IP Data Plane (Contd.)

CPSC 433/533, Spring 2021

Anurag Khandelwal

Administrivia

- HW2 out today
  - **Lead:** Ramla
  - Will test knowledge on IP, and some initial concepts in TCP
- Have to move my OH again…
  - Earlier by 1h: **3pm to 4pm**
  - Same link…

Let’s take a quick look at the IPv6 header…

IPv6

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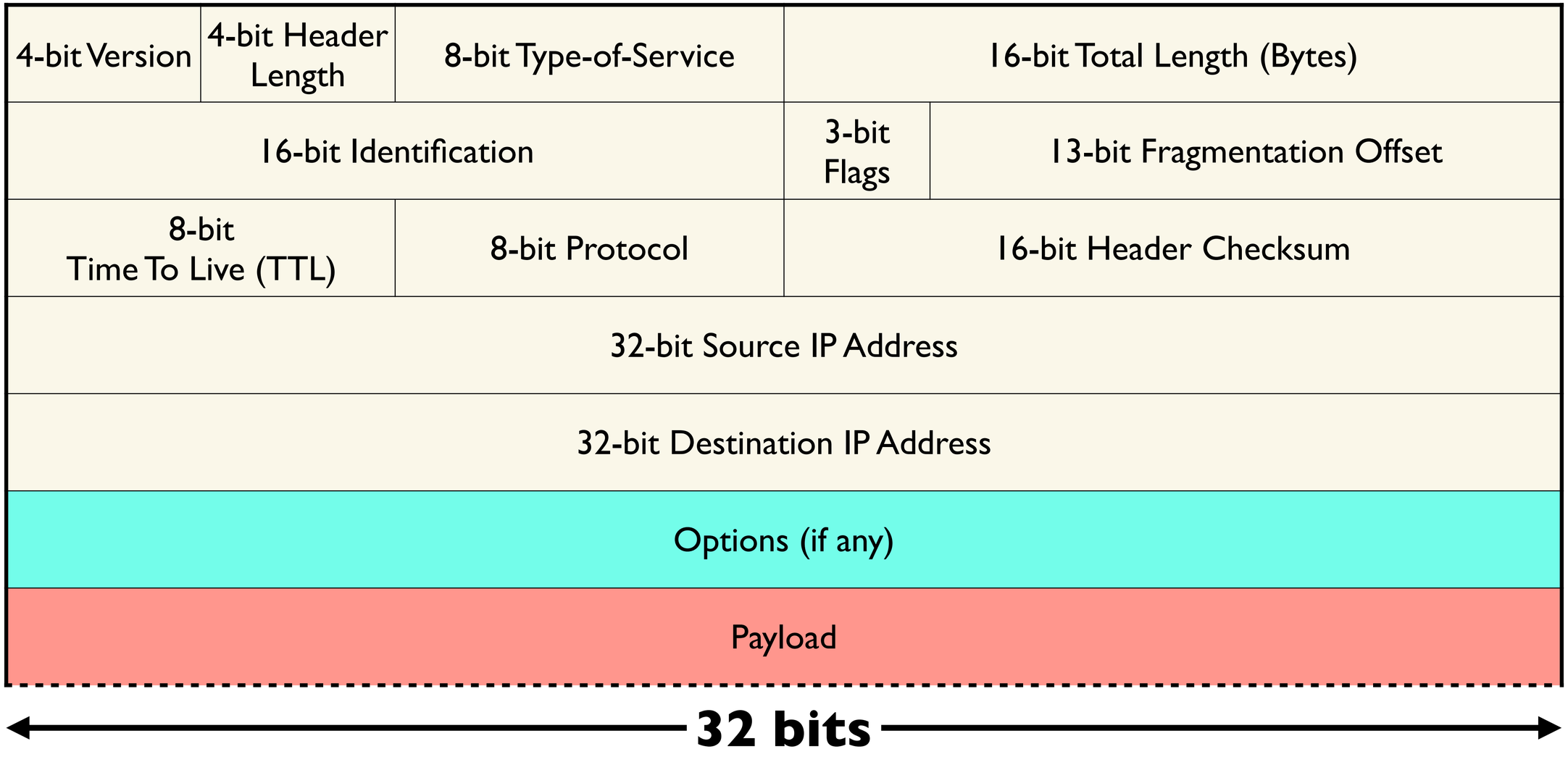
  - "Spring cleaning" for IP
- **Result is an elegant, if unambitious, protocol**

What "clean up" would you do?



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- **Added Flow Label**

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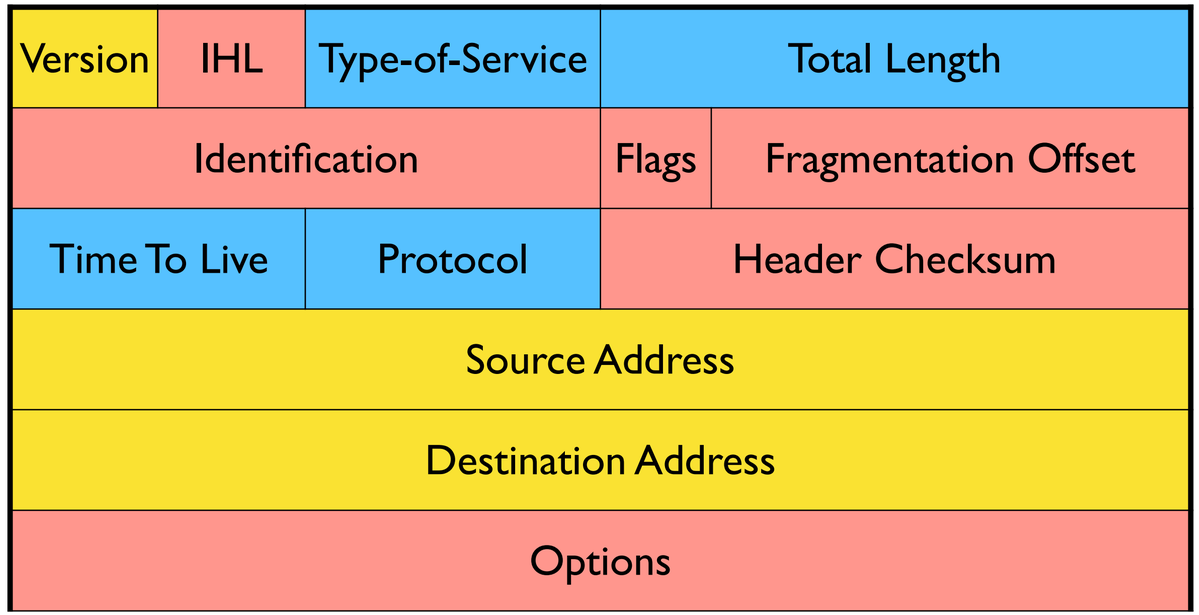

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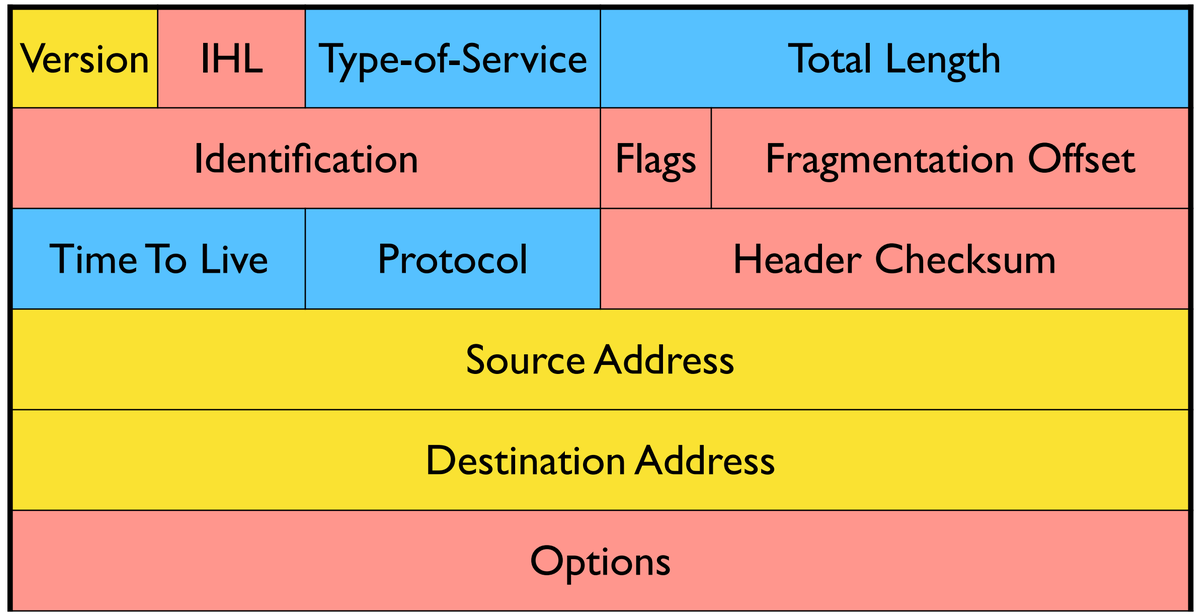

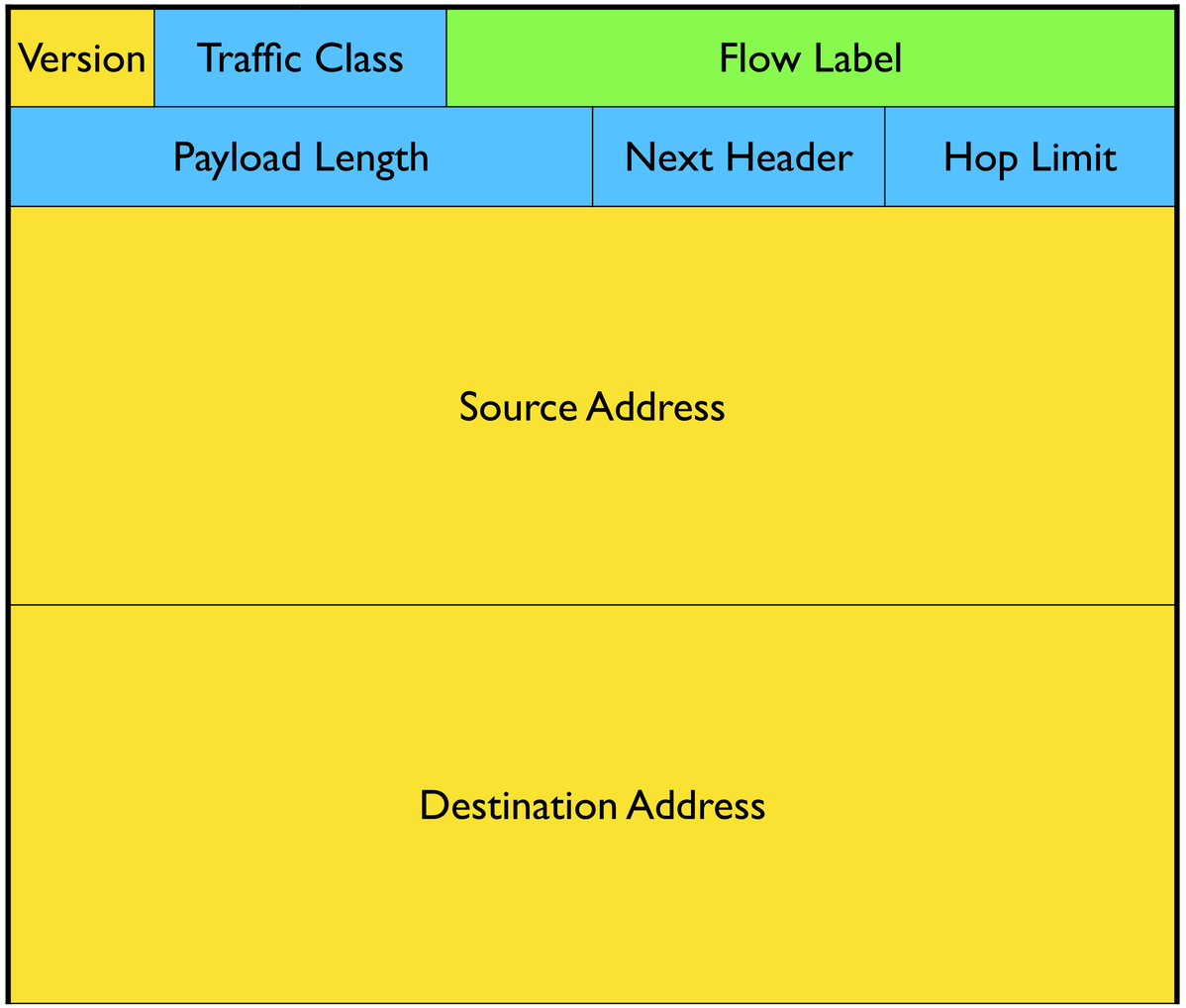

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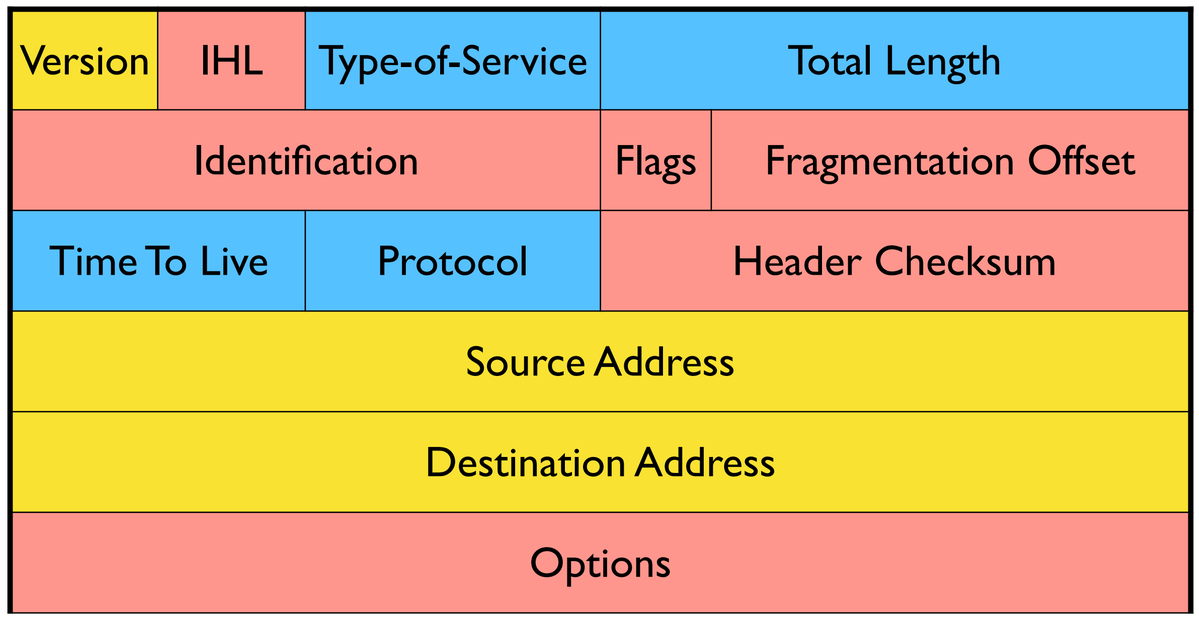

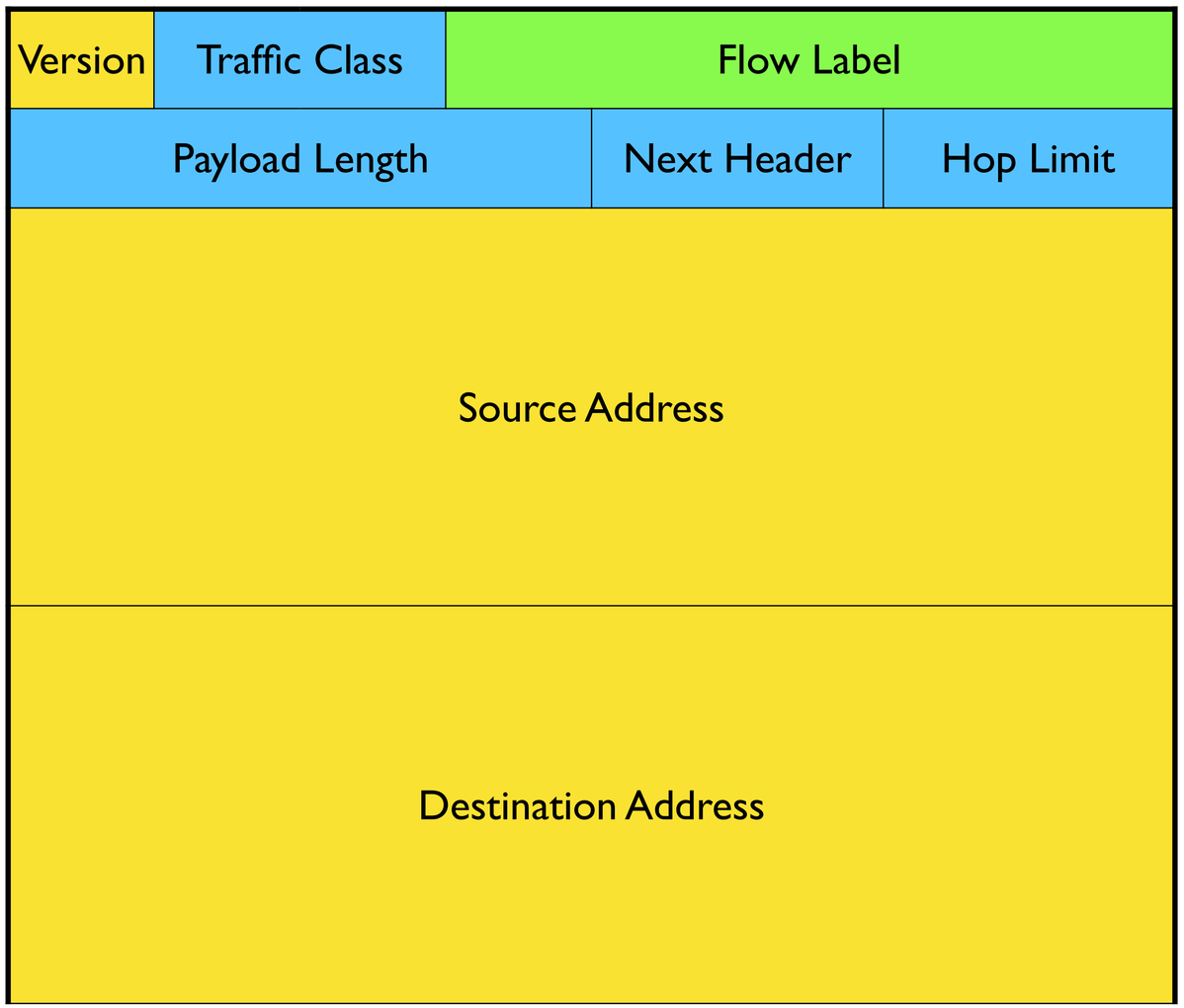

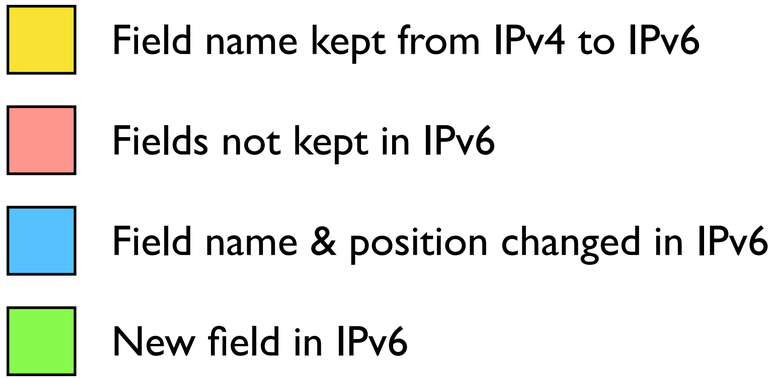

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- **Simplify handling:**
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  - Eliminated header length
    - *Why couldn't IPv4 do this?*
- **Provide general flow label for packet**
  - Not tied to semantics
  - Provides great flexibility

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- **Plus feature interactions**
  - E.g., what happens to IP options when we fragment?
- **And future evolution**

IP Routers

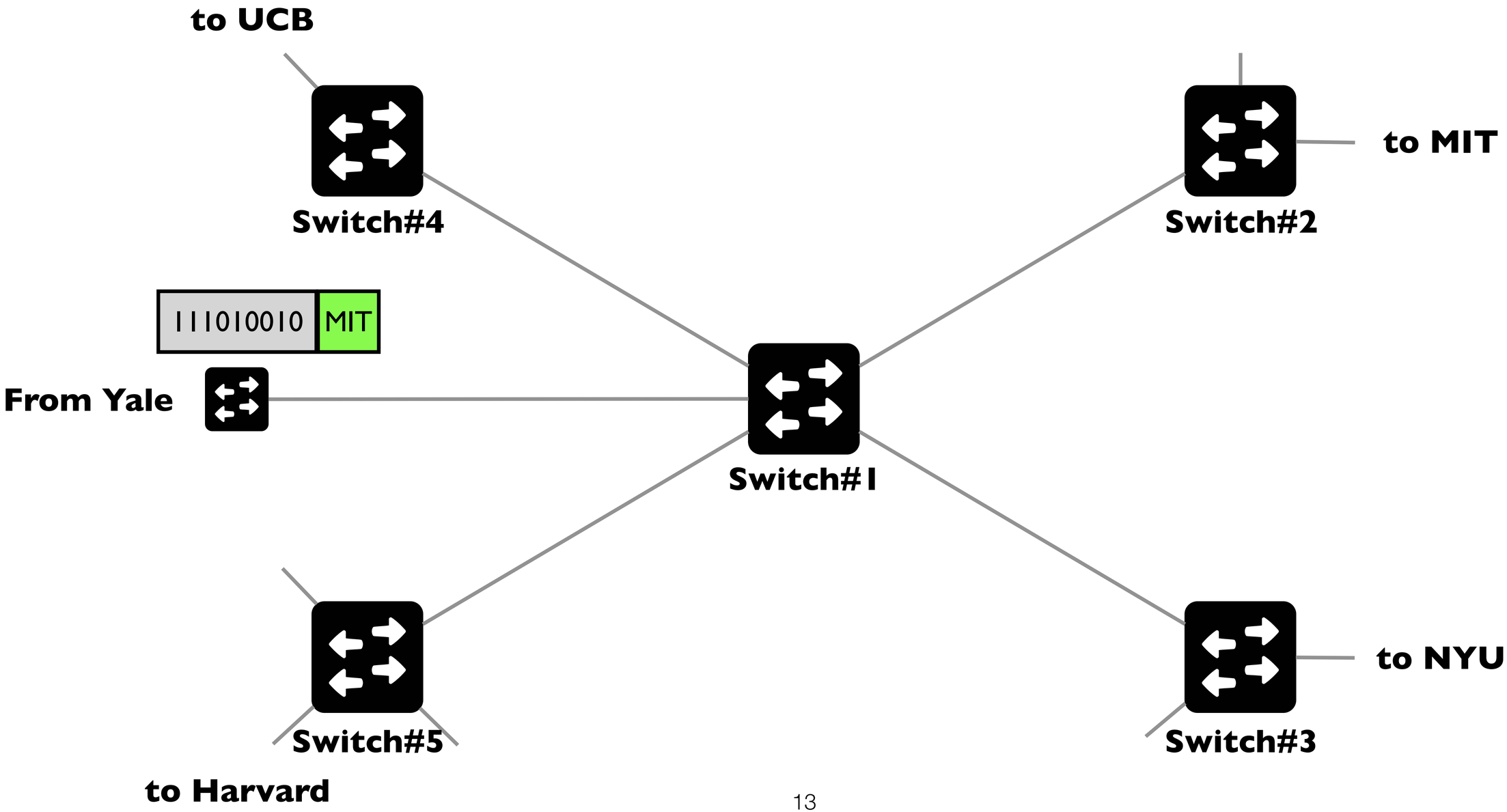
Context

- **Control Plane**
  - How to route traffic to each possible destination
  - Jointly computed using IGP (OSPF, RIP, etc.) and BGP
- **Data Plane**
  - **So Far:** Necessary fields in IP header of each packet for *end-system & routers*
  - **Rest of today's class:** How IP routers forward packets

