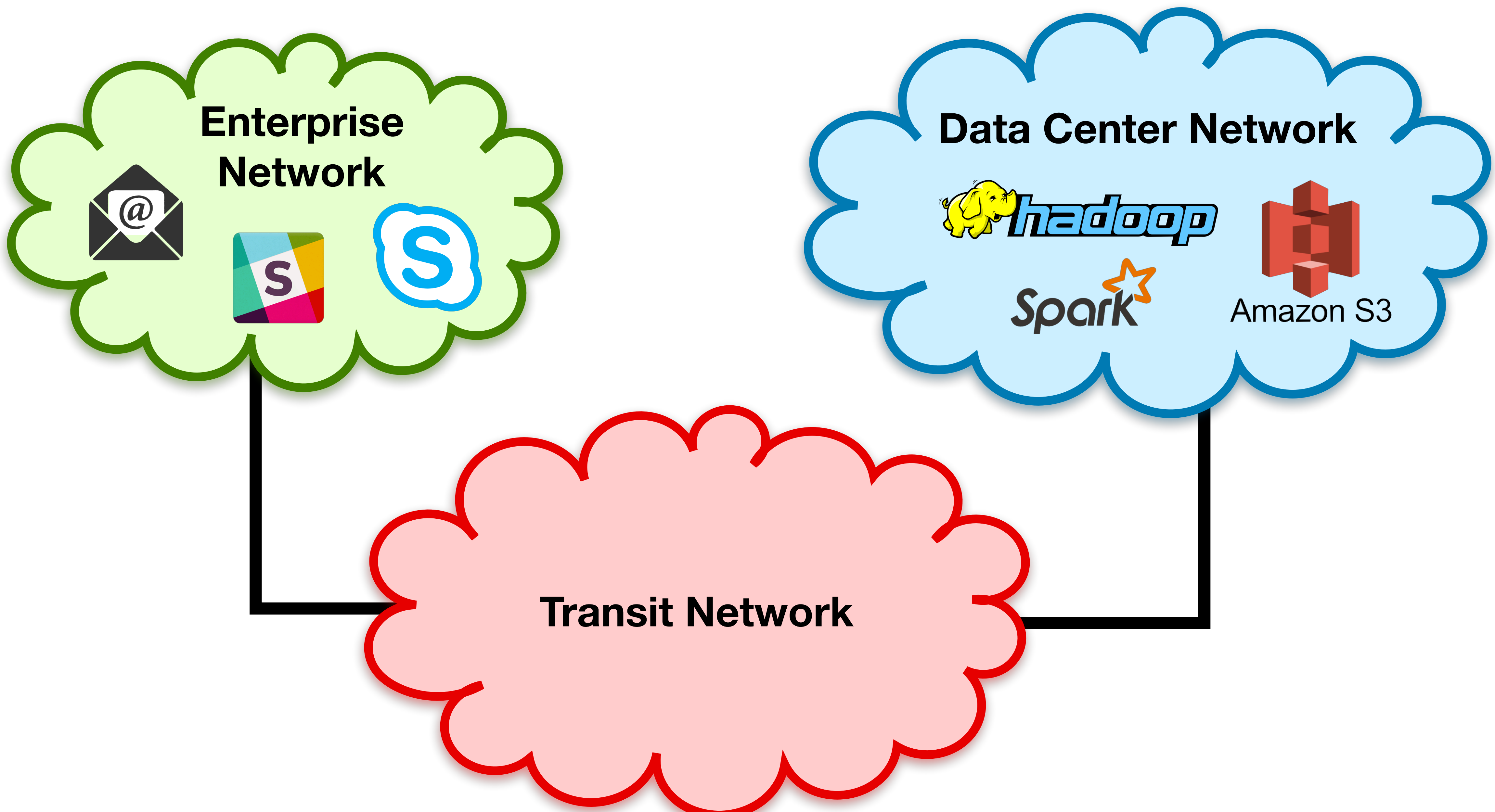
Stateful Programming of High-Speed Network Hardware

Mina Tahmasbi Arashloo

Final Public Oral Presentation

Advisor: Jennifer Rexford
Readers: David Walker, Arvind Krishnamurthy
Examiners: Nick Feamster, Michael Freedman

Networks of Unprecedented Diversity and Scale



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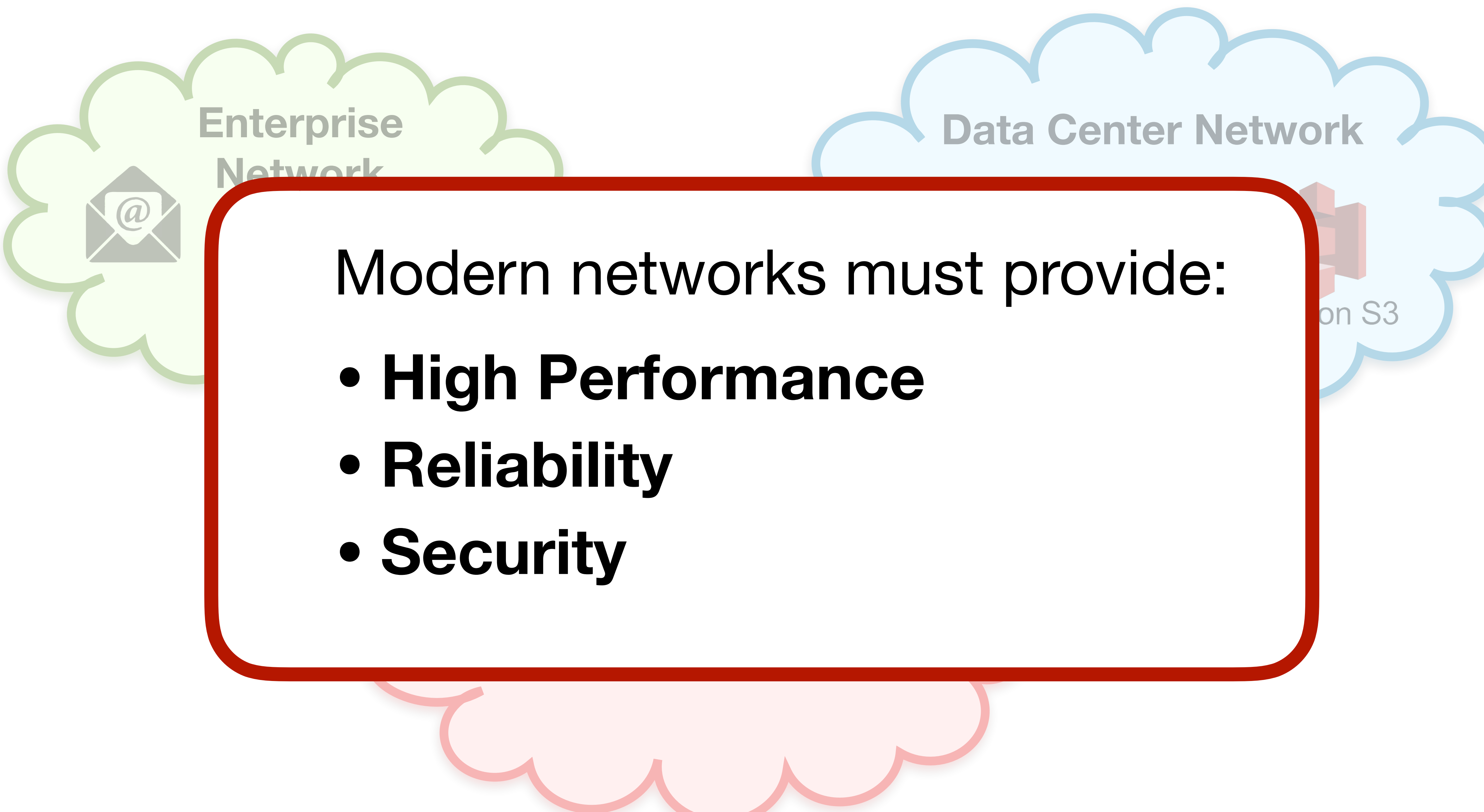
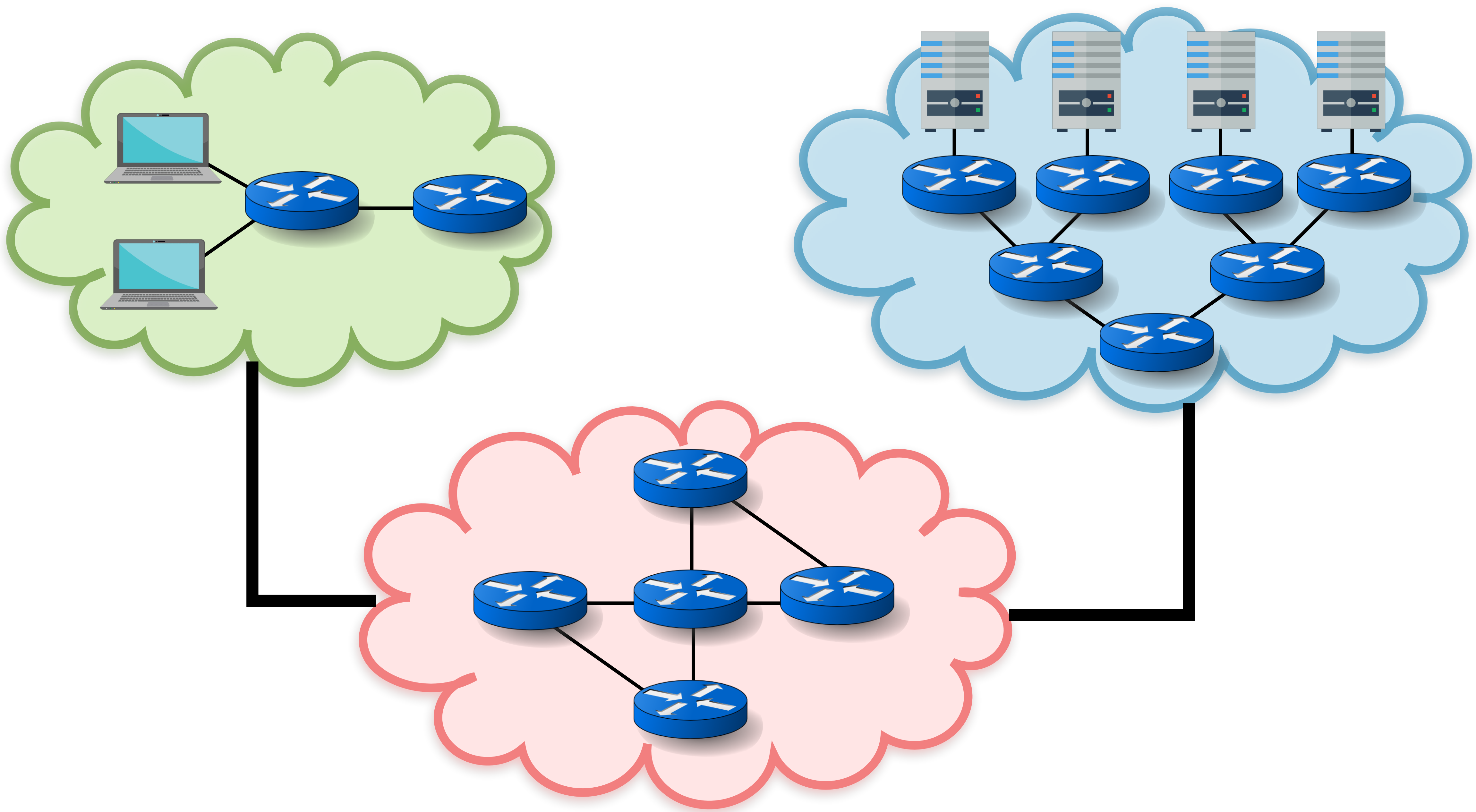


Modern networks must provide:

- **High Performance**
- **Reliability**
- **Security**

The Evolution of Network Hardware



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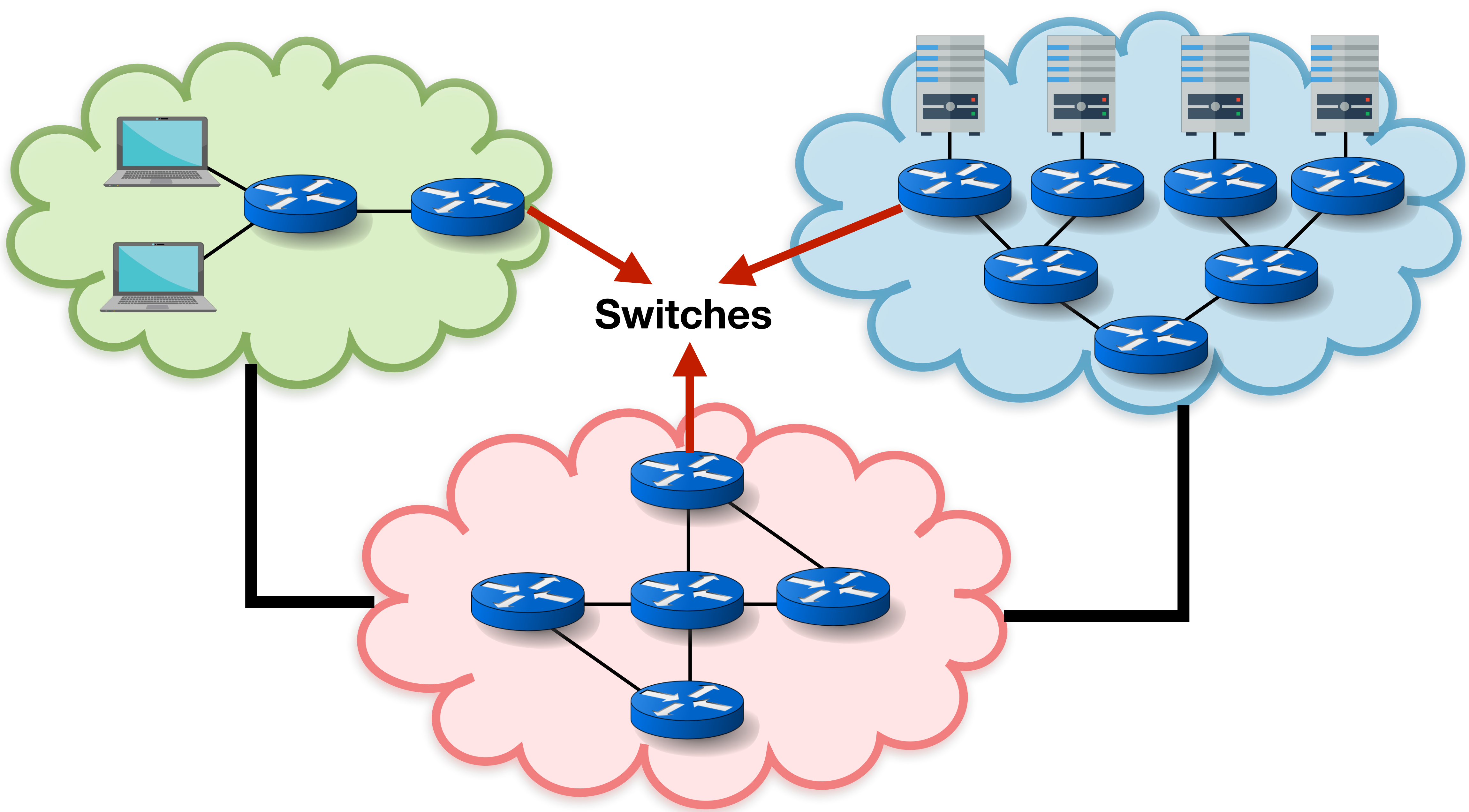

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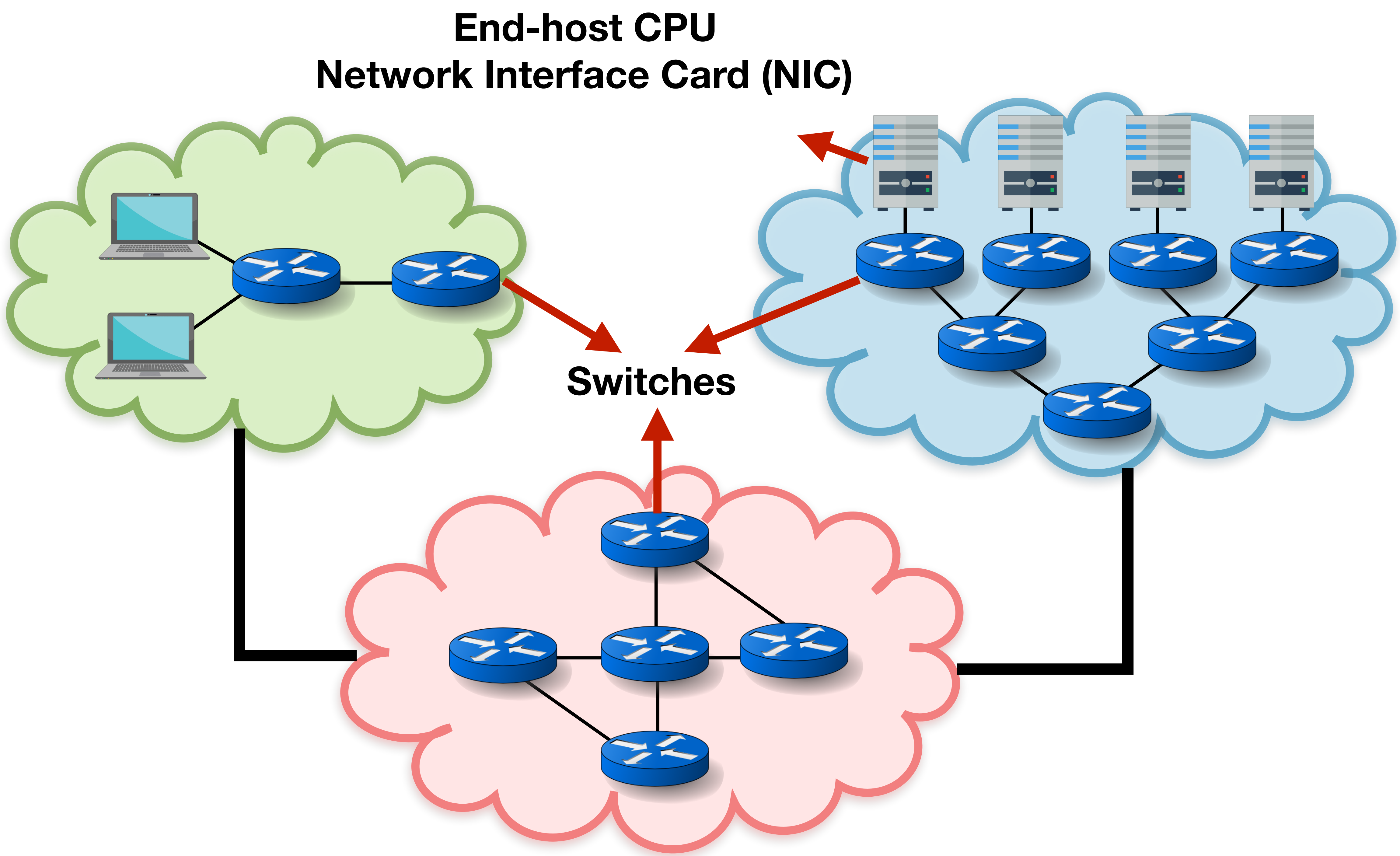
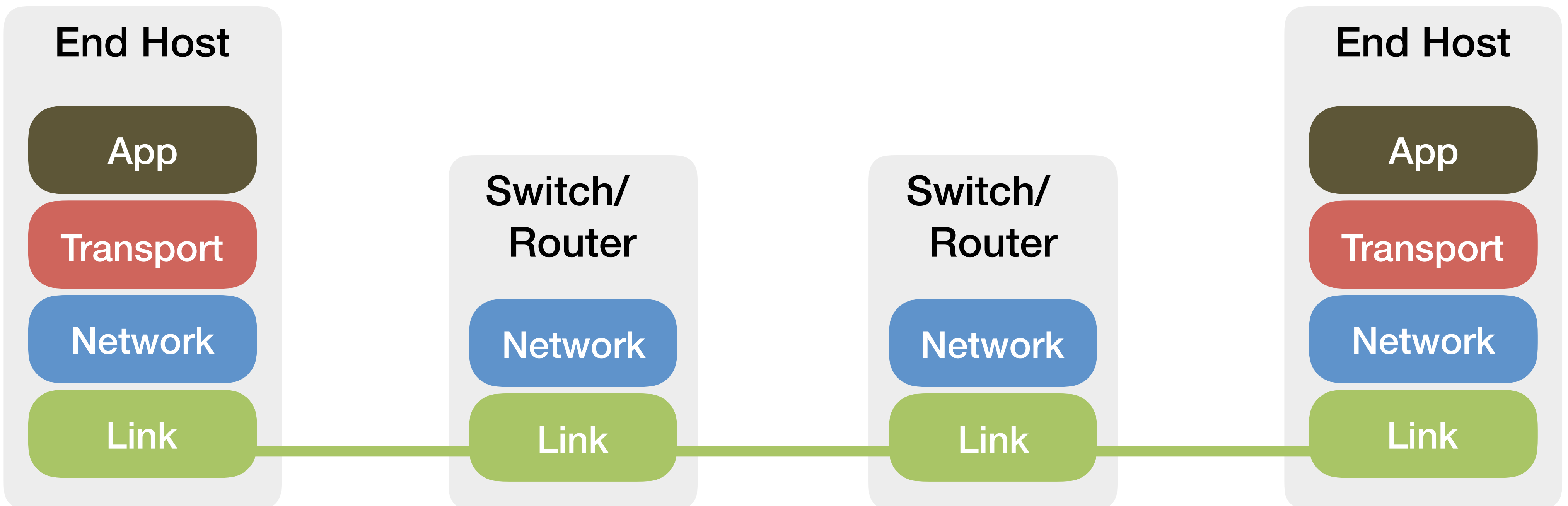


Early Networks: Stateful Edge, Stateless Core



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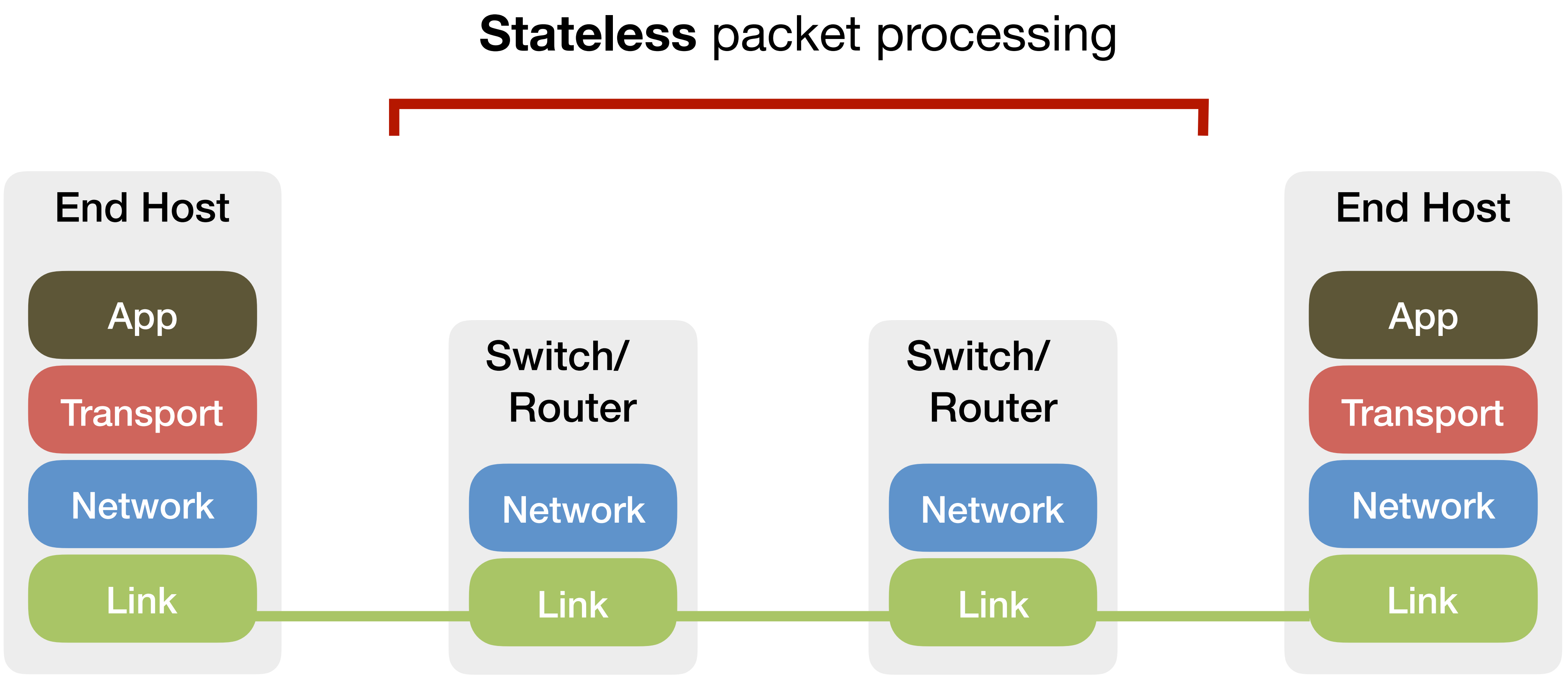

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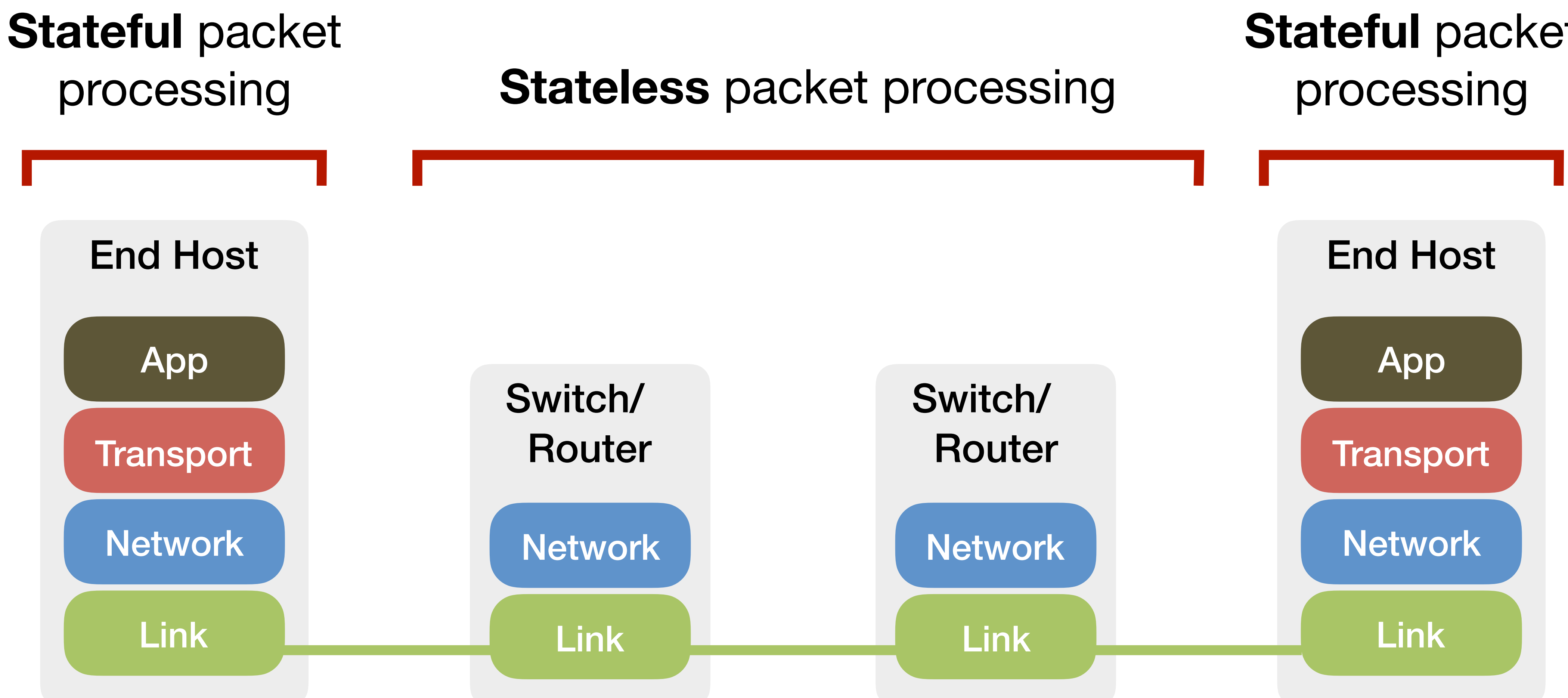

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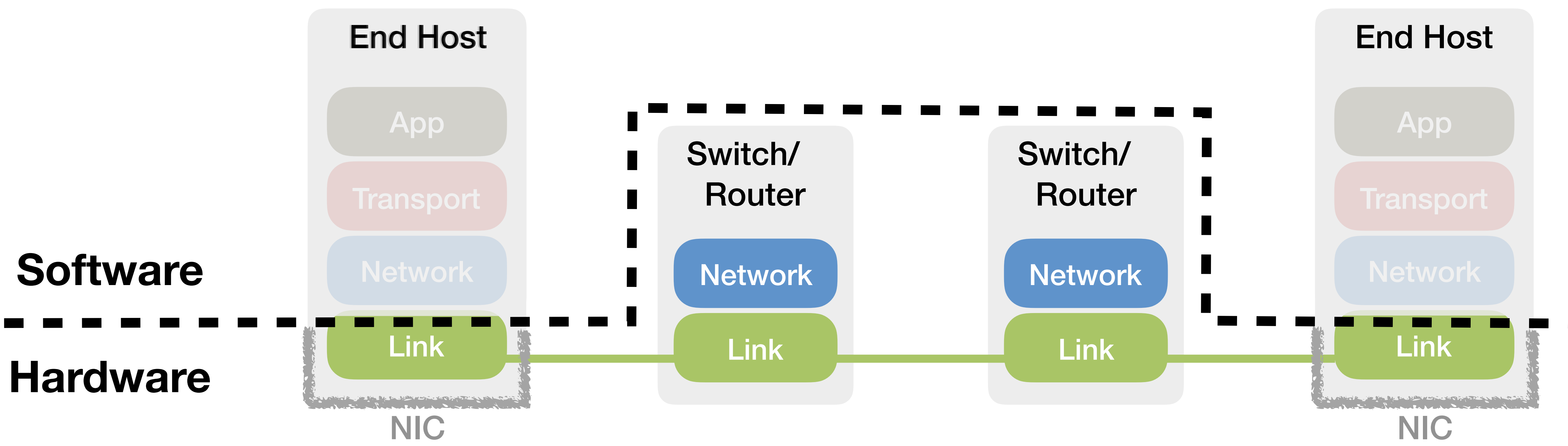

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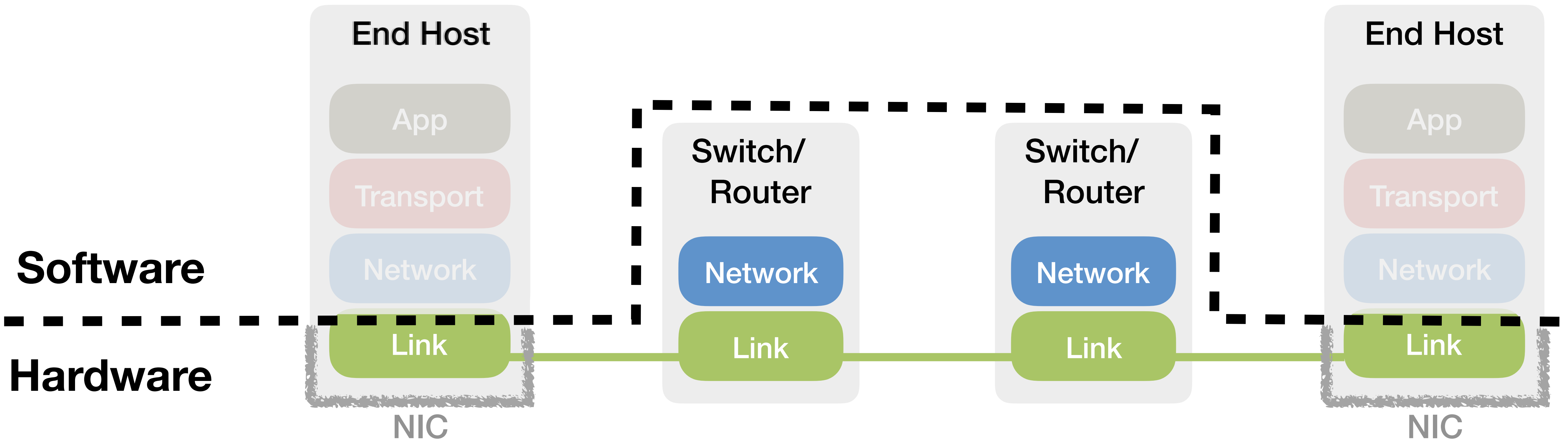
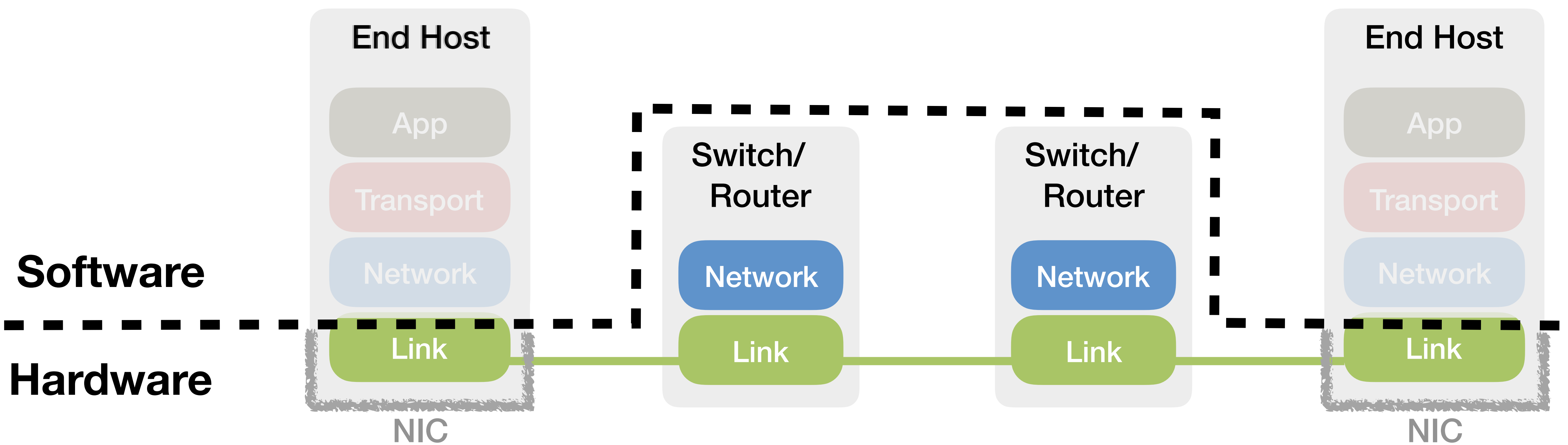


Network Hardware

High-Speed

The Need for Stateful Processing in Hardware



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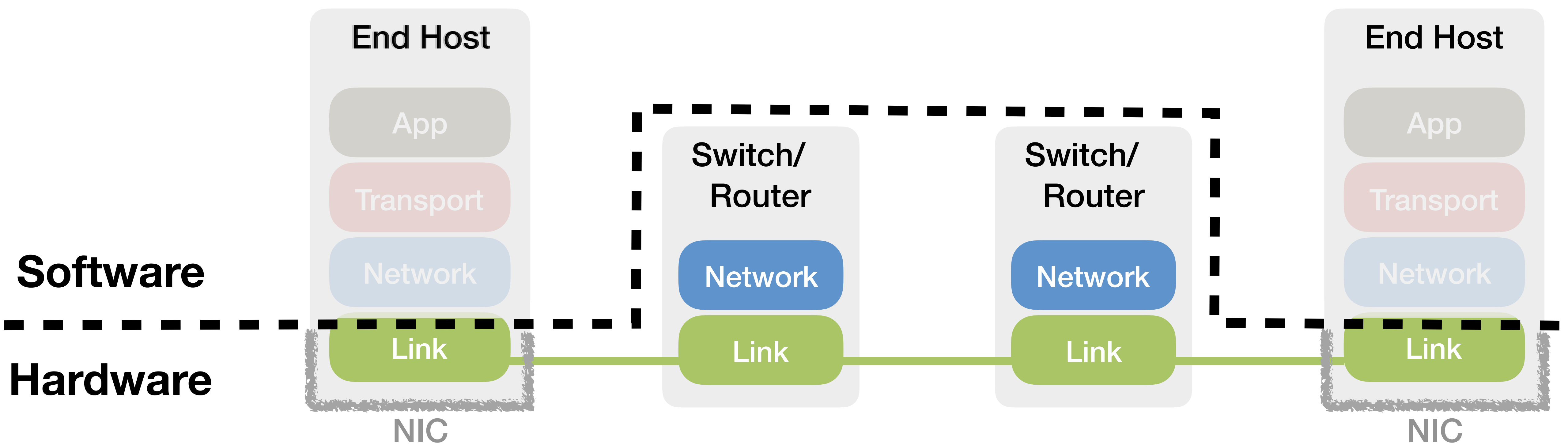
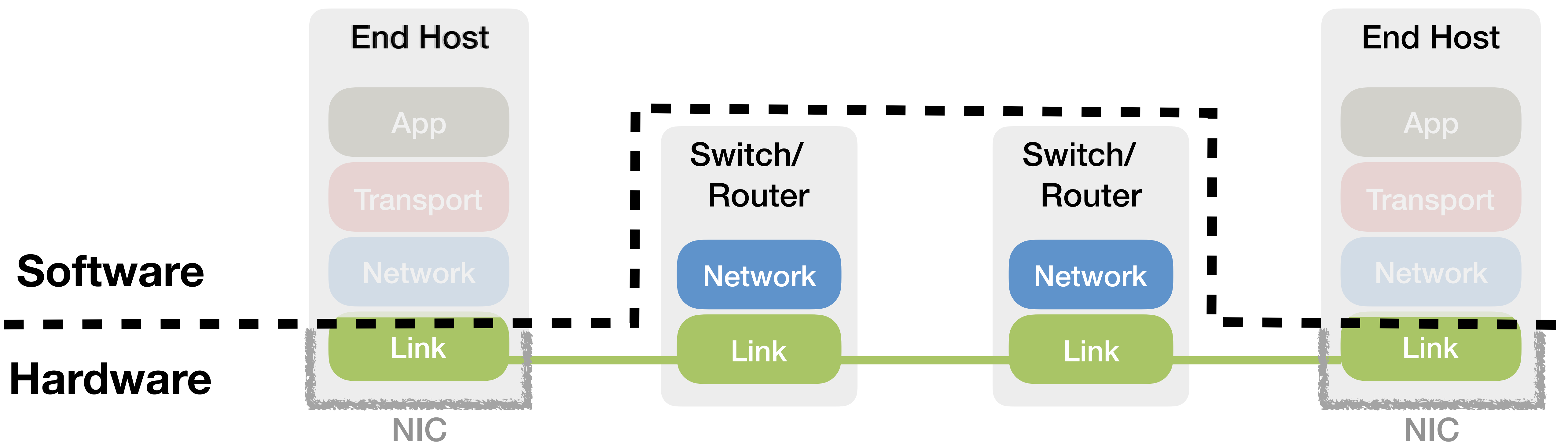


Network Hardware {
High-Speed
Stateful Packet Processing??

Trend #1: In-Network Stateful Processing



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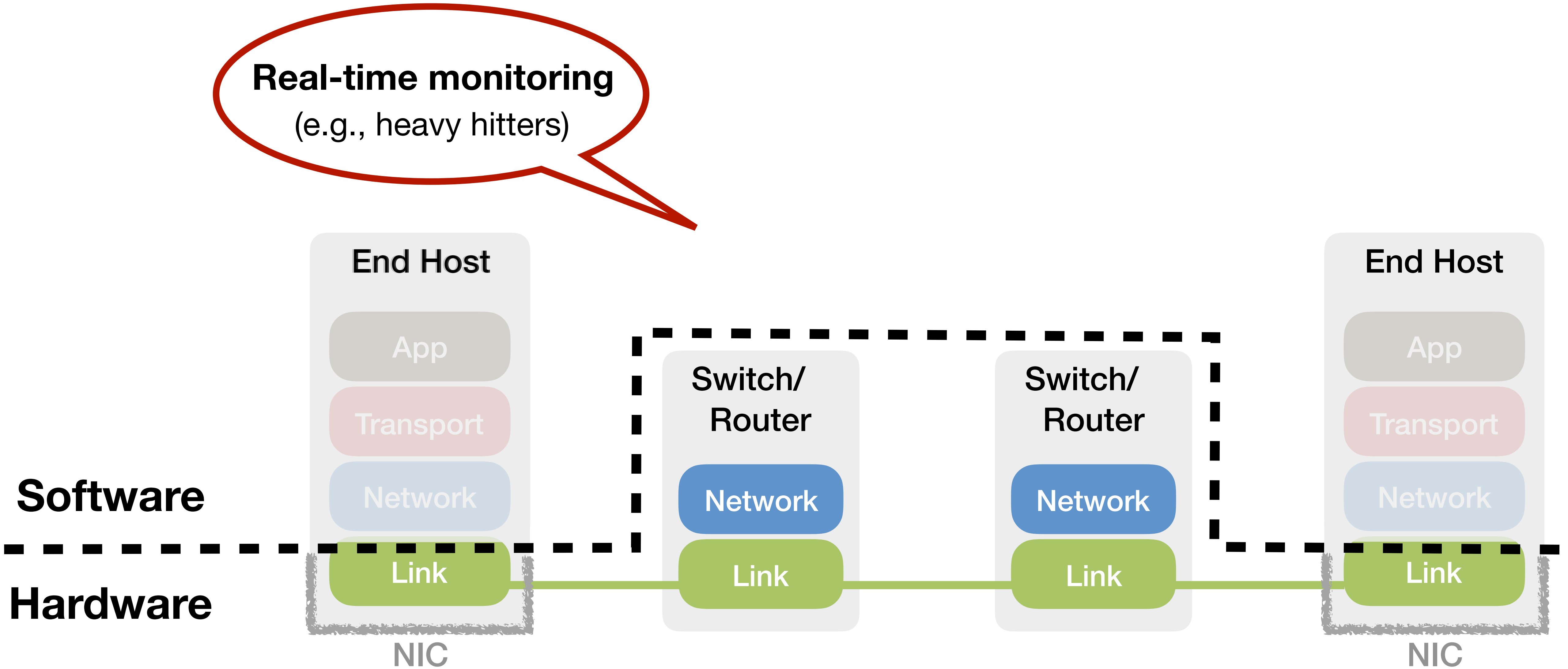

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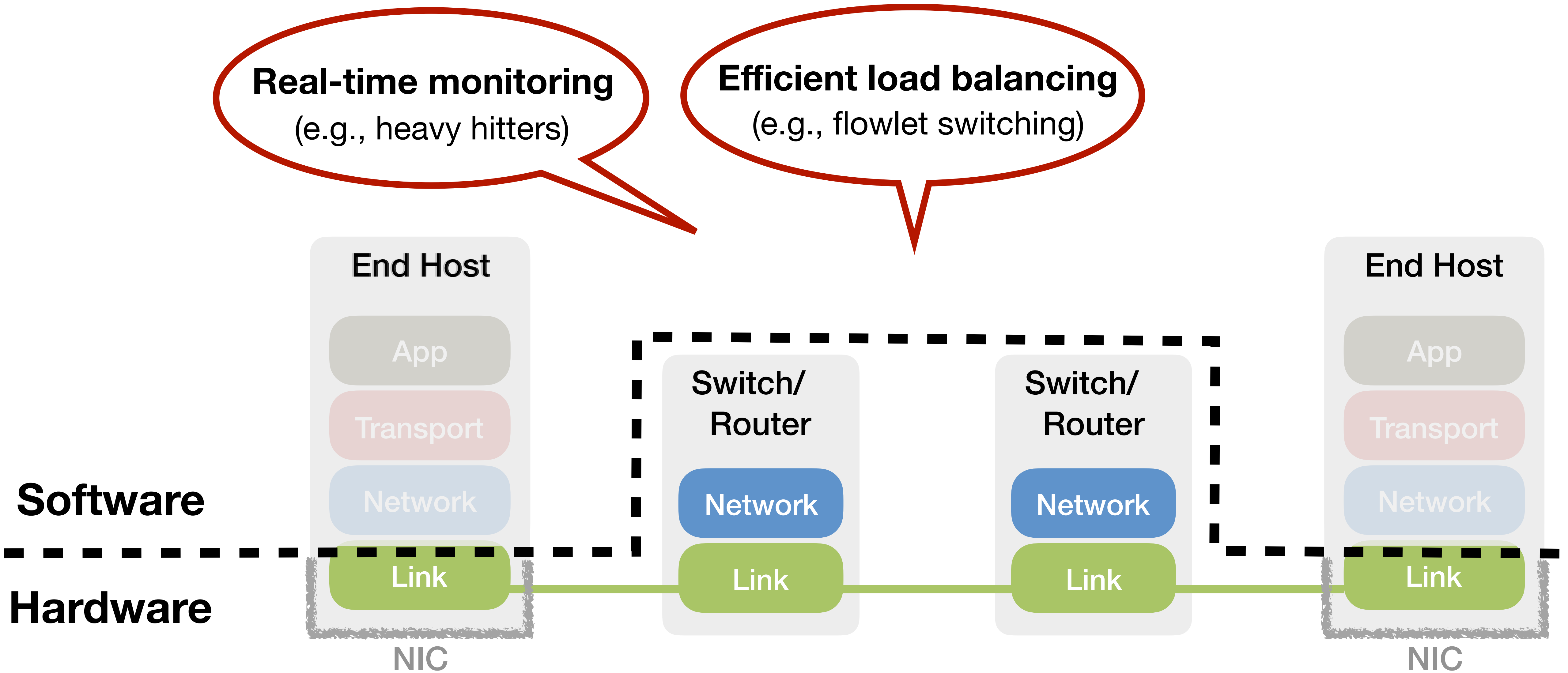

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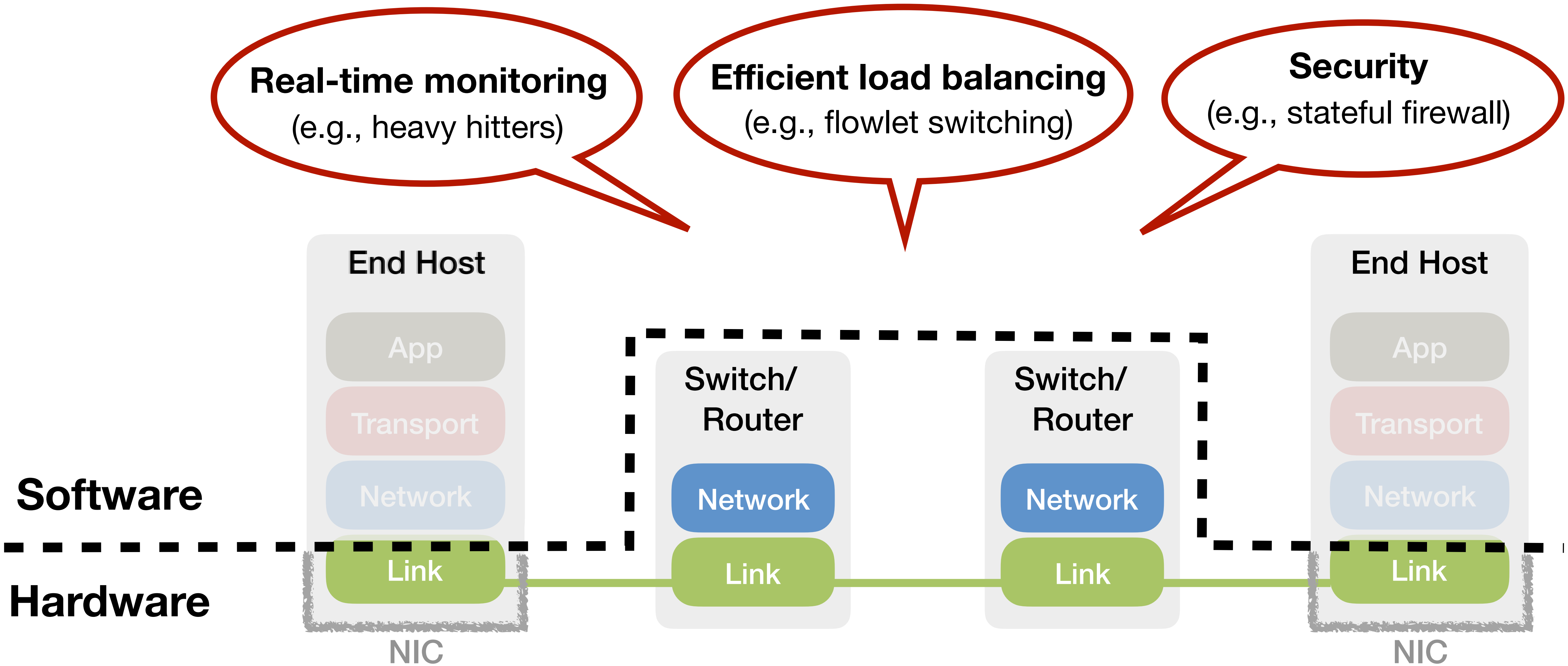

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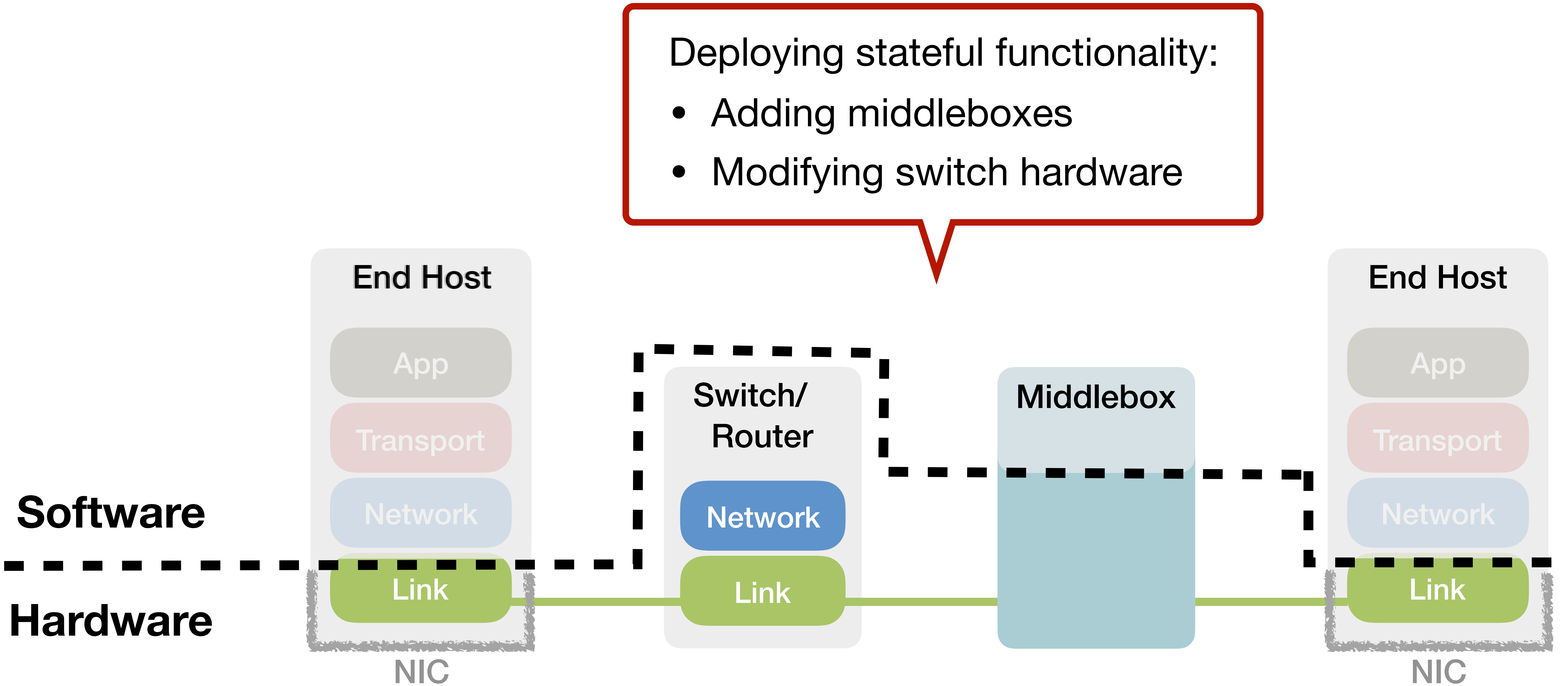
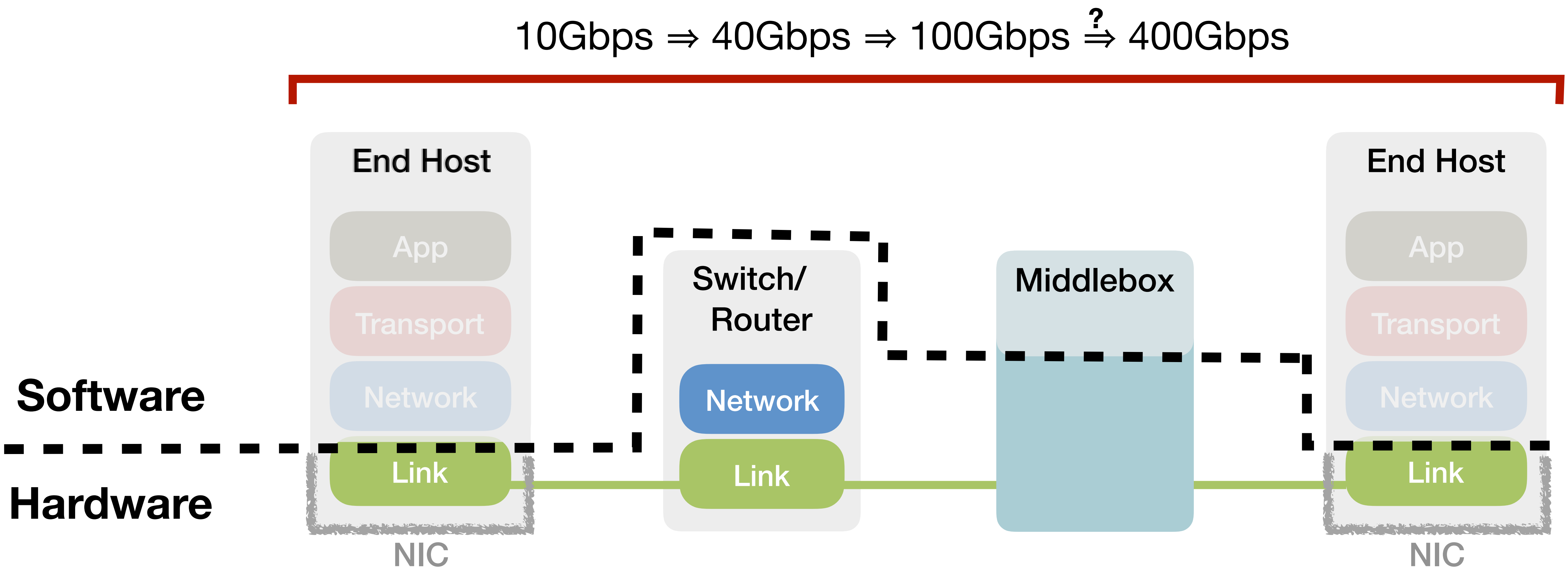


Trend #2: Increasing Link Speeds



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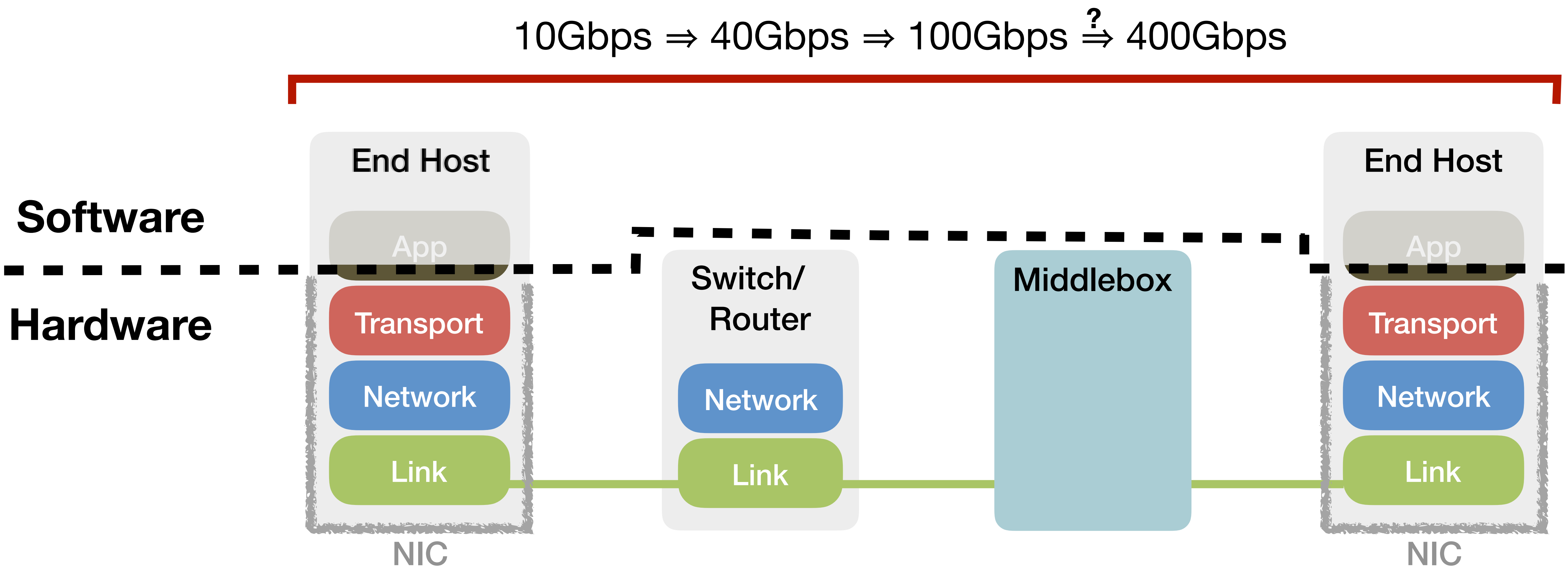

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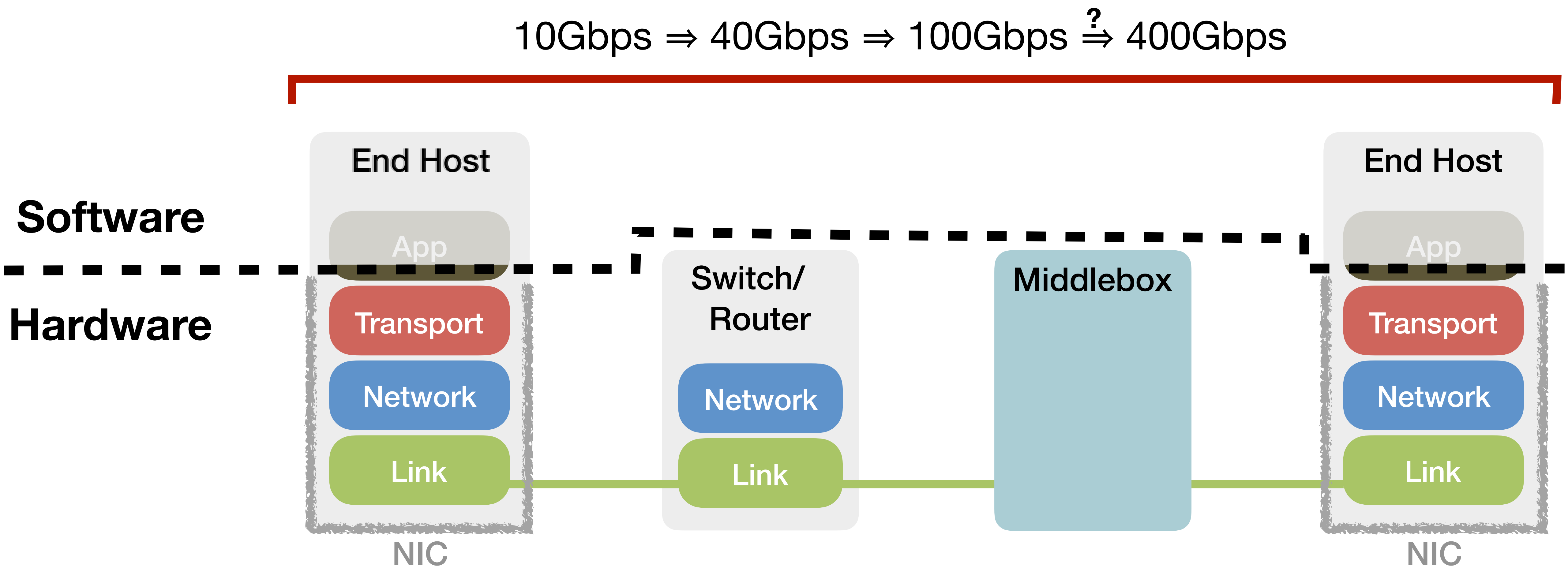
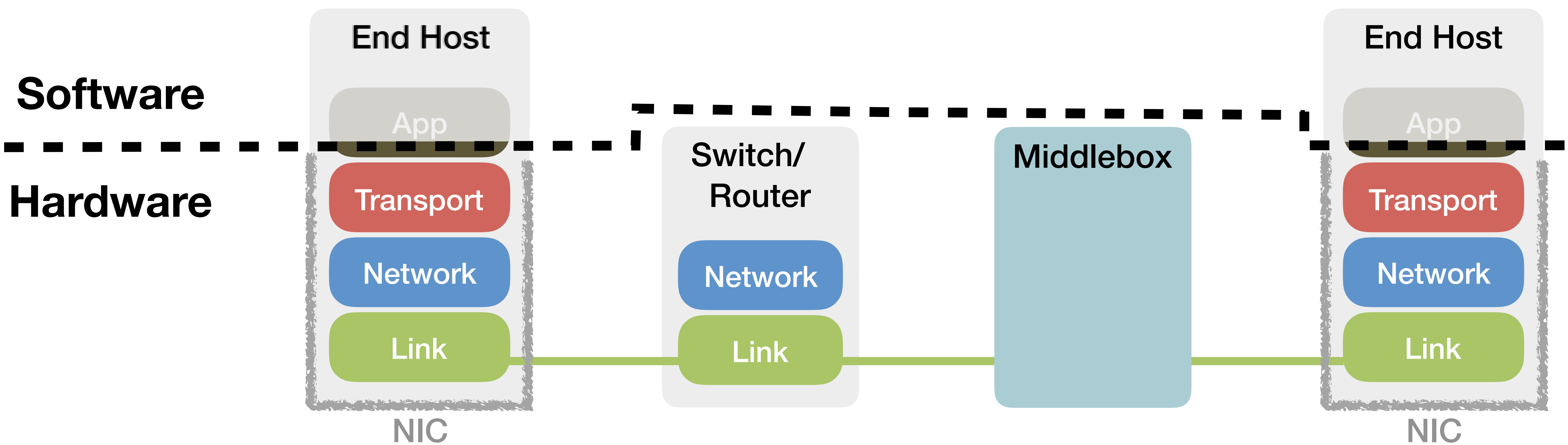


Network Hardware
- High-Speed
- Stateful Packet Processing

What about Flexibility?



