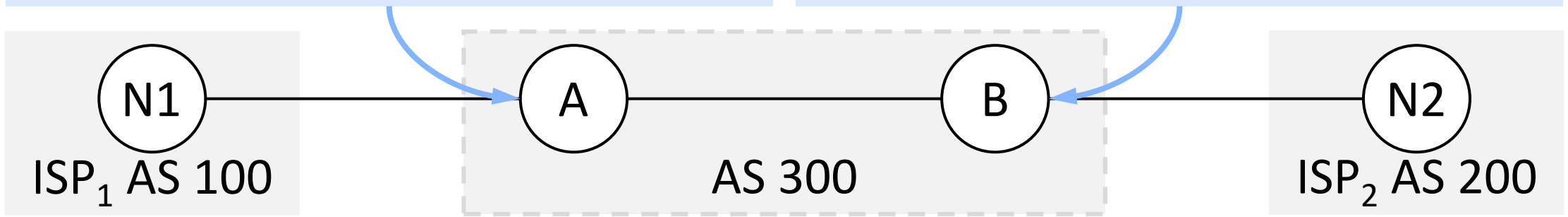
Equivalence



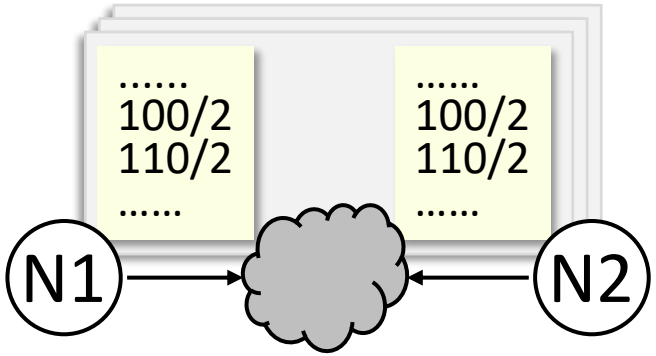
For 100/2 and 110/2

```
route-policy im1 permit node 100
  if-match prefix 100/2 110/2
  set-local-preference 200
```

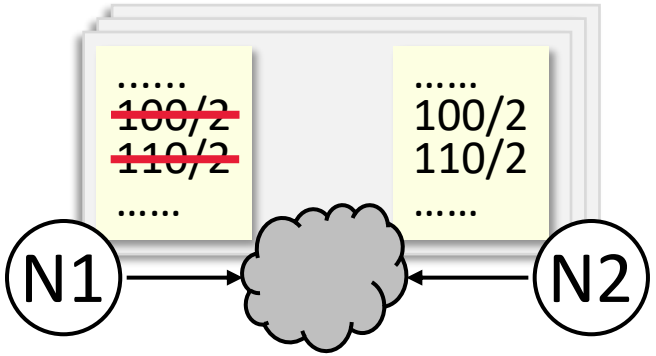
```
route-policy im2 permit node 100
  if-match prefix 100/2 110/2
  set-local-preference 100
```



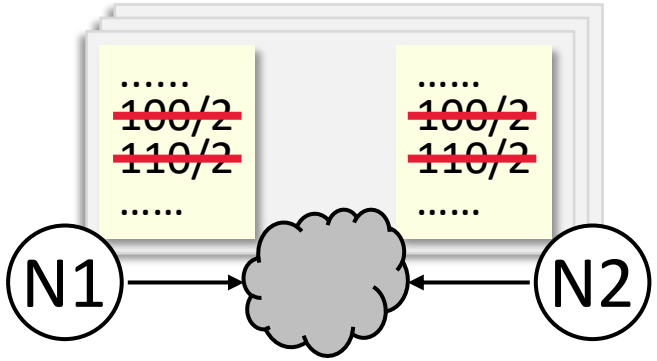
How to Explore Equivalences?



EC#1: N1 announces 100/2, 110/2



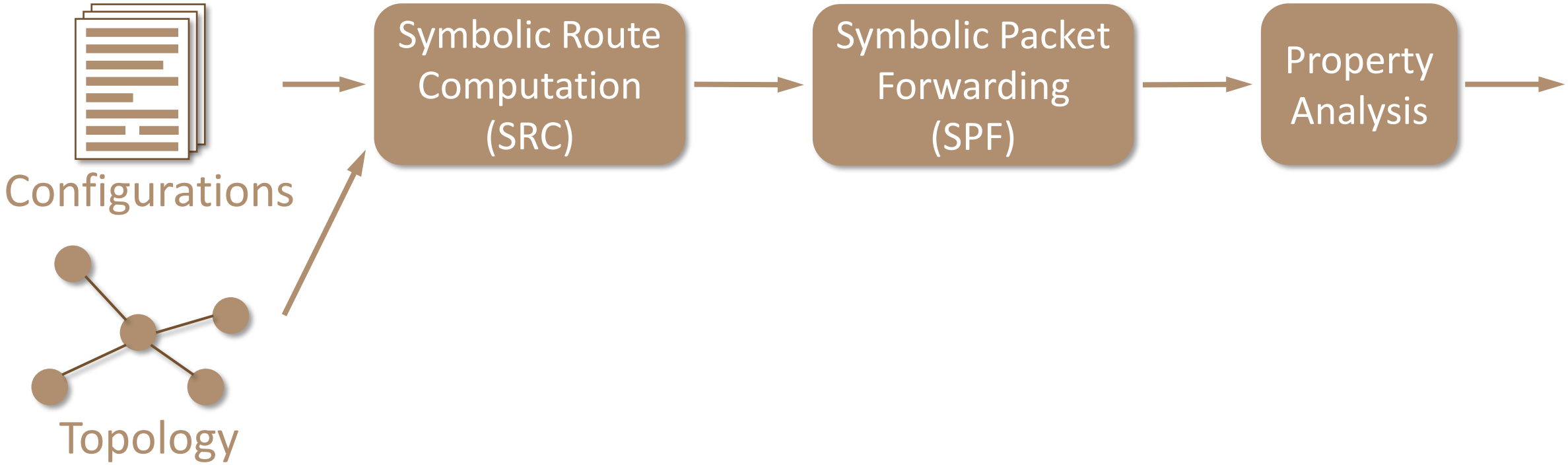
EC#2: Only N2 announces 100/2, 110/2



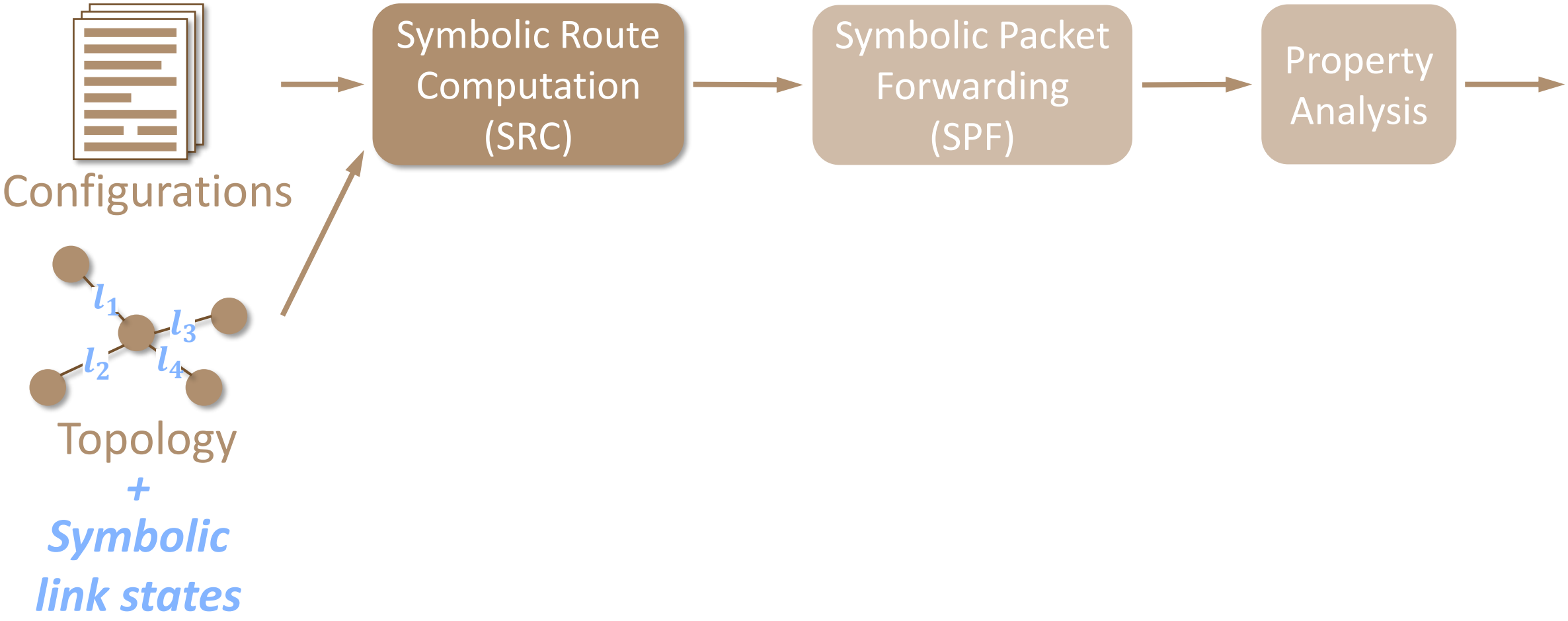
EC#3: No announcement for 100/2, 110/2

SRE[7] SIGCOMM'22
Symbolic simulation

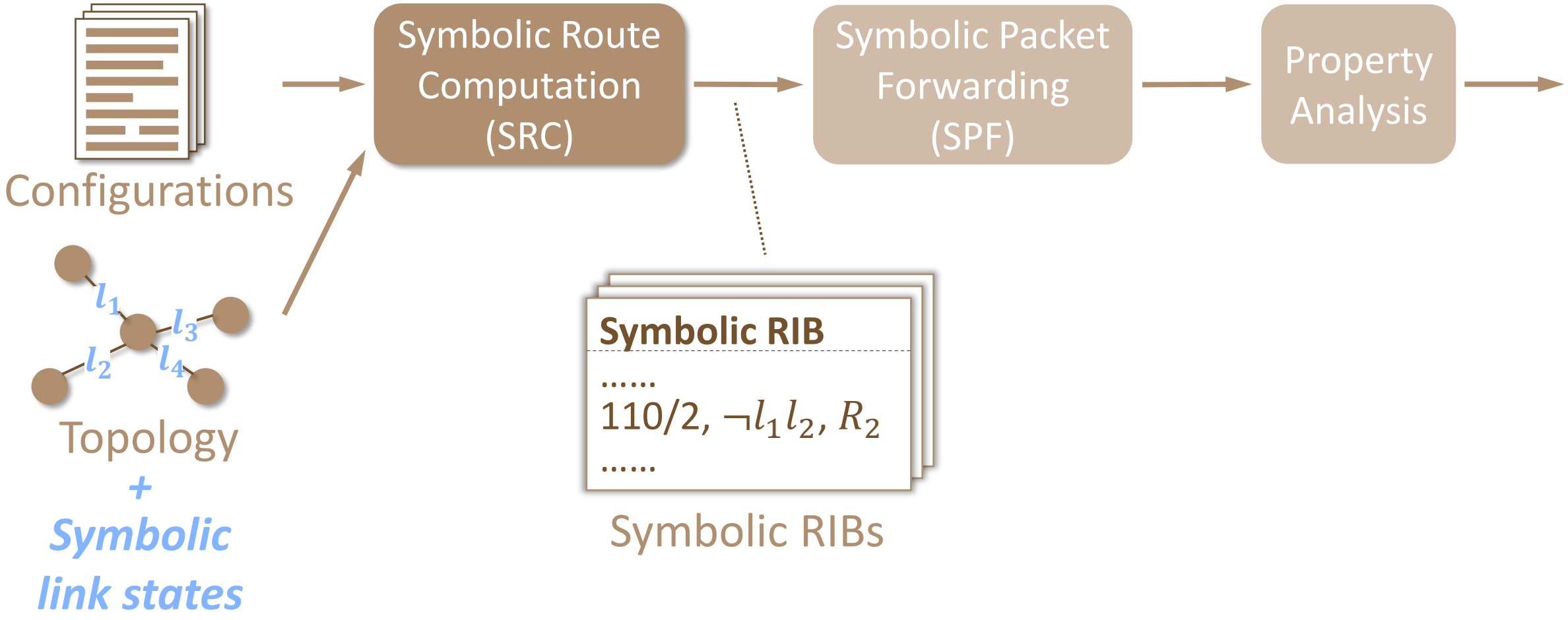
Workflow of Symbolic Simulation[7]