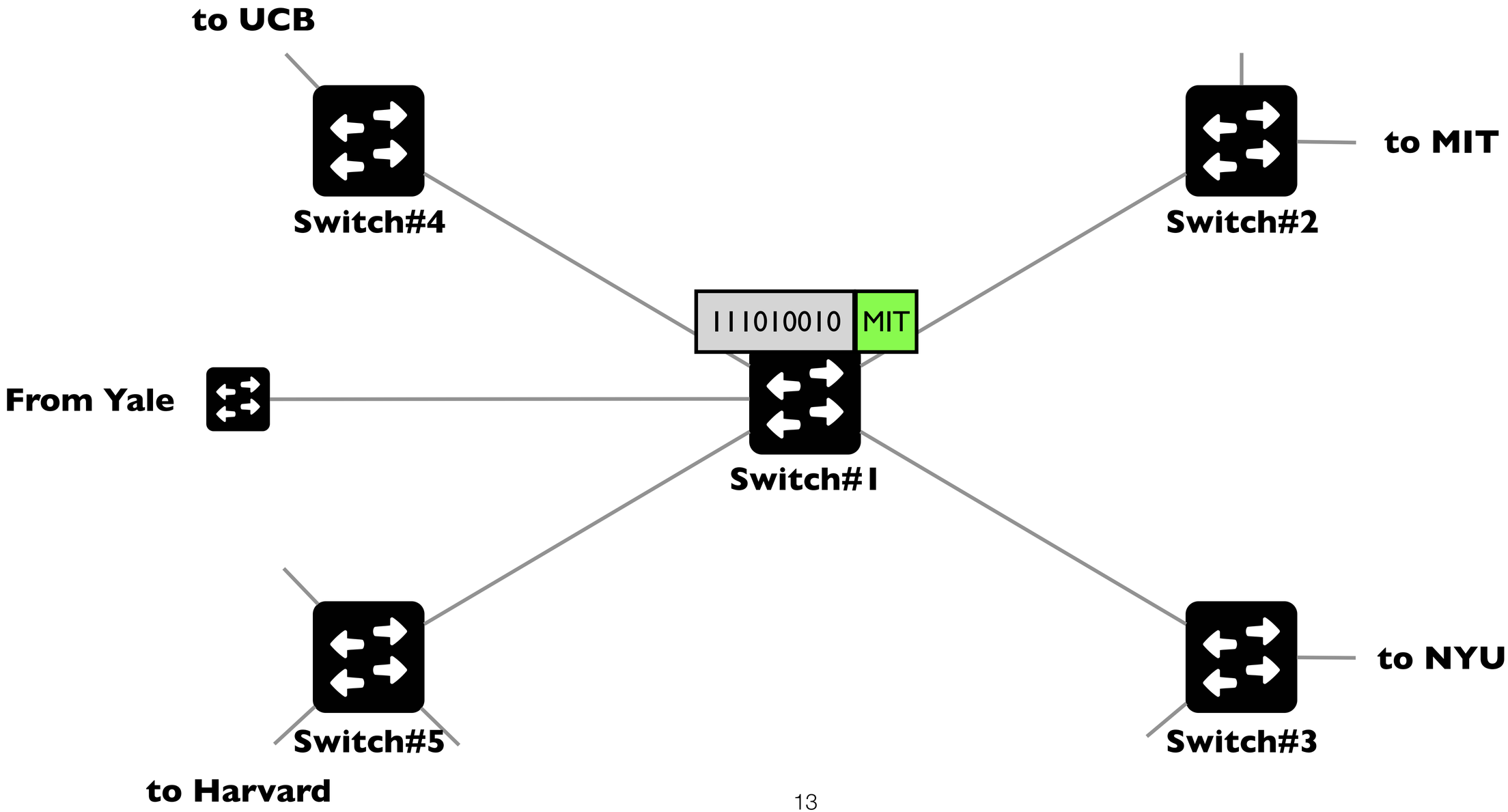
IP Routers

- **Core building block of the Internet infrastructure**
- **$120B+ industry!**
- **Vendors:** Cisco, Juniper, Huawei, HPE, Arista, Dell, EMC, Nokia (merged with Alcatel-Lucent)
  - *account for > 90%*

Lecture#4: Routers Forward Packets



Lecture#4: Routers Forward Packets



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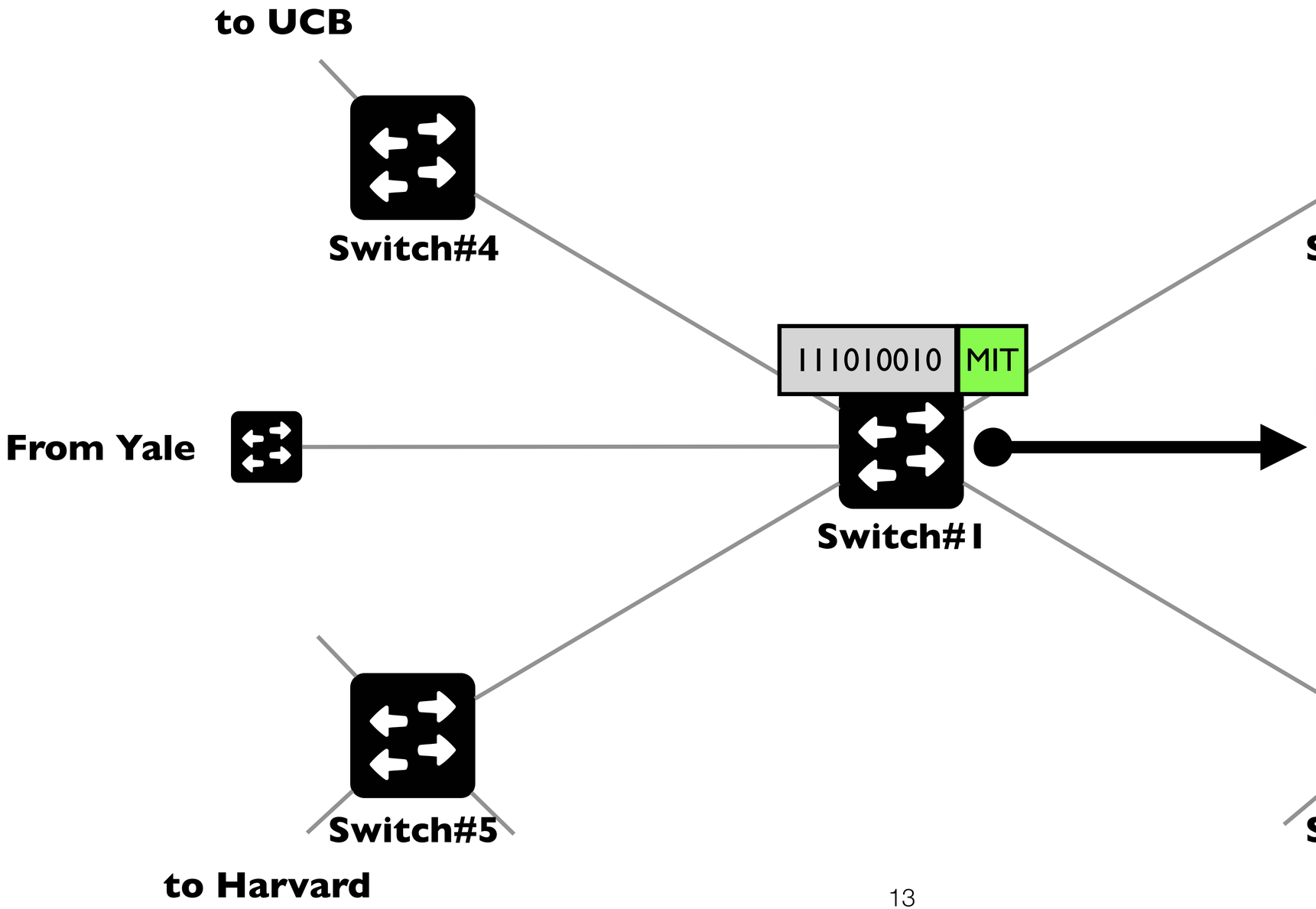

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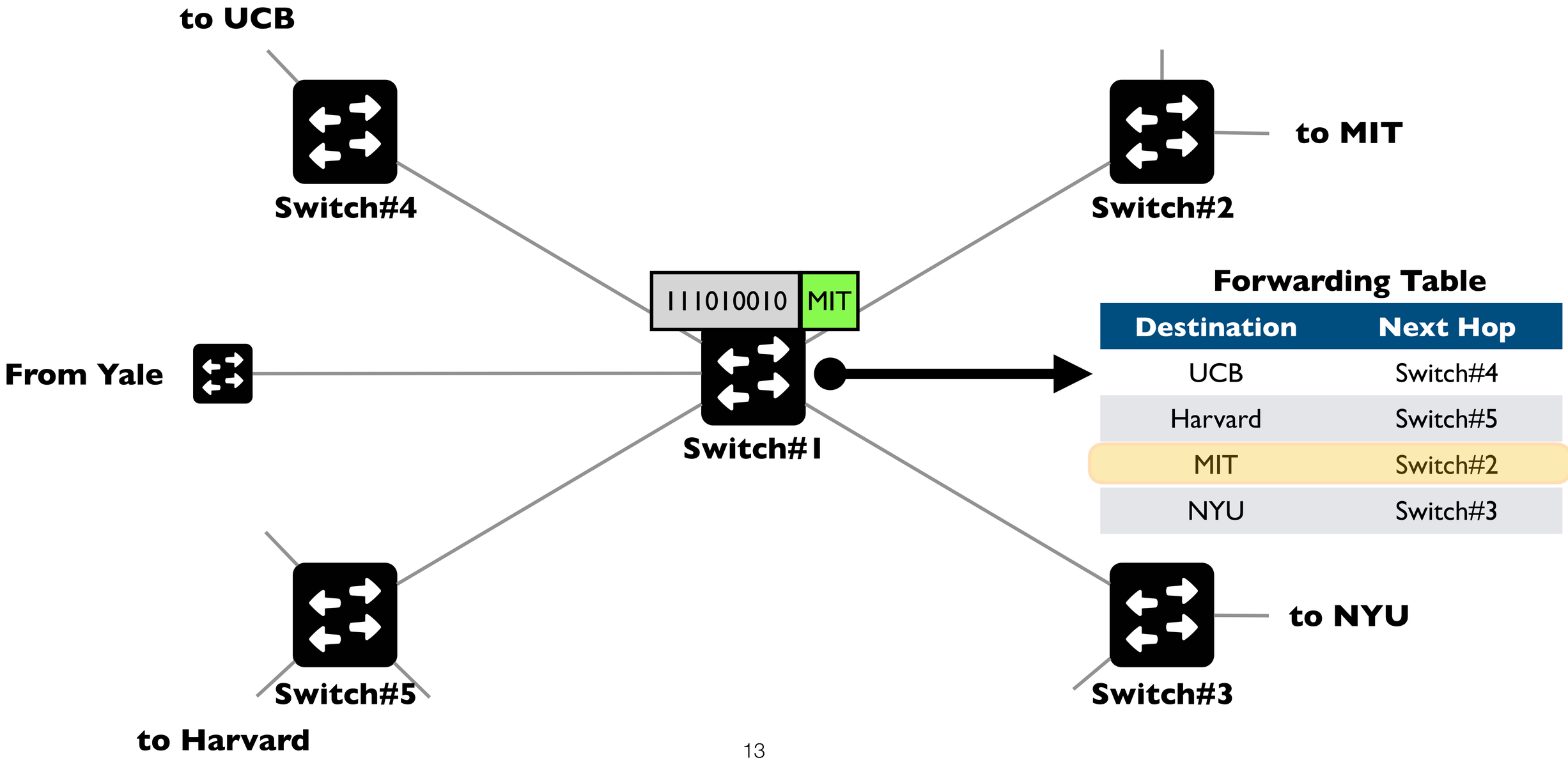

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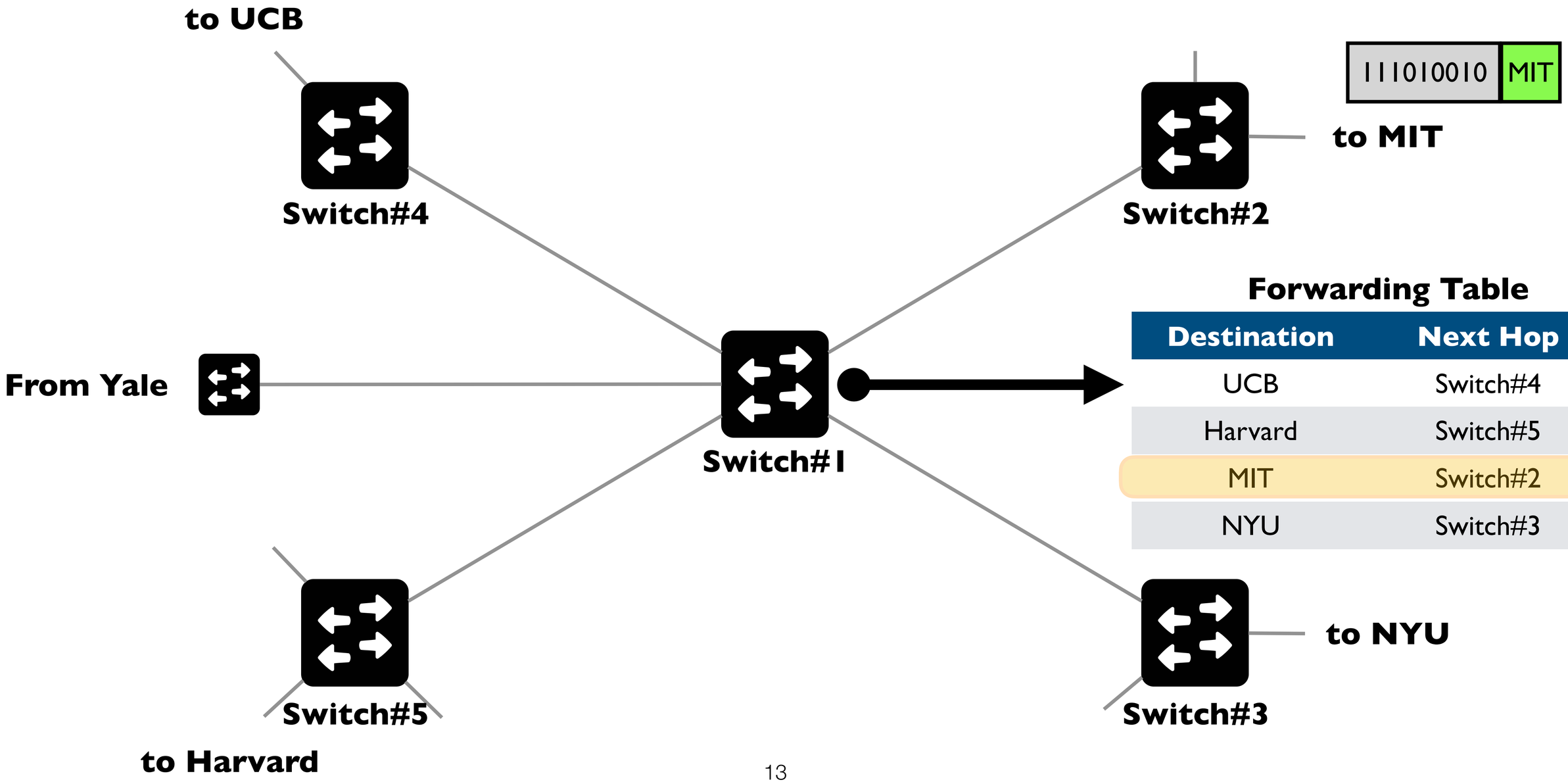

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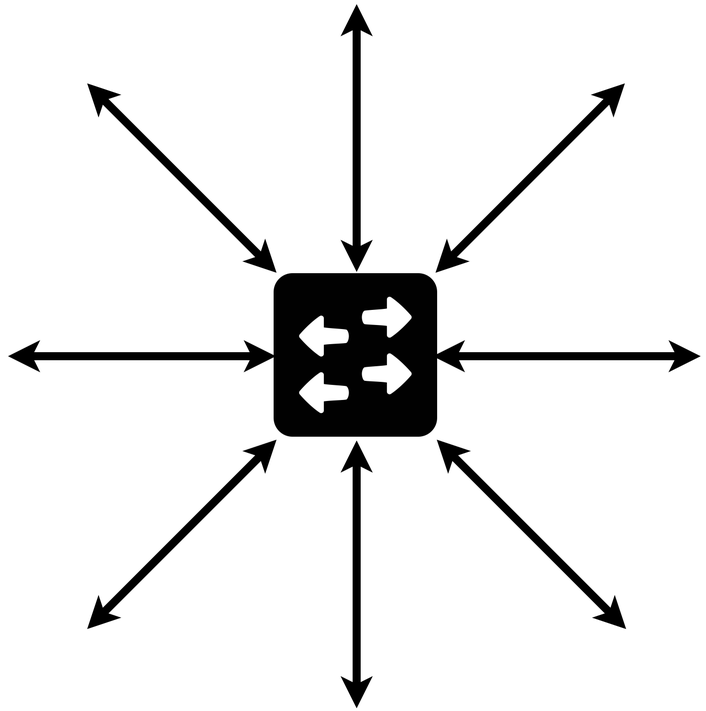

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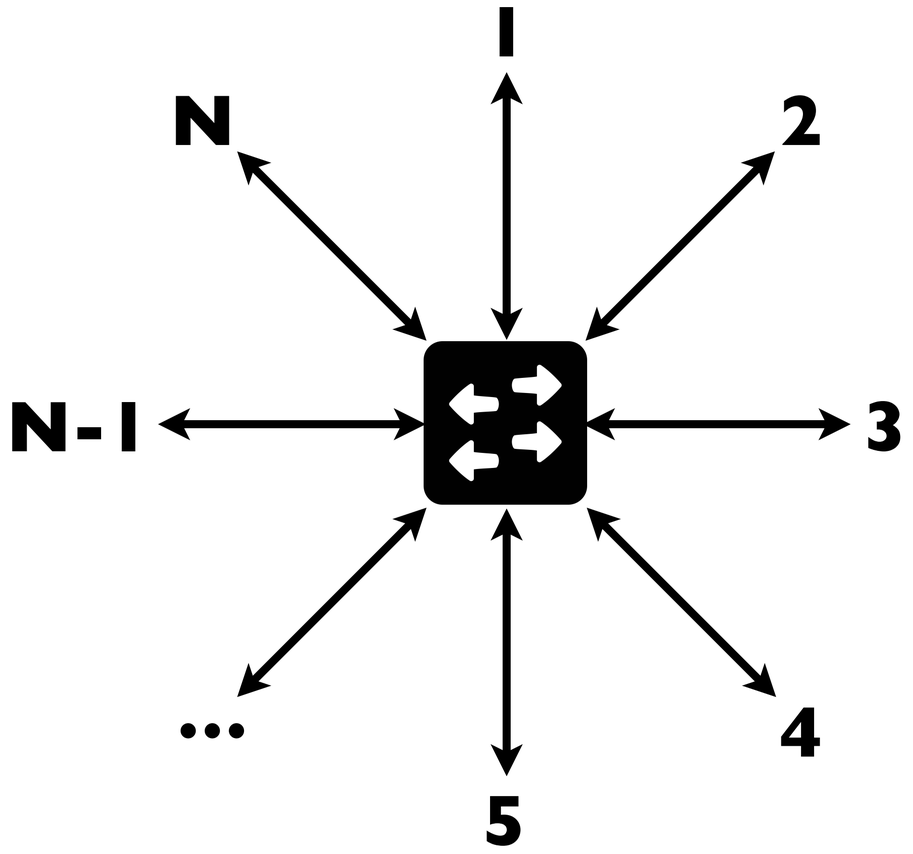

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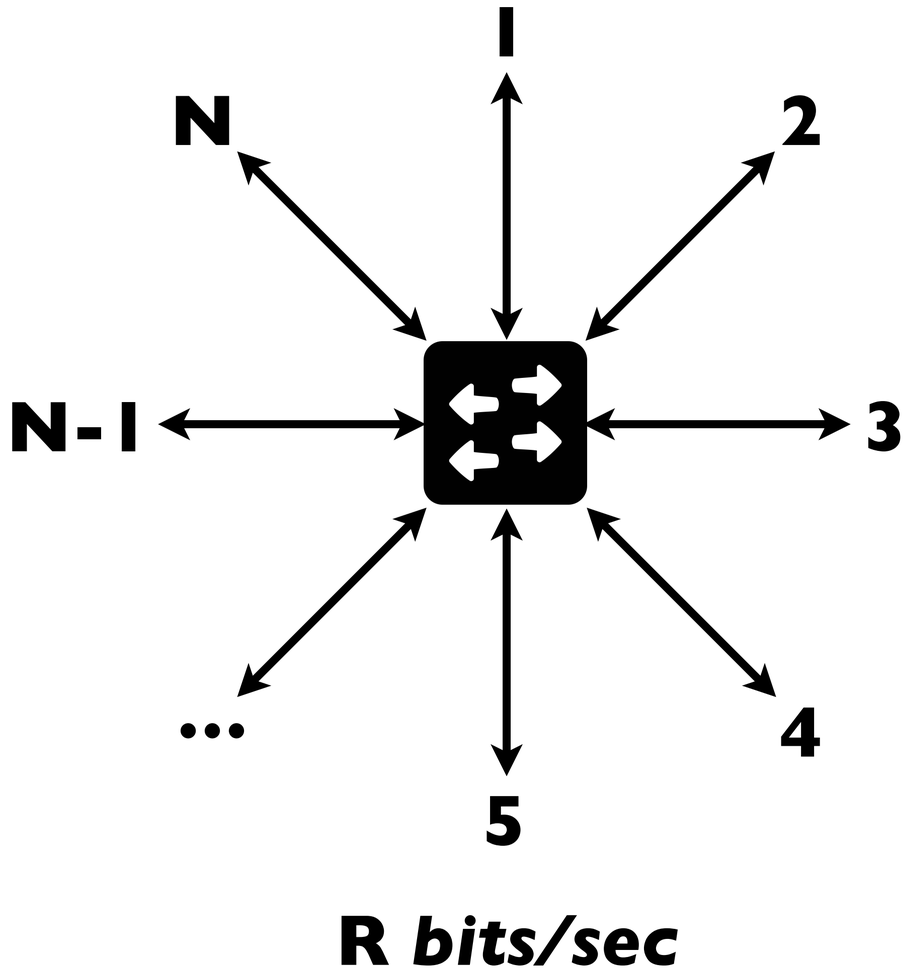

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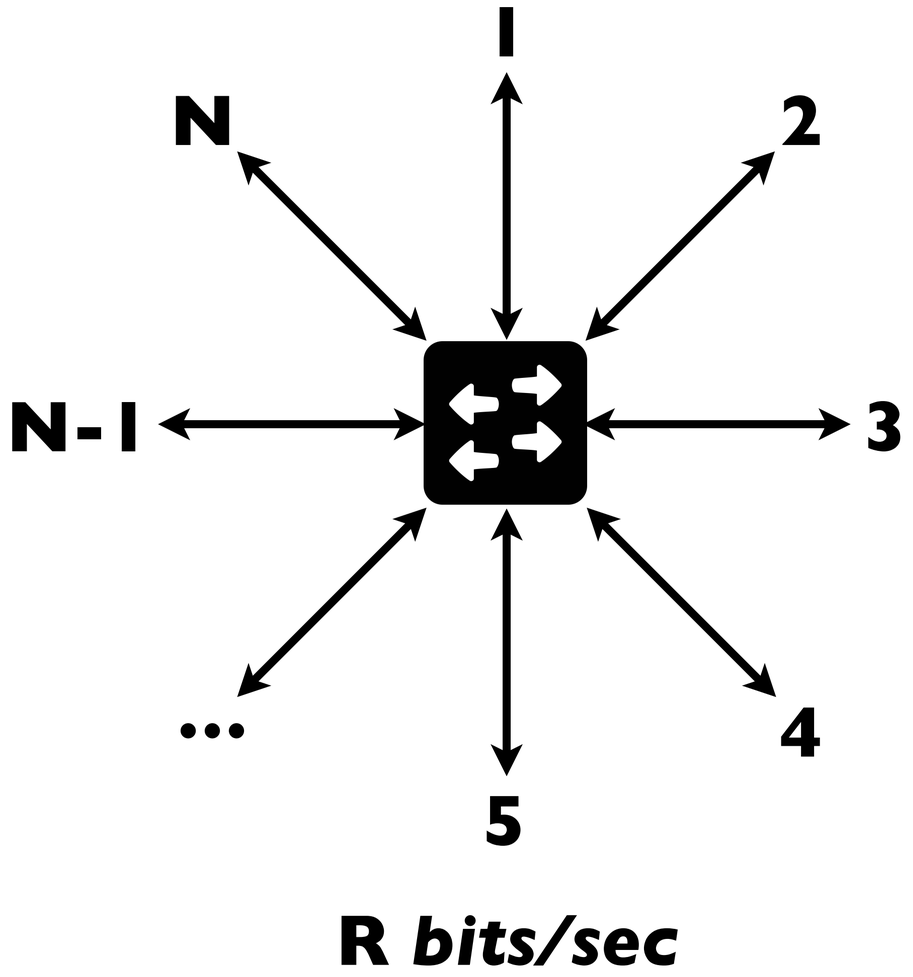
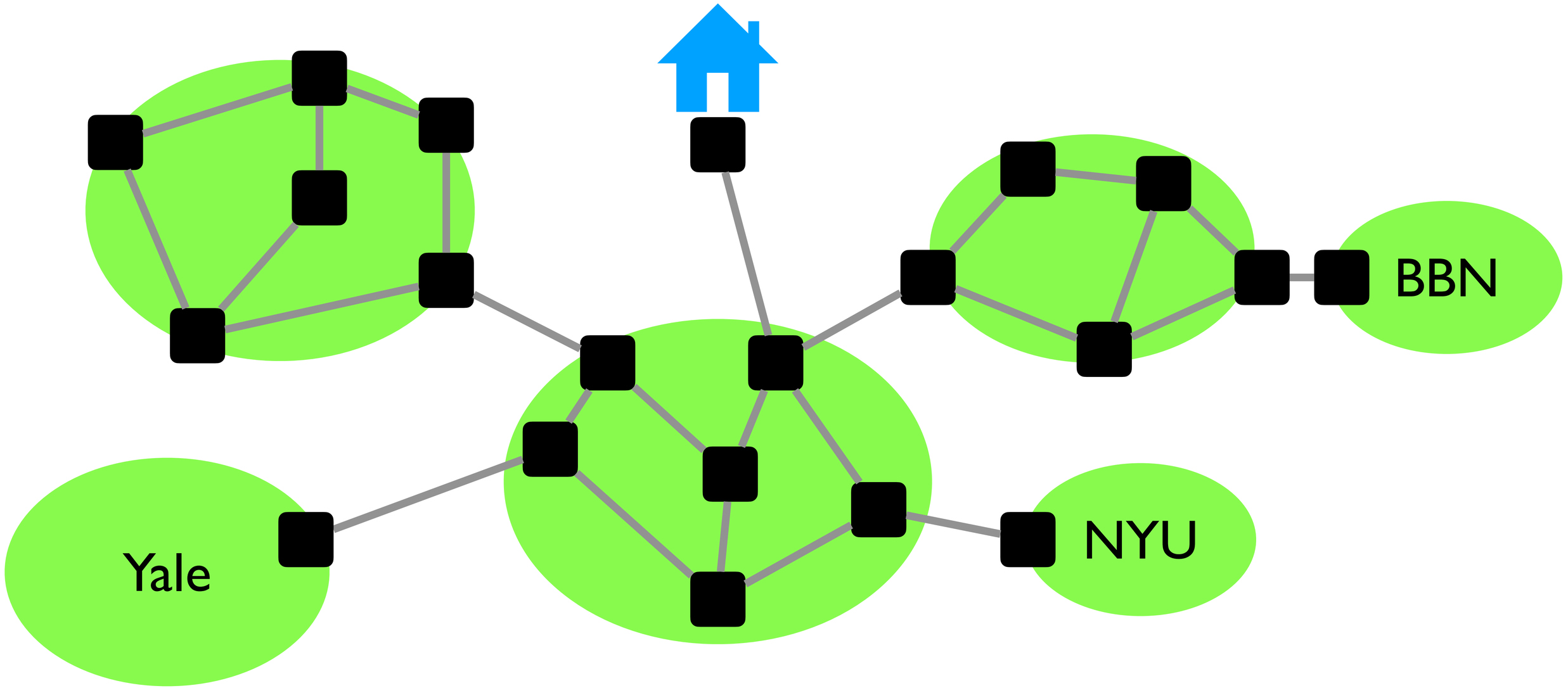