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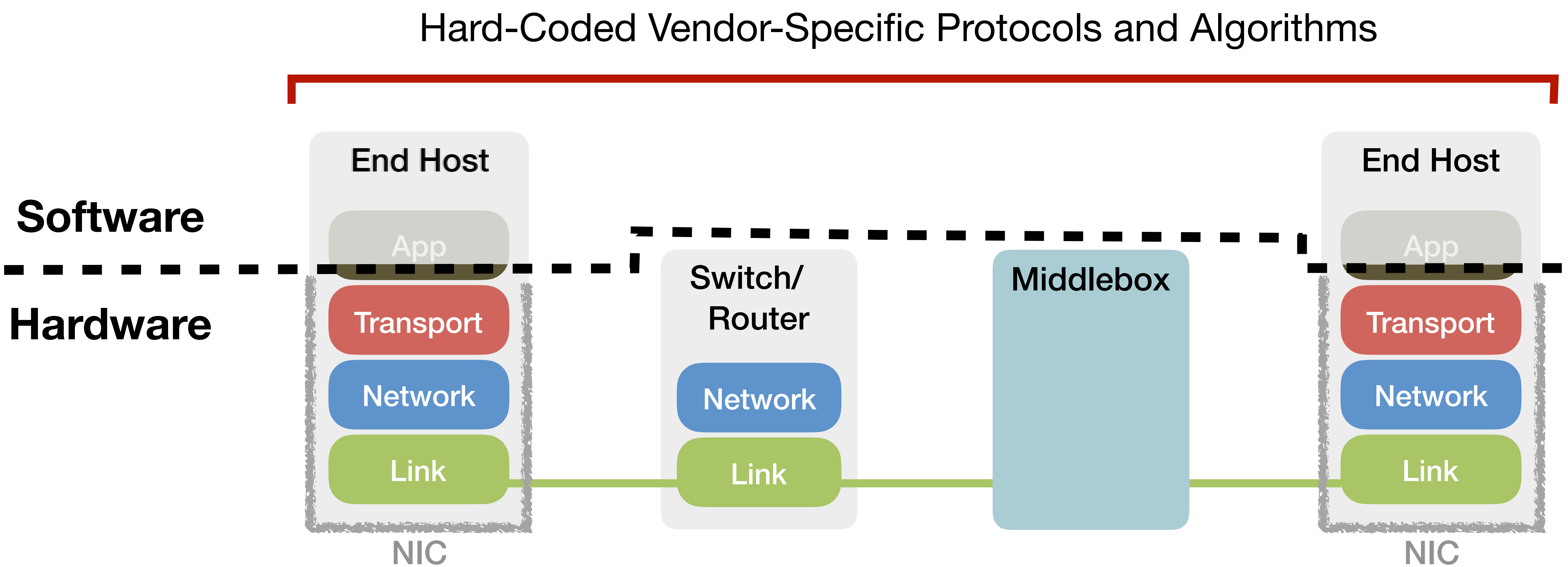
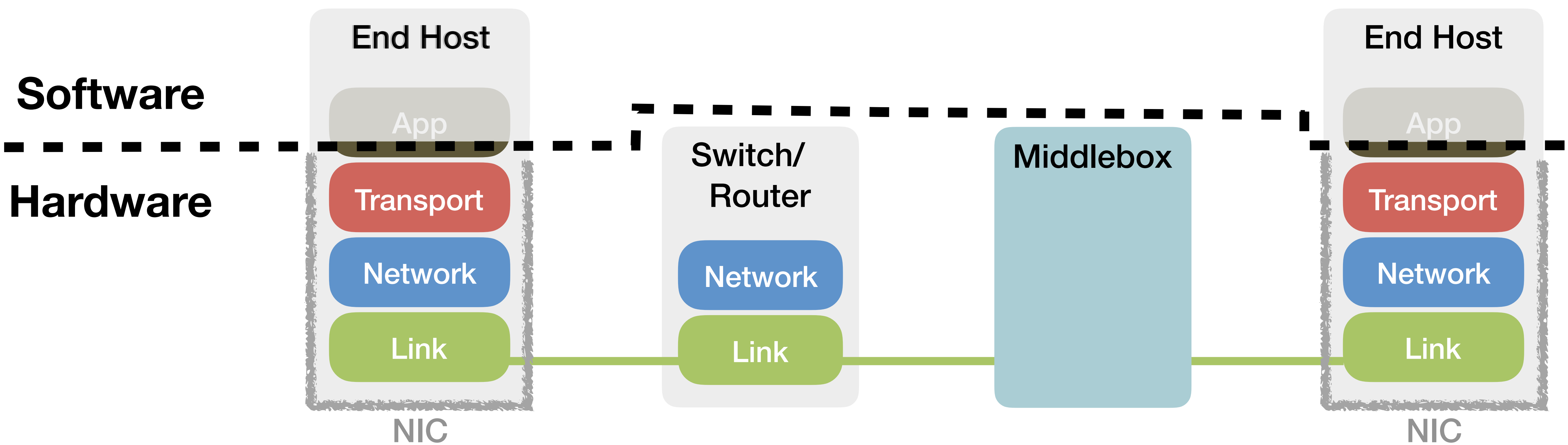


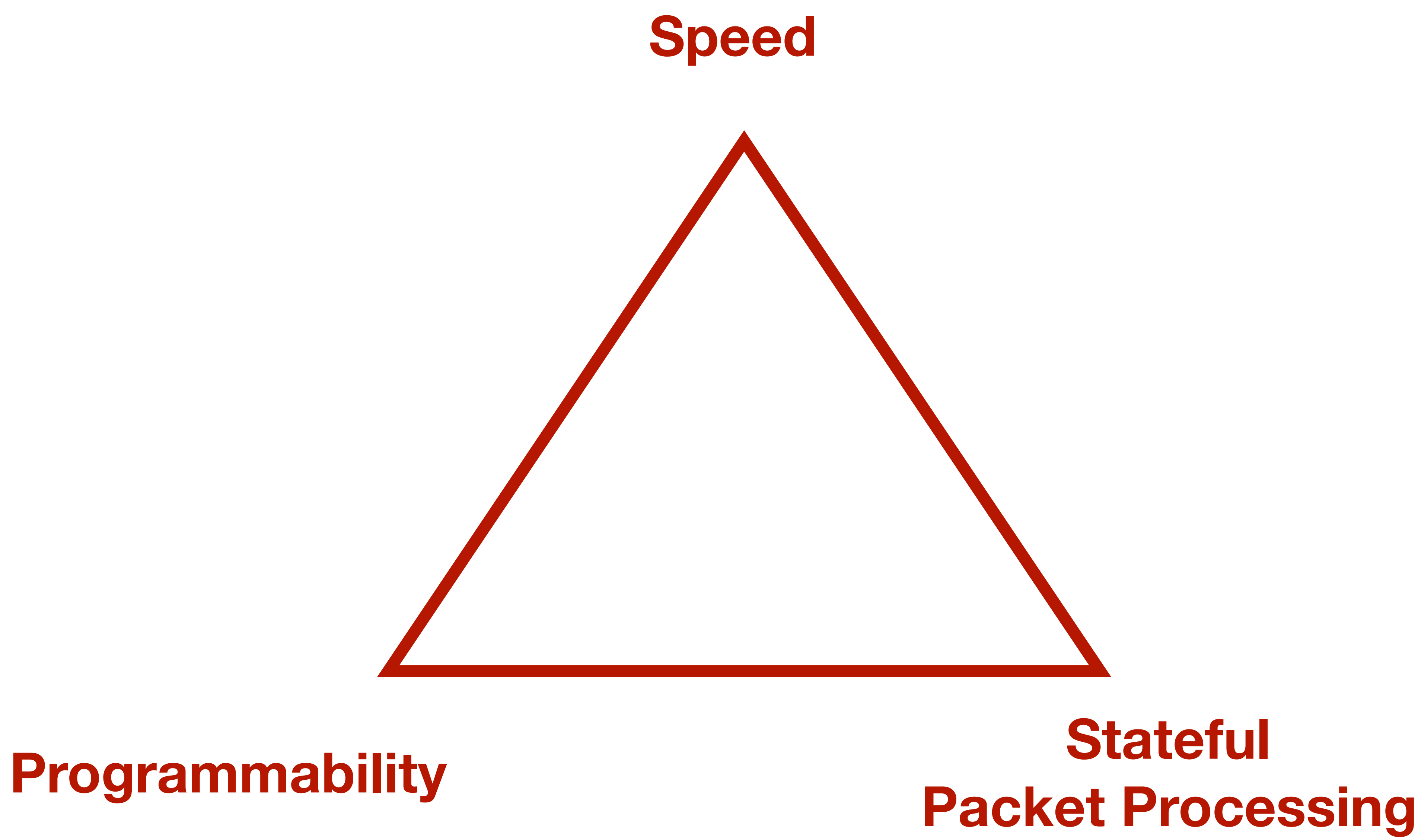
Requirements of Today's Network Hardware



Network Hardware

- High-Speed
- Stateful Packet Processing
- Programmable

Network Hardware Design Space



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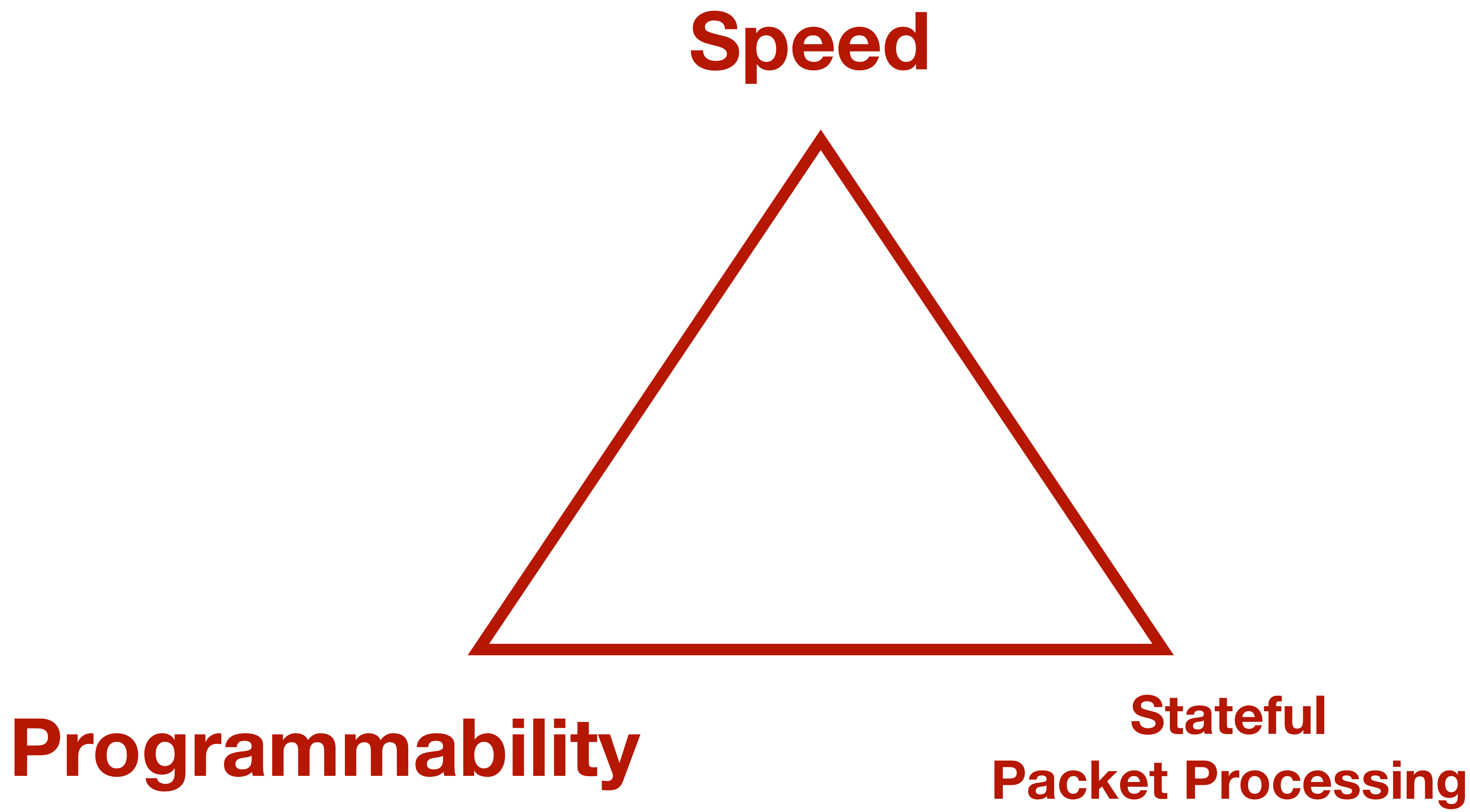

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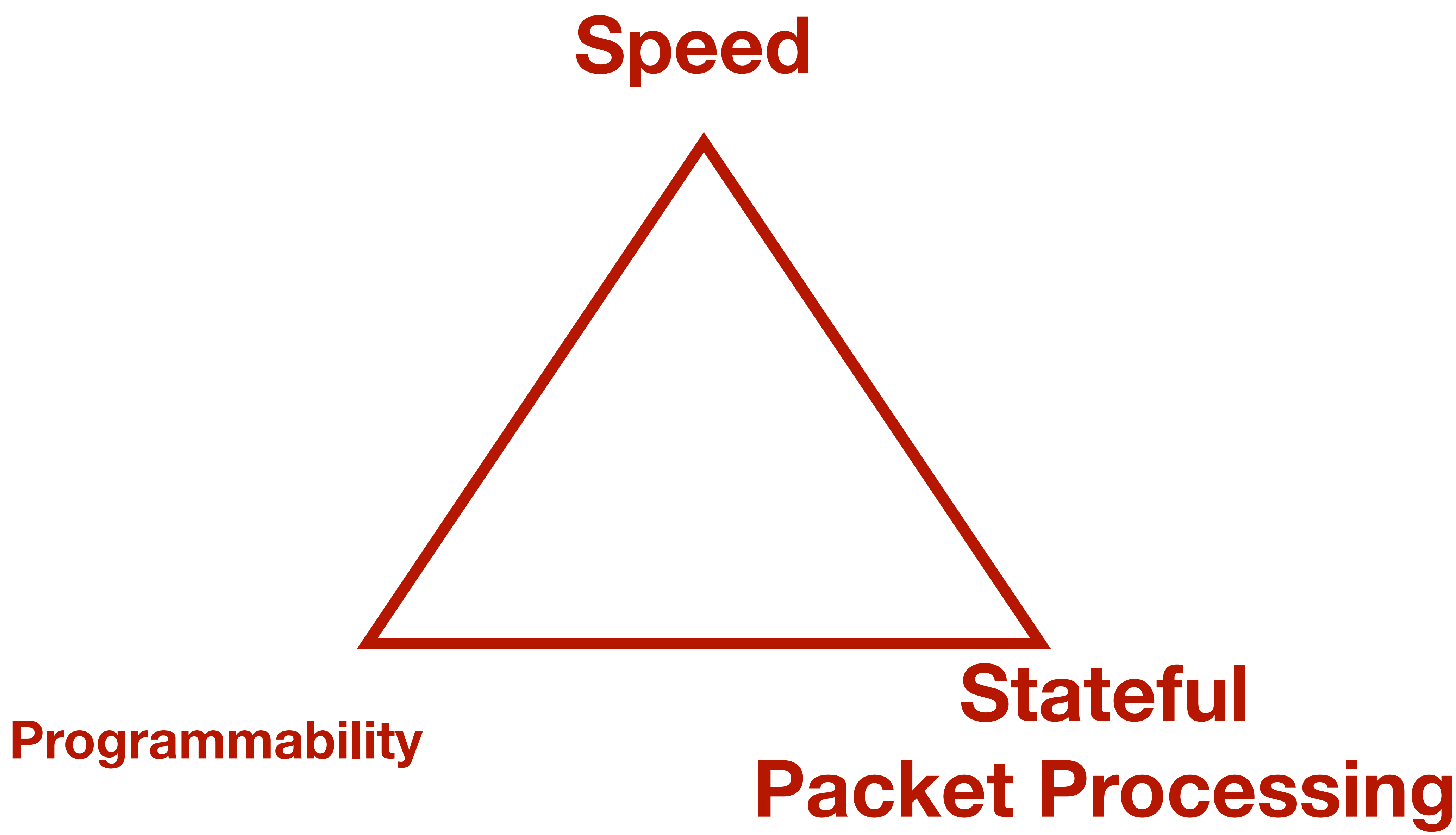

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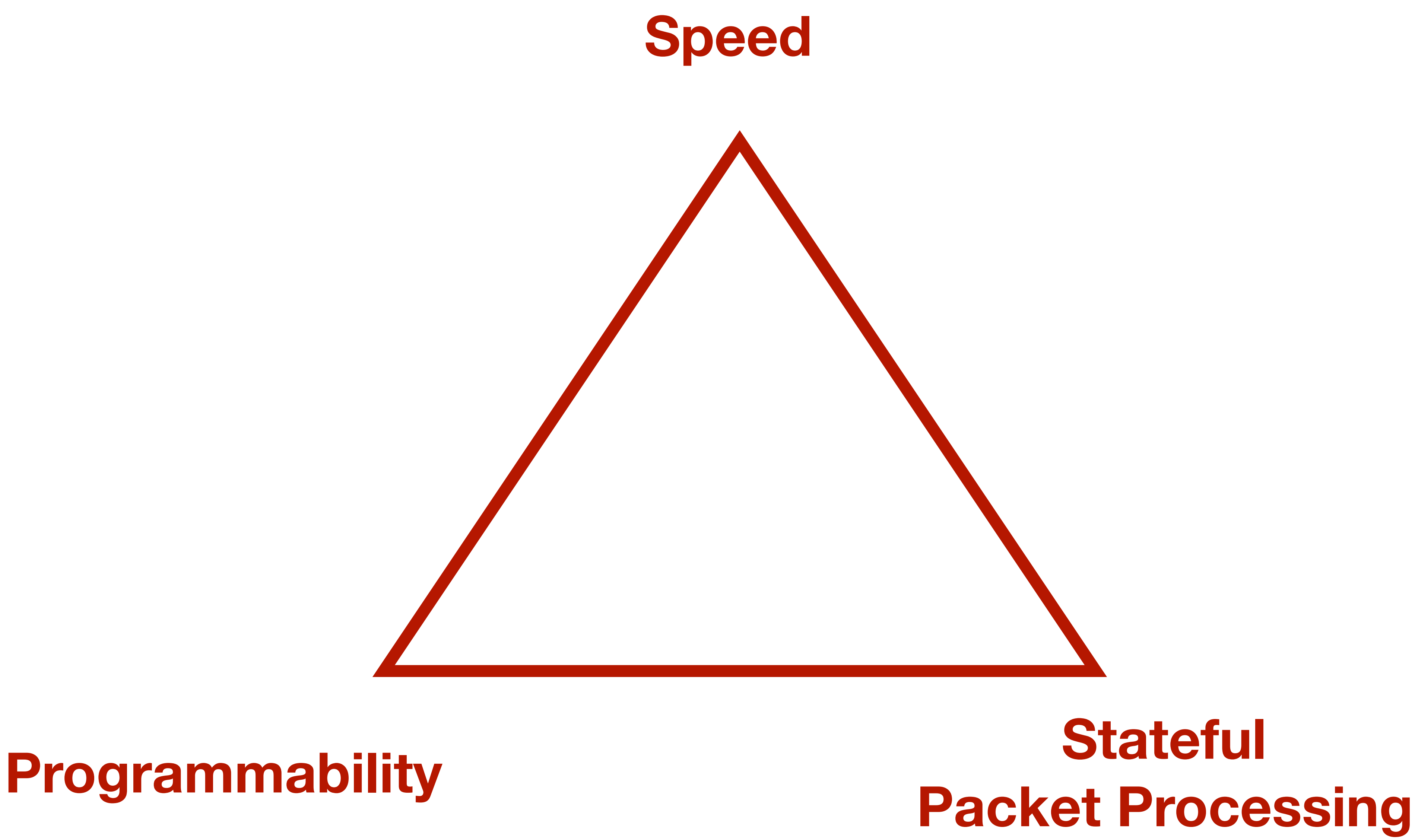

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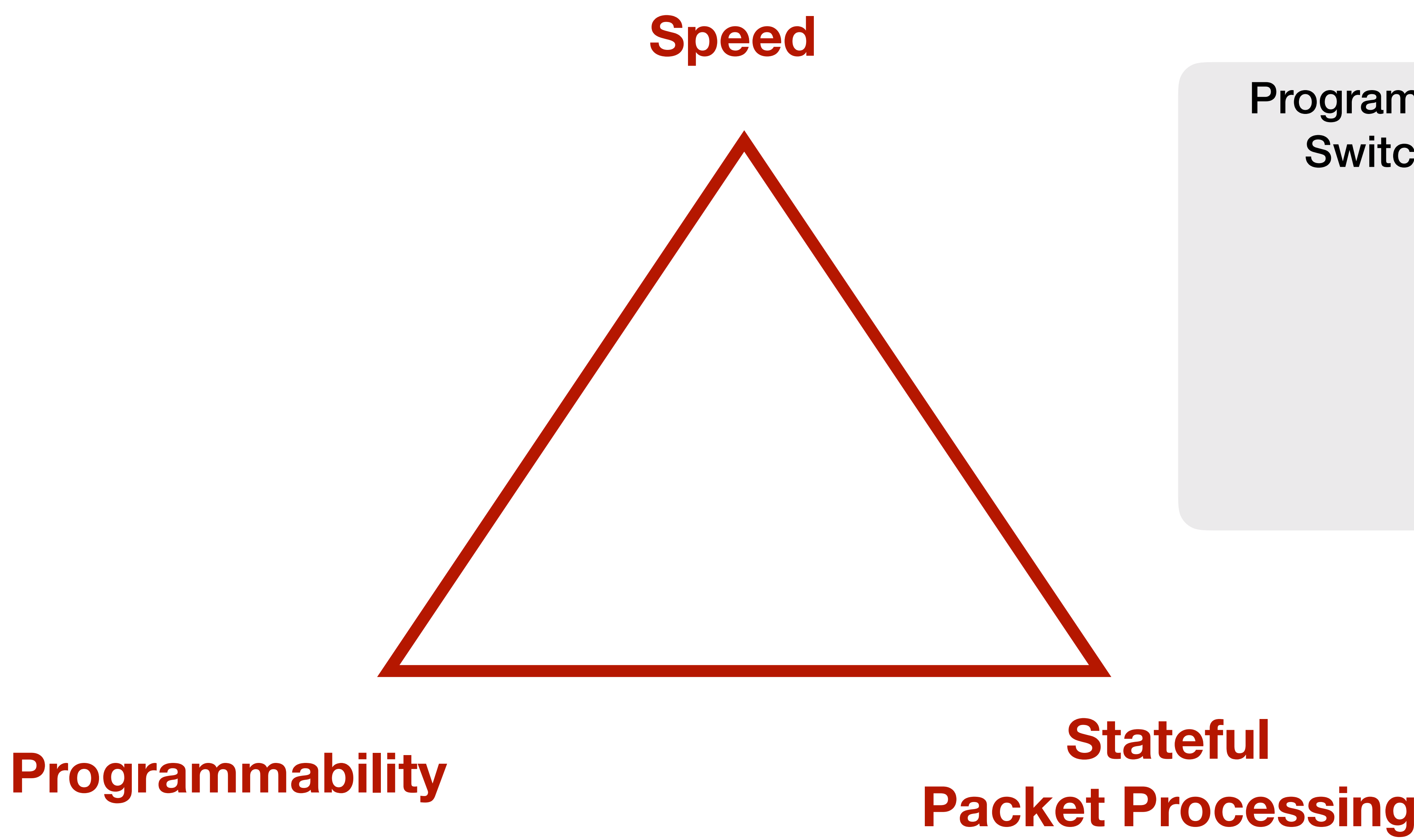
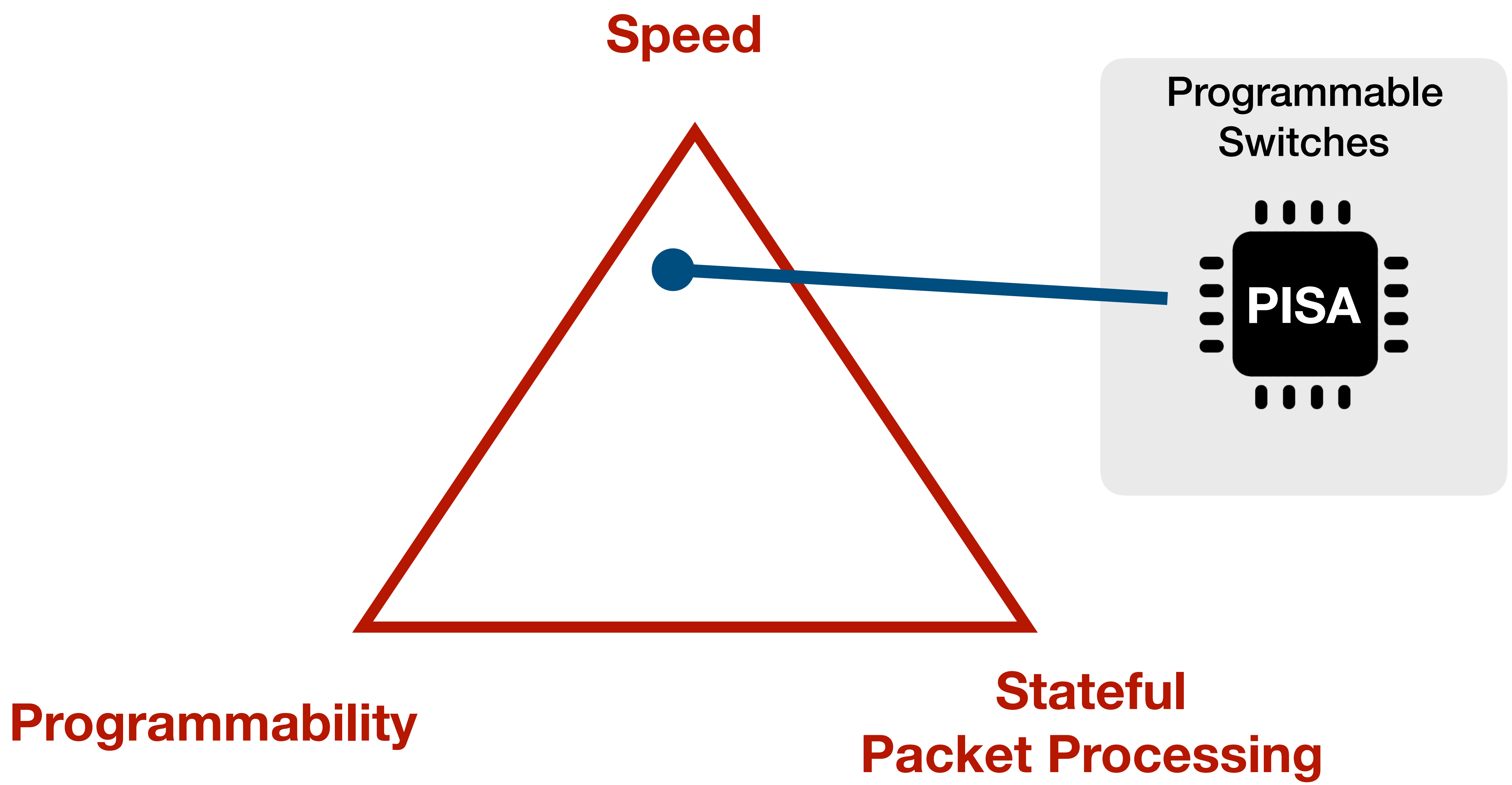


Programmable
Switches

Network Hardware Design Space



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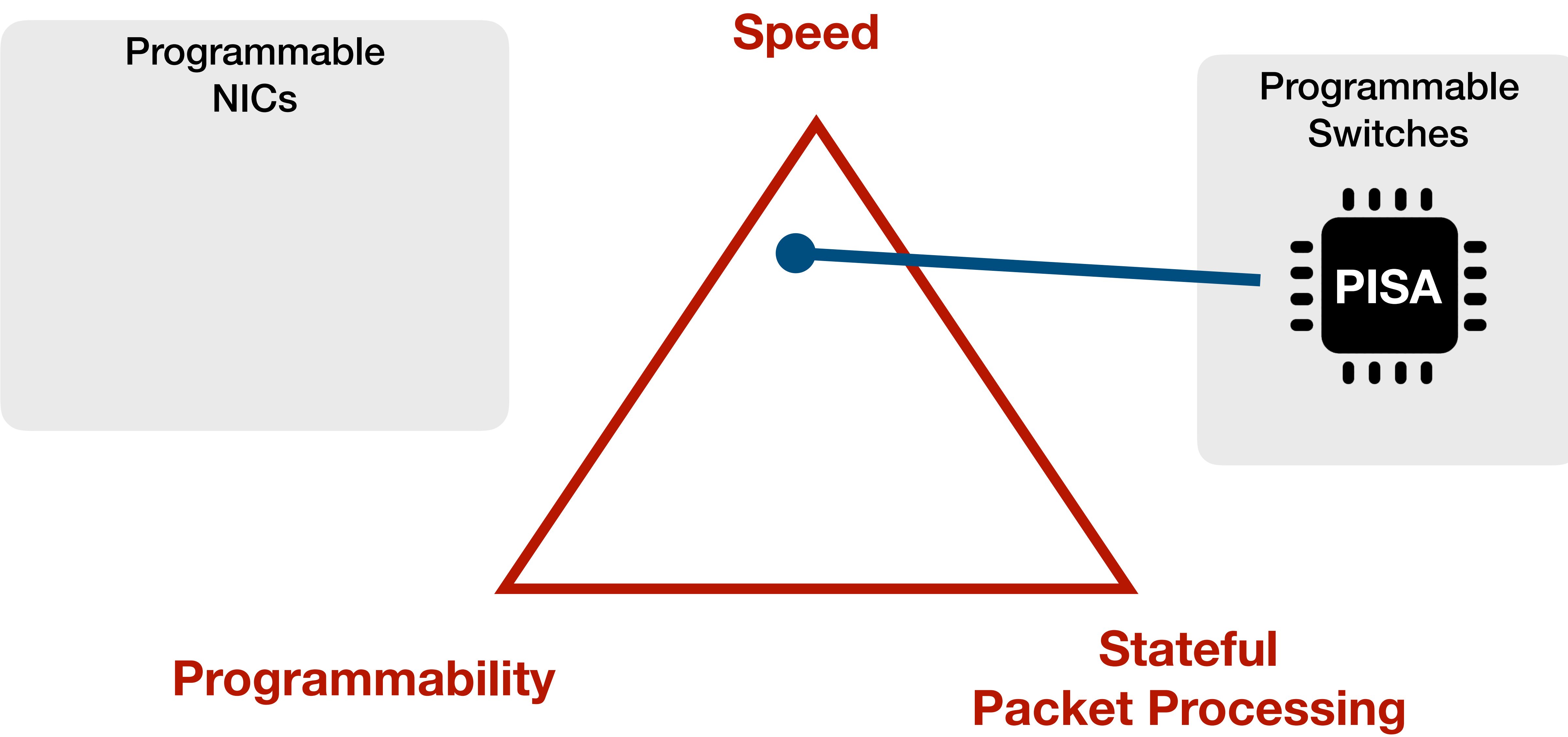

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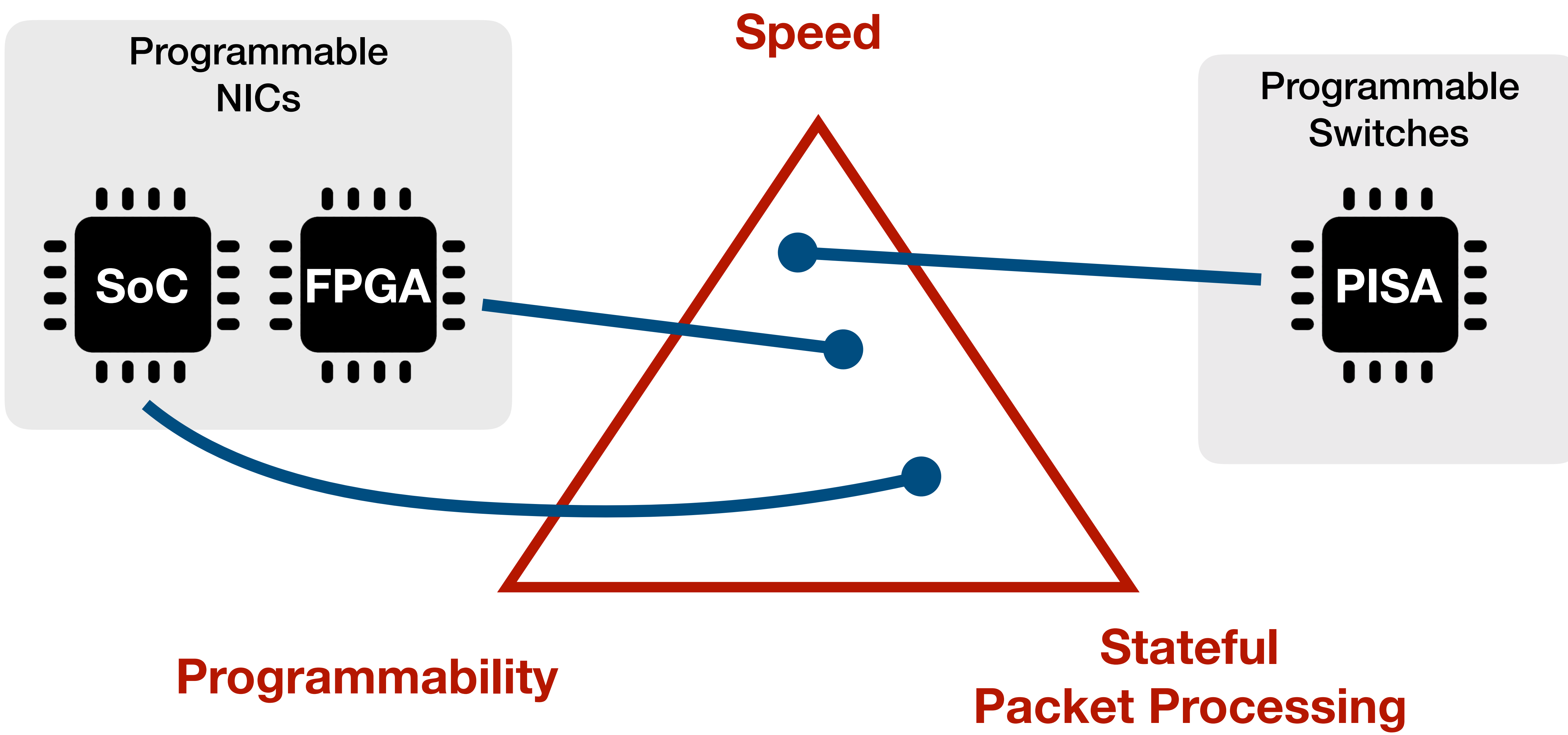

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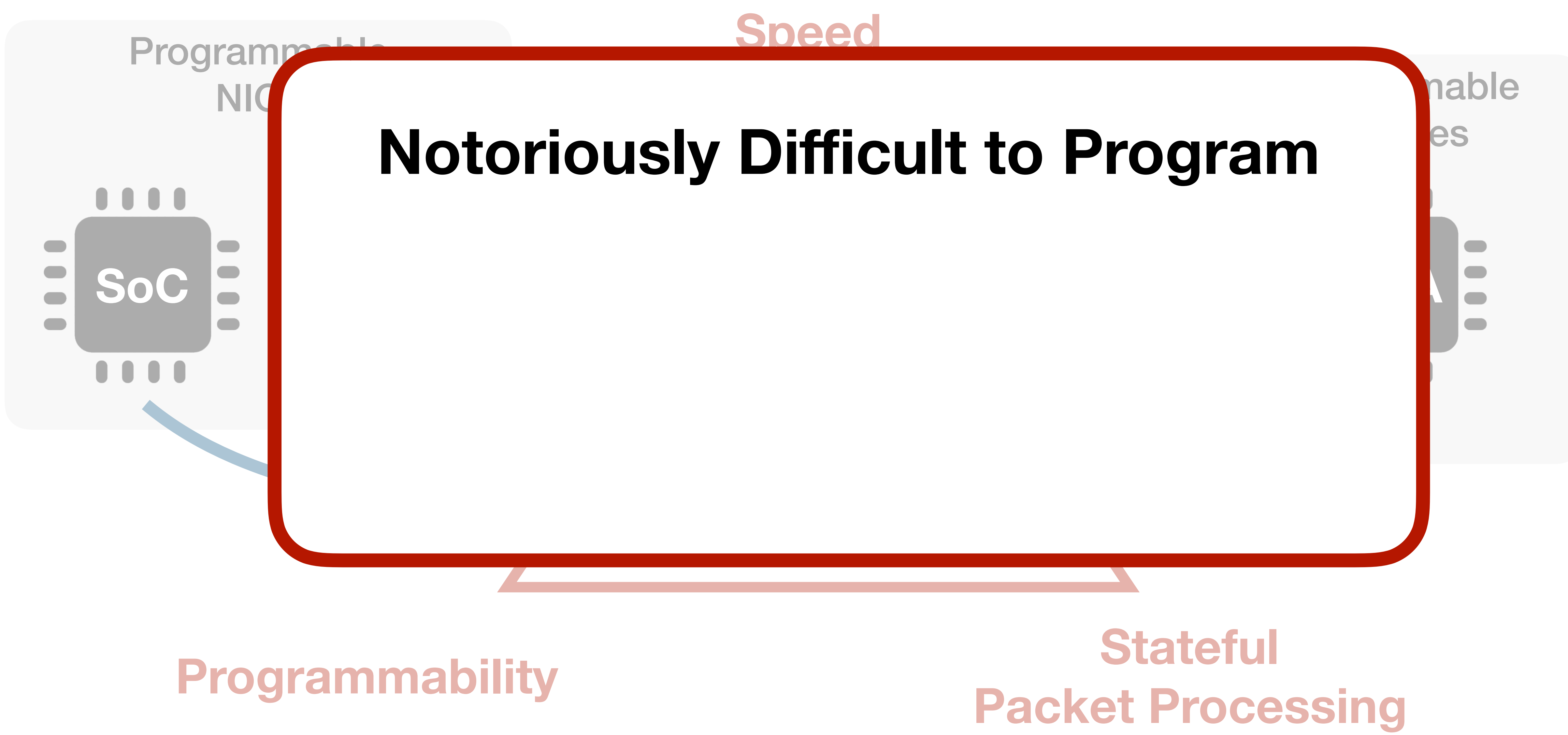
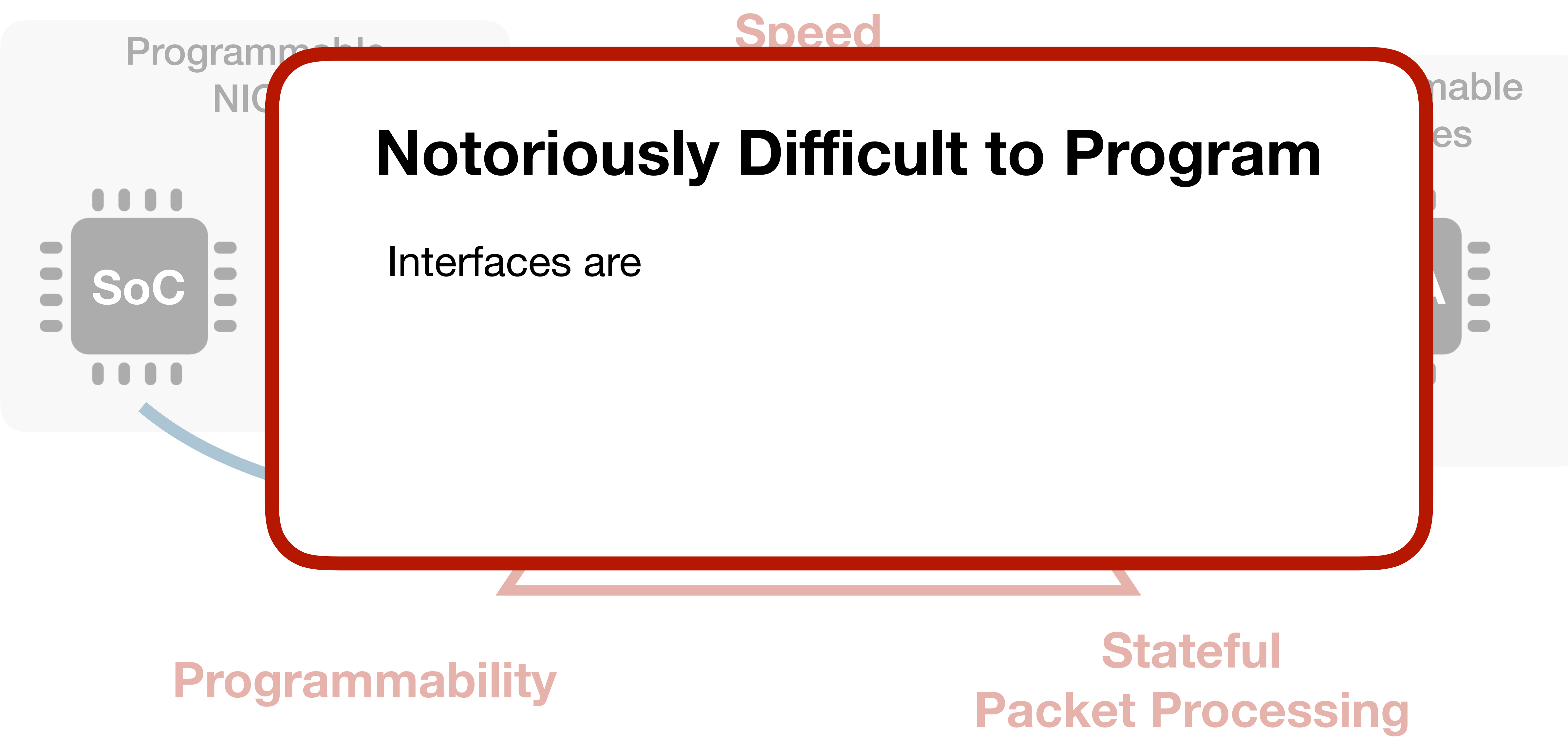


Network Hardware Design Space

Notoriously Difficult to Program

Interfaces are



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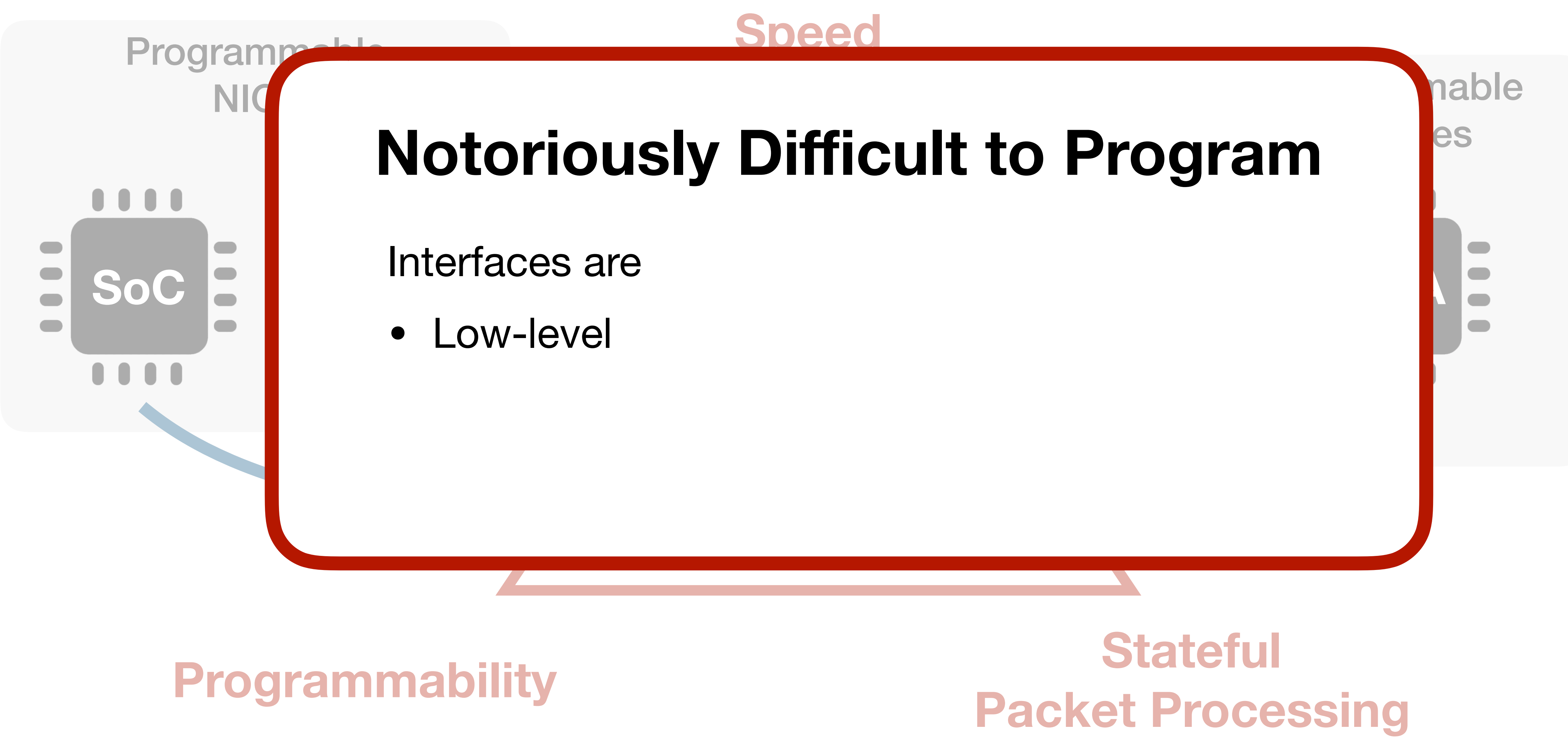

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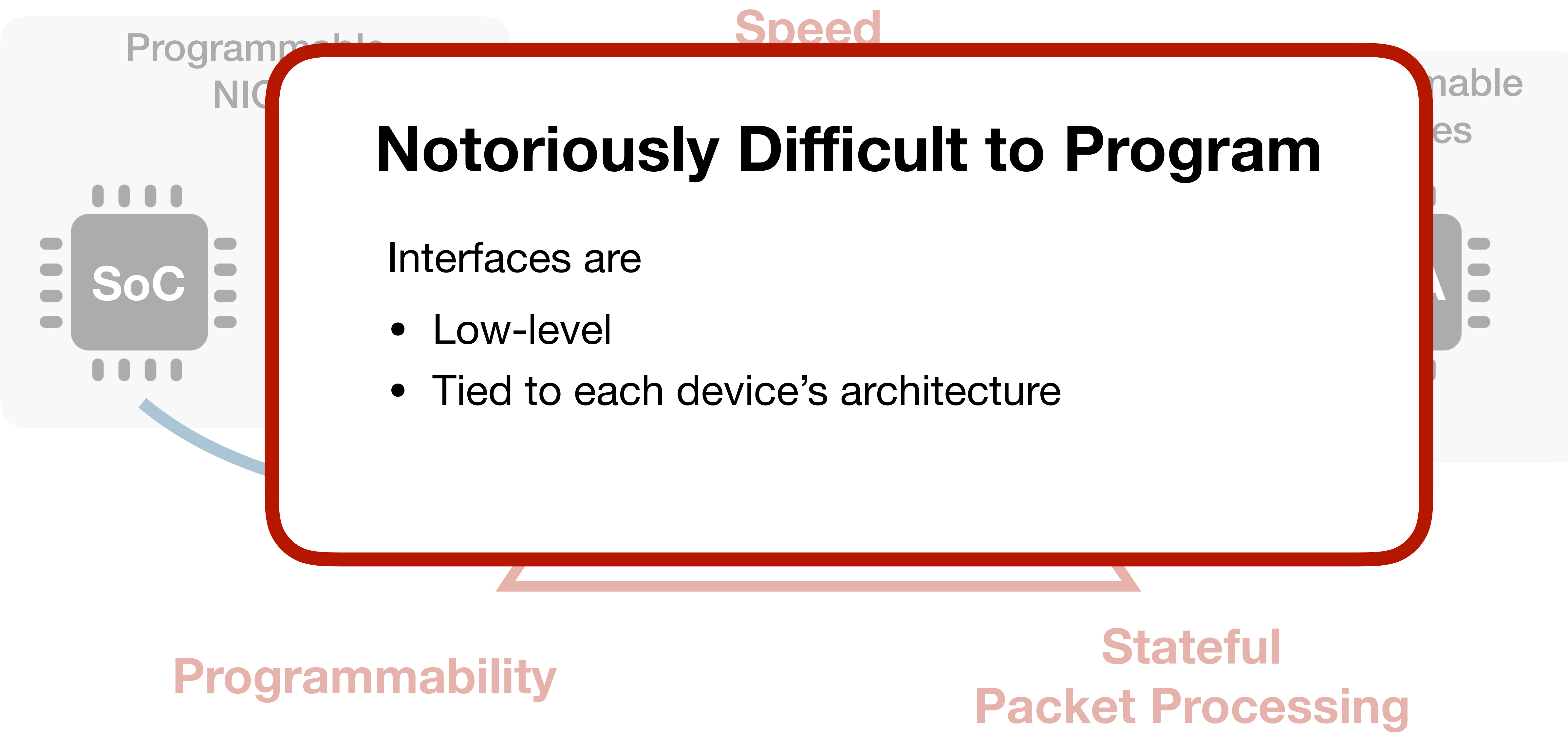
Interfaces are

- Low-level

Network Hardware Design Space



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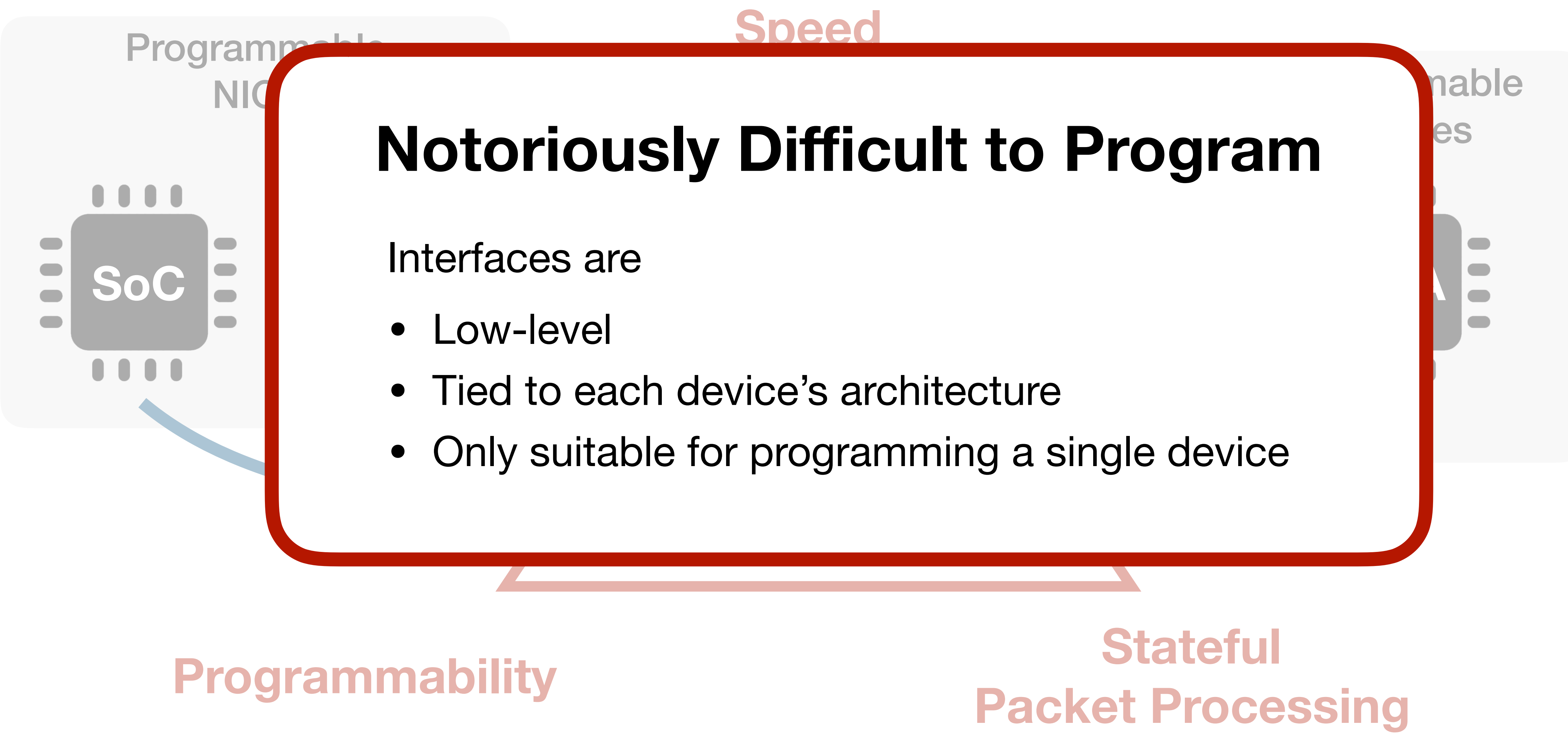


Notoriously Difficult to Program

Interfaces are

- Low-level
- Tied to each device’s architecture
- Only suitable for programming a single device

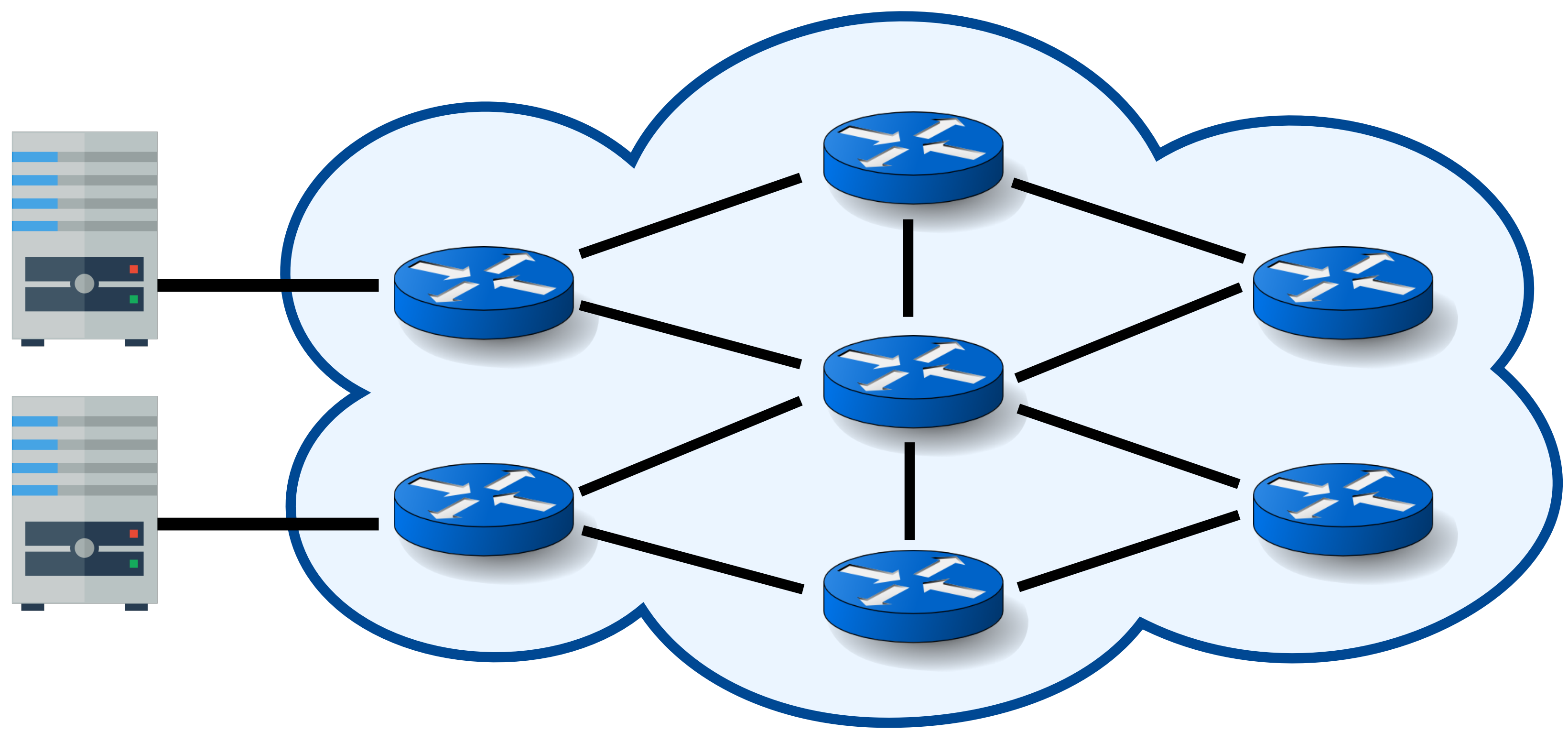
This Dissertation

Design and implementation of

***modular and high-level** programming abstractions*

*for **stateful** programming of **high-speed** network hardware*

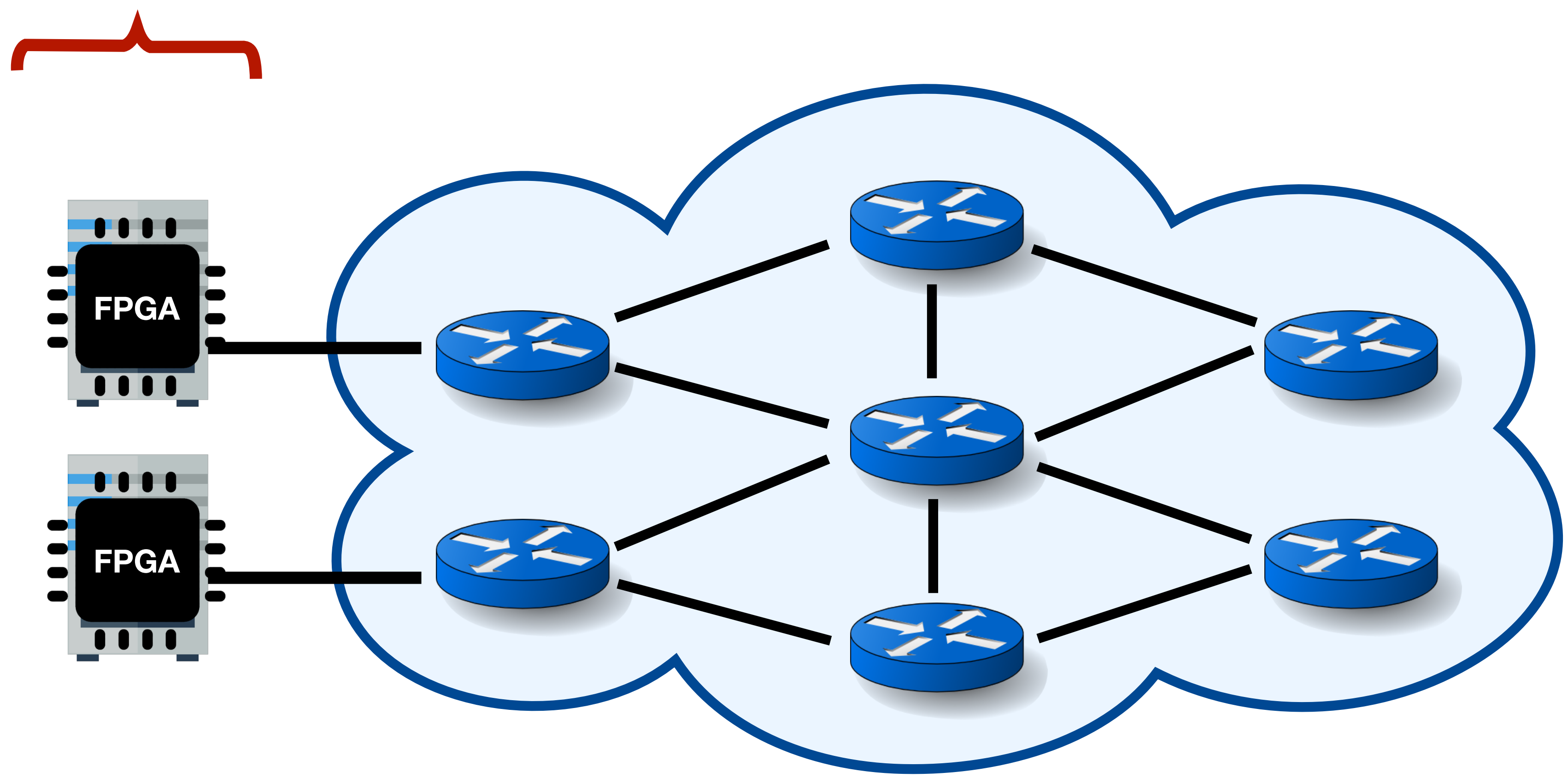
This Dissertation



This Dissertation

Tonic

[Under revision for NSDI'20]



This Dissertation

Tonic
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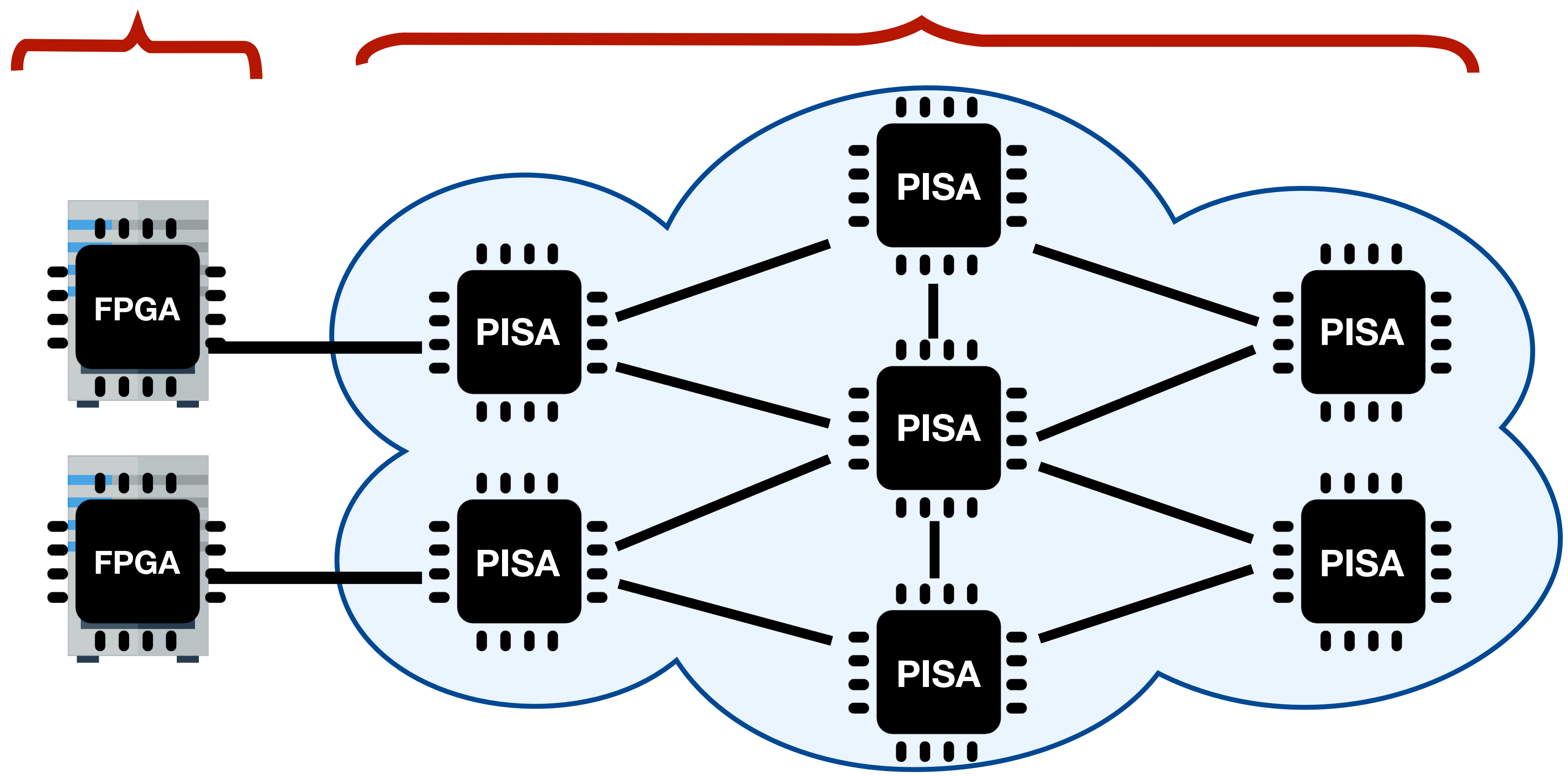
SNAP
[SIGCOMM'16]



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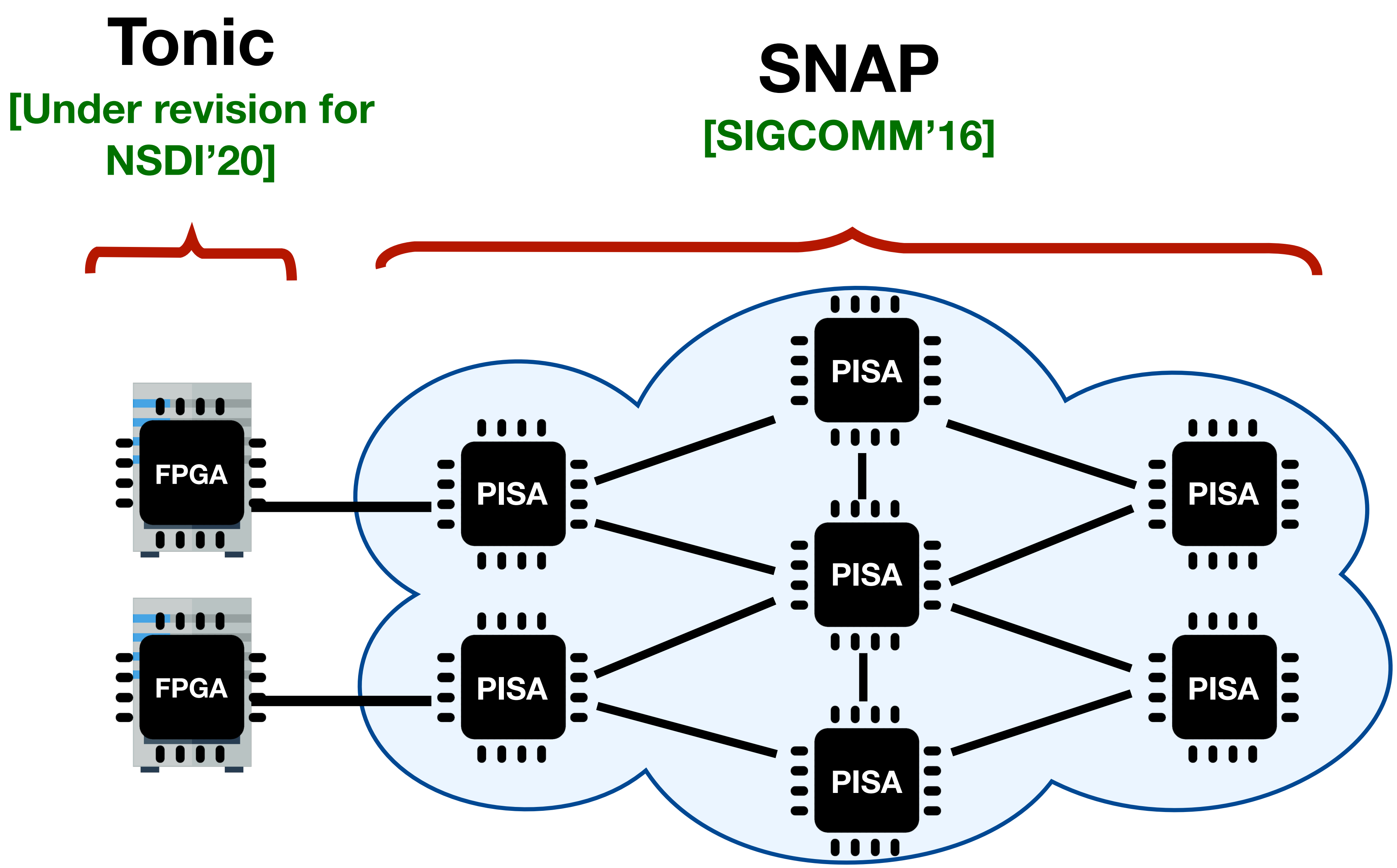
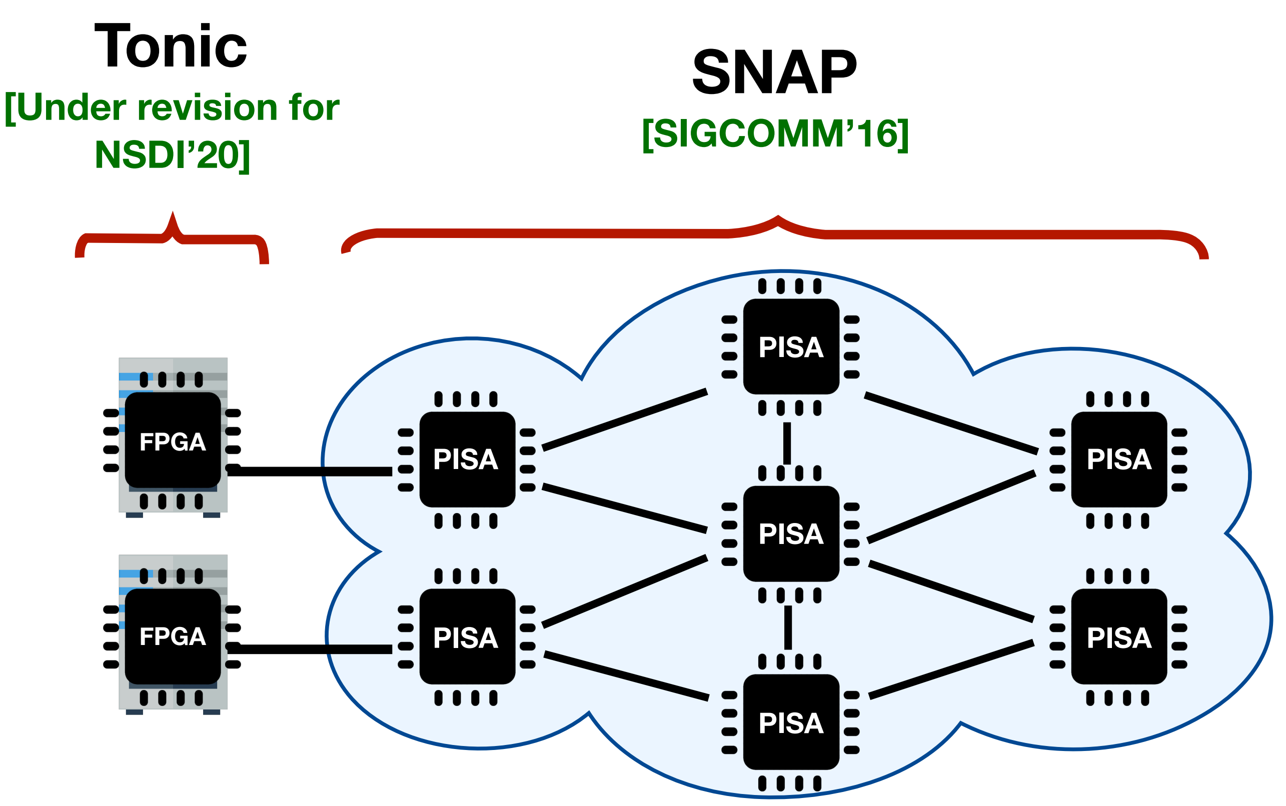