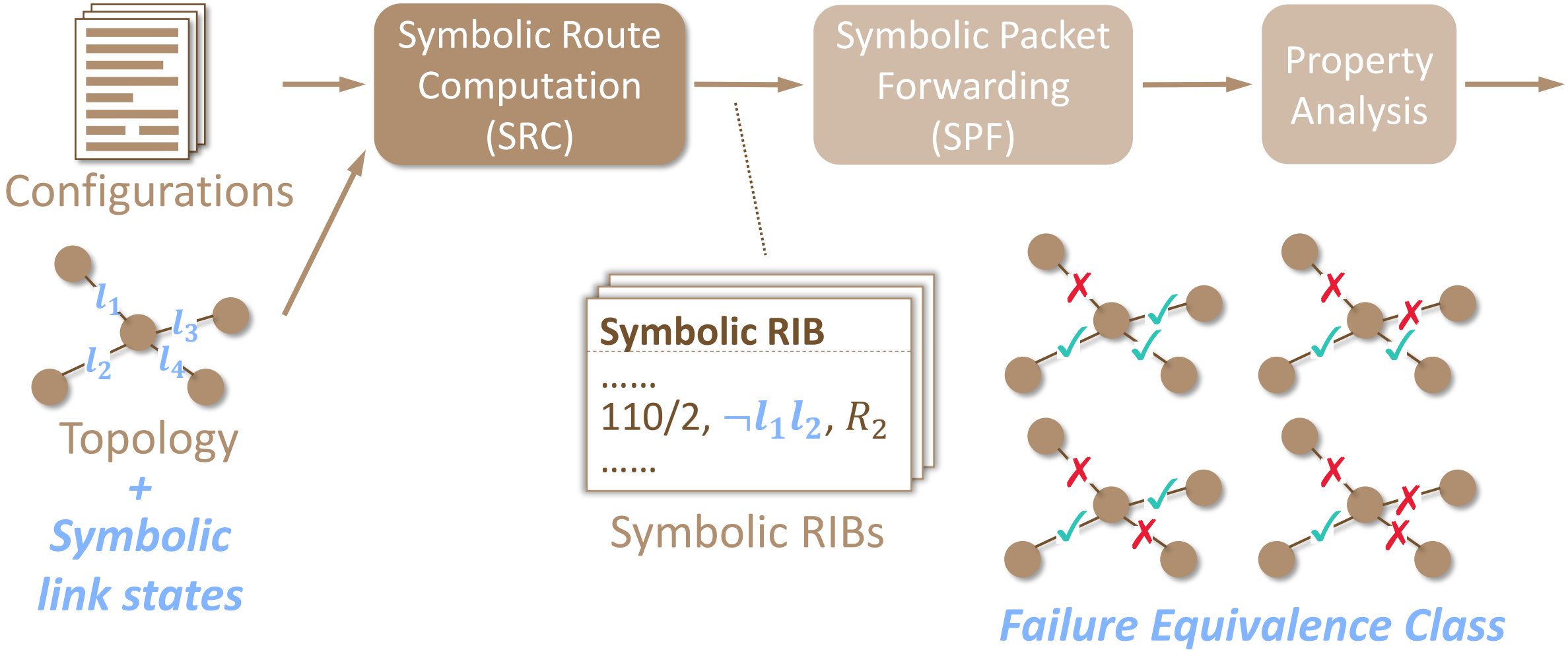
SRE Makes Link Symbolic



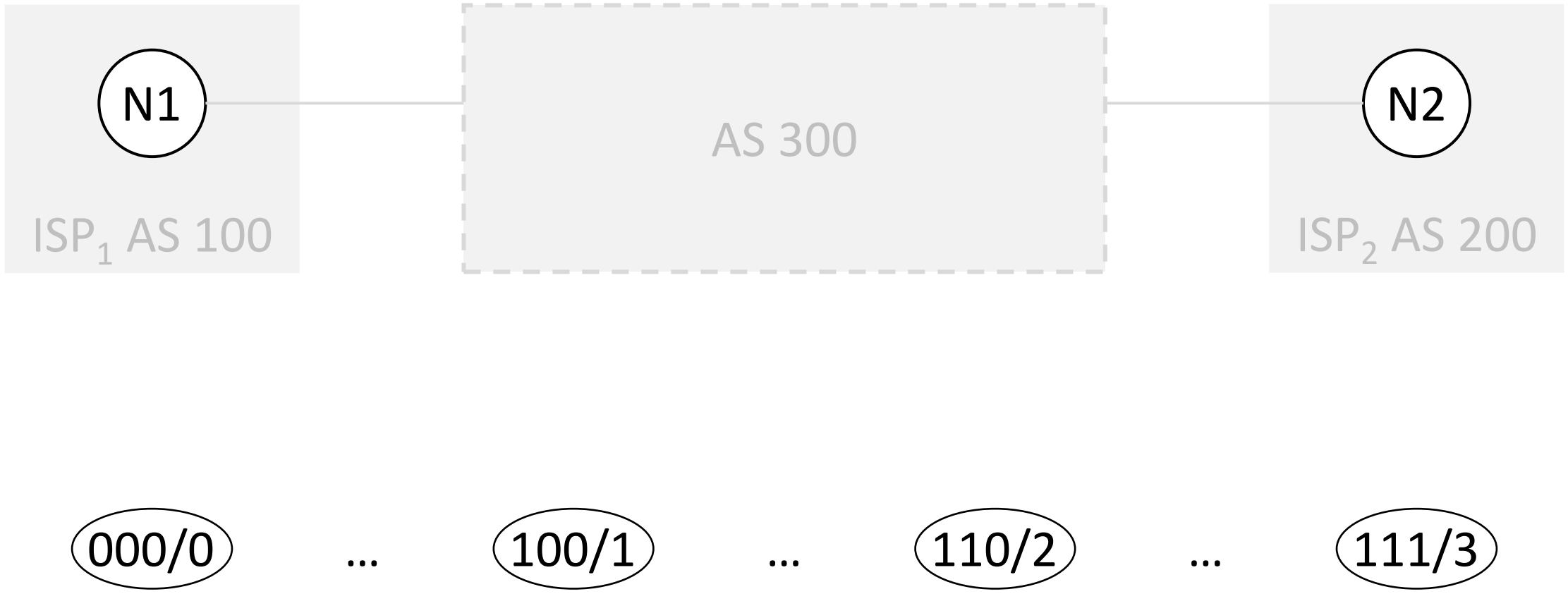
SRE Computes Failure Equivalence Classes



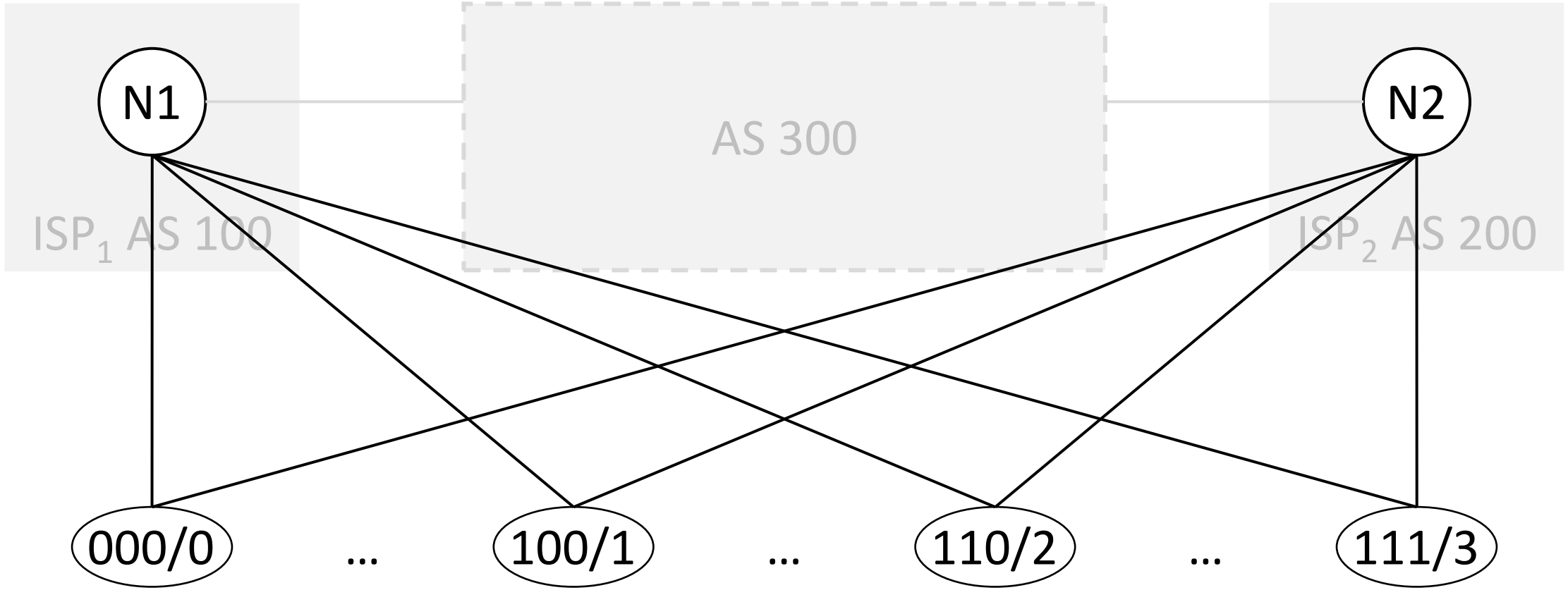
SRE Computes Failure Equivalence Classes