Networks & Routers



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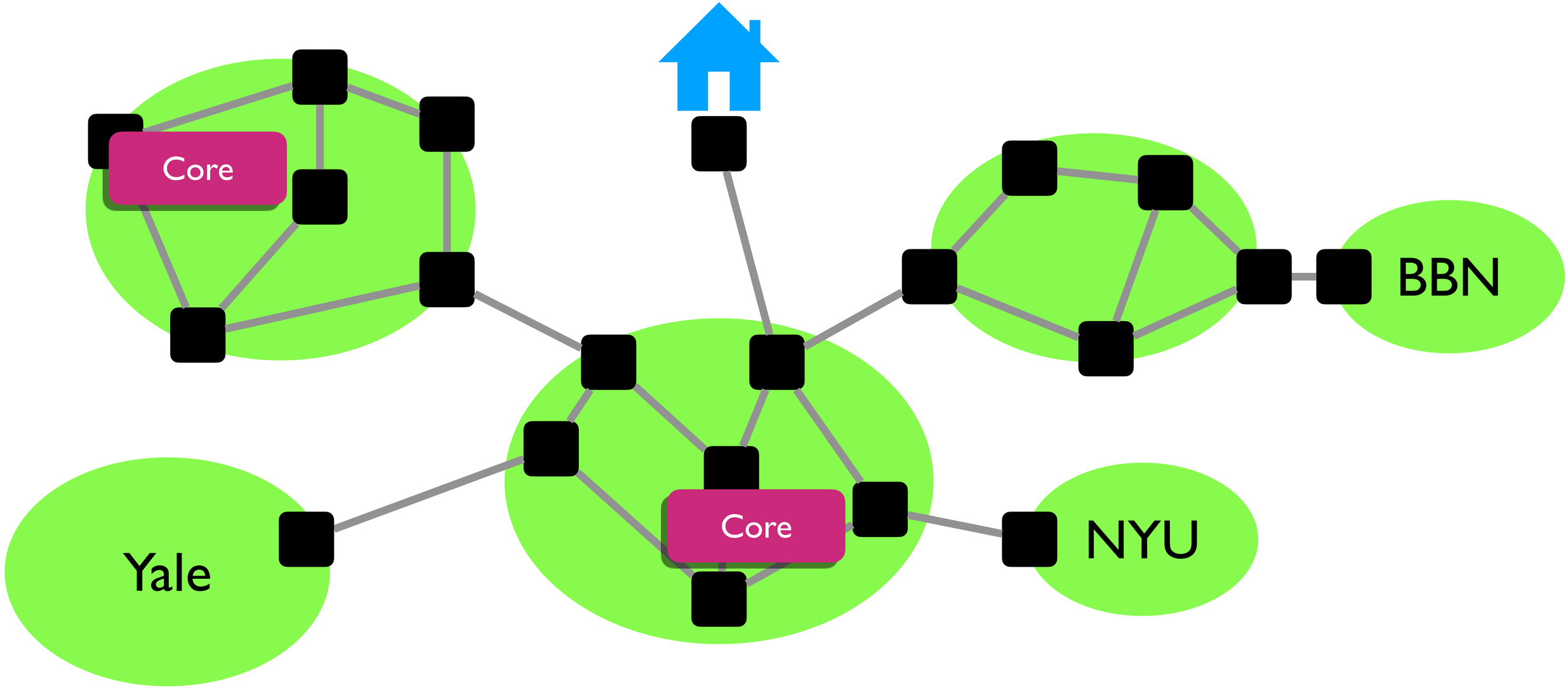

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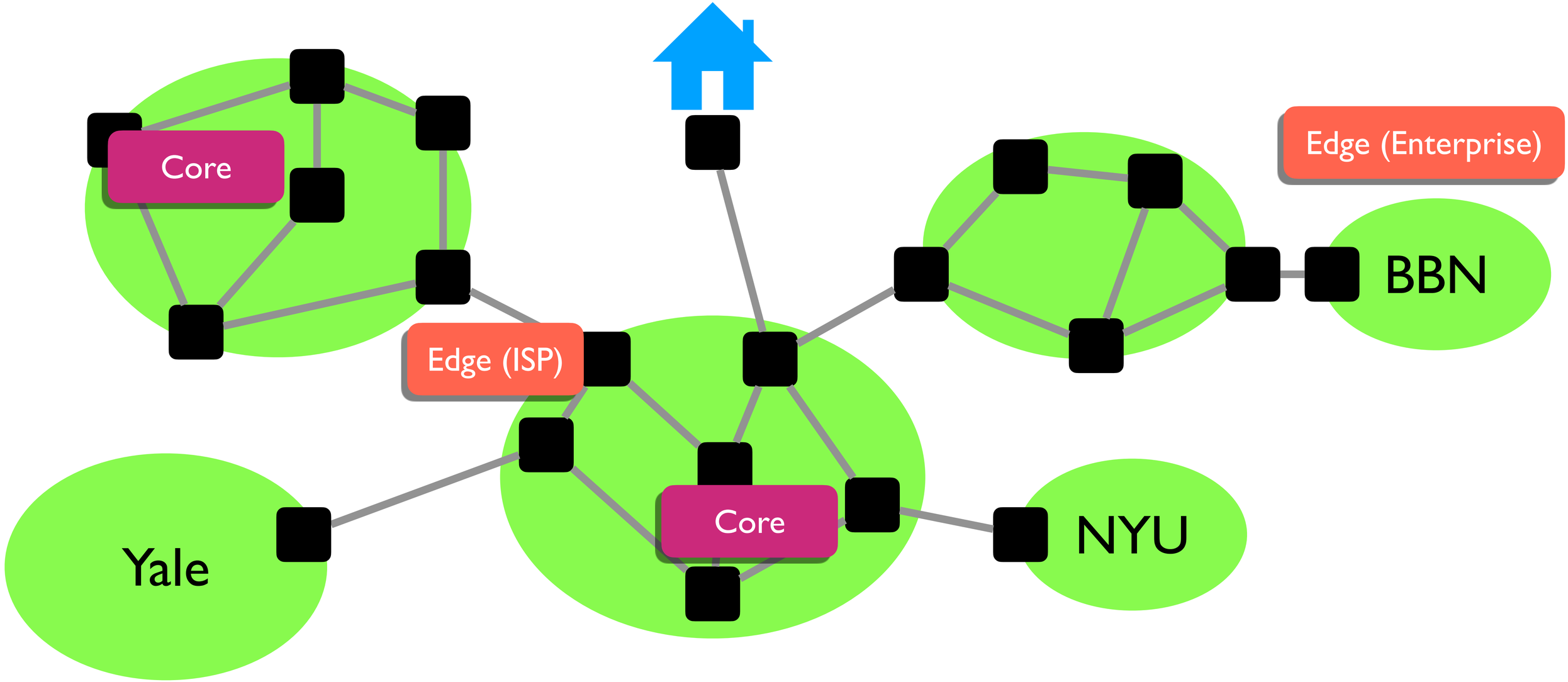

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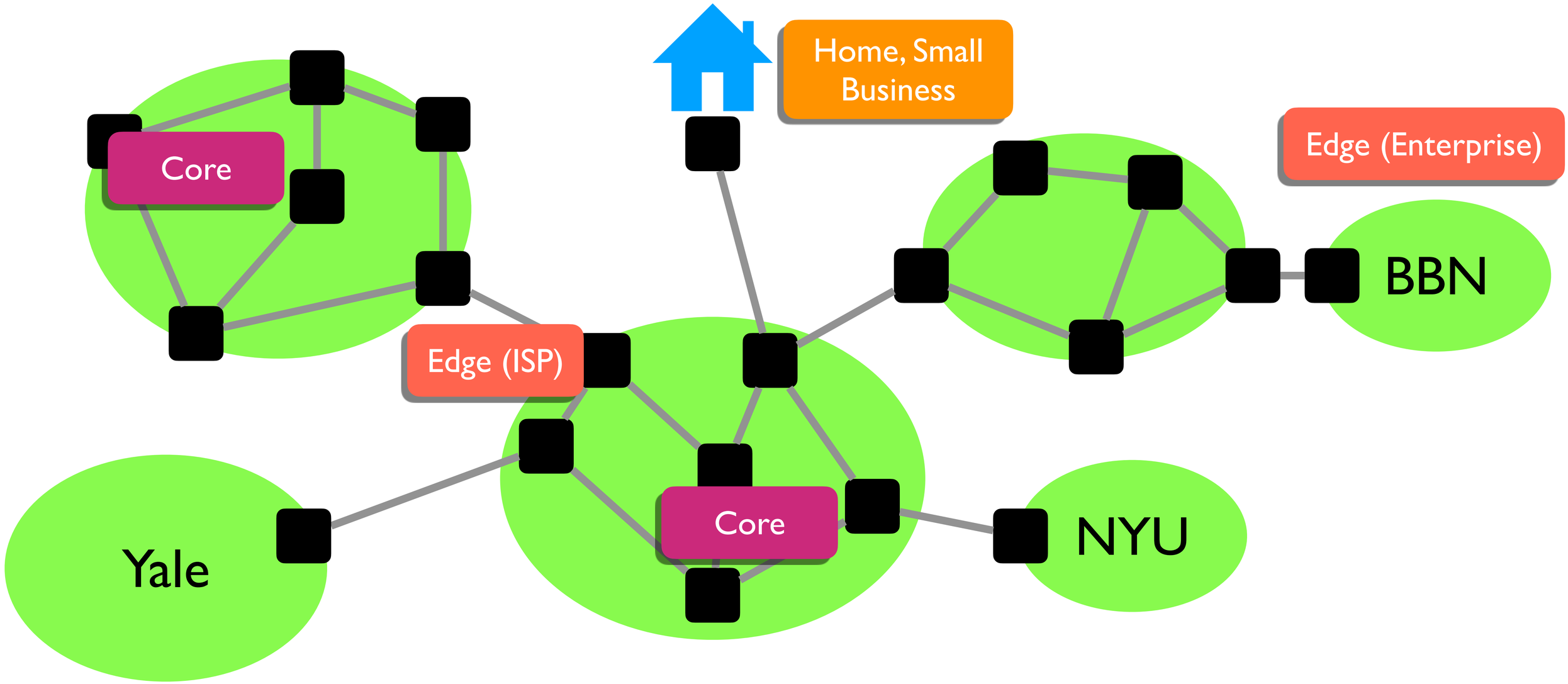

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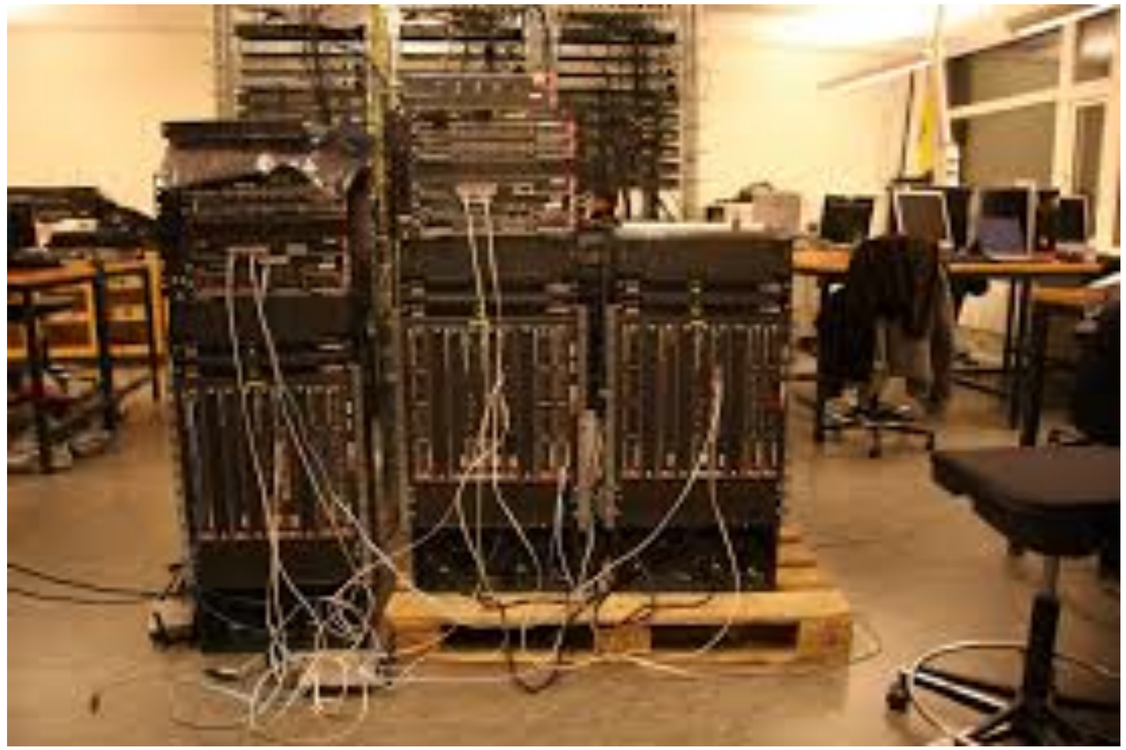

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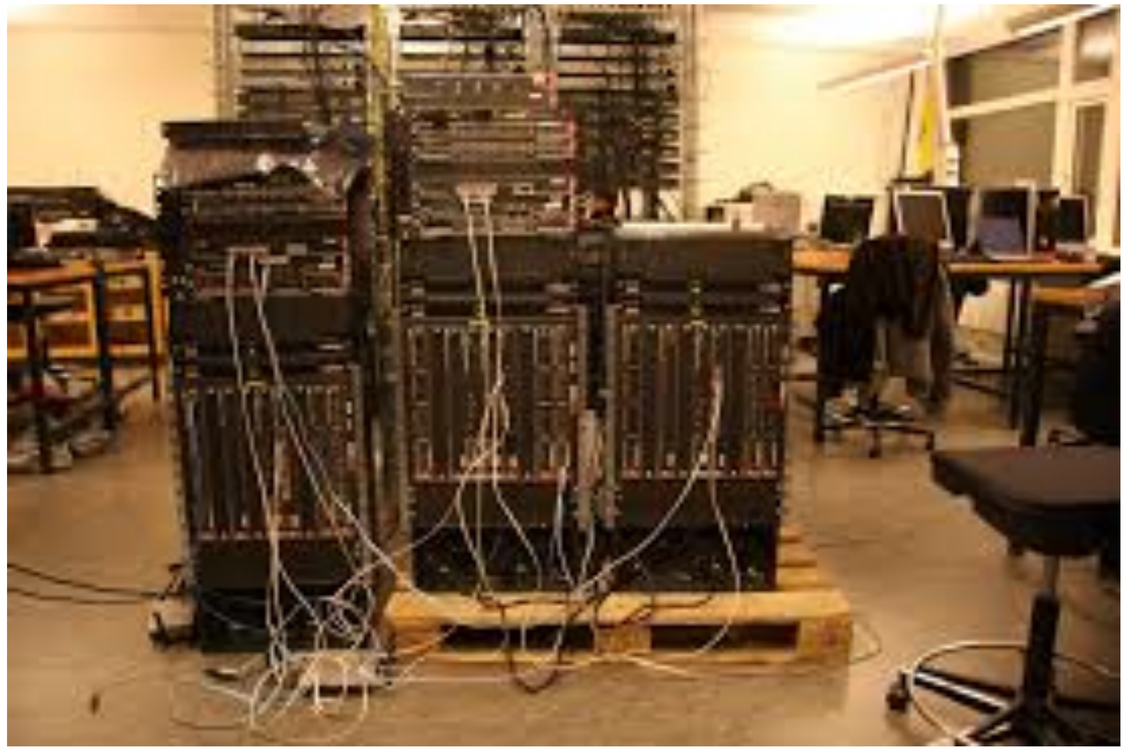

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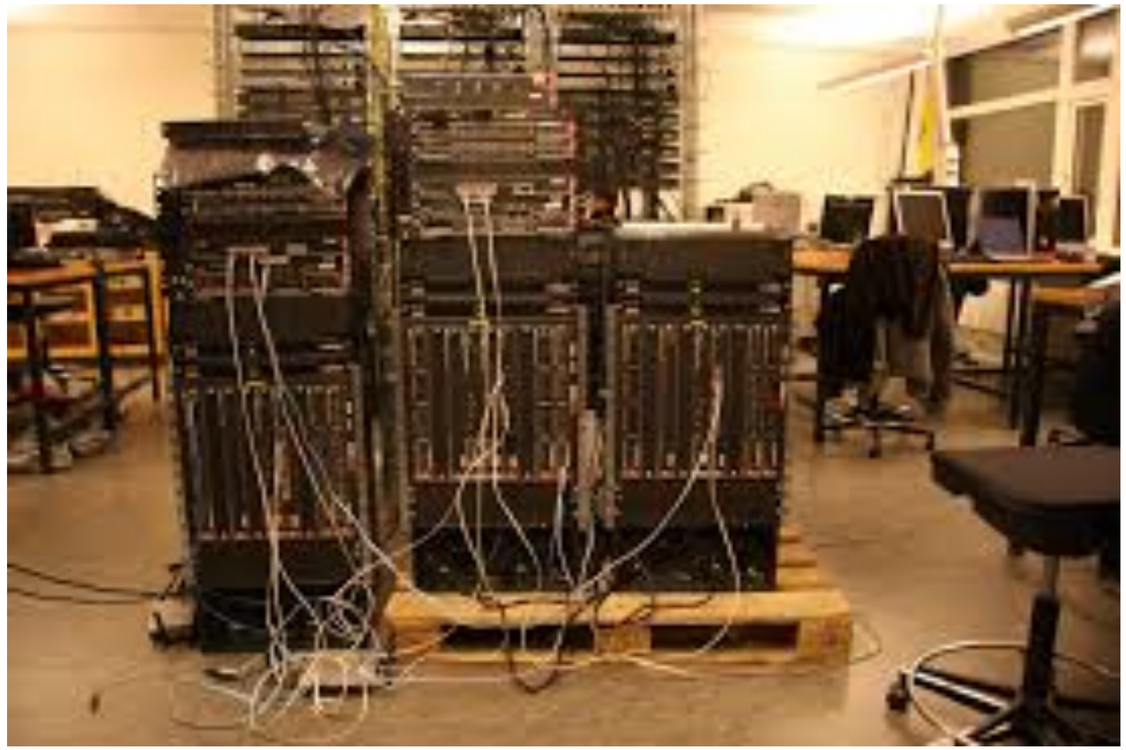

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Examples of Routers (Edge)

- **Cisco ASR**
  - **R** = 1/10/40 Gbps
  - **N x R** = 120 Gbps

Examples of Routers (Small Business)

- **Cisco 3945E**
  - **R** = 10/100/1000 Mbps
  - **N x R** <10 Gbps

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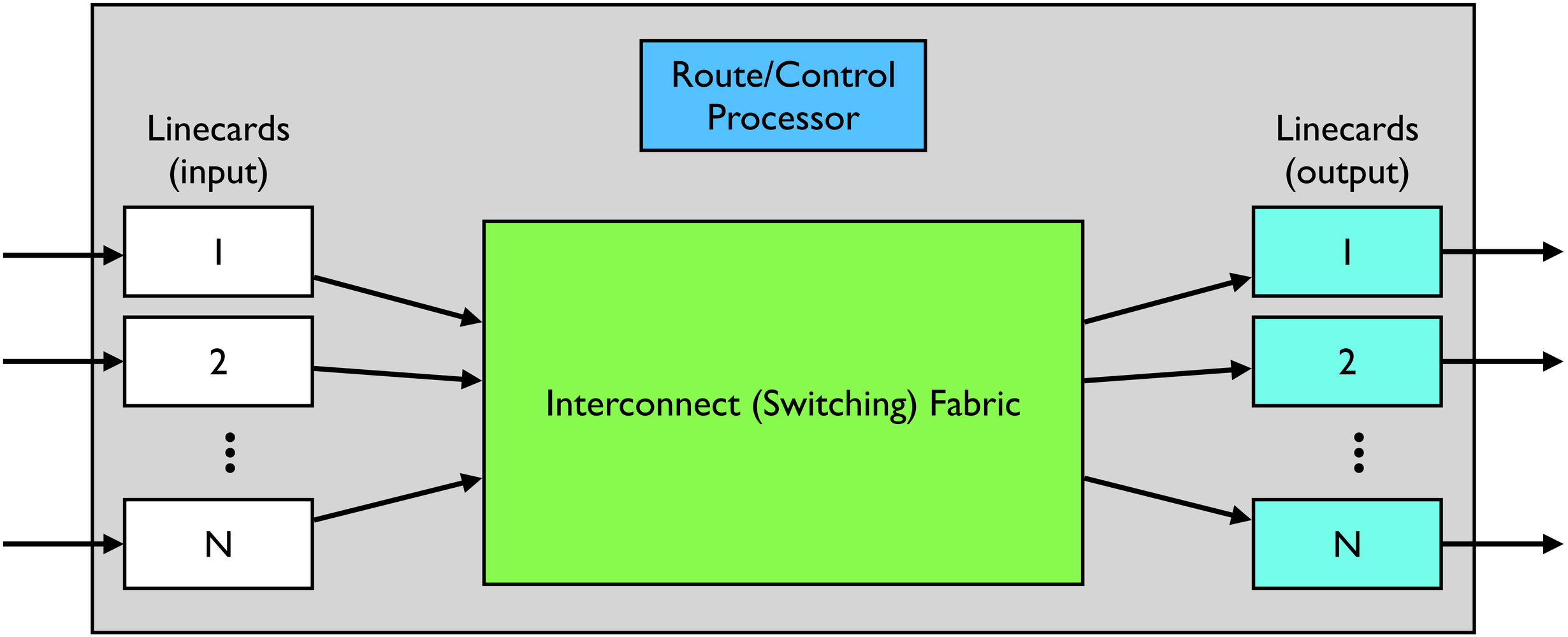