This Dissertation

- With an emphasis on
  - modularity
  - minimizing development effort



Enabling Programmable Transport Protocols on High-Speed NICs

Mina Tahmasbi Arashloo[1], Alexey Lavrov[1],
Manya Ghobadi[2], Jennifer Rexford[1],
David Walker[1], and David Wentzlaff[1]

[1] Princeton University, [2] MIT

TCP 101

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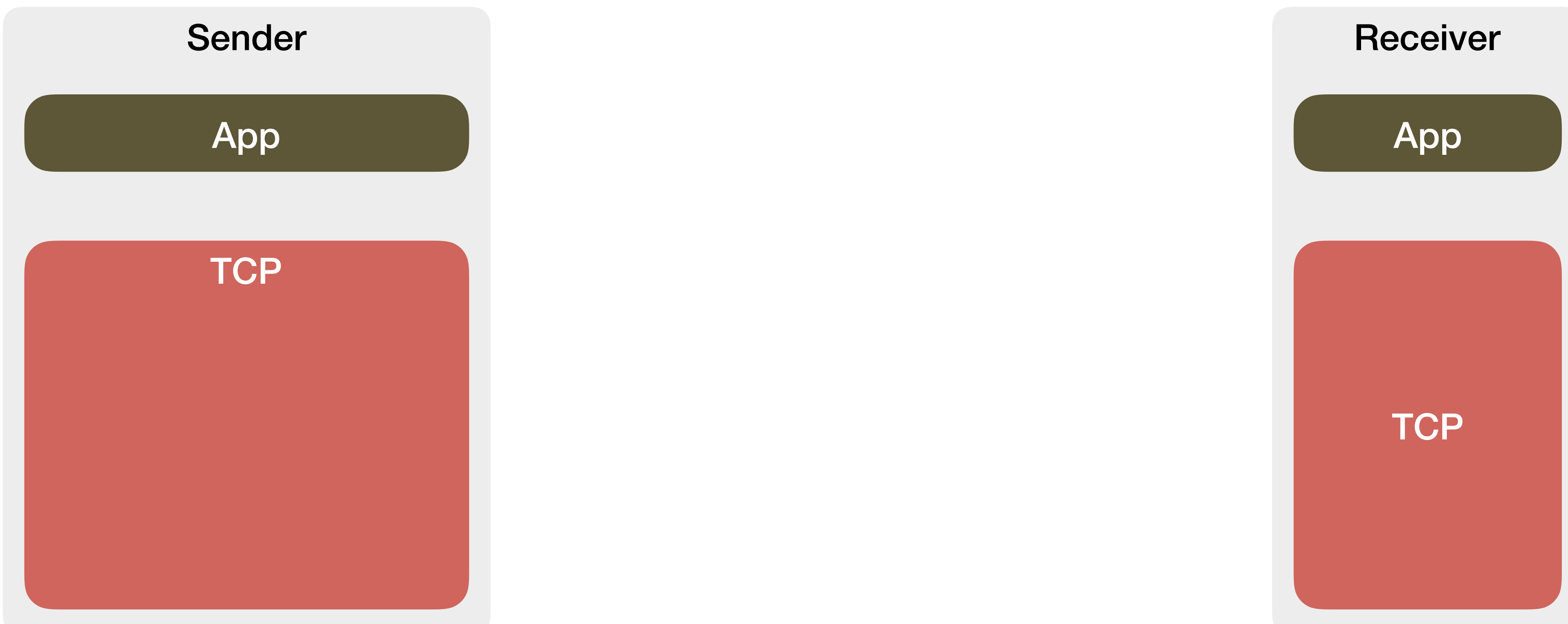
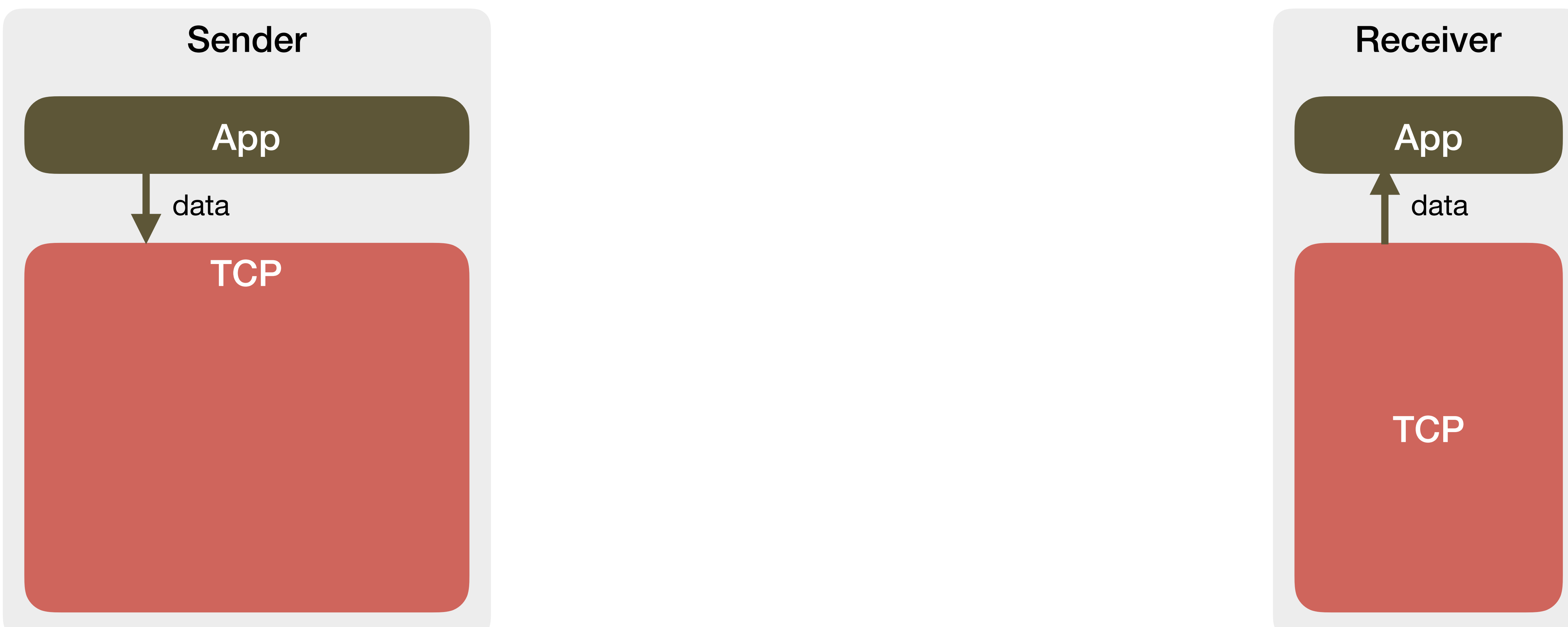
- The most common transport protocol



TCP 101

- The most common transport protocol
- Performs **reliable data delivery** and **congestion control**



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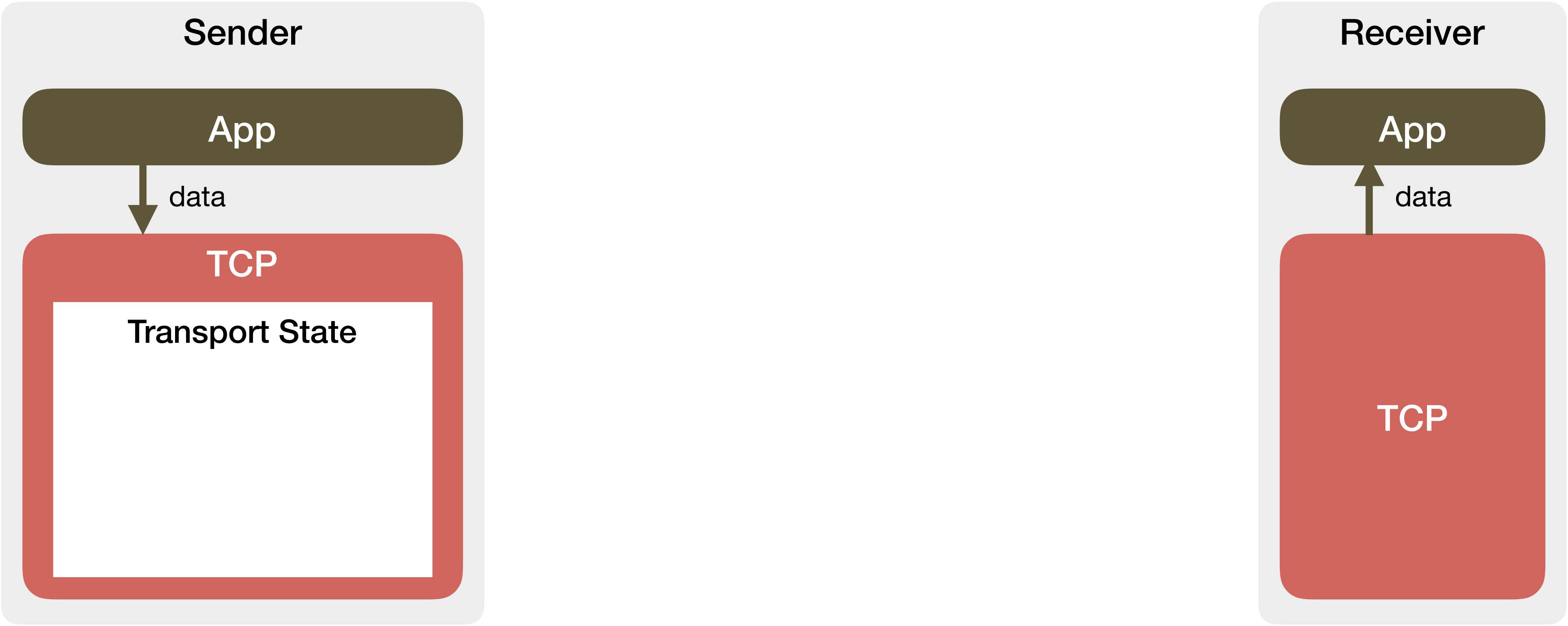

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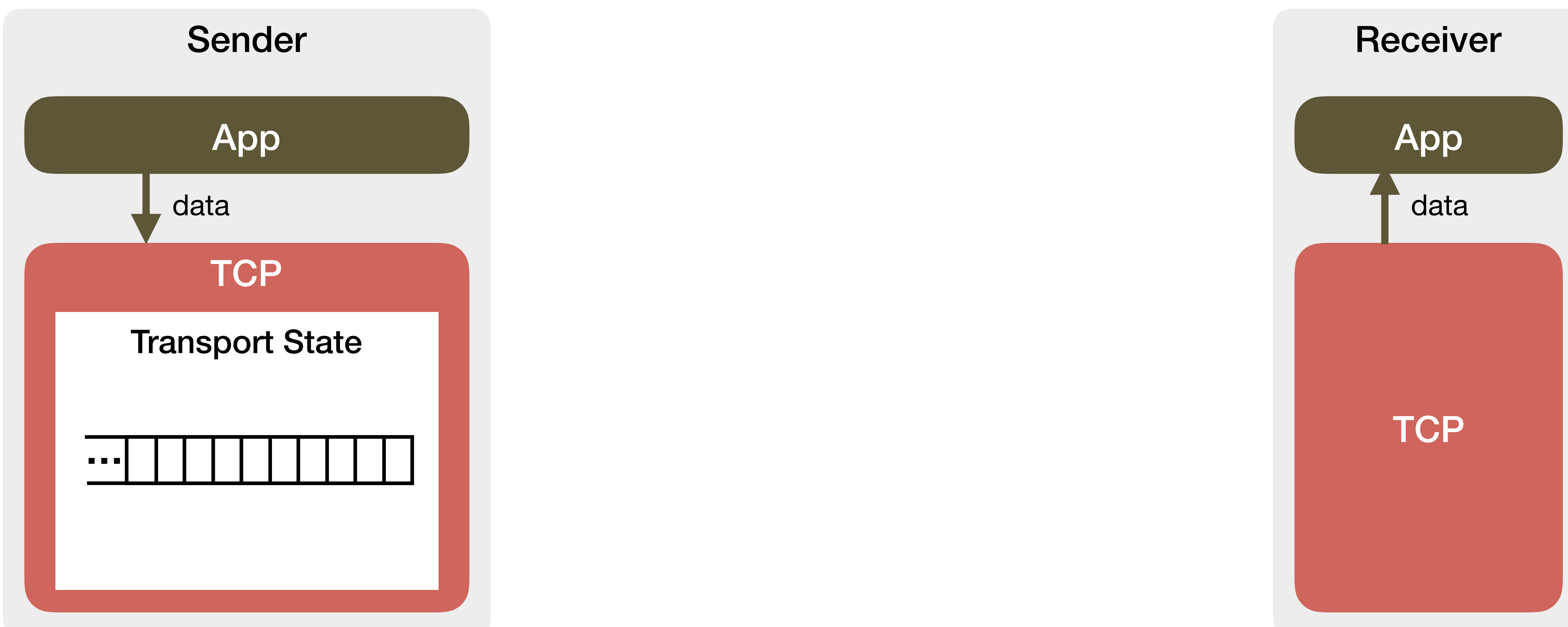

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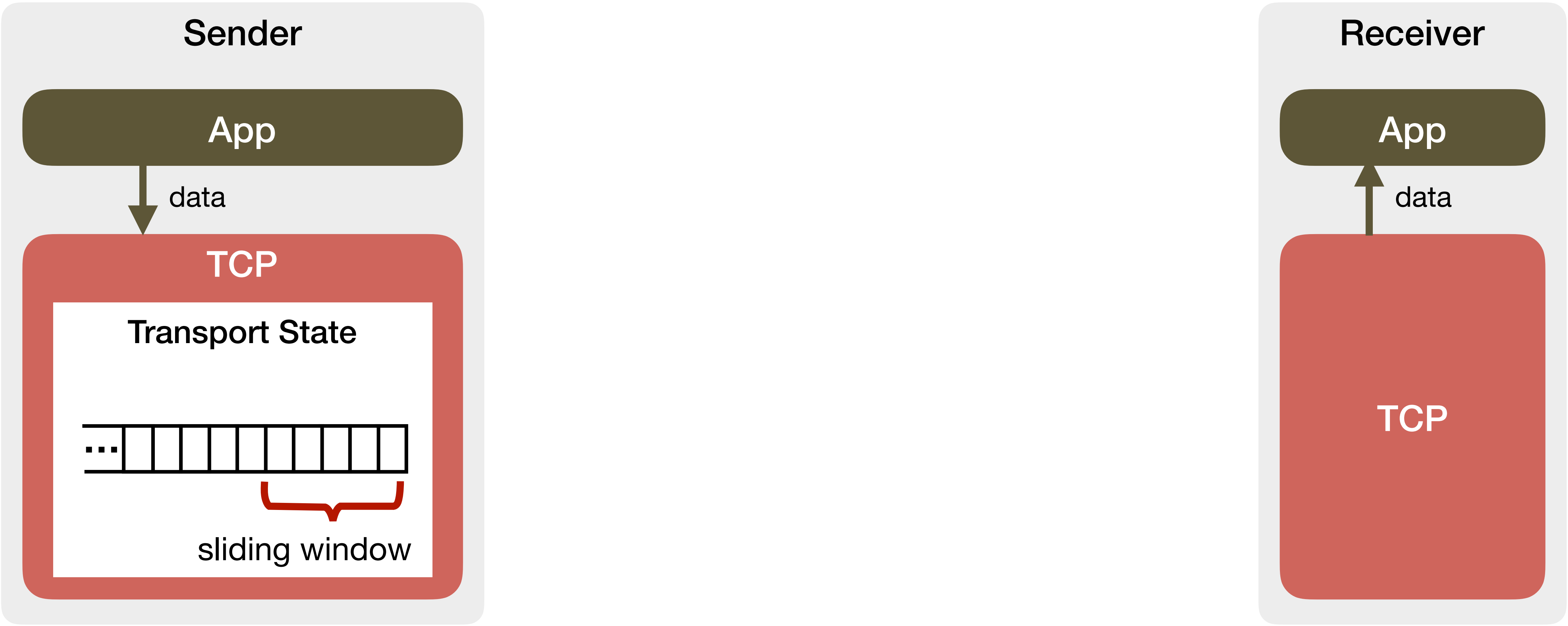

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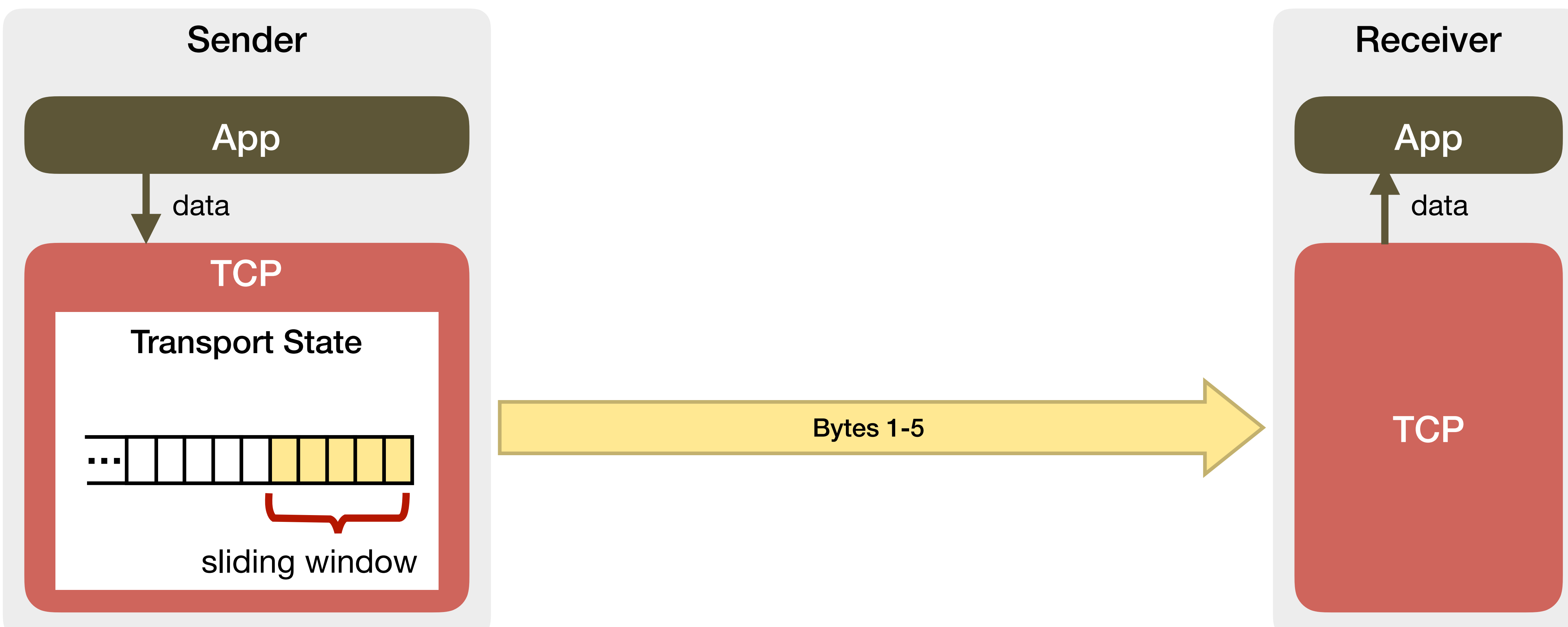

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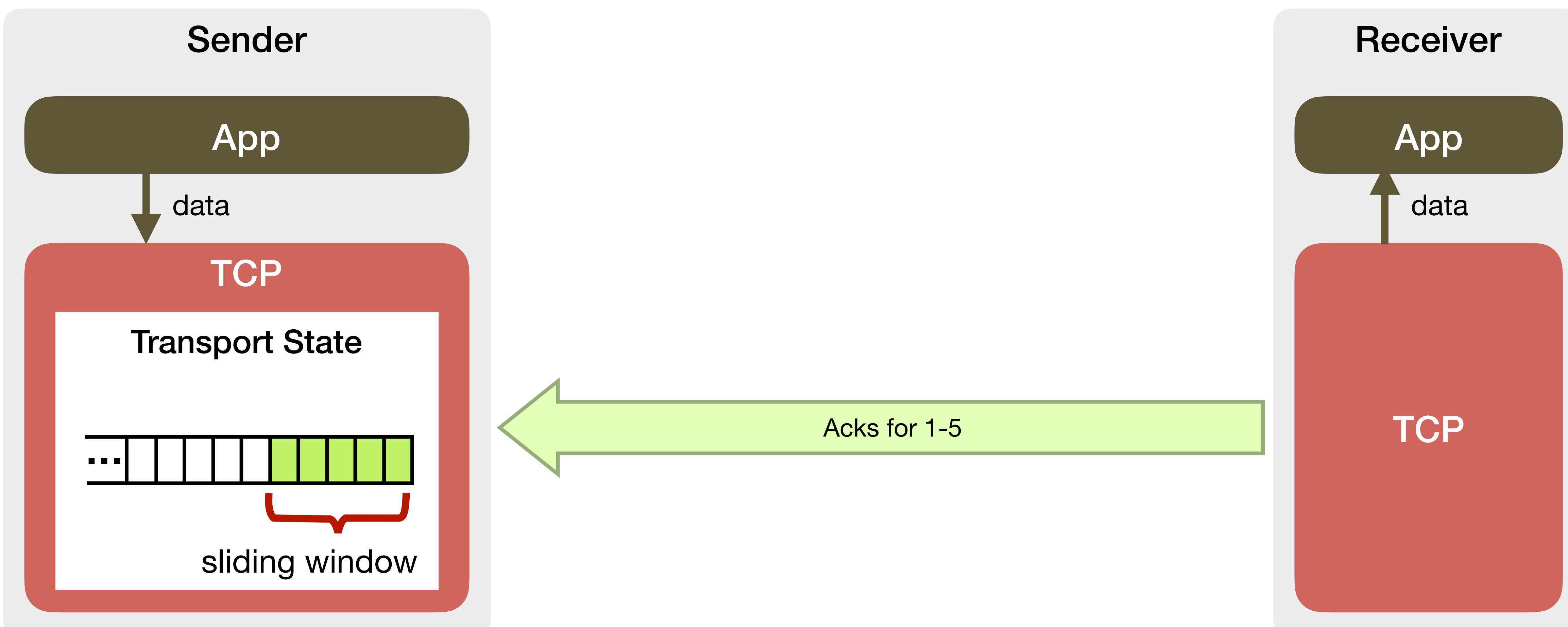

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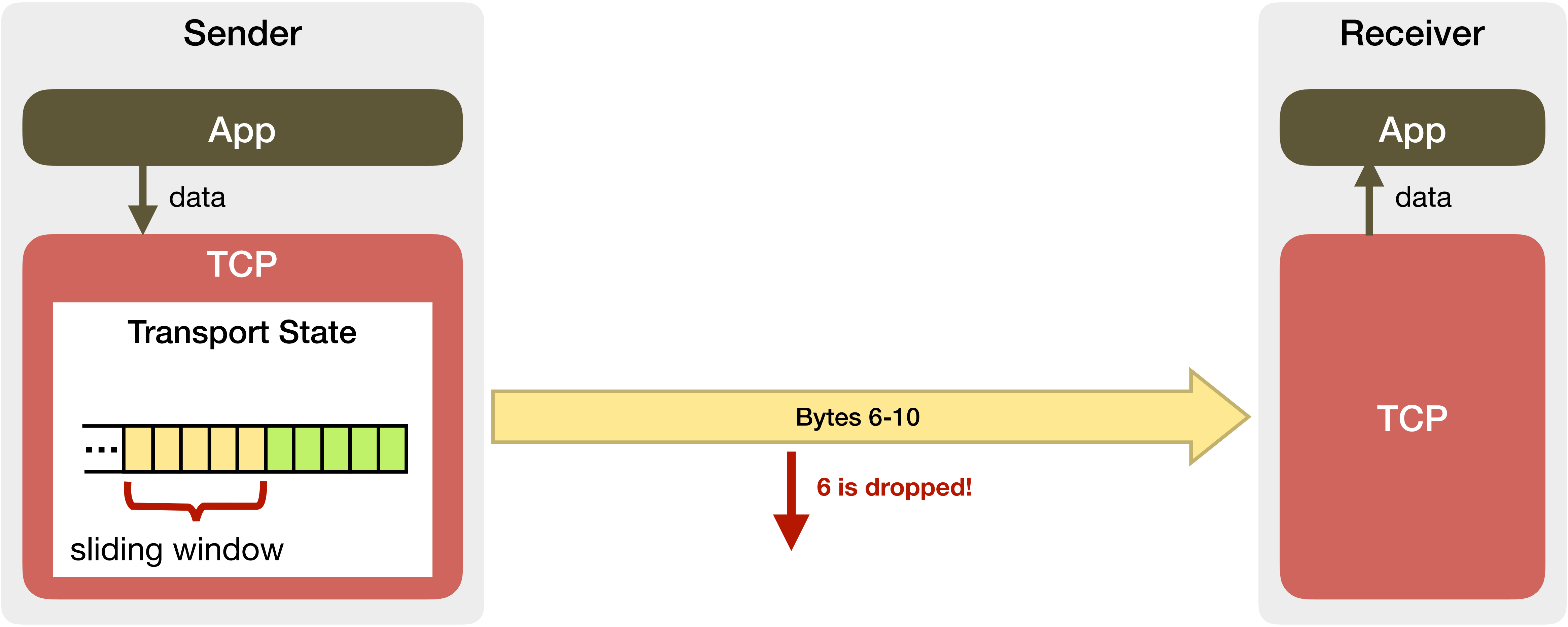

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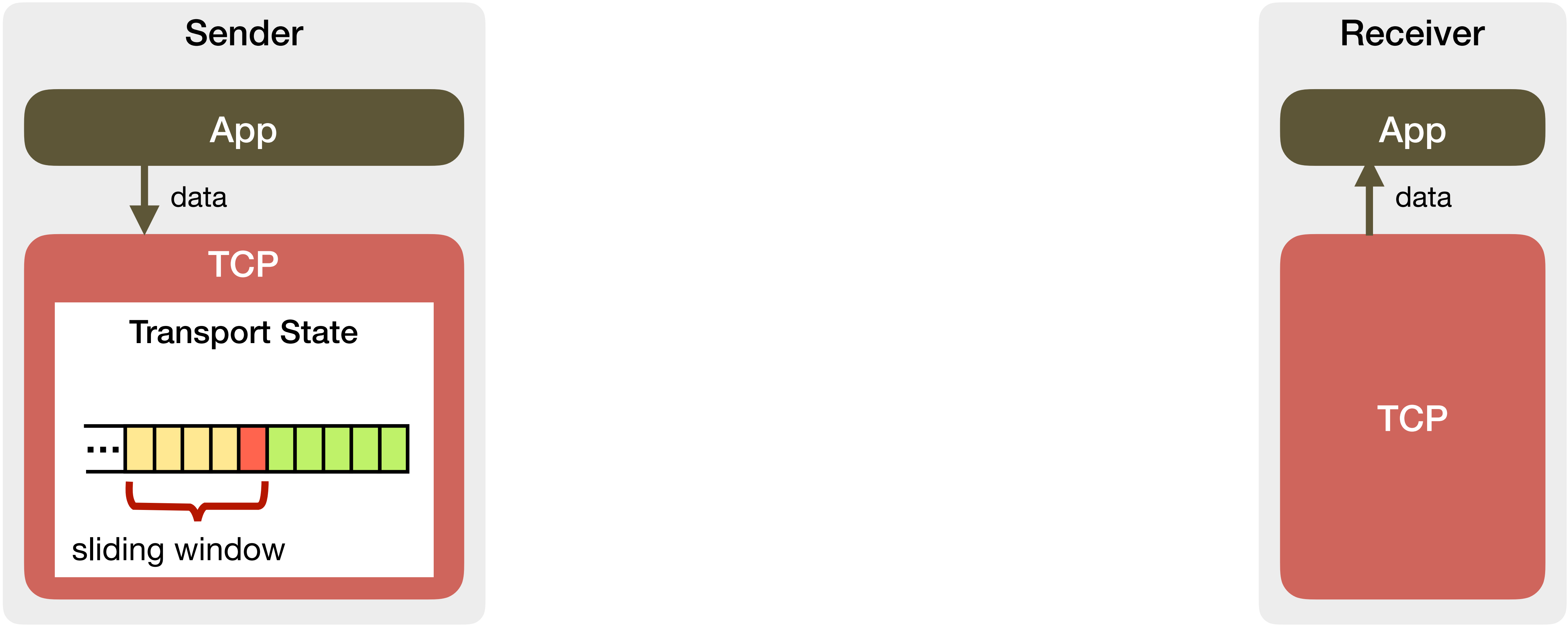

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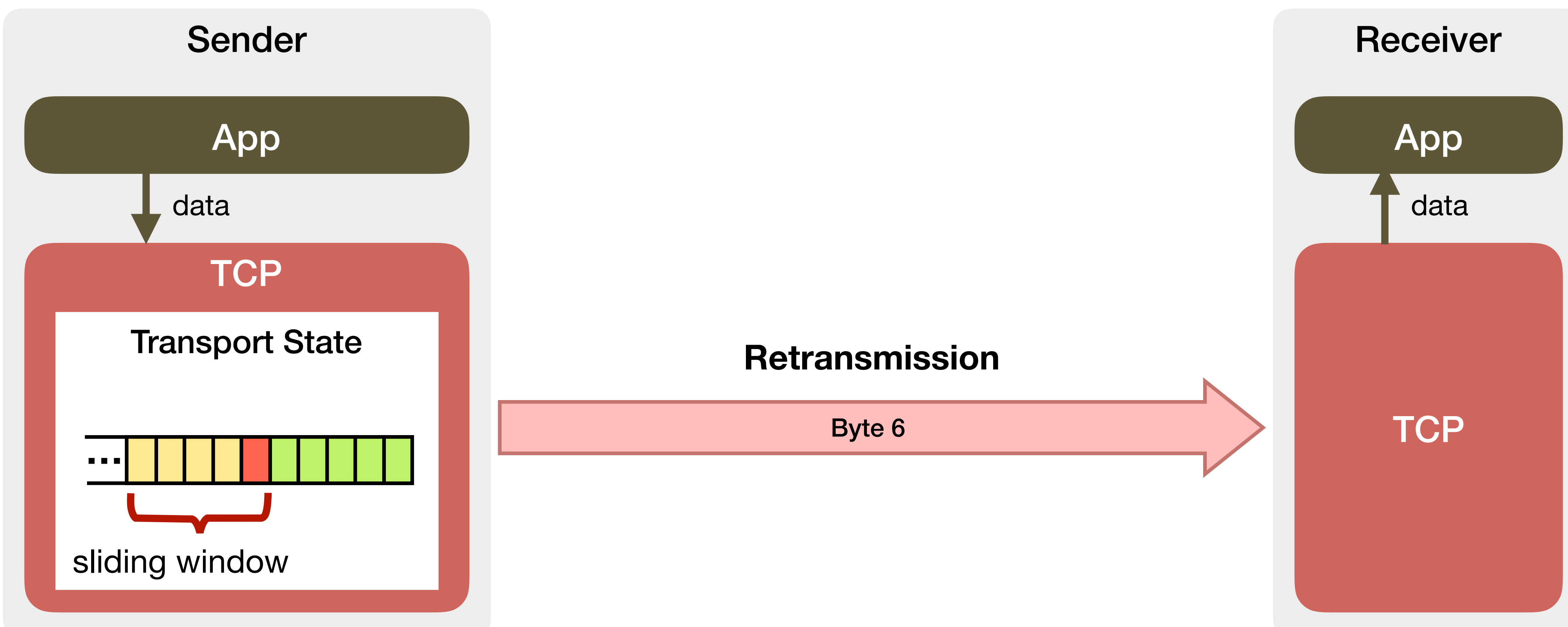

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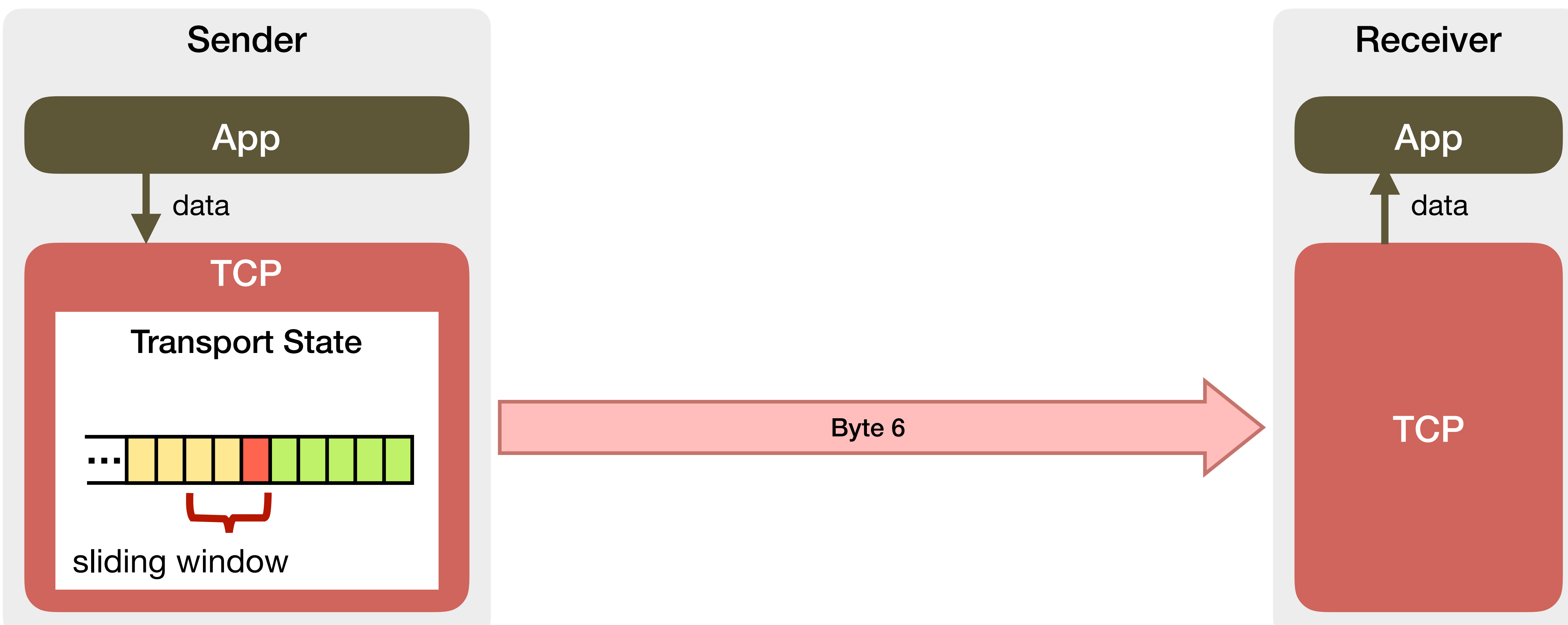

Window Adjustment

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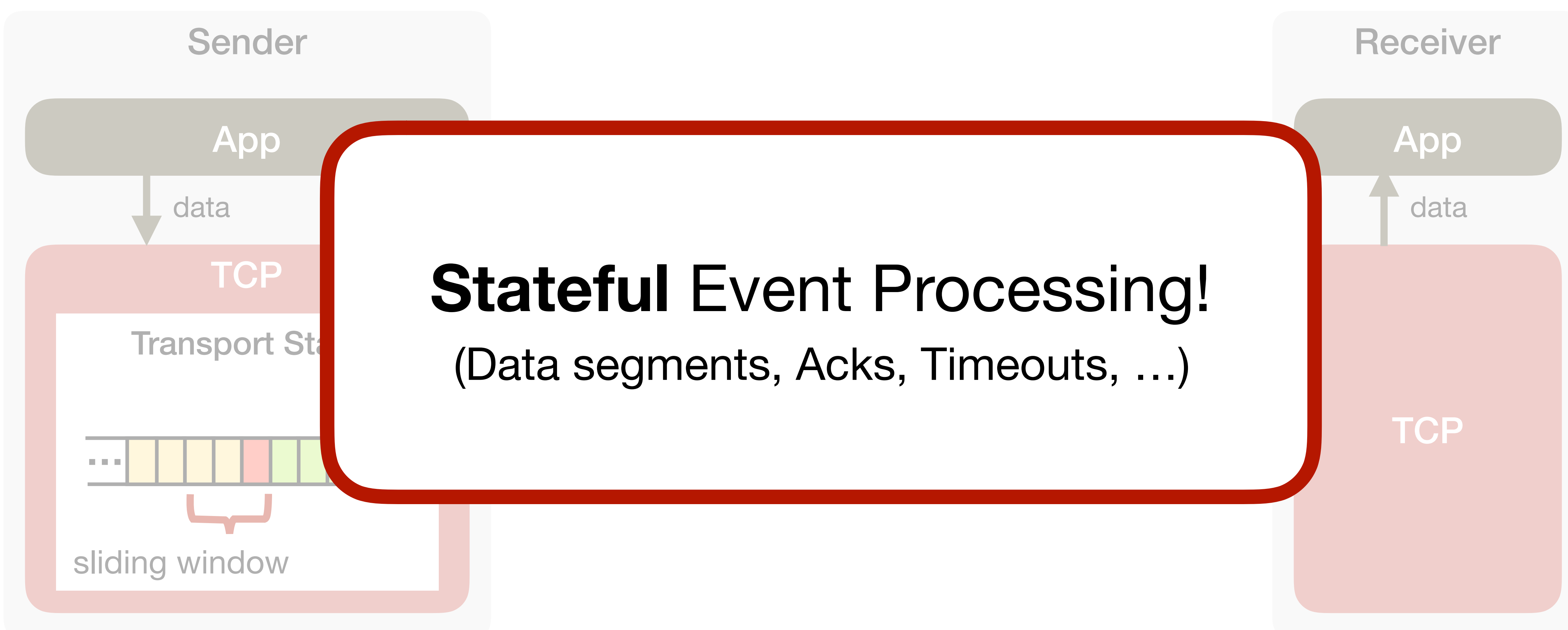

Constant Innovation in Transport Protocols

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NDP
XCP
Homa
Karuna
PCC
DCTCP
D3
DCQCN
New Reno
Reno
IRN
pHost
CUBIC
QUIC
Sprout
TIMELY
BIC
Tahoe
RCP
BBR
TCP Vegas
PCC Vivace

Network Stacks in Data Centers

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Target	CPU Overhead	Transport Programmability

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Software	kernel user space	30-40%	✔

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Software	**kernel** **user space**	**30-40%**	✔
Fixed-Function Hardware	**NIC**	**~none**	✘

Network Stacks in Data Centers

	Target	CPU Overhead	Transport Programmability
Software	kernel user space	30-40%	✔
Fixed-Function Hardware	NIC	~none	✘
Programmable Hardware (Tonic)	NIC	~none	✔

Challenges of Hardware Programming for High-Speed NICs

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- **Timing Constraints**
  - Median packet size in data centers is 200 bytes
  - At 100 Gbps, one 128-byte packet every ~10 ns
    - Back-to-back stateful event processing

Challenges of Hardware Programming for High-Speed NICs

- **Timing Constraints**
  - Median packet size in data centers is 200 bytes
  - At 100 Gbps, one 128-byte packet every ~10 ns
    - Back-to-back stateful event processing
- **Memory Constraints**
  - A few megabytes of high-speed memory
  - More than a thousand active flows
  - A few kilobits of per-flow state

Challenges of Hardware Programming for High-Speed NICs

- Timing Constraints
  - M
  - A
- Me
  - A
  - M
  - A few kilobits of per-flow state

Tonic

- A **programmable** hardware architecture
  - running at **100** Gbps
  - within **memory limits of commodity NICs**
- to implement transport protocols
  - with **modest development effort**

Main Observation

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Common transport patterns as reusable components

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- drive the design of an efficient hardware “template” for transport logic

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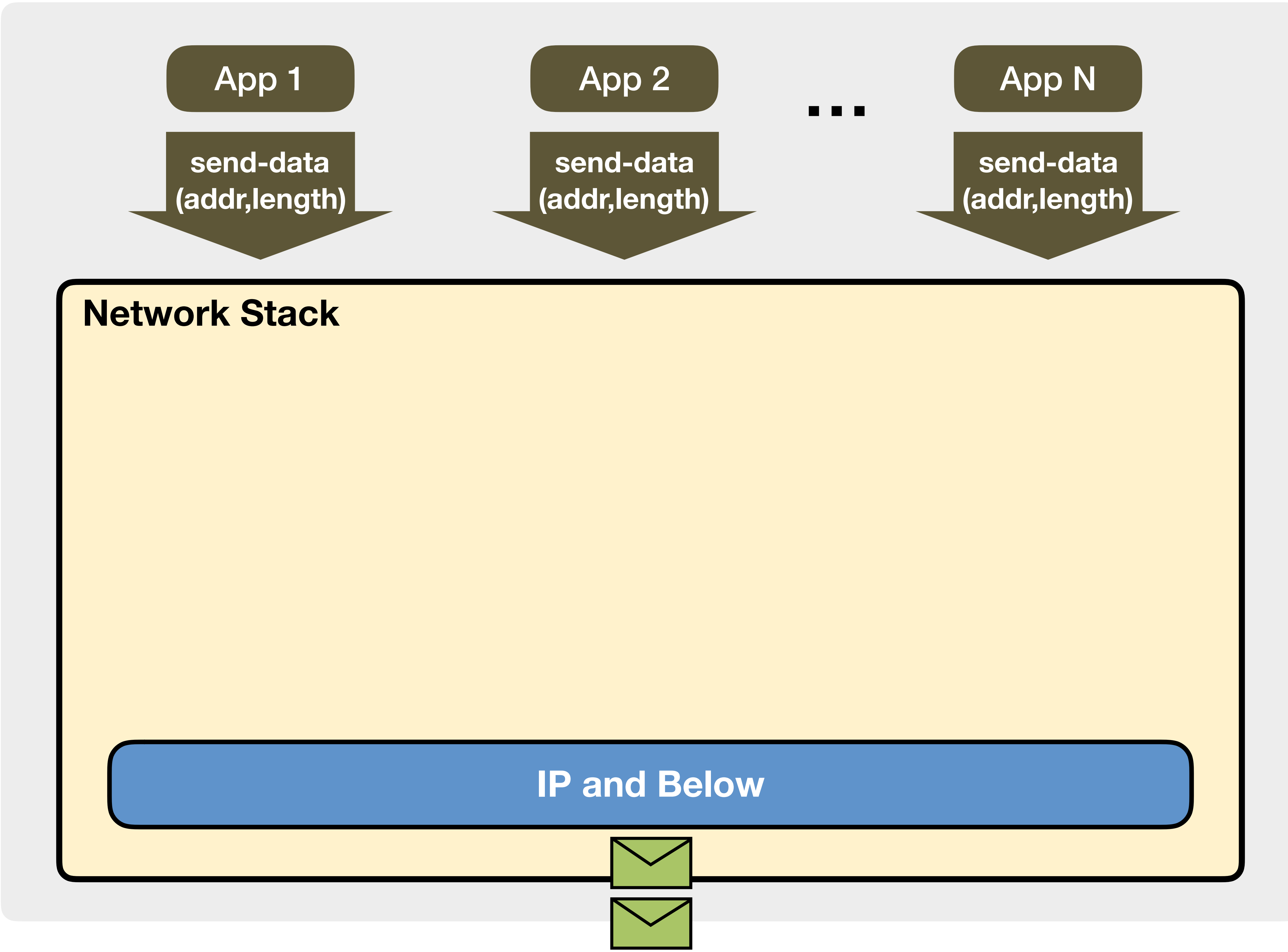
Common transport patterns as reusable components

- drive the design of an efficient hardware “template” for transport logic
- reduce the functionality users must specify

The Transport Layer



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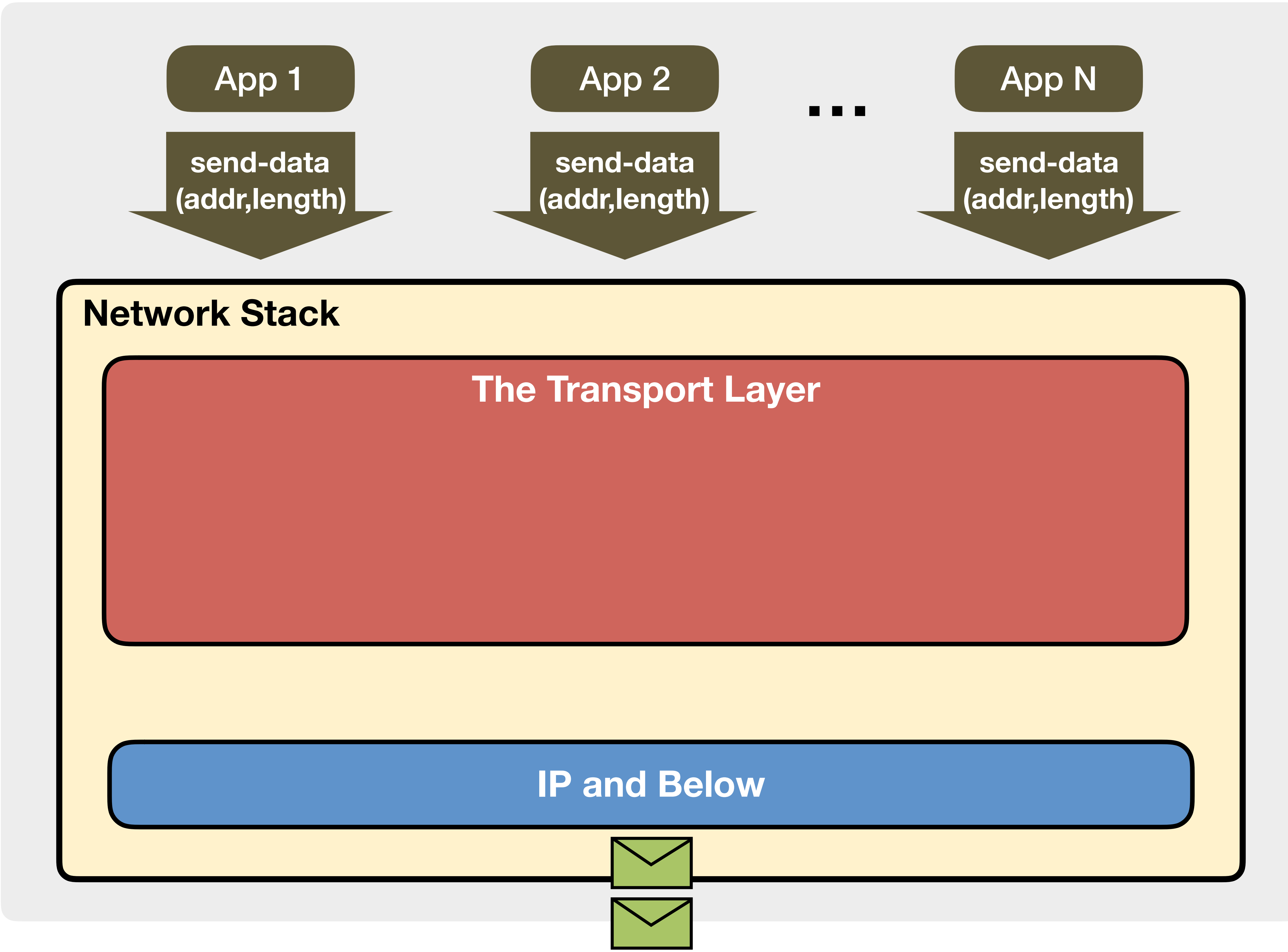

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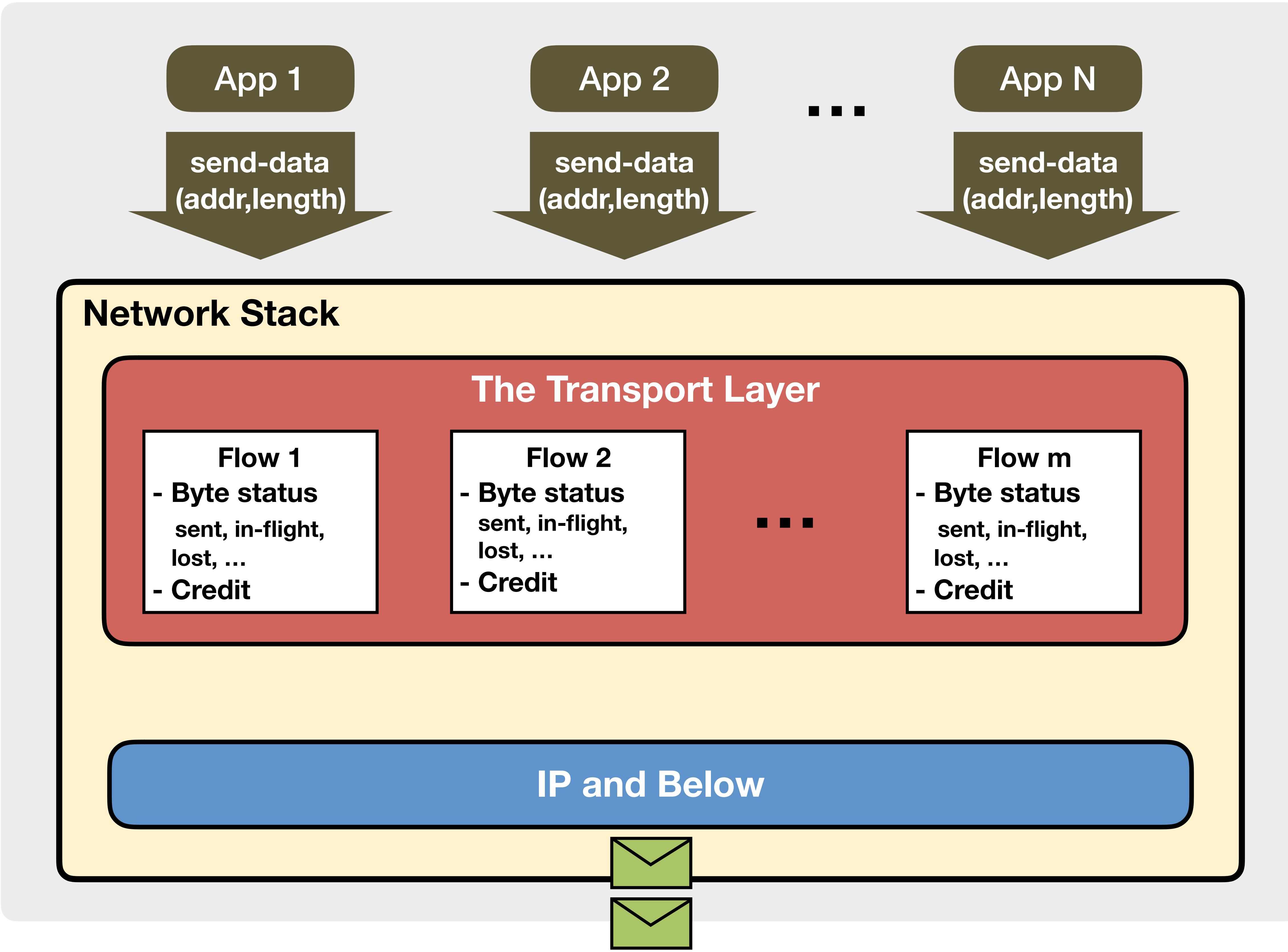

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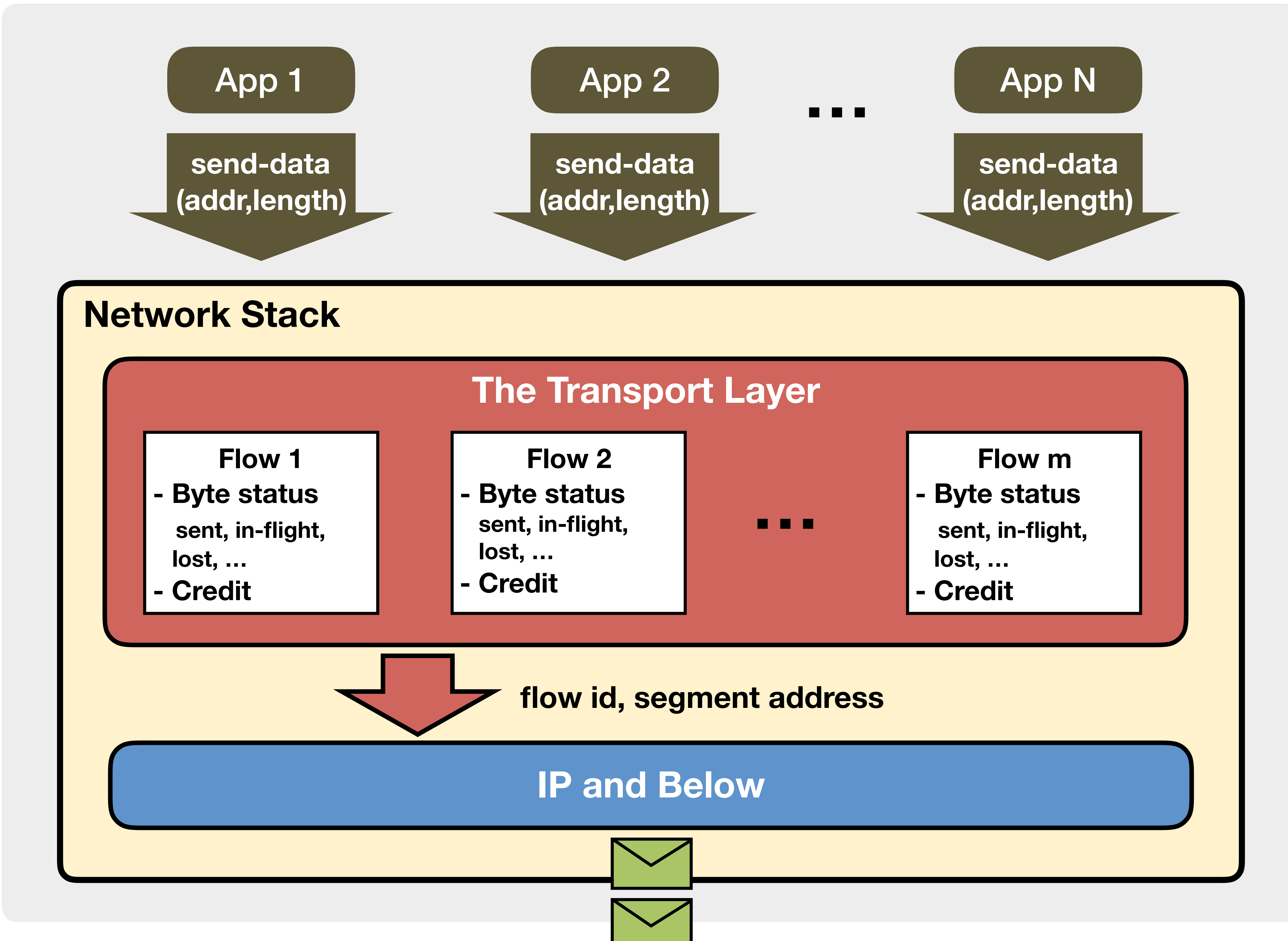

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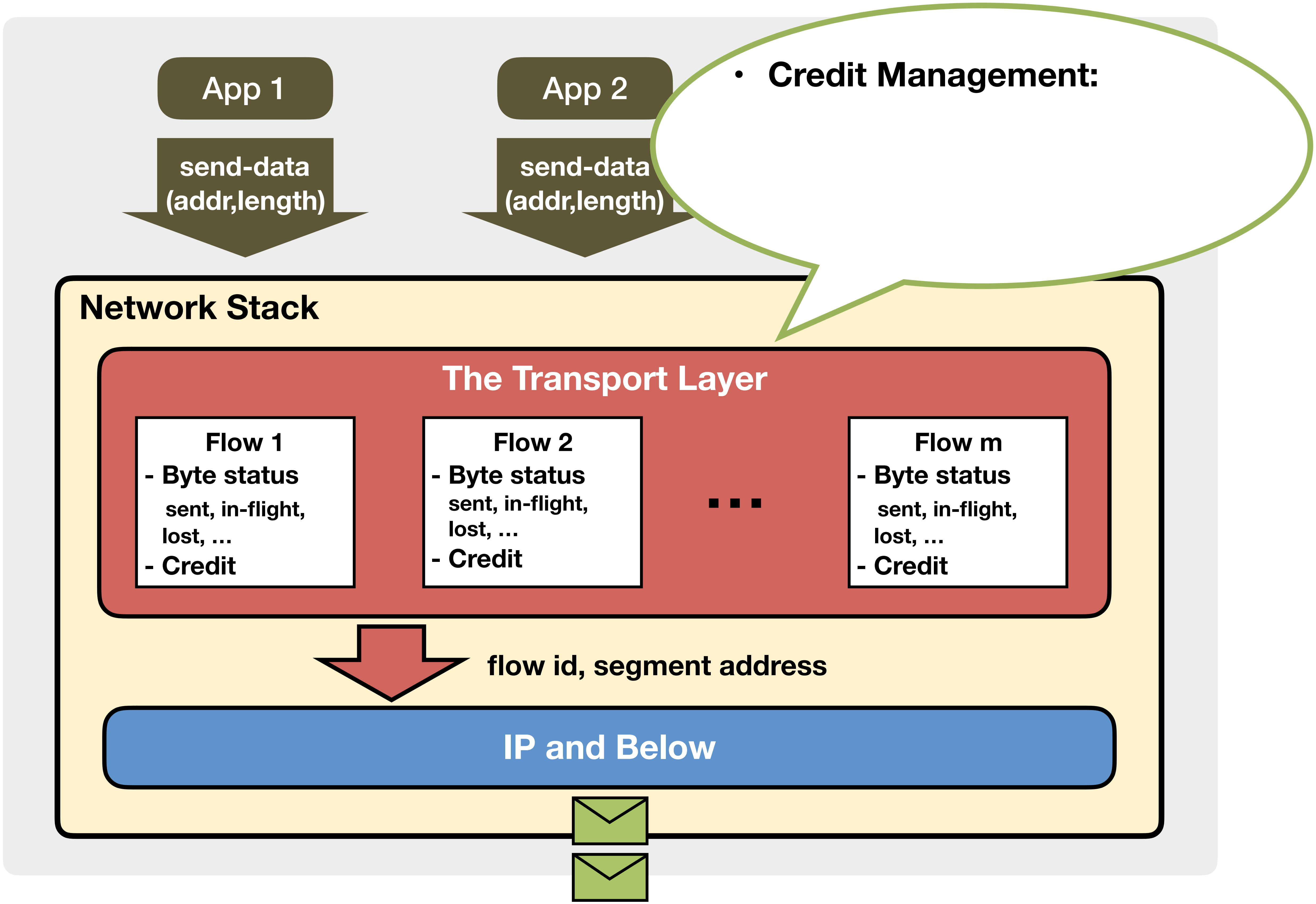

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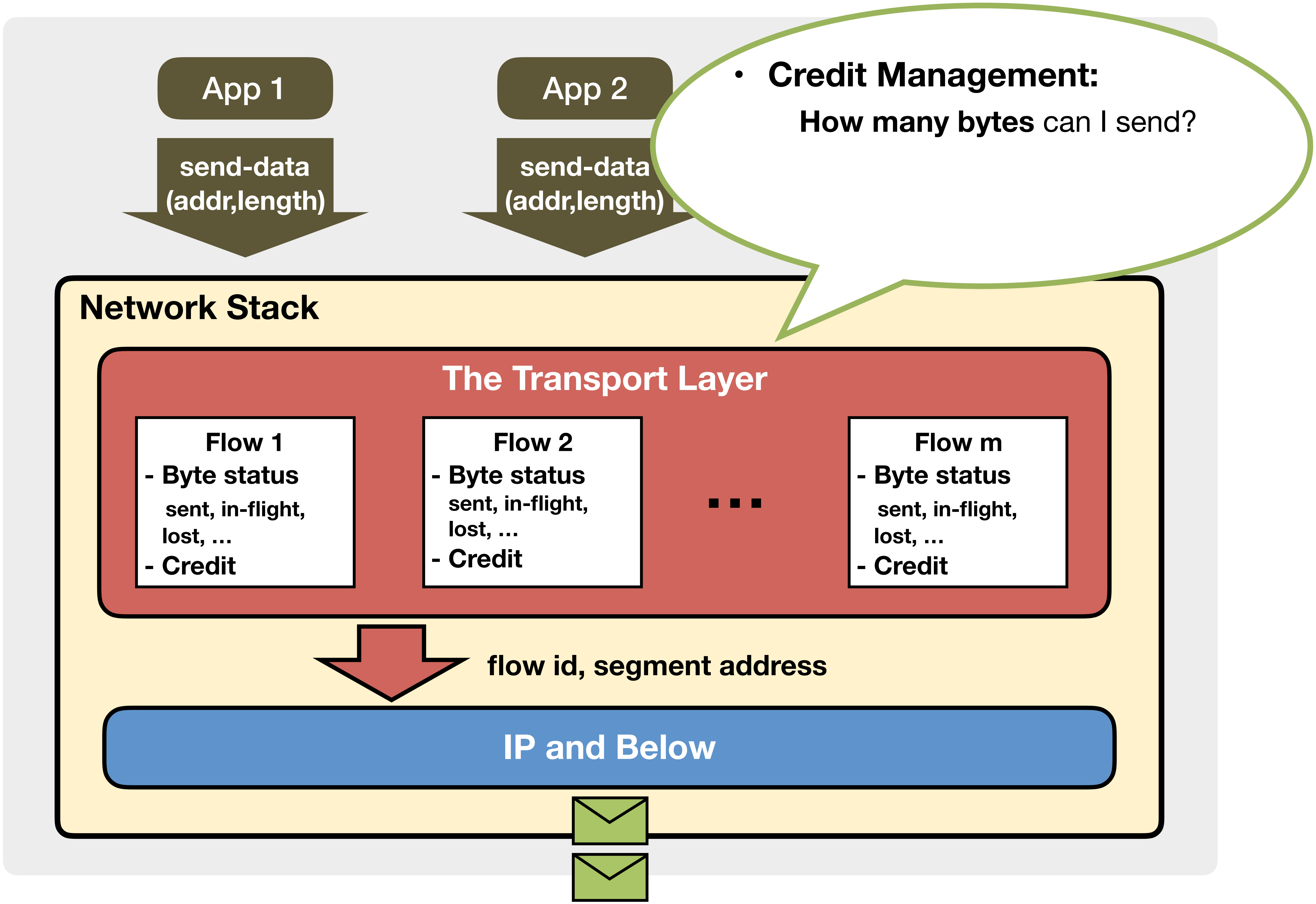

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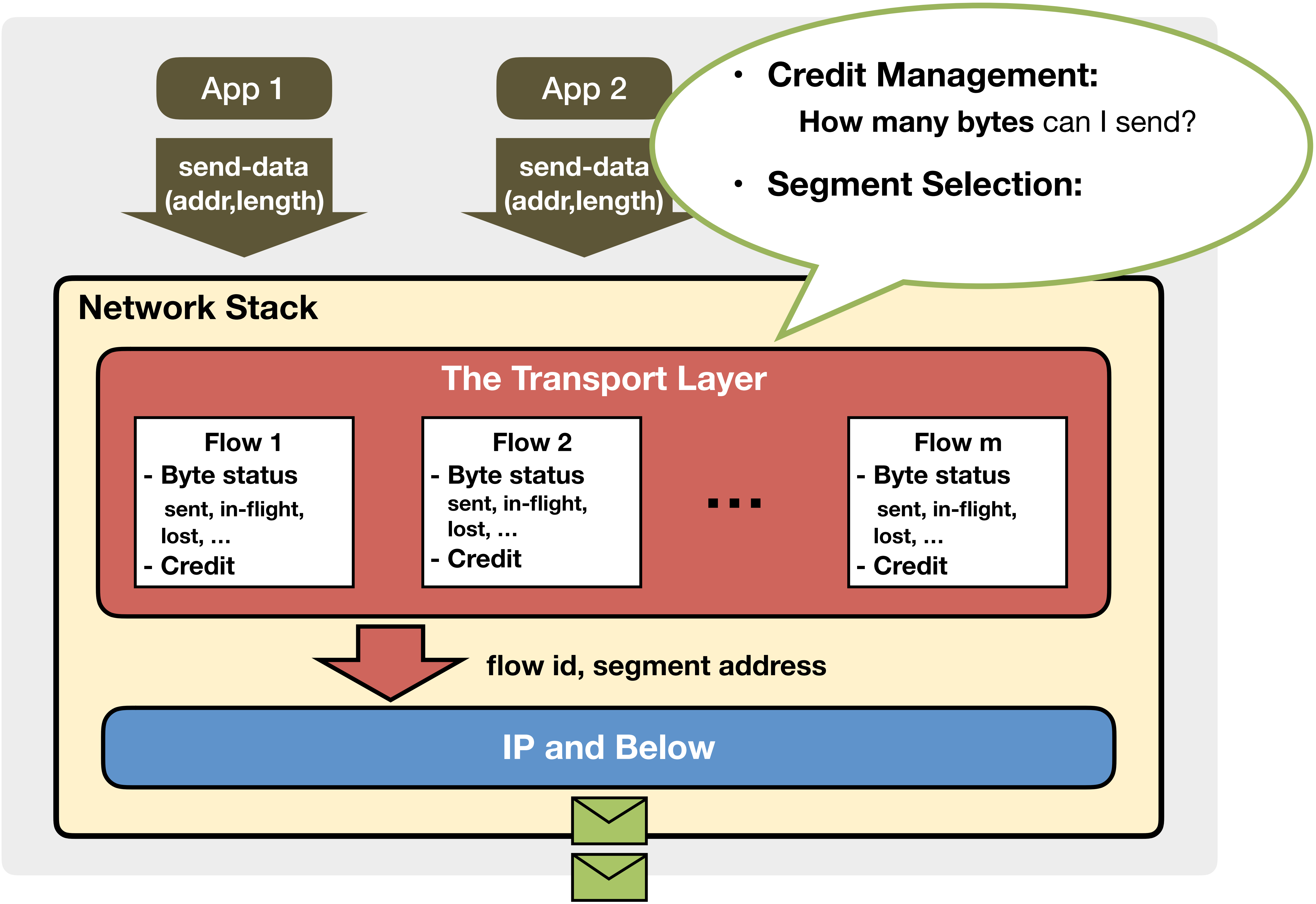