Modeling Symbolic Routes As Symbolic Links

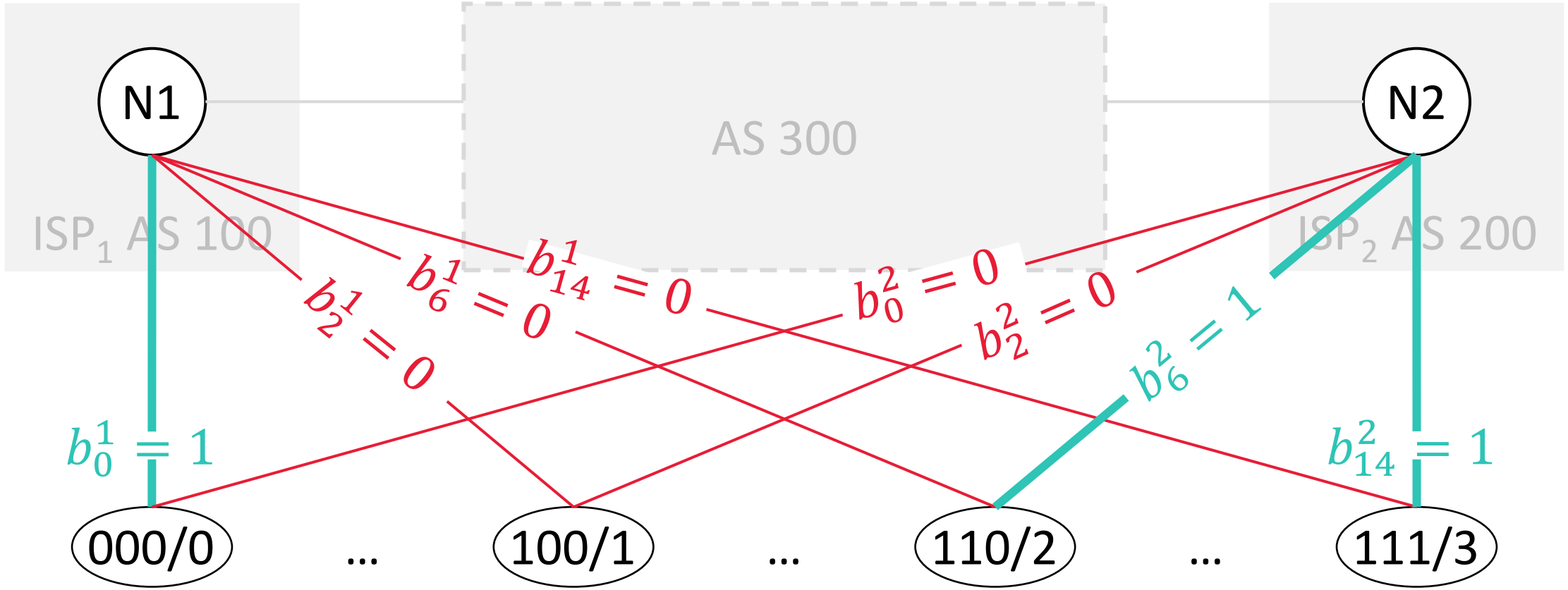


Modeling Symbolic Routes As Symbolic Links

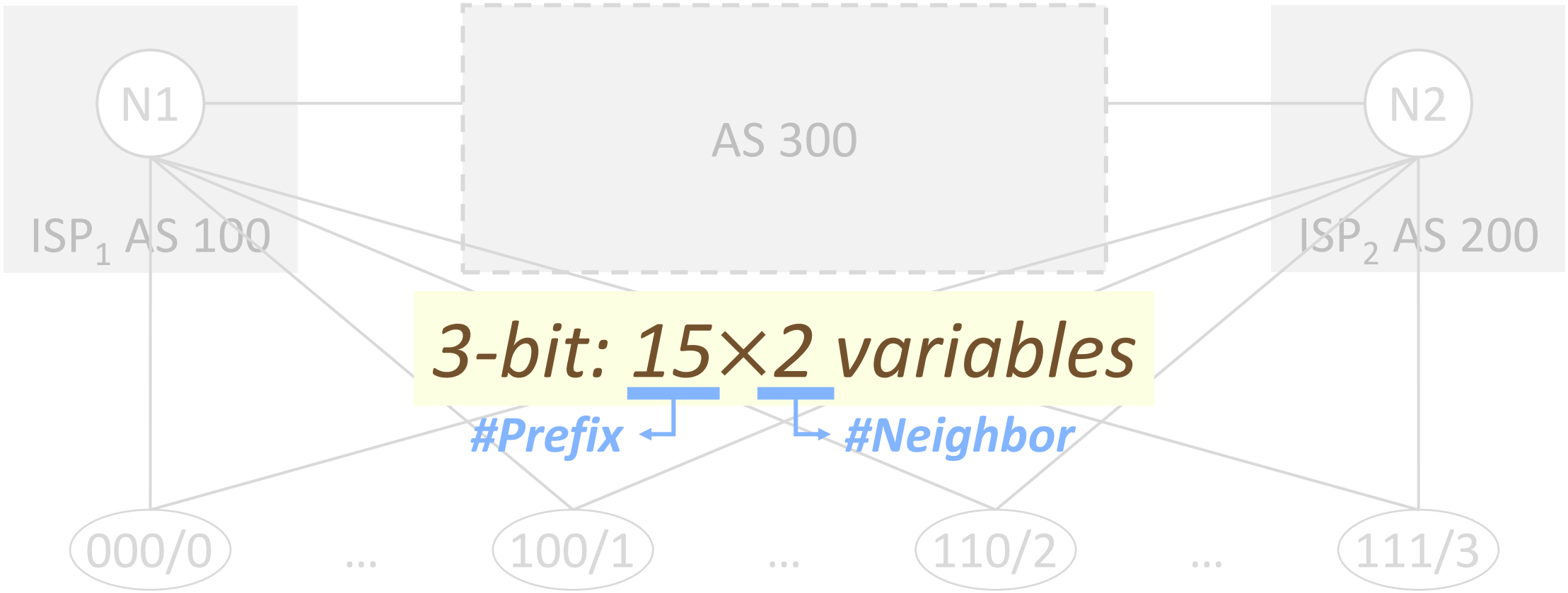


SRE Encoding: Select by Link Variables

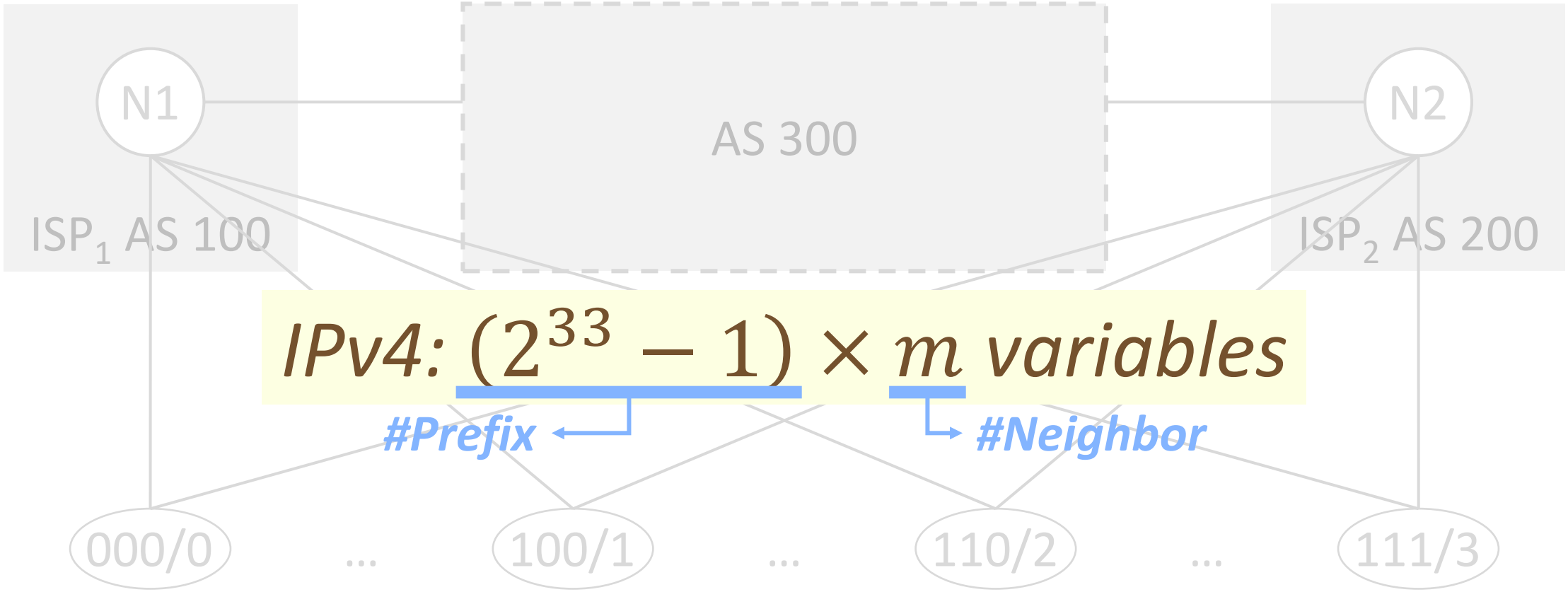
$N1$ announces 000/0, $N2$ announces 110/2 and 111/3



SRE Encoding: Select by Link Variables



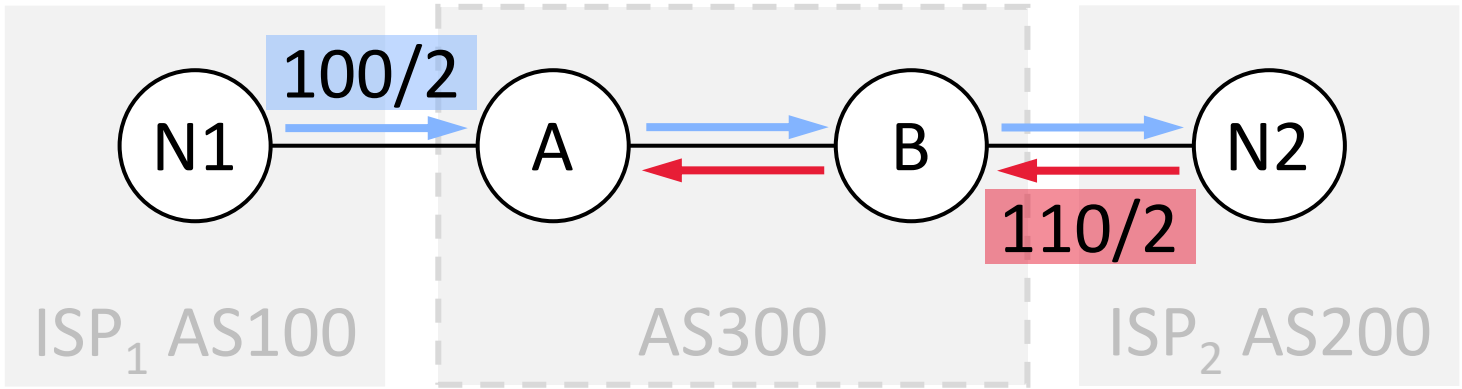
SRE Encoding: Select by Link Variables



$$\textit{IPv4: } \underbrace{(2^{33}-1)}_{\#\textit{Prefix}} \times \underbrace{m}_{\#\textit{Neighbor}} \textit{ variables}$$

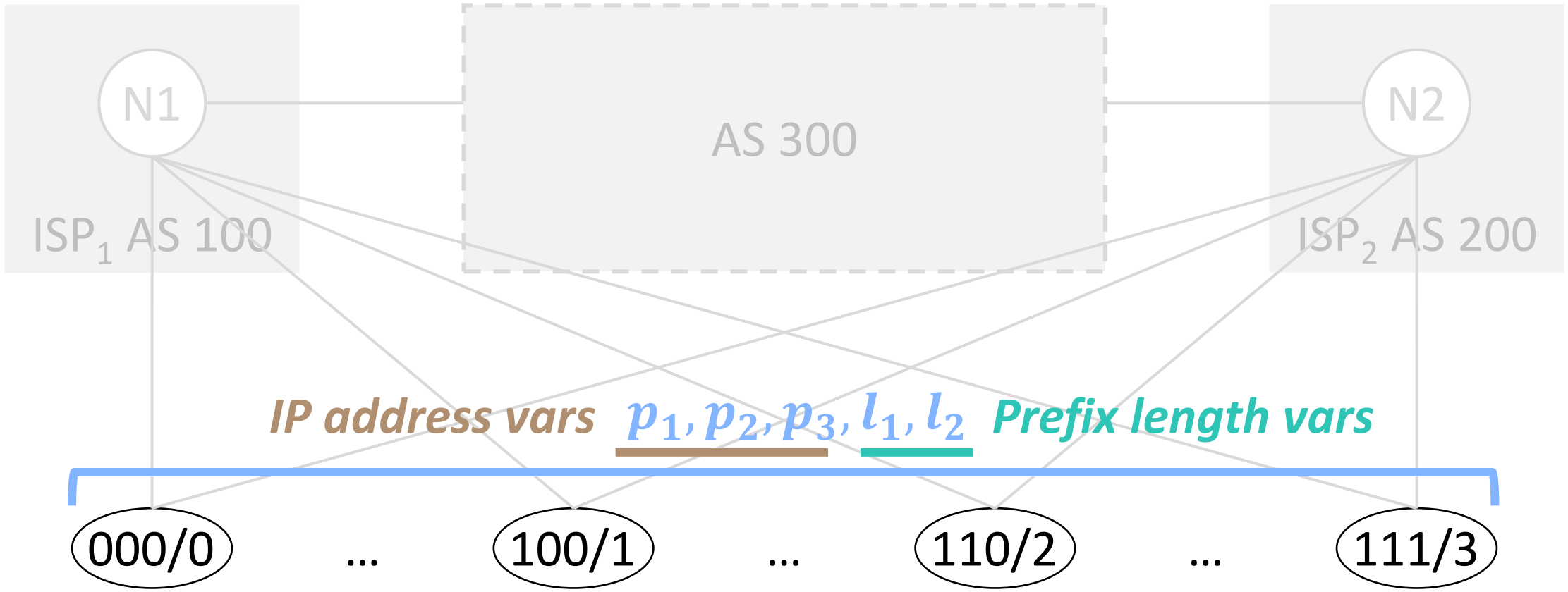
Observation2: Independency in Route Computation

Prefixes mostly Independent[1]