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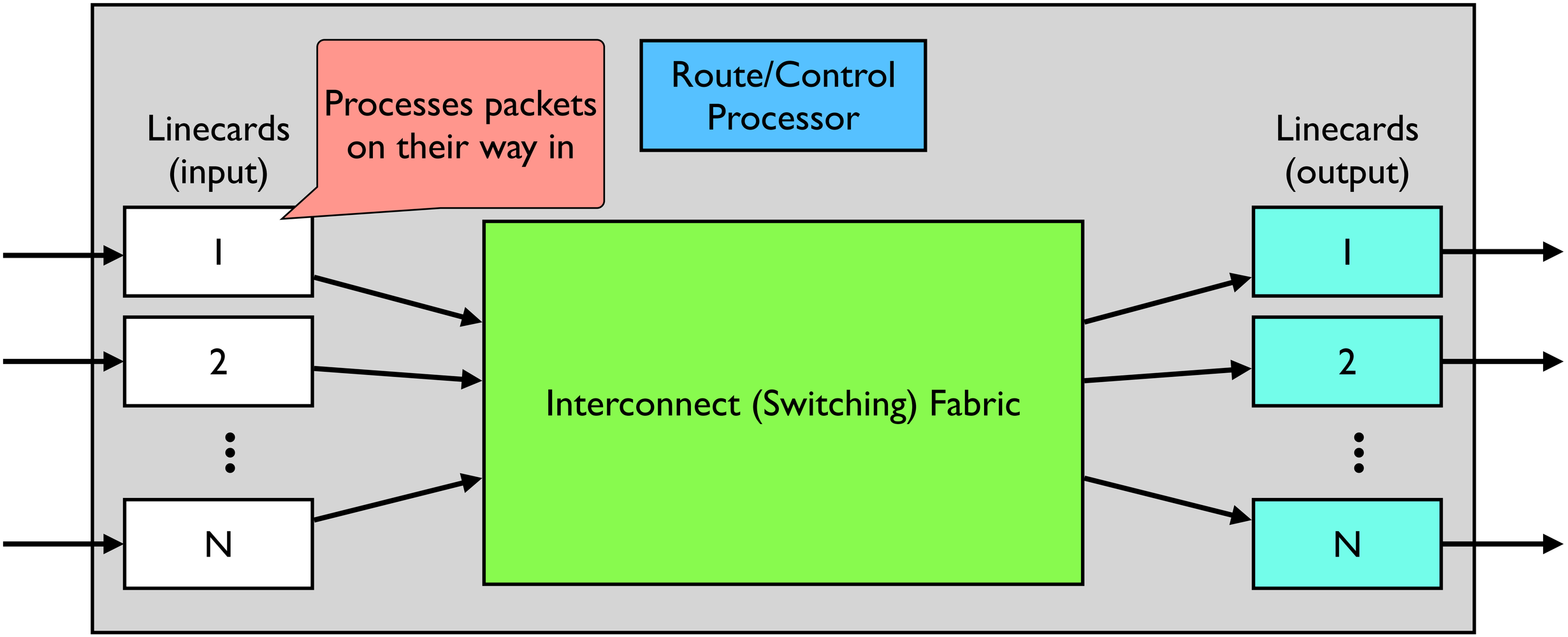

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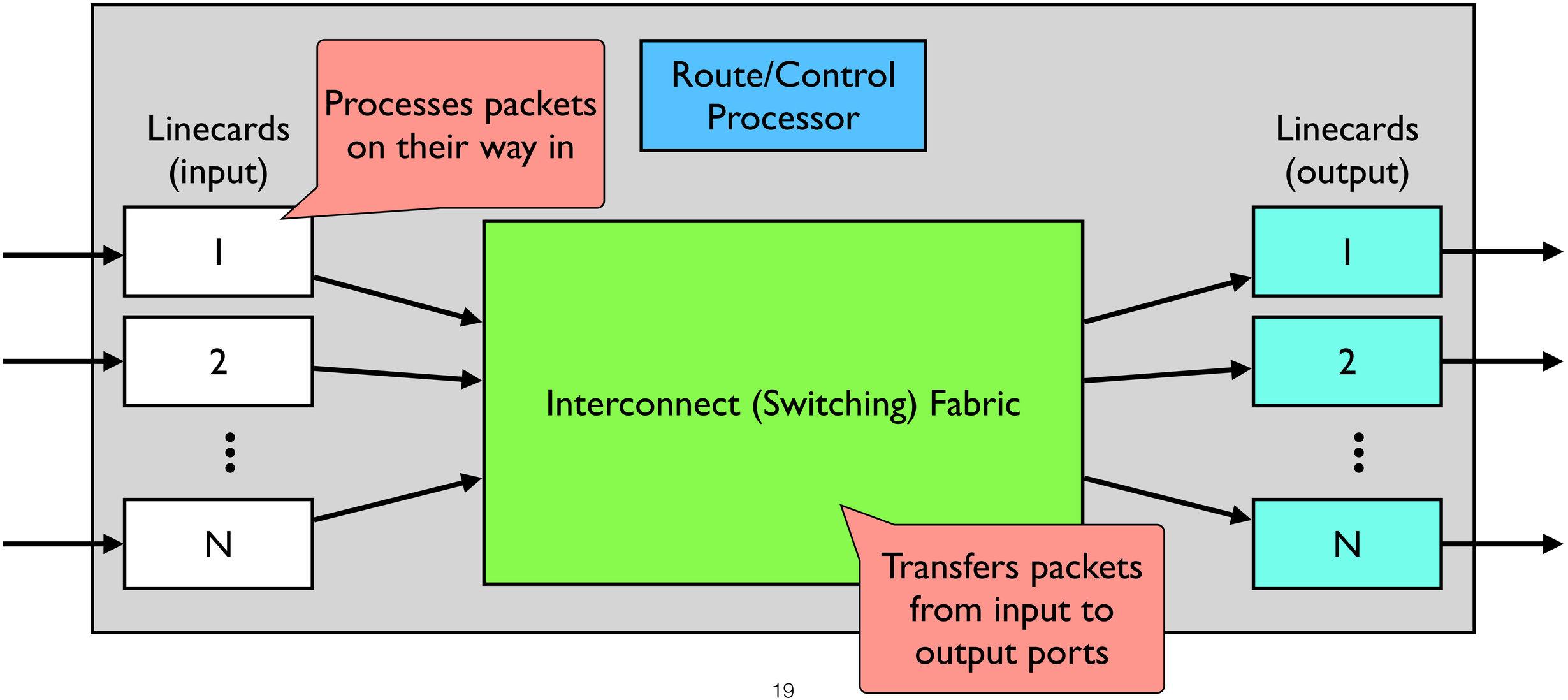

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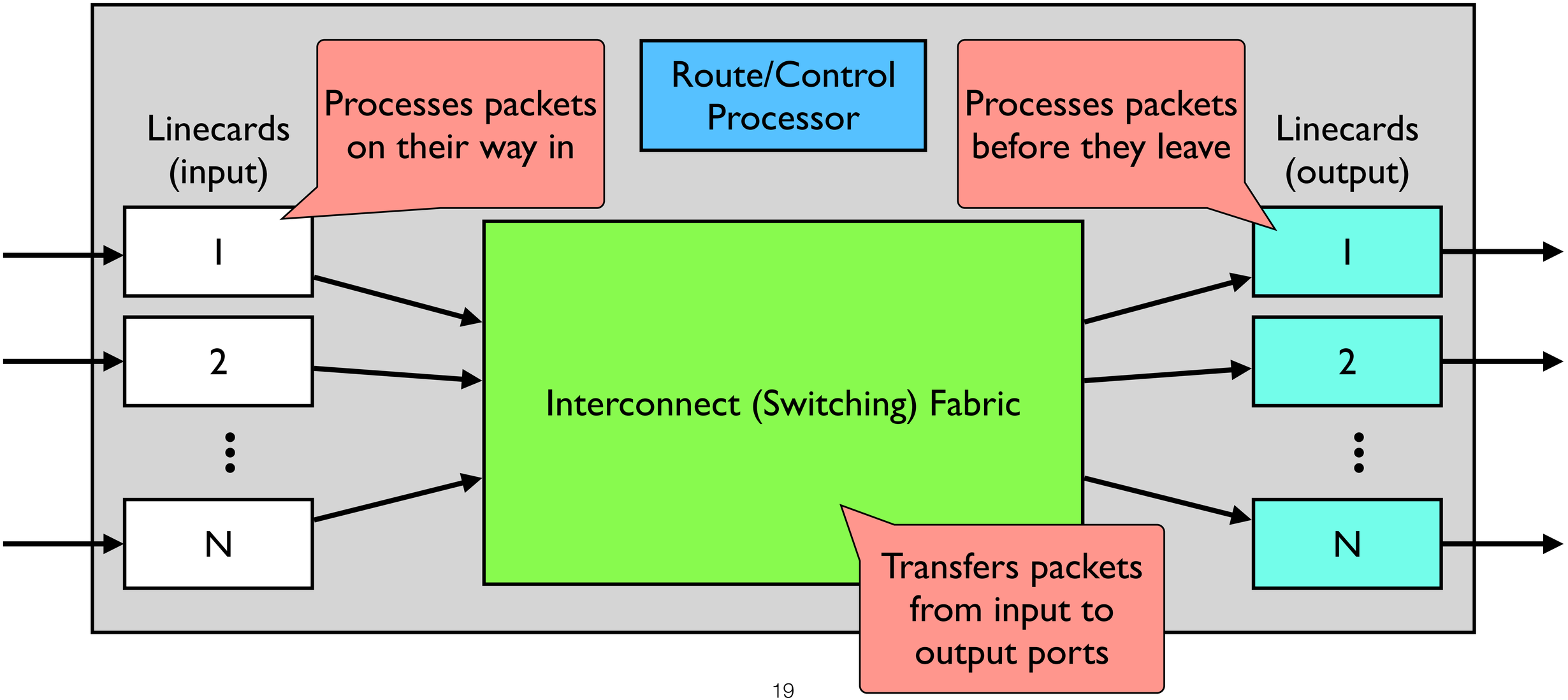

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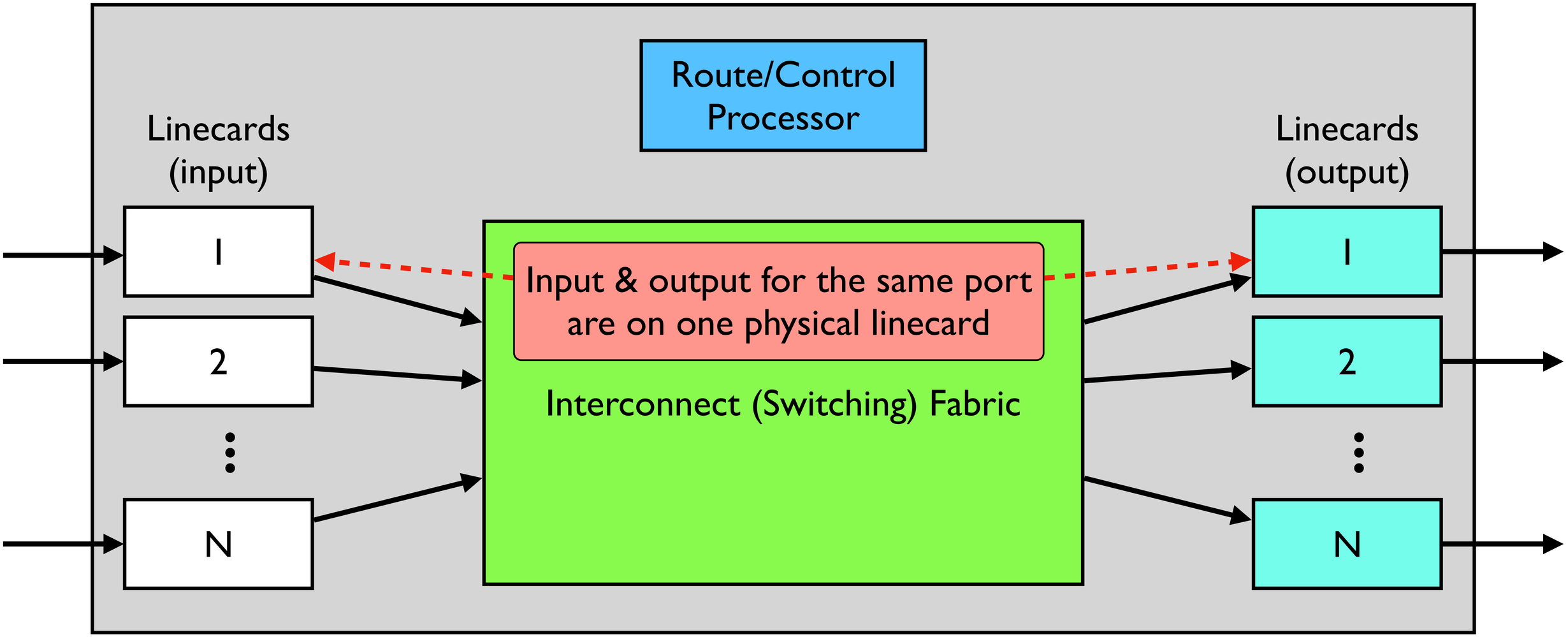

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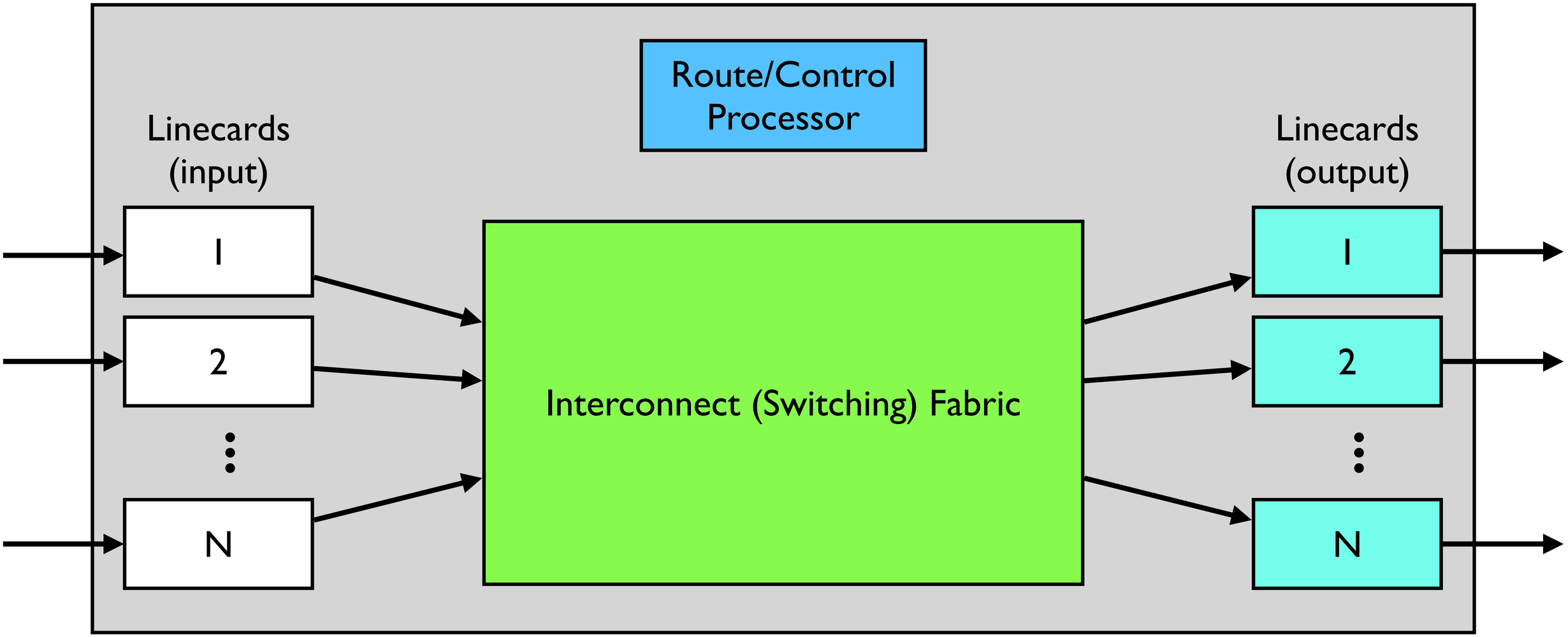

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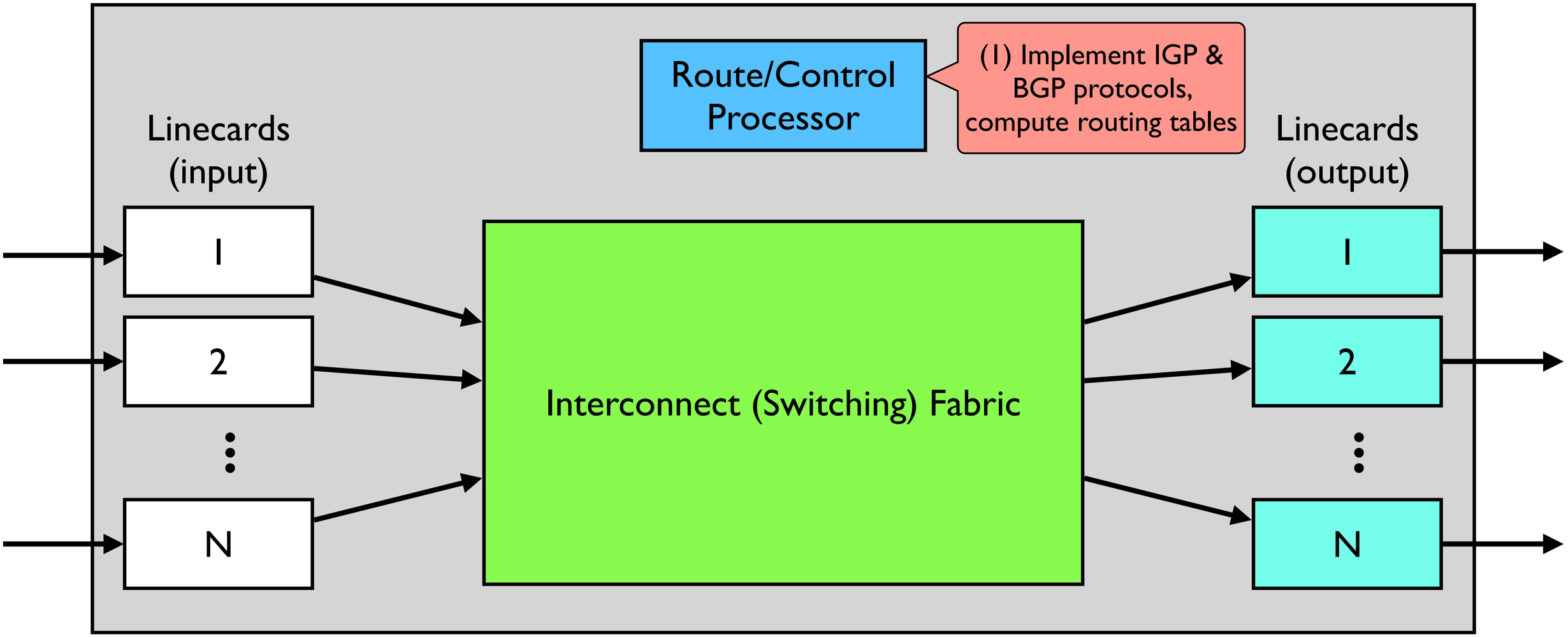

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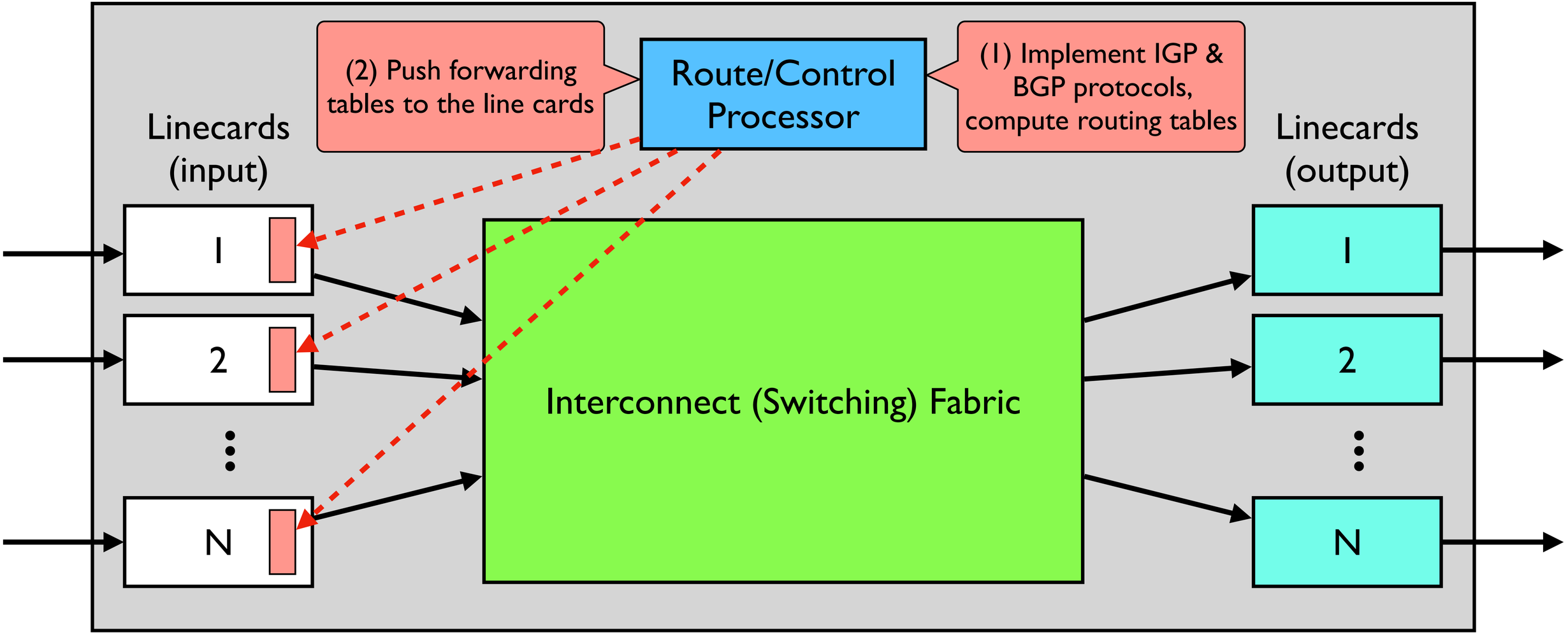

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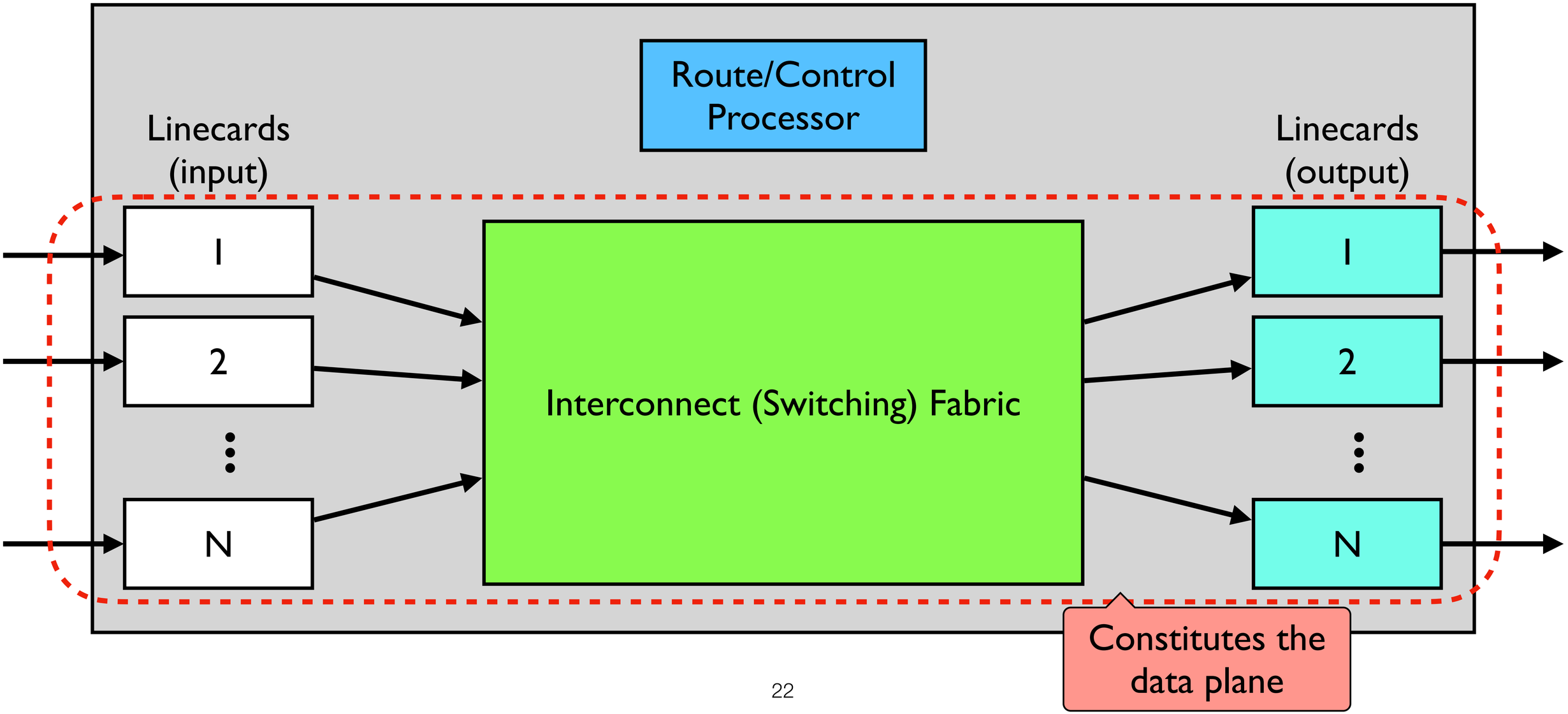