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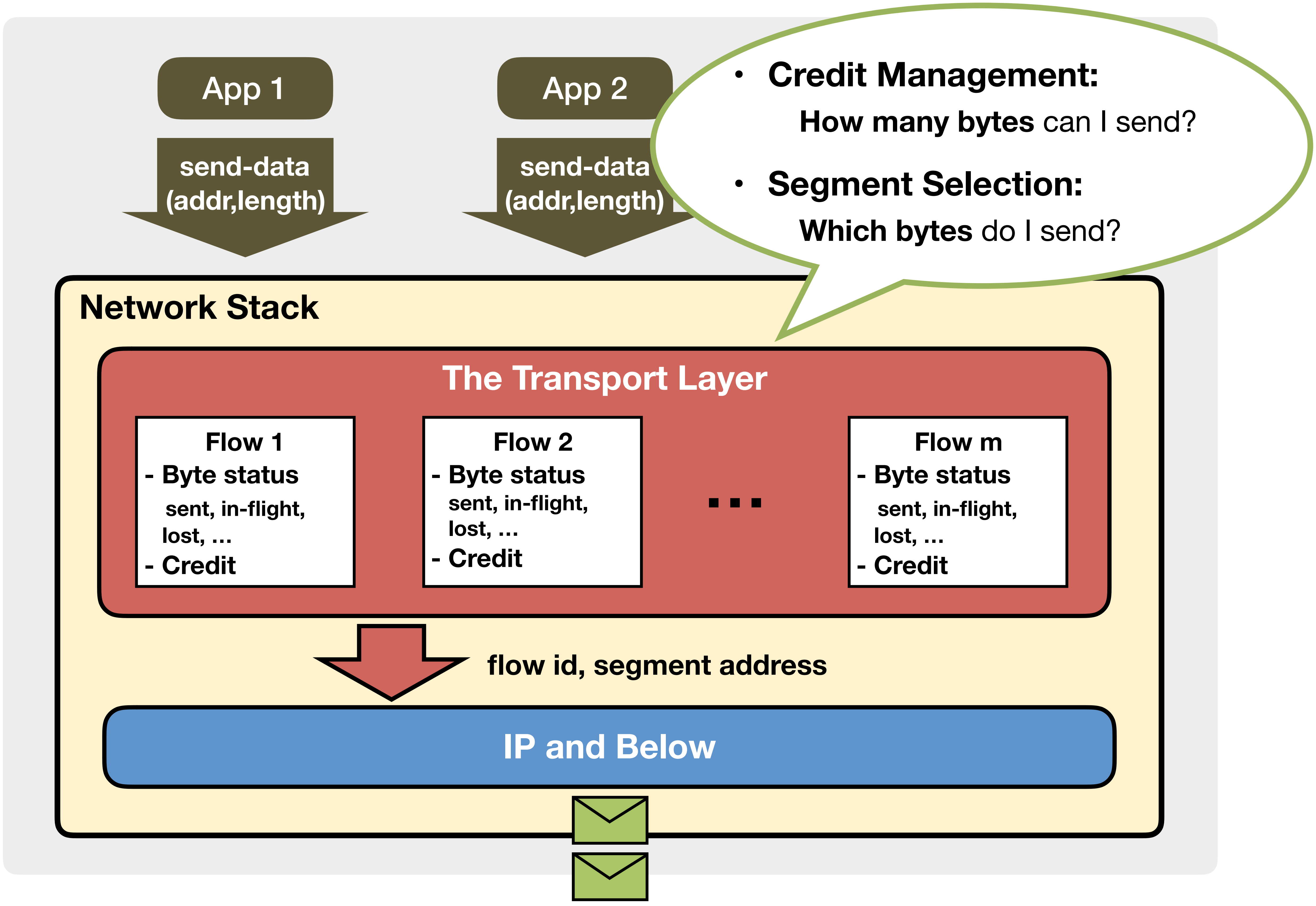
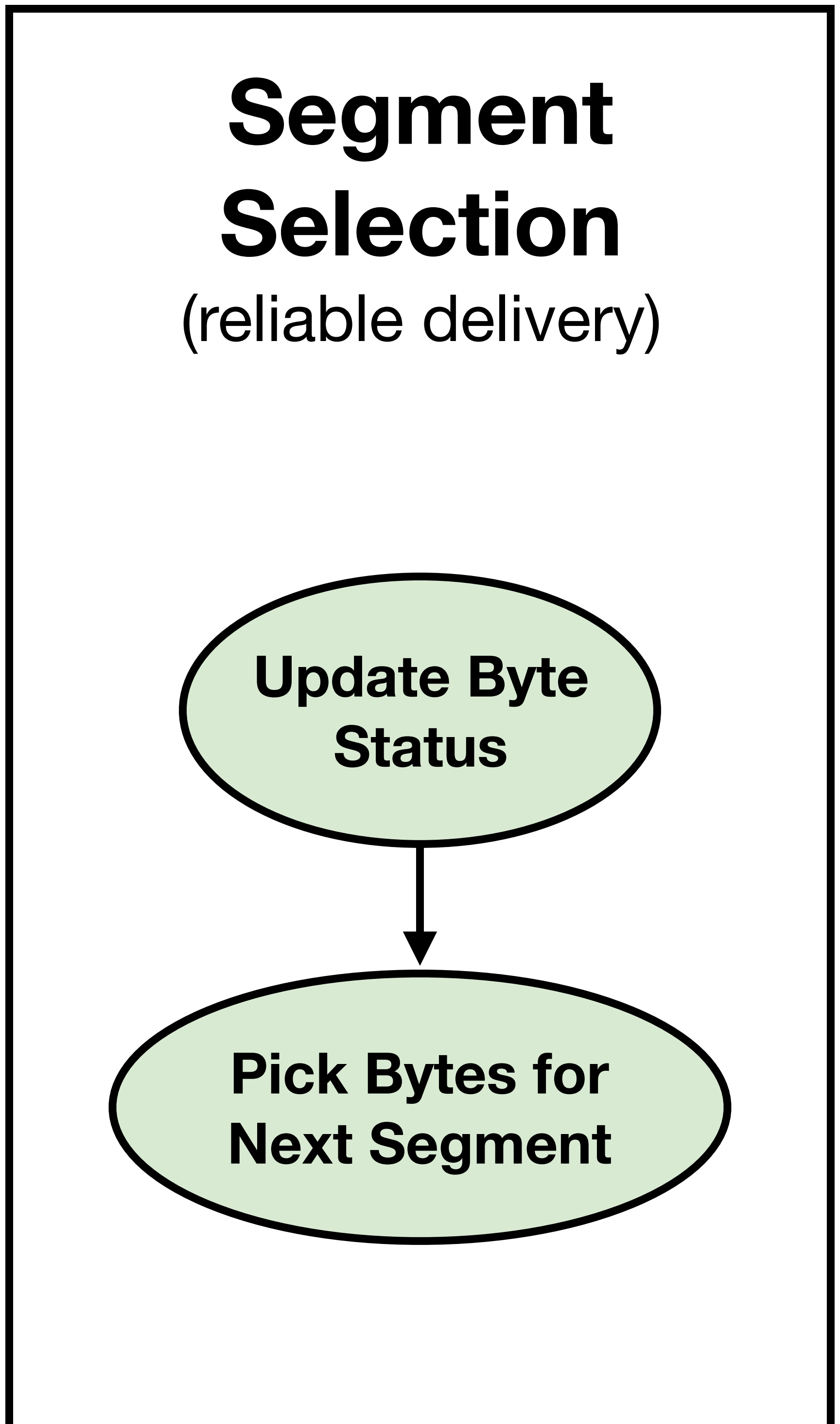


Segment Selection Patterns



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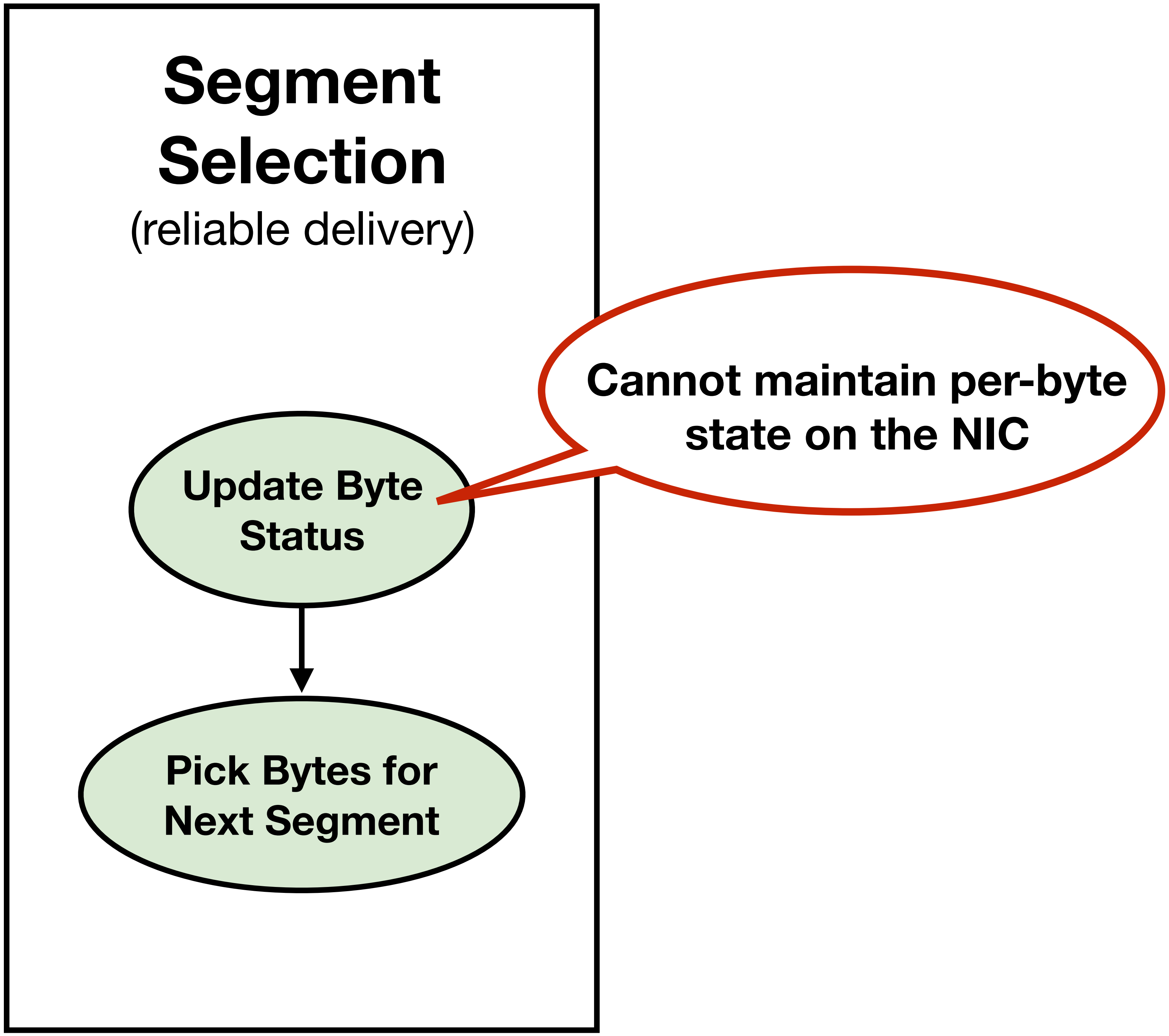

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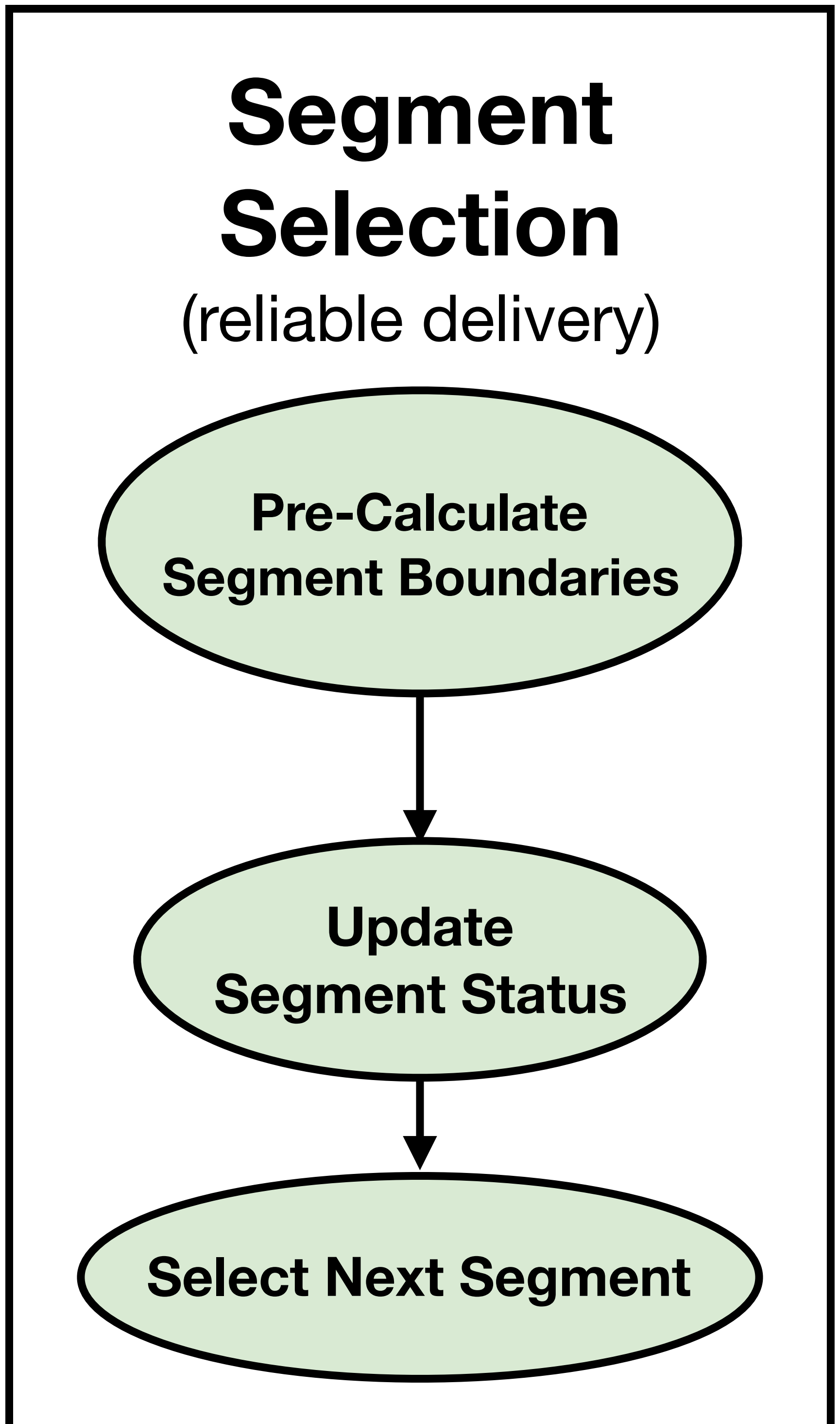

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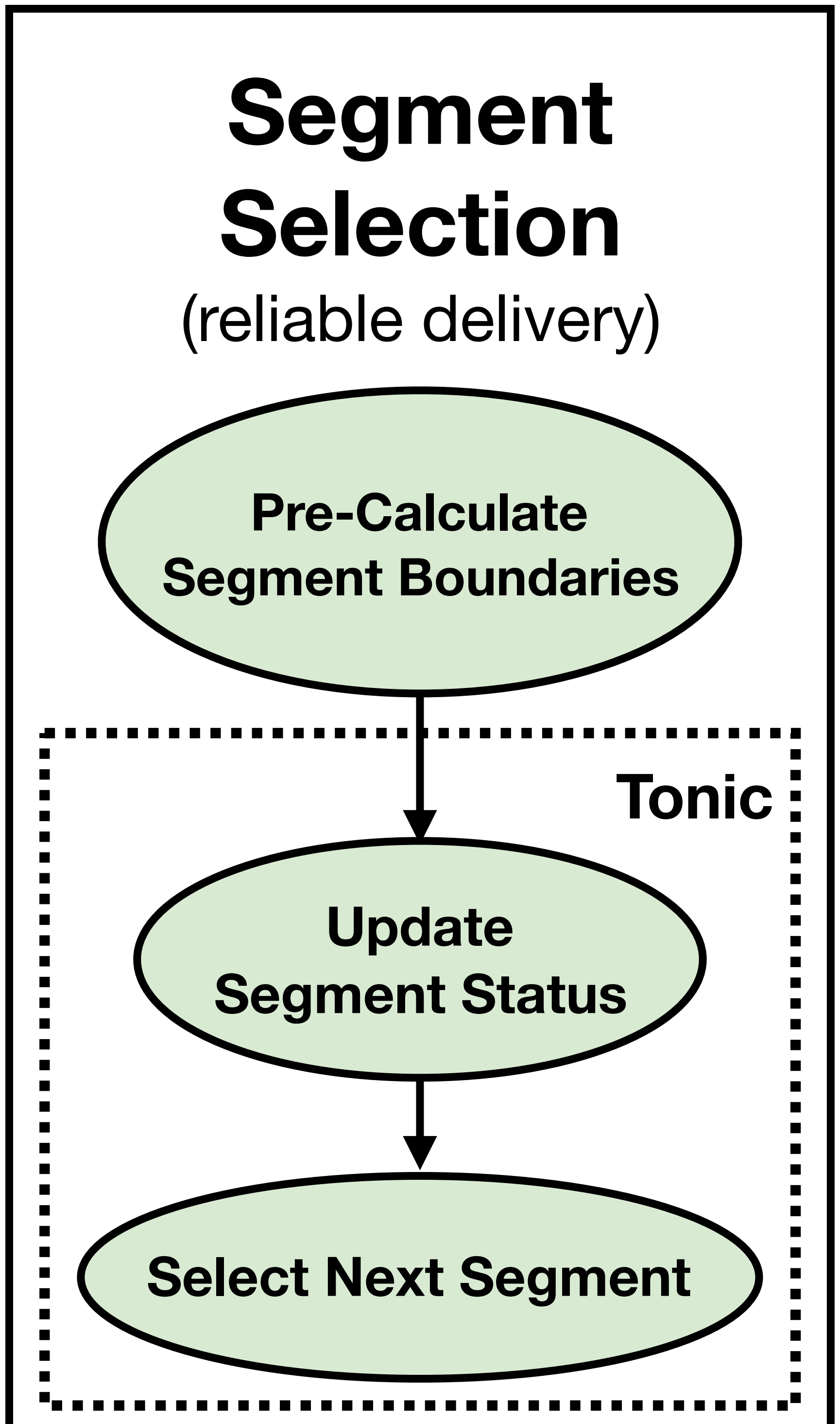

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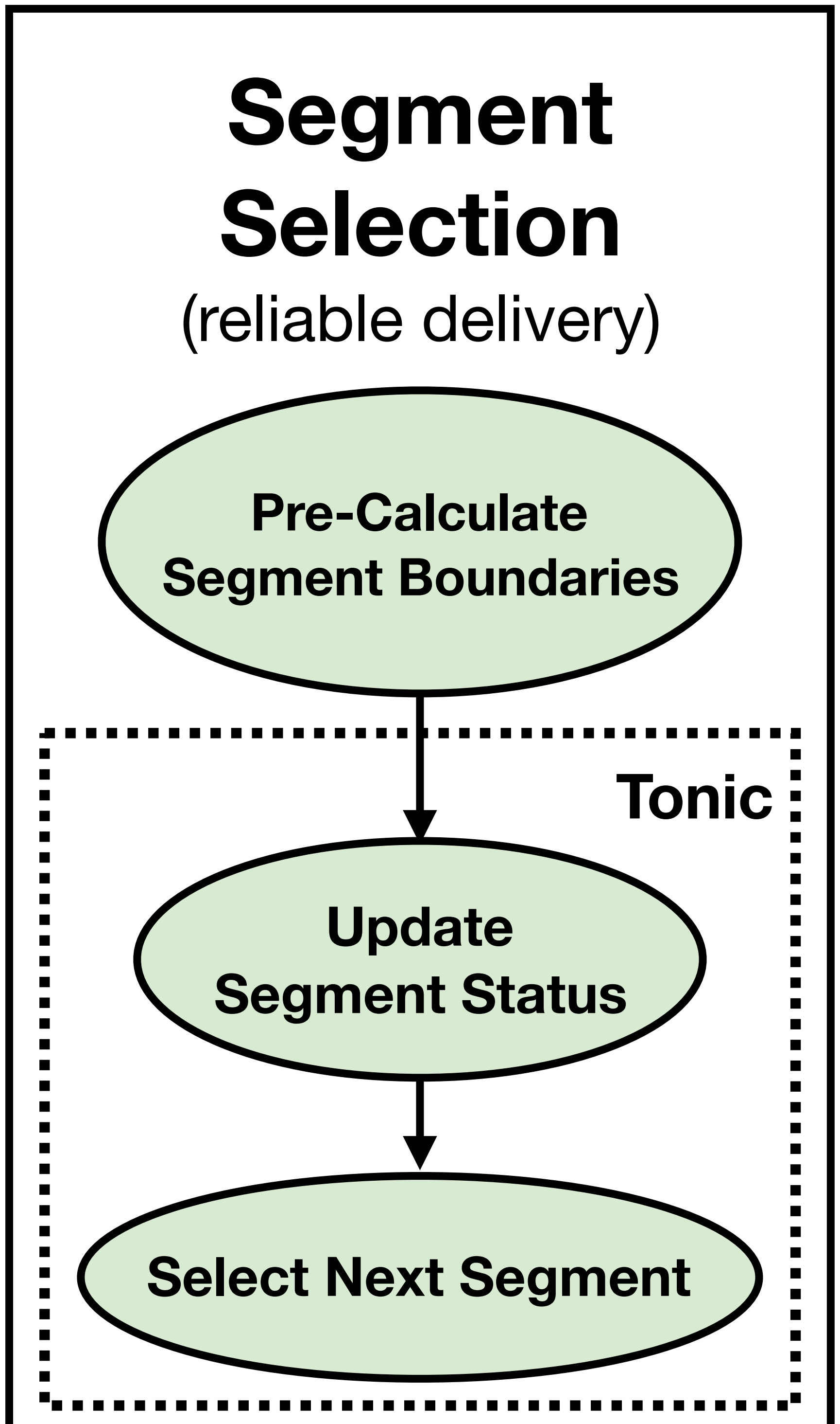

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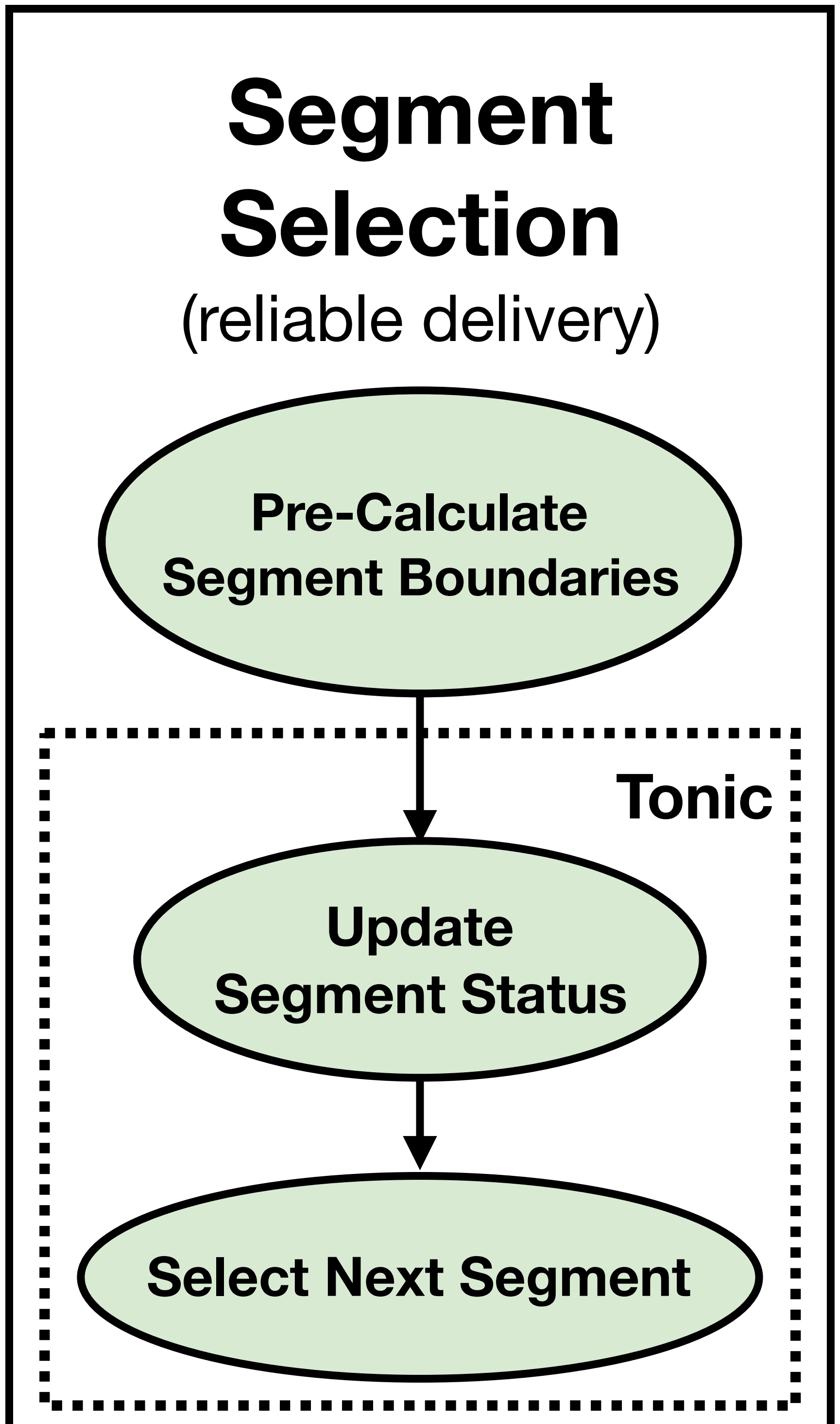

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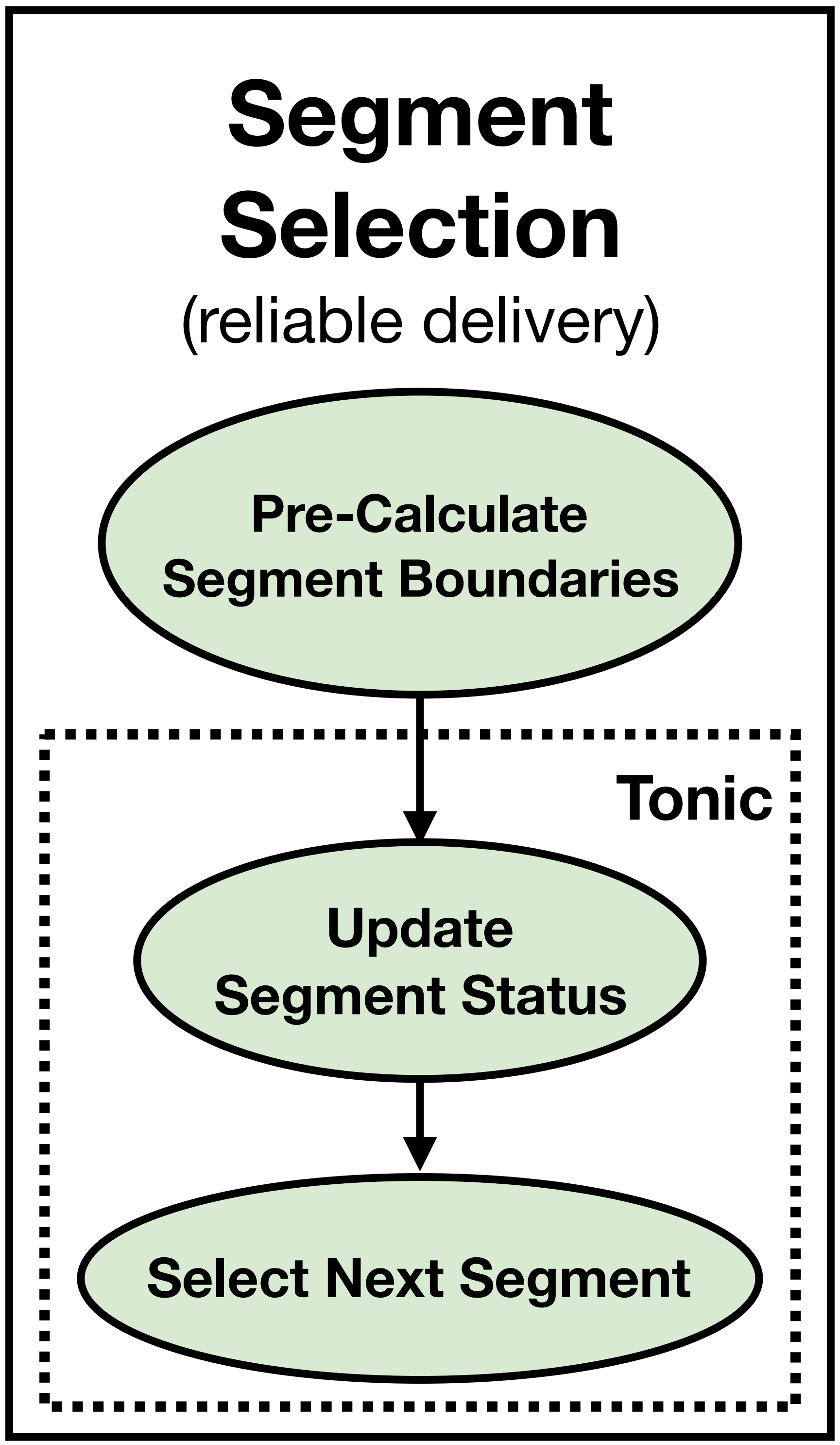

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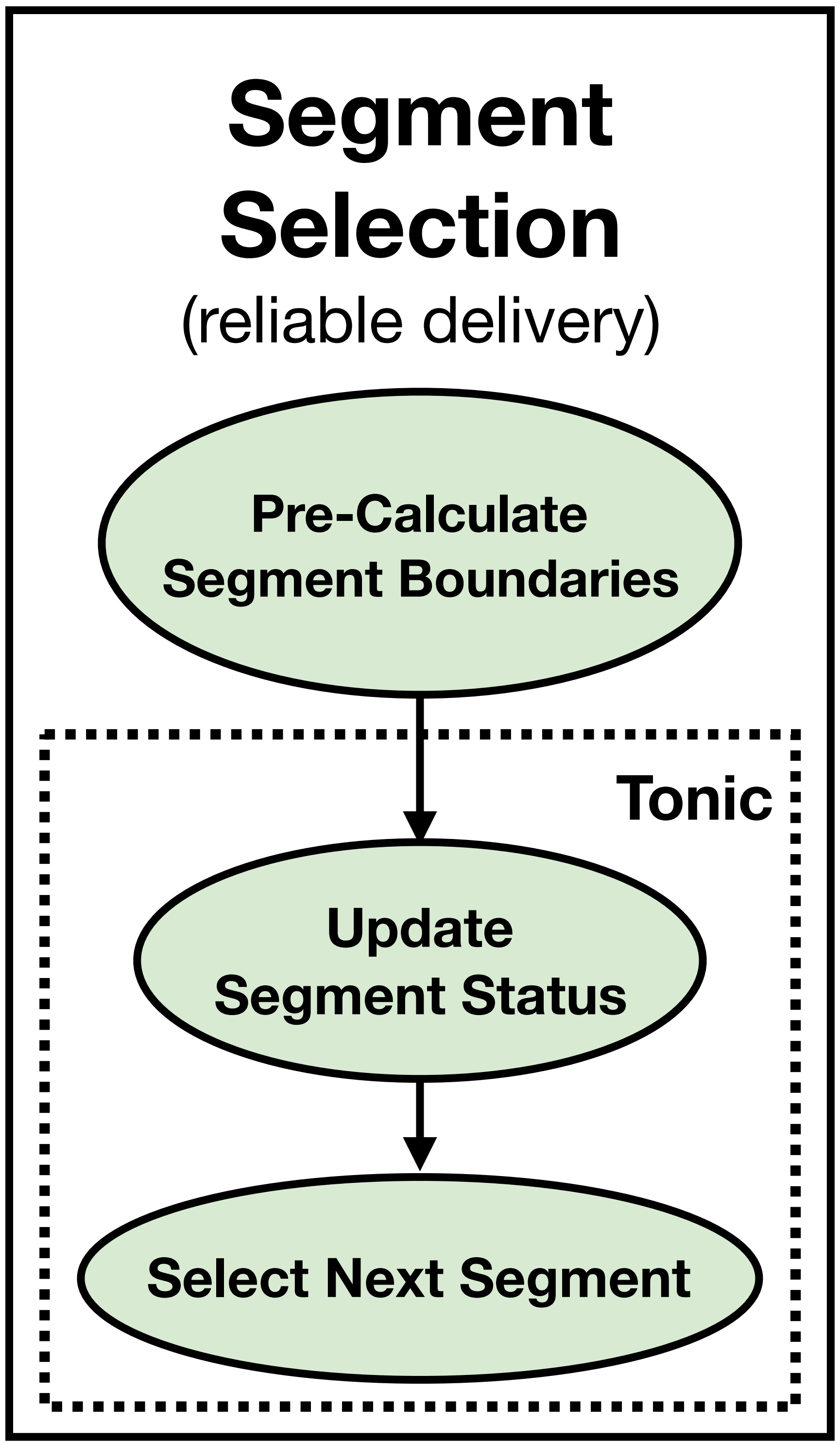

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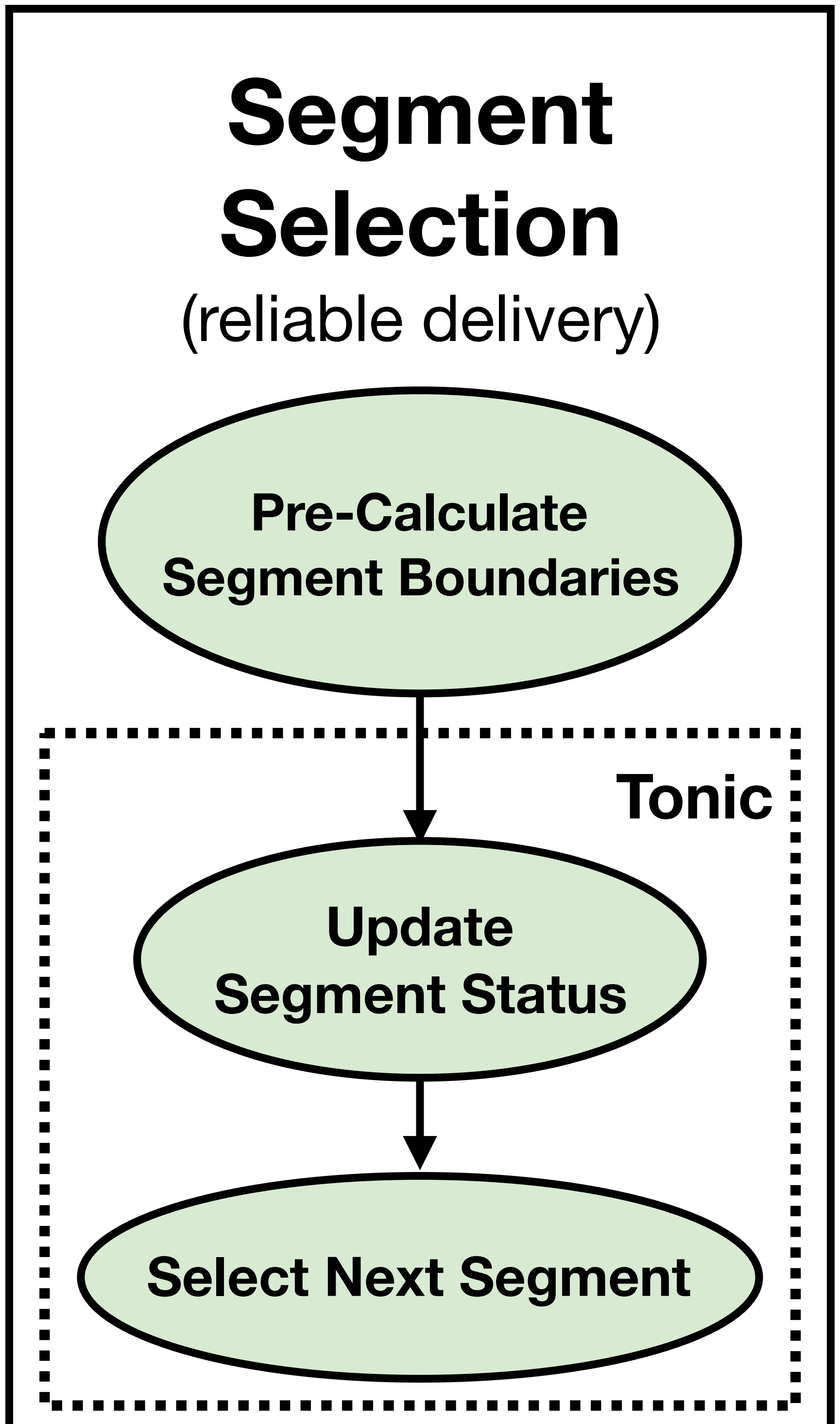

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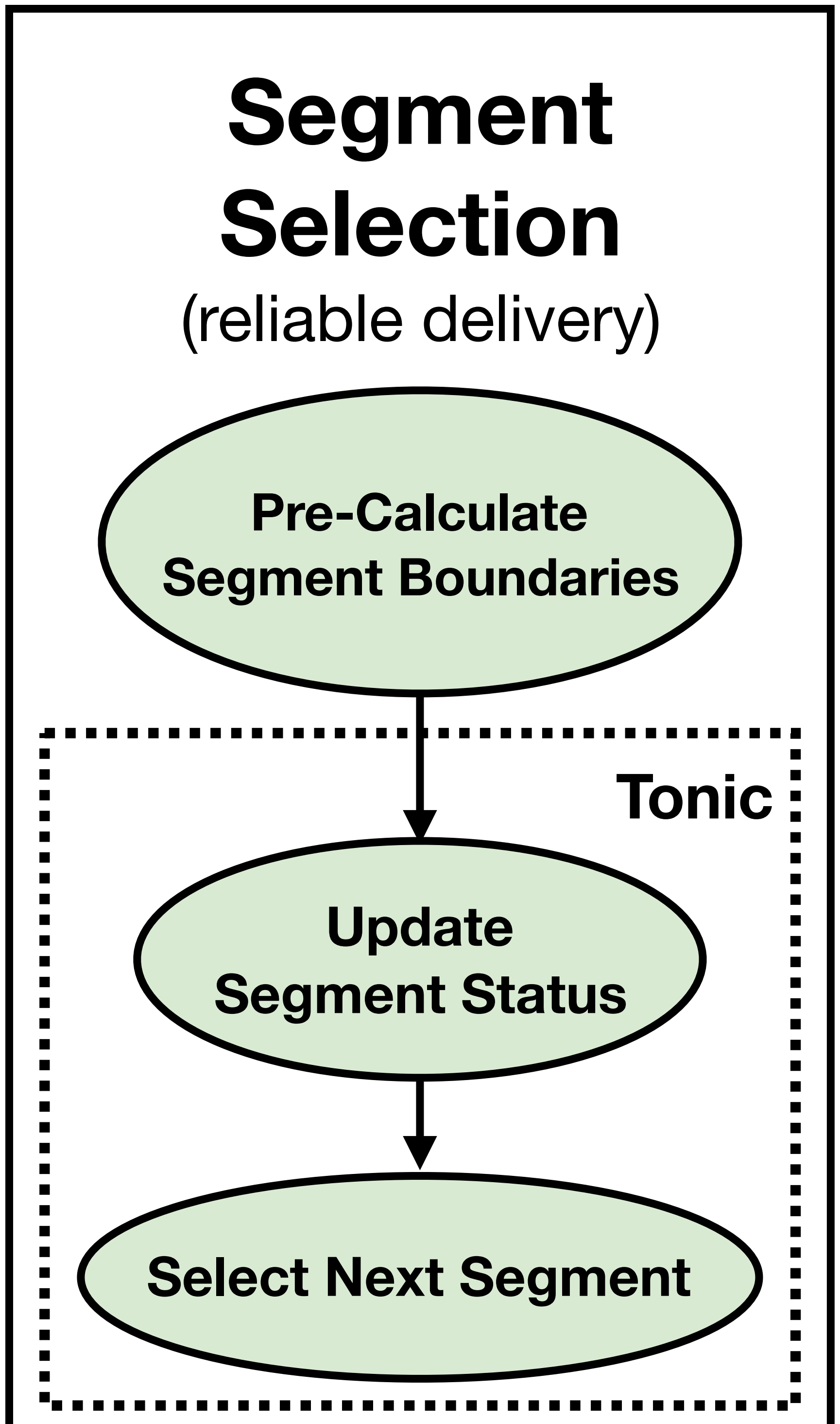

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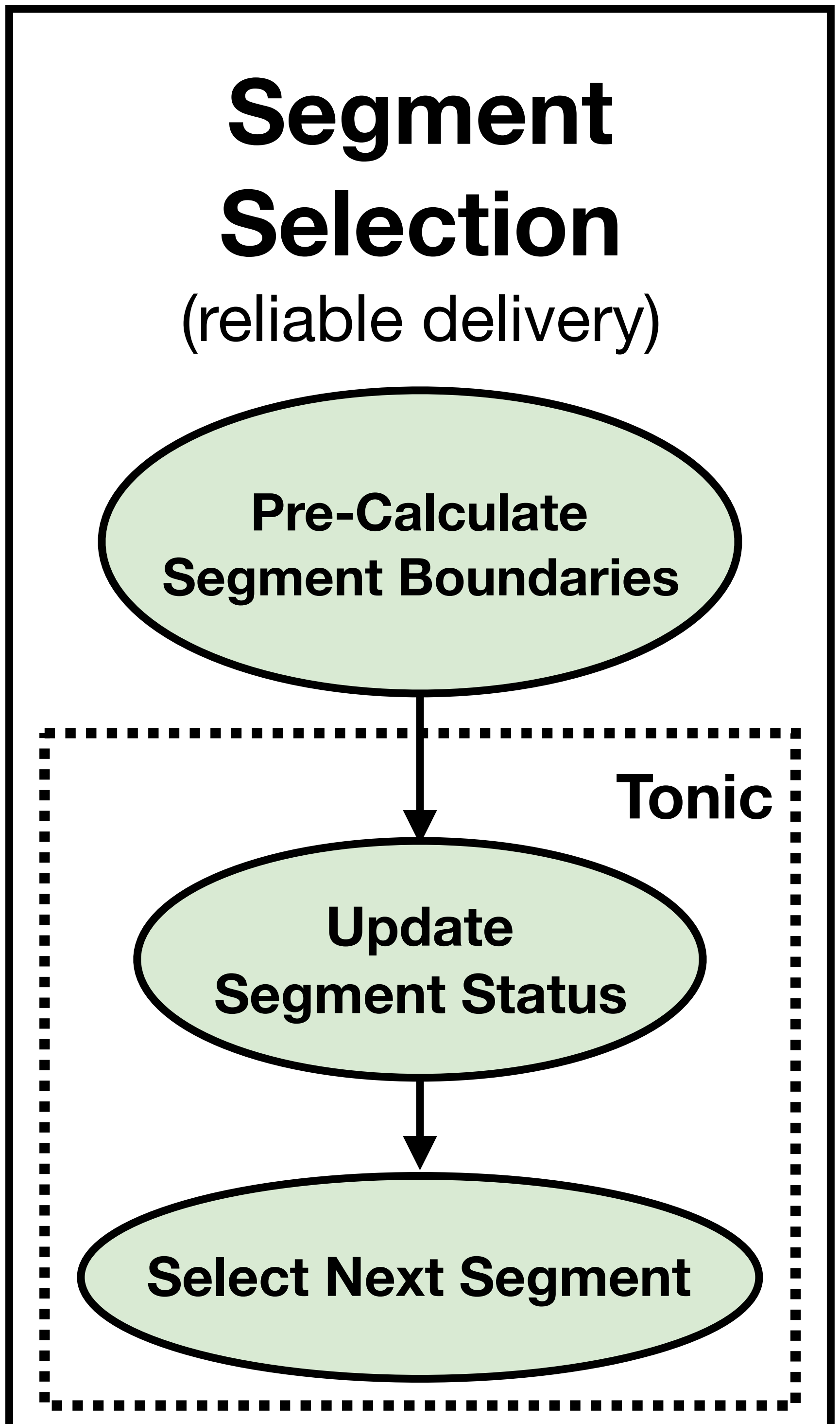

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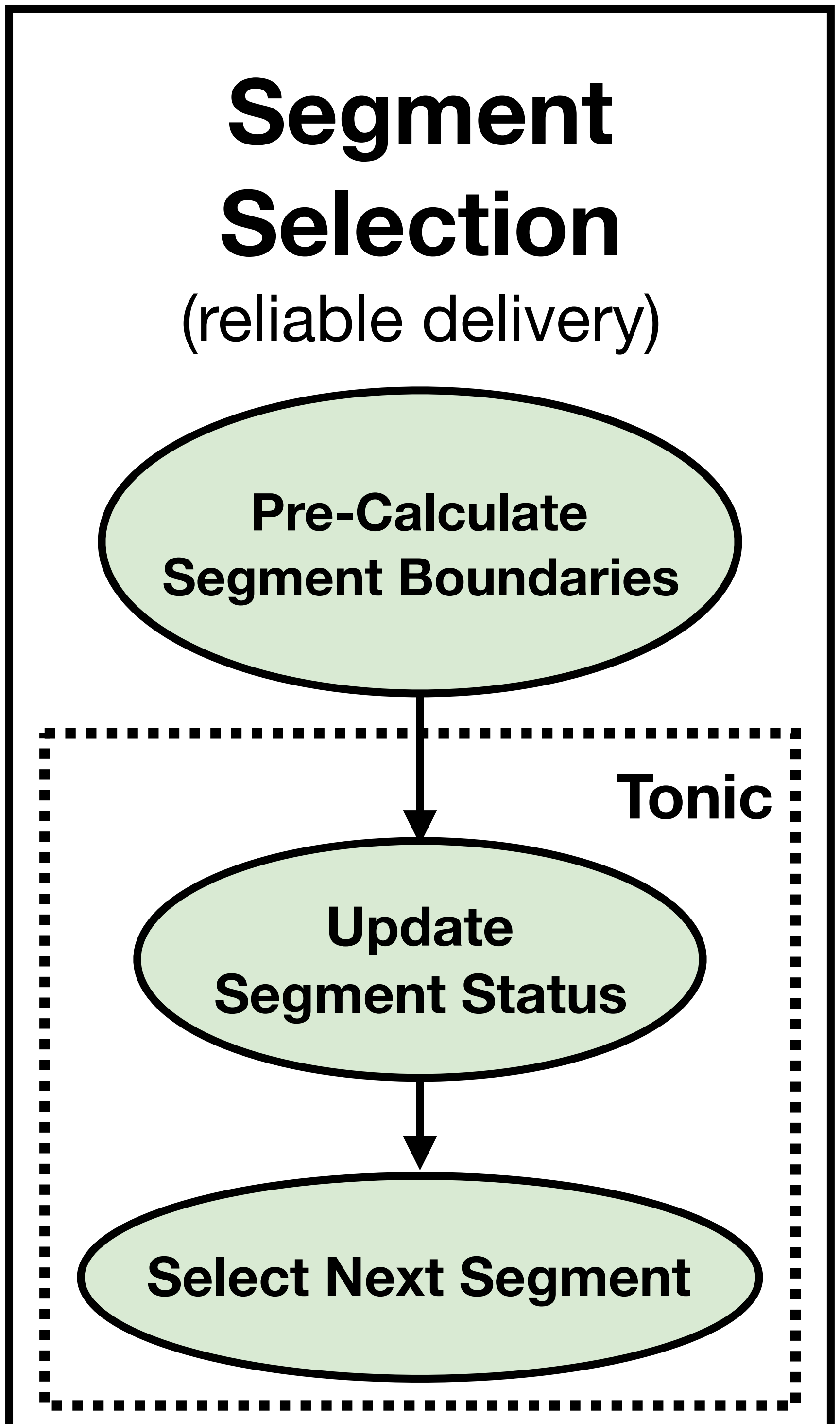

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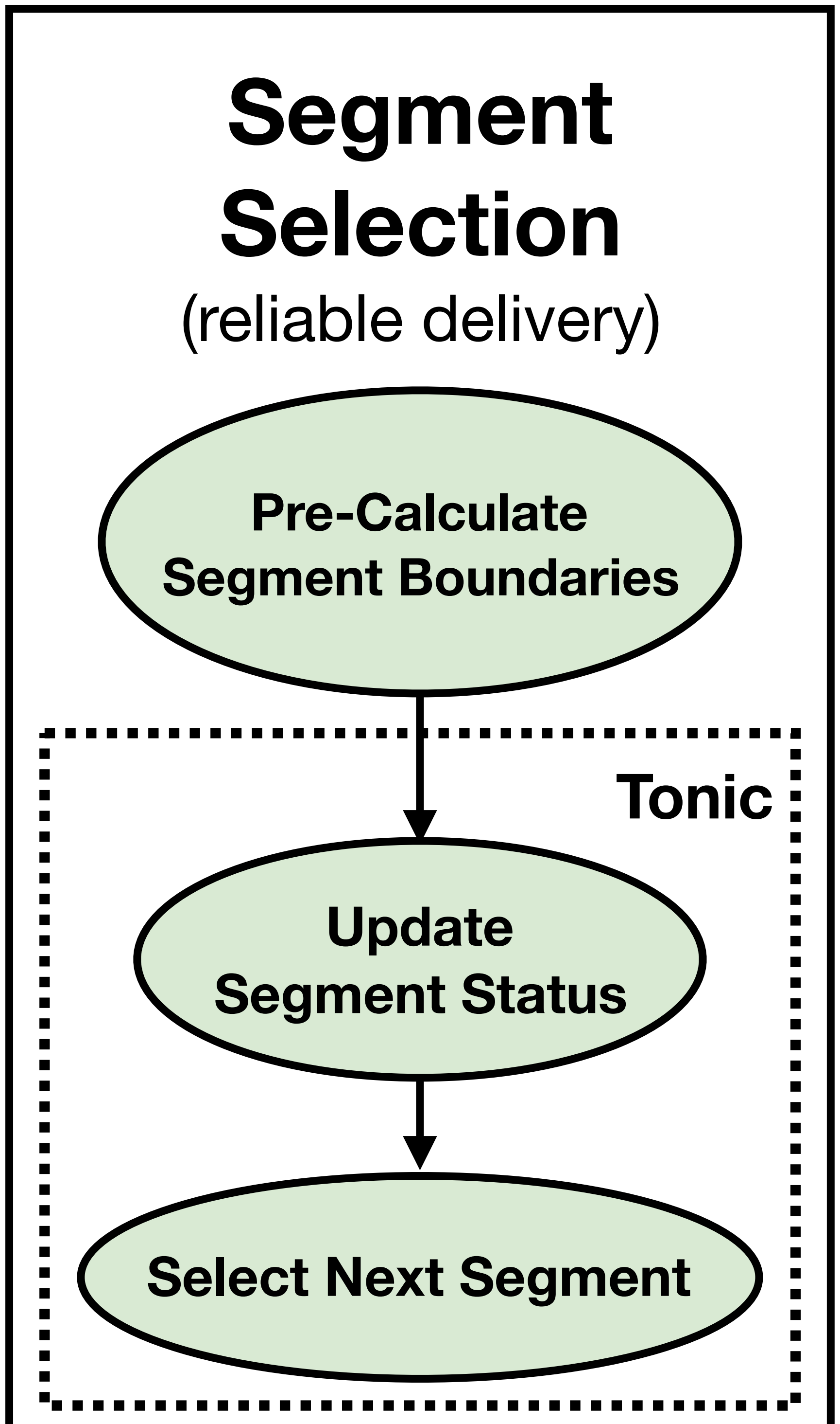

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Concurrent State Update

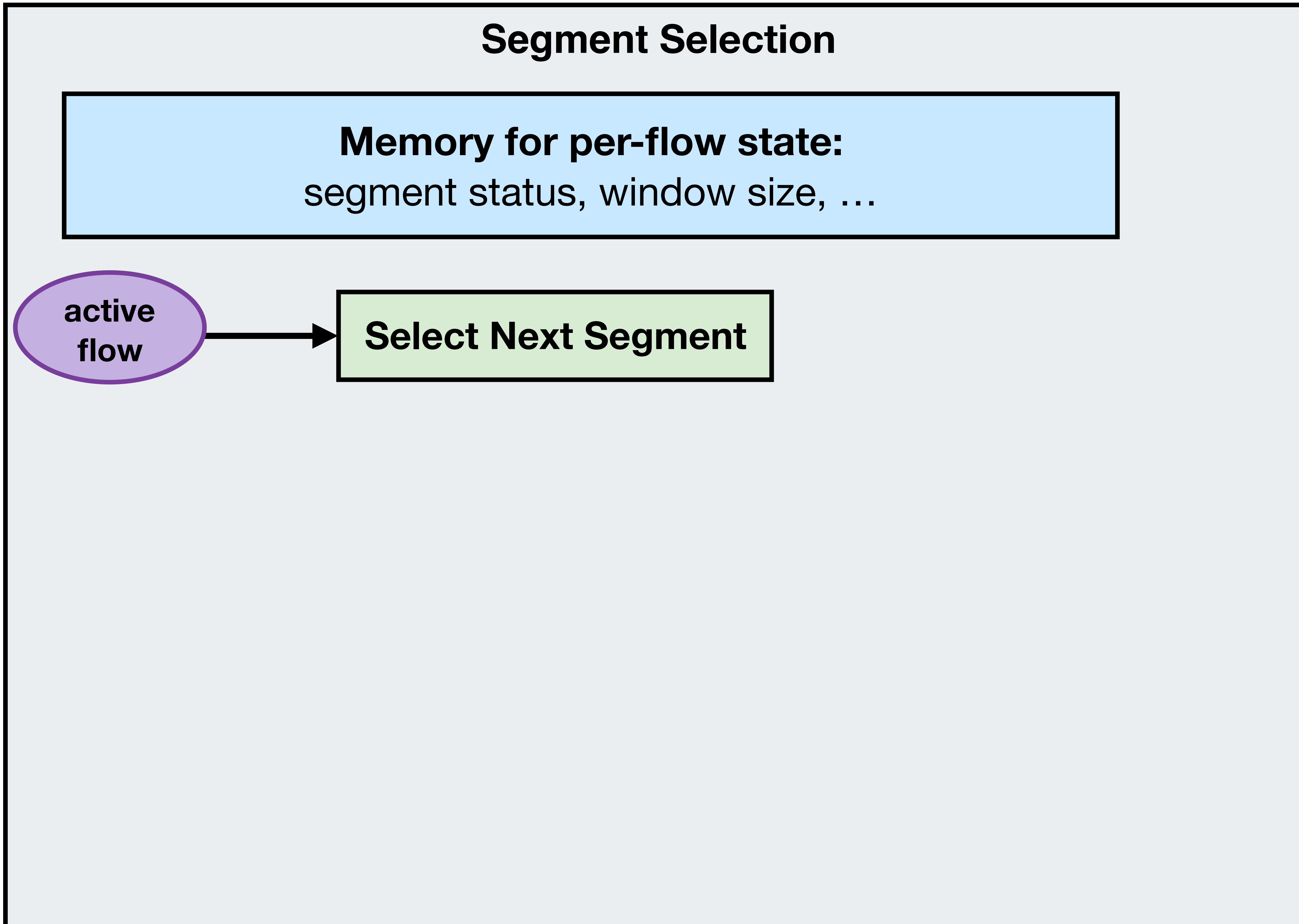
Segment Selection

Concurrent State Update

Segment Selection

Memory for per-flow state:
segment status, window size, …

Concurrent State Update



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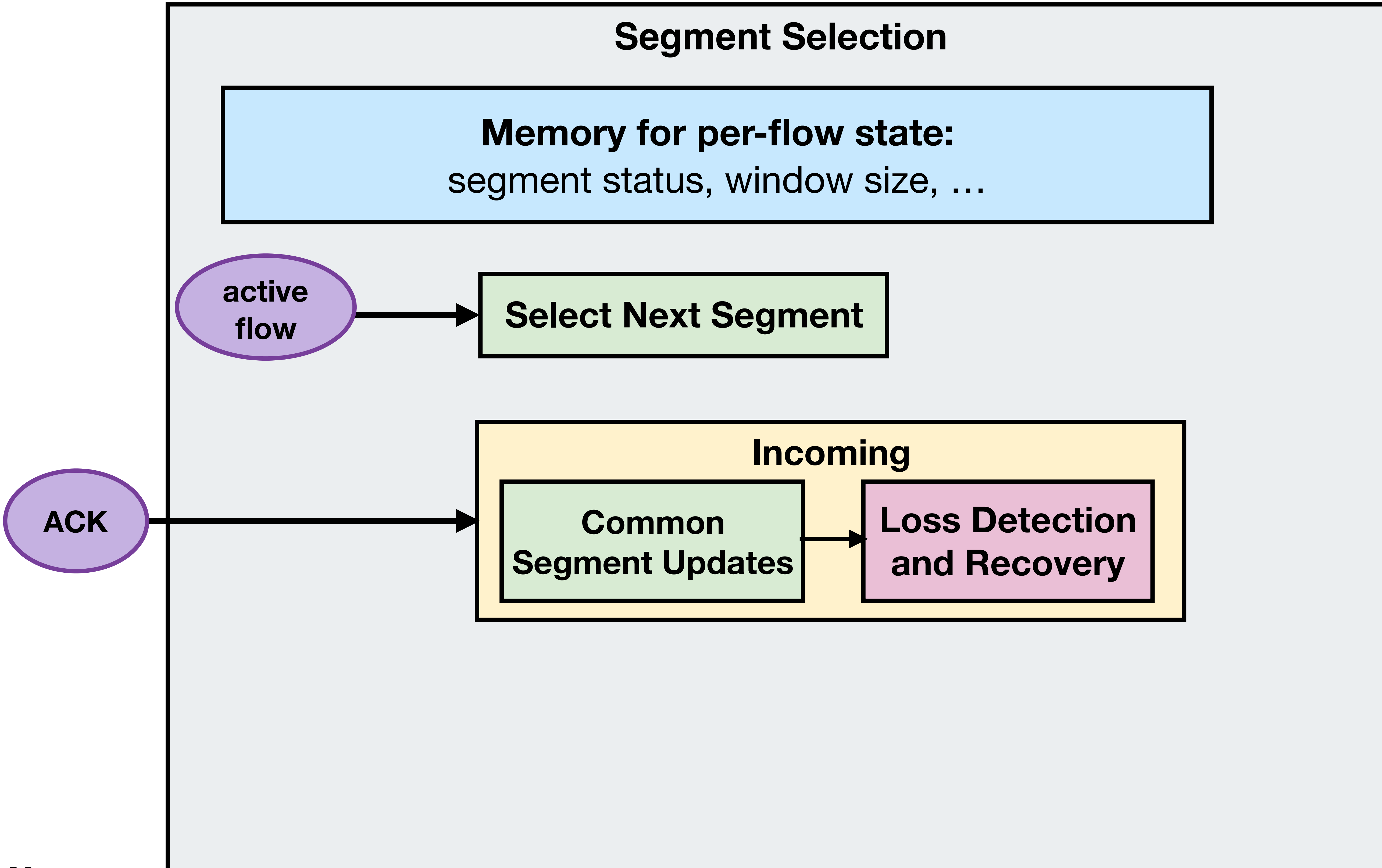

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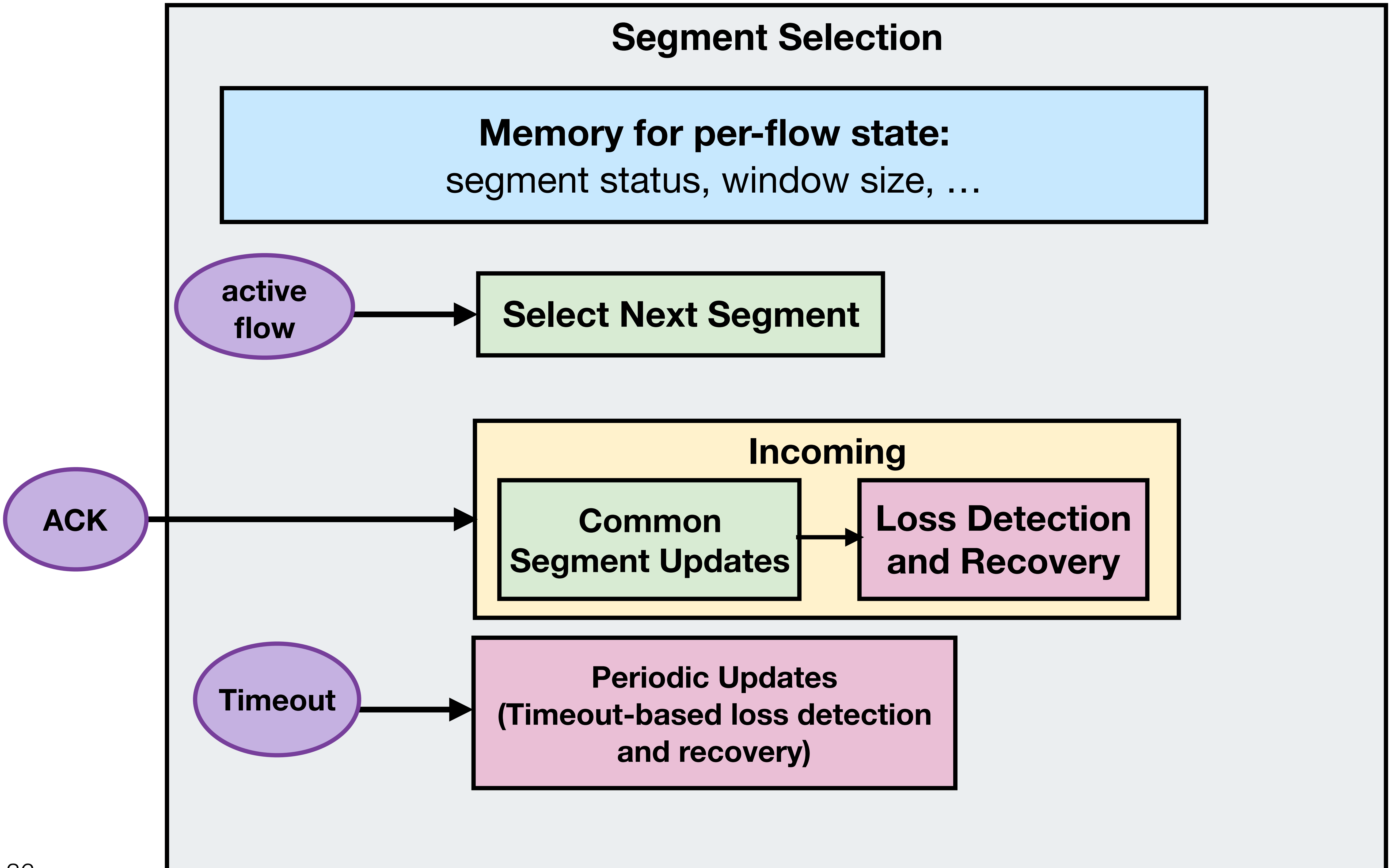

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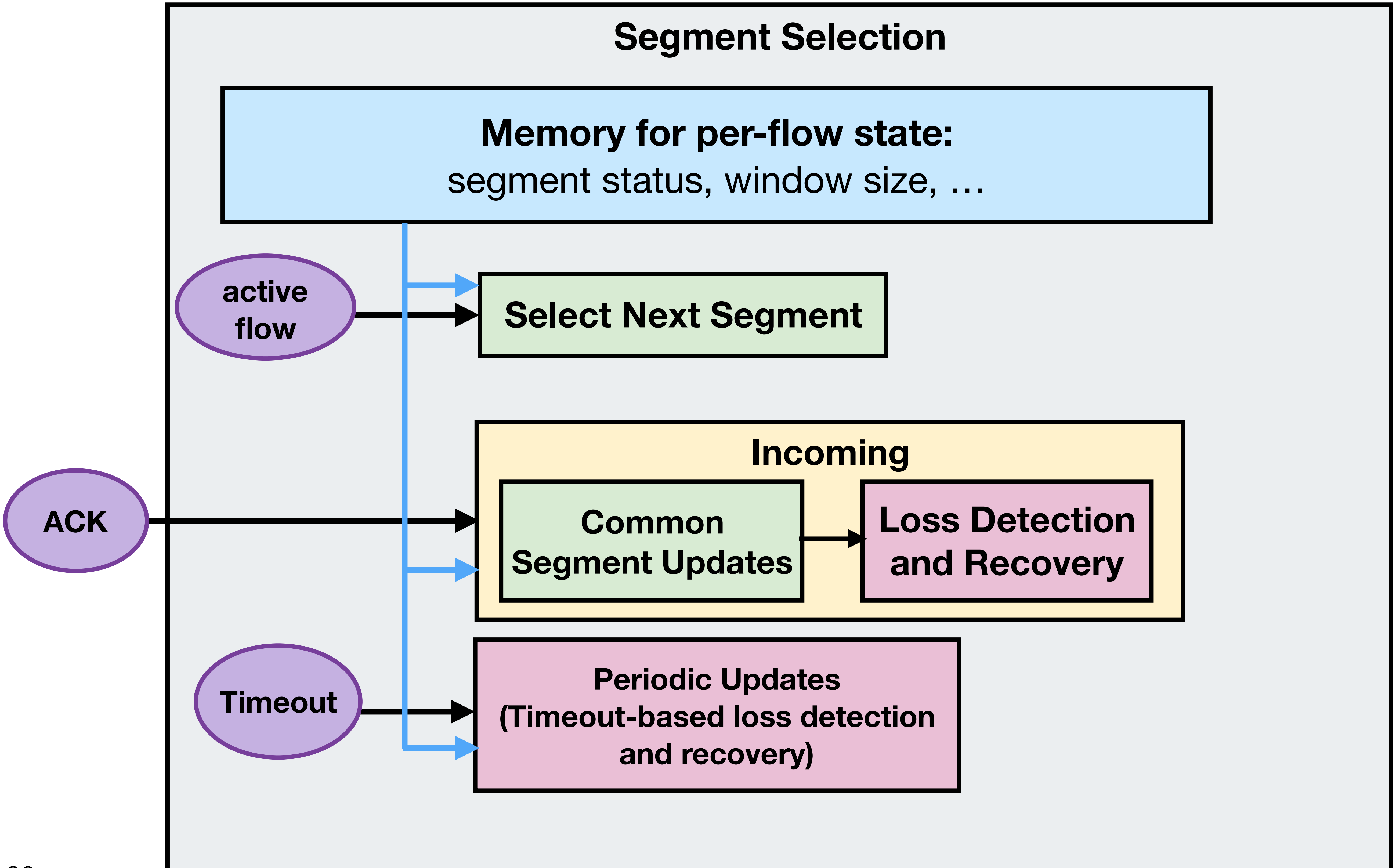