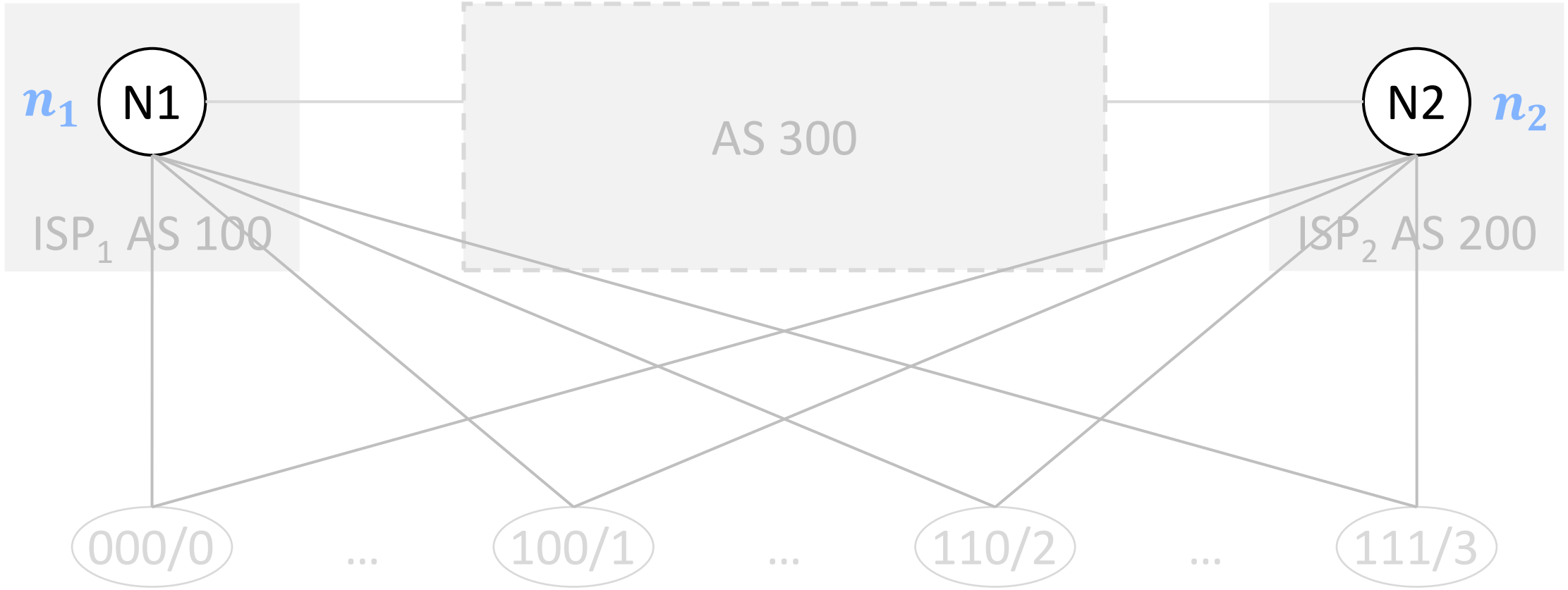


1 Network features like route aggregation can cause dependencies, please refer to our paper for more details.

Expresso Encoding: First Select Prefixes

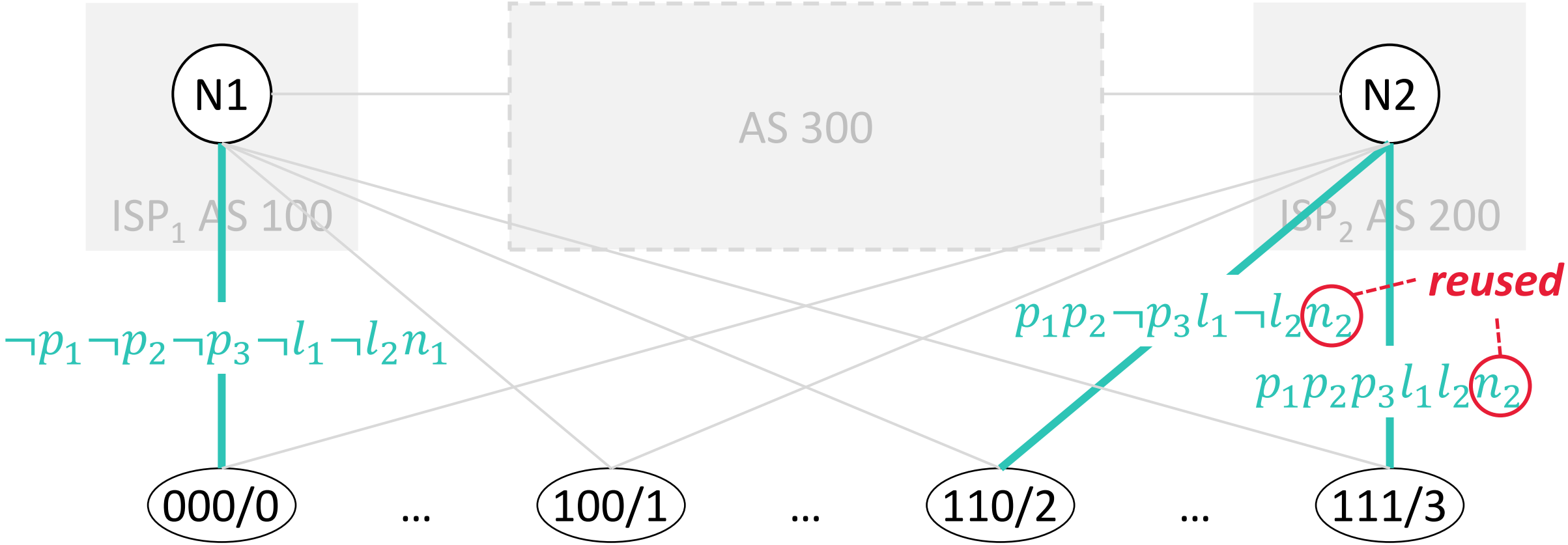


Expresso Encoding: Then Select Advertisers

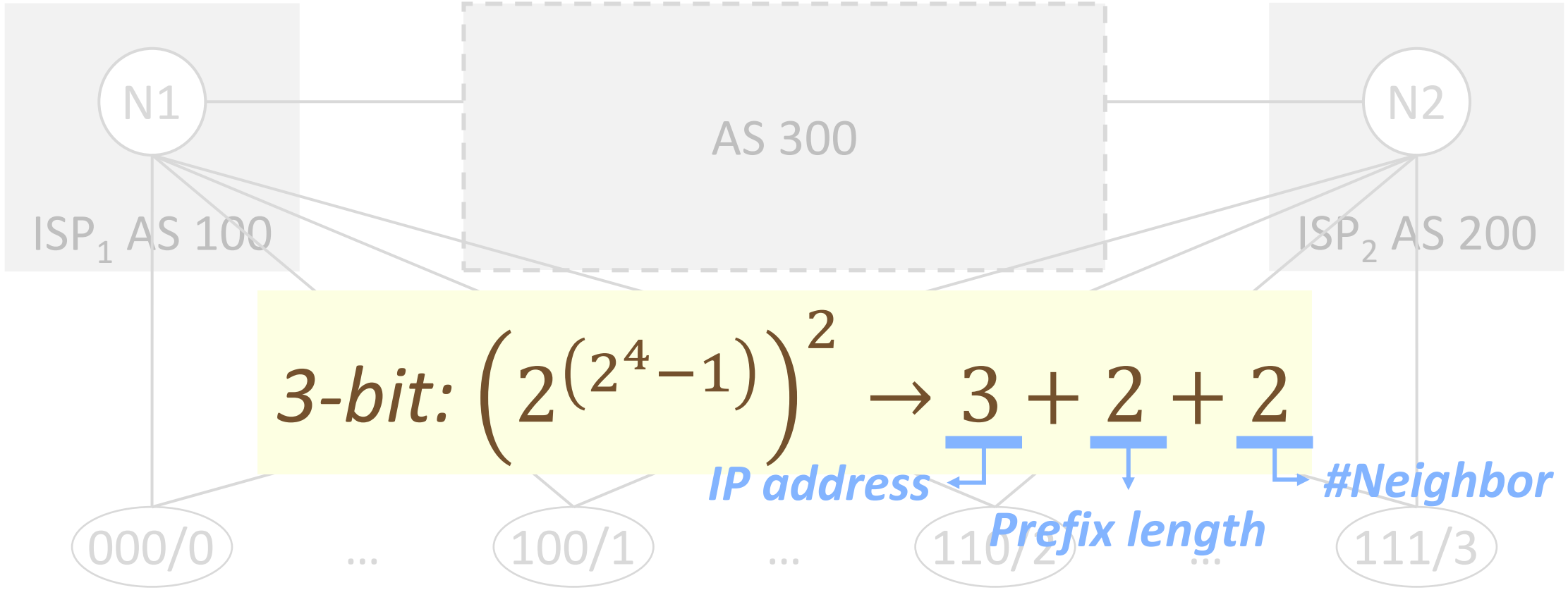


Example

$N1$ announces 000/0, $N2$ announces 110/2 and 111/3

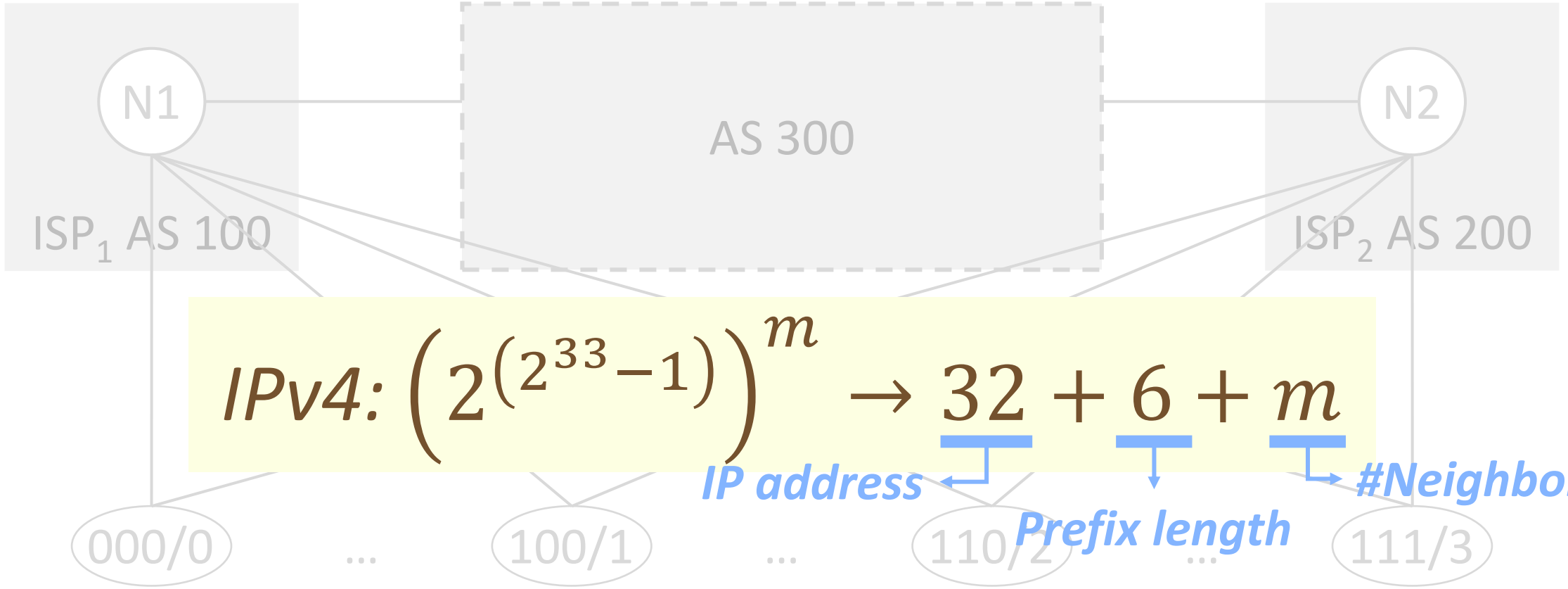


Expresso Encoding



$$\textit{3-bit: } \left(2^{(2^4-1)}\right)^2 \rightarrow \underbrace{3}_{\textit{IP address}} + \underbrace{2}_{\textit{Prefix length}} + \underbrace{2}_{\textit{\#Neighbor}}$$

Expresso Encoding

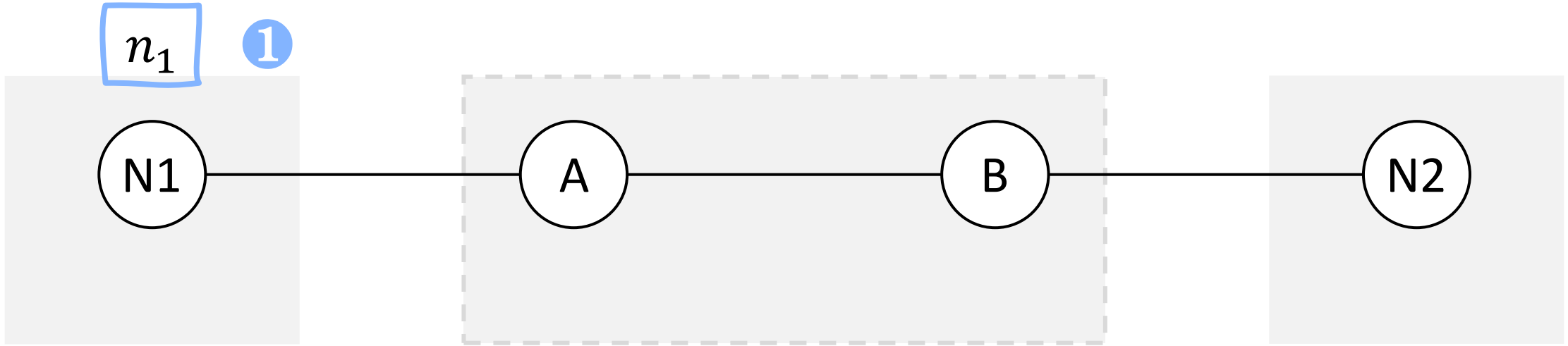


$$\textit{IPv4: } \left(2^{(2^{33}-1)}\right)^{m} \rightarrow \underline{32} + \underline{6} + \underline{m}$$