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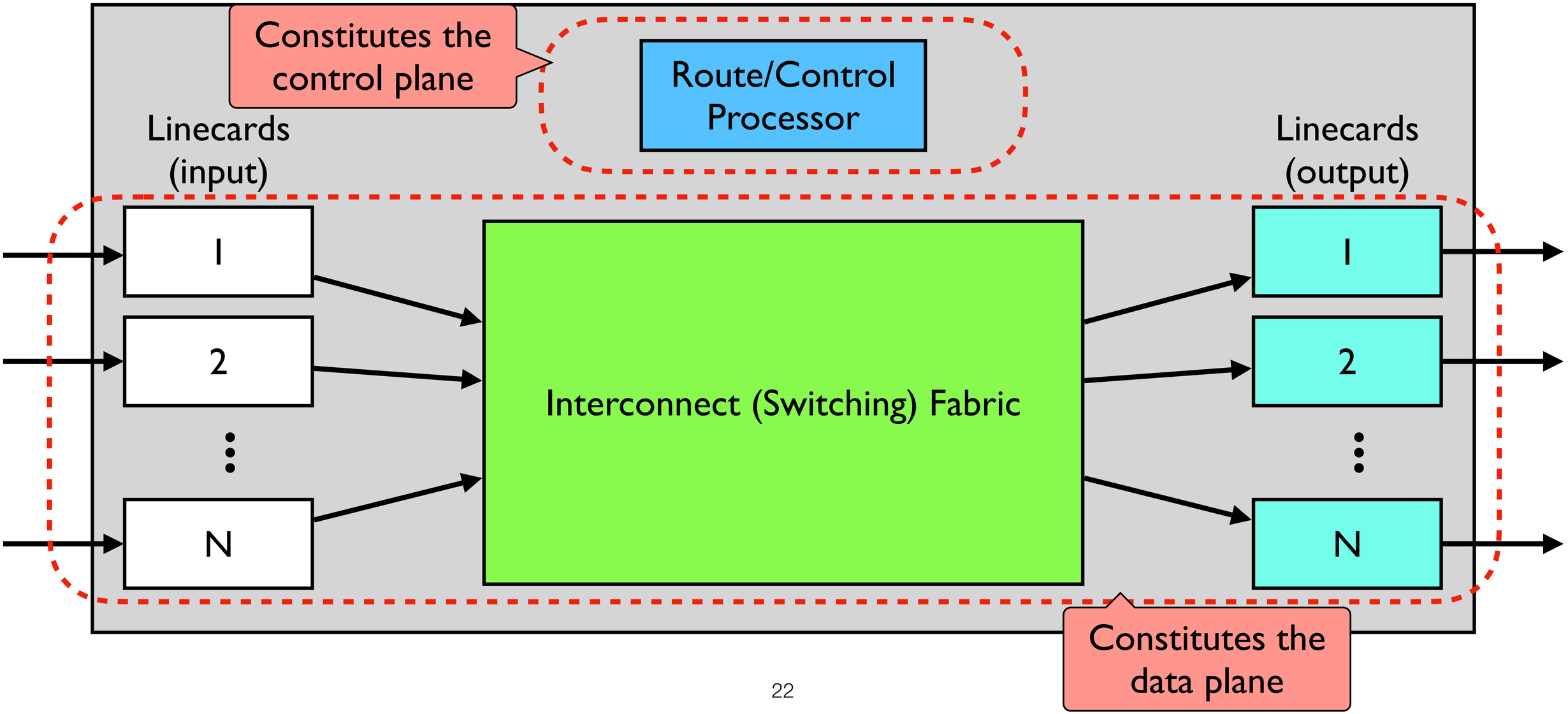

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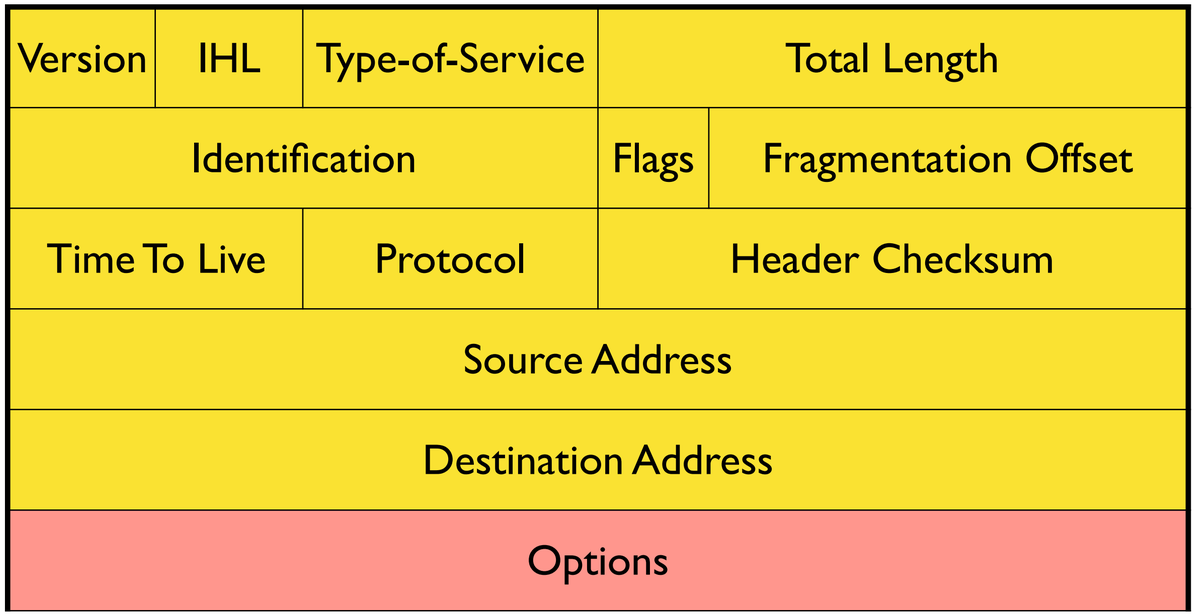

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  - "Exception processing" often done at control processor

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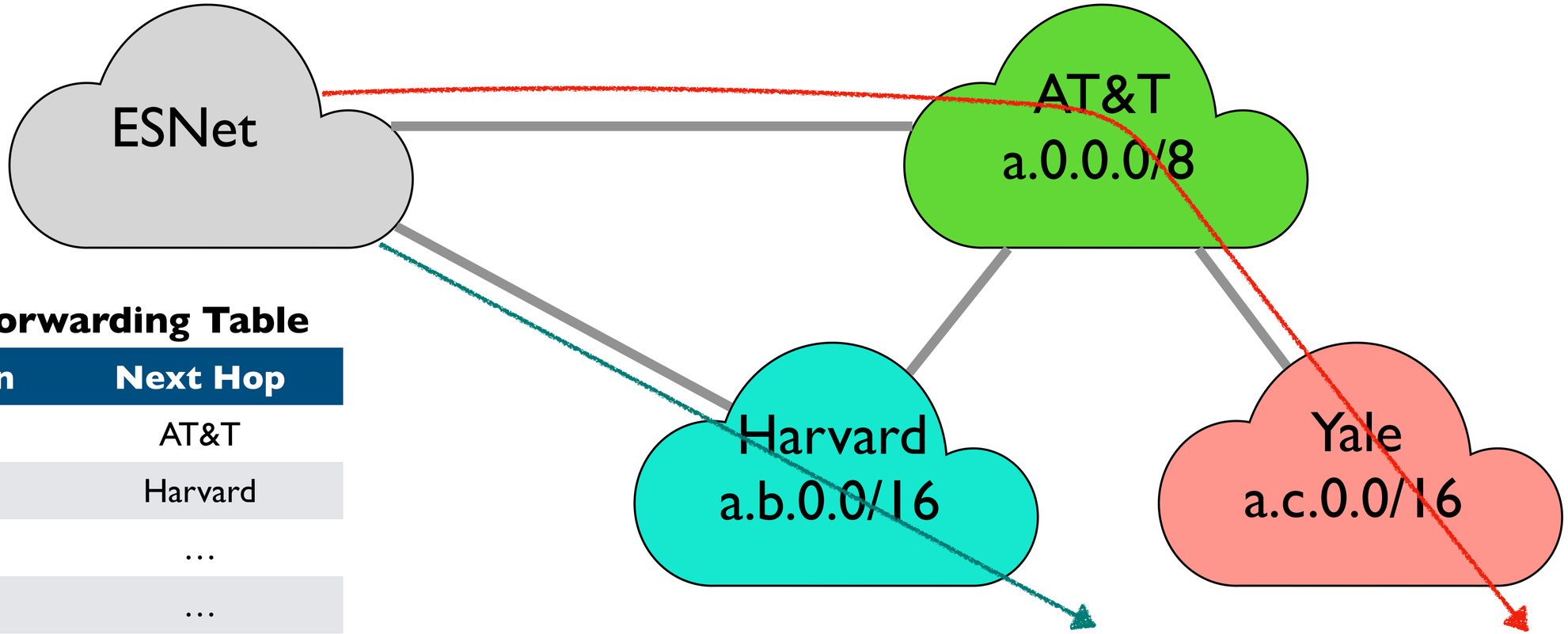
  - We've already seen this!

But aggregation is imperfect…

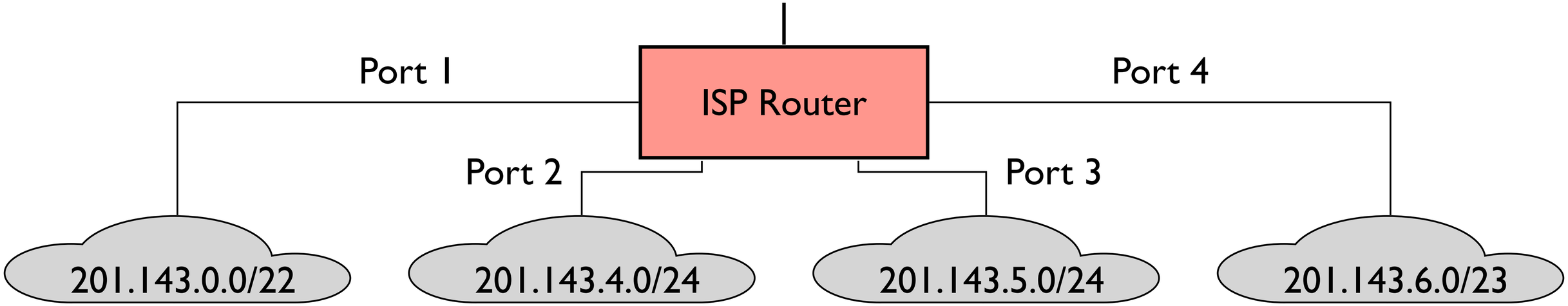
ESNet must maintain routing entries for a.*.*.* and a.b.*.*



ESNet's Forwarding Table

Destination	Next Hop
a.*.*.*	AT&T
a.b.*.*	Harvard
…	…
…	…

Example #1: 4 prefixes, 4 ports



Prefix	Port
201.143.0.0/22	Port 1
201.143.4.0/24	Port 2
201.143.5.0/24	Port 3
201.143.6.0/23	Port 4

Finding a match

Prefix	Port
201.143.0.0/22	Port 1
201.143.4.0/24	Port 2
201.143.5.0/24	Port 3
201.143.6.0/23	Port 4

Finding a match

- **Incoming packet destination: 201.143.7.0**

Prefix	Port
201.143.0.0/22	Port 1
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Finding a match

- **Incoming packet destination: 201.143.7.0**

201.143.0.0/22

201.143.4.0/24

201.143.7.0/25

201.143.6.0/23

Routing Table

Finding a match

- **Incoming packet destination: 201.143.7.0**

11001001	10001111	00000111	10100010

201.143.0.0/22

201.143.4.0/24

201.143.7.0/25

201.143.6.0/23

Routing Table

Finding a match

- **Incoming packet destination: 201.143.7.0**

Routing Table

201.143.0.0/22

201.143.4.0/24

201.143.7.0/25

201.143.6.0/23

Finding a match

- **Incoming packet destination: 201.143.7.0**

Routing Table

201.143.0.0/22

201.143.4.0/24

201.143.7.0/25

201.143.6.0/23

Finding a match

- **Incoming packet destination: 201.143.7.0**

201.143.0.0/22

201.143.4.0/24

NOT Check an address against all destination prefixes & select the prefix it matches on the most bits

201.143.7.0/25

201.143.6.0/23

Routing Table

Finding Match Efficiently

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  - On average: O(number of entries)

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Finding Match Efficiently

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- **Leverage tree structure of binary strings**
  - Setup tree-like data structure
- **Return to example:**

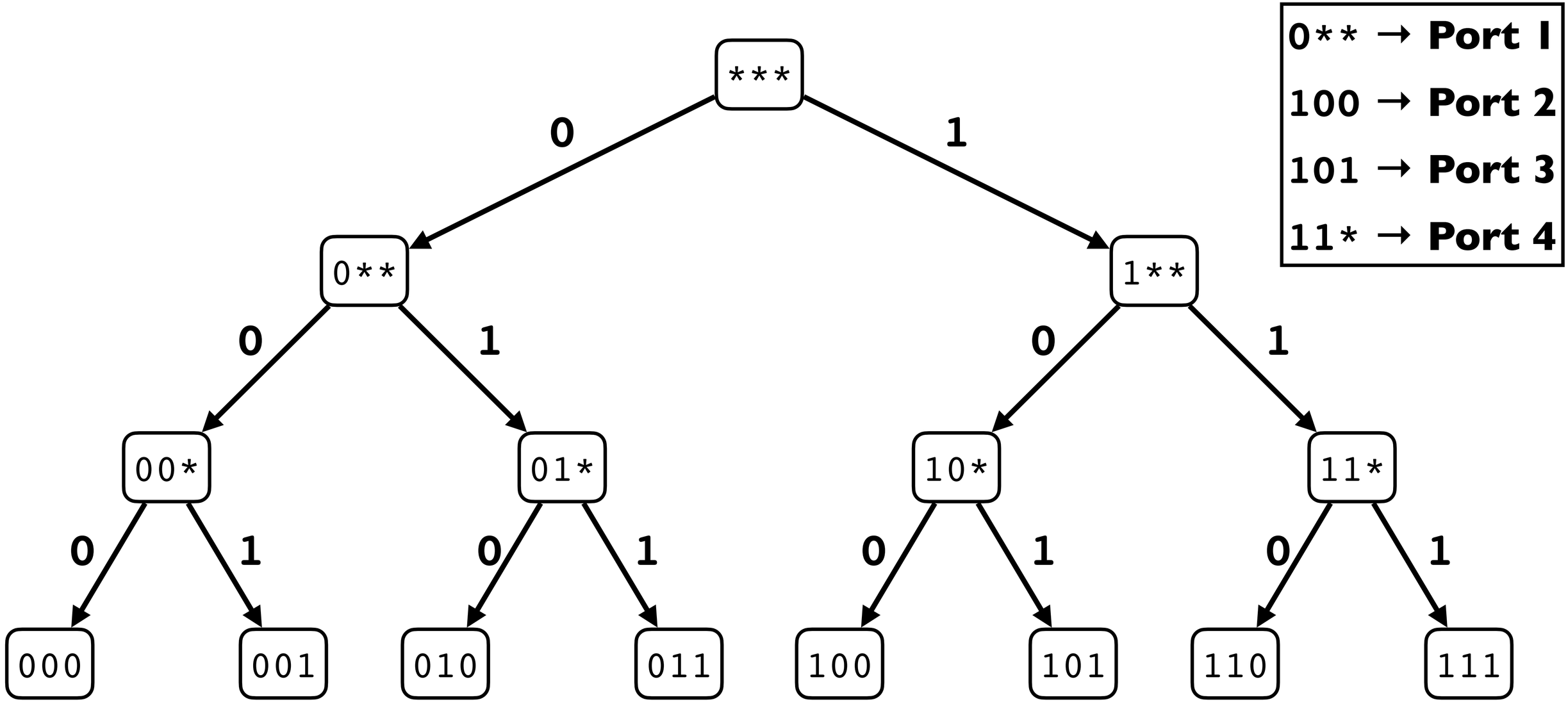
Prefix	Port
11001001100011110000**0**********	**Port 1**
11001001100011110000**100********	**Port 2**
11001001100011110000**101********	**Port 3**
11001001100011110000**11*********	**Port 4**

Consider four three-bit prefixes

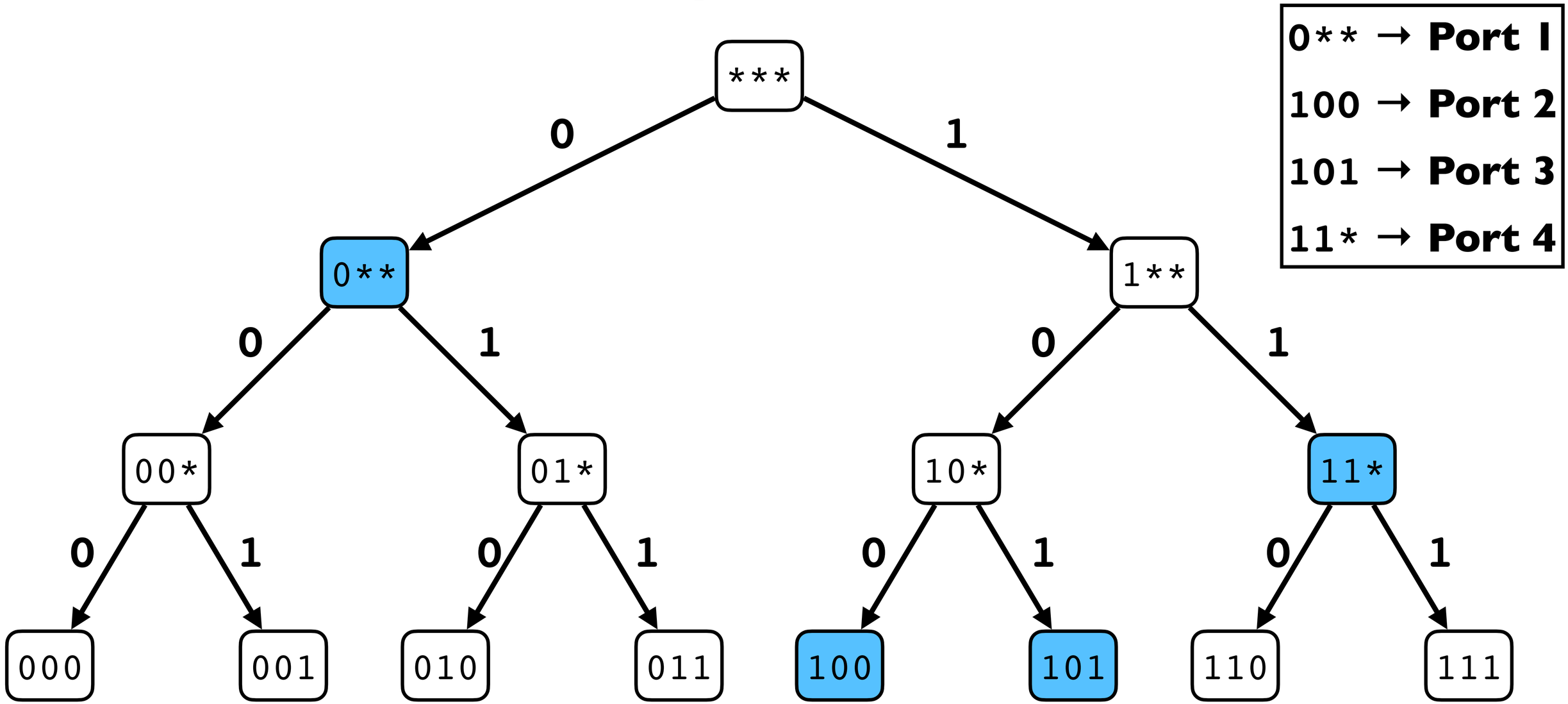
- **Just focusing on the bits where all the action is…**

- **`0**` → Port 1**
- **`100` → Port 2**
- **`101` → Port 3**
- **`11*` → Port 4**

Tree Structure



Walk Tree: Stop at Prefix Entries



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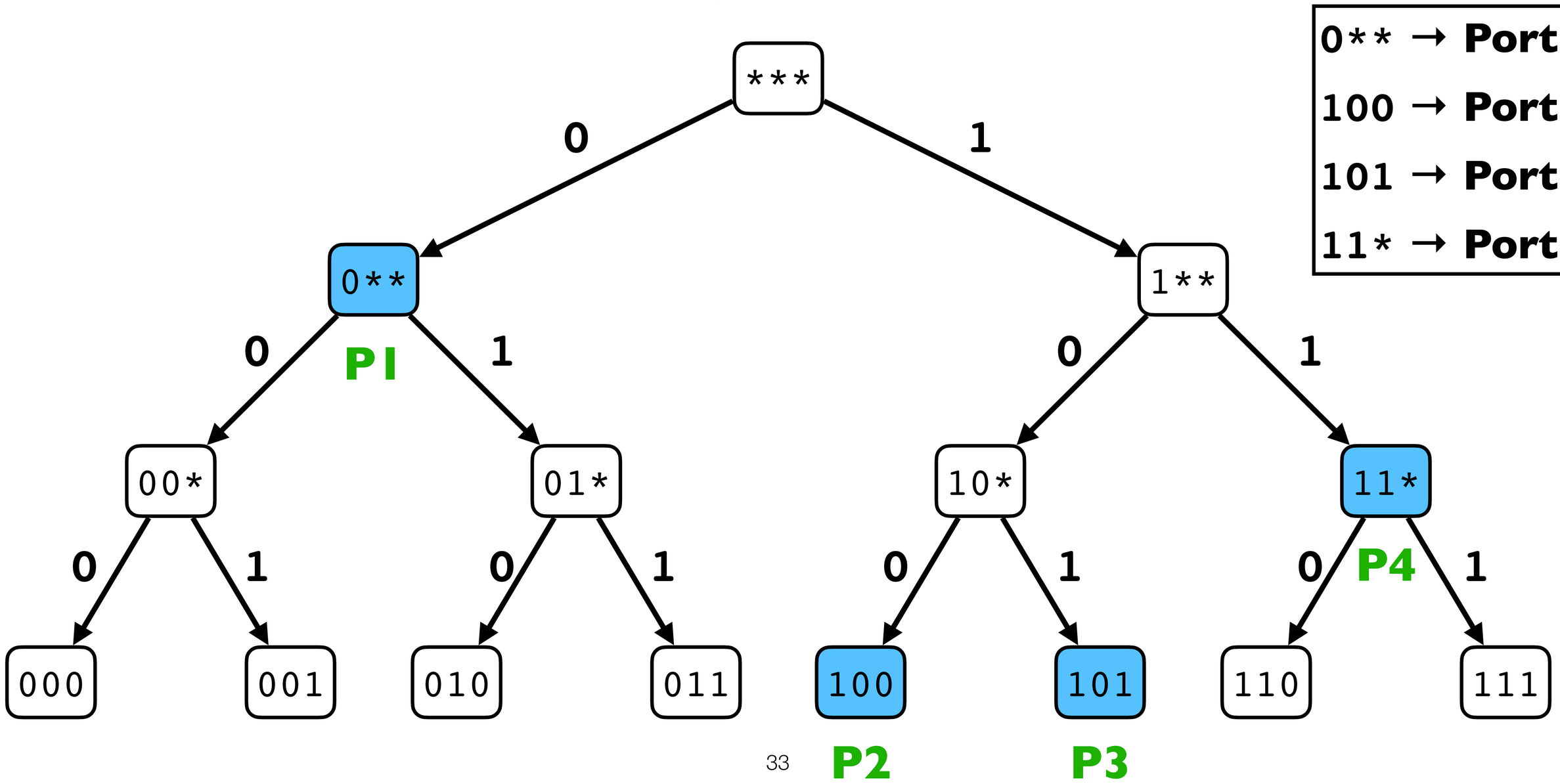
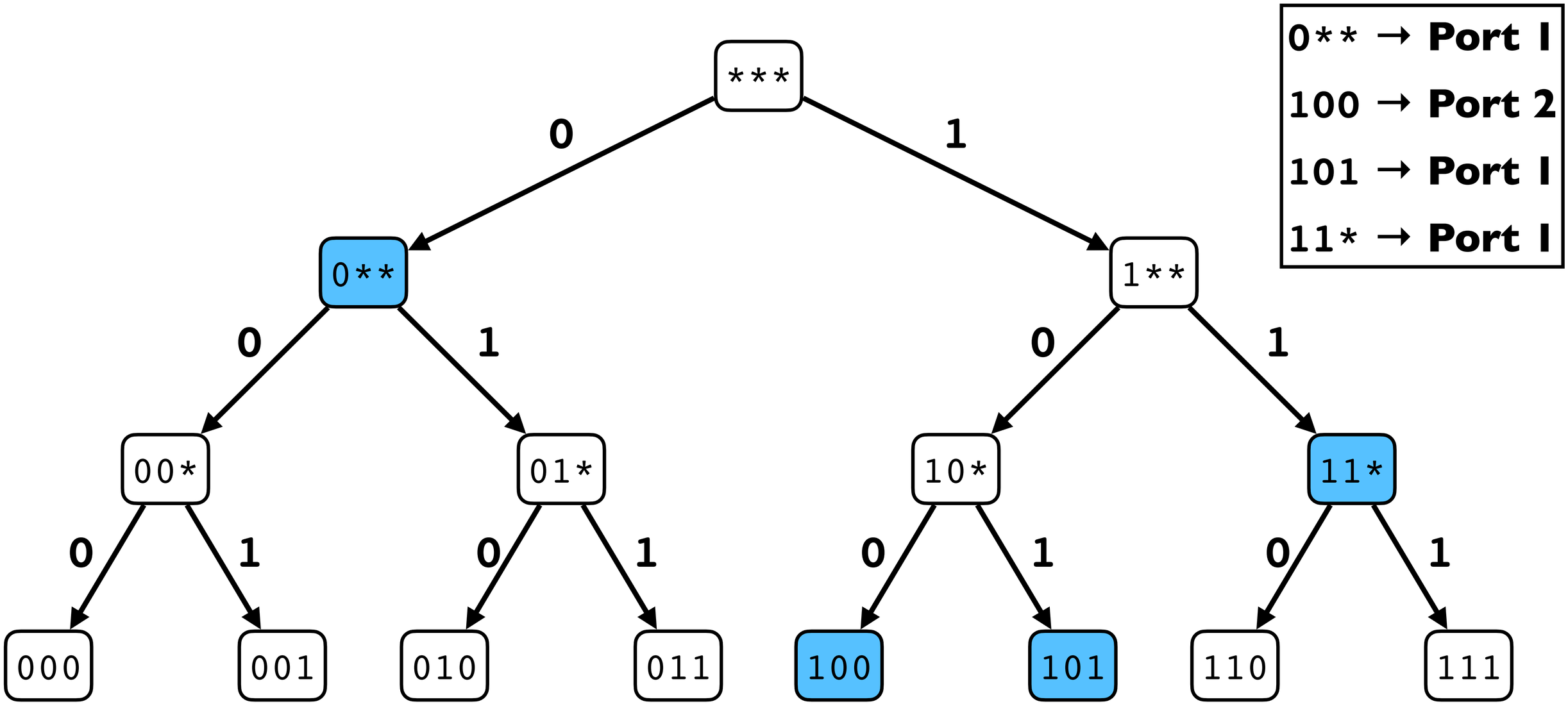