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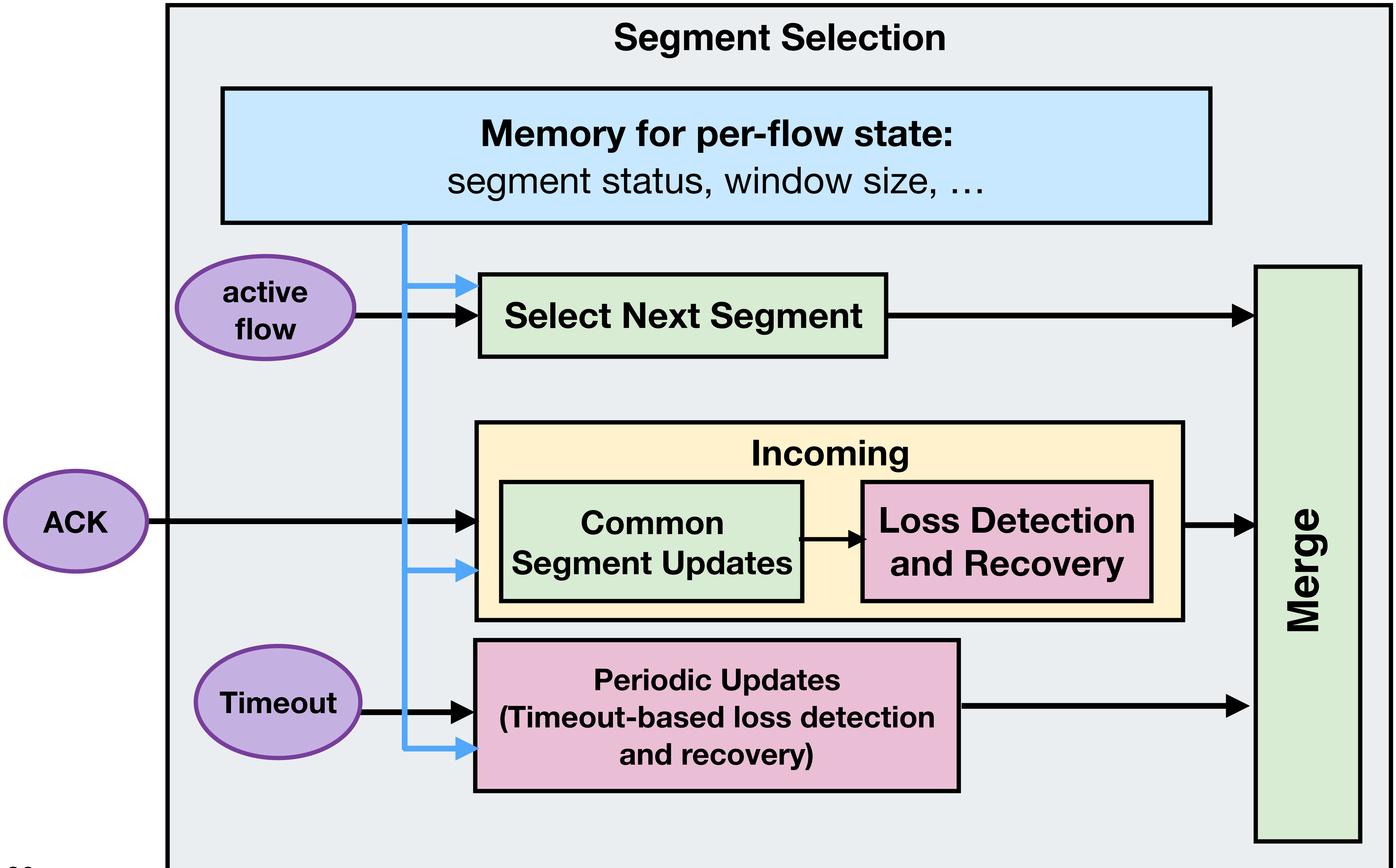

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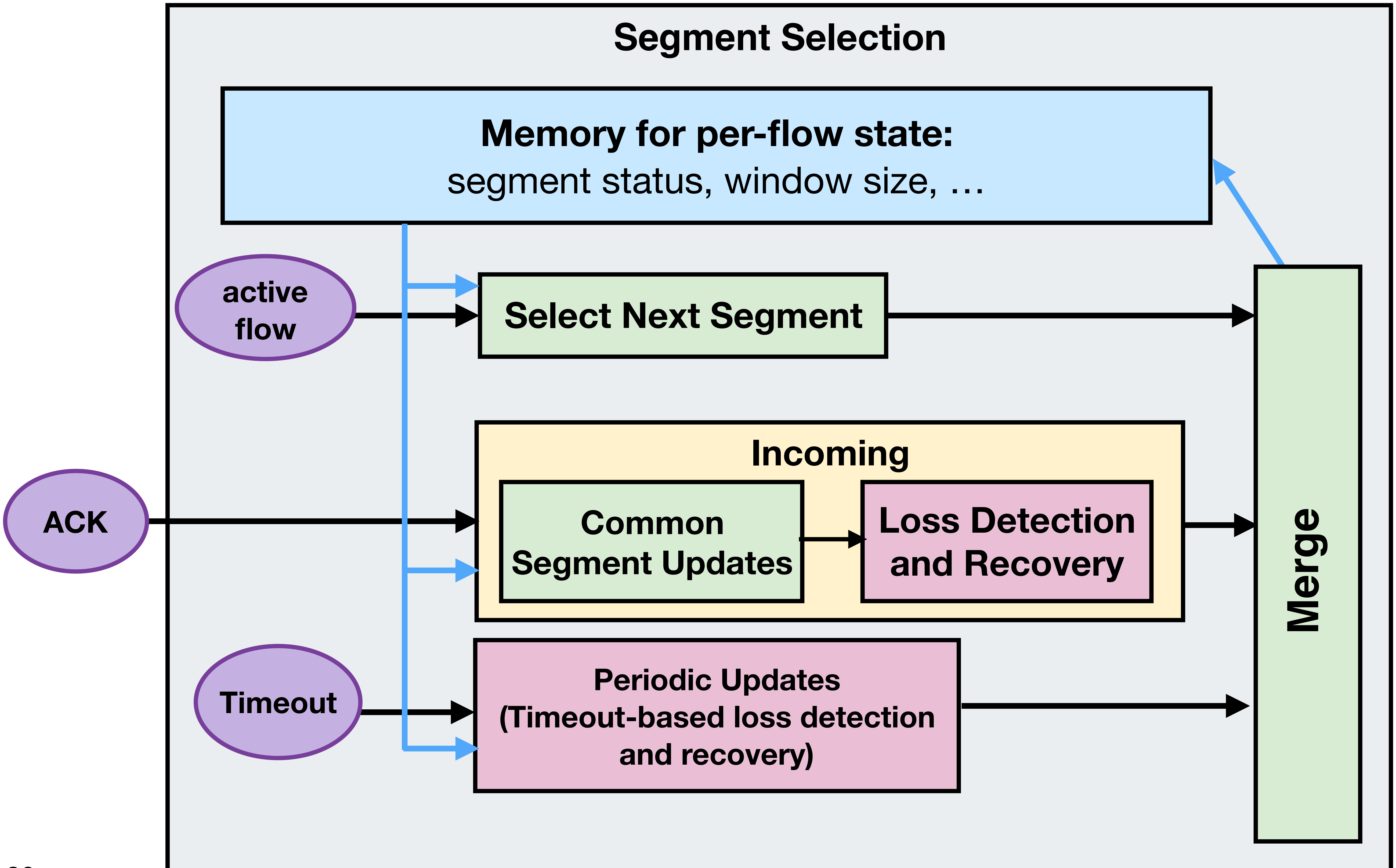

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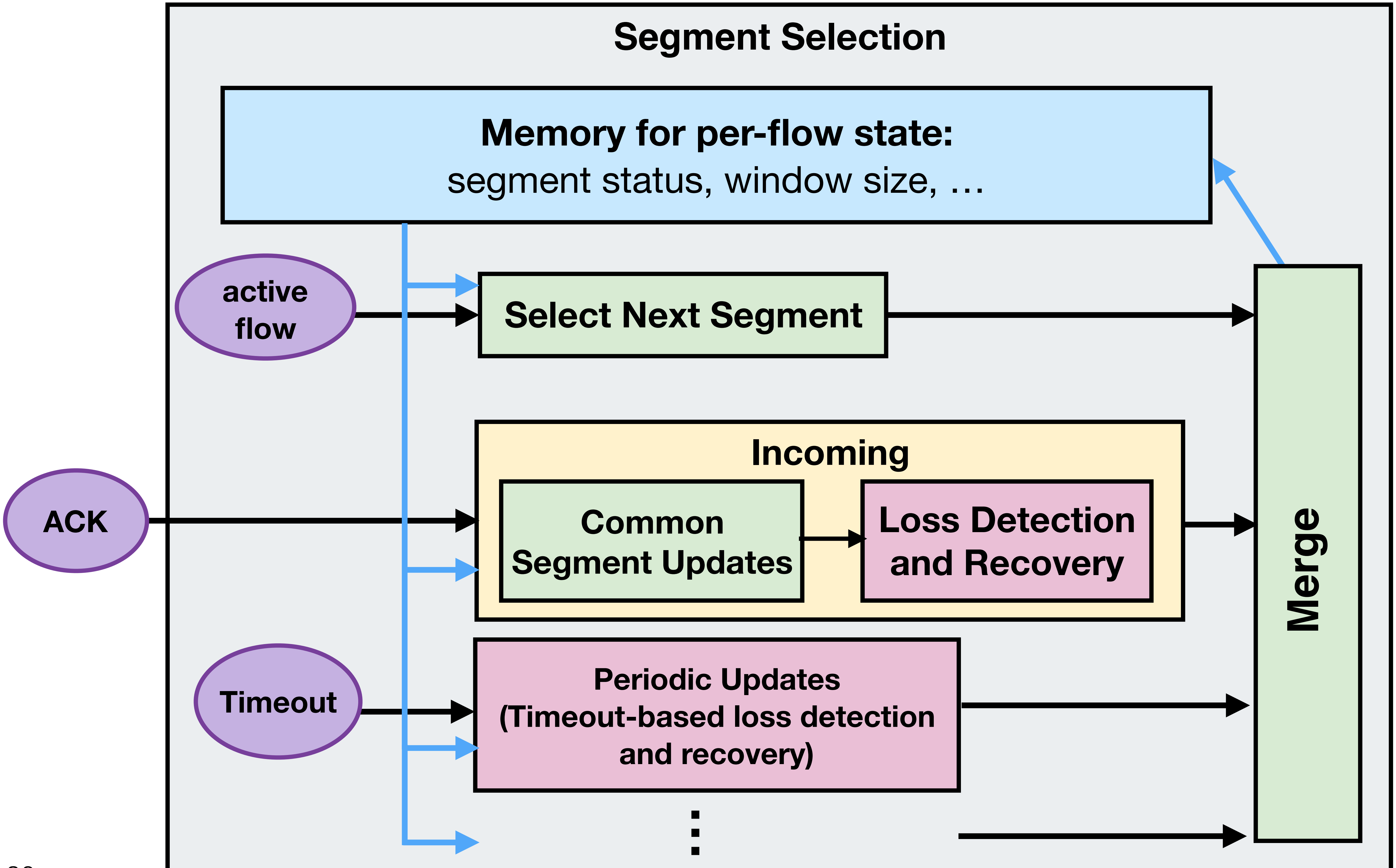

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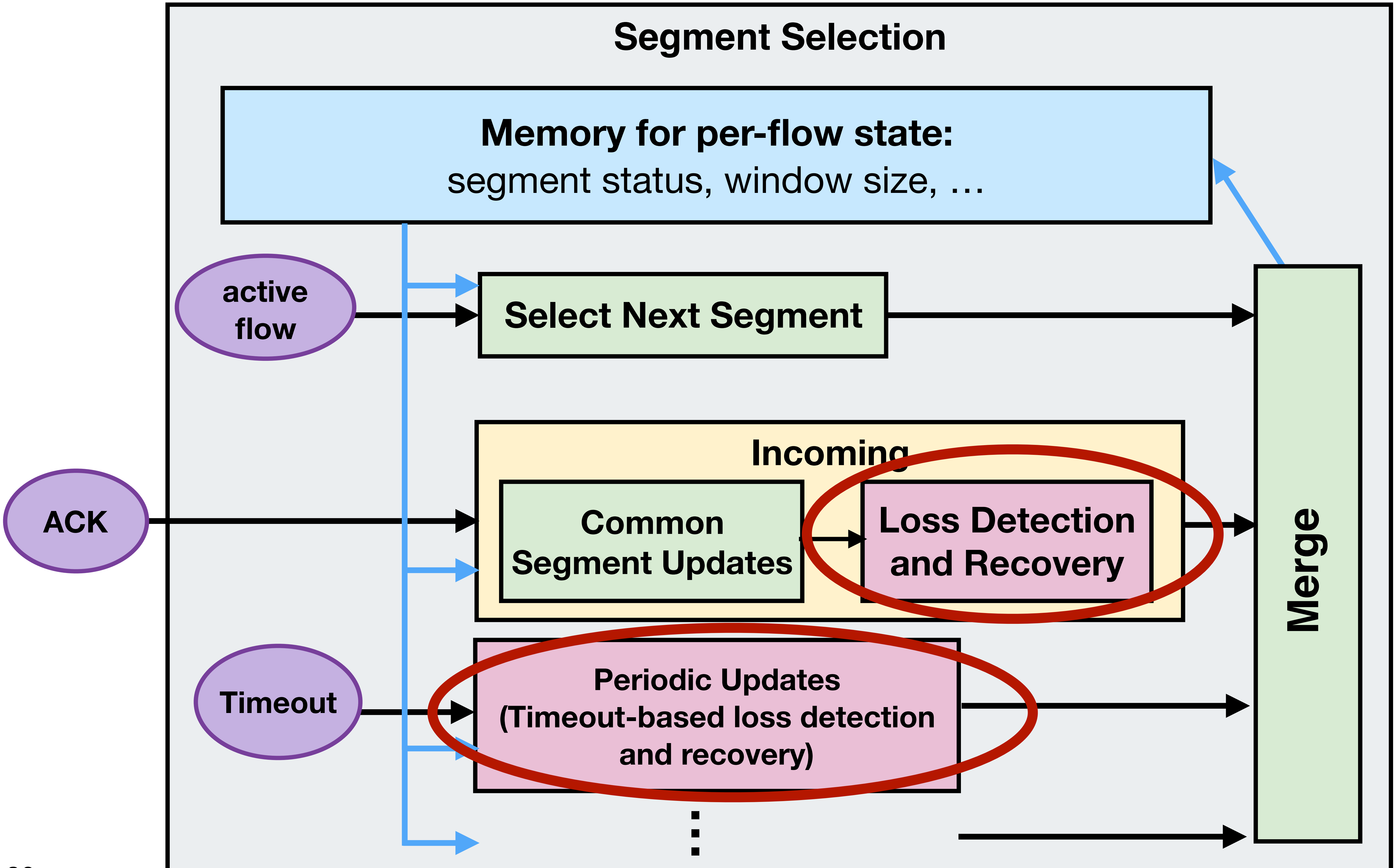

Credit Management Patterns

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Credit Management
(congestion control)

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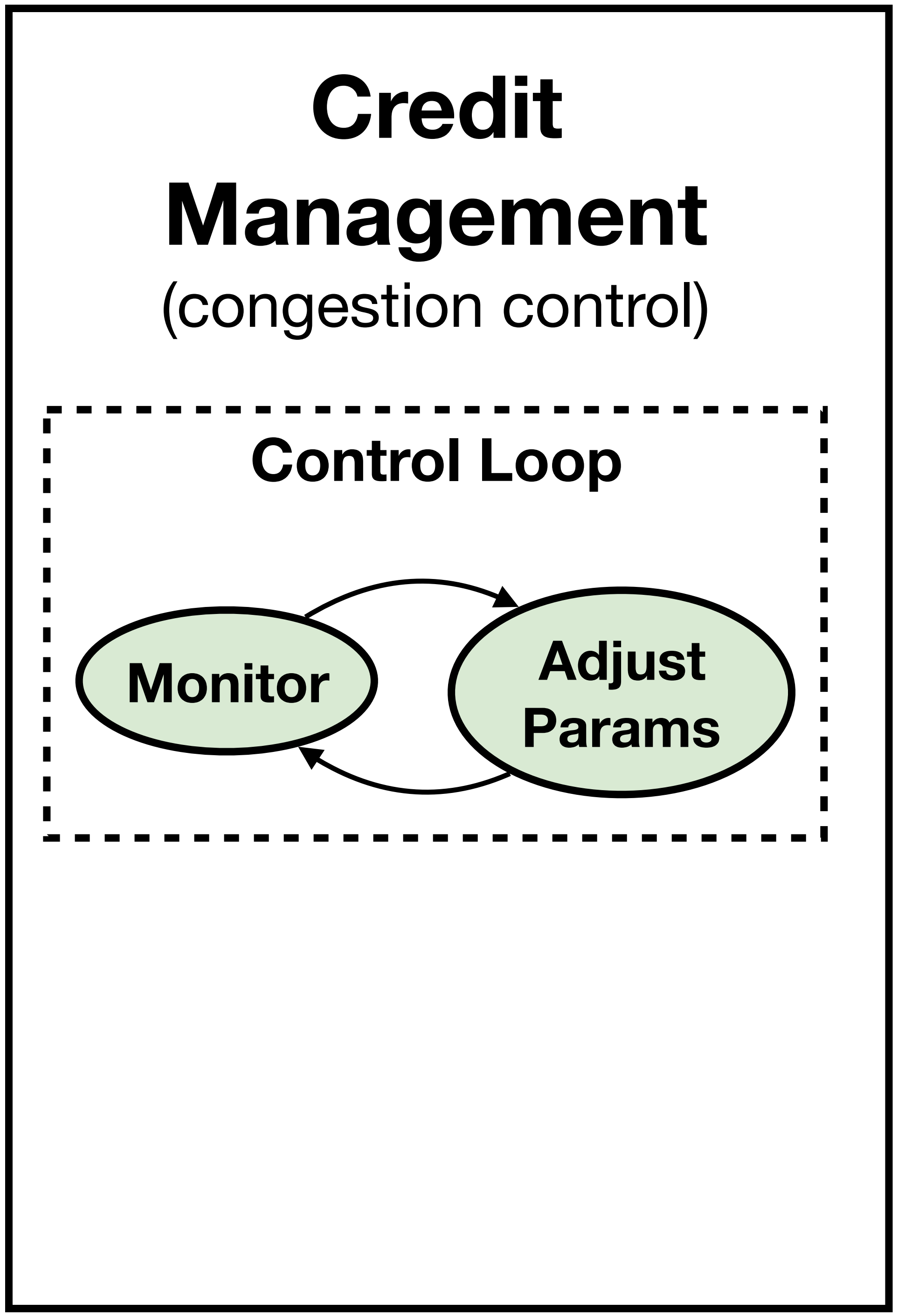

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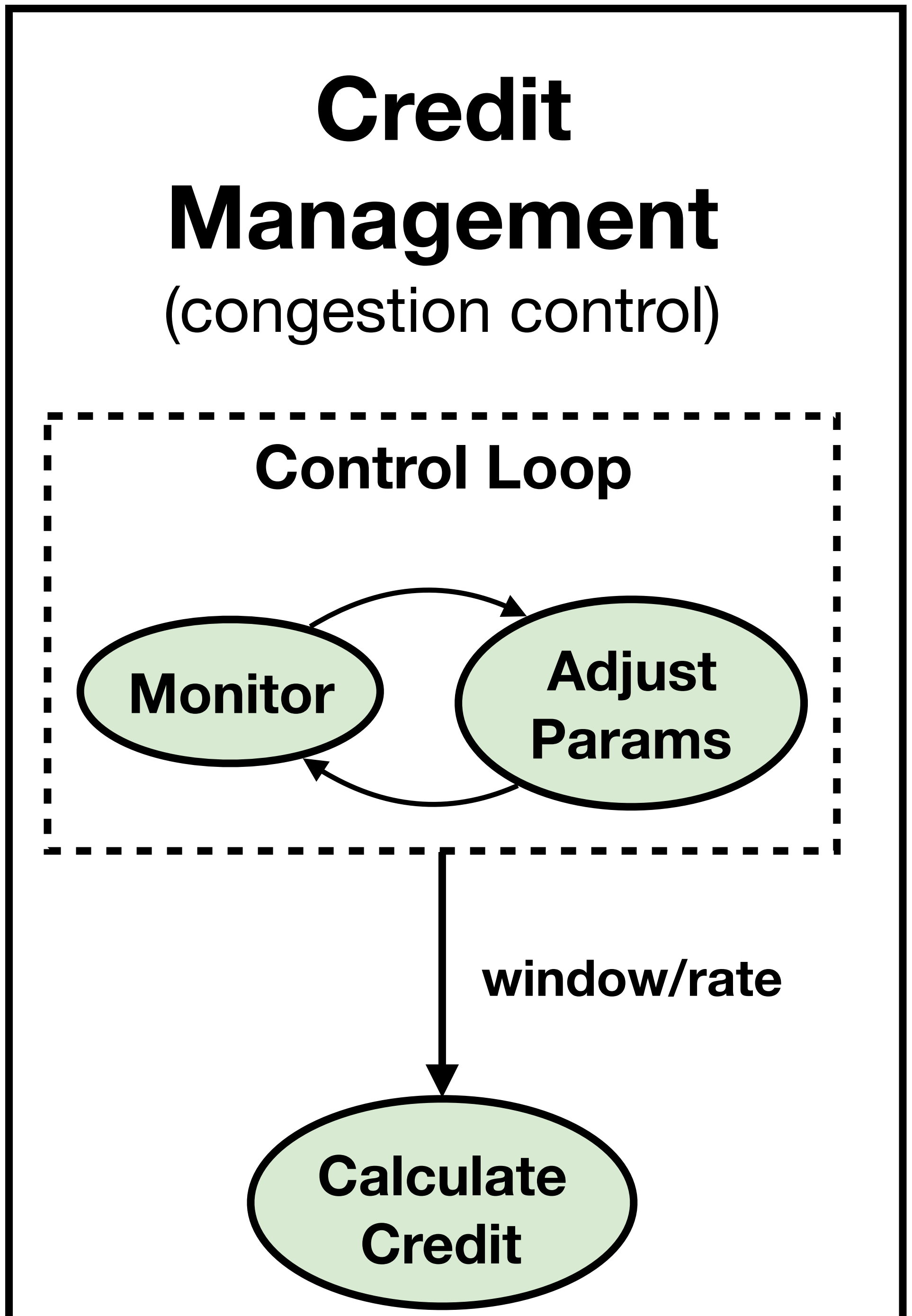

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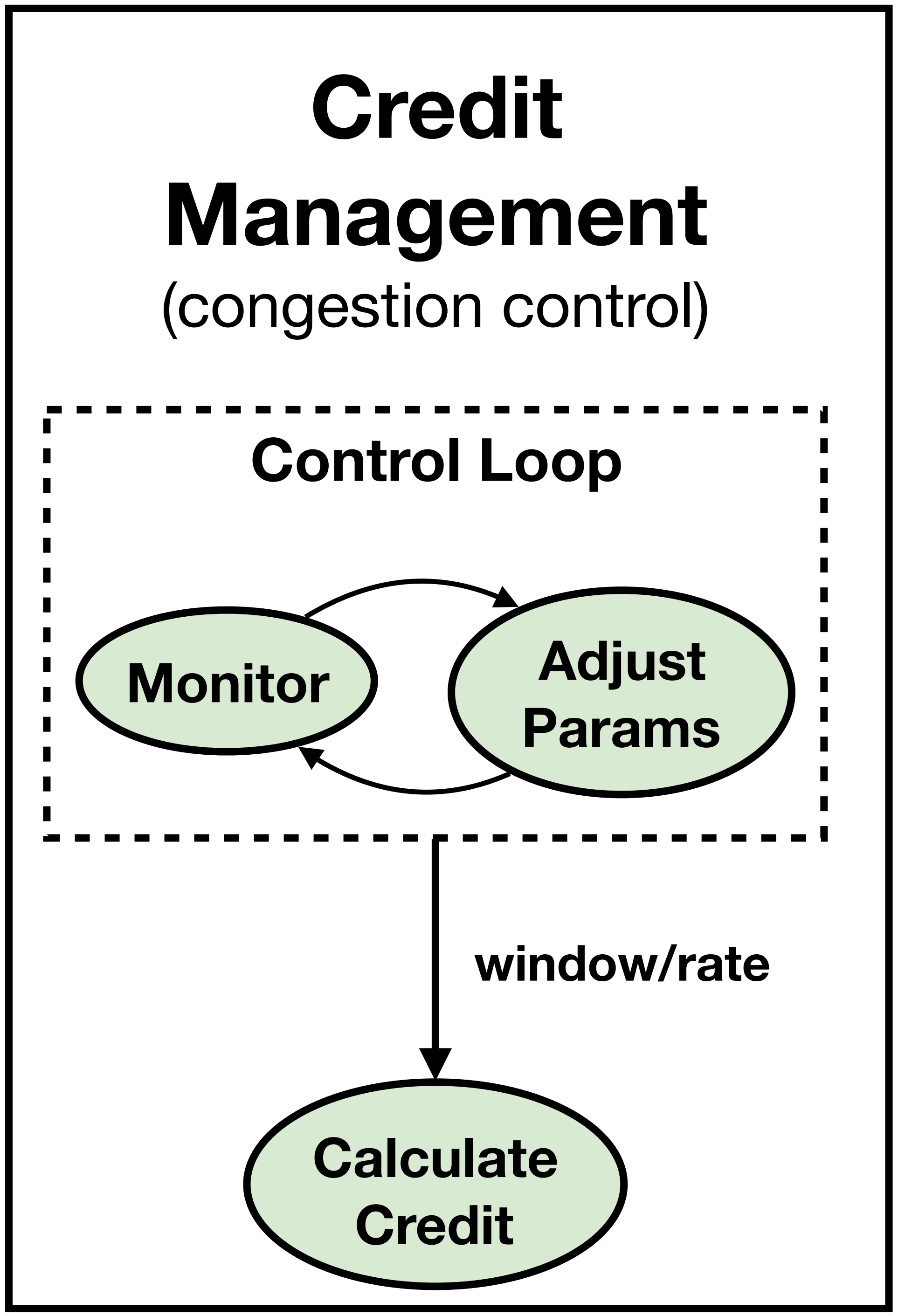
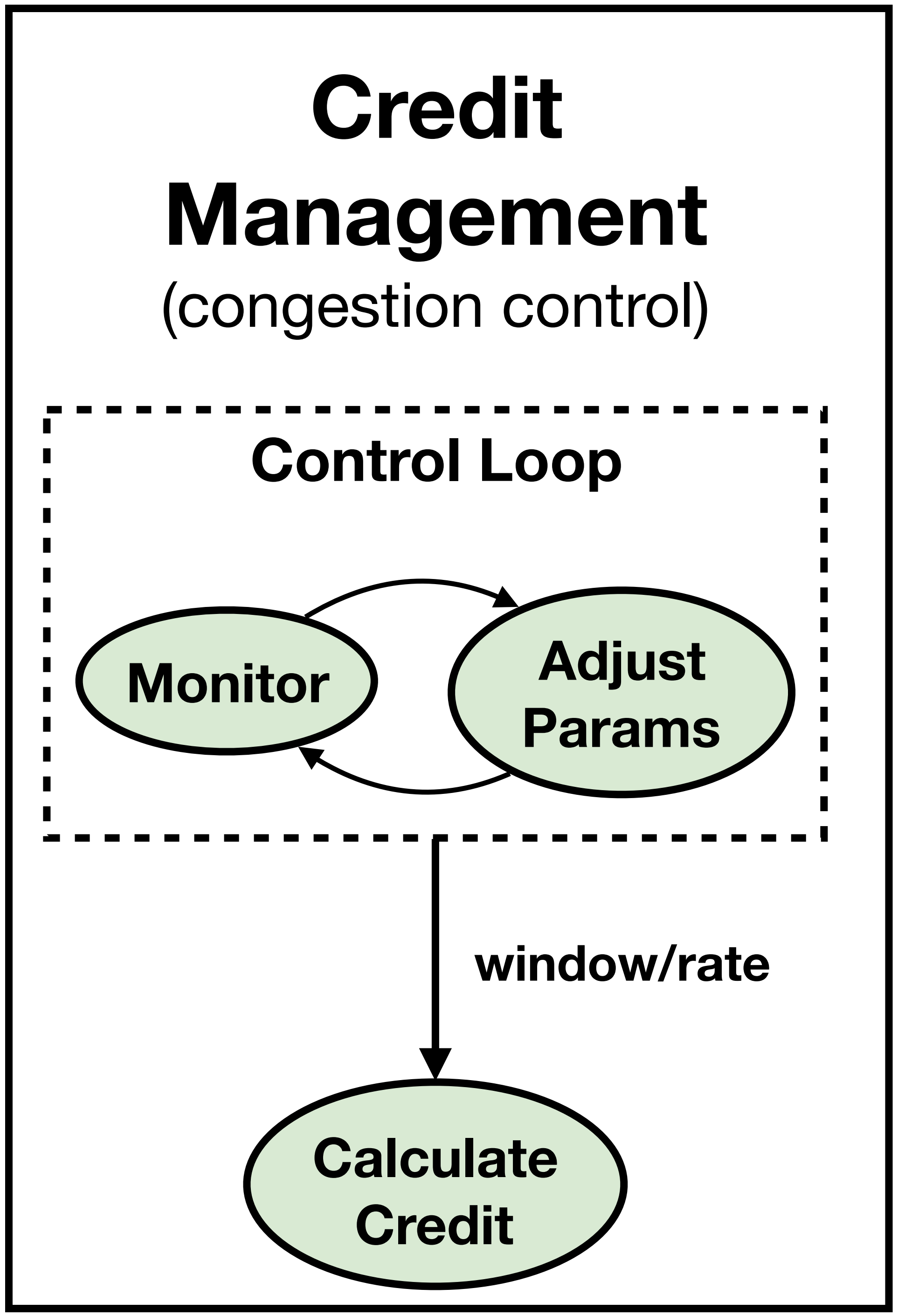


1. **Three common credit calculation schemes**

Credit Management Patterns



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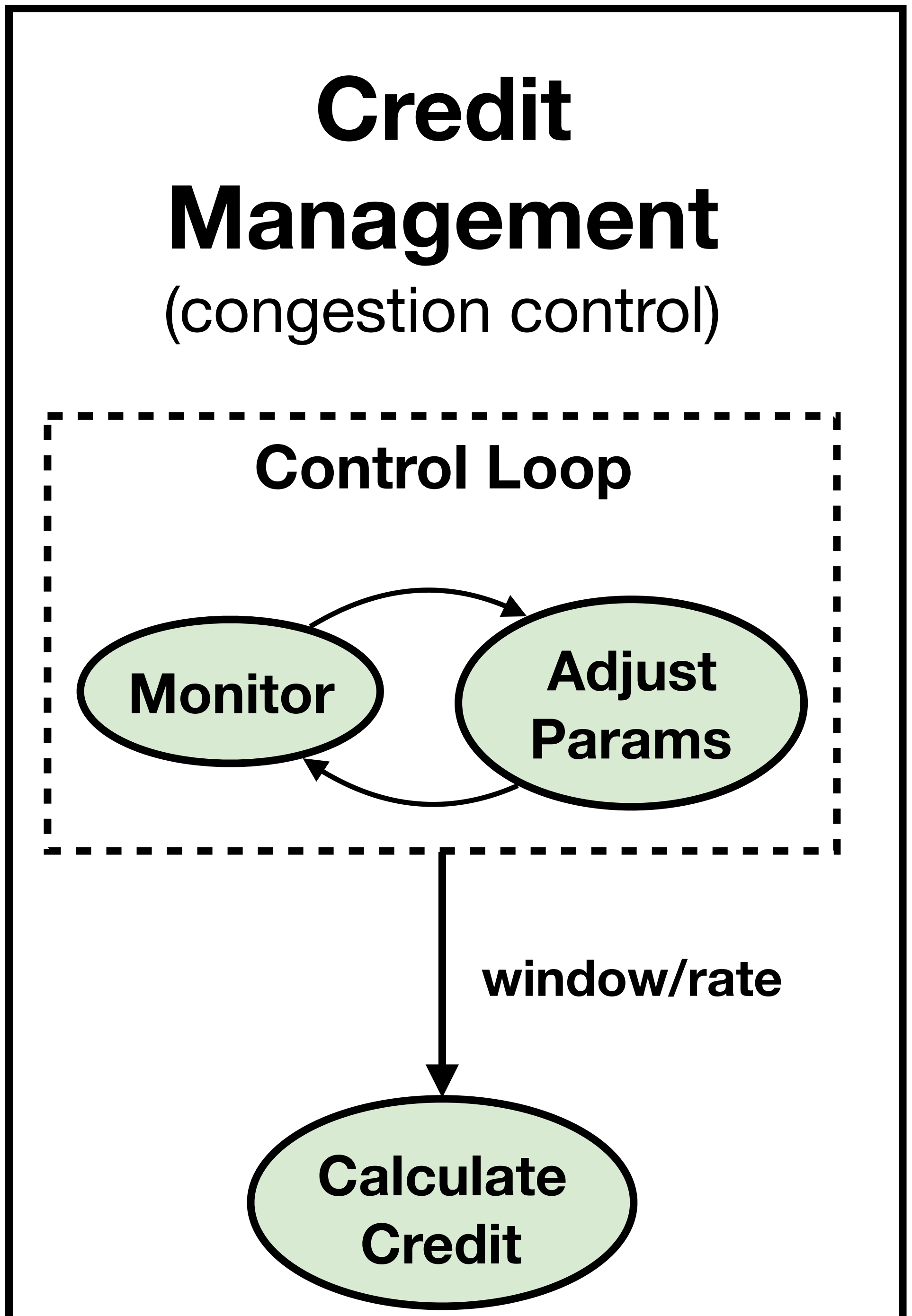

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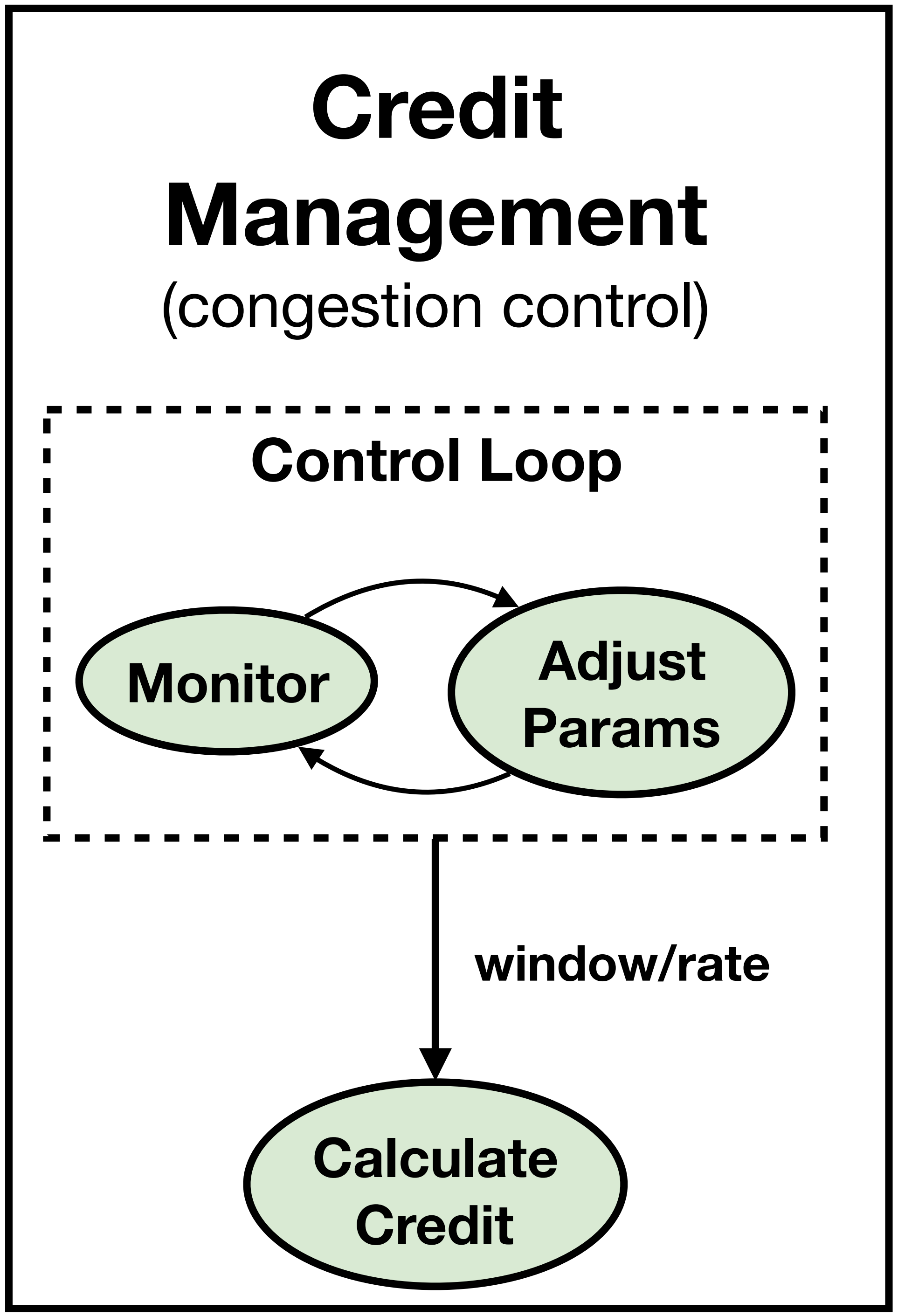

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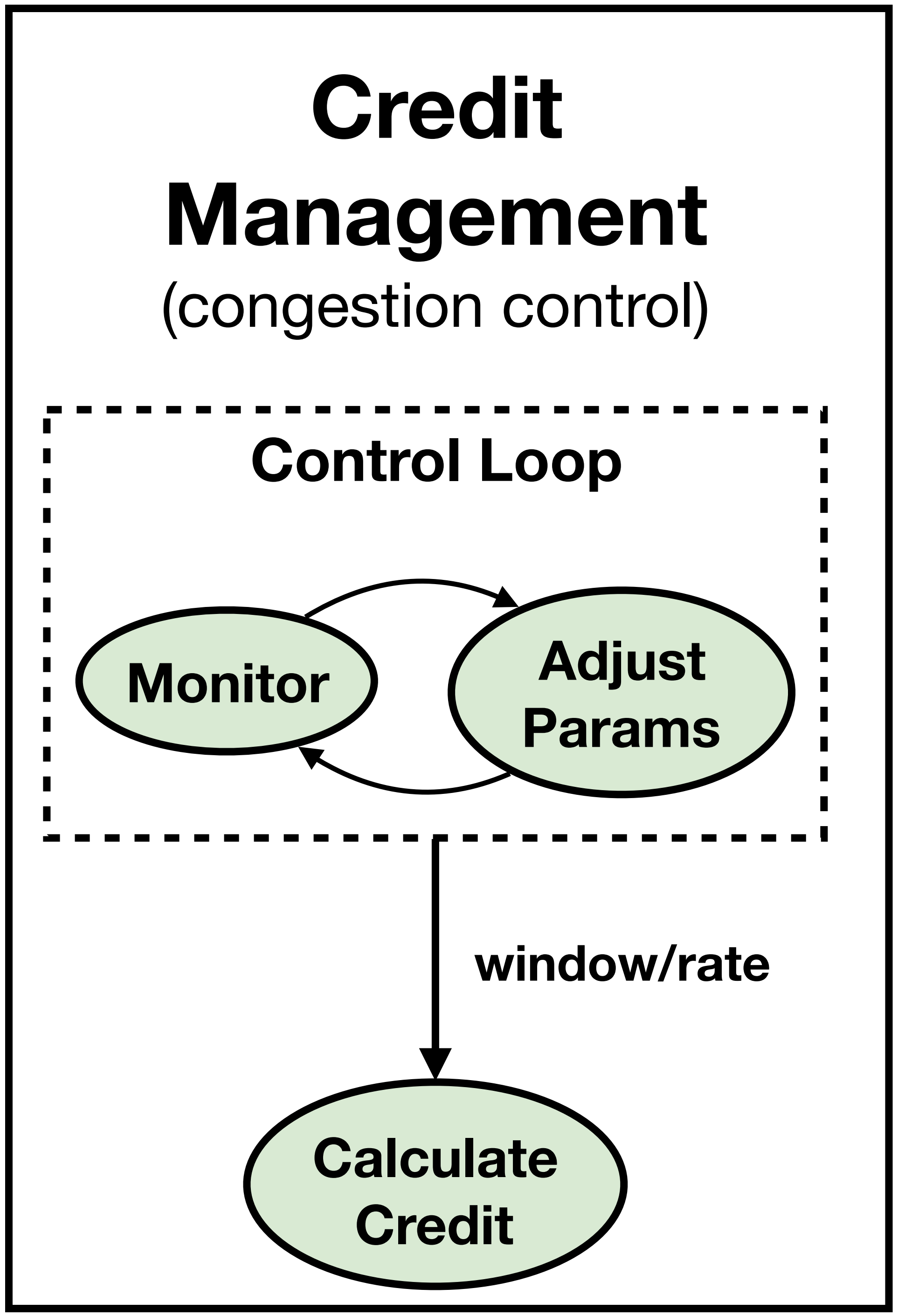

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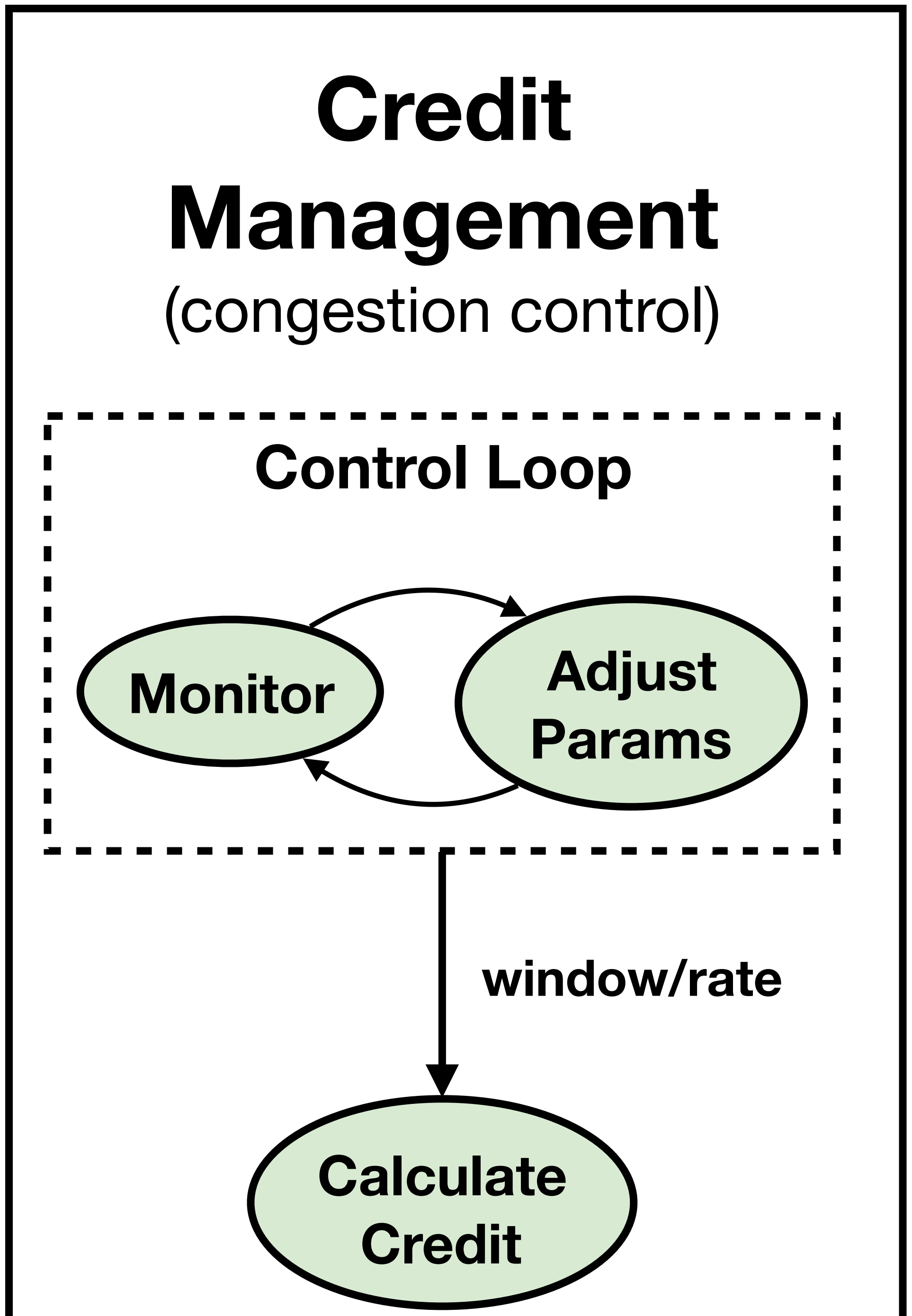

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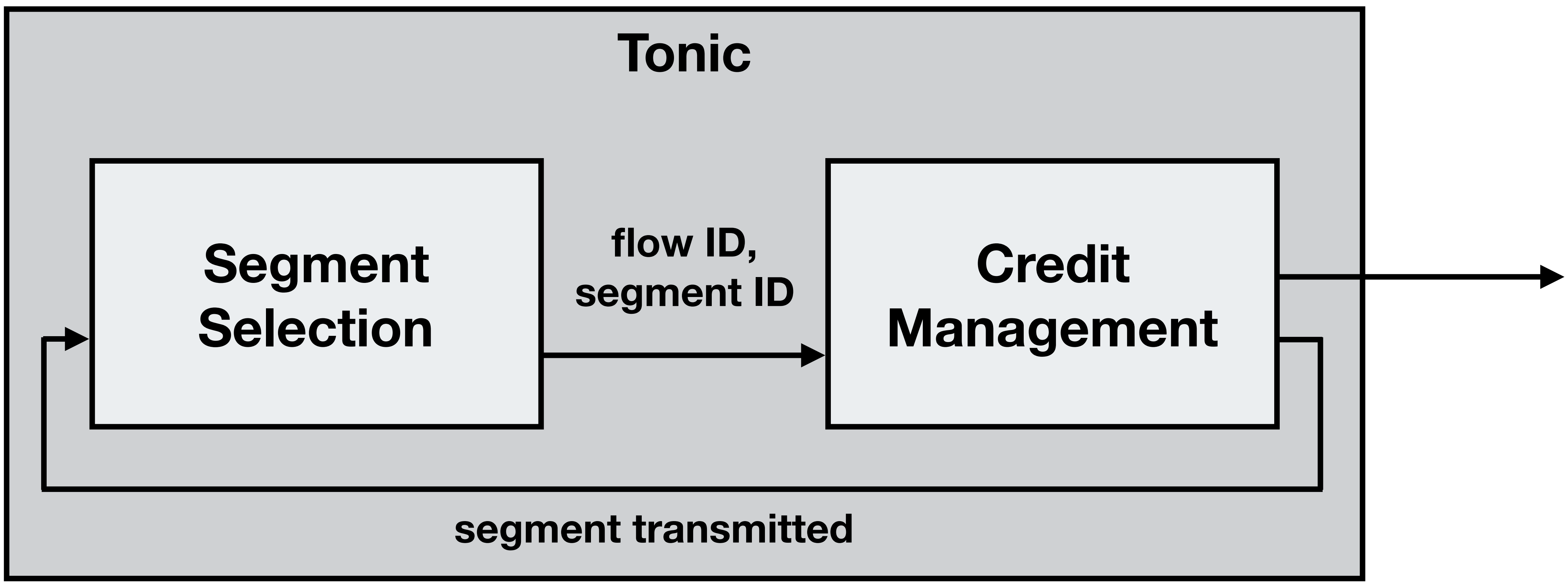
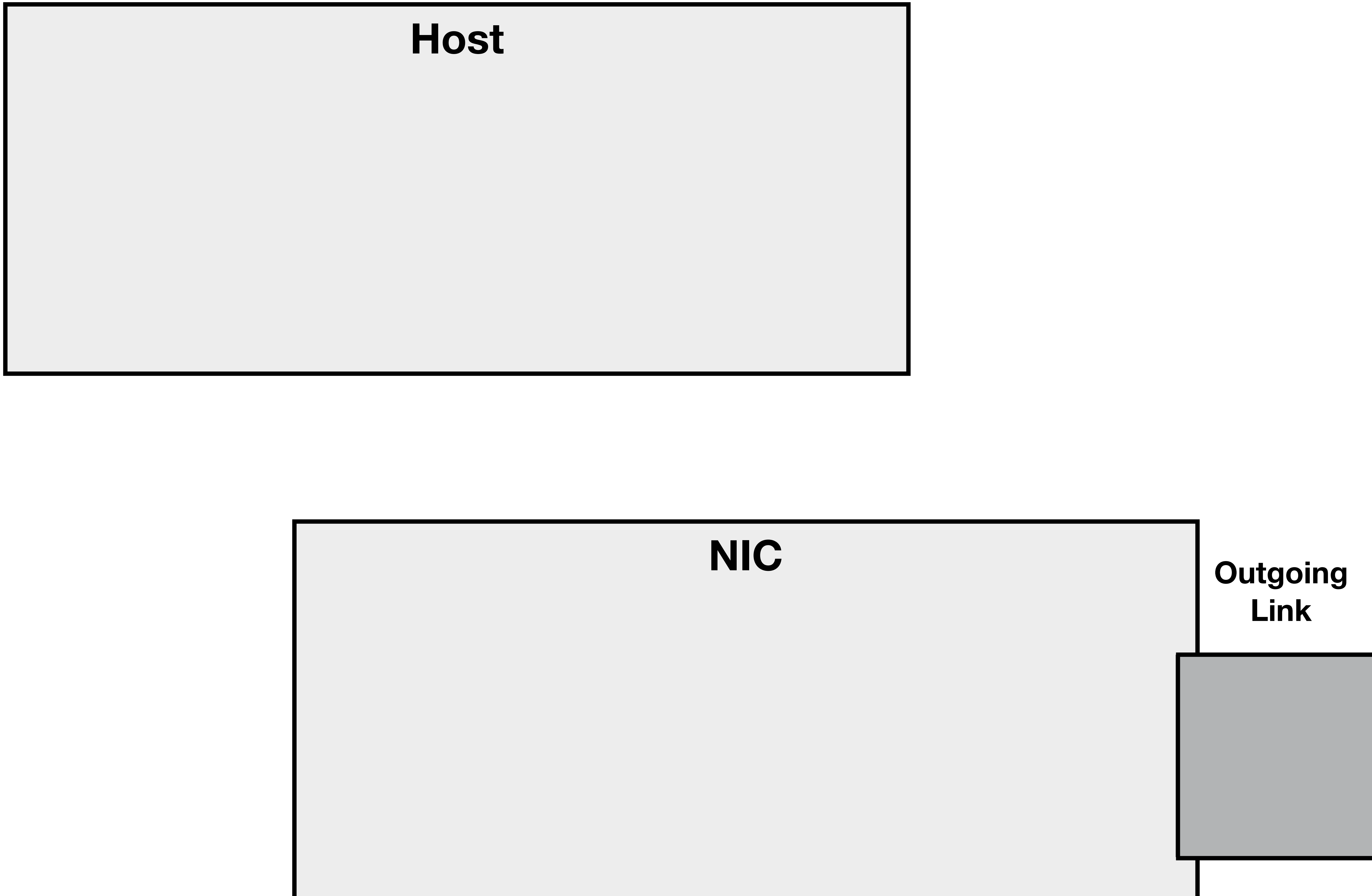
The Two Engines



Integration into the Network Stack



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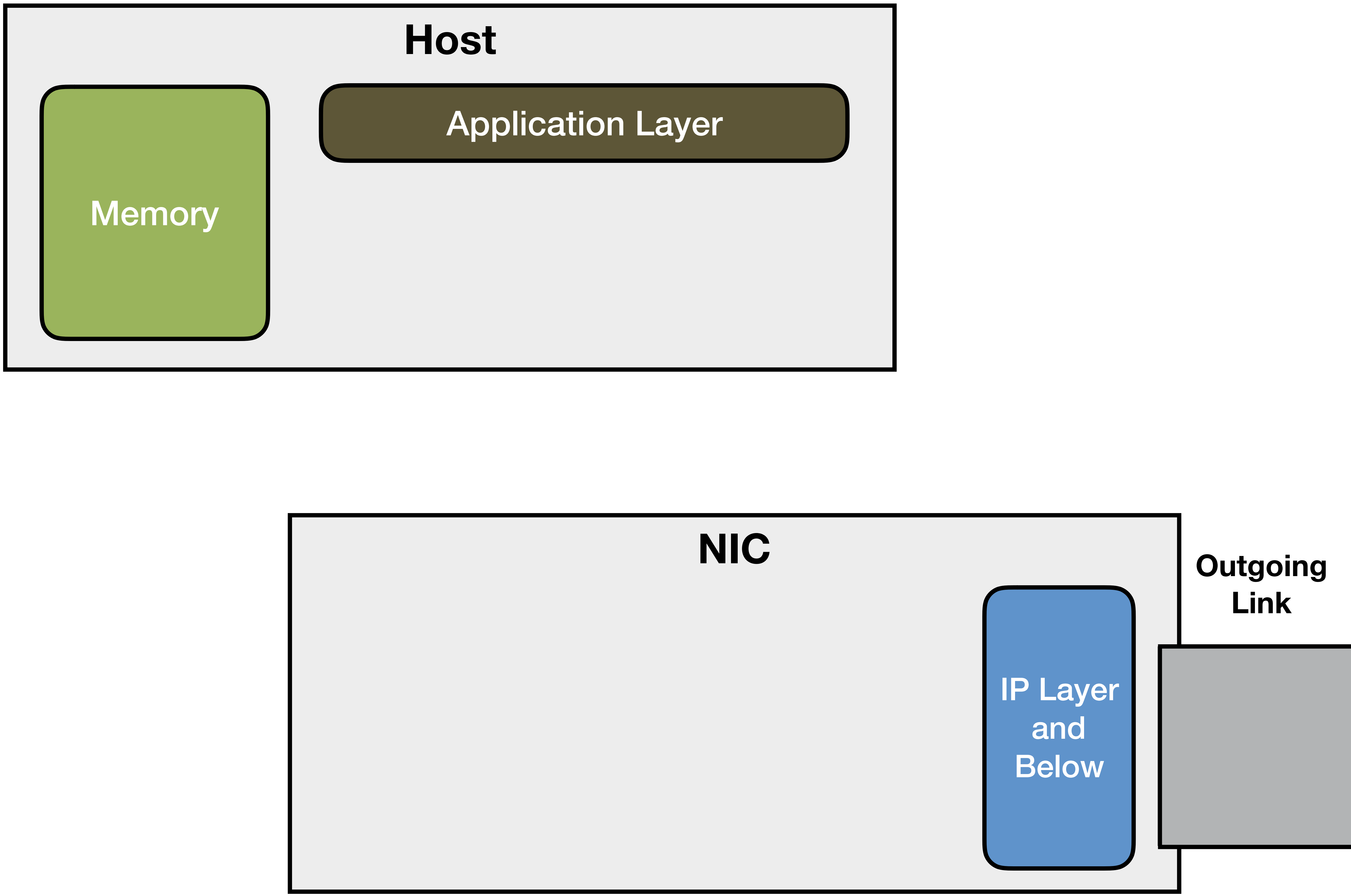

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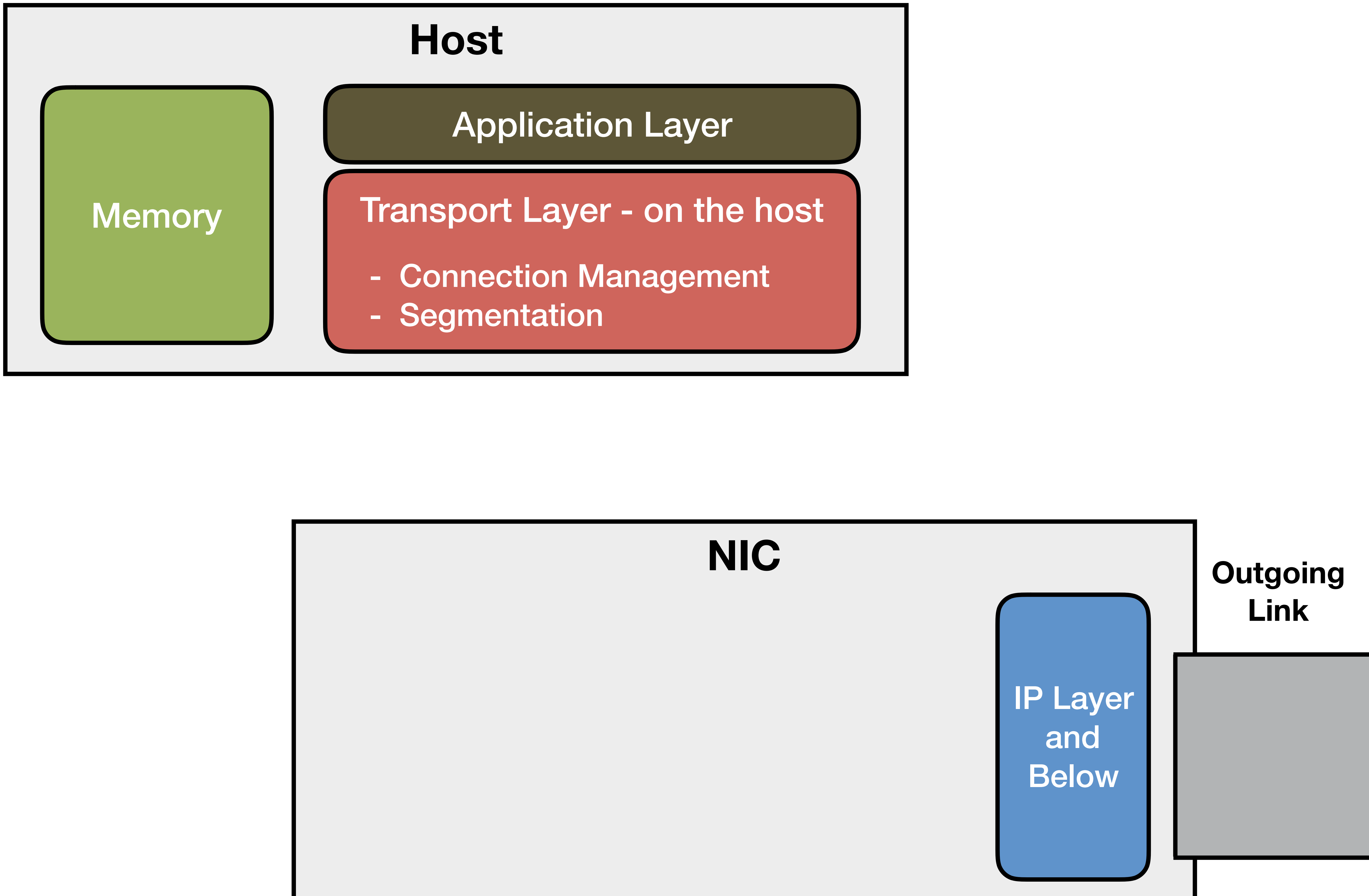

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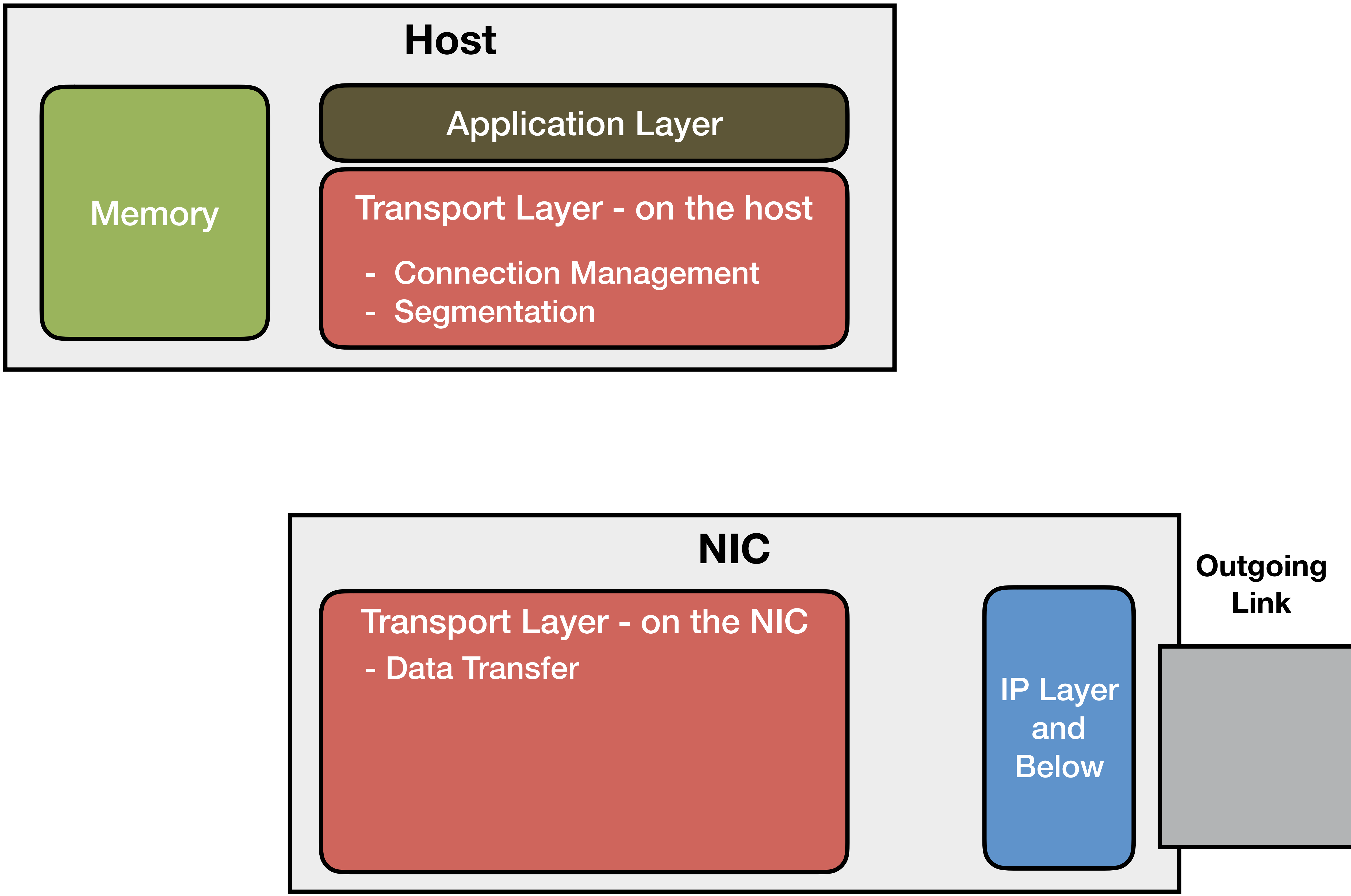

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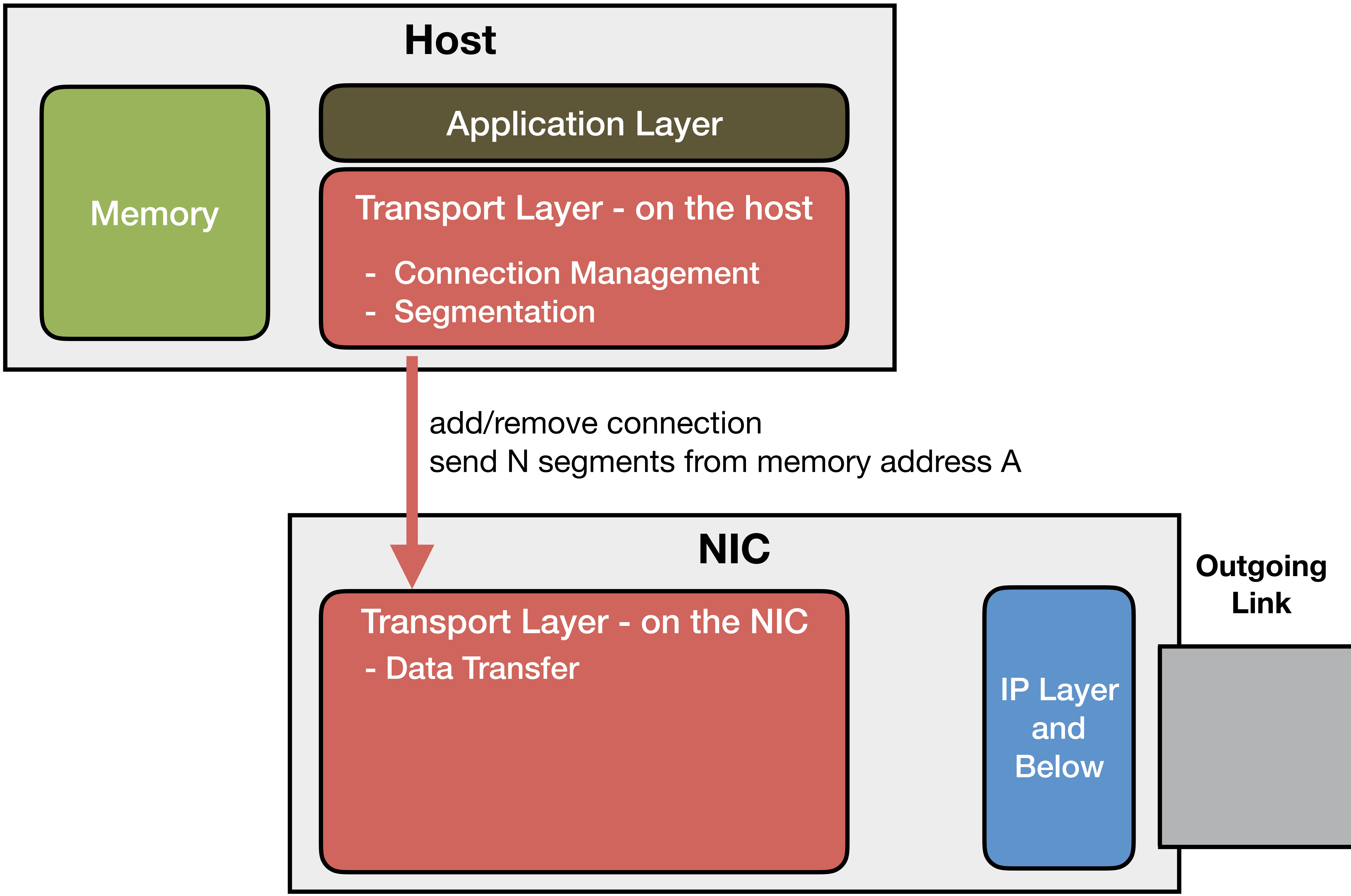