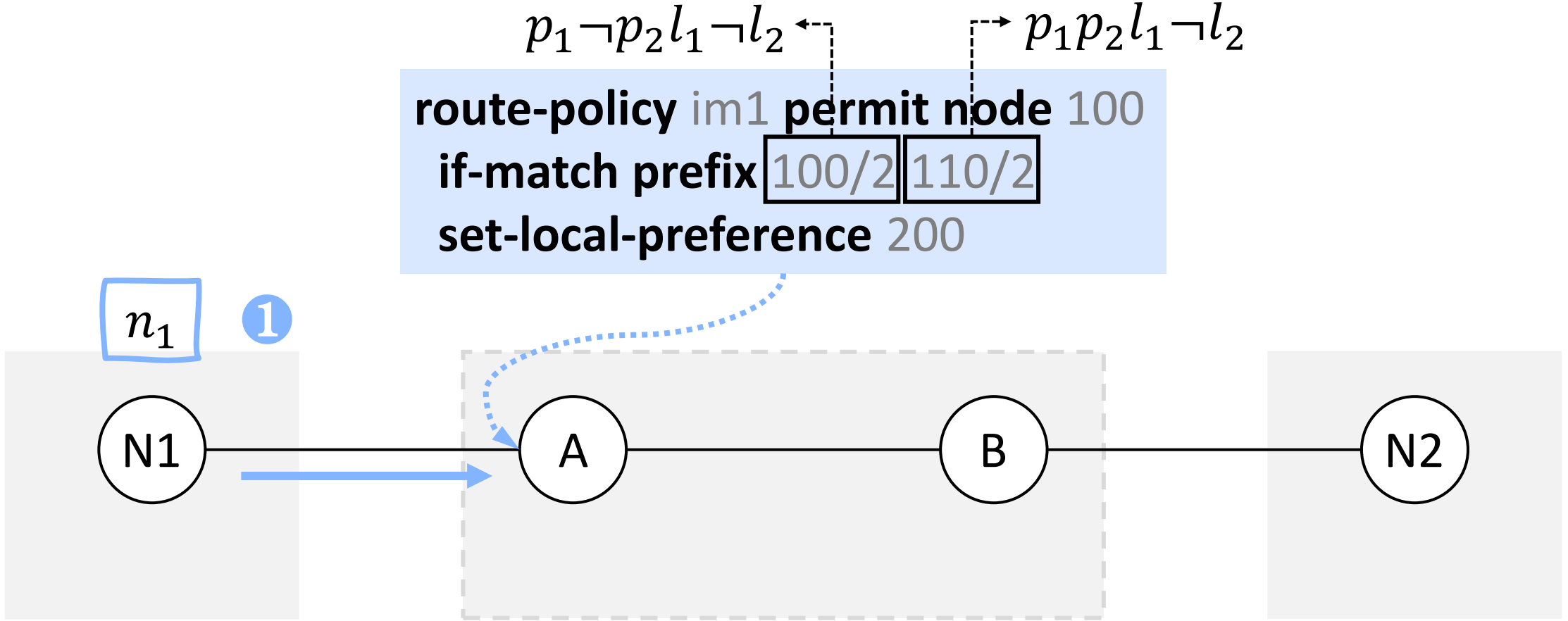
IP address *Prefix length* *#Neighbor*

Expresso SRC: Initialize Symbolic Route

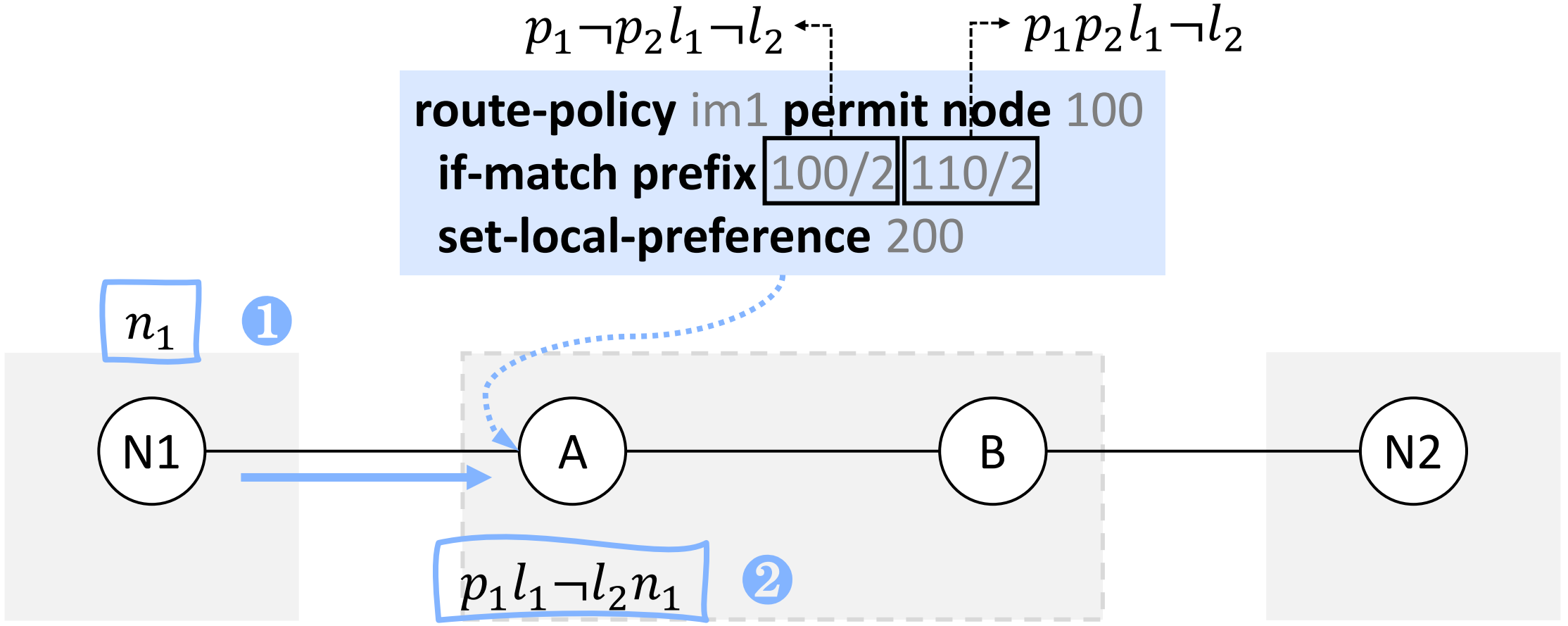
Arbitrary prefixes announced by N1



Expresso SRC: Route Propagation

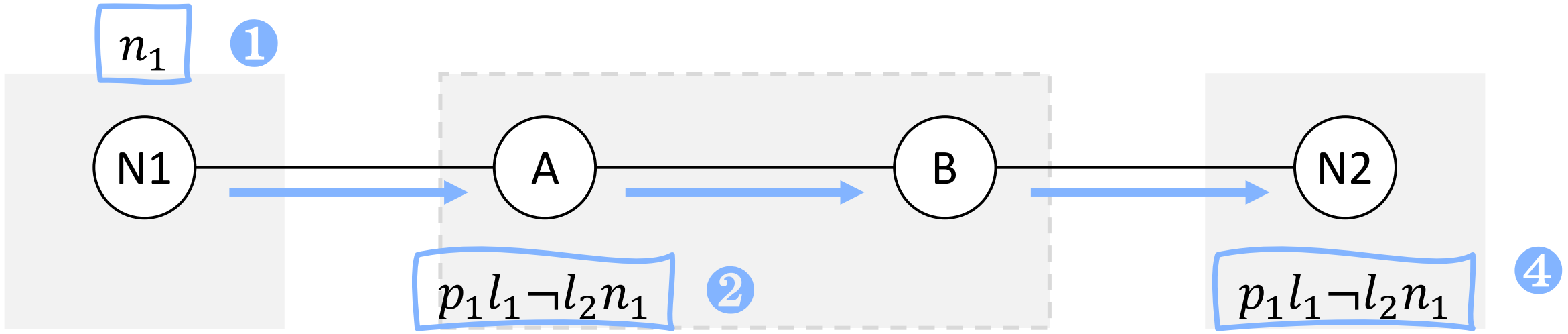


Expresso SRC: Apply Routing Policy

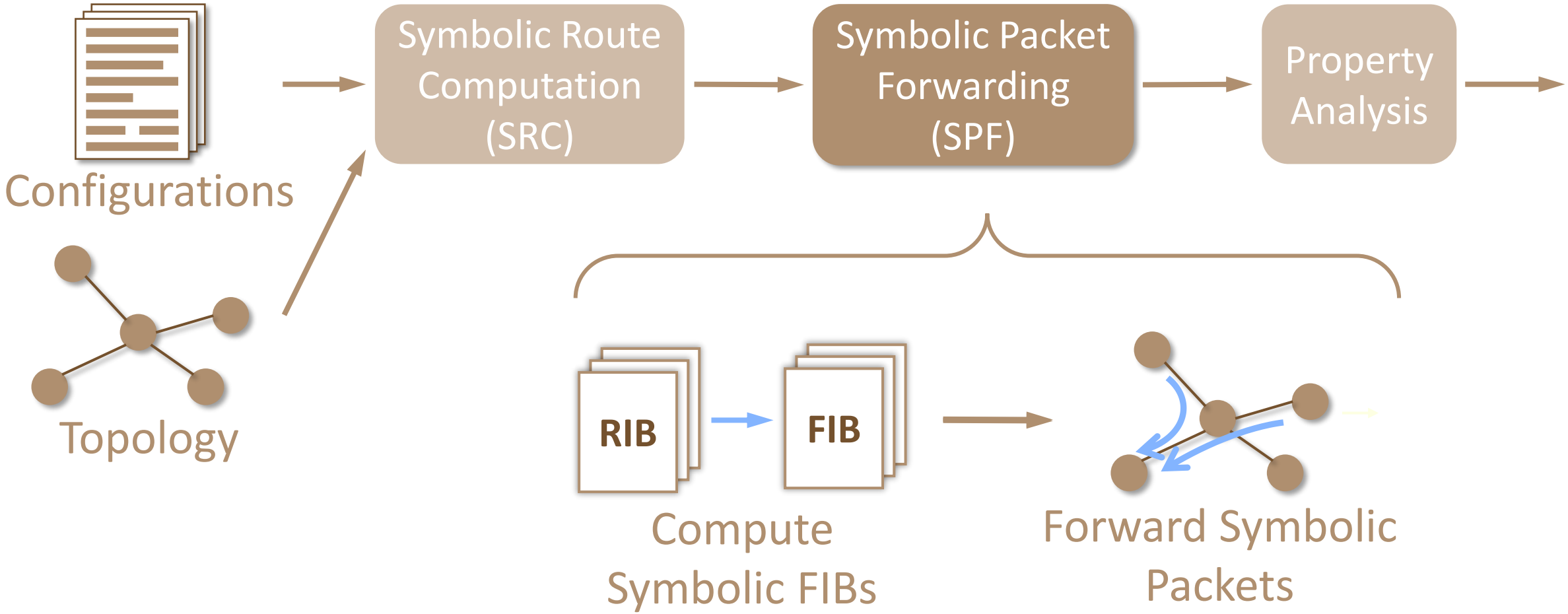


$$n_1 \wedge (p_1 \neg p_2 l_1 \neg l_2 \vee p_1 p_2 l_1 \neg l_2)$$

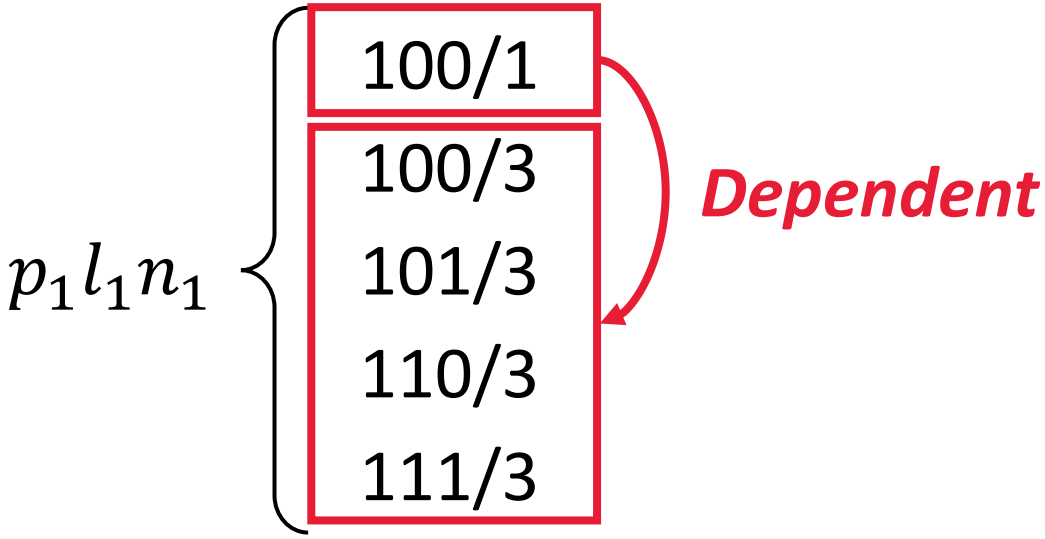
Expresso SRC: Route Propagation



Symbolic Packet Forwarding



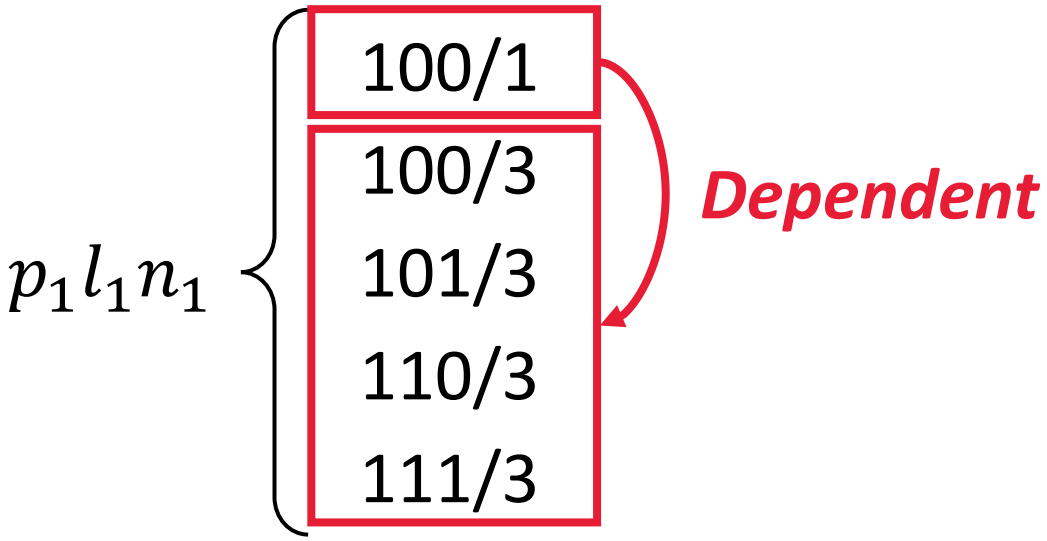
Prefix Dependency in Packet Forwarding Due to Longest Prefix Match