Slightly Different Example

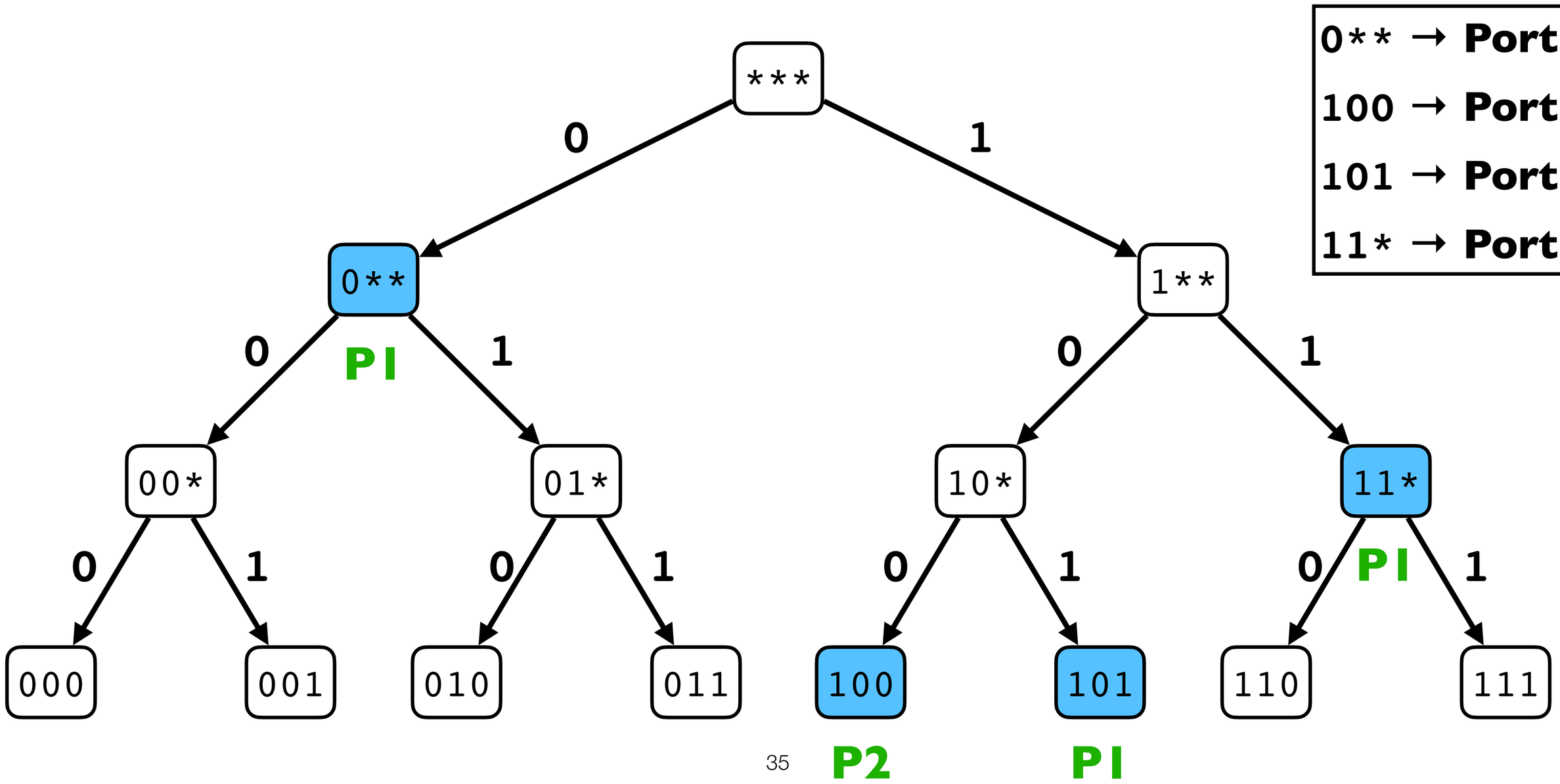
- **Several of the unique prefixes go to the same port**

- **0** → **Port 1**
- **100** → **Port 2**
- **101** → **Port 1**
- **11*** → **Port 1**

Prefix Tree


0** → Port 1
100 → Port 2
101 → Port 1
11* → Port 1
***
0
1
0**
1**
0
1
0
1
00*
01*
10*
11*
0
1
0
1
0
1
0
1
000
001
010
011
100
101
110
111

Prefix Tree


0** → Port 1
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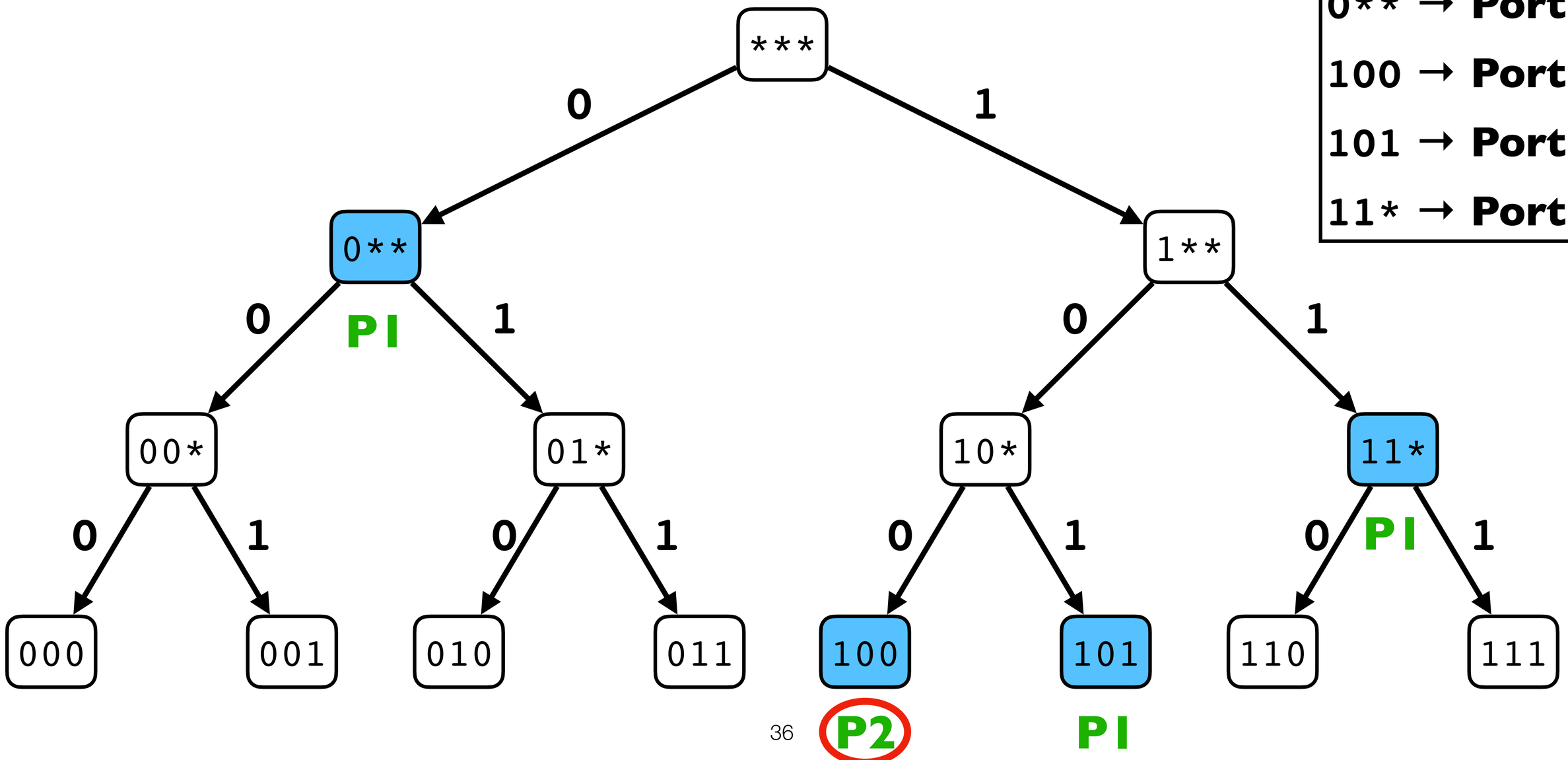
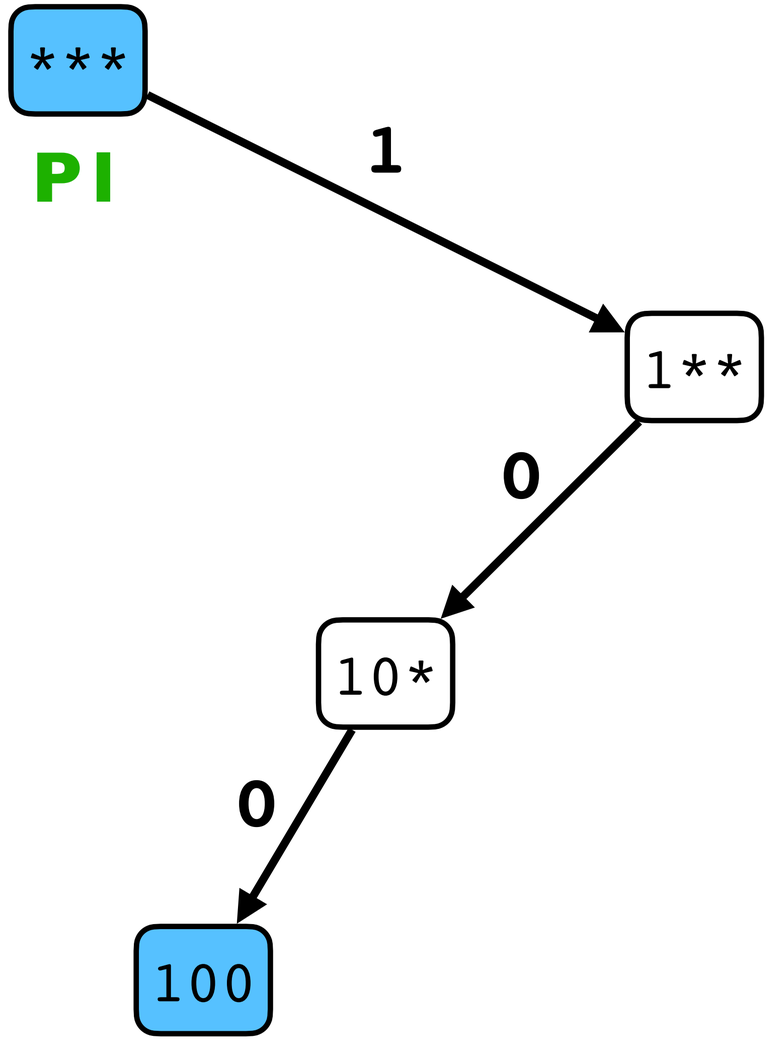
***
0
1
0**
1**
0
P1
1
0
1
00*
01*
10*
11*
0
1
0
1
0
1
0
P1
1
000
001
010
011
100
101
110
111
P2
P1

More Compact Representation

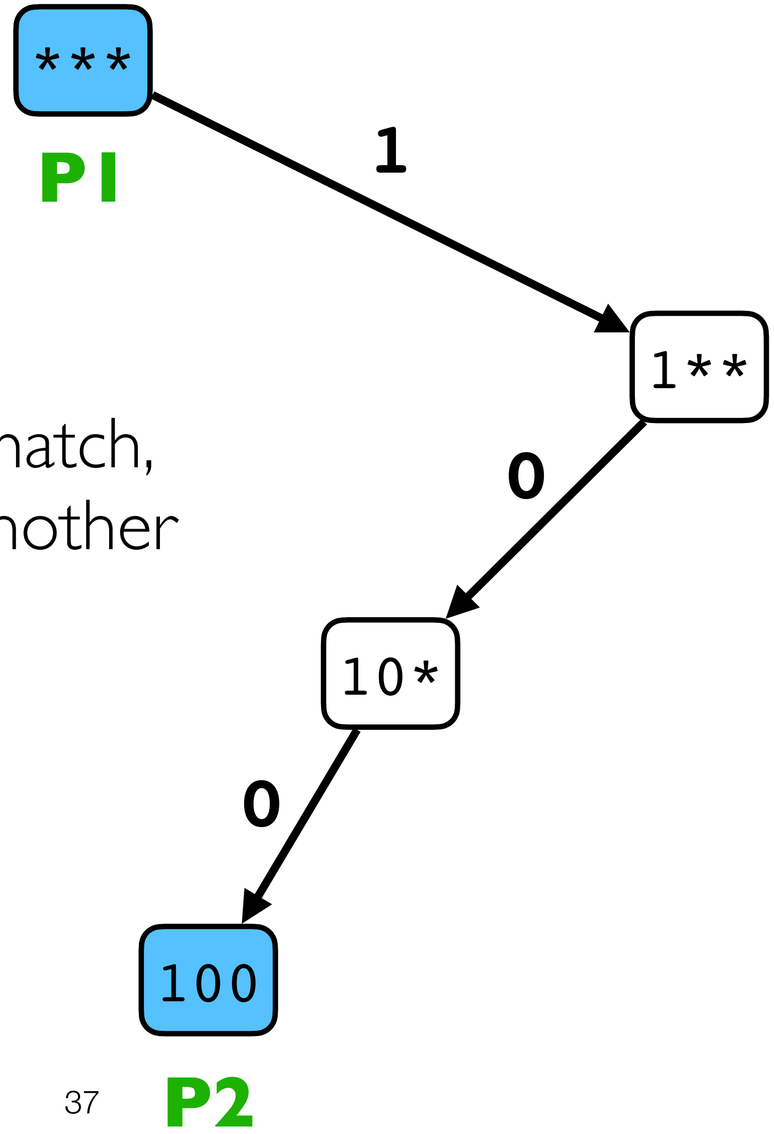


More Compact Representation



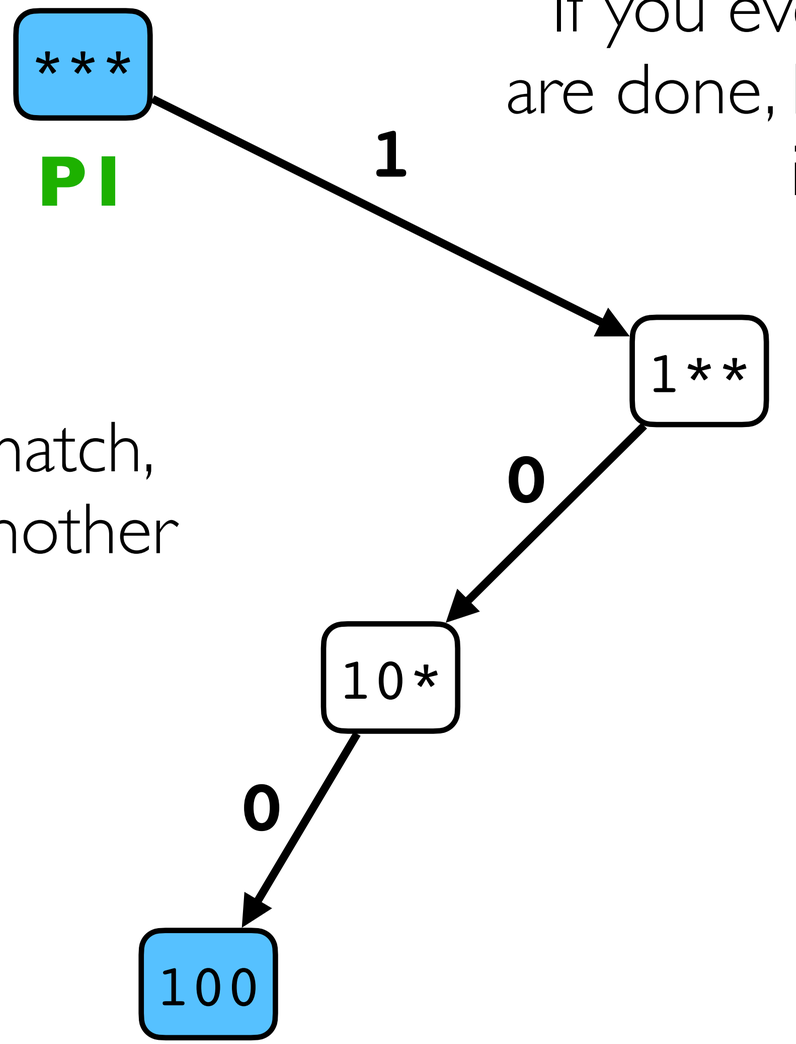
More Compact Representation

Record port associated with latest match, and only override when it matches another prefix during walk down tree



More Compact Representation

If you ever leave path, you are done, last matched prefix is answer



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- **Real routers use far more advanced/complex solutions than the approaches just described**
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- **Real routers use far more advanced/complex solutions than the approaches just described**
  - But what we discussed is their starting point
- **With many heuristics and optimizations that leverage real world patterns**
  - Some destinations more popular than others
  - Some ports lead to more destinations
  - Typical prefix granularities

Recap: Input Linecards

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  - Update packet header (easy)
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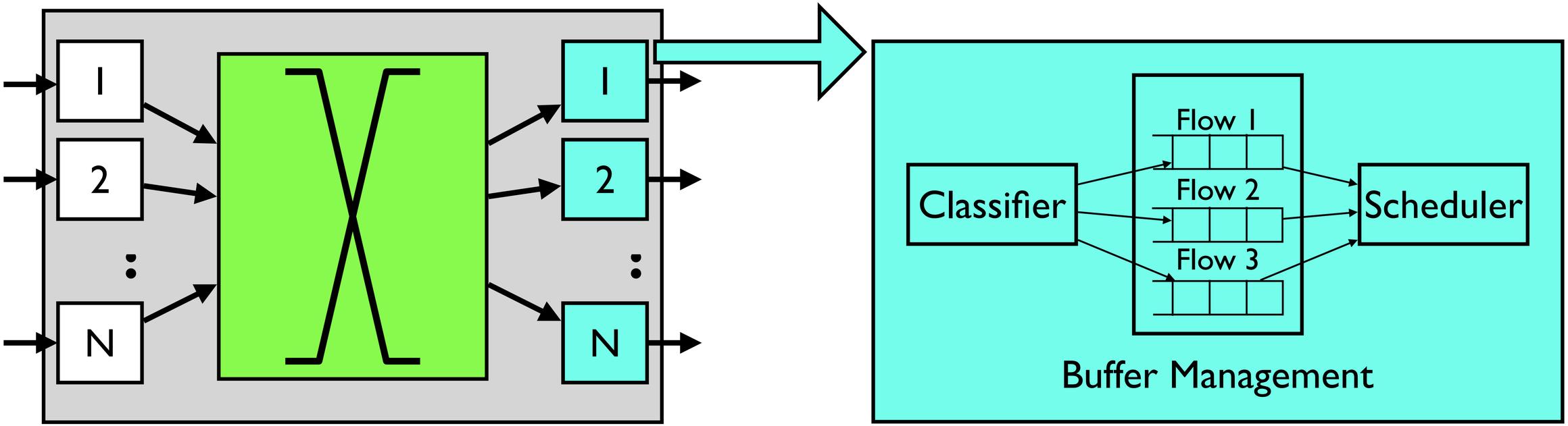
- **Tasks involved:**
  - Update packet header (easy)
  - LPM lookup on destination address (harder)
- **Mostly implemented with specialized hardware**

Output Linecard

- **Packet classification:** map each packet to a "flow"
  - Flow (for now): set of packets between two particular endpoints
- **Buffer management:** decide when and which packet to drop
- **Scheduler:** decide when and which packet to transmit



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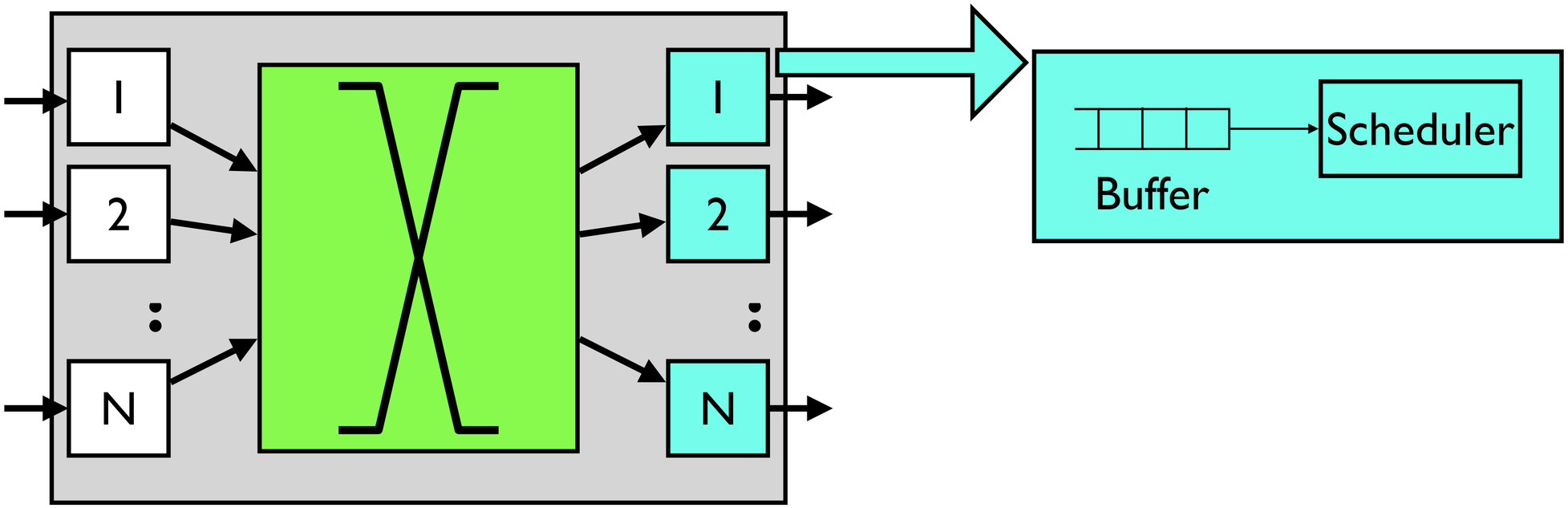
- **Scheduler:** decide when and which packet to transmit

- **Used to implement various forms of policy**
  - Deny all e-mail traffic from ISP-X to Y (access control)
  - Route IP telephony traffic from X to Y via PHY_CIRCUIT (policy)
  - Ensure that no more than 50 Mbps are injected from ISP-X (QoS)

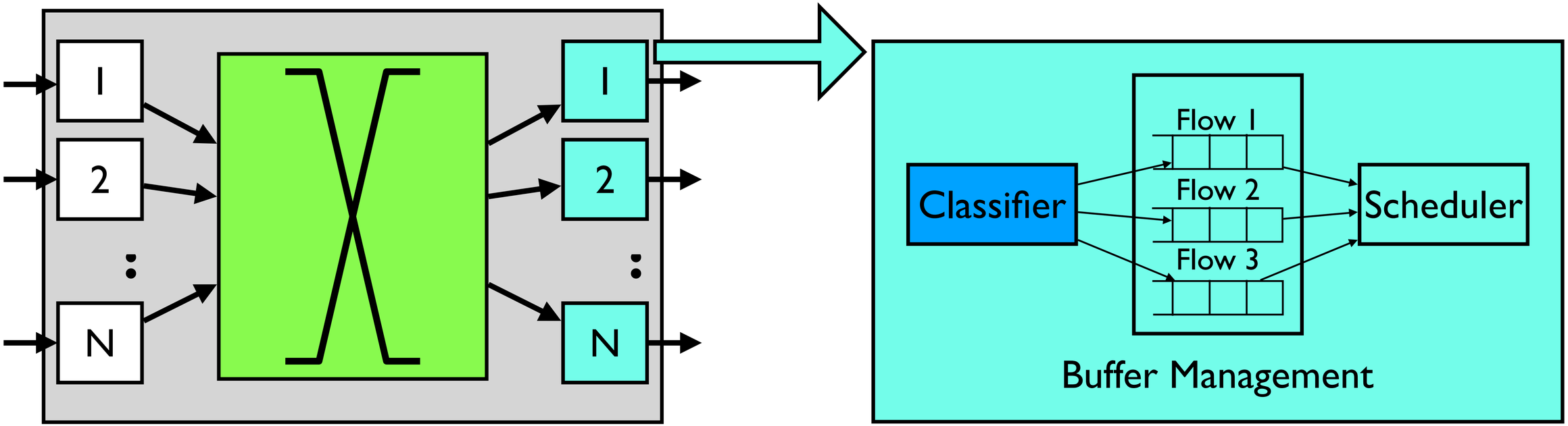
Simplest: FIFO Router

- **No classification**
- **Drop-tail buffer management:** when buffer is full, drop the incoming packet
- **First-in-First-Out (FIFO) Scheduling:** schedule packets in the same order they arrive



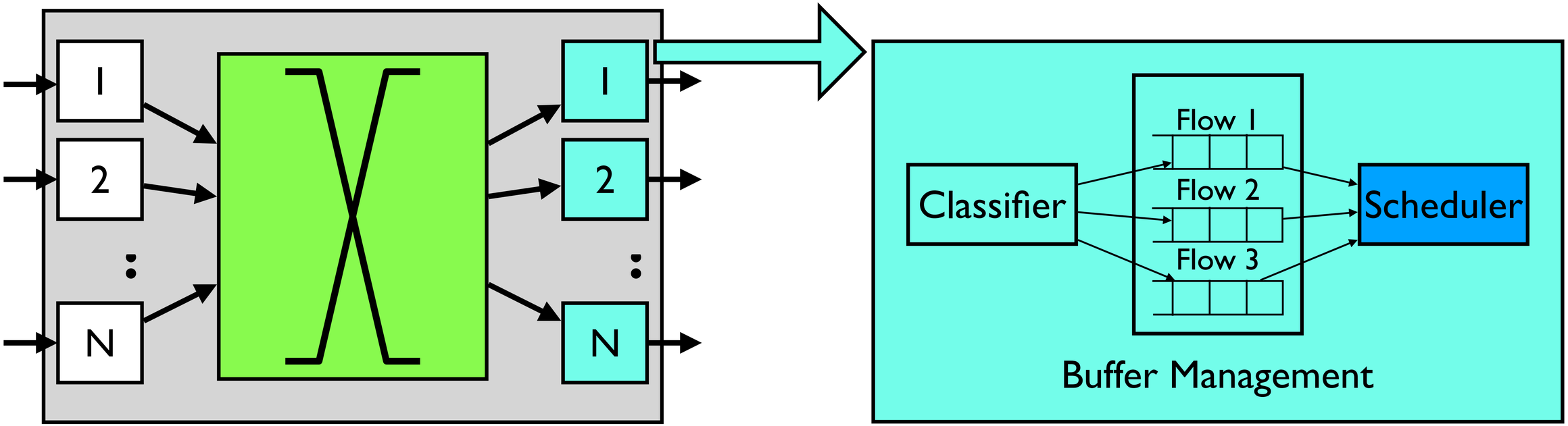
Packet Classification

- **Classify an IP packet based on fields in the packet header, e.g,**
  - Src/dst IP address, src/dst TCP port number, Type-of-Service (ToS), Protocol
- **In general fields are specified by range**
  - Classification requires a multi-dimensional range search!