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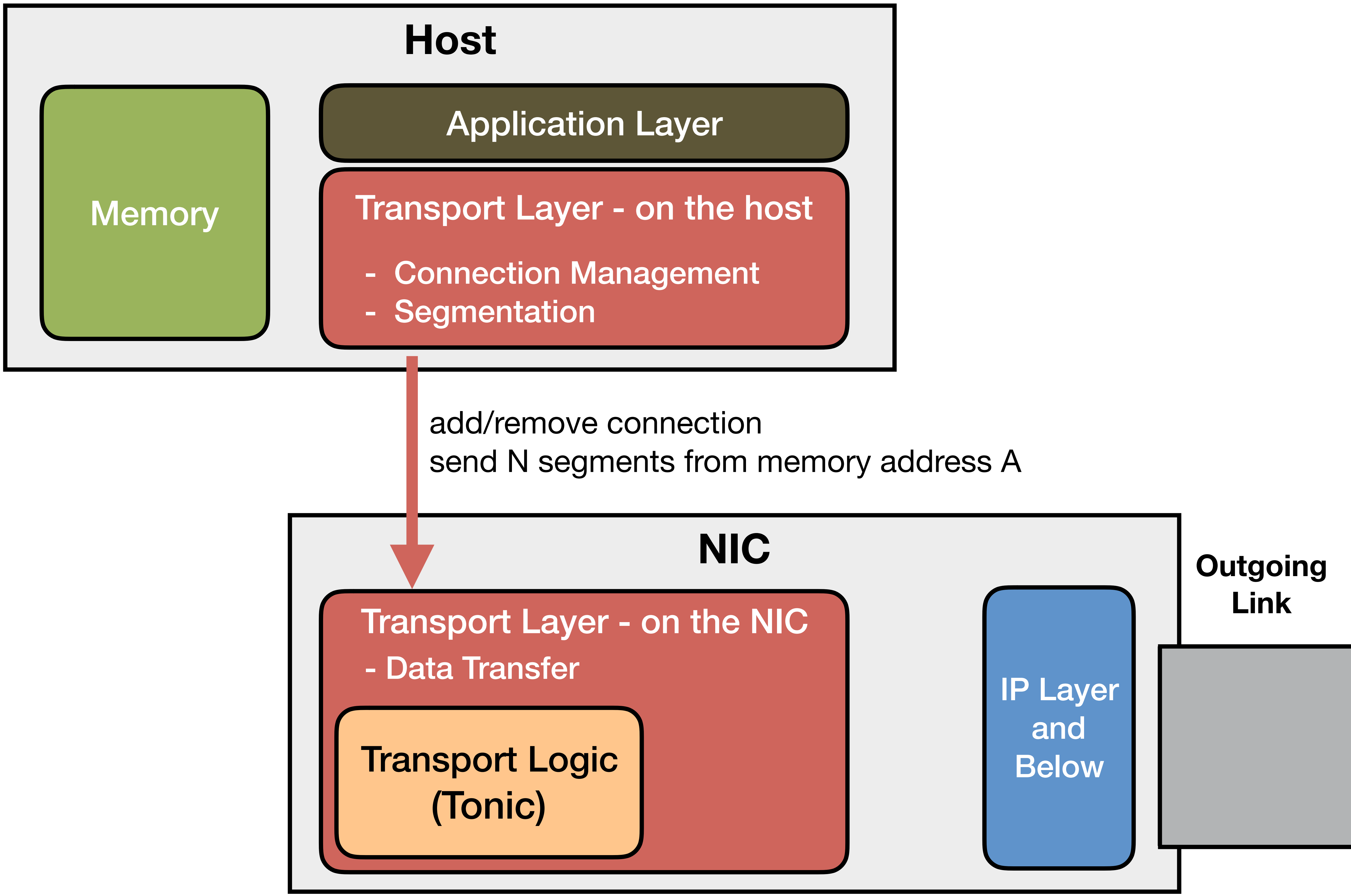

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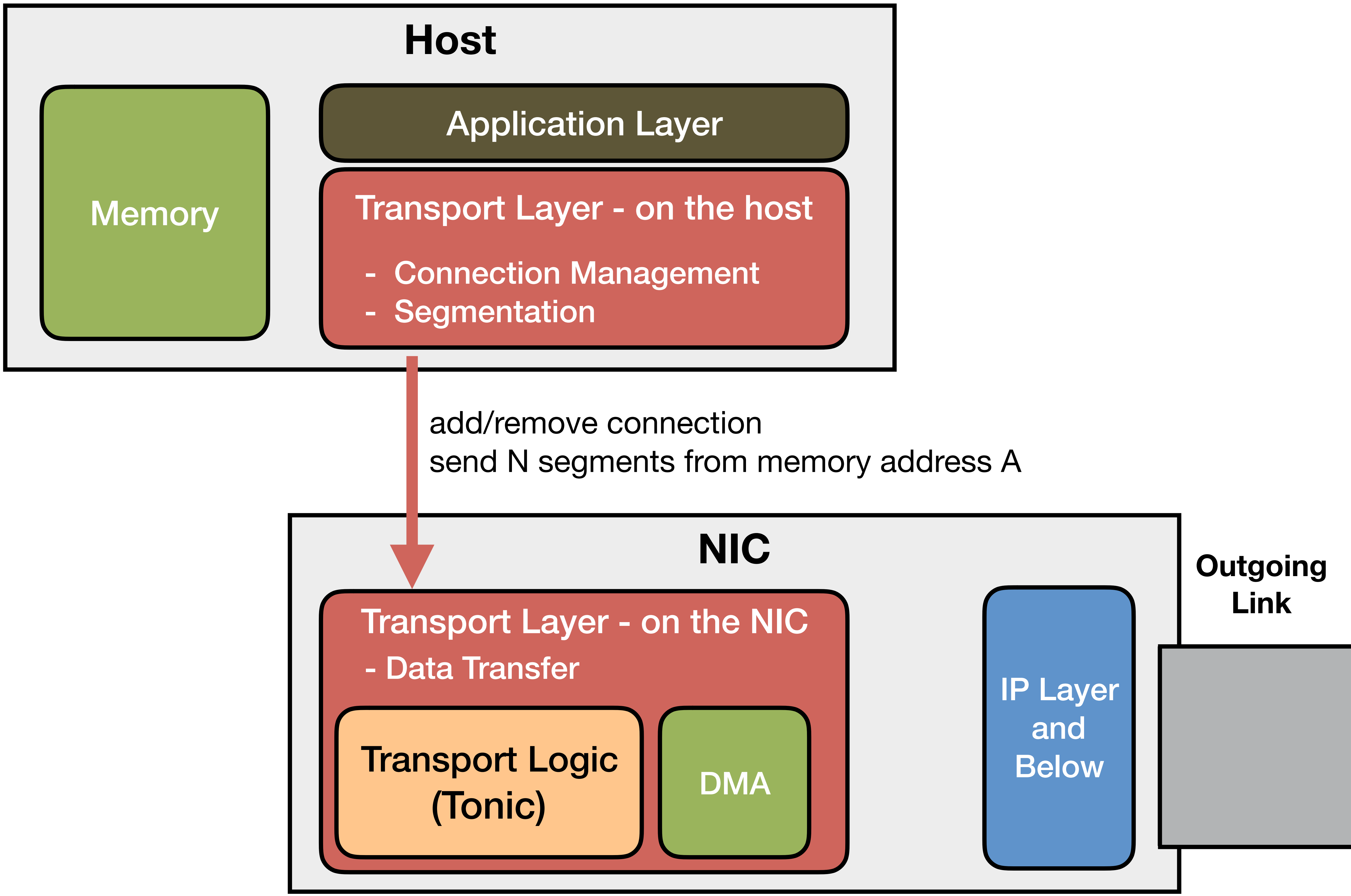

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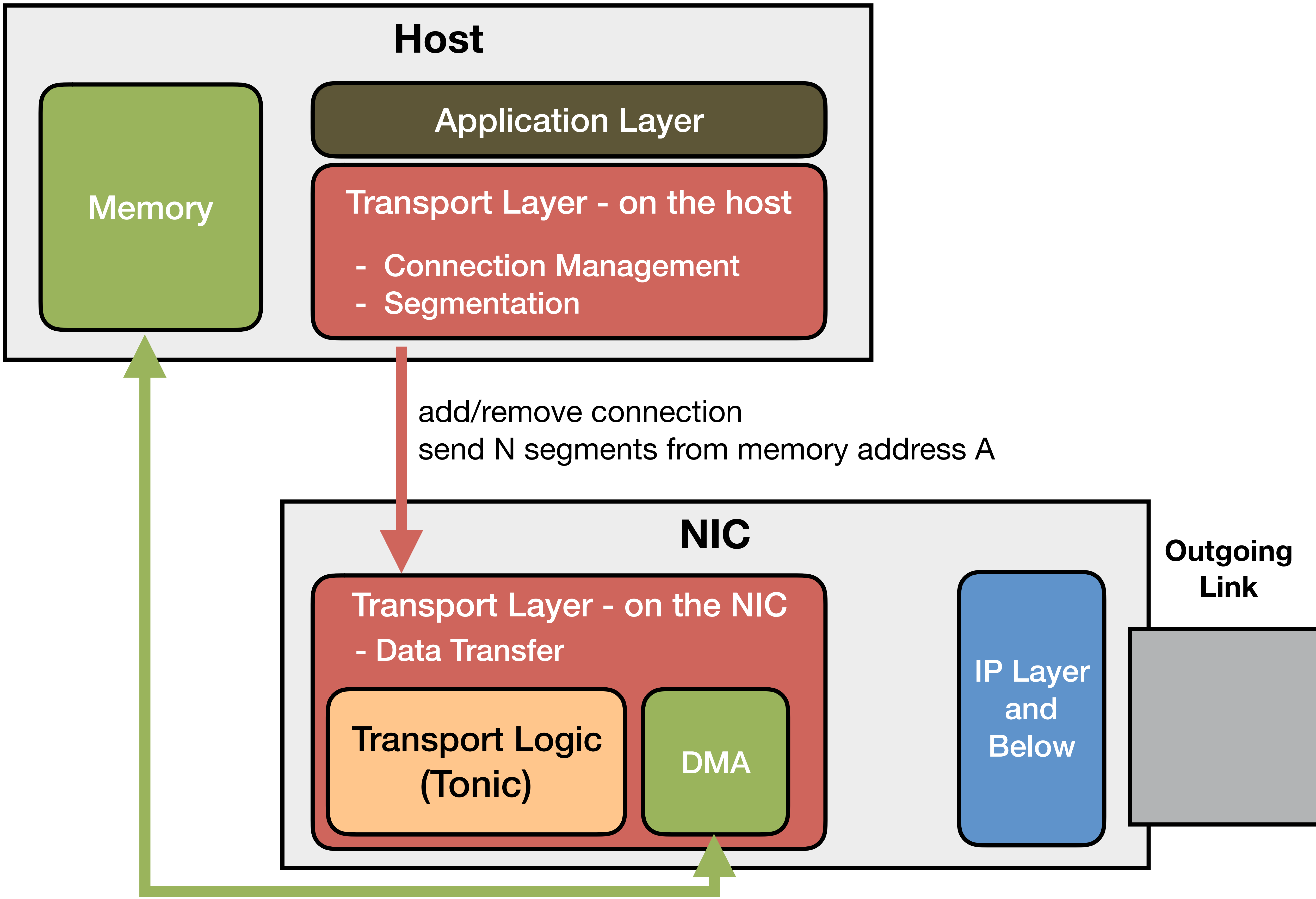

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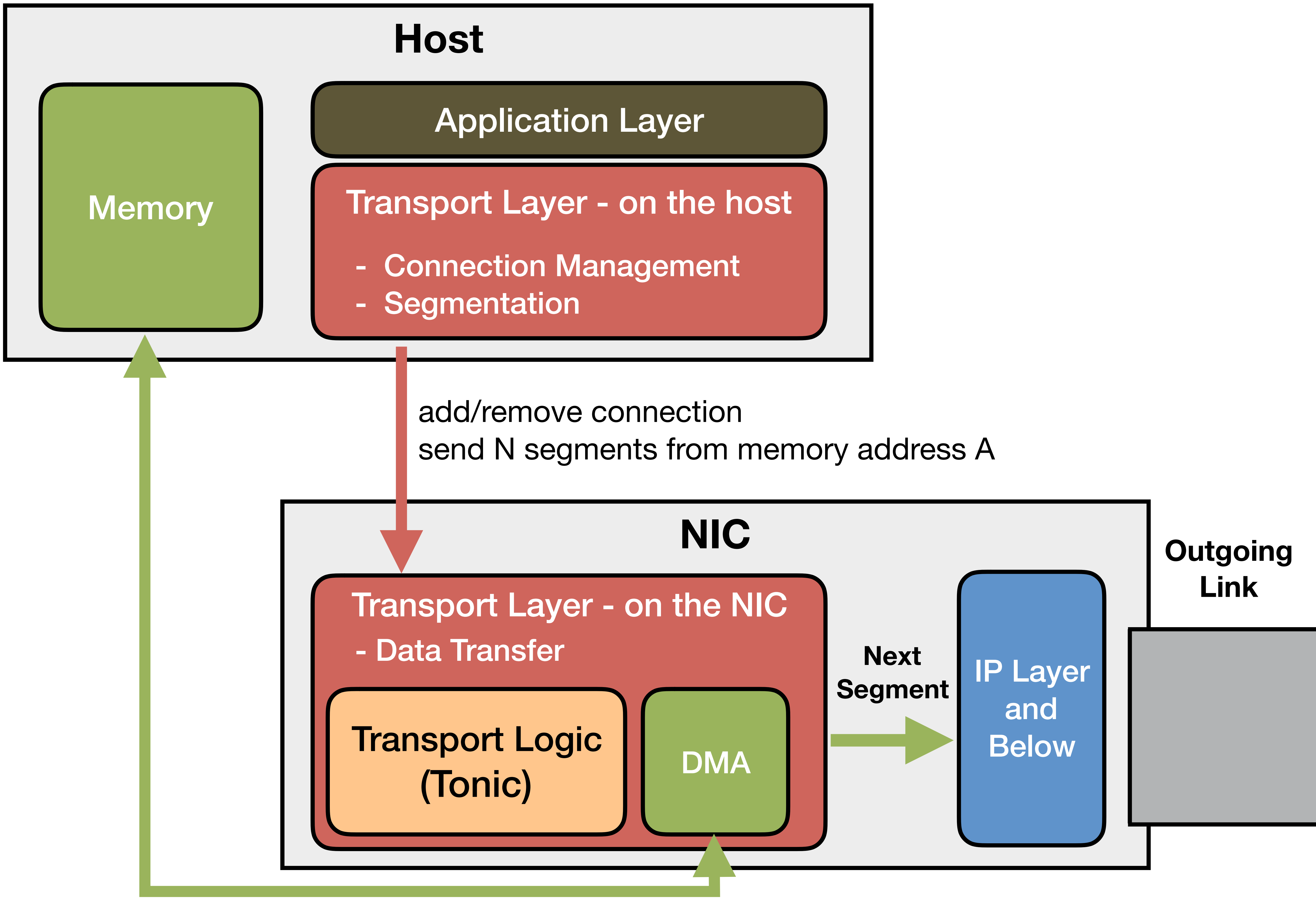

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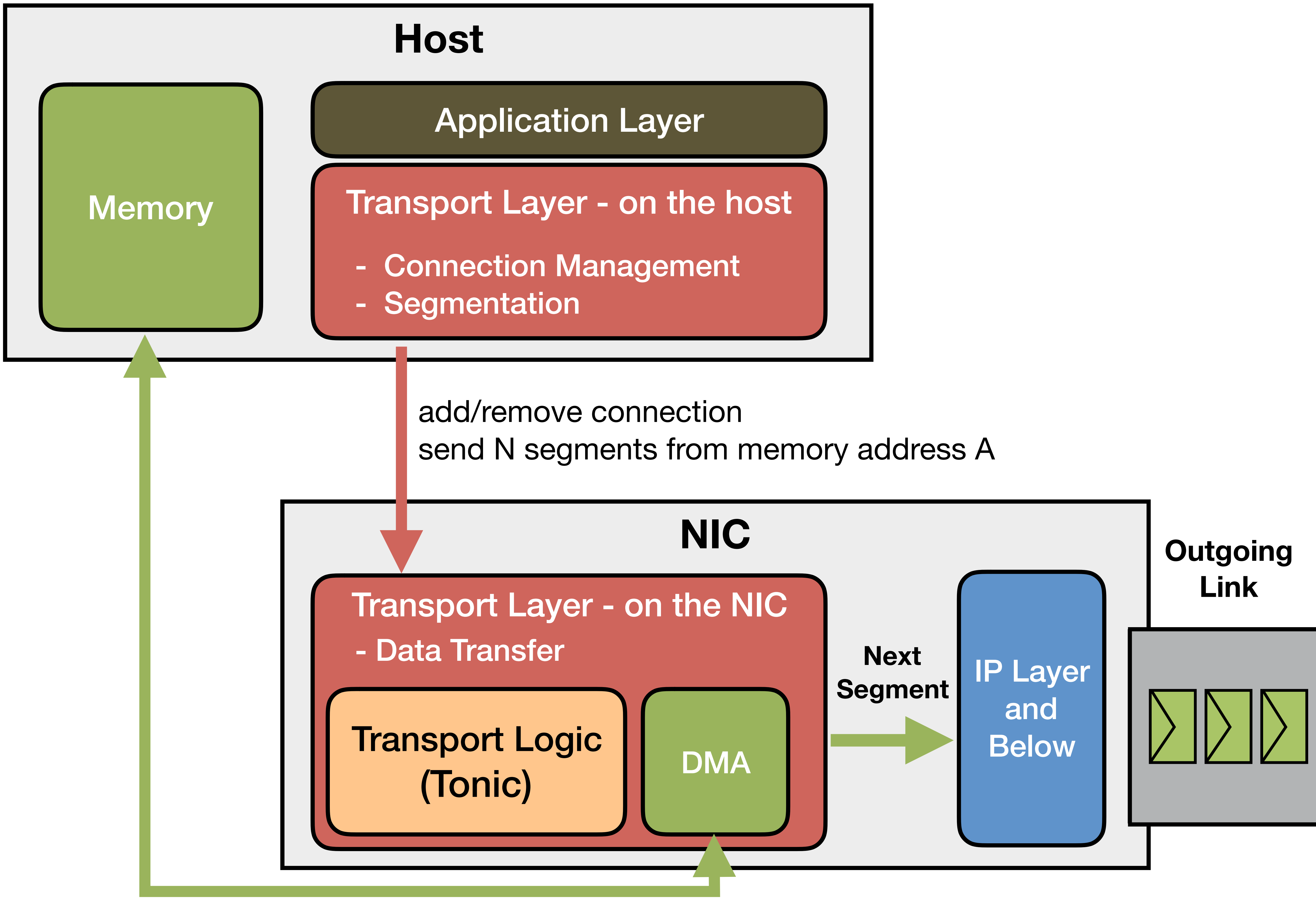

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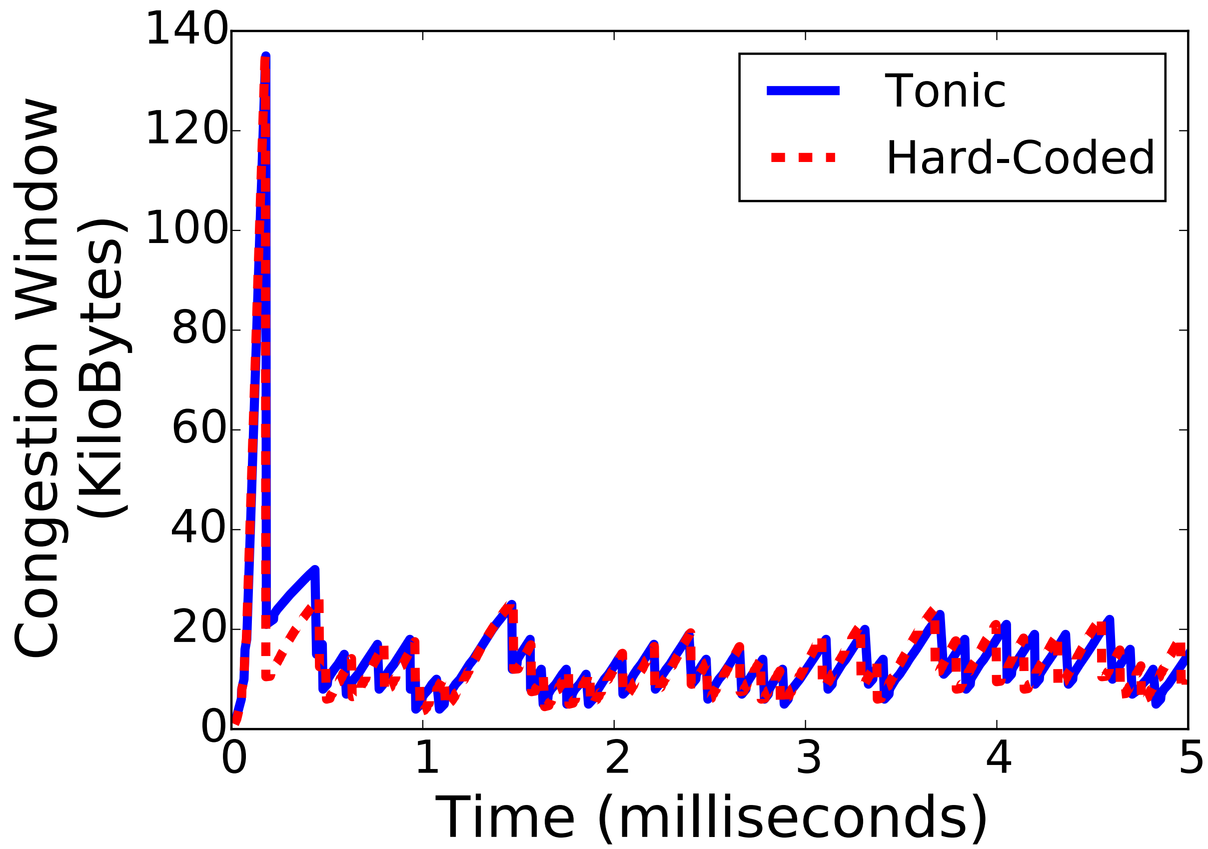
- Re-usable modules are 8K lines of *Verilog* code
  - uses 35% of total logic resources

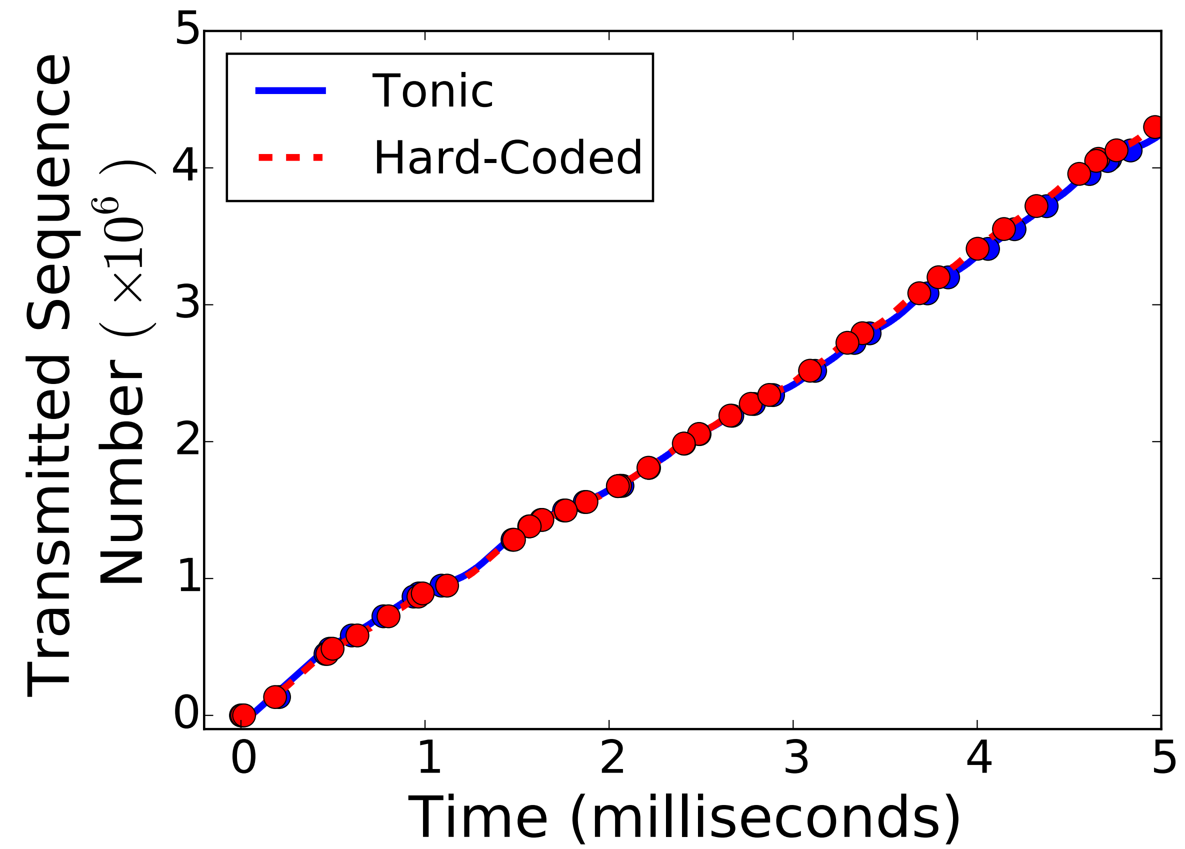
Evaluation - Scalability

	Metric	**Results**	
Complexity of User-Defined Logic	logic levels	$(0, 31]$	meets timing
		$(31, 42]$	depends on operations
		$(42, 65]$	violates timing
User-Defined State	bytes	256	grant token
		340	rate
		448	congestion window
Window Size	segments	256	
Concurrent Flows	count	2048	

Evaluation - End-to-End Simulations

- Cycle-accurate hardware simulator for Tonic within NS3
- Compared existing protocols with Tonic implementations
  - TCP New Reno (plots shown below) and DCQCN





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- Enables implementing transport protocols at high-speed
  - with **modest development effort**
- Exploits domain-specific optimizations
  - Implementing common transport patterns as re-usable modules

SNAP: Stateful Network-Wide Abstractions for Packet Processing

Mina Tahmasbi Arashloo[1], Yaron Koral[1], Michael Greenberg[2], Jennifer Rexford[1], and David Walker[1]

[1] Princeton University, [2] Pomona College

In-Network Stateful Applications

Source	Application
Chimera (USENIX Security'12)	Number of domains sharing the same IP address
	Number of distinct IP addresses under the same domain
	DNS TTL change tracking
	DNS tunnel detection
	Sidejack detection
	Phishing/spam detection
FAST (HotSDN'14)	Stateful firewall
	FTP monitoring
	Heavy-hitter detection
	Super-spreader detection
	Sampling based on flow size
	Selective packet dropping (MPEG frames)
	Connection affinity
Bohatei (USENIX Security'15)	SYN flood detection
	DNS reflection (and amplification) detection
	UDP flood mitigation
	Elephant flows detection
Others	Bump-on-the-wire TCP state machine
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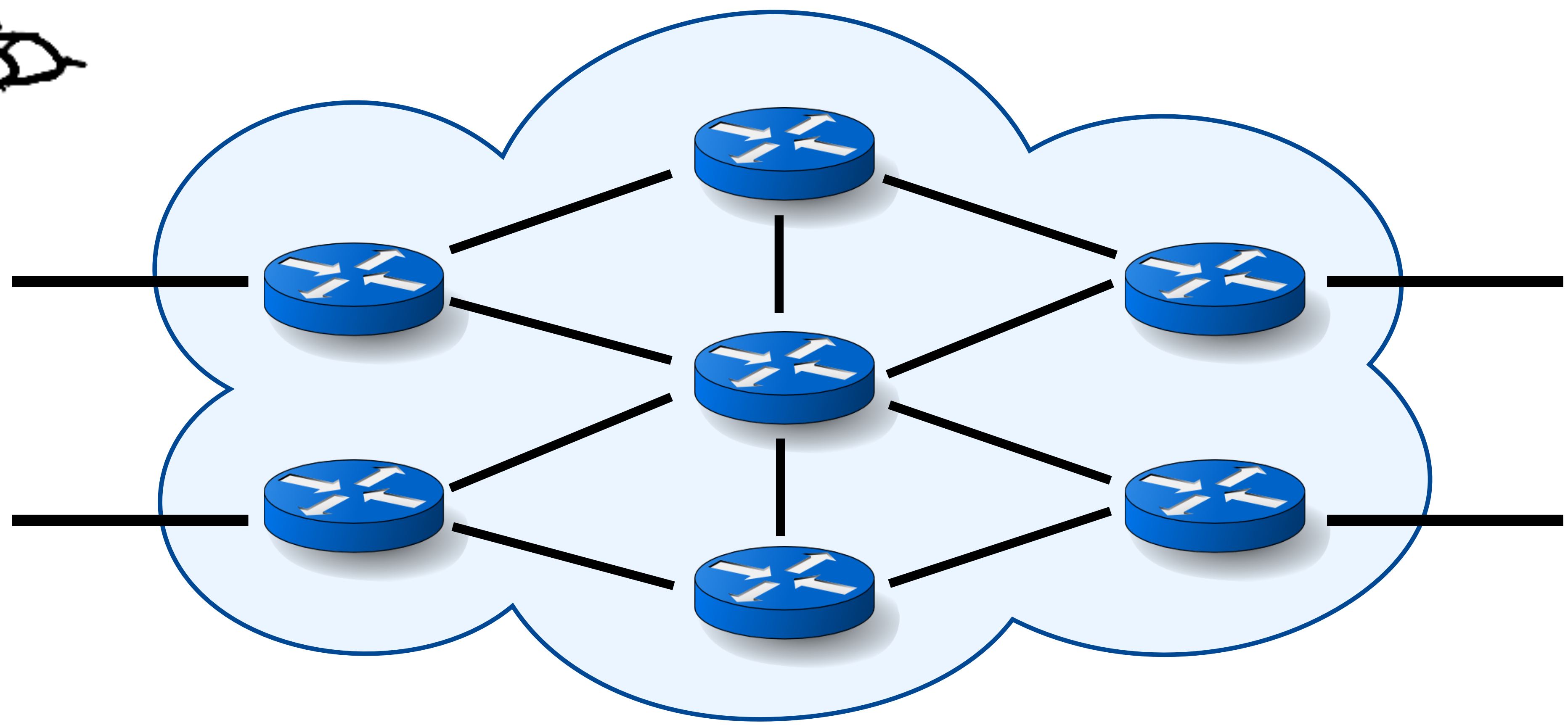
Programmable switches expose **data plane state** through a programming interface!

Distributed Stateful Programming is Challenging



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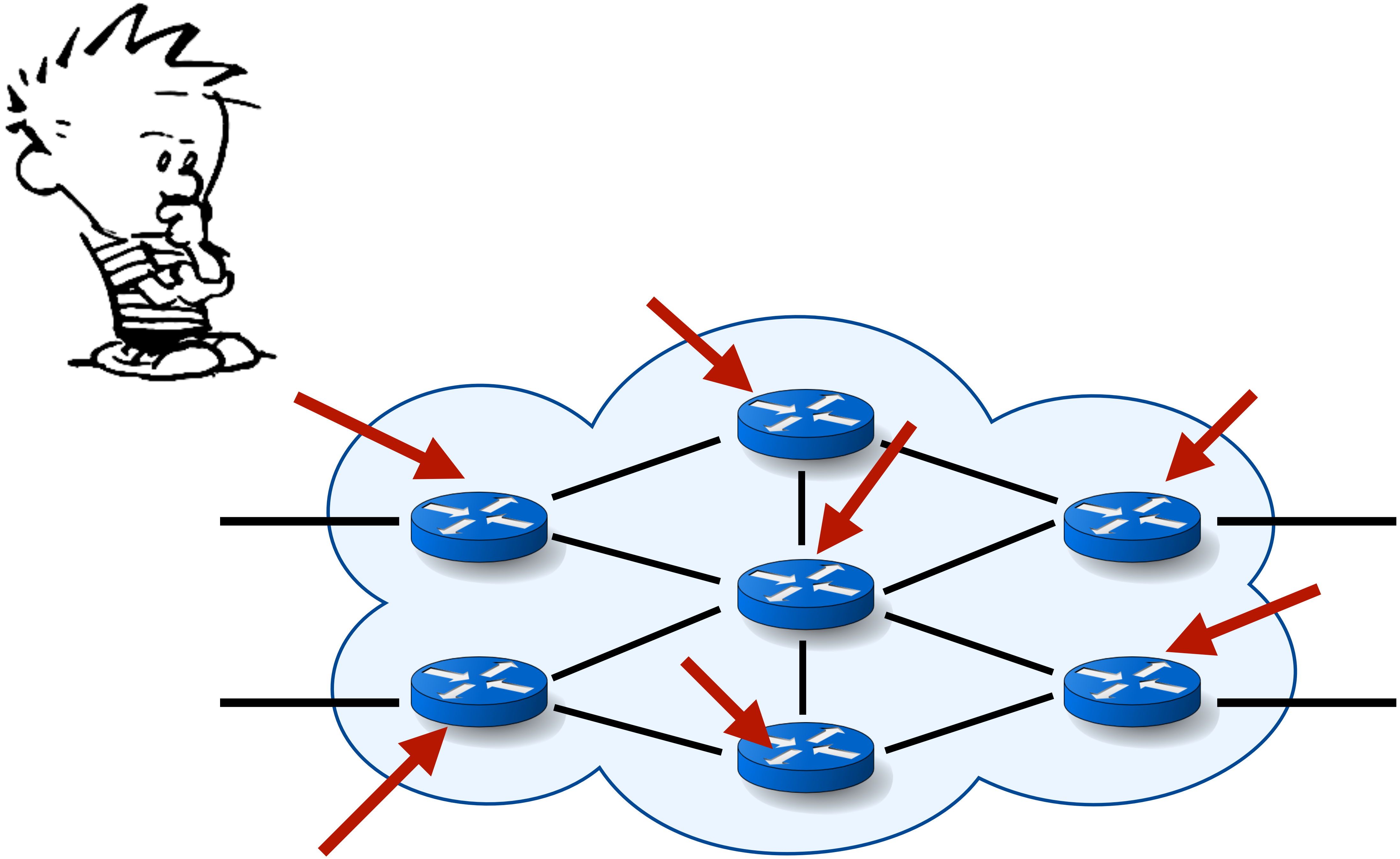

Distributed Stateful Programming is Challenging

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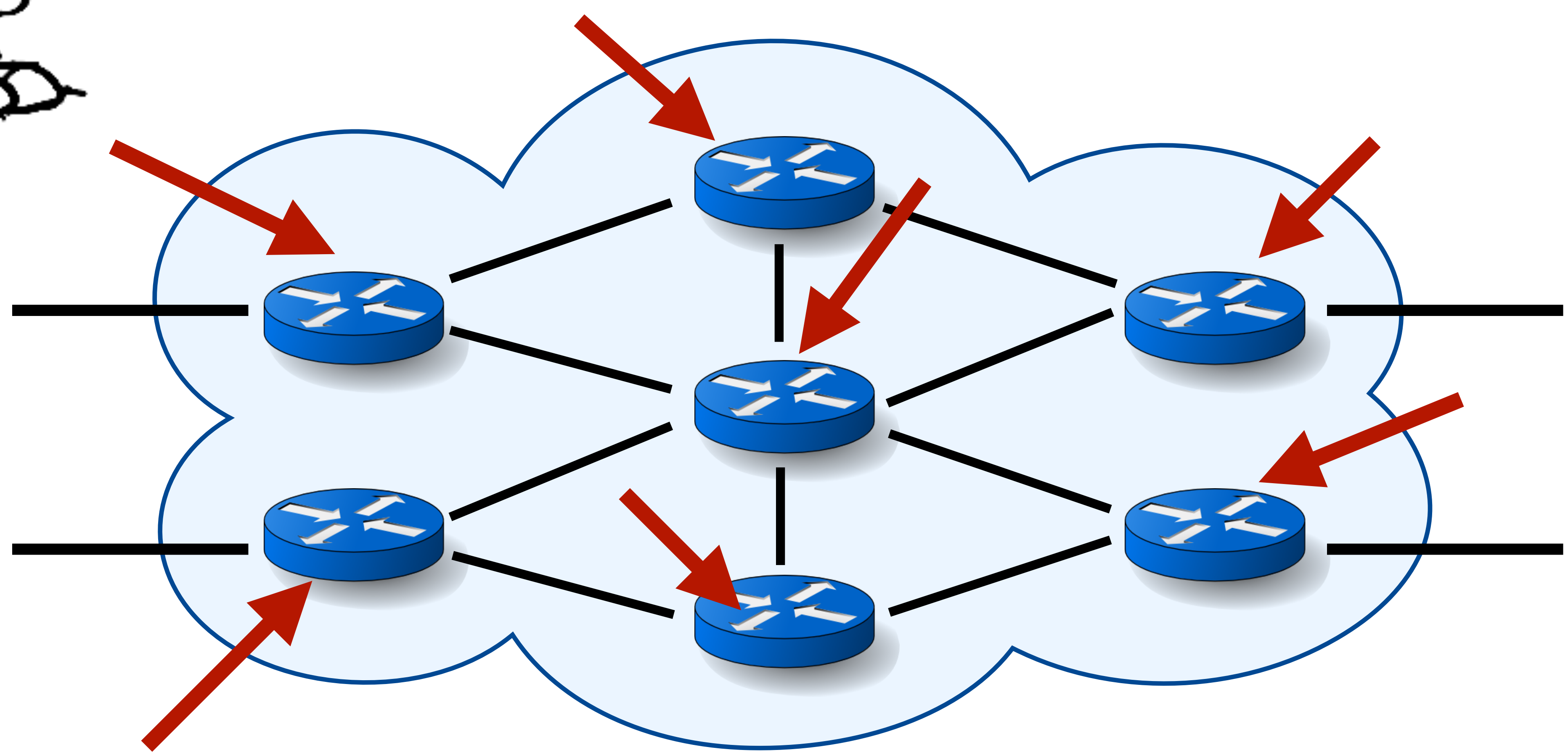

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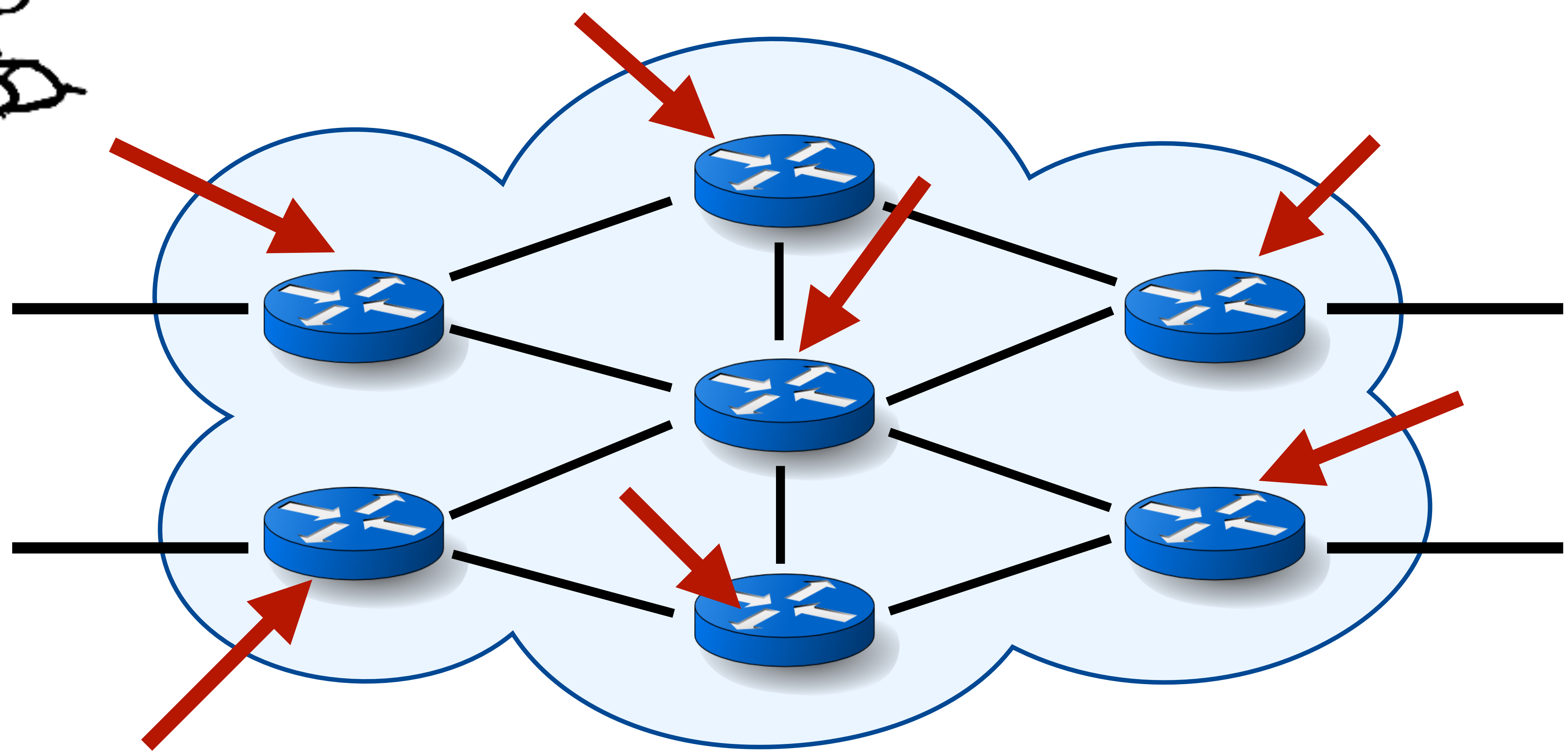

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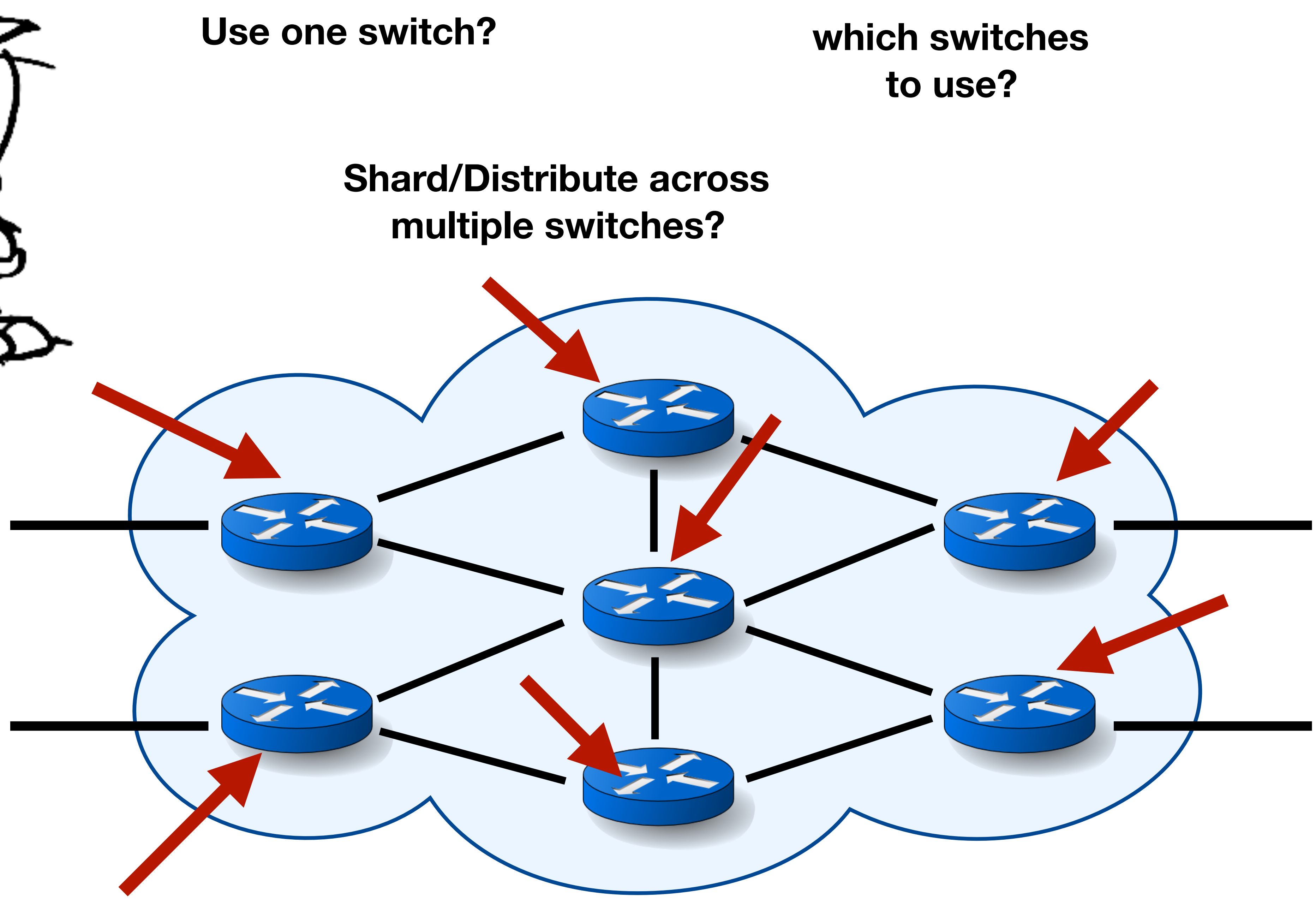

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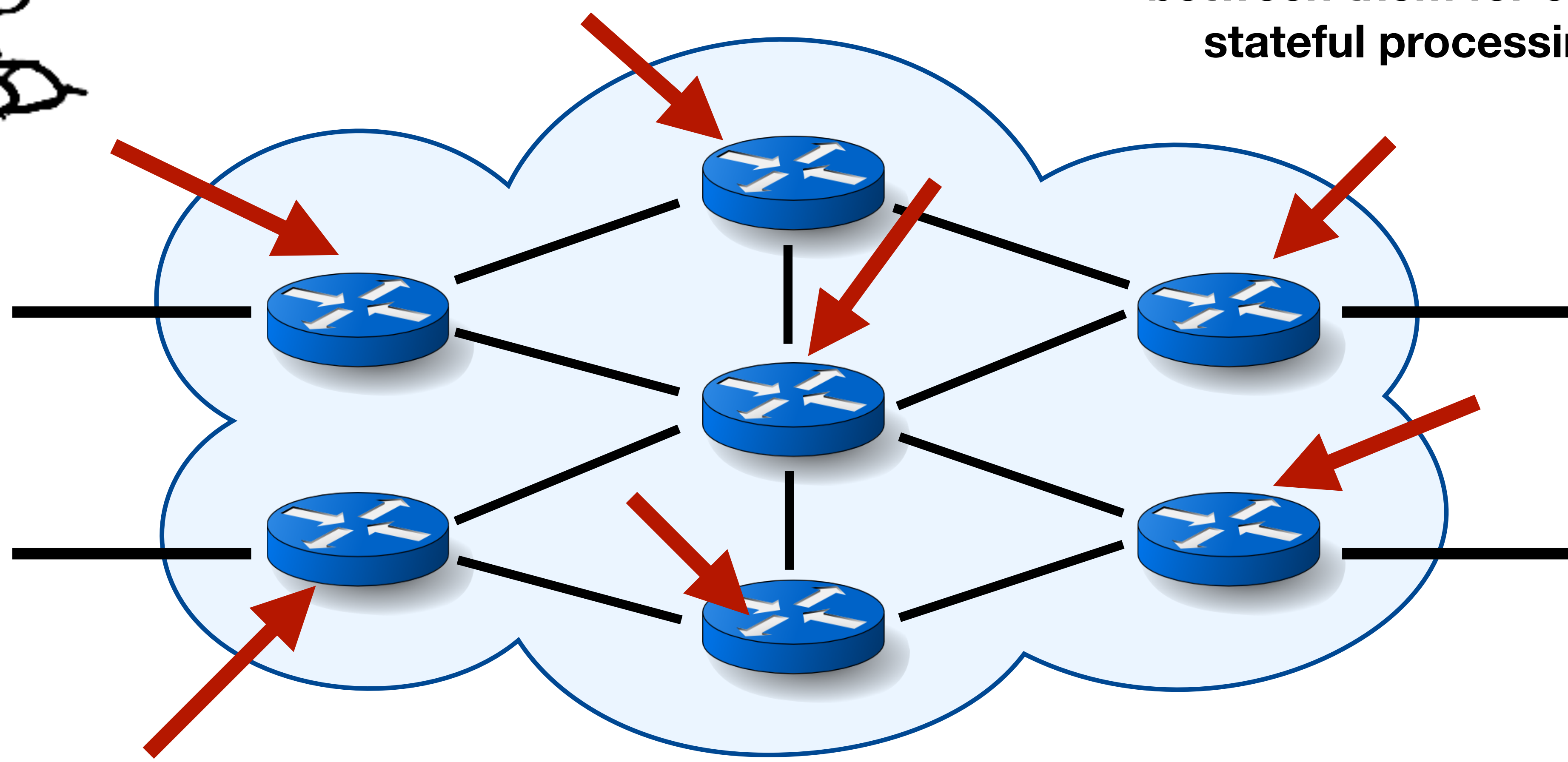

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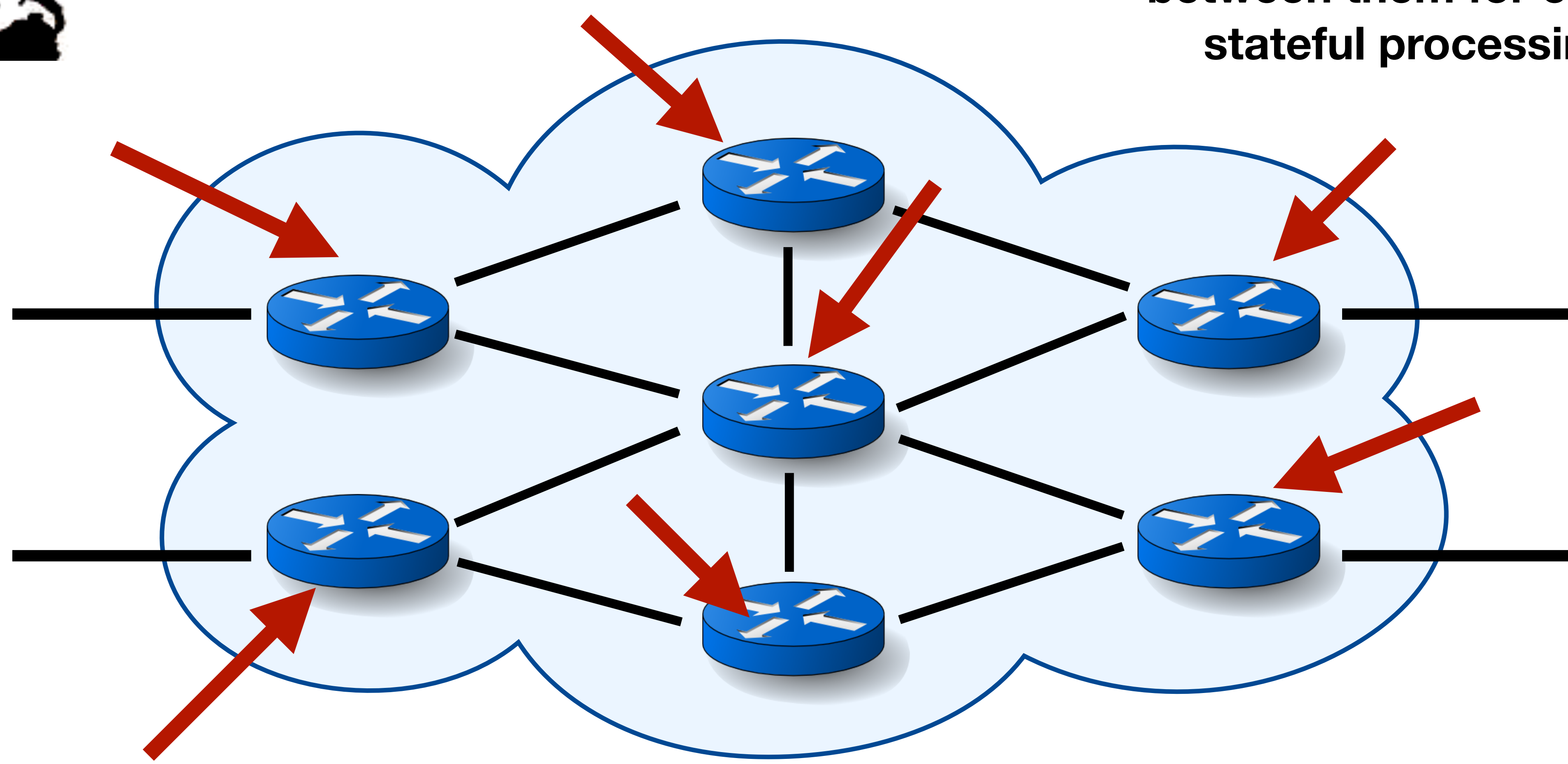

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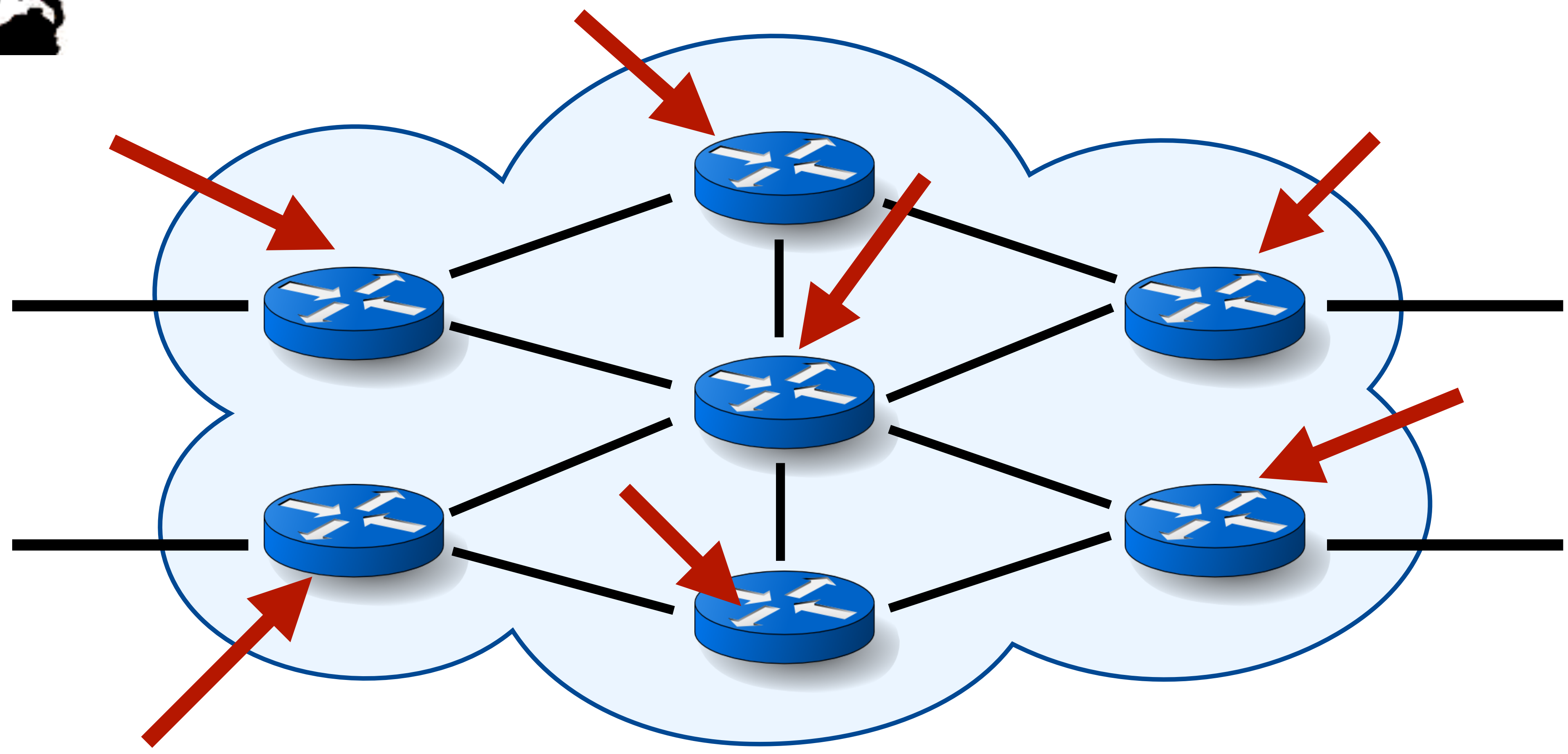

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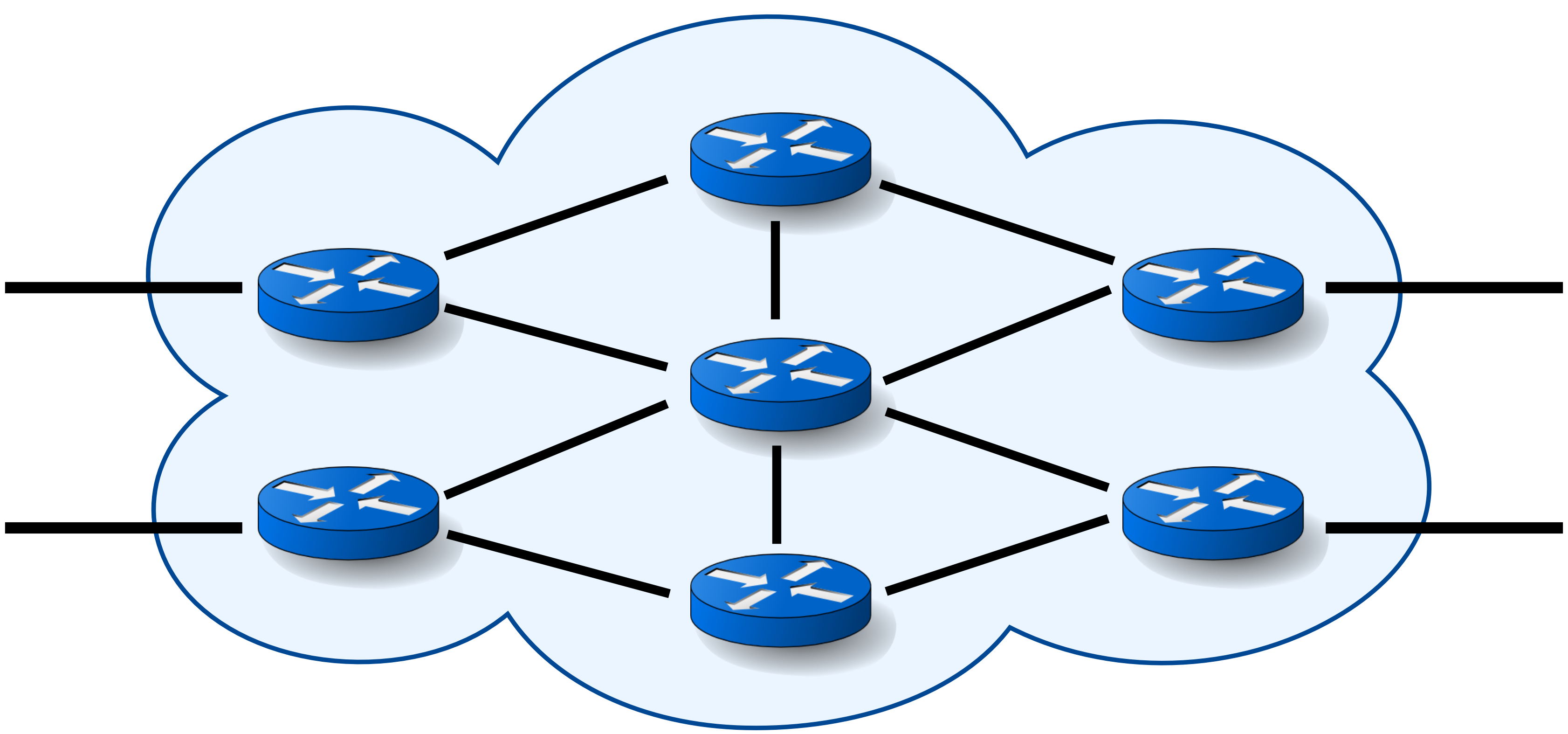

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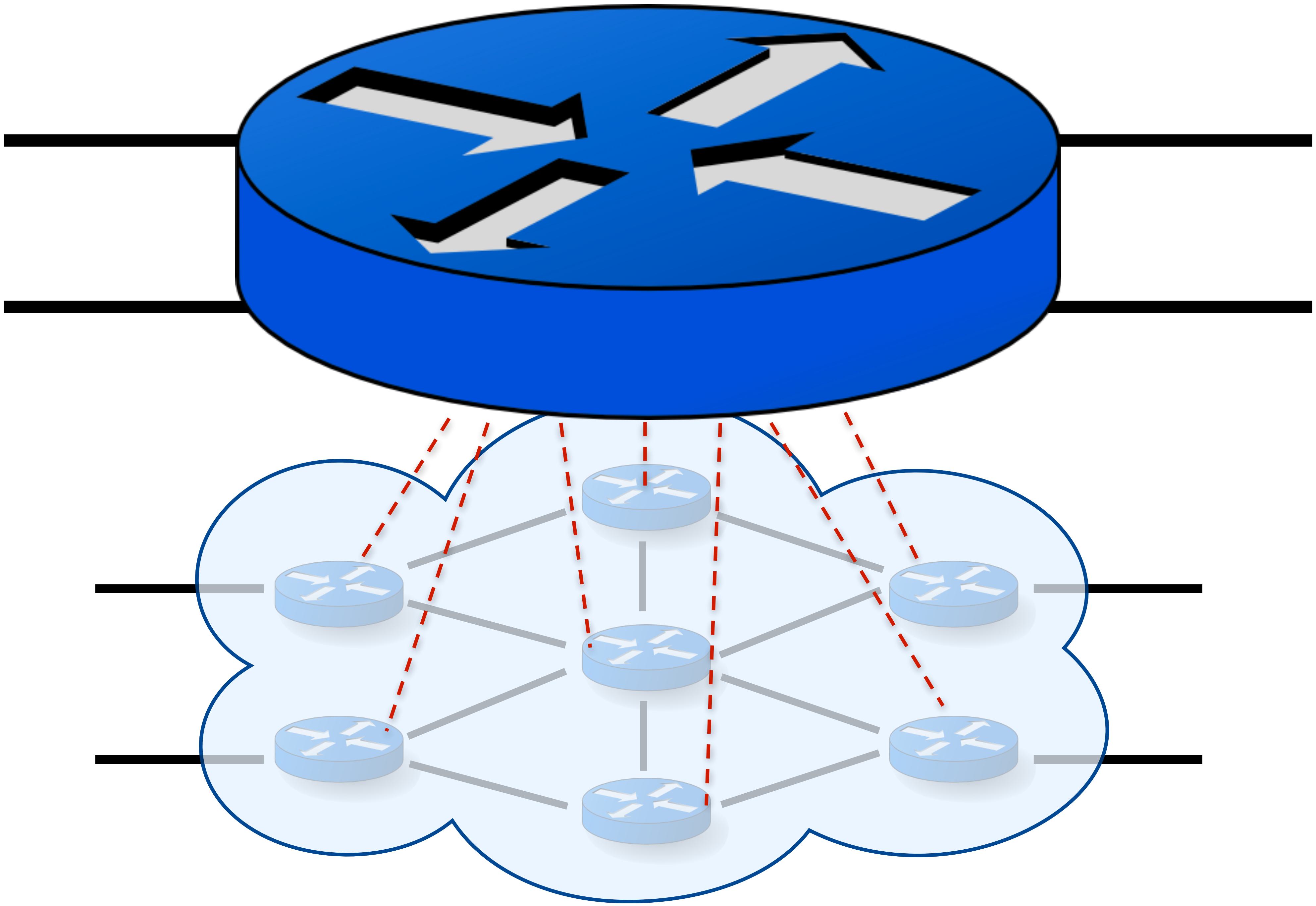