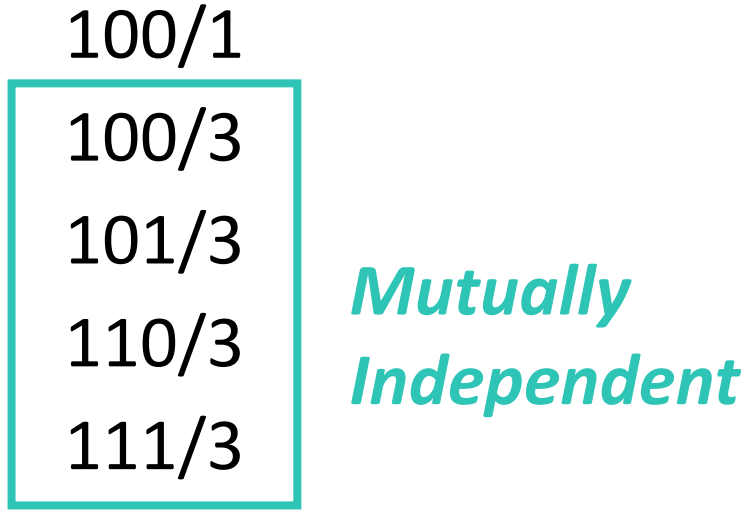


1 *variable per neighbor is* ***not enough any more****.*

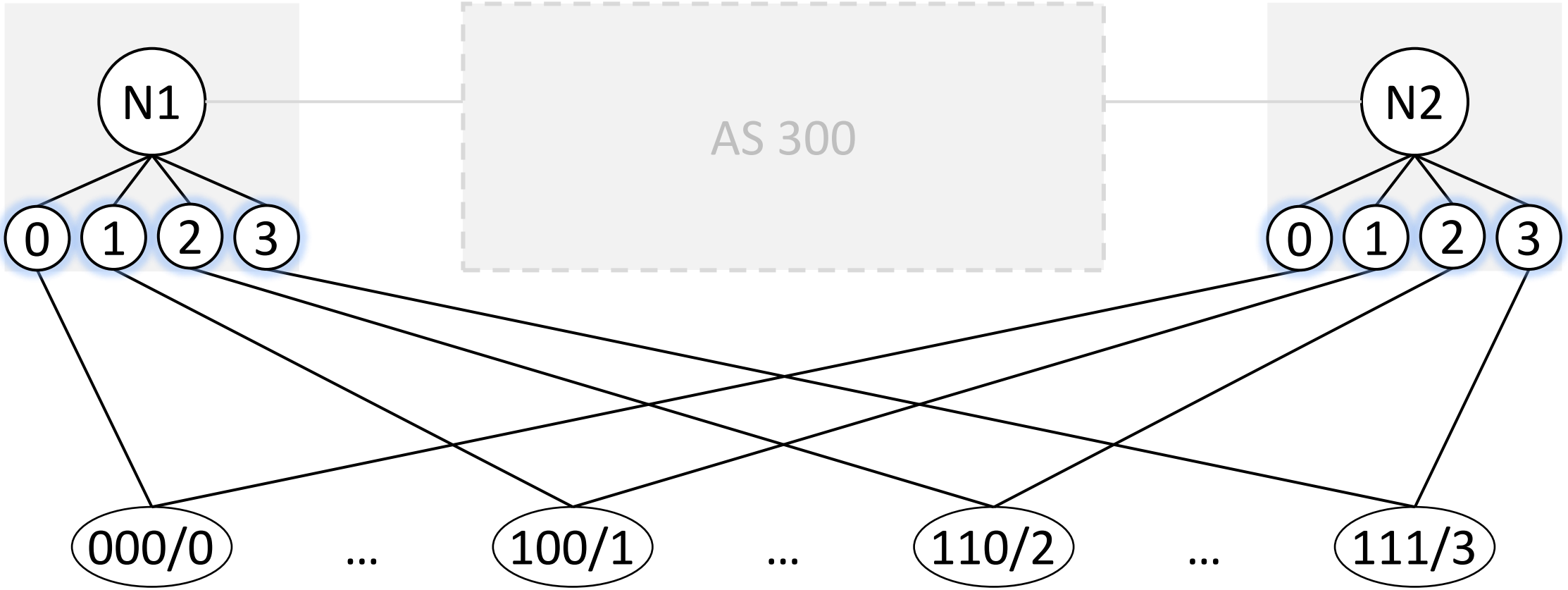
15 *variables per neighbor now?*

Observation3: Dependency is Limited to Different Prefix Length

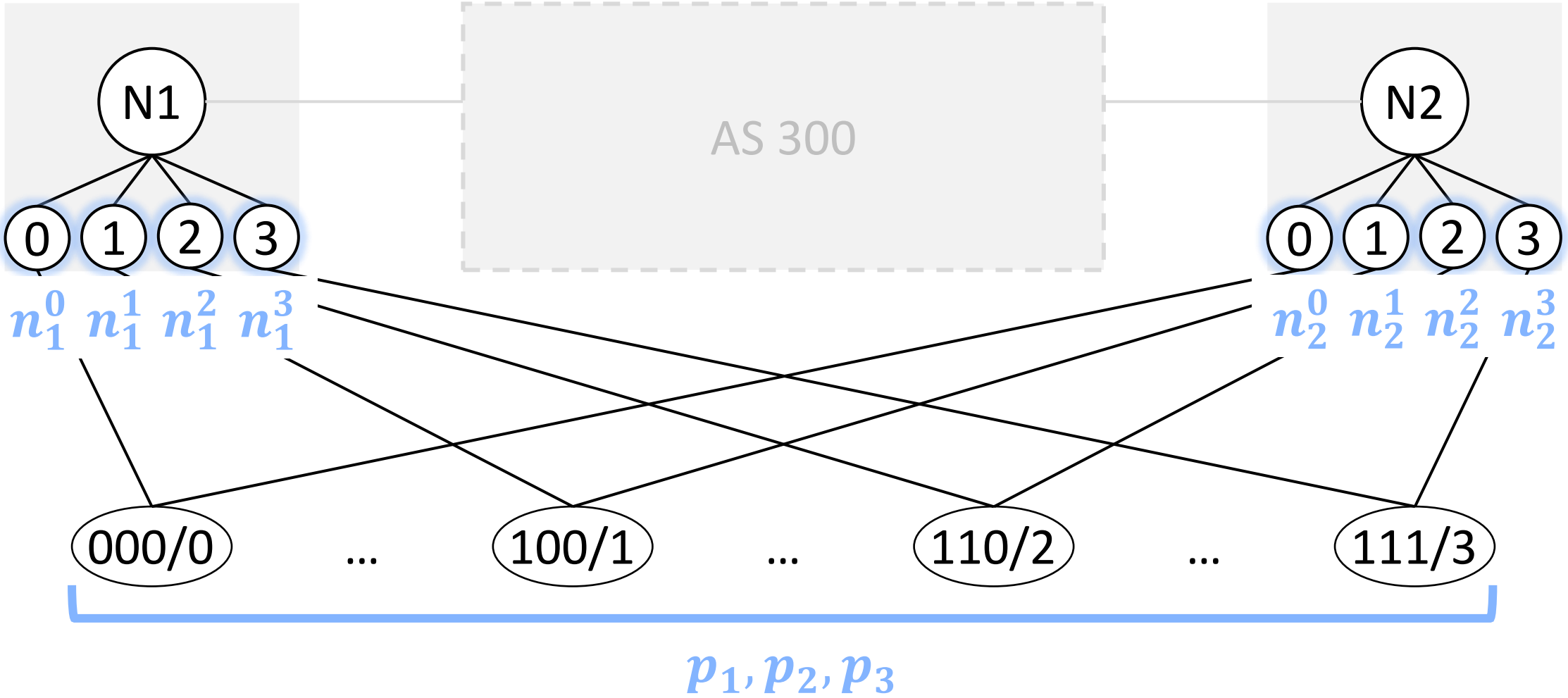




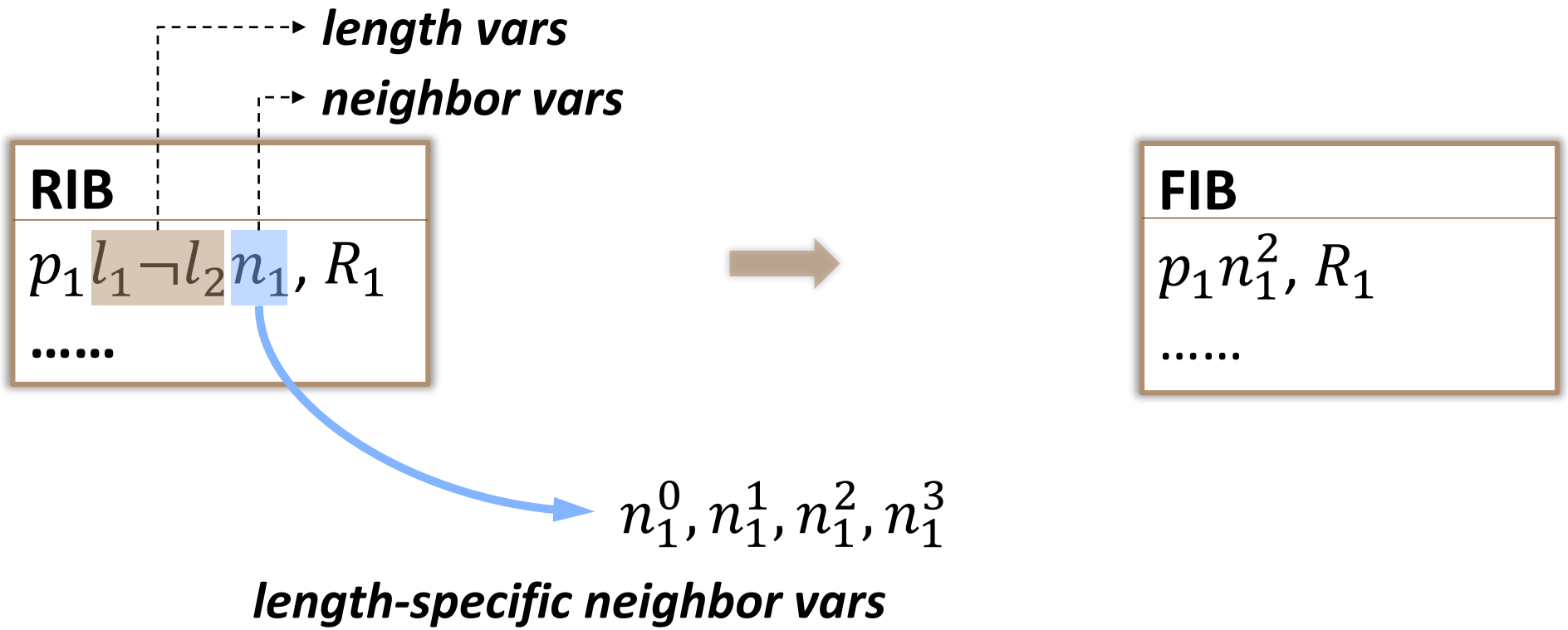
Expresso Data Plane Encoding



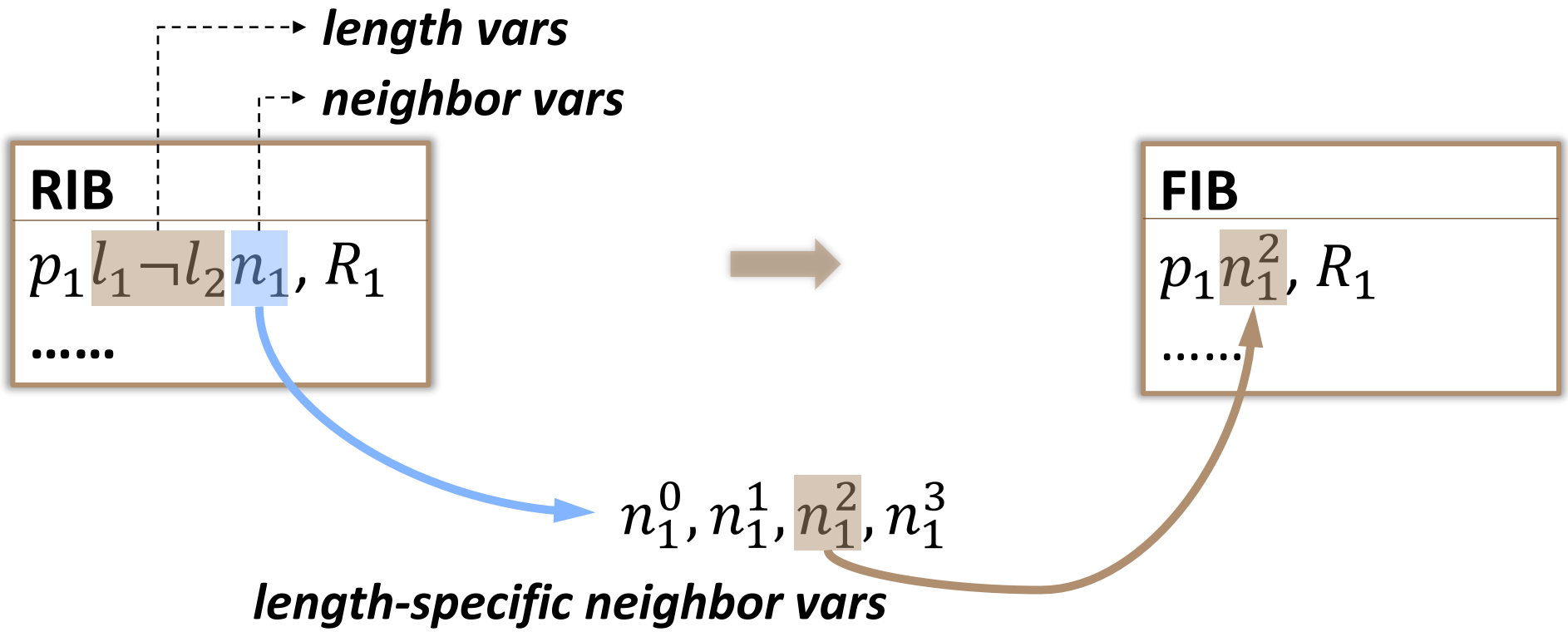
Expresso Data Plane Encoding



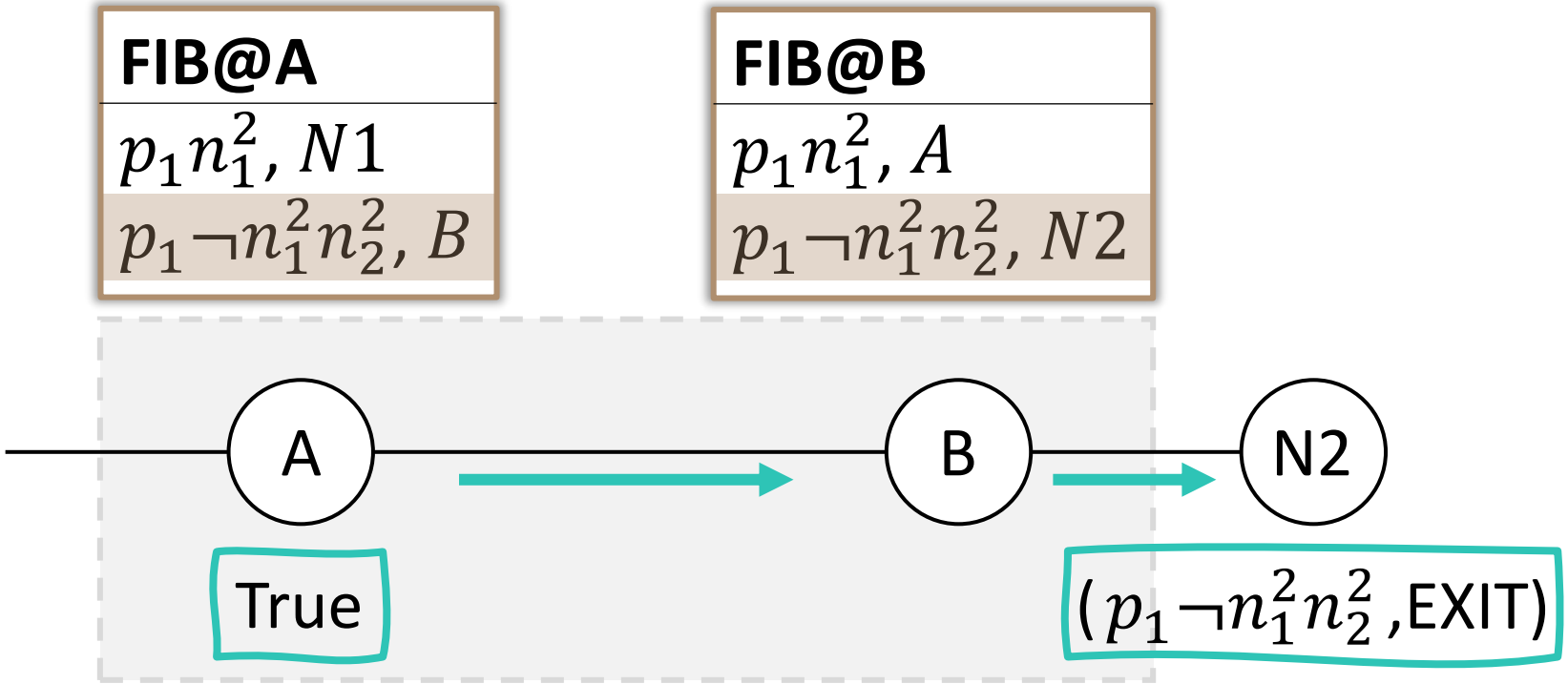
Expresso Compute Symbolic FIBs



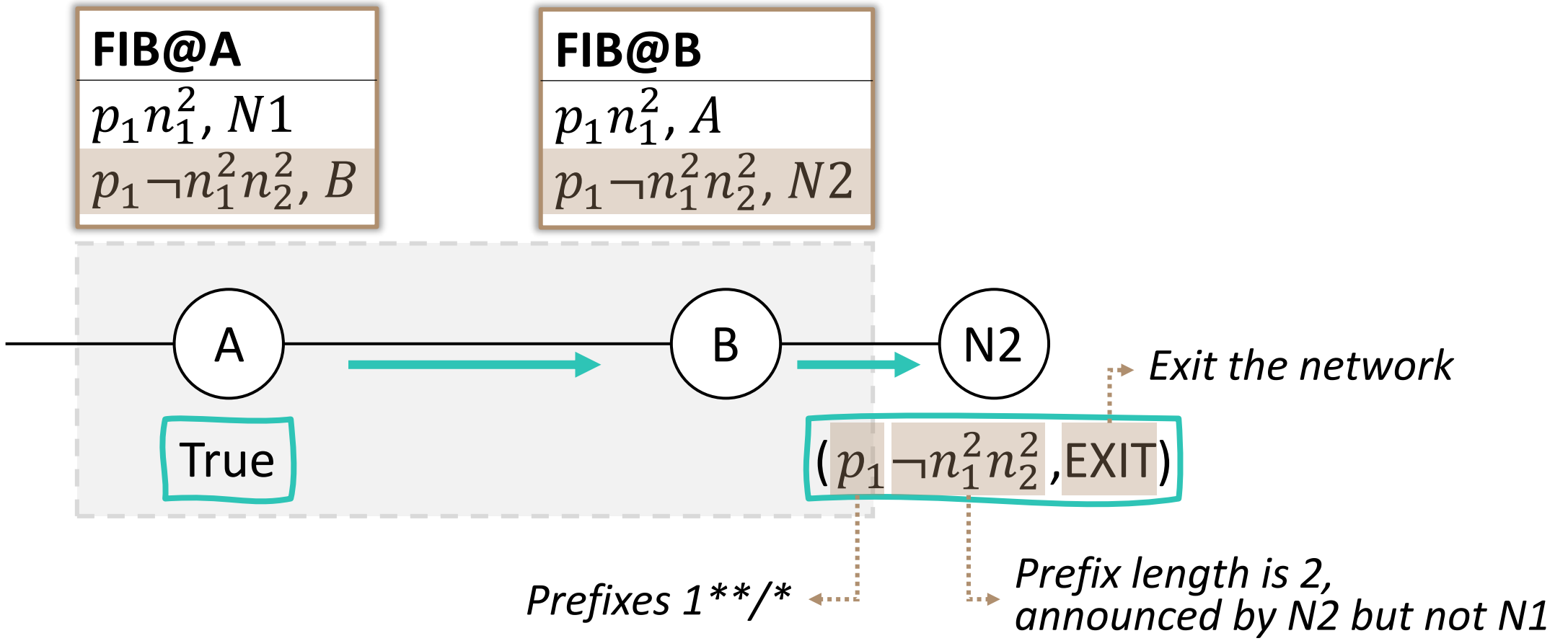
Expresso Compute Symbolic FIBs



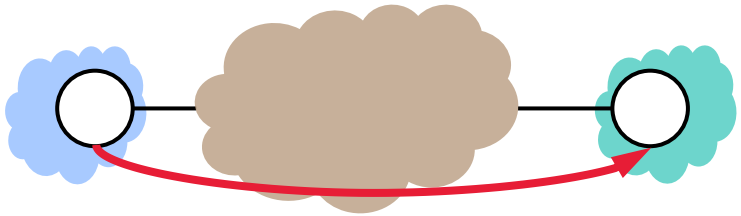
Expresso compute PECs



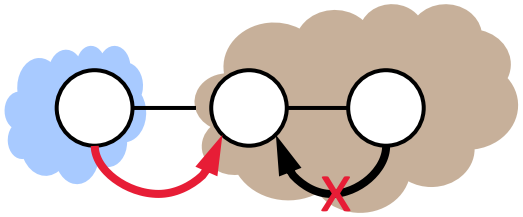
Expresso compute PECs