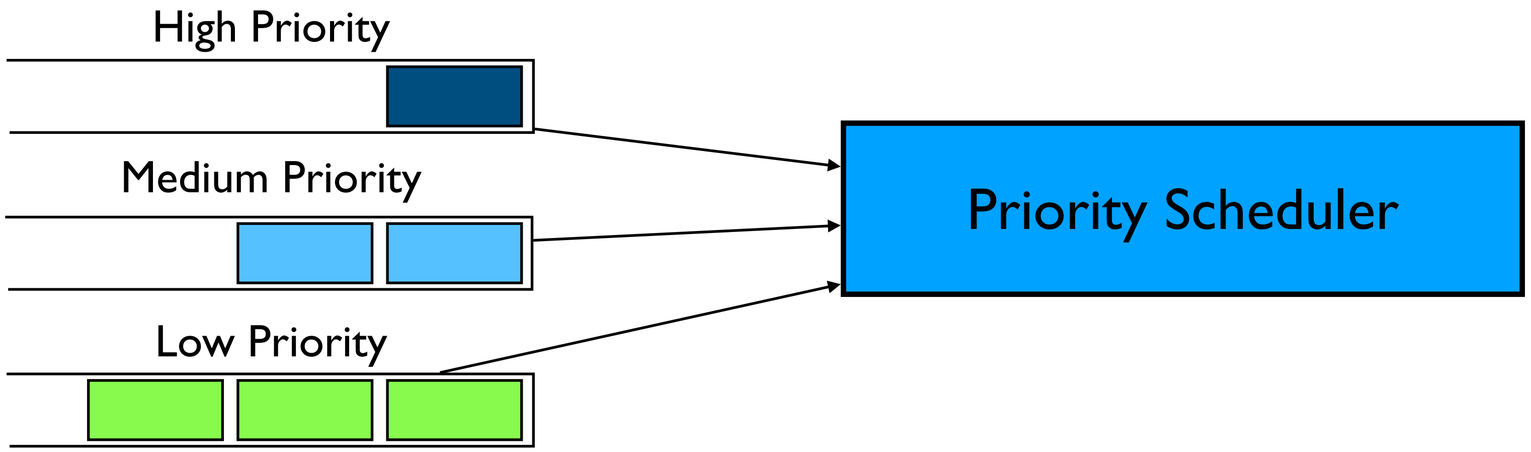
Scheduler

- **One queue per "flow"**
- **Scheduler decides when and from which queue to send a packet**
- **Goals of a scheduling algorithm**
  - (1) Fast! (2) Depends on the policy being implemented (fairness, priority, etc.)



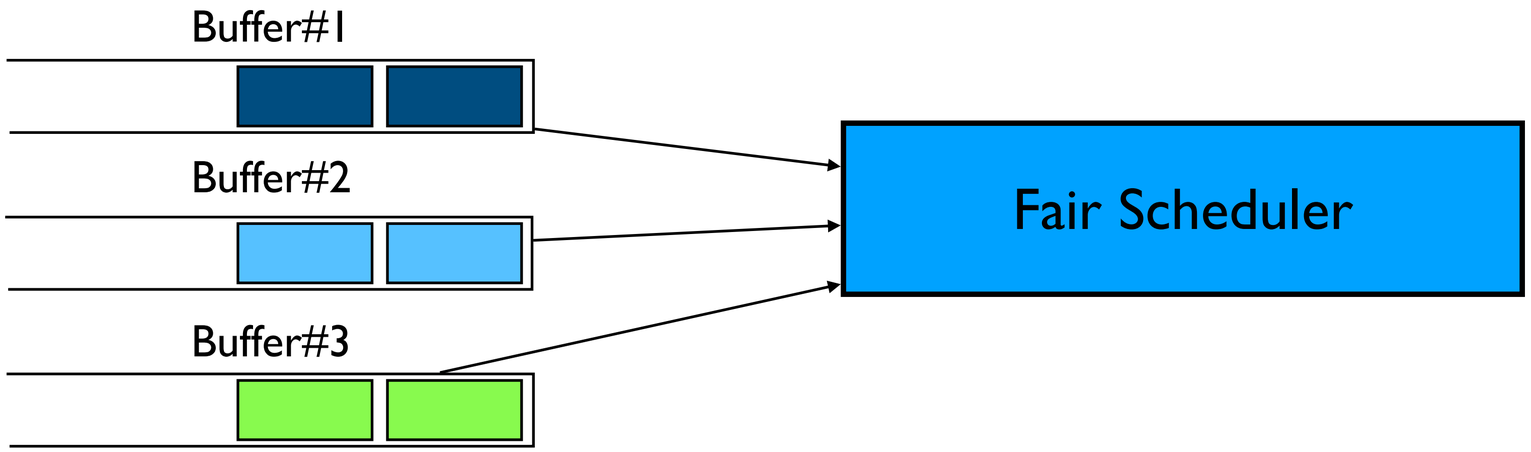
Example: Priority Scheduler

- **Priority Scheduler:** packets in the highest priority queue are always served *before* the packets in lower priority queues



Example: Round-Robin Scheduler

- **Priority Scheduler:** packets are served from each queue in turn



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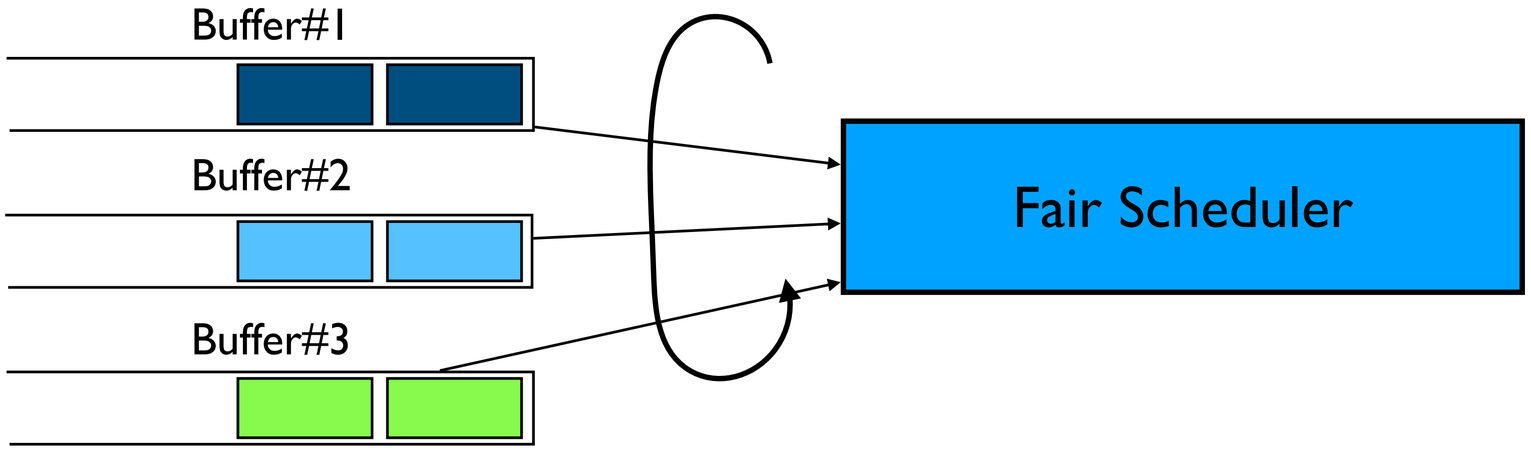
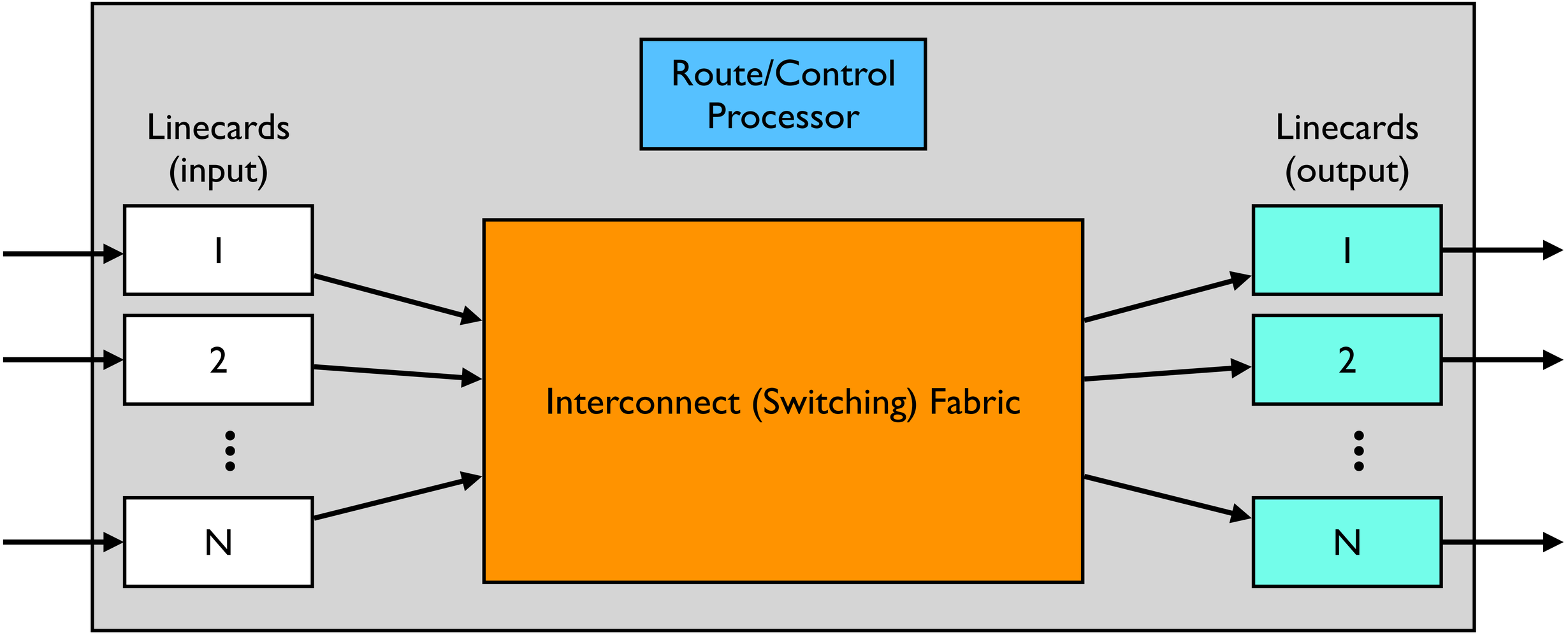
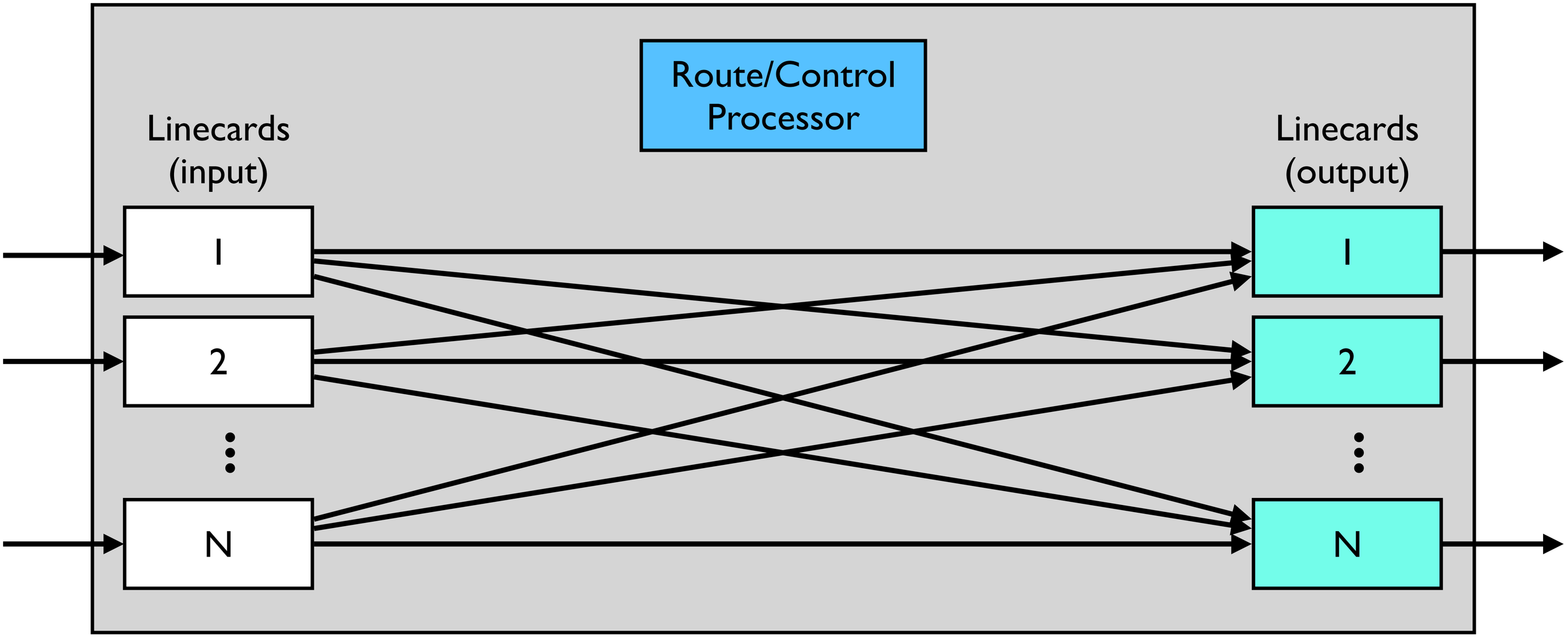


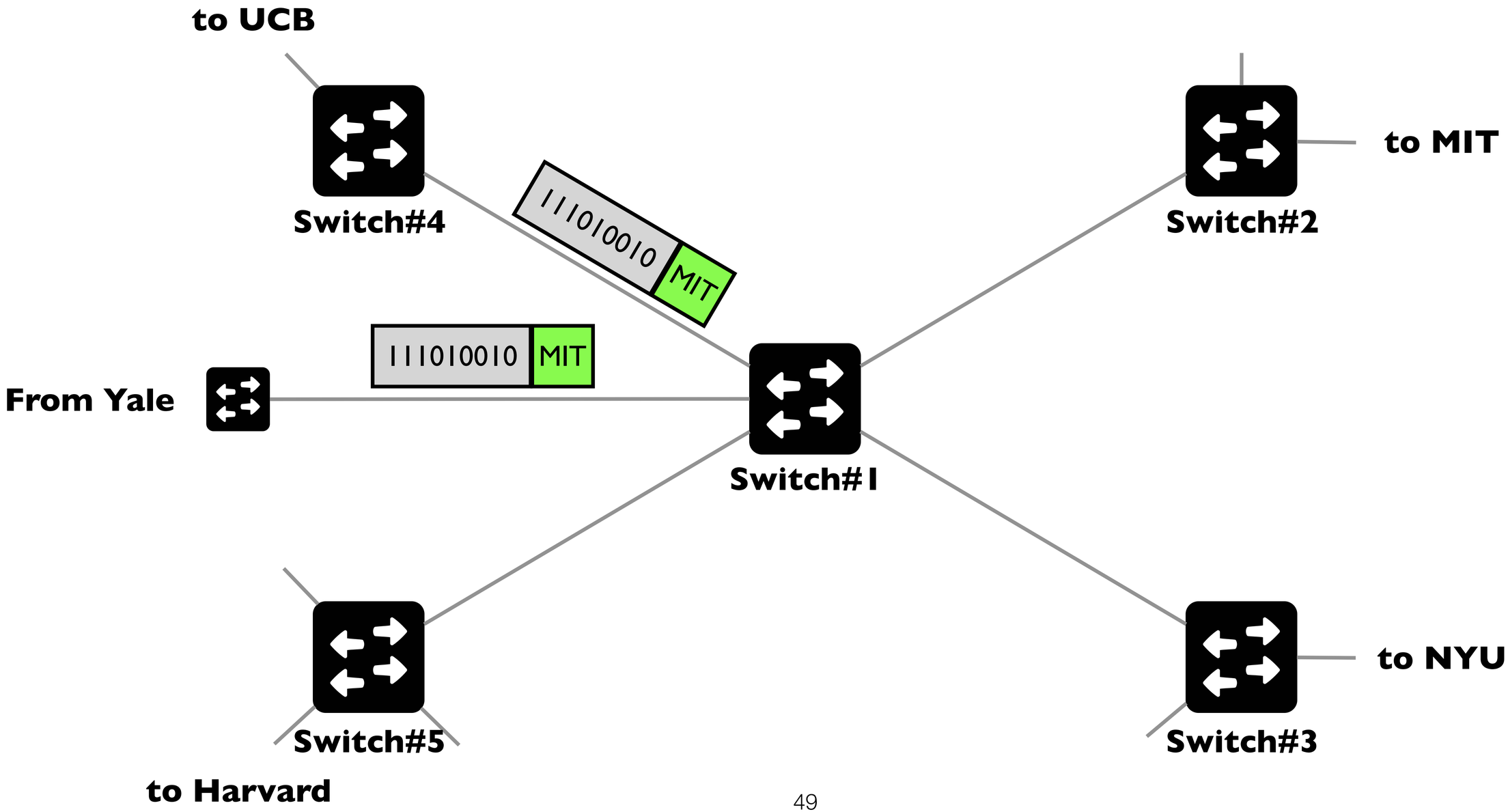
Connecting Input to Output: Switch Fabric



Today's Switch Fabrics: Mini-Network!



What's hard about the switch fabric?



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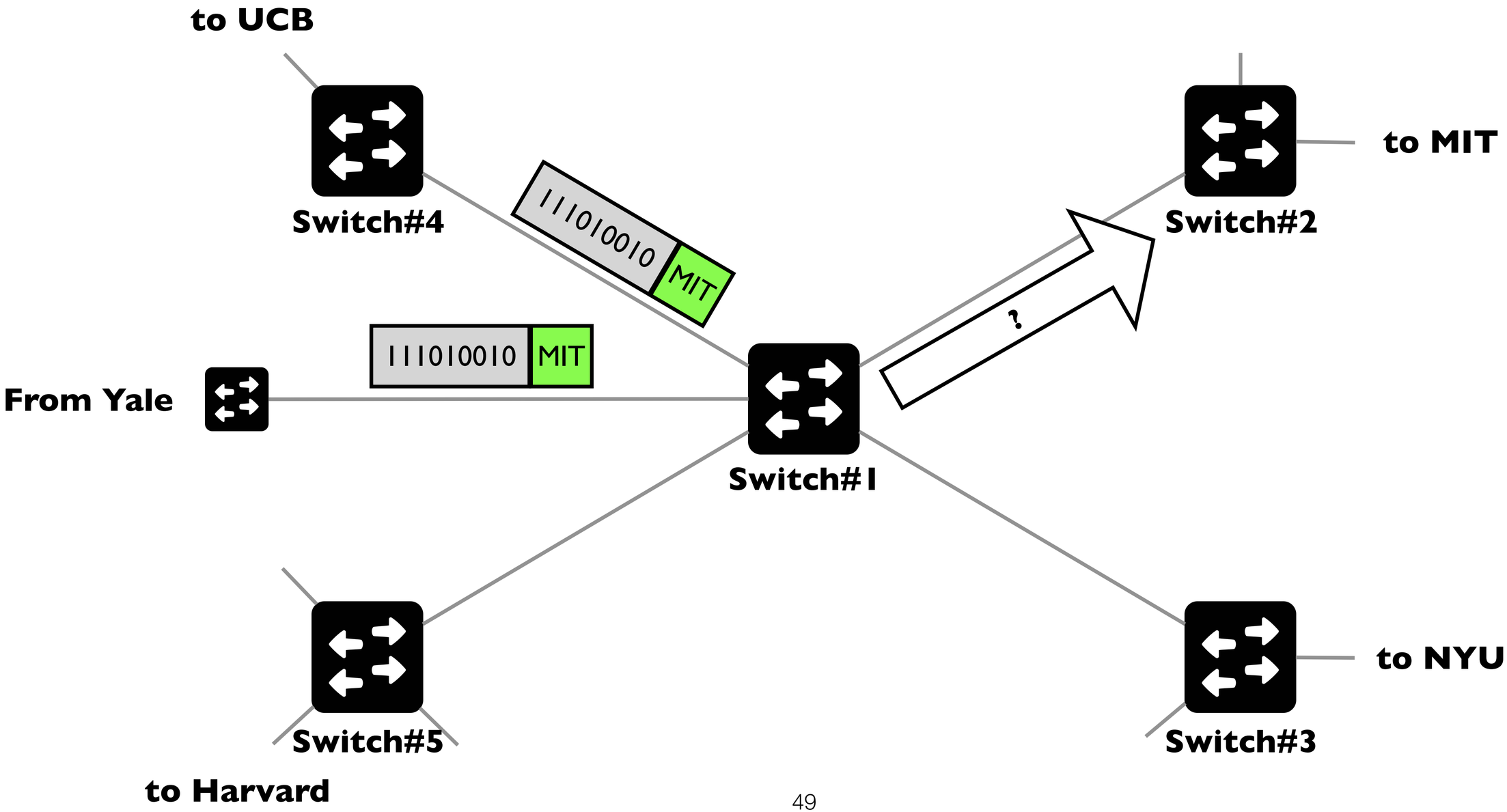