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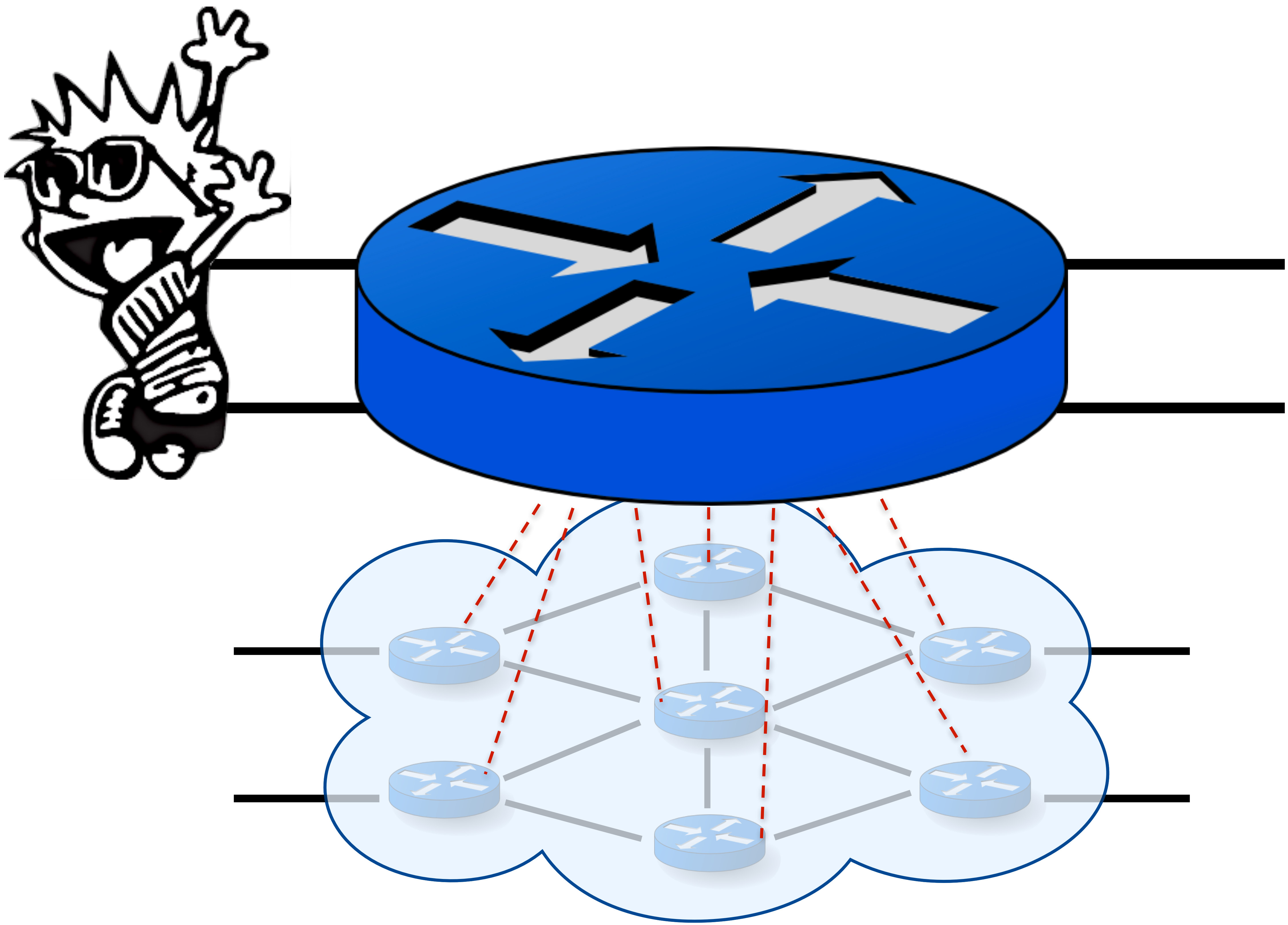
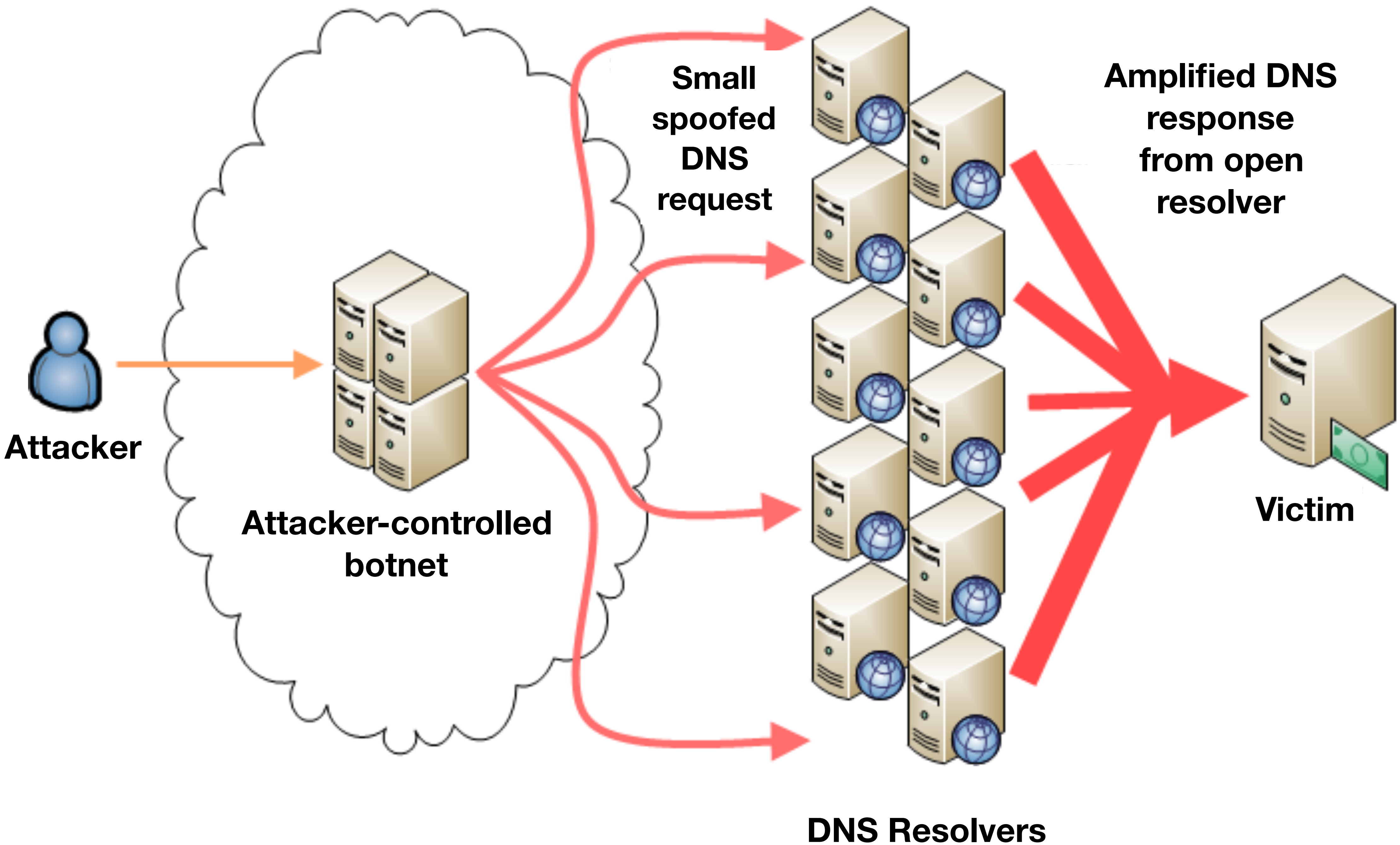


Example - Detecting DNS Reflection Attacks



http://ddosandbotnets.blogspot.com

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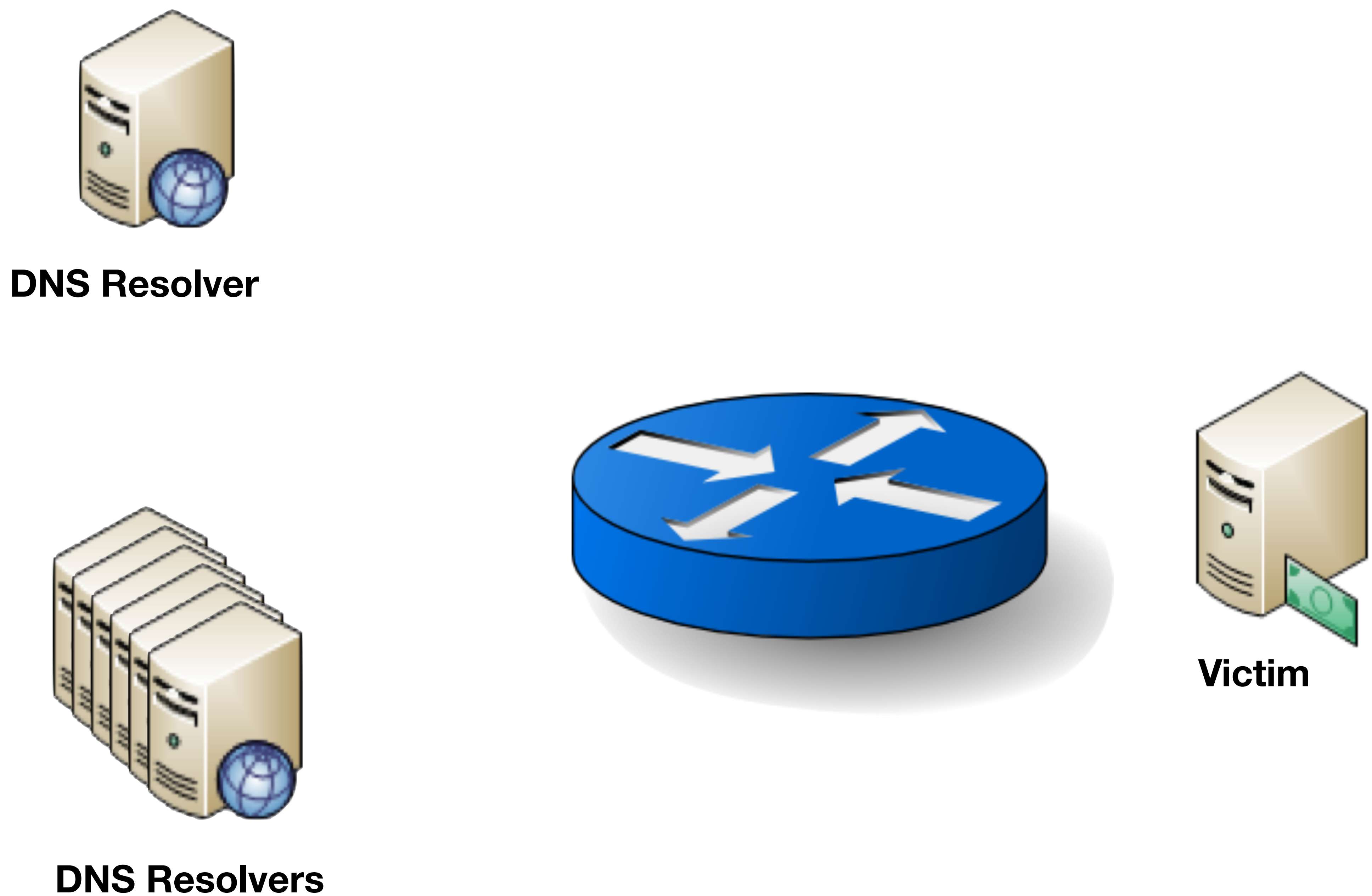

Bohatei: flexible and elastic DDoS defense, Fayaz et.al., USENIX SECURITY 15

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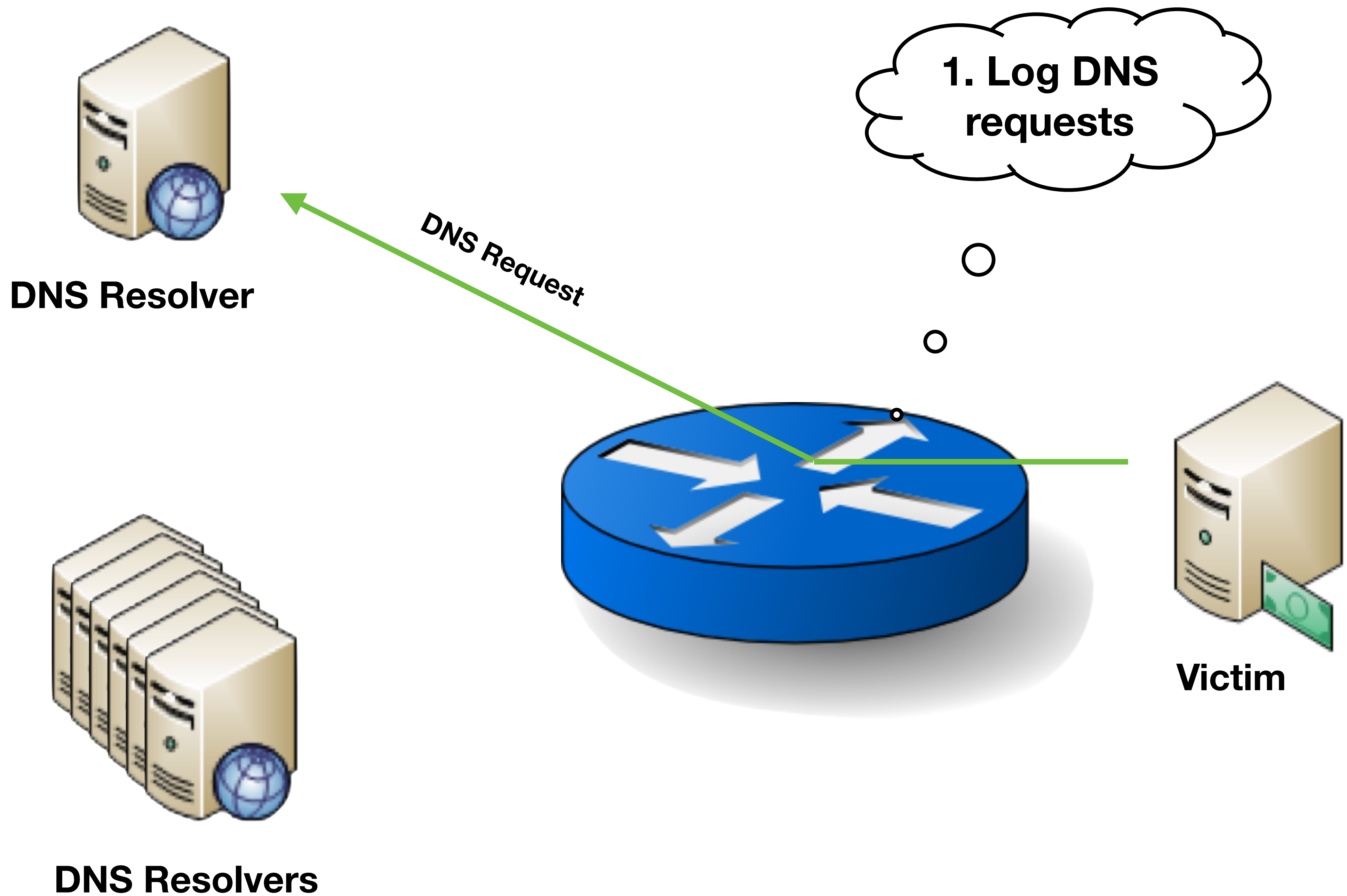

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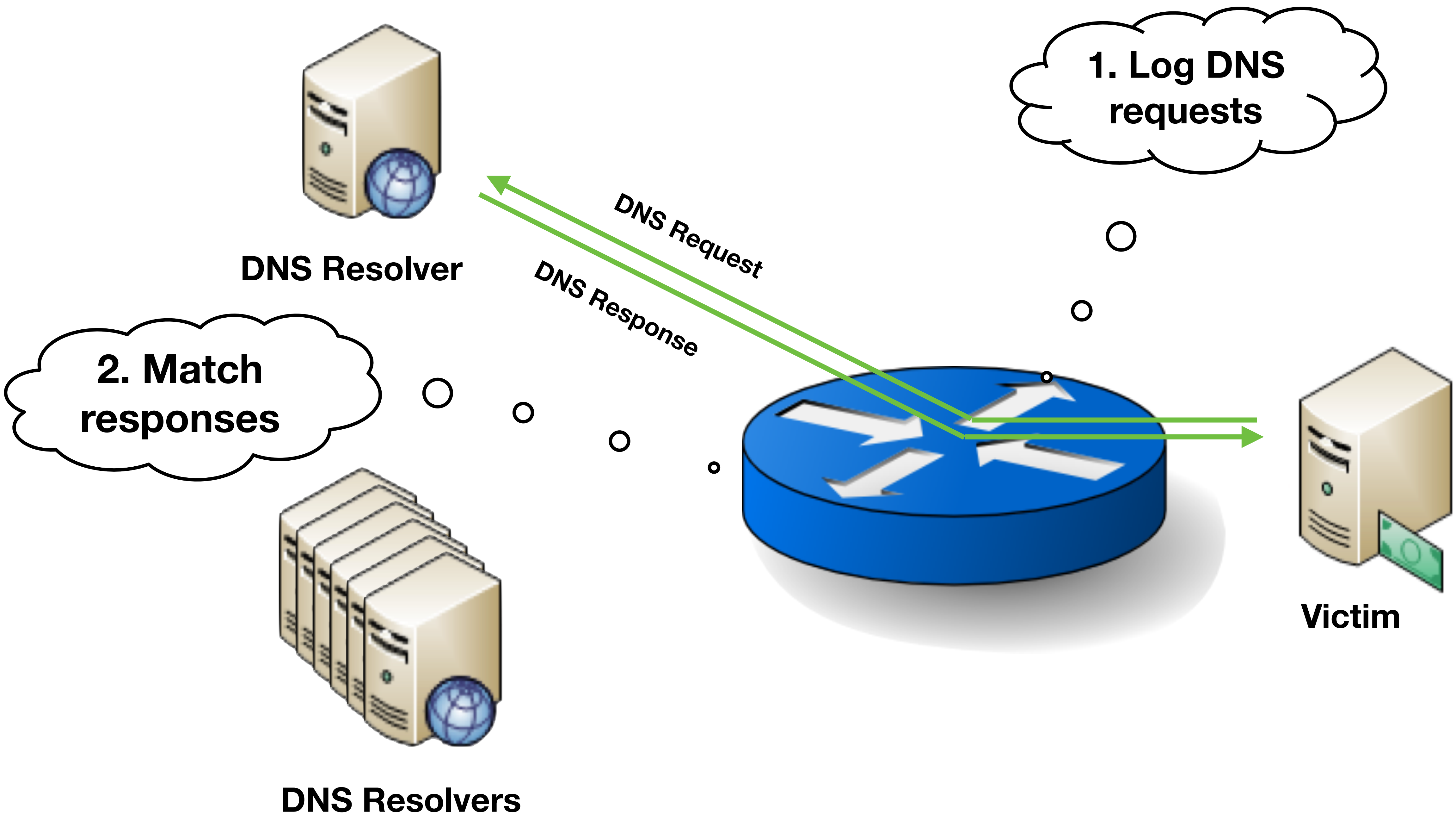

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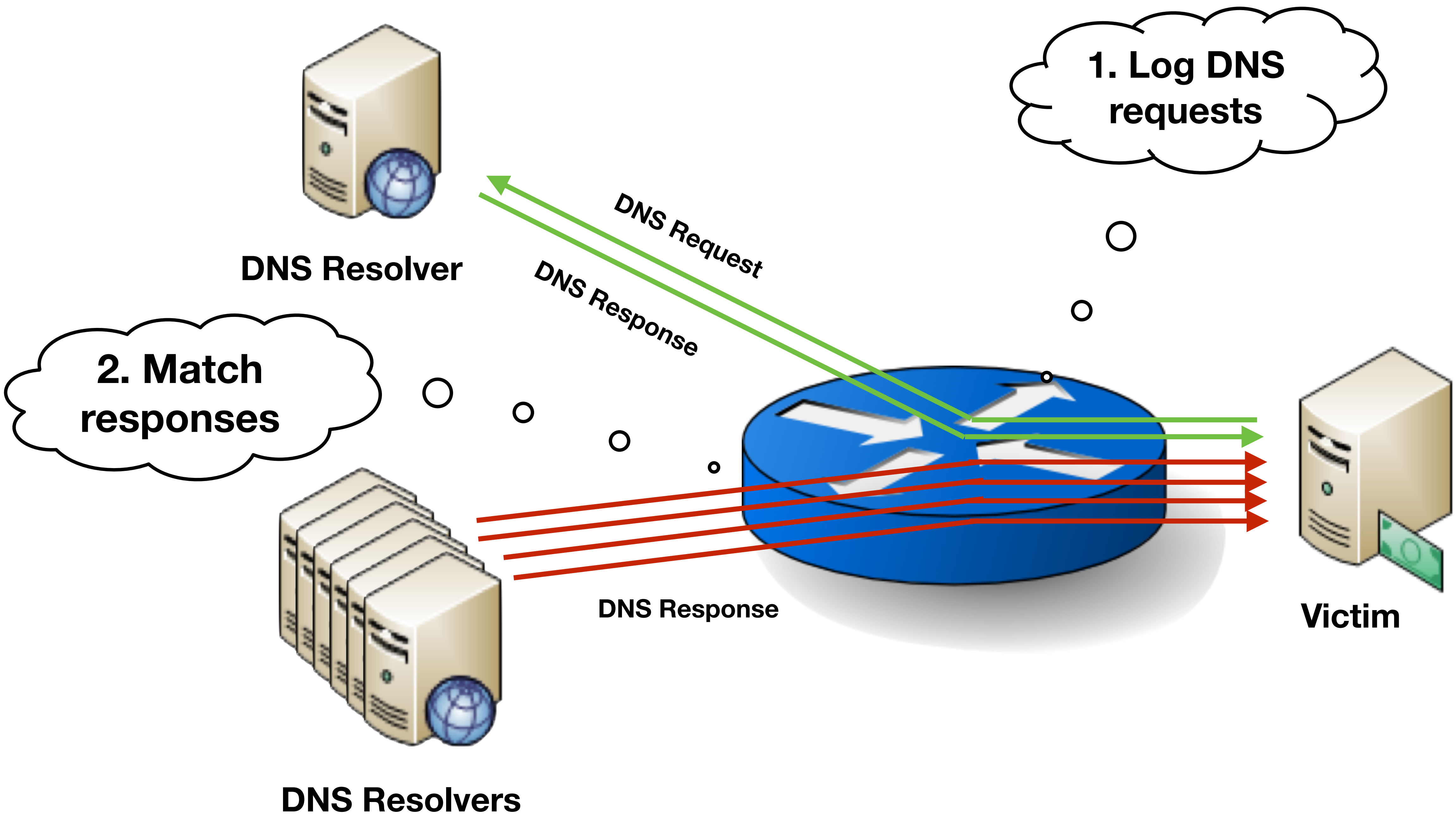

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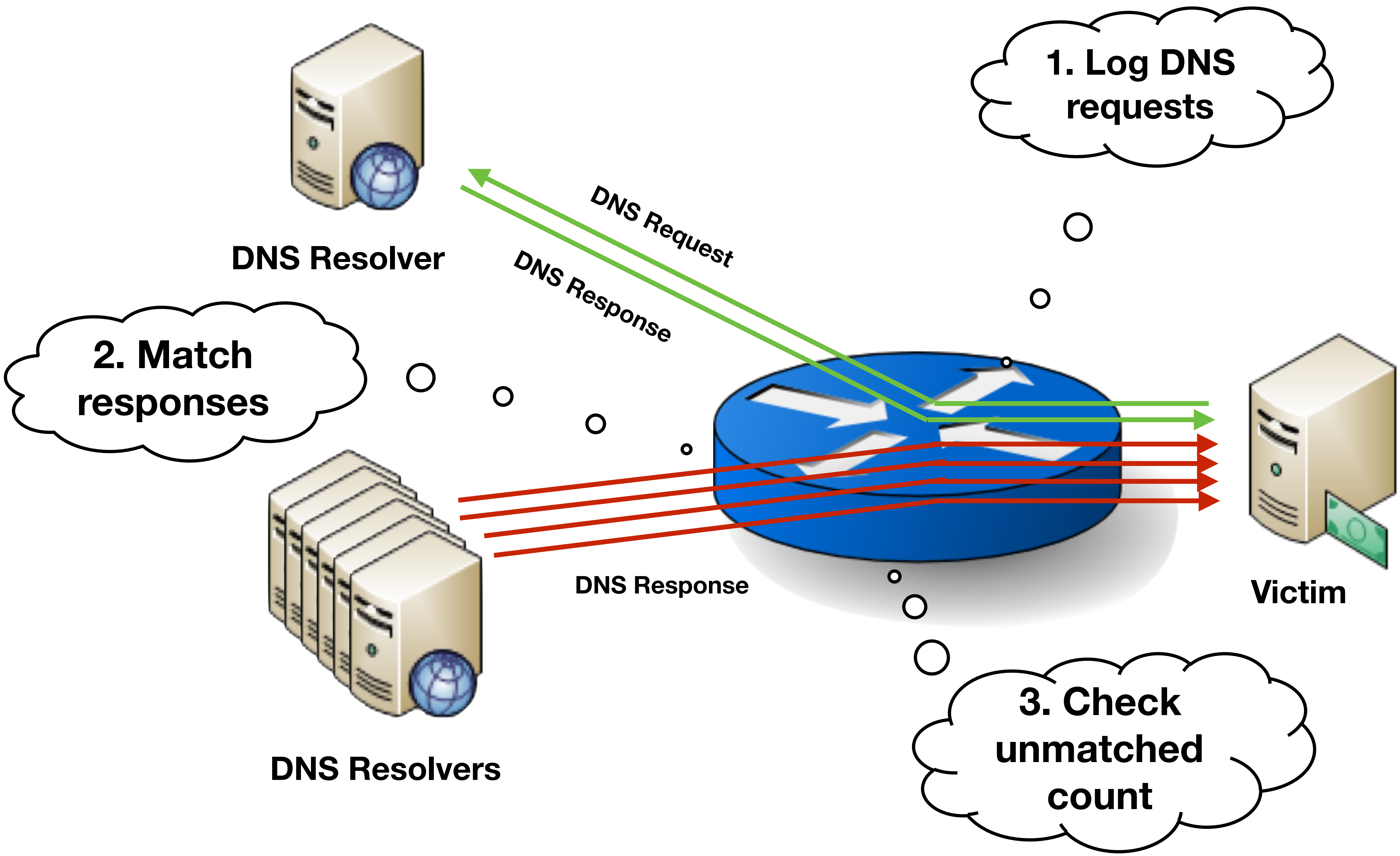

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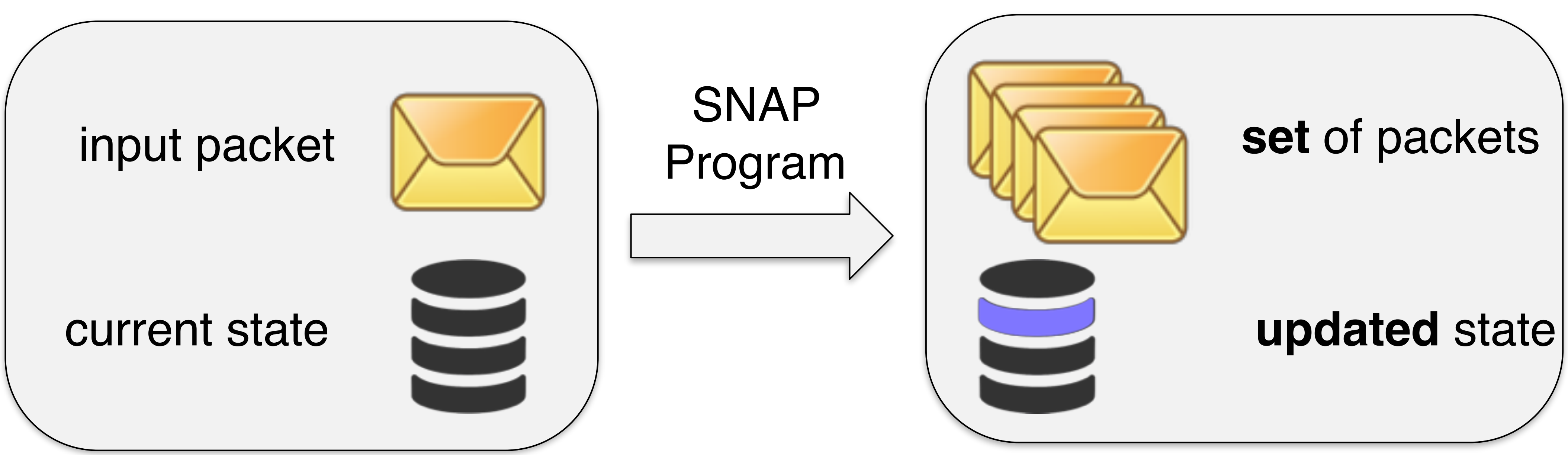
SNAP Language

Stateful Packet Processing Functions

- A function specifying
  - how to process each packet
  - based on its **fields** and the **program state**



DNS Reflection Detection in SNAP

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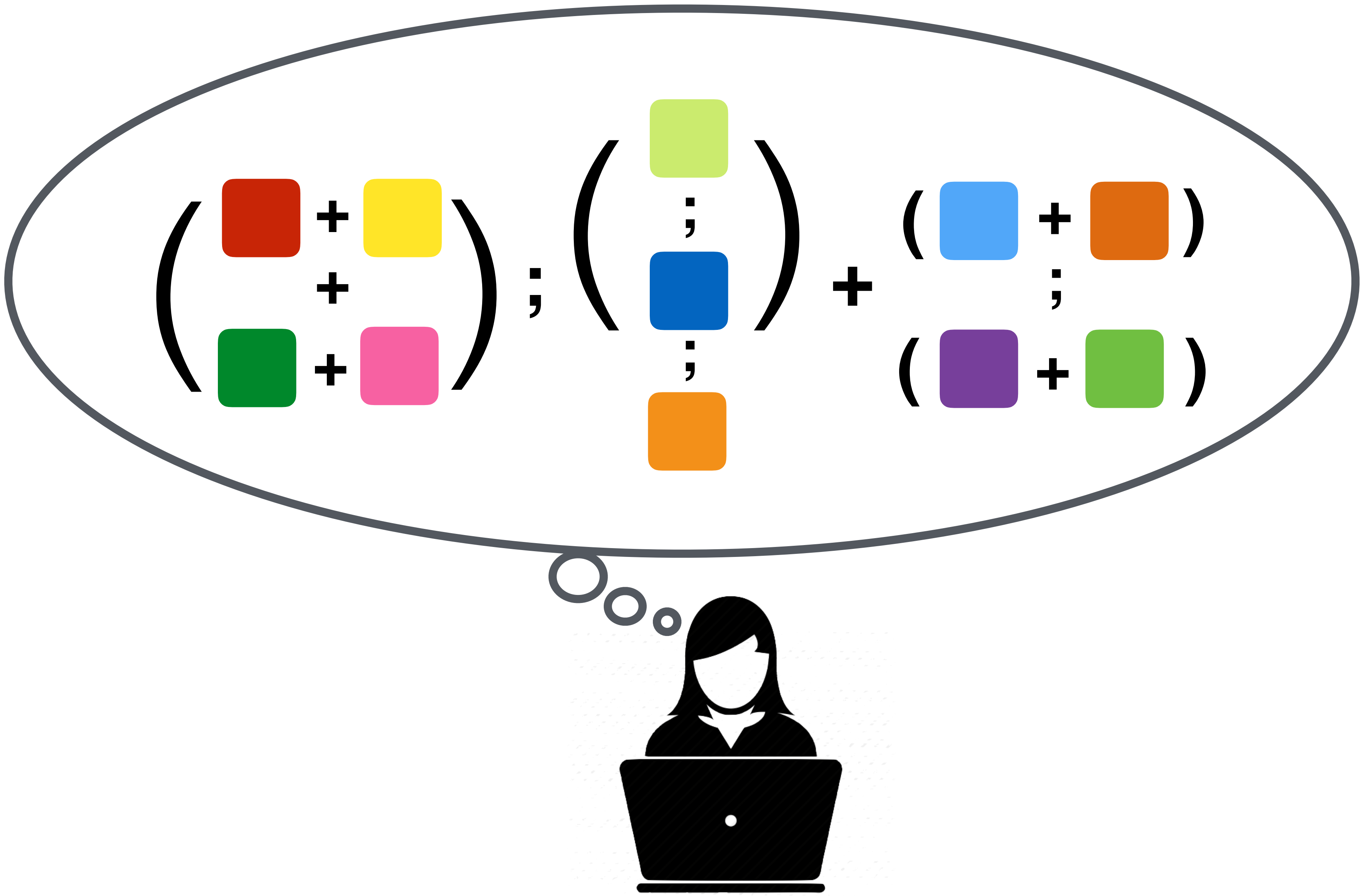
Program Composition



SNAP Compiler

Where to Place State Variables?

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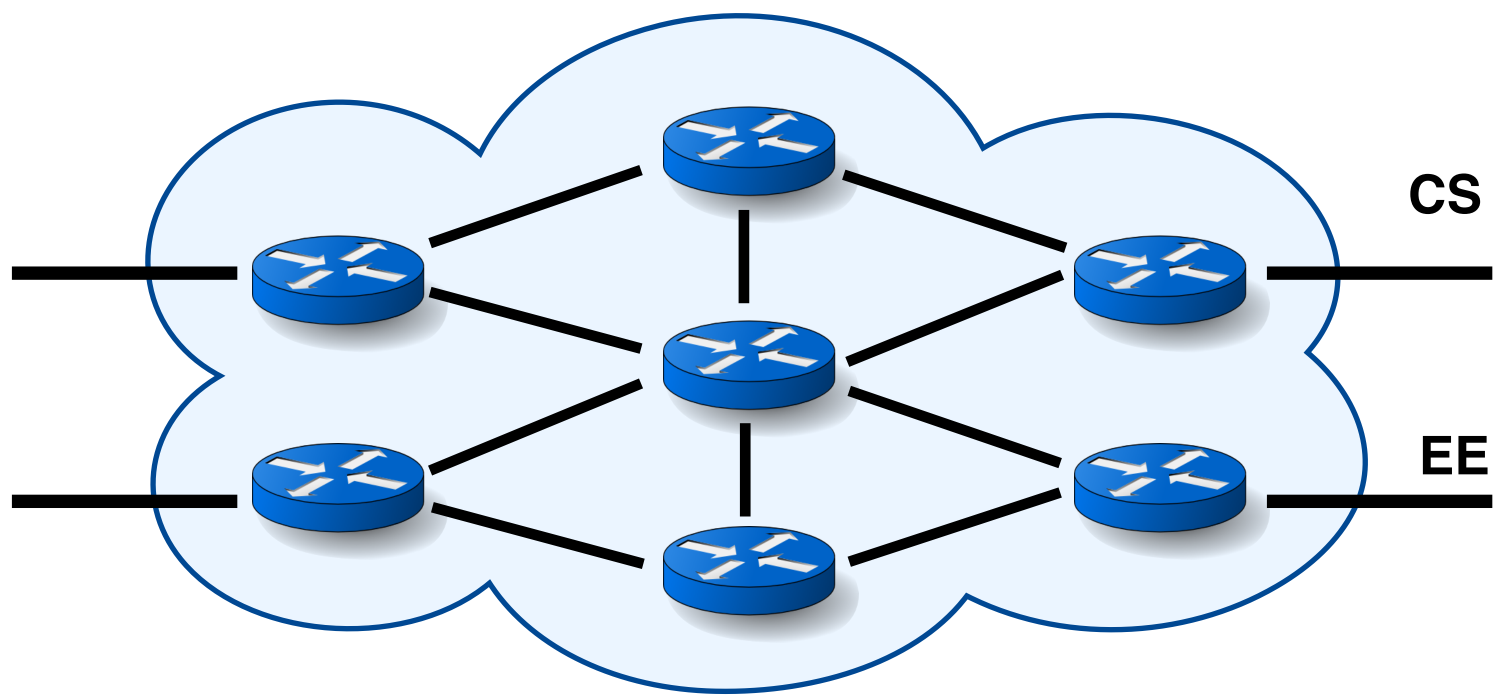
```
if dstip = CSNET then outport ← CS
else if dstip = EENET then outport ← EE
else if dstip = ISP1NET then outport ← ISP1
else if dstip = ISP2NET then outport ← ISP2
else drop
```



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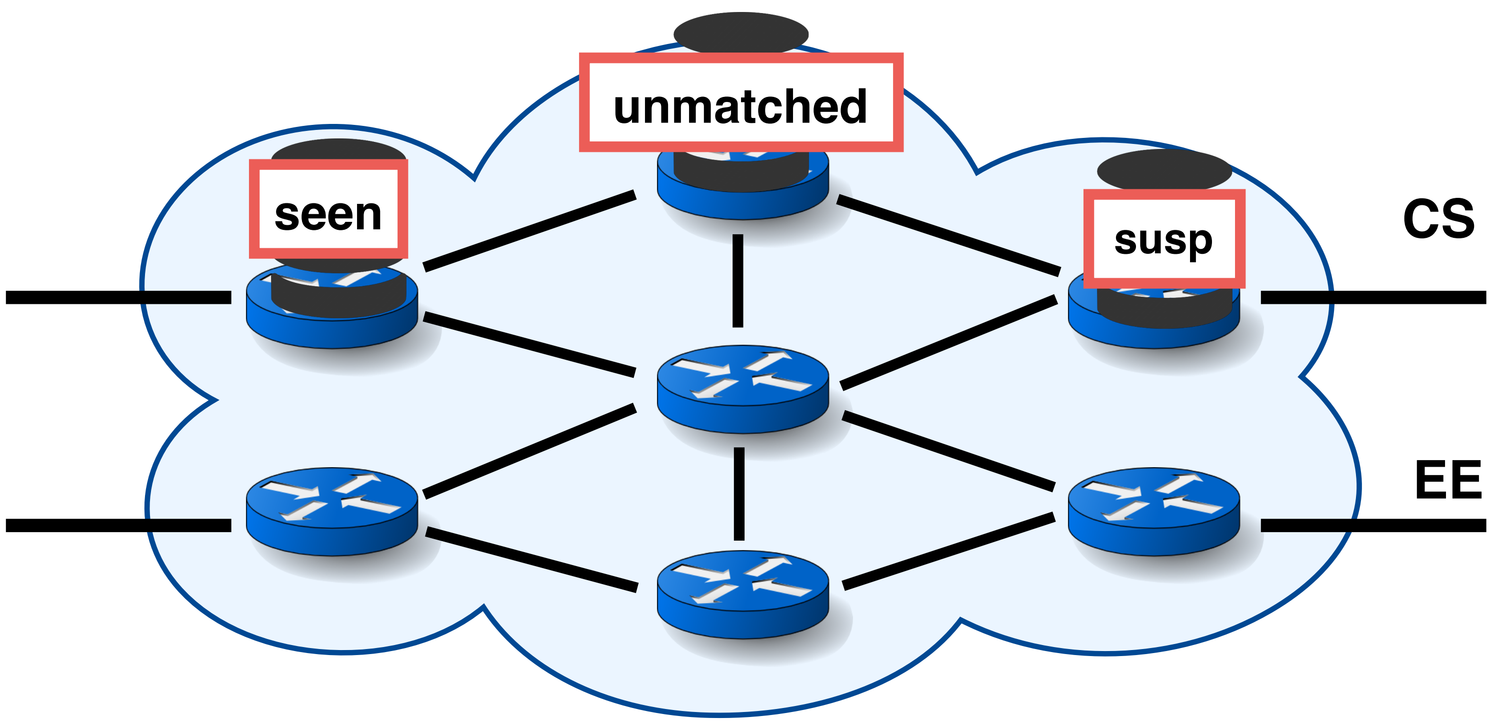

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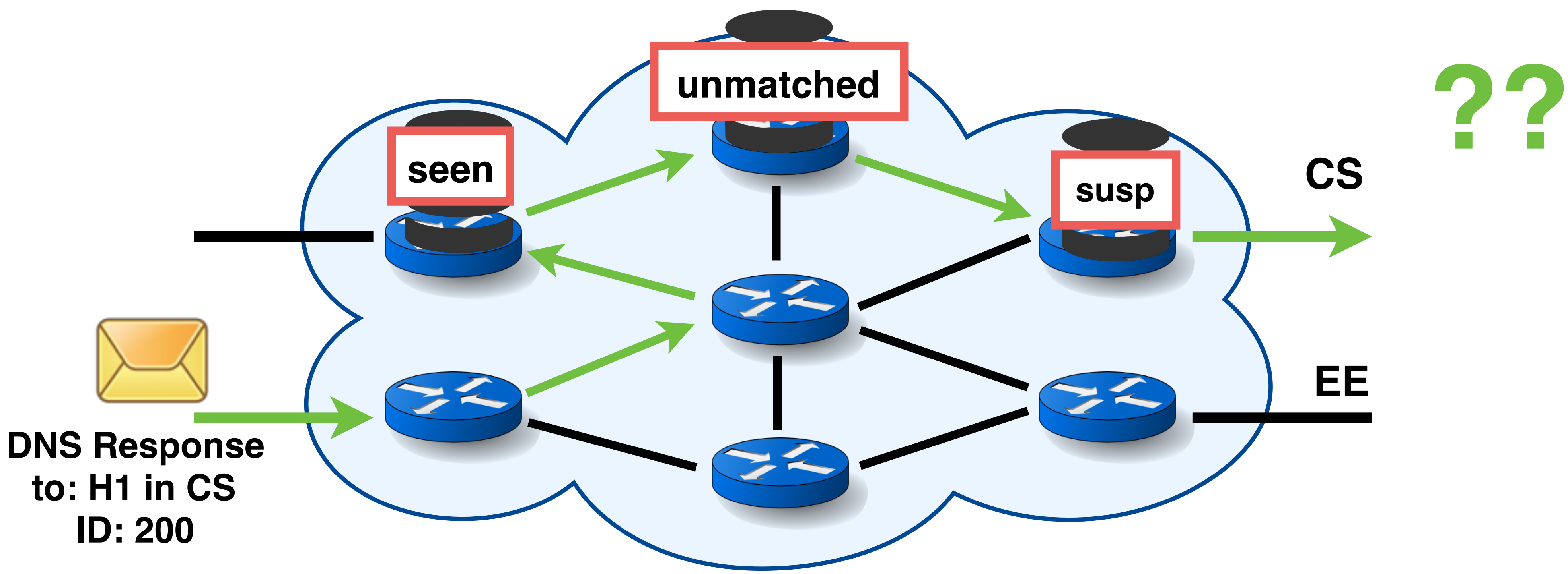

Program Analysis

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- For each flow, find
  - all the state variables that it needs
  - the order in which the state variables should be visited

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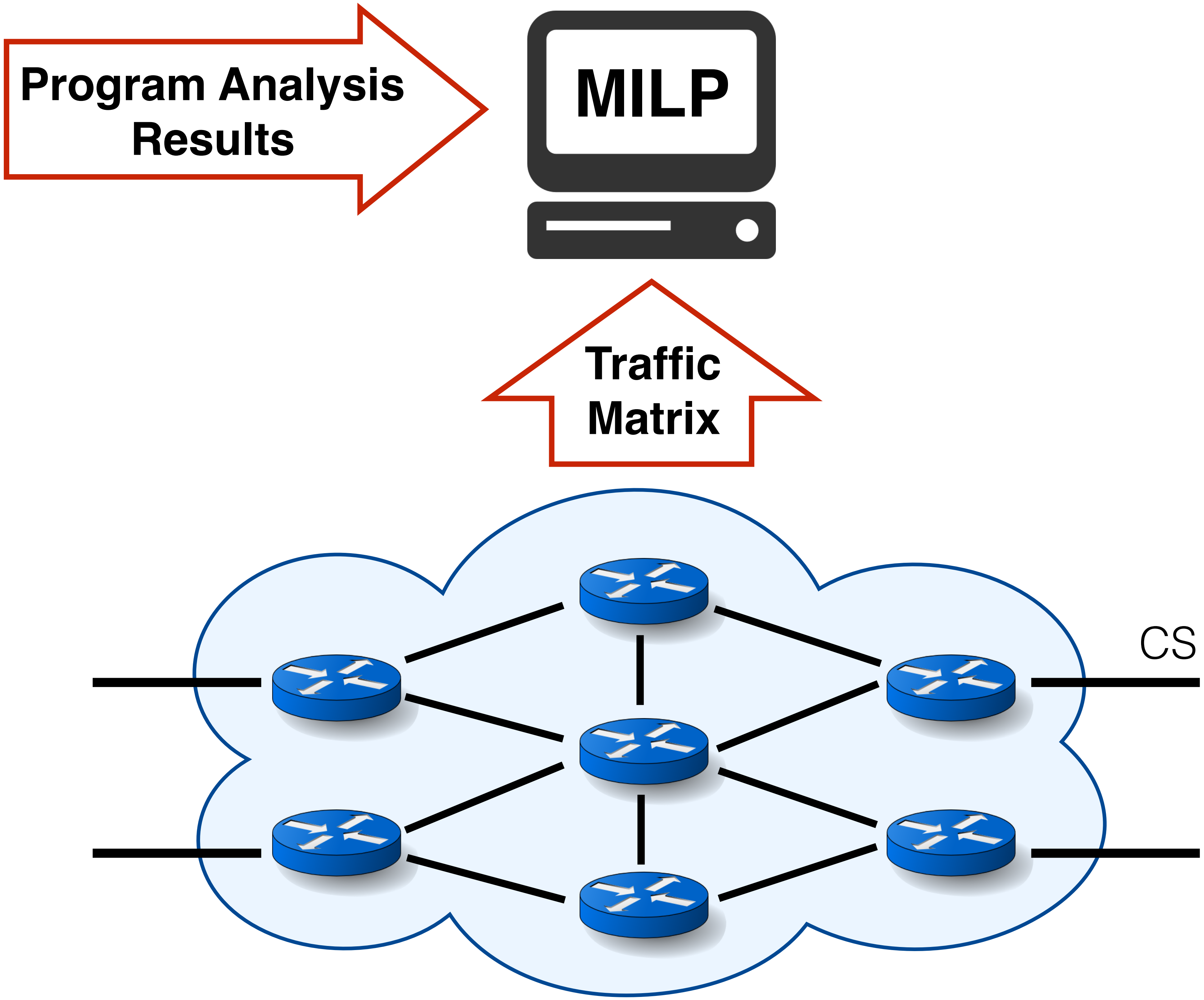
  - all the state variables that it needs
  - the order in which the state variables should be visited
- A flow can be defined at any granularity
  - As long as its traffic statistics is available
  - E.g., All DNS packets to the CS subnet need all three state variables
  - E.g., All packets from the CS subnet need `seen`.

Mixed-Integer Linear Program (MILP)



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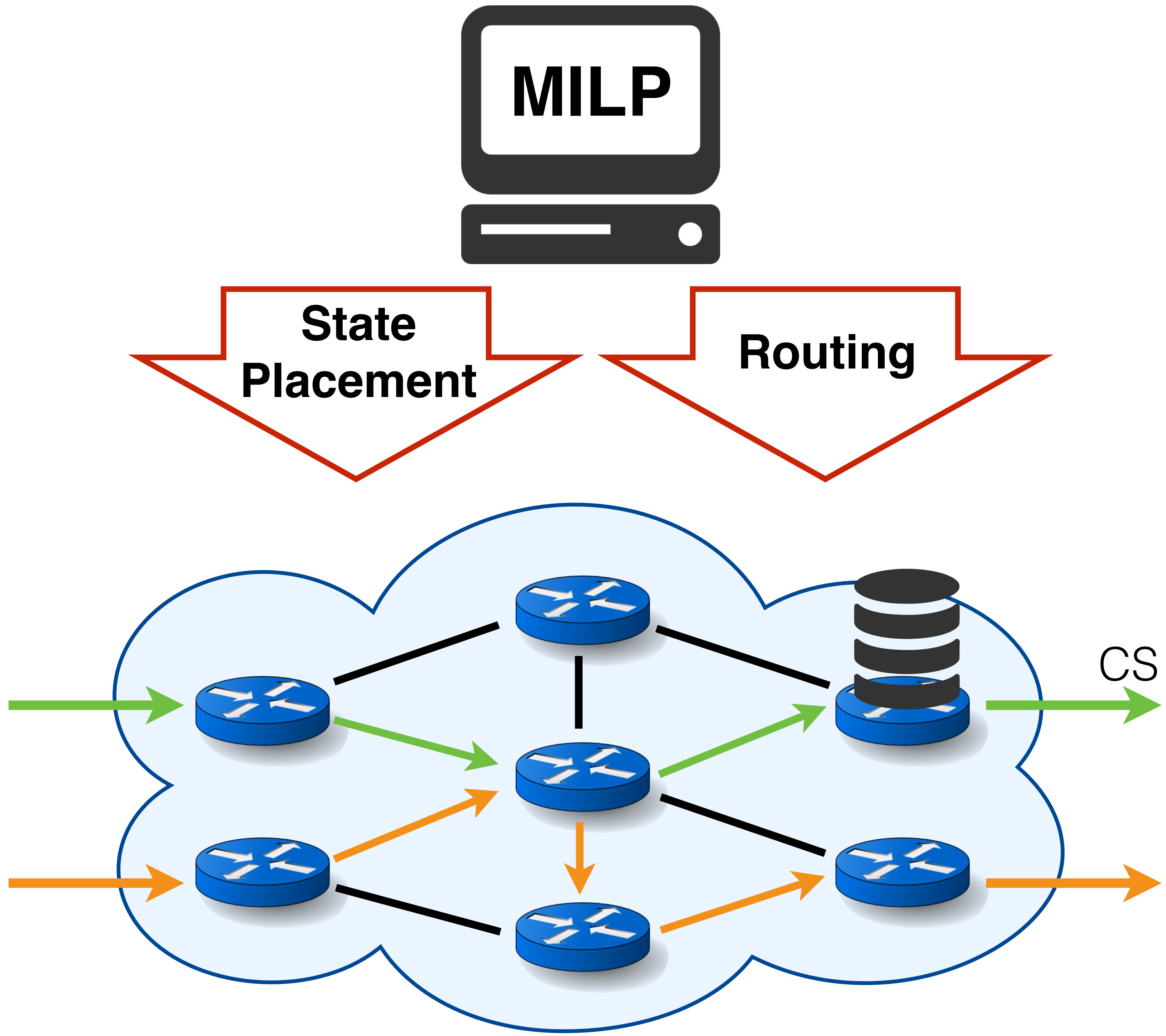
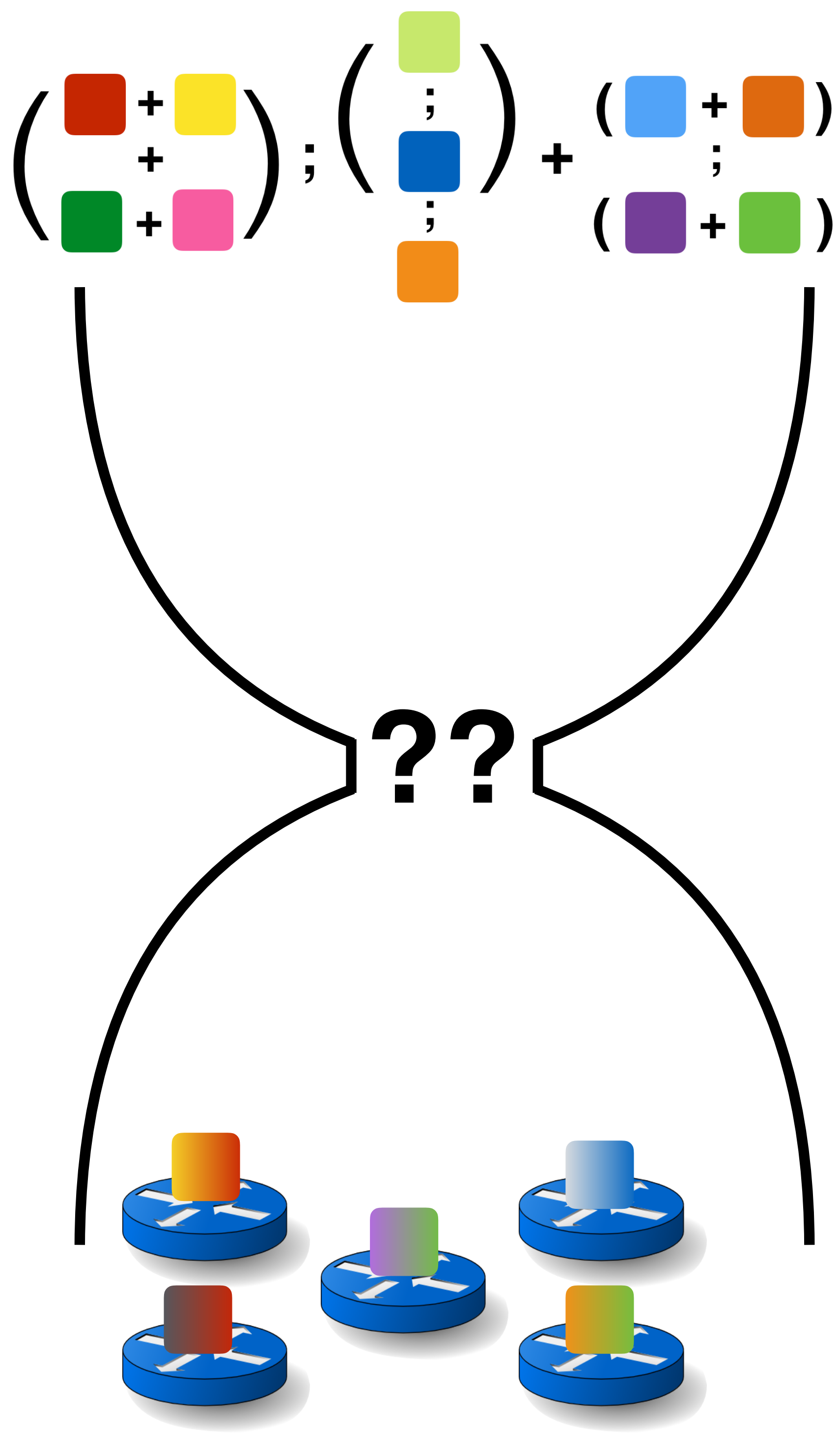


How to distribute a SNAP program?



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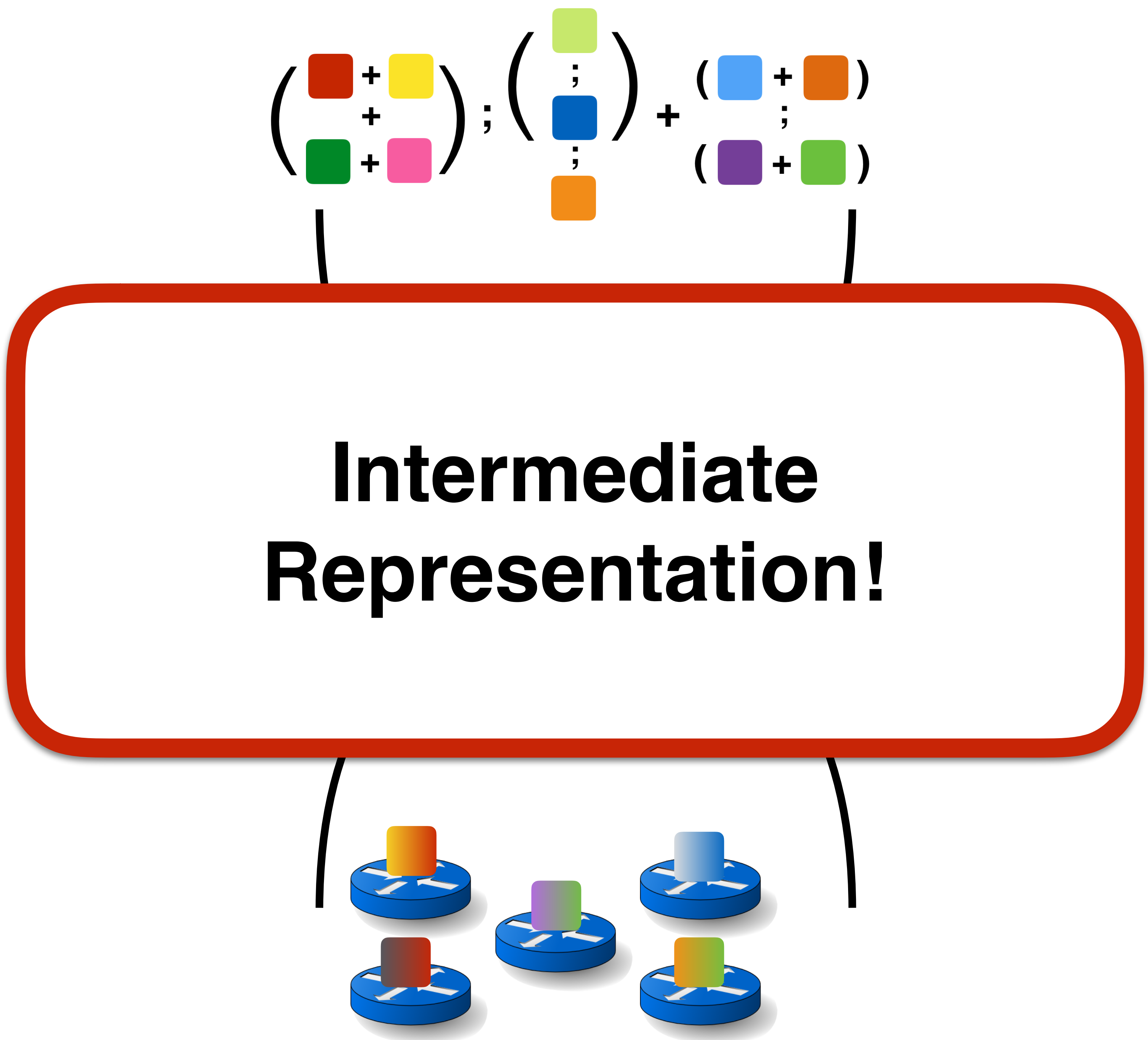
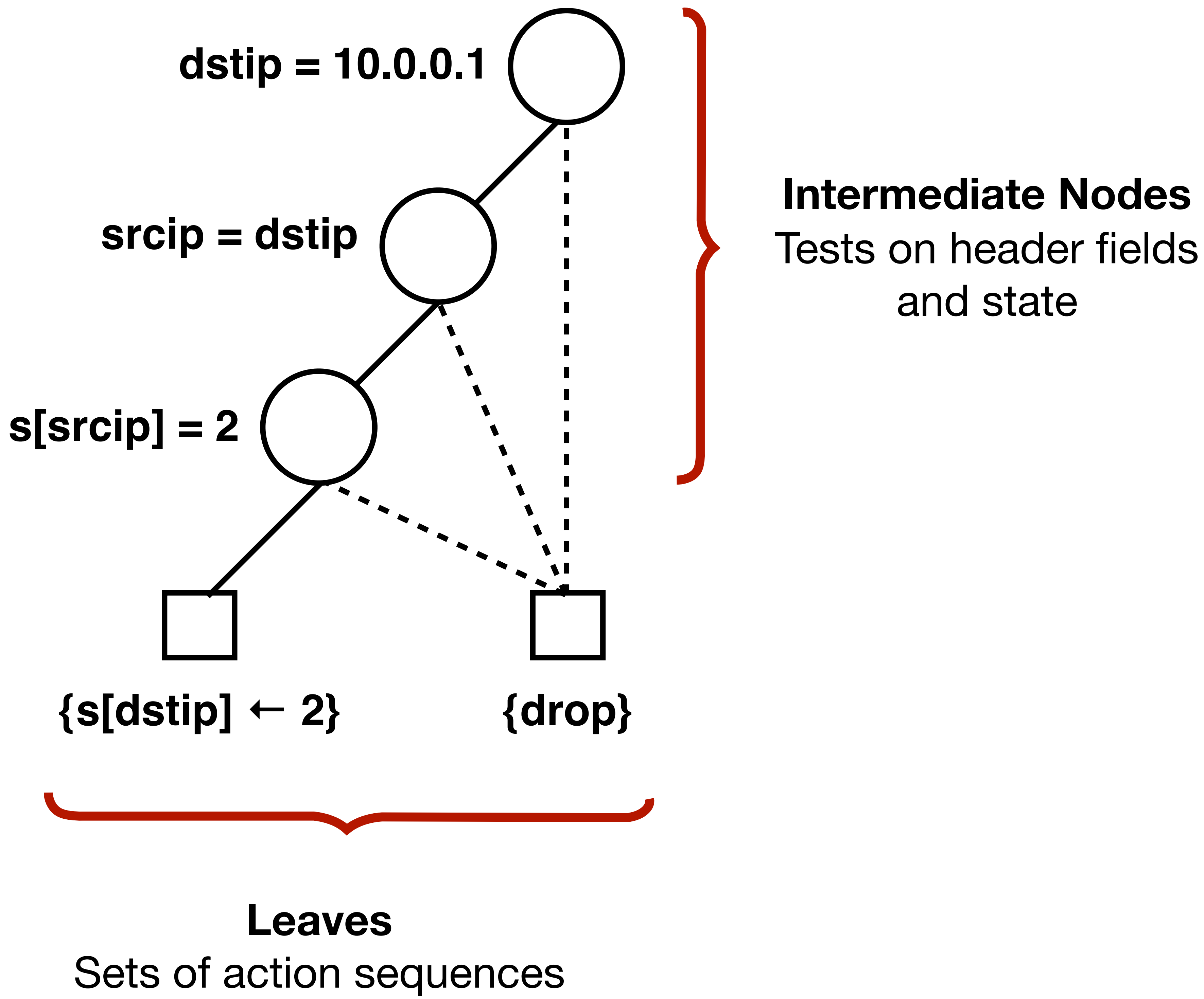


Extended Forwarding Decision Diagrams (xFDDs)



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xFDD for DNS Reflection Detection

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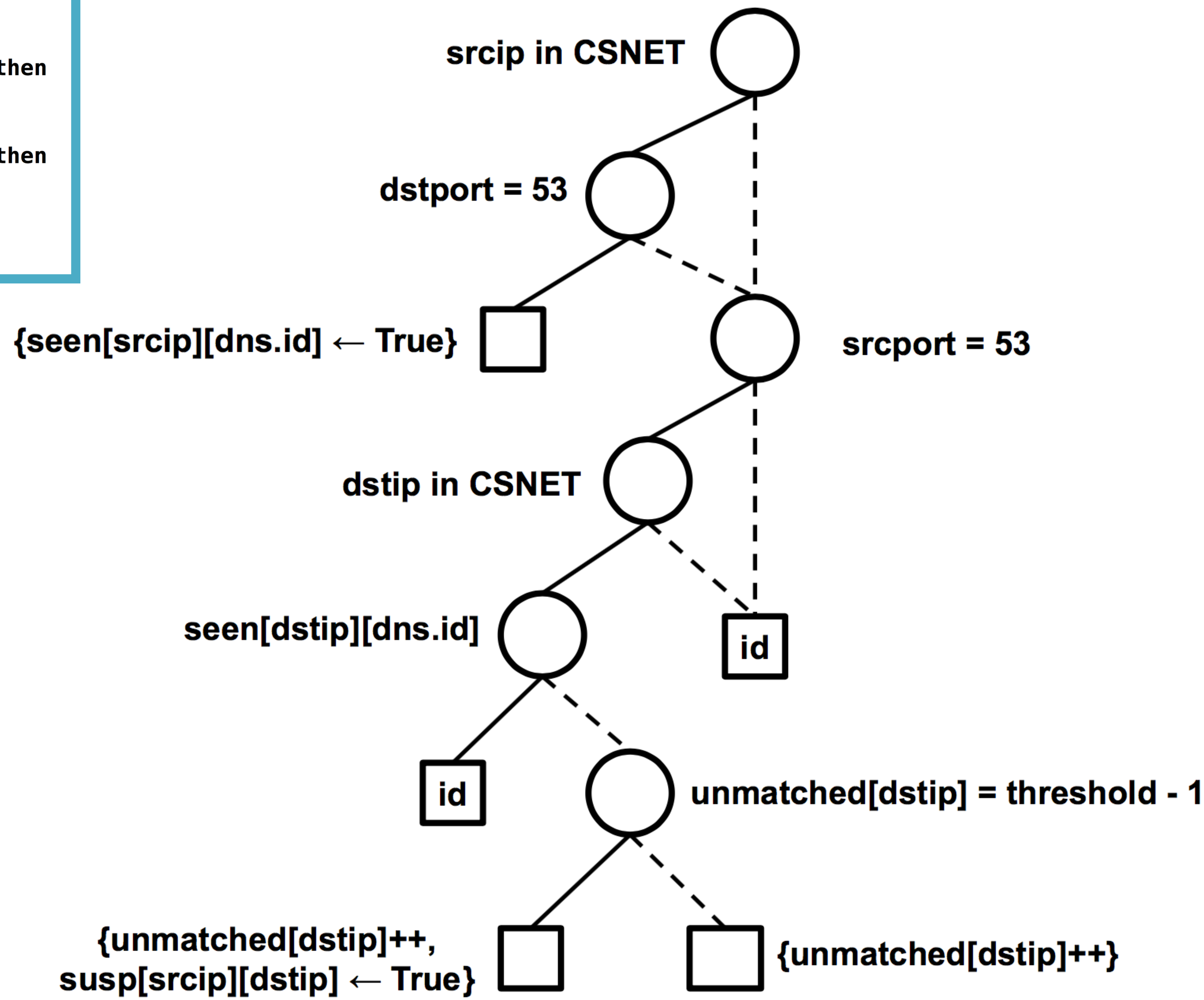

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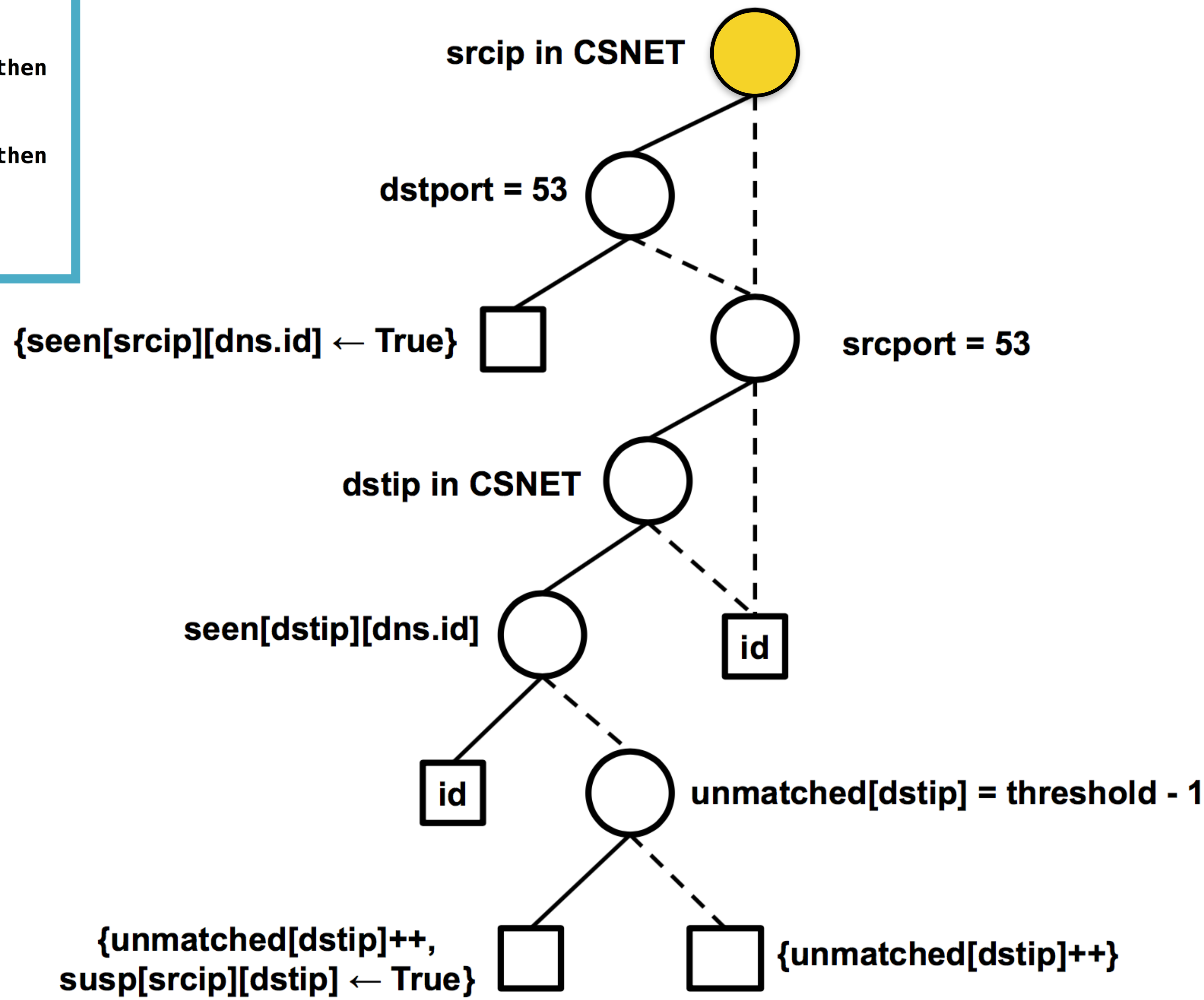