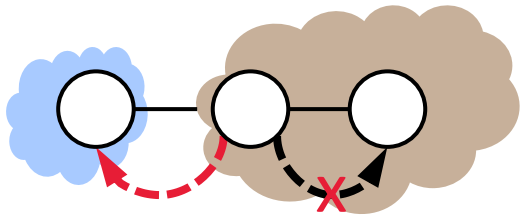
Property Analysis



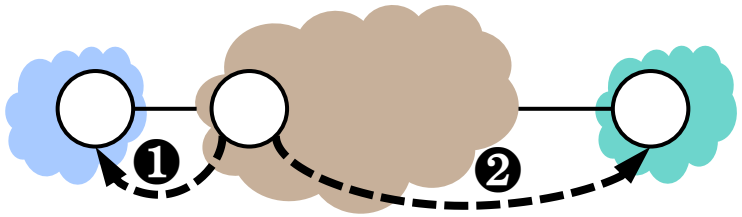
Route Leak



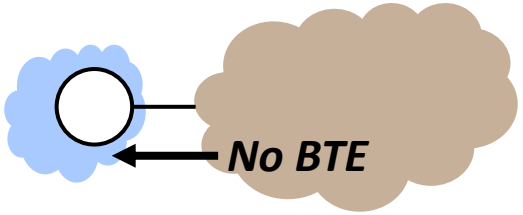
Route Hijack



Traffic Hijack



Egress Preference

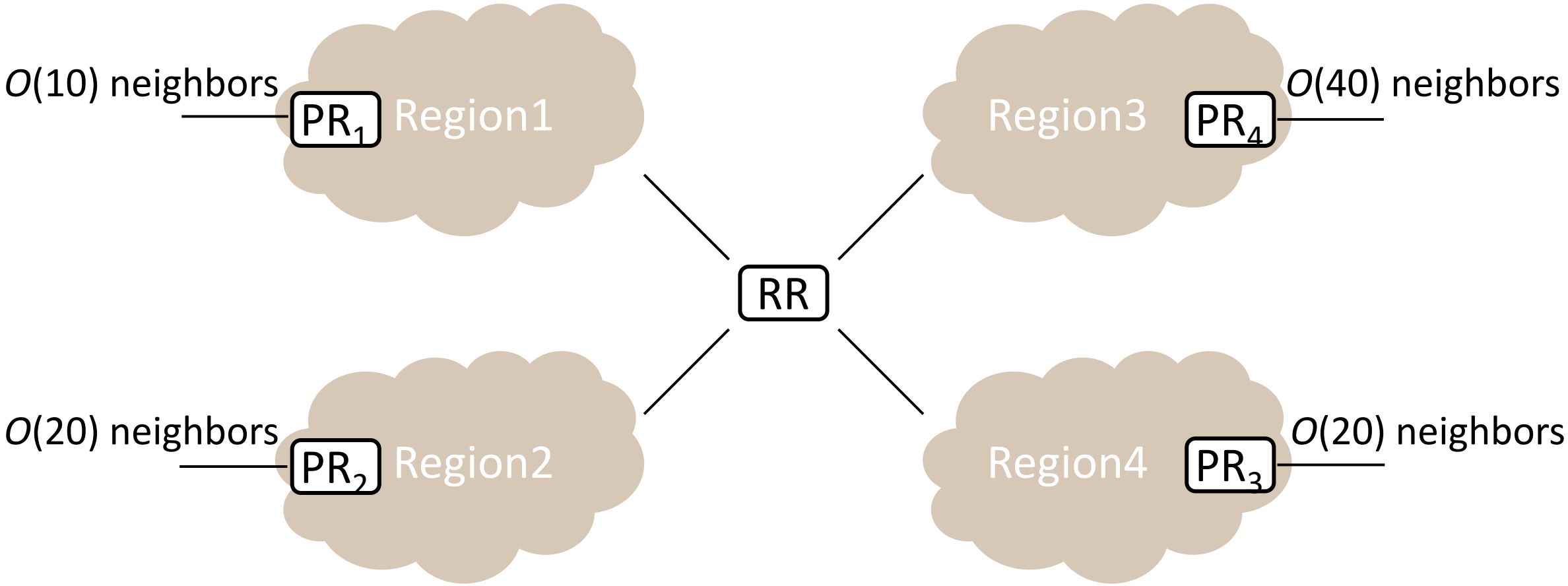


Block To External

Evaluation Results

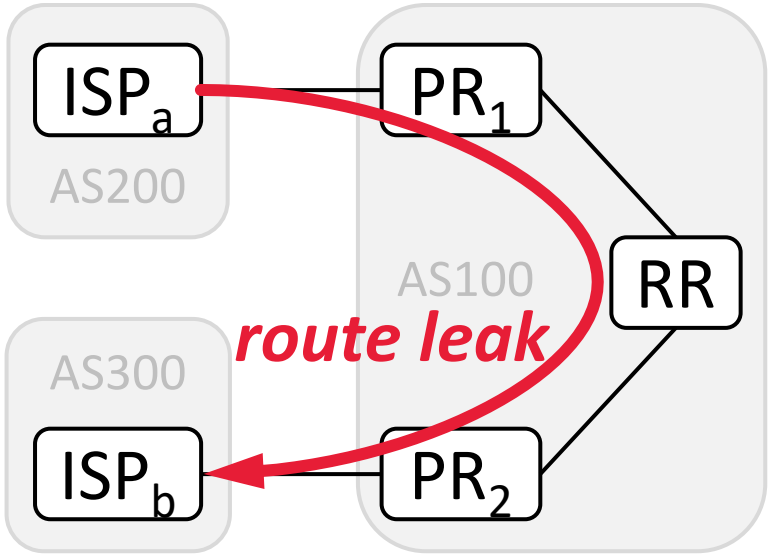
On the WAN of a Cloud Service Provider (CSP)

A Cloud Service Provider's WAN

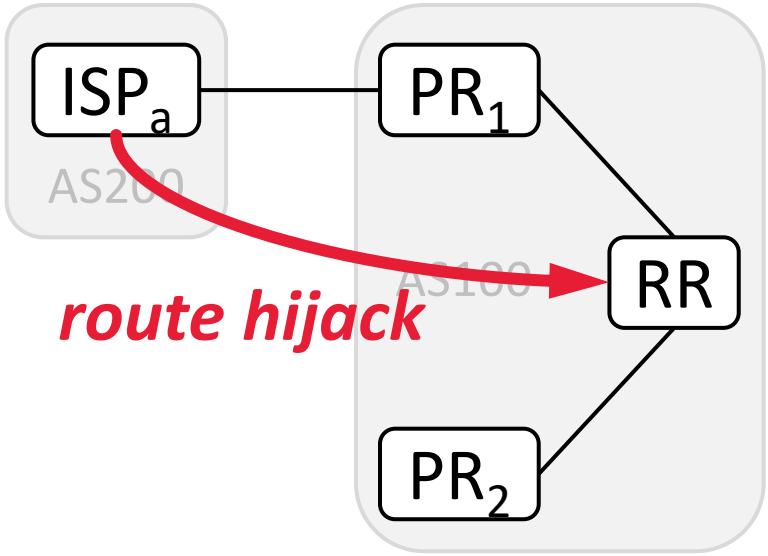


PR: Peering Router, RR: Route Reflector

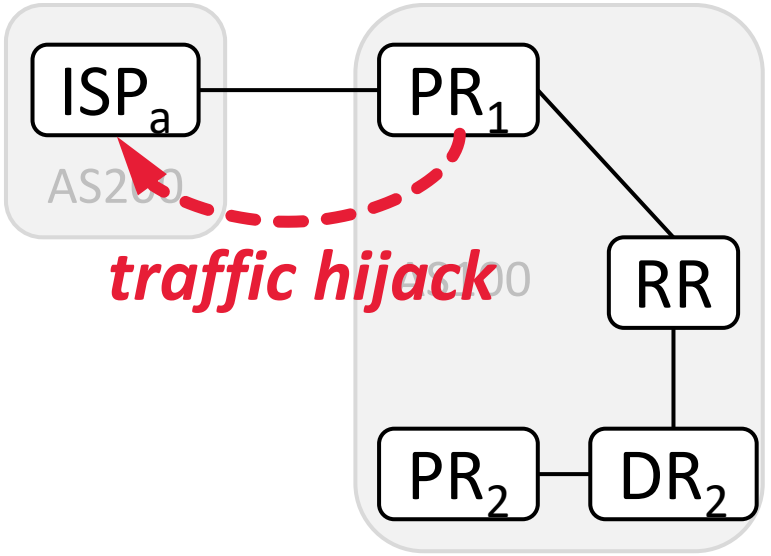
Found Violations



***6** confirmed*

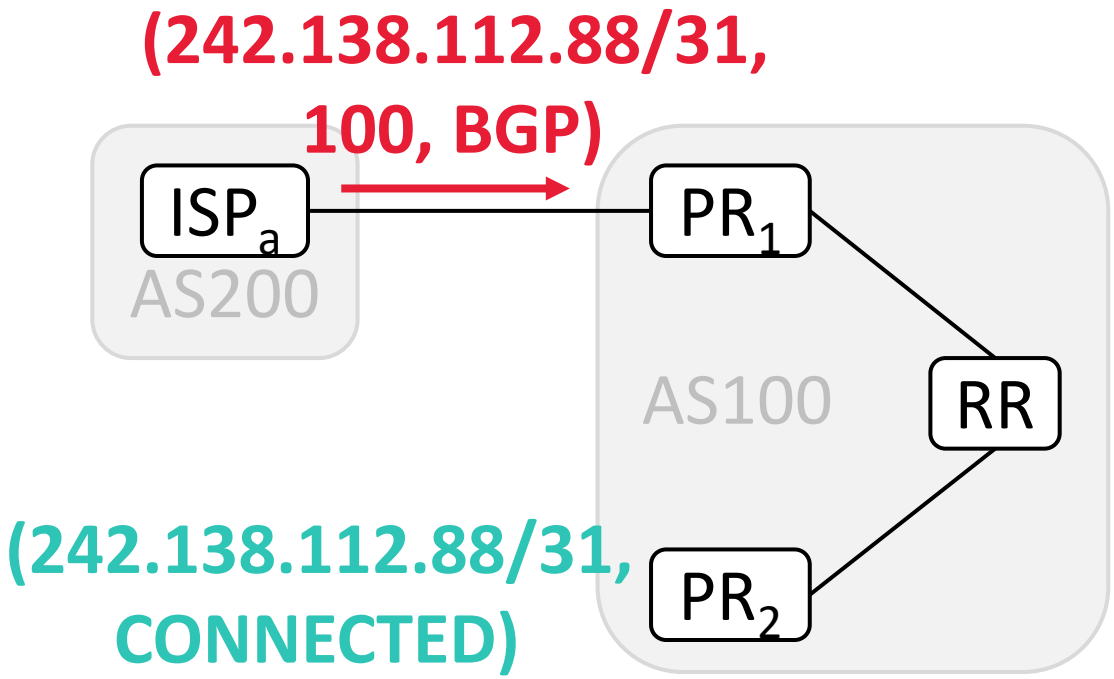


***17** confirmed*



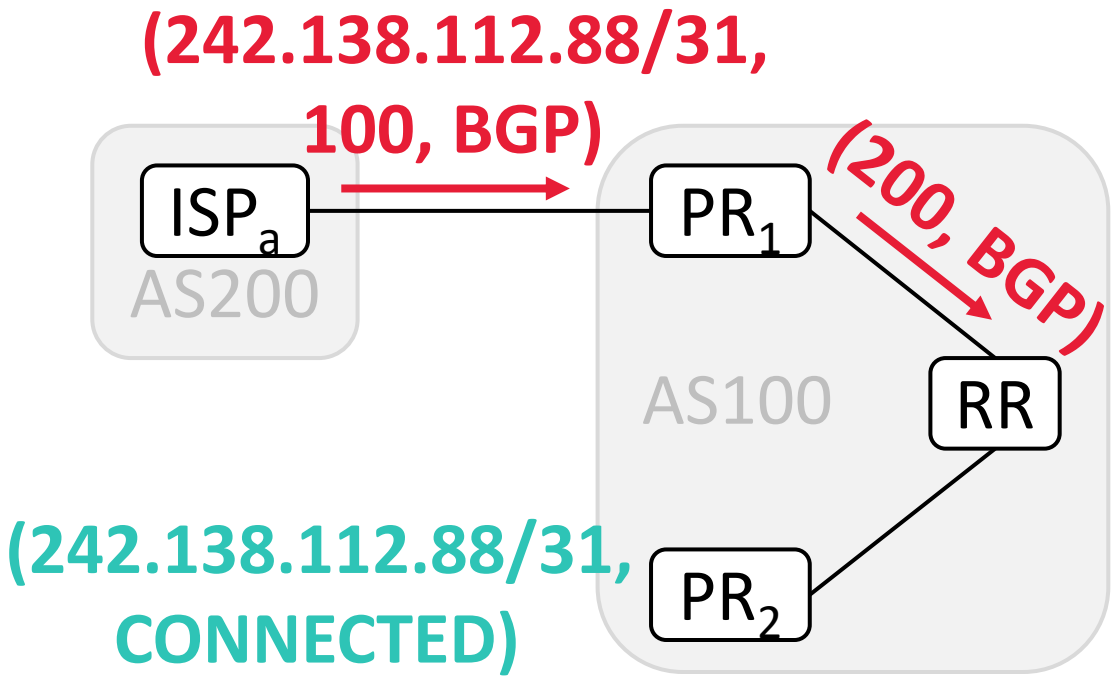
***19** confirmed*

Case Study (A Route Hijack)