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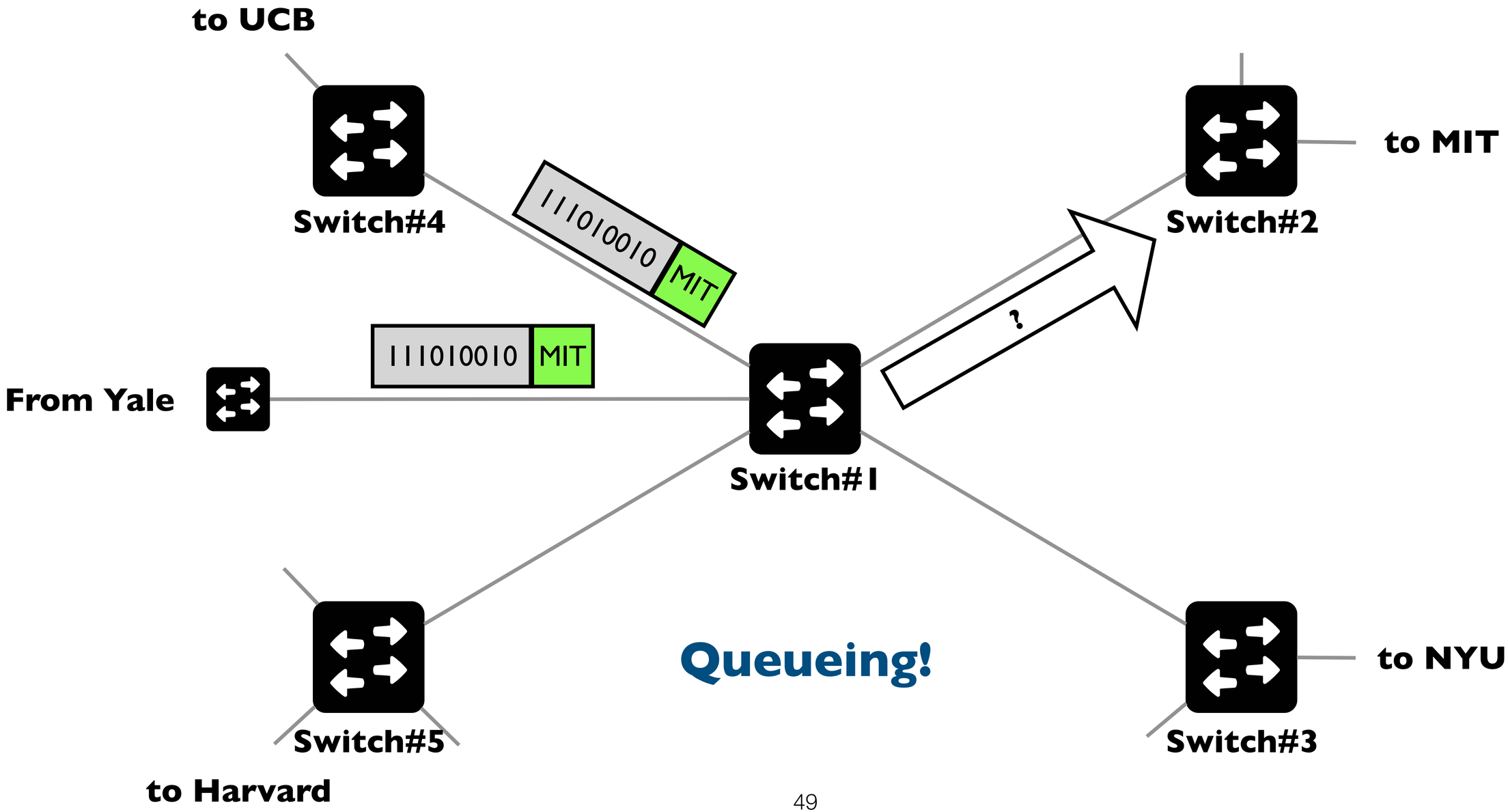
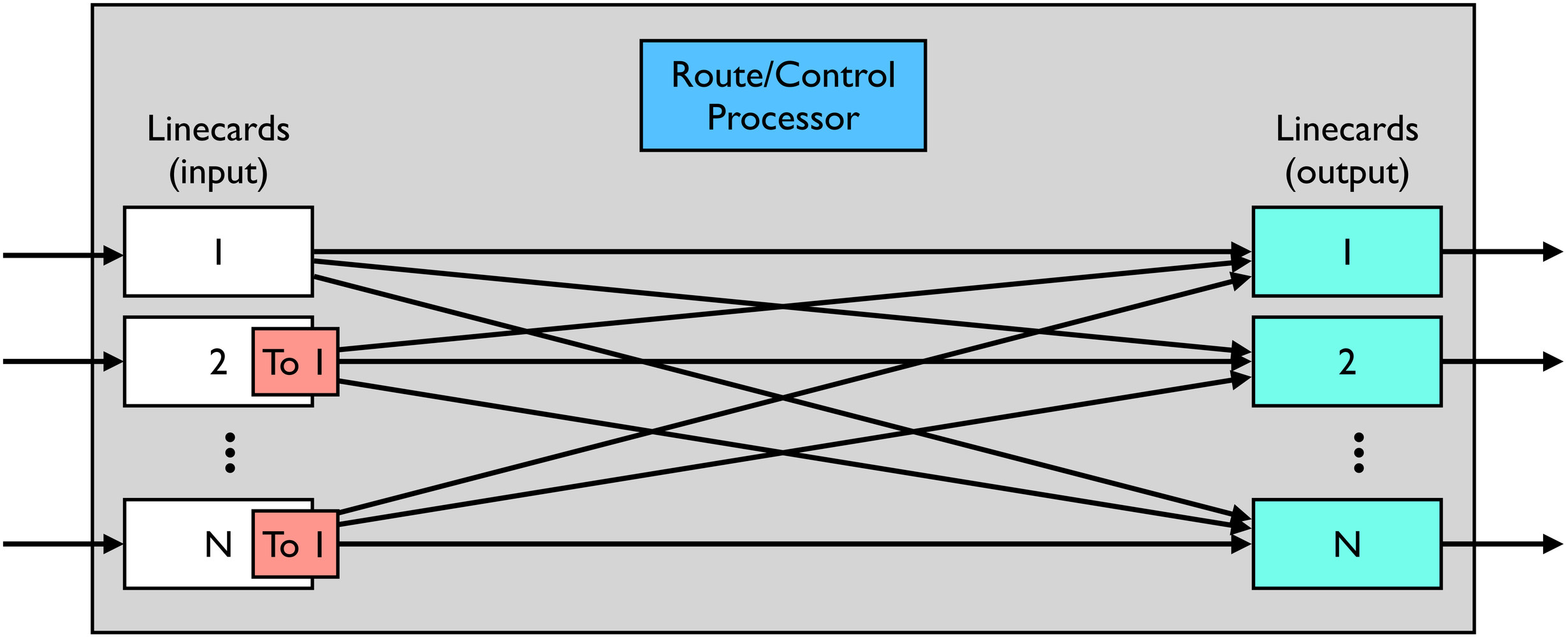
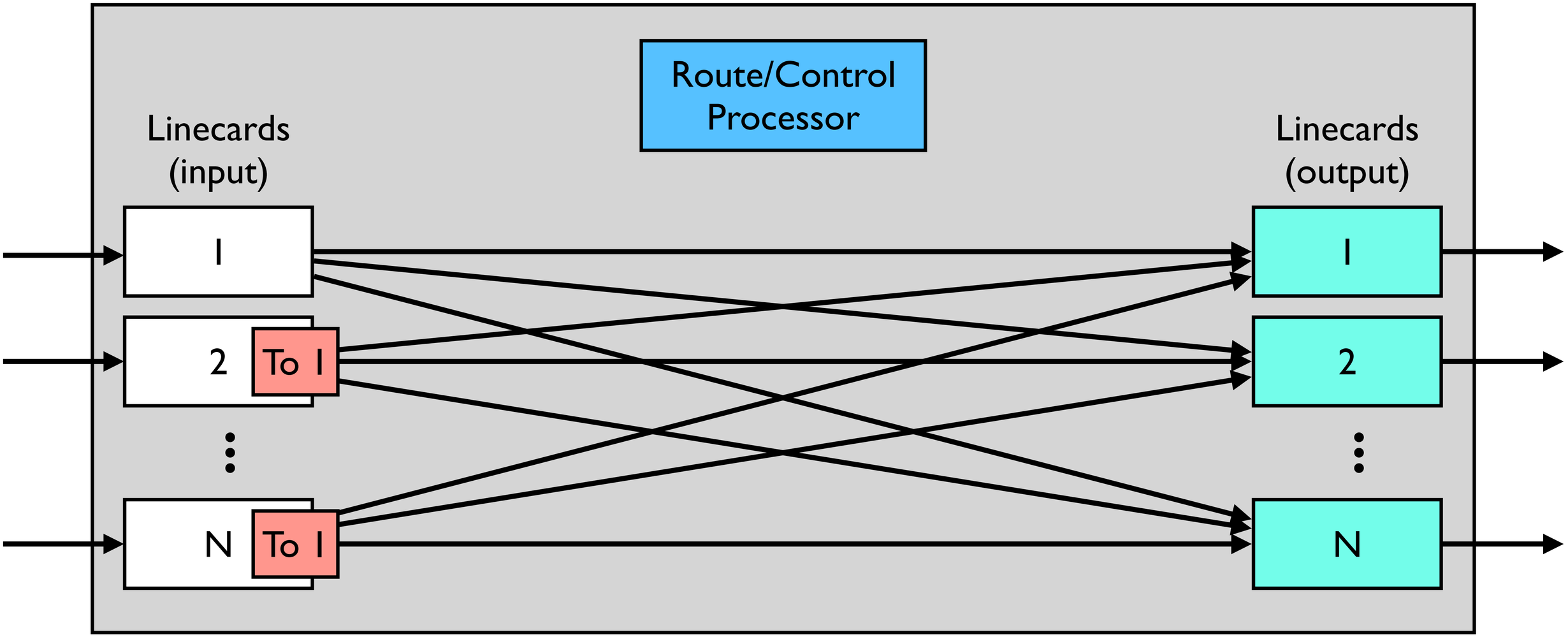


Queueing


Route/Control Processor
Linecards (input)
Linecards (output)
1
2
To 1
N
To 1
1
2
N

Output Queueing



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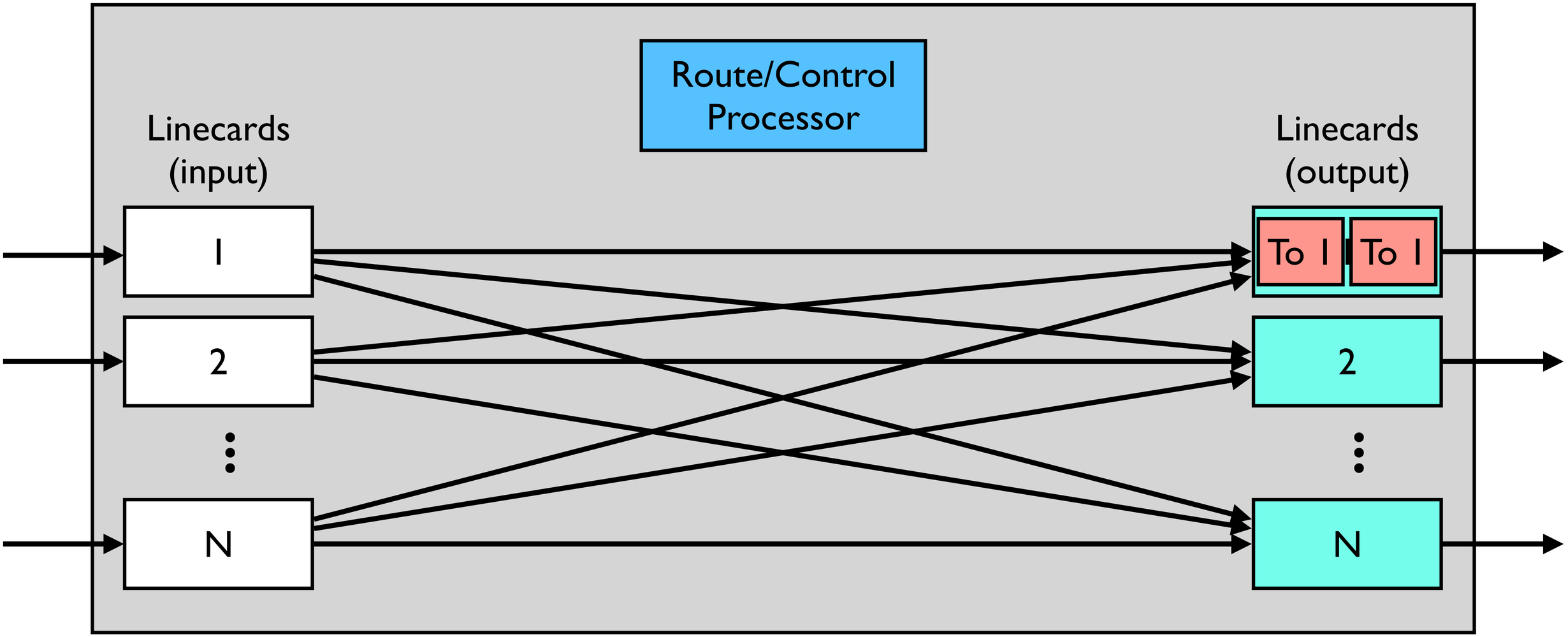
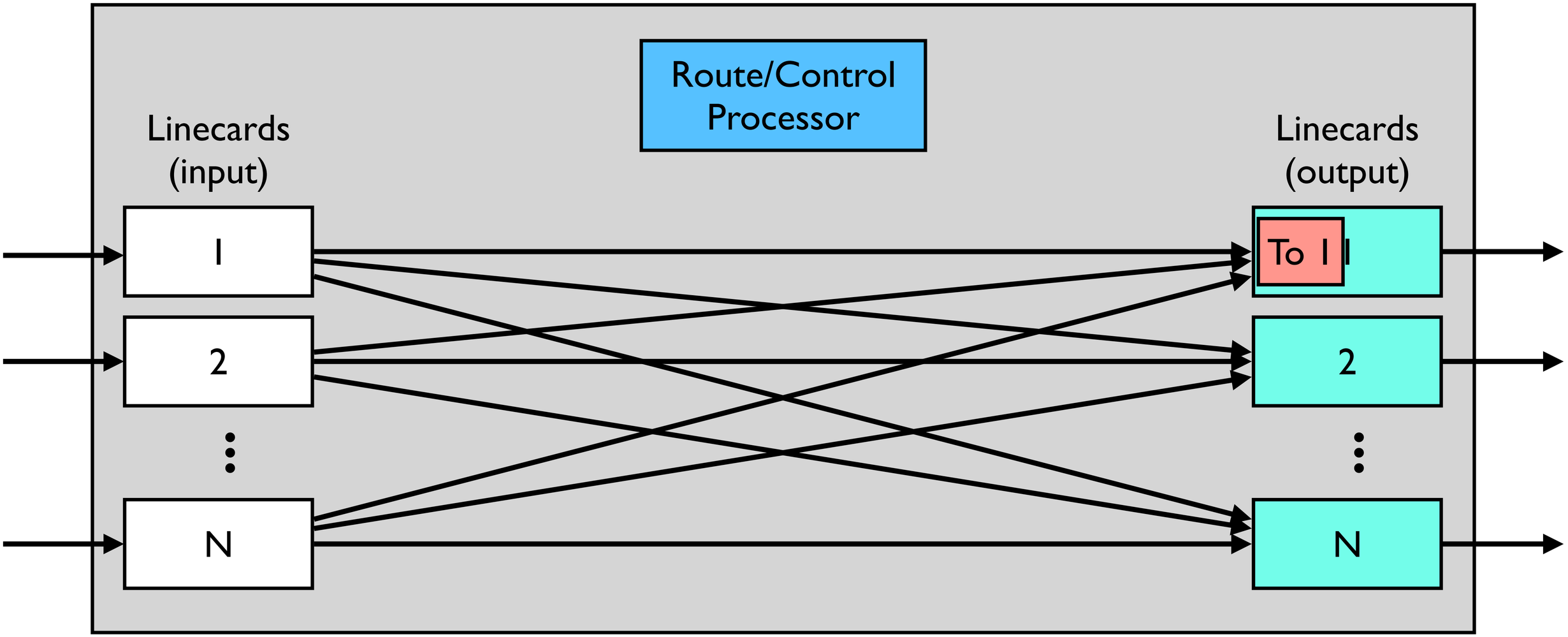


Output Queueing



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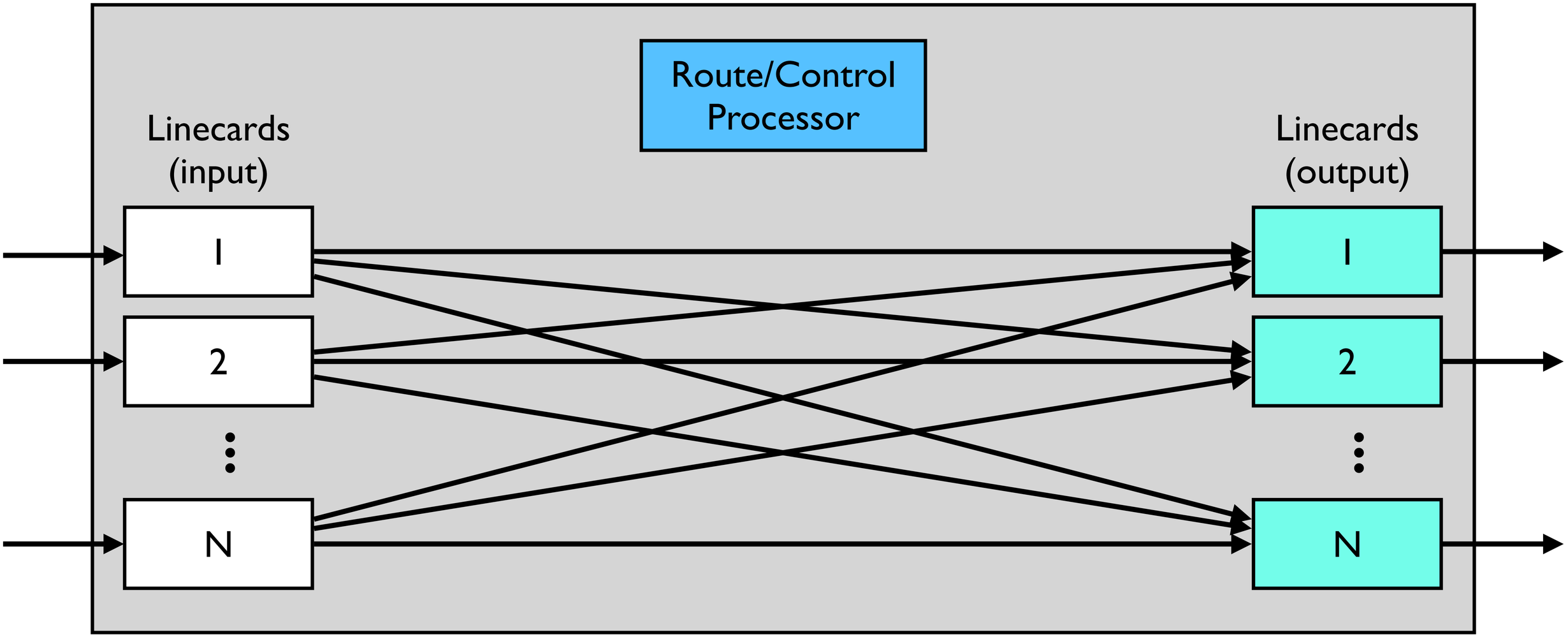

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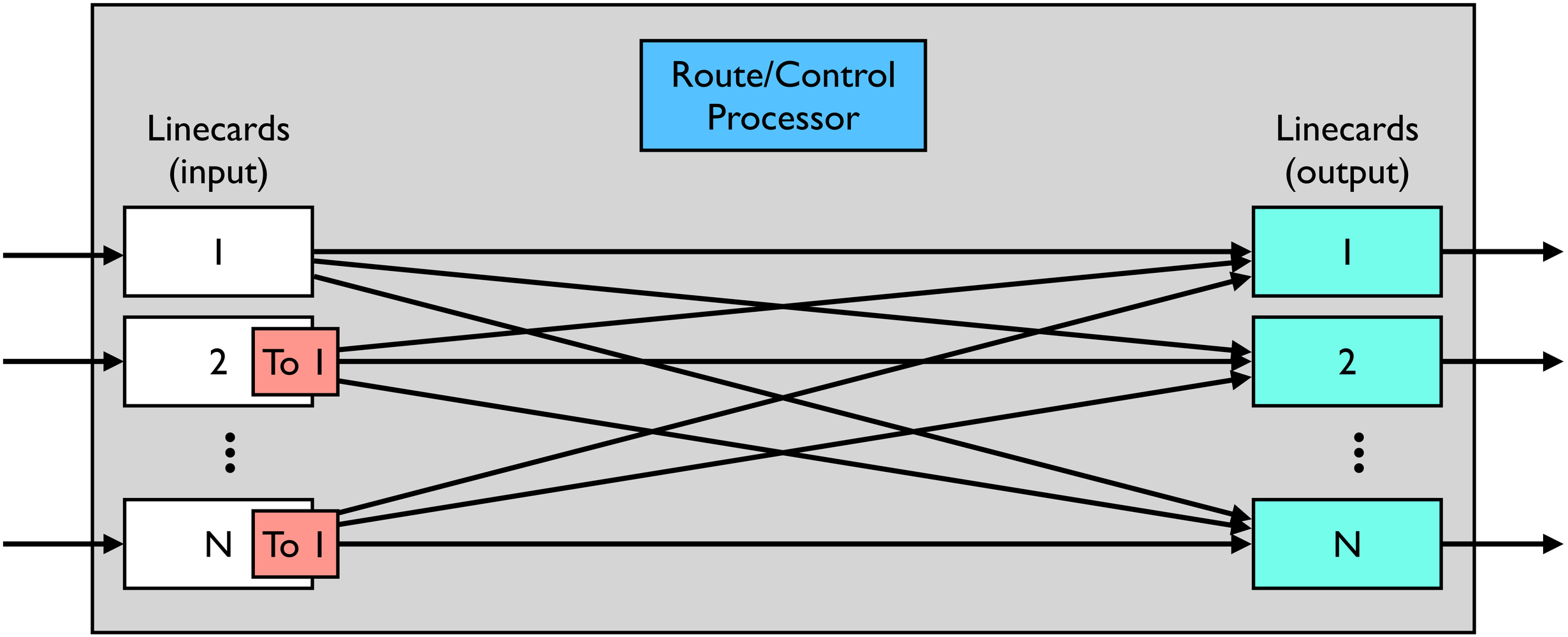

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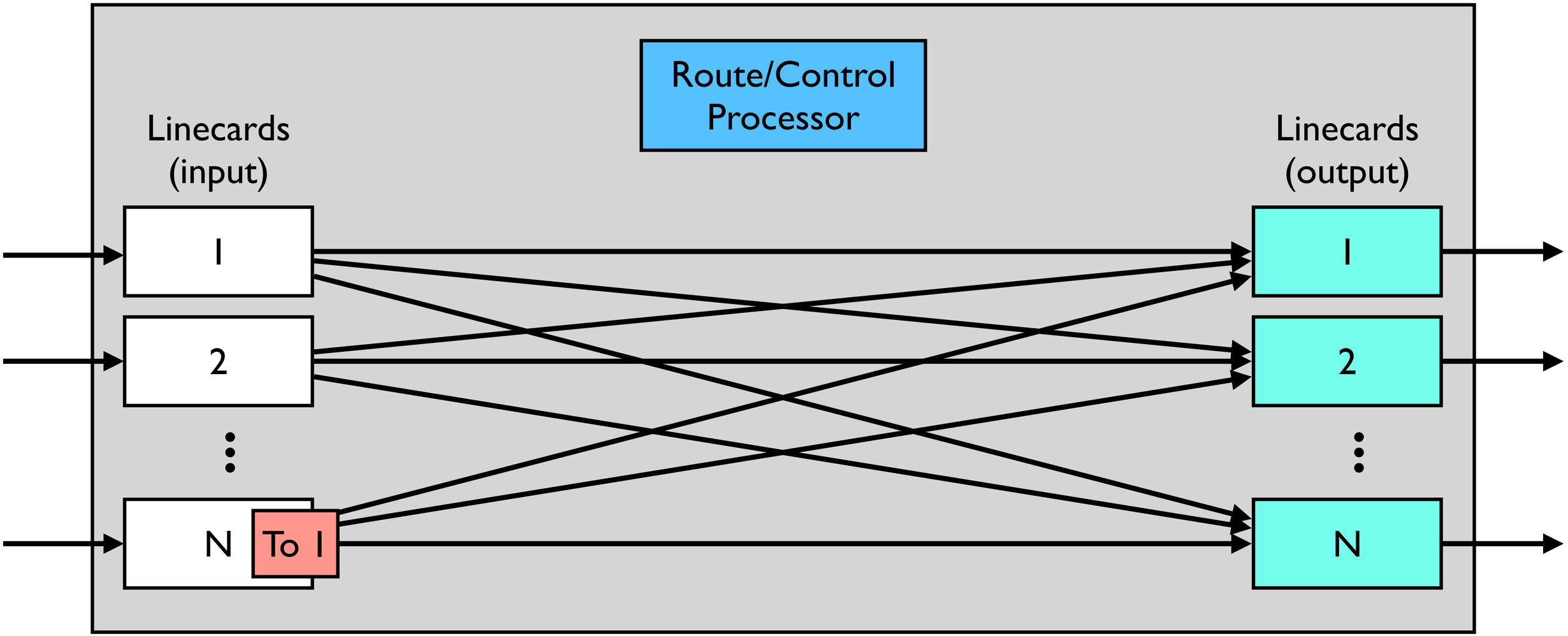

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