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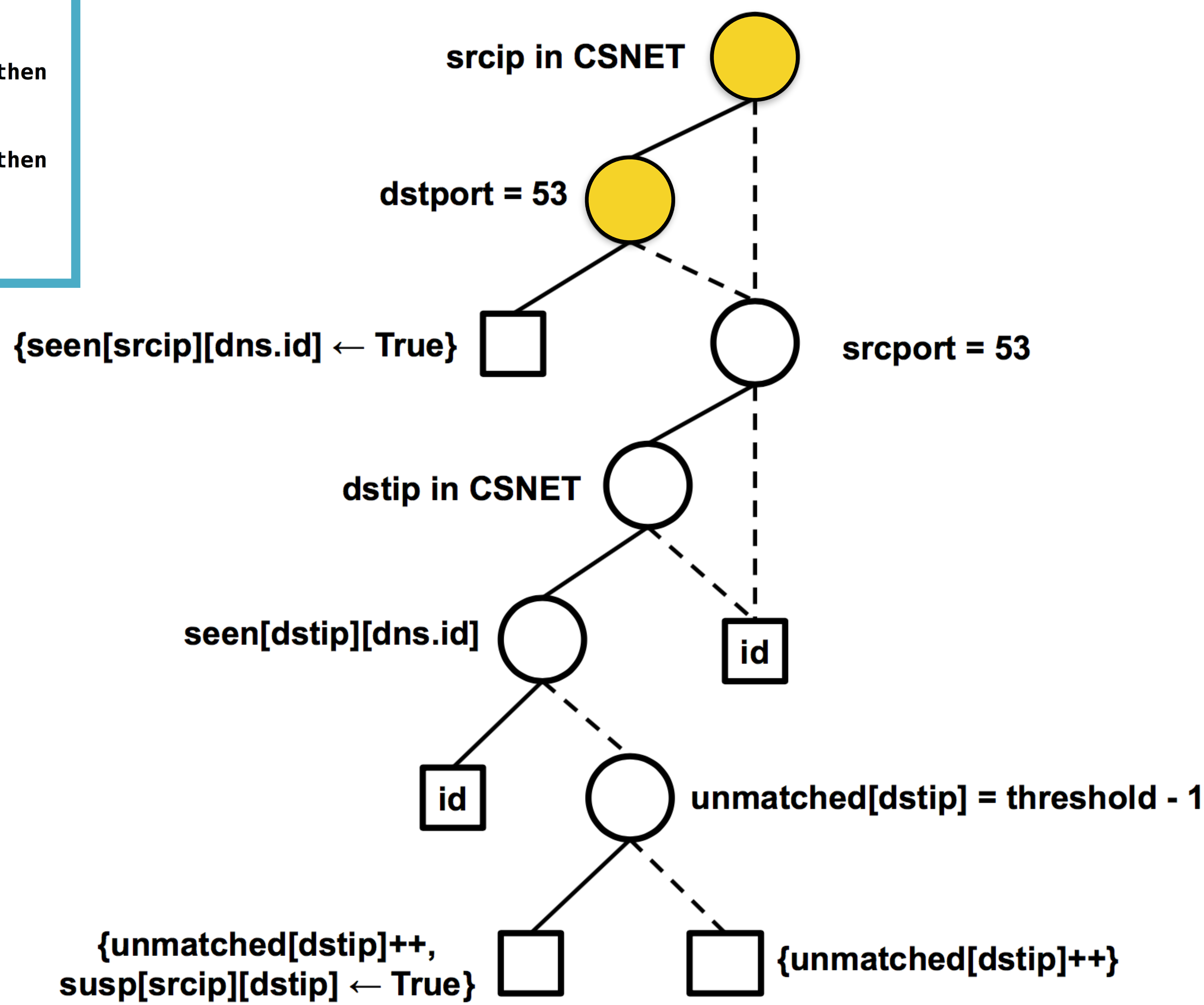

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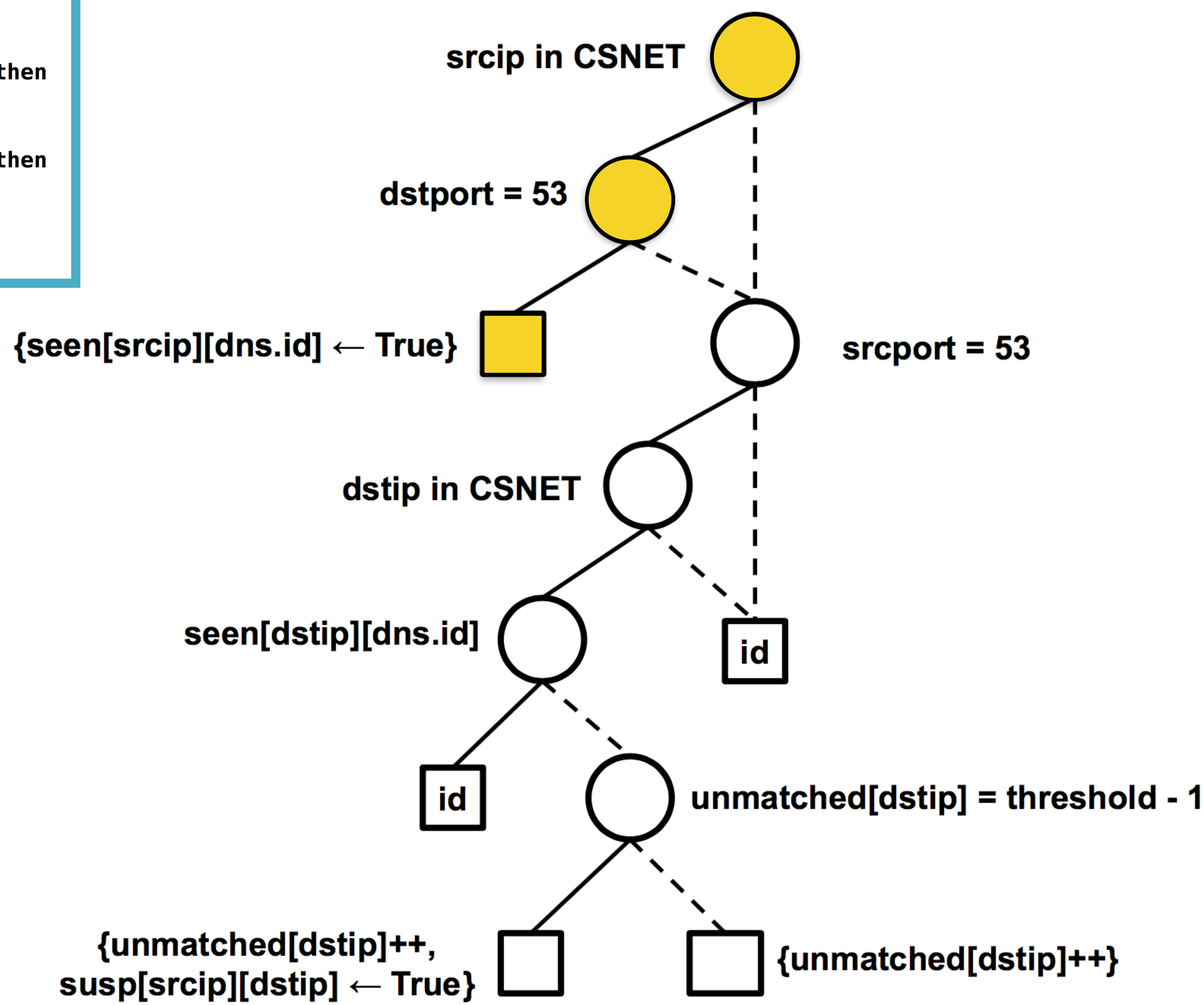
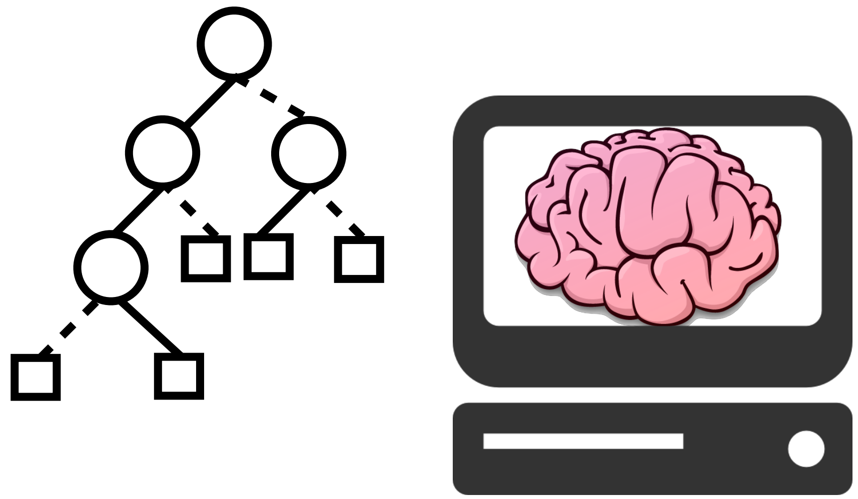
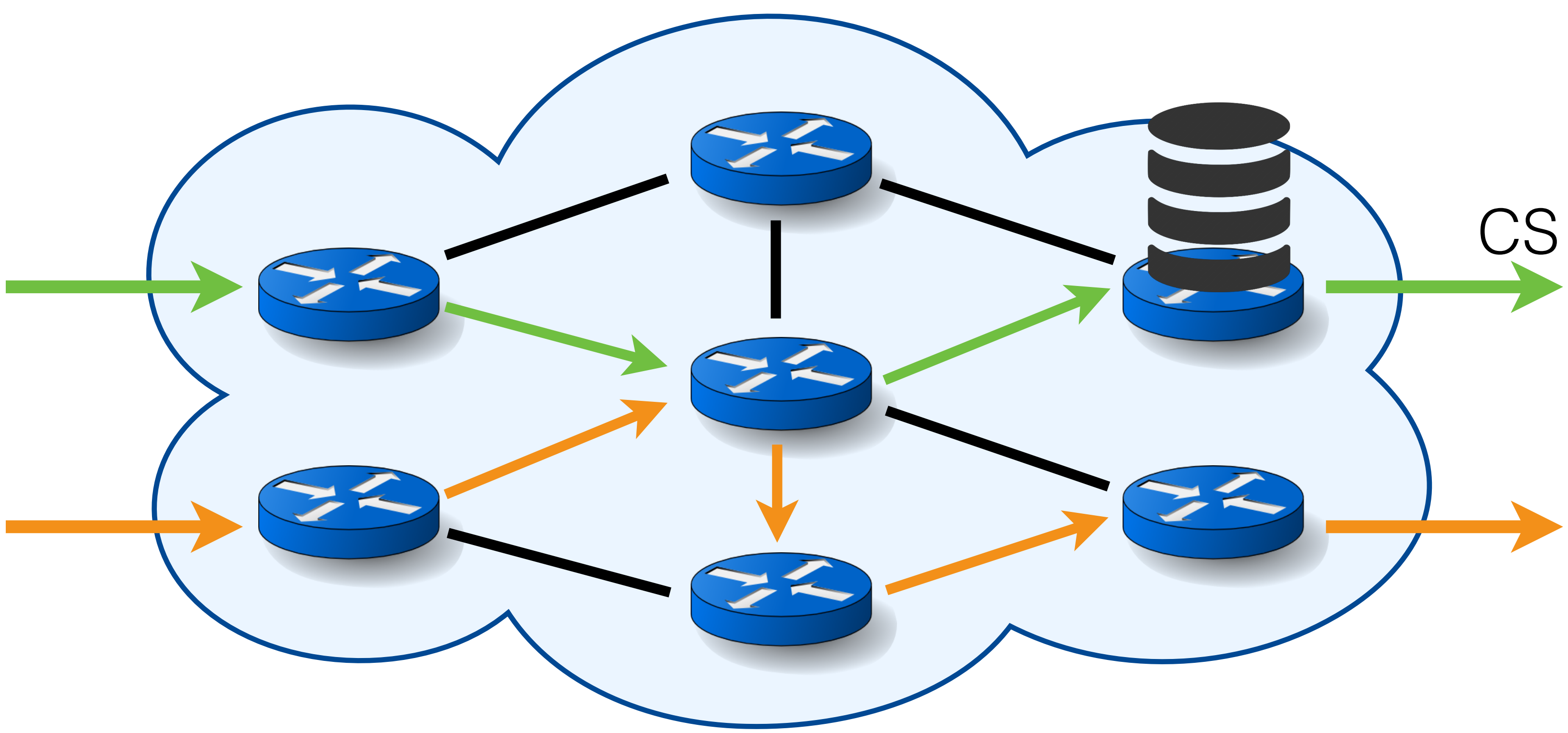


Partitioning and Distribution of the xFDD





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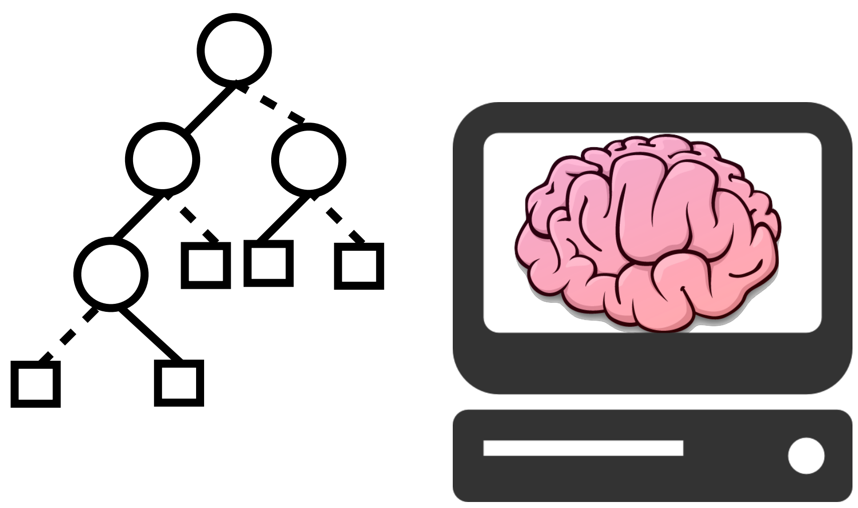

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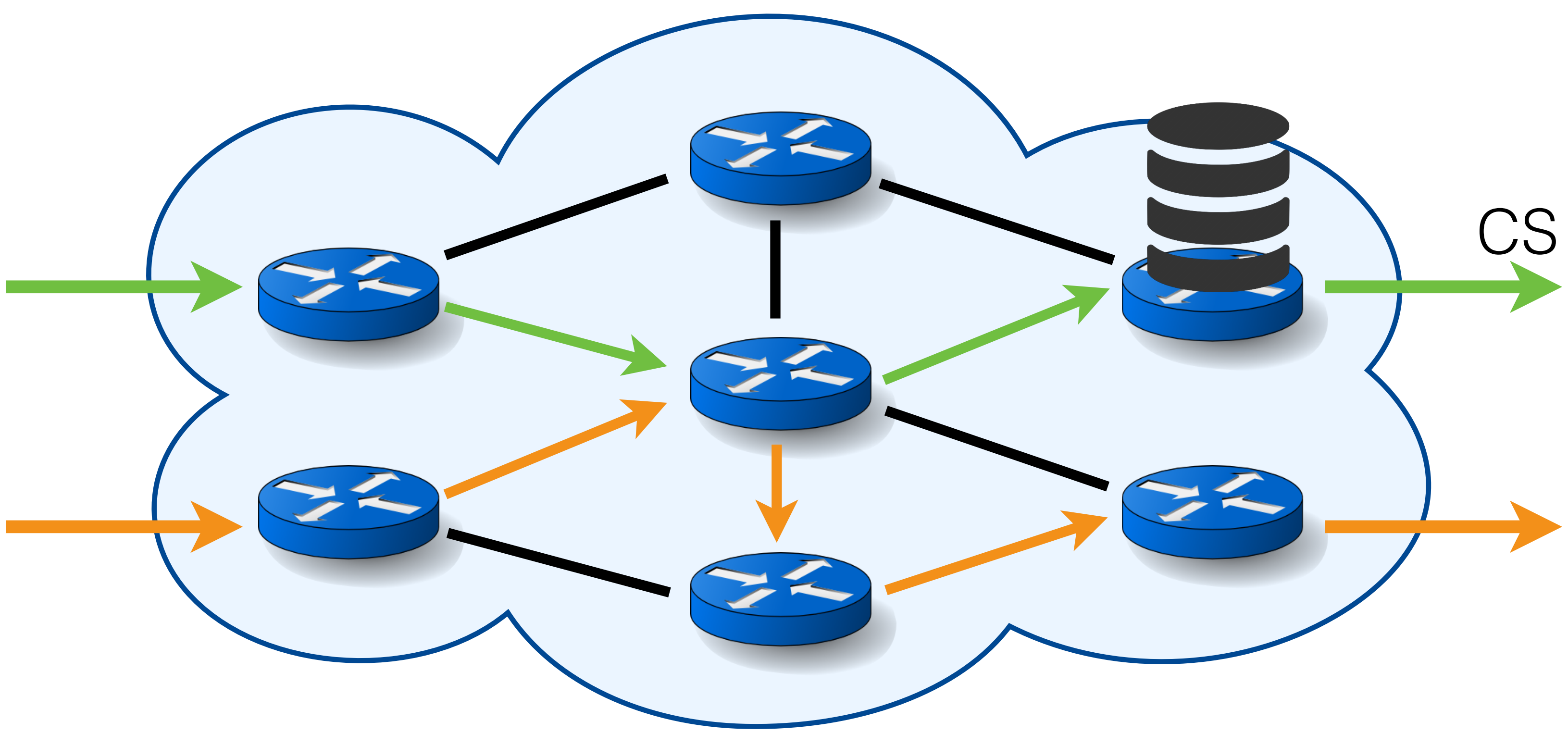

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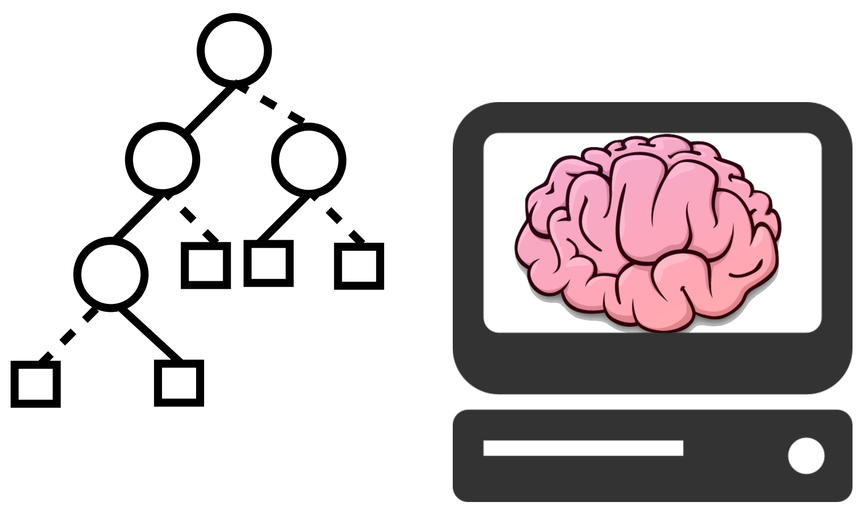

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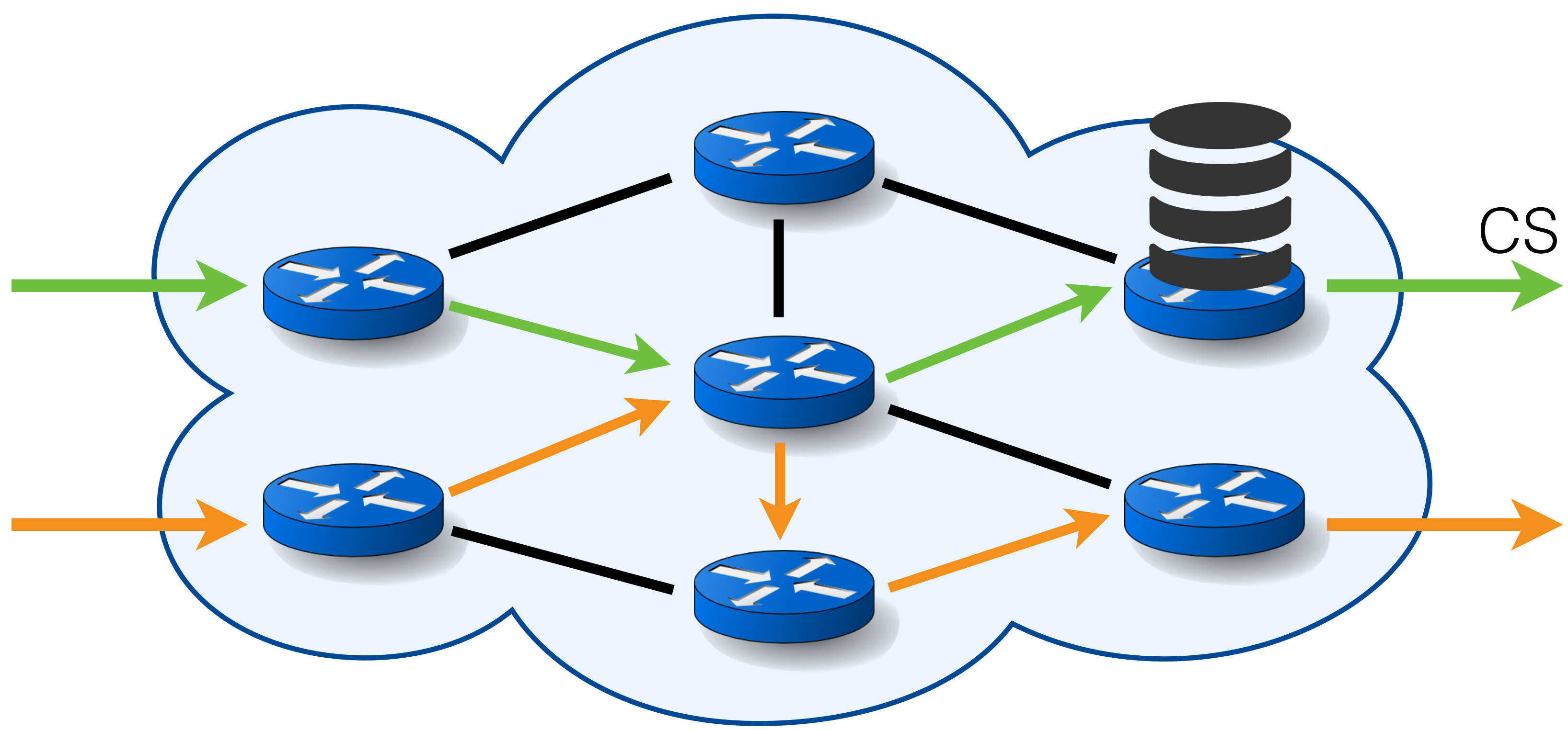

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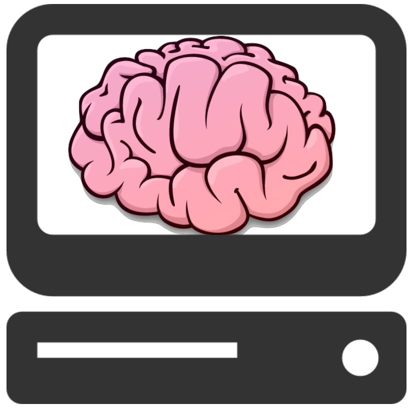

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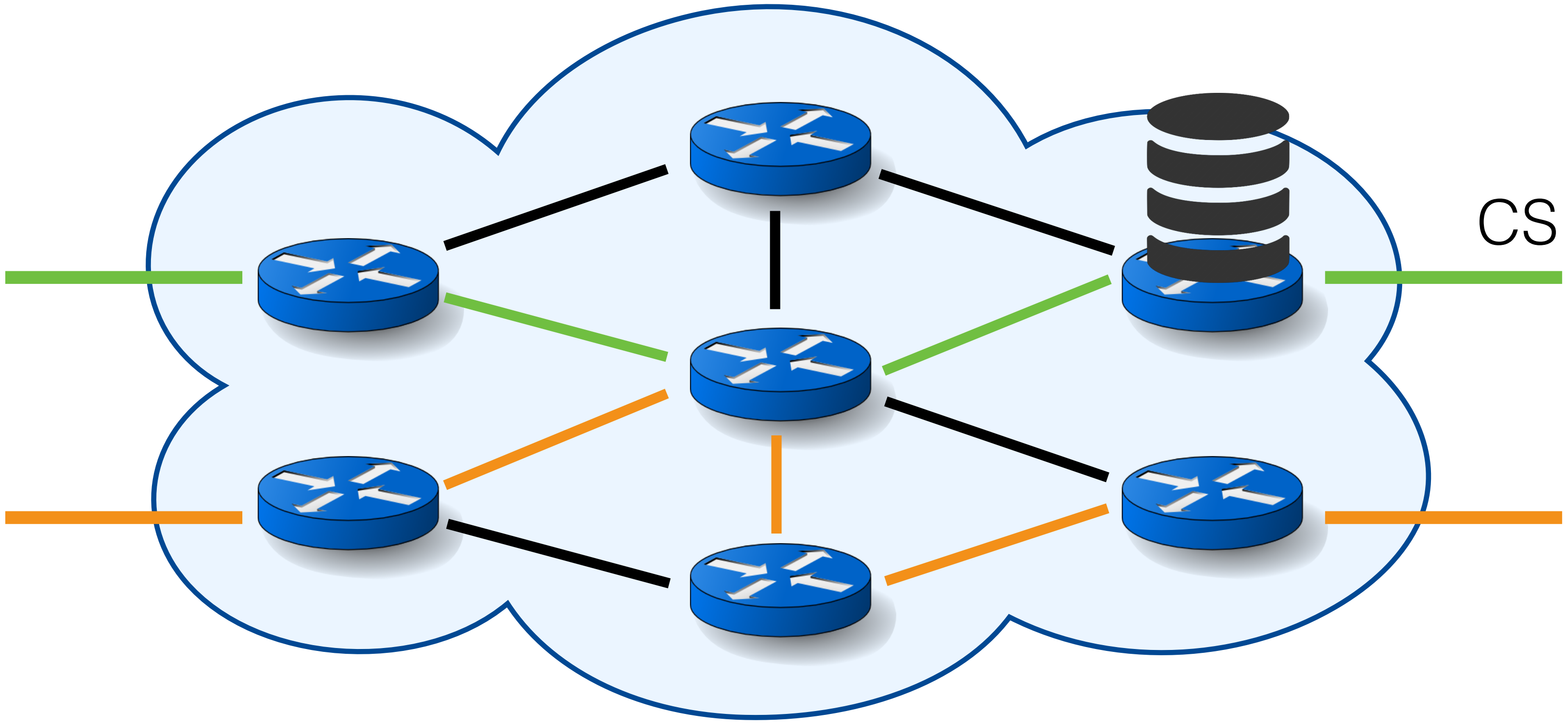

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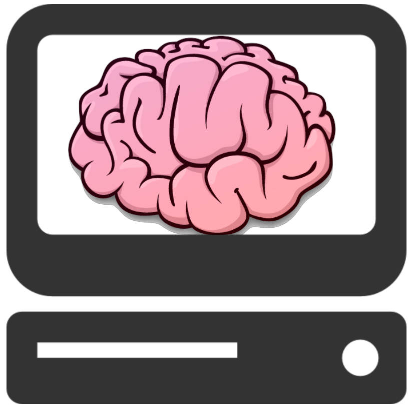

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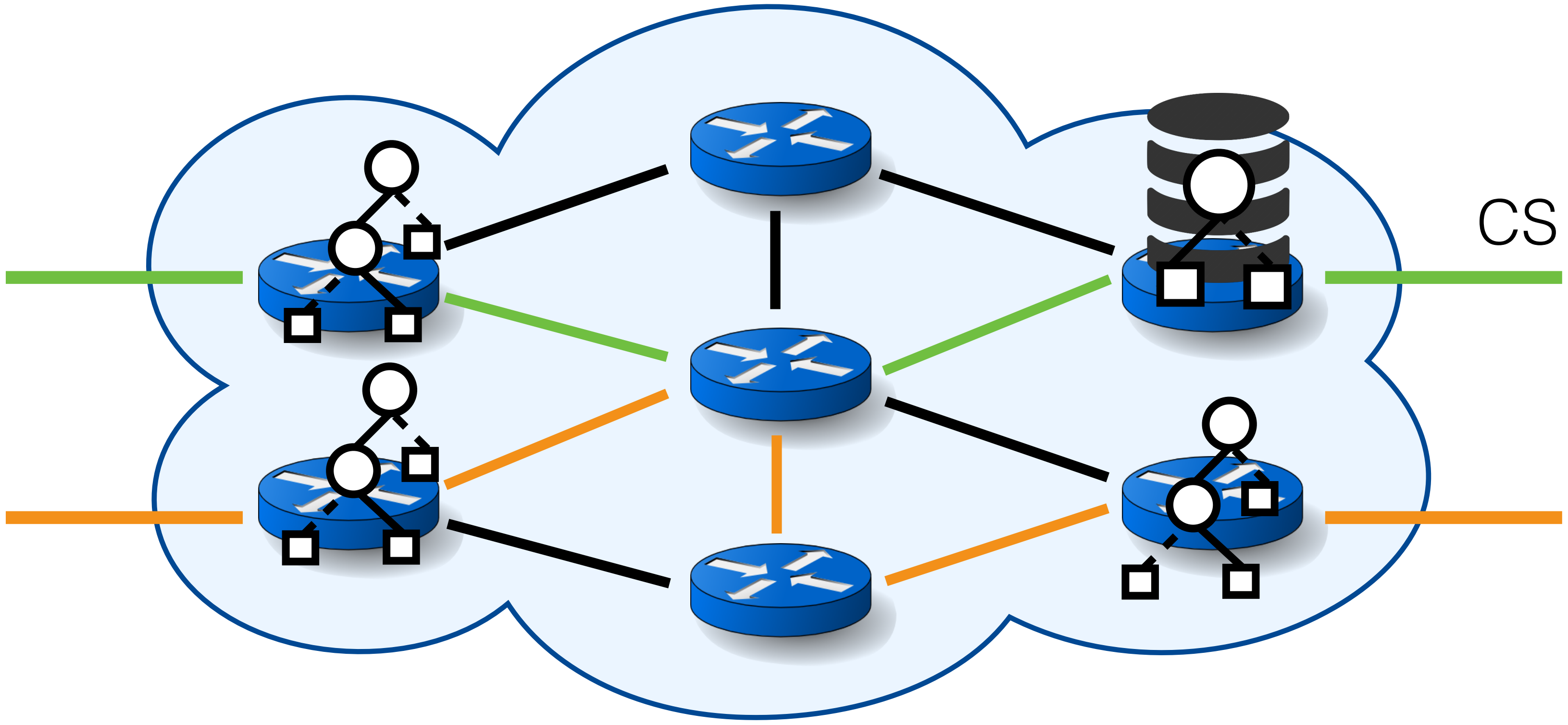

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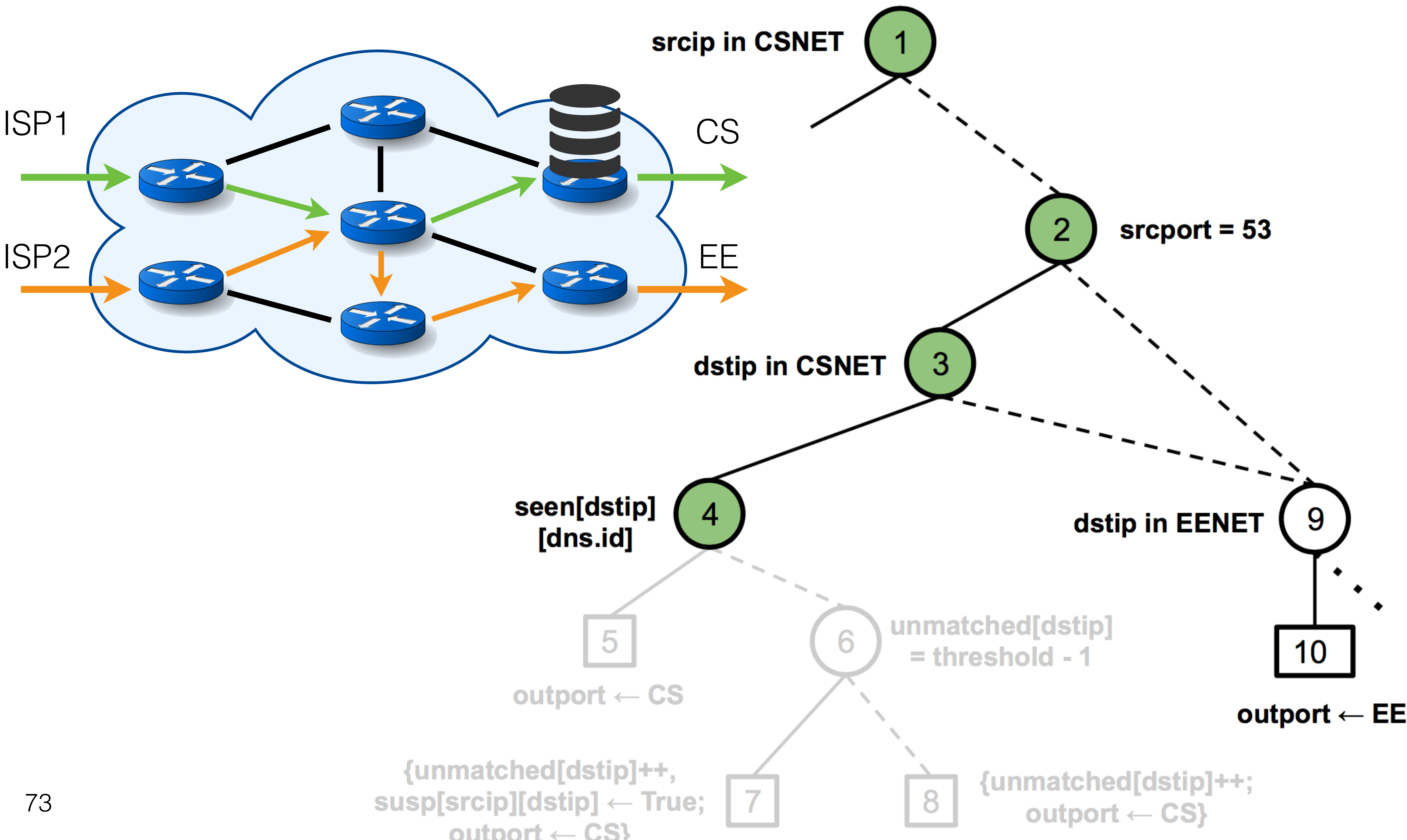

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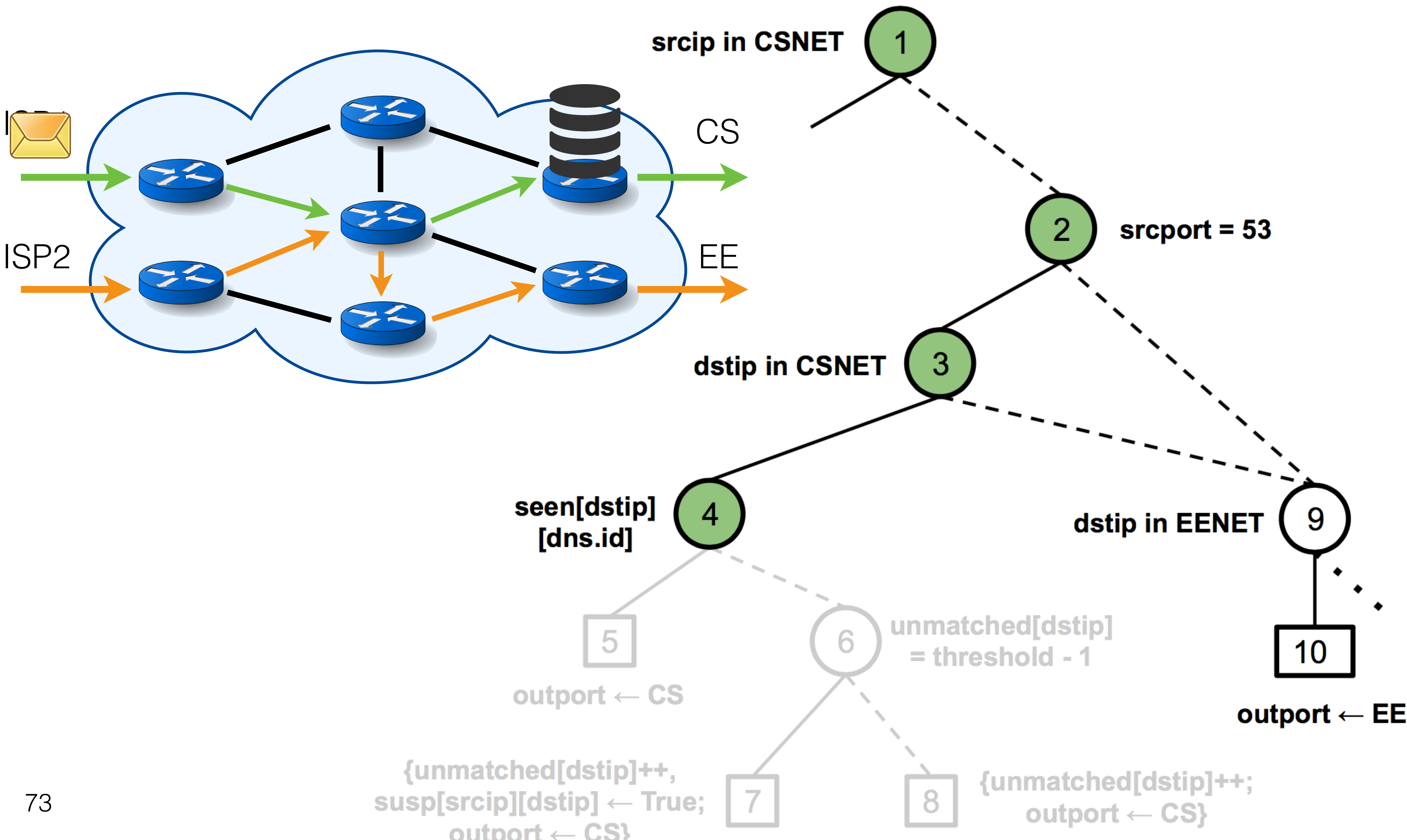

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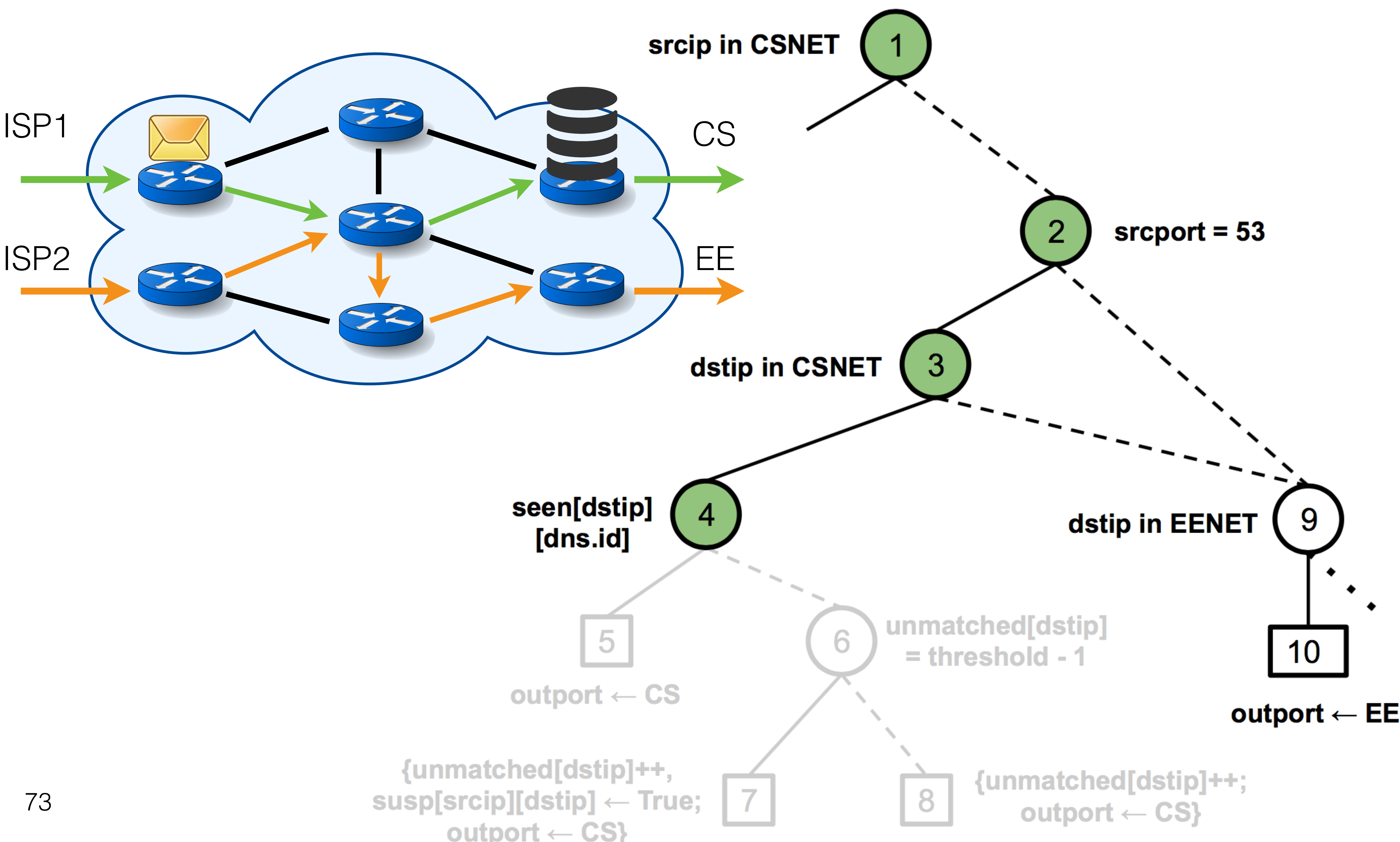

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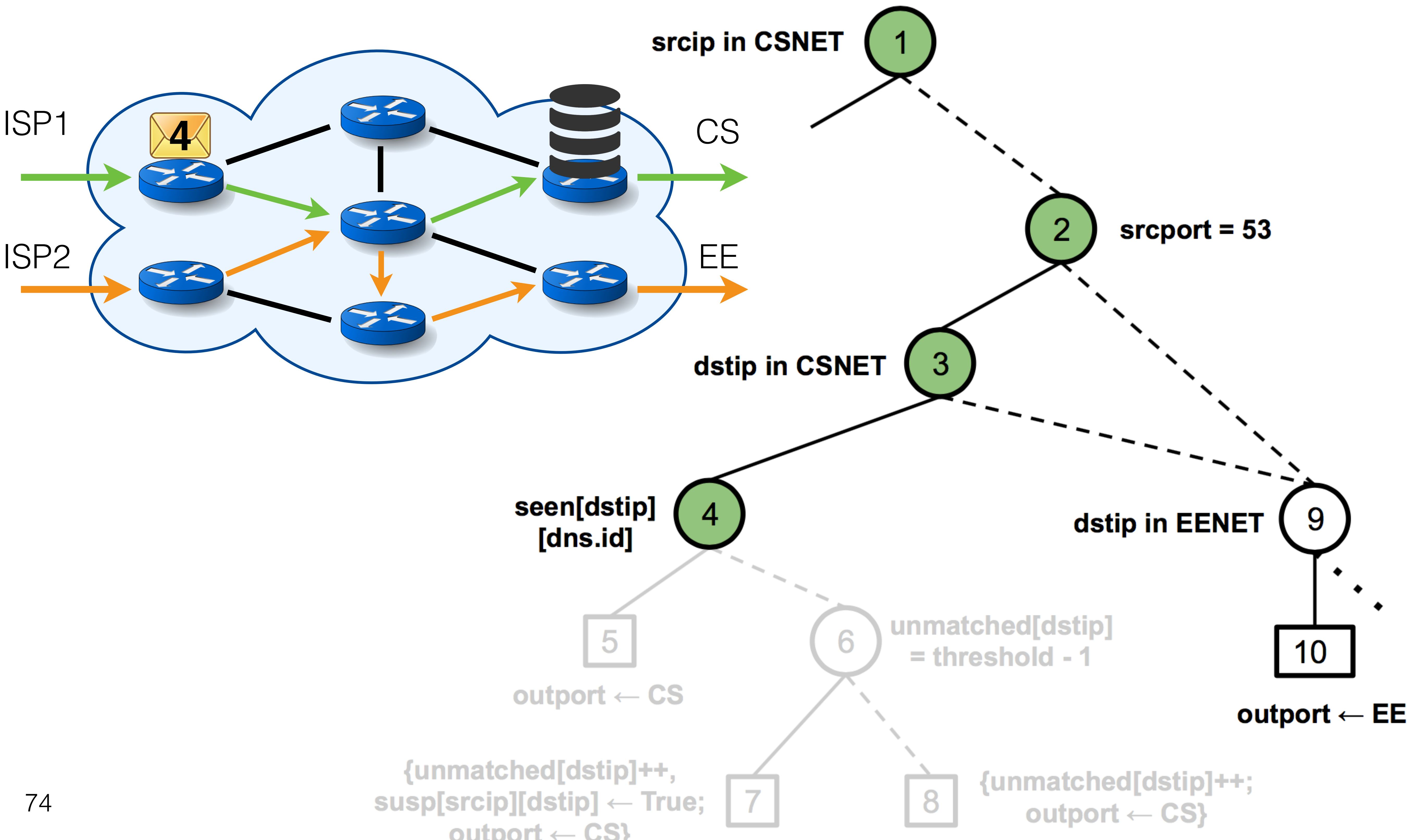

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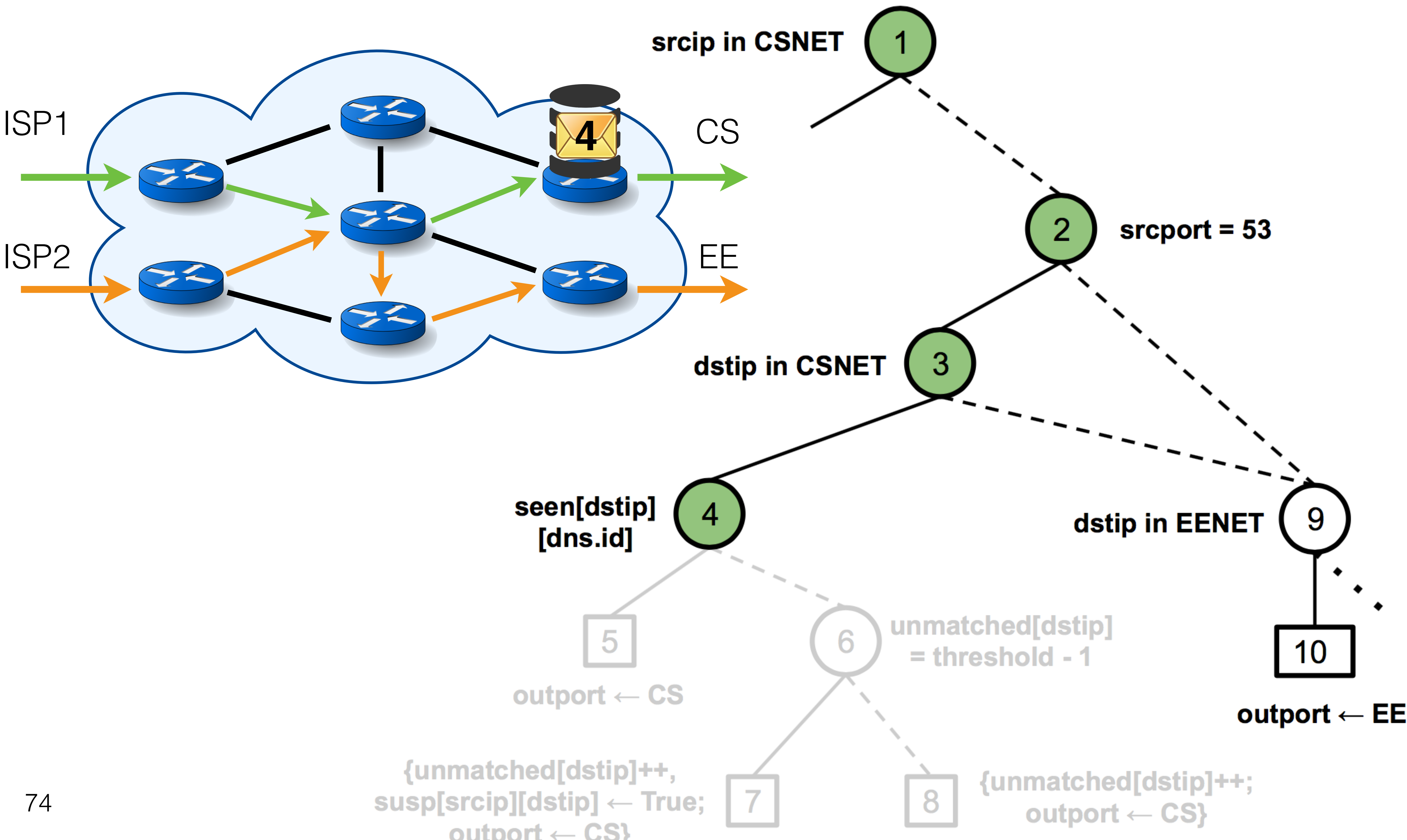

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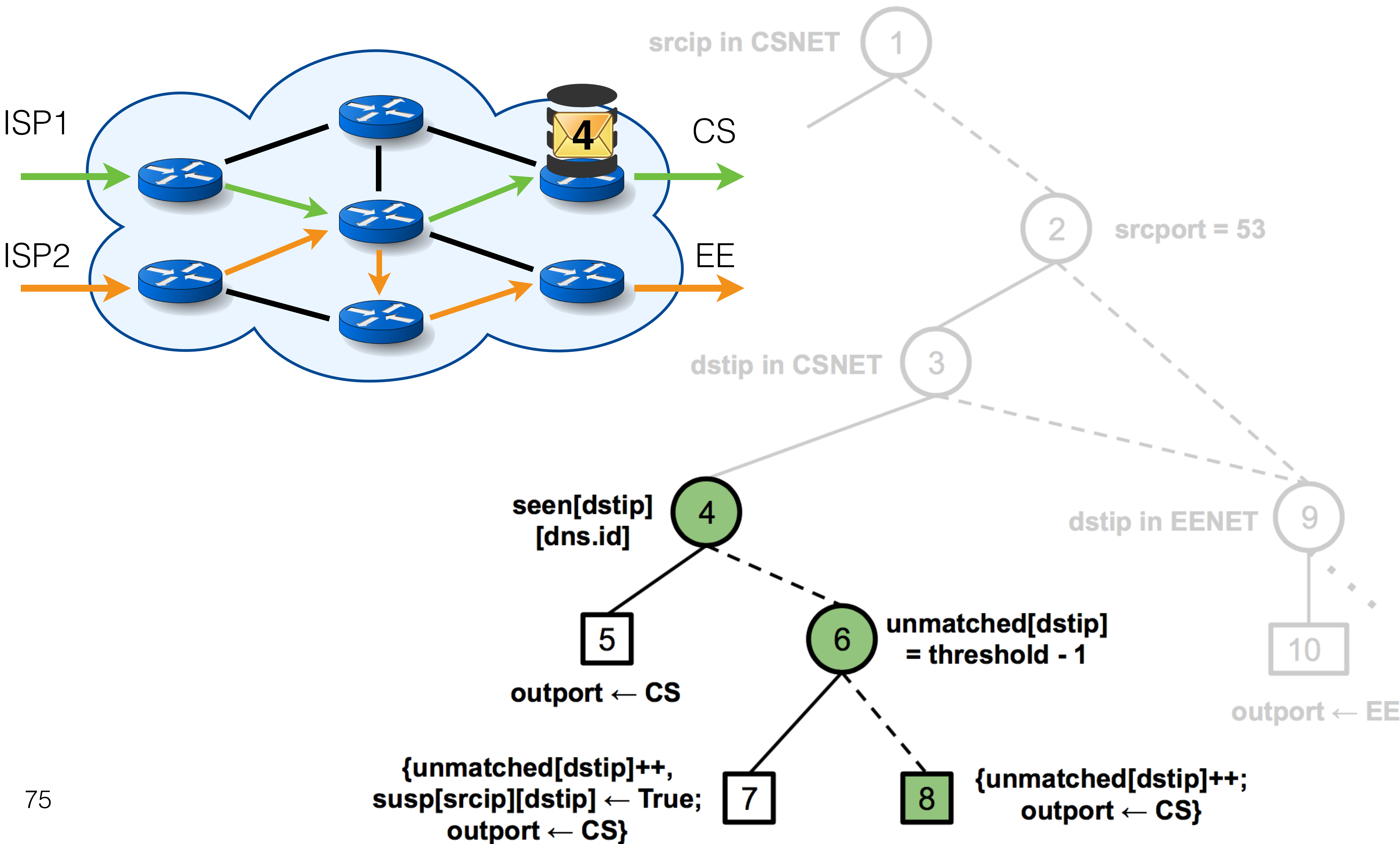

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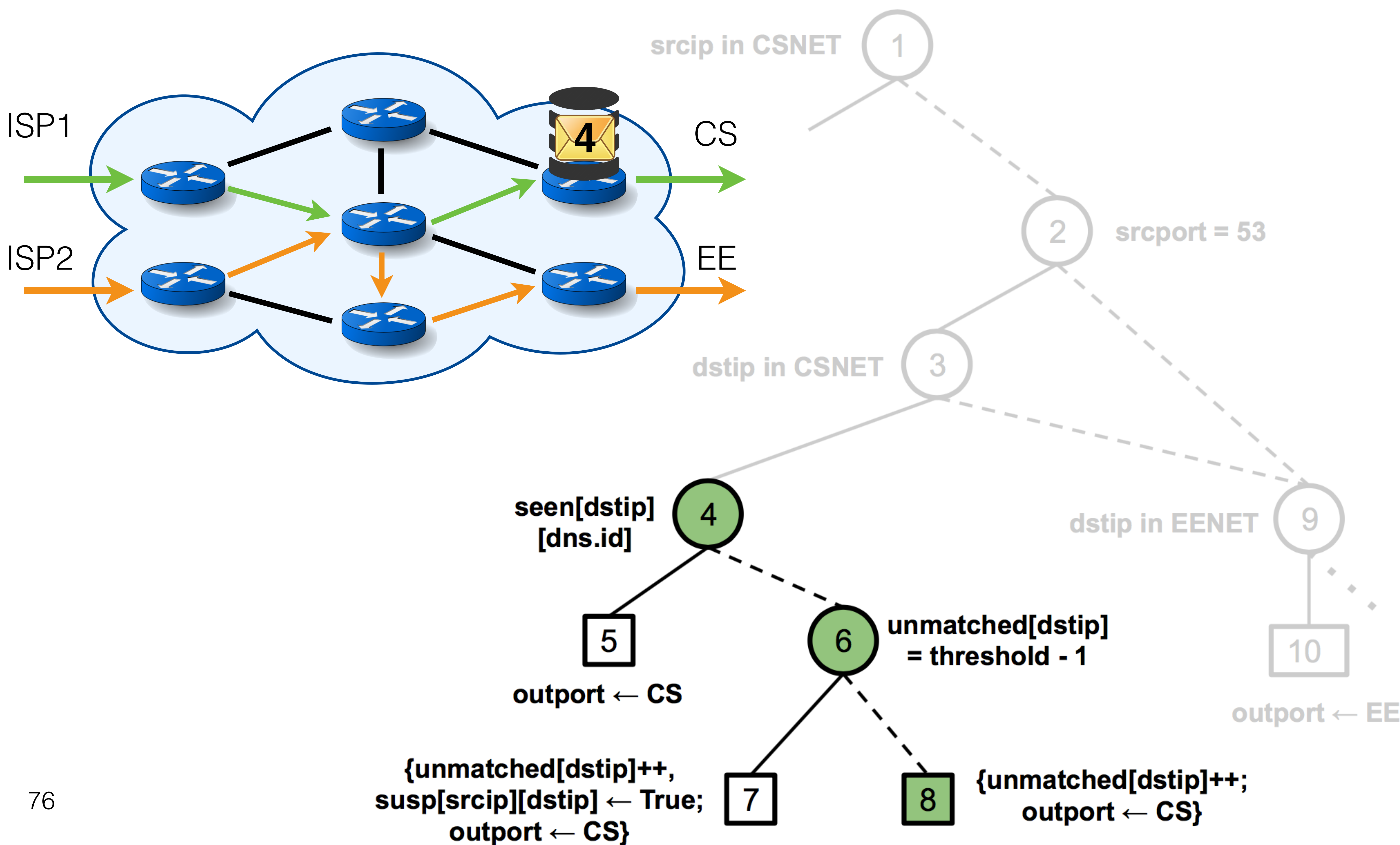

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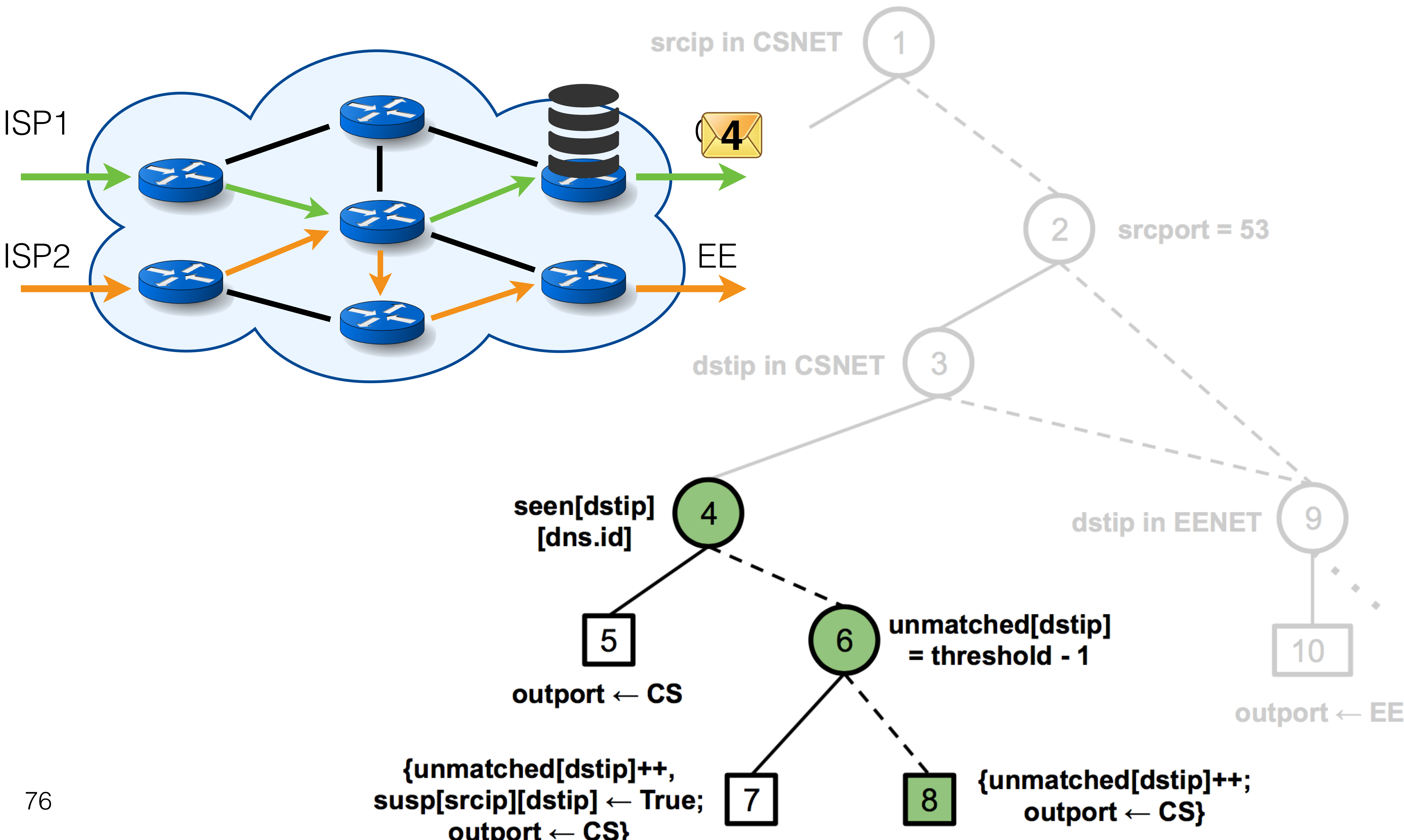

Compiler Evaluation

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- 7 Campus and ISP topologies

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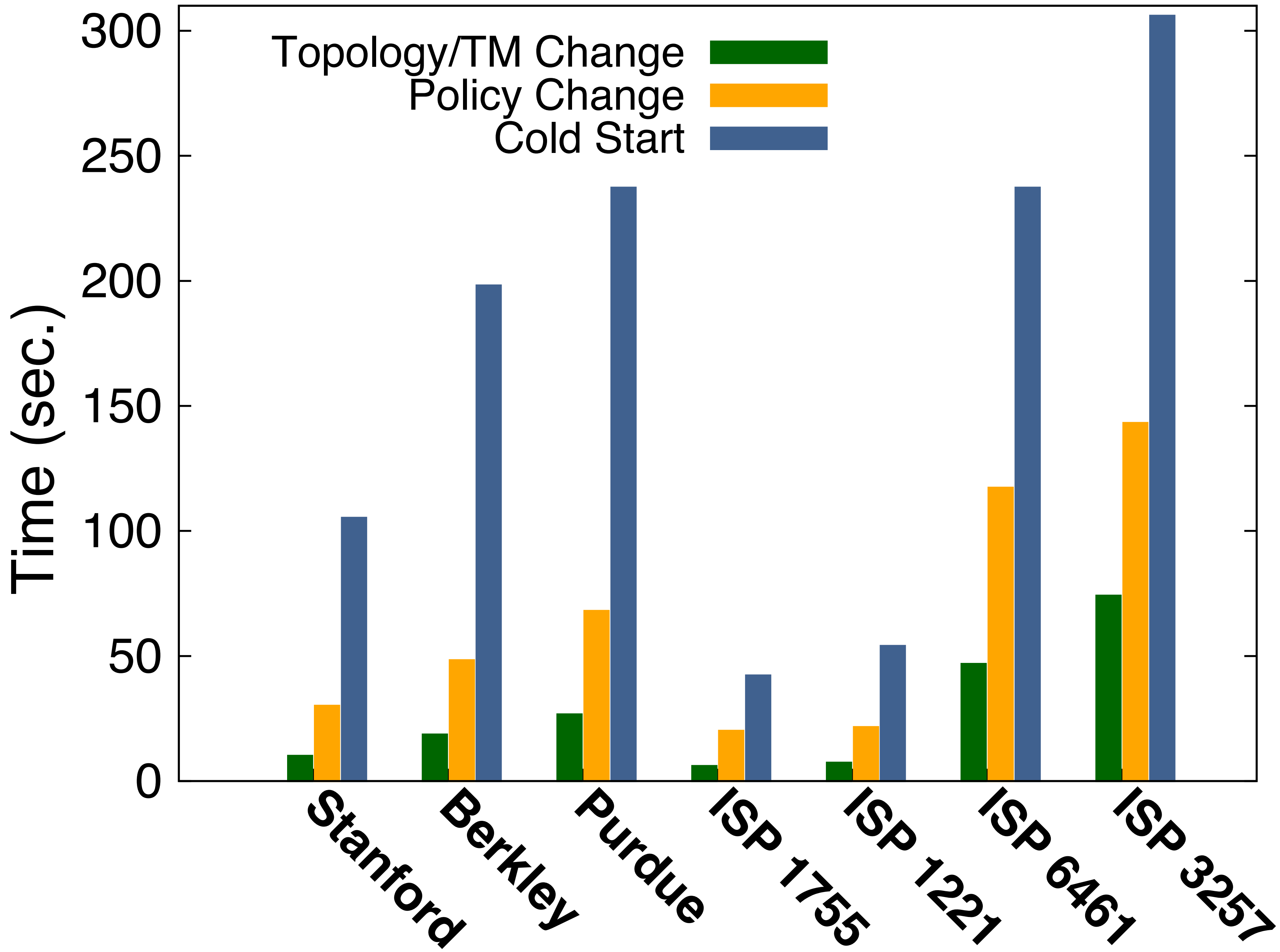
- Order of 100s of switches and links

Compiler Evaluation

- 7 Campus and ISP topologies
- Order of 100s of switches and links
- Scenarios
  - Cold start (freq. weeks)
  - Policy change (freq. days)
  - Topology/TM change (freq. minutes)

Compiler Evaluation - Results



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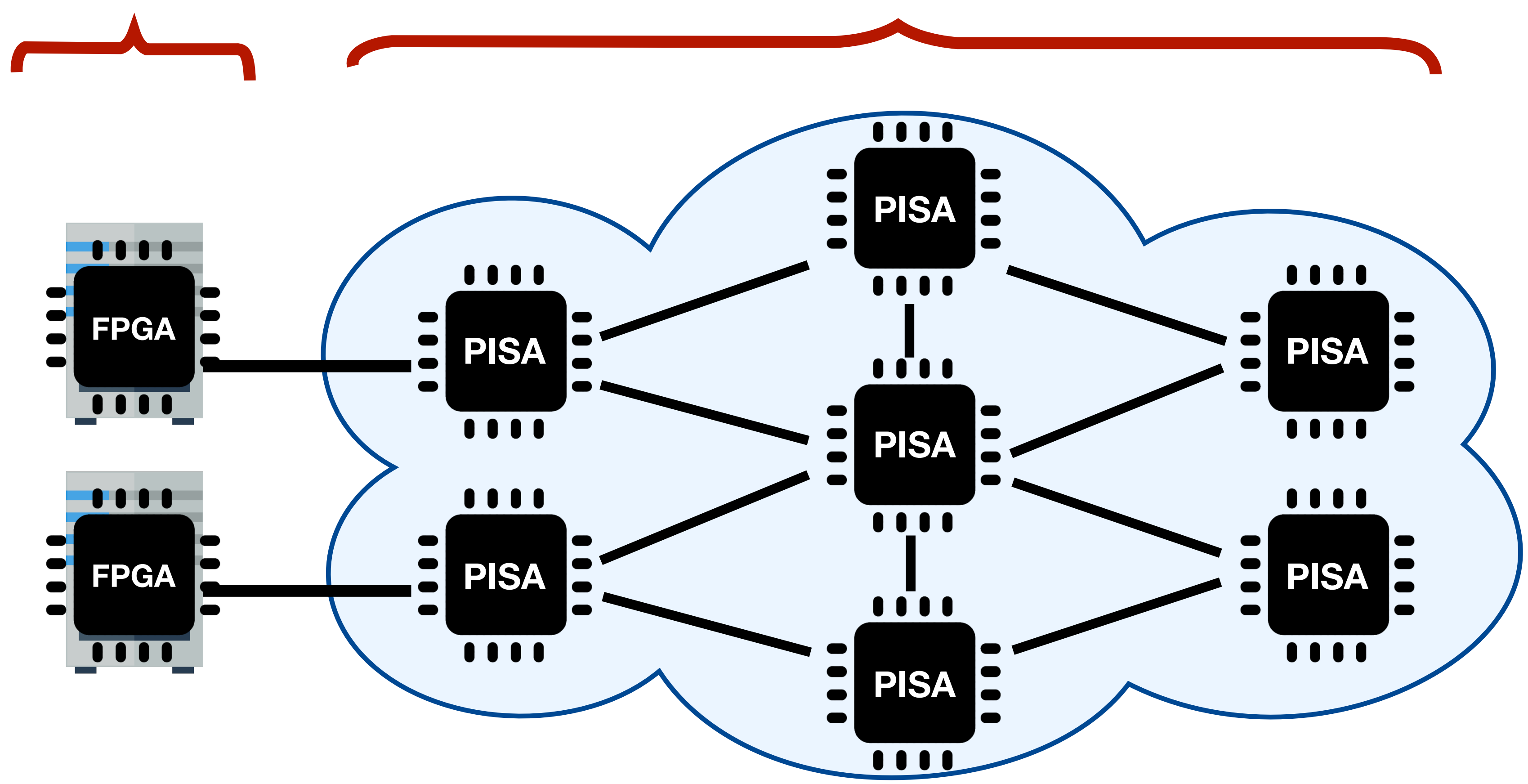
  - Intuitive and flexible composition
- SNAP Compiler
  - Decides state placement and routing
  - Distributes an intermediate representation of the program across the network

Stateful Programming of High-Speed Network Hardware

Tonic
[Under revision for NSDI'19]

SNAP
[SIGCOMM'16]



Thank You!