PR: Peering Router, RR: Route Reflector

Case Study (A Route Hijack)



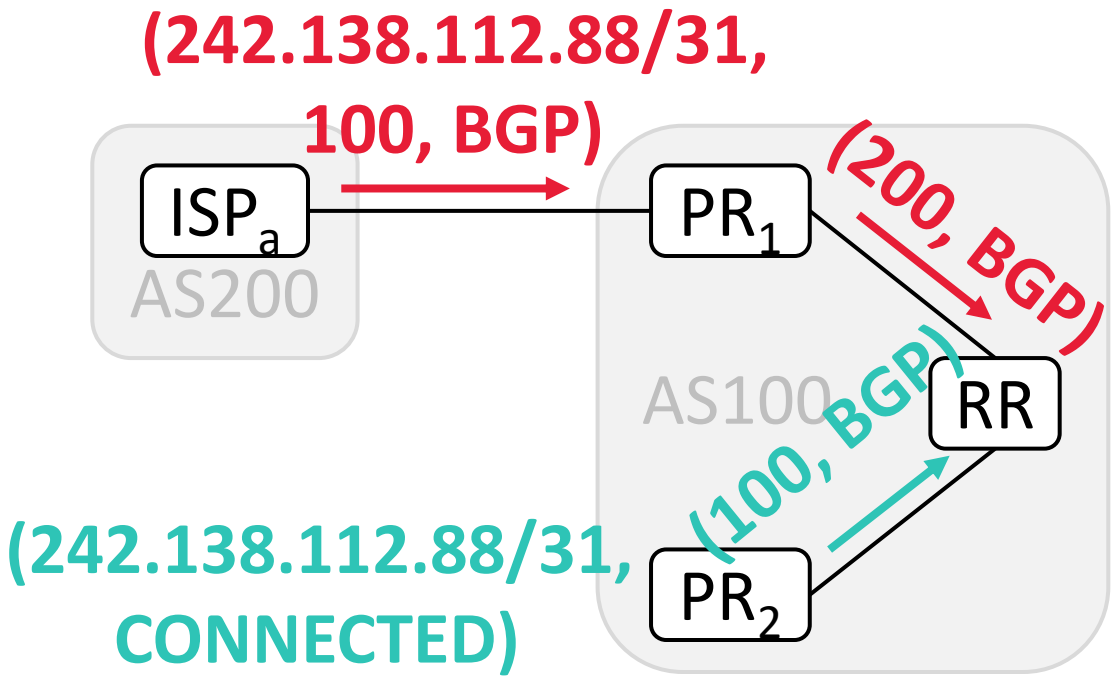

```
route-policy import node 100
   if-match prefix-list list1
   set-local-preference 200

ip prefix list1 node 100 deny 114.247.96.0 20 le 32
ip prefix list1 node 200 deny 123.29.0.0 20 le 32
ip prefix list1 node 300 deny 137.155.0.0 18 le 32
ip prefix list1 node 400 deny 92.230.128.0 18 le 32
ip prefix list1 node xxx deny 242.138.120.0 20 le 32
ip prefix list1 node 500 permit 0.0.0.0 0 le 32
```

missing

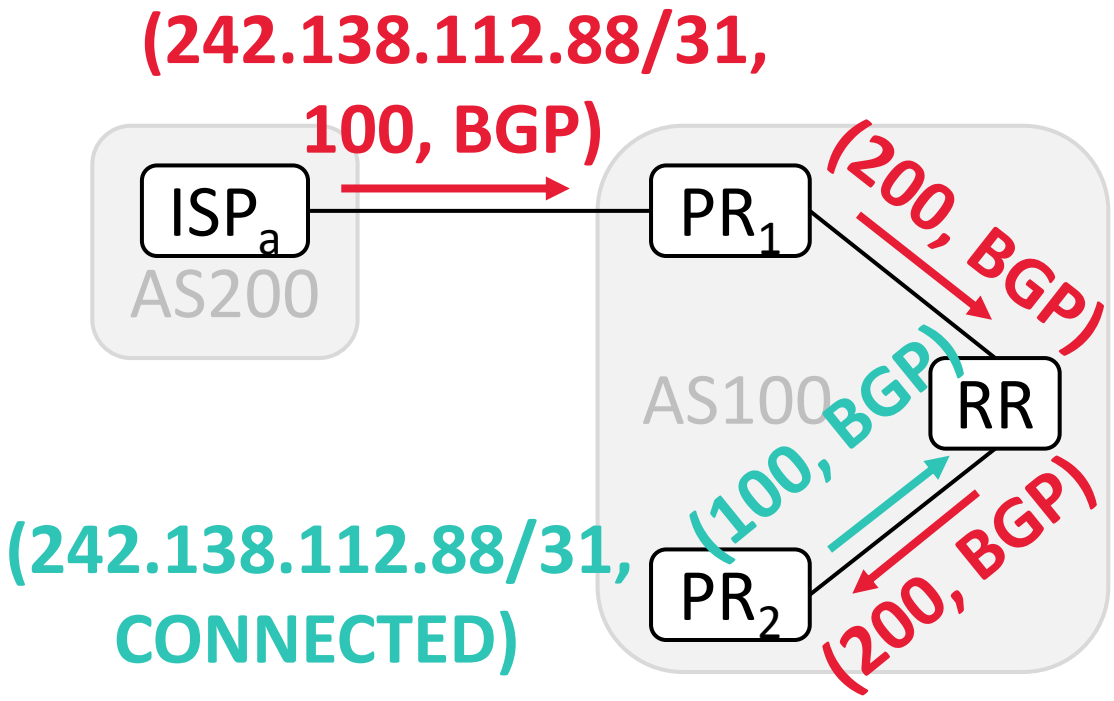
PR: Peering Router, RR: Route Reflector

Case Study (A Route Hijack)



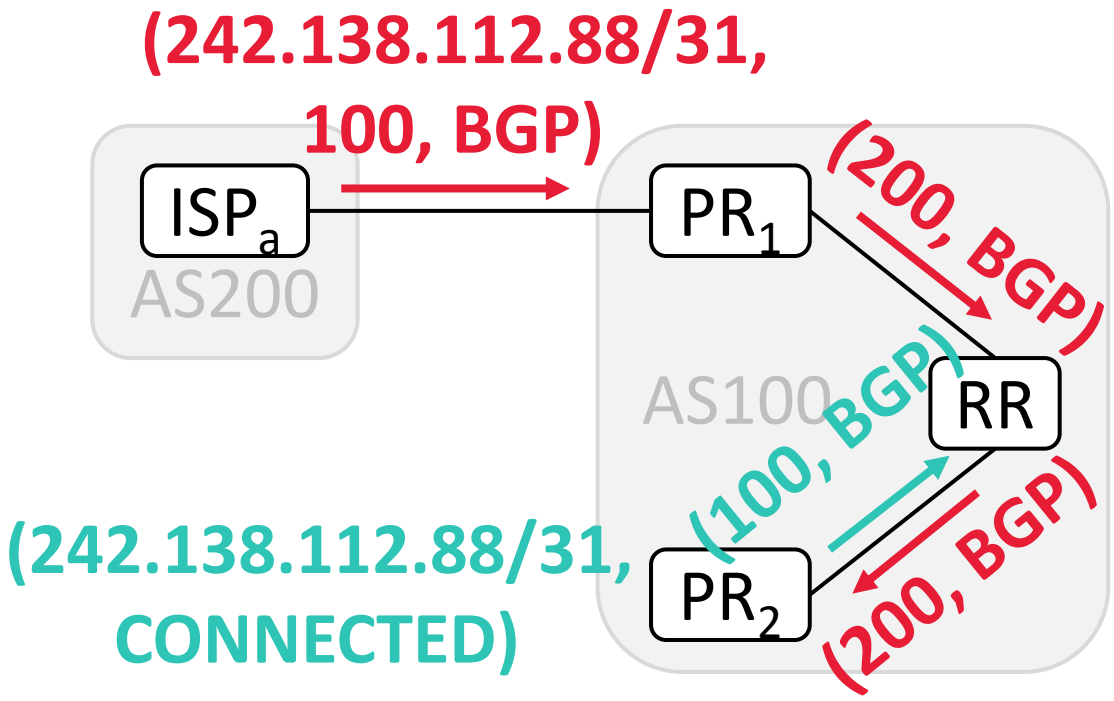
PR: Peering Router, RR: Route Reflector

Case Study (A Route Hijack)



PR: Peering Router, RR: Route Reflector

Case Study (A Route Hijack)

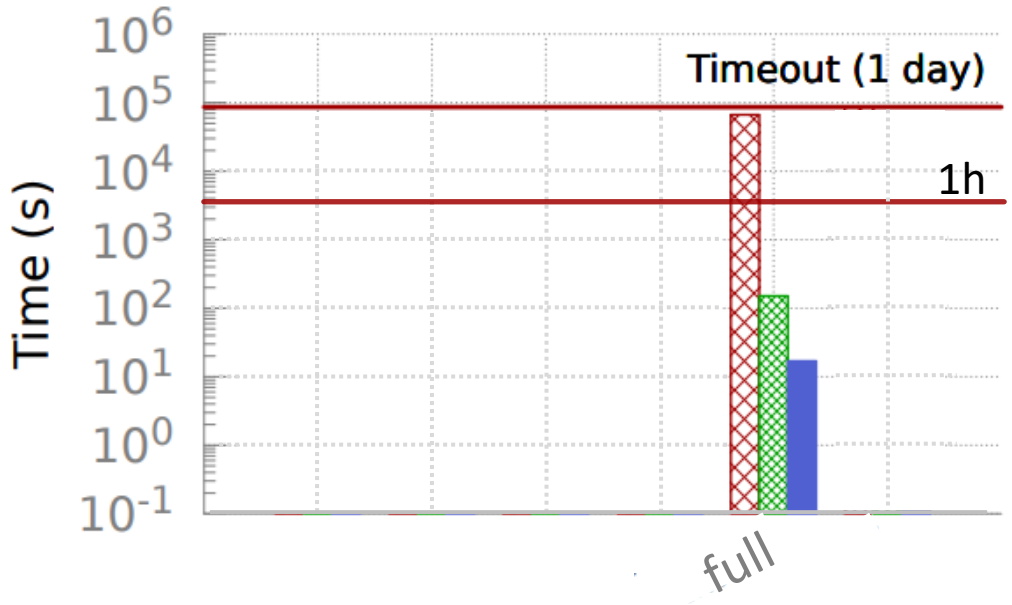


RIB@RR
.....
242.138.112.88/31, 200, PR_1, ISP_a
.....

route hijack

PR: Peering Router, RR: Route Reflector

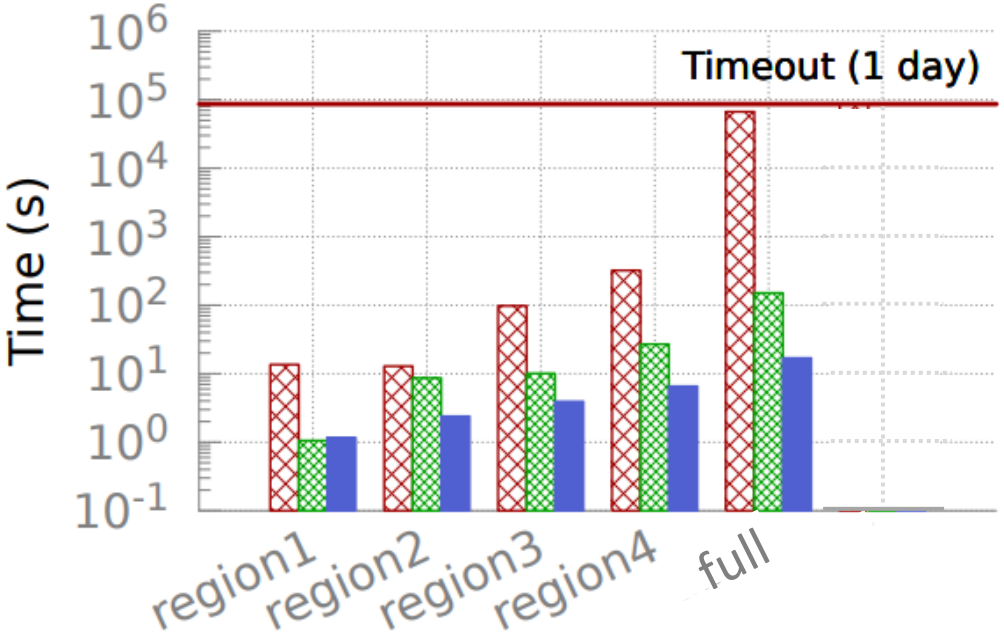
Performance



Minesweeper*
Expresso
Expresso⁻

Minesweeper ≈1 day
Expresso <1h

Performance



Minesweeper*
Expresso
Expresso⁻

Expresso is 1-4 orders of magnitude faster

Summary

- ***External route caused incidents*** are common and costly.
- ***External route environment space is colossal*** and ***existing verifiers*** cannot explore it efficiently.
- Expresso uses ***equivalences*** and ***independencies*** to efficiently explore the space of external routes through ***symbolic simulation***.
- Expresso finds ***real violations*** on a CSP's WAN.

Expresso: Comprehensively Reasoning About External Routes Using Symbolic Simulation

Dan Wang

Peng Zhang

Aaron Gember-Jacobson

Xi'an Jiaotong University

Colgate University

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[12] Weitz, Konstantin, et al. "Scalable verification of border gateway protocol configurations with an SMT solver." *Proceedings of the 2016 acm sigplan international conference on object-oriented programming, systems, languages, and applications*. 2016.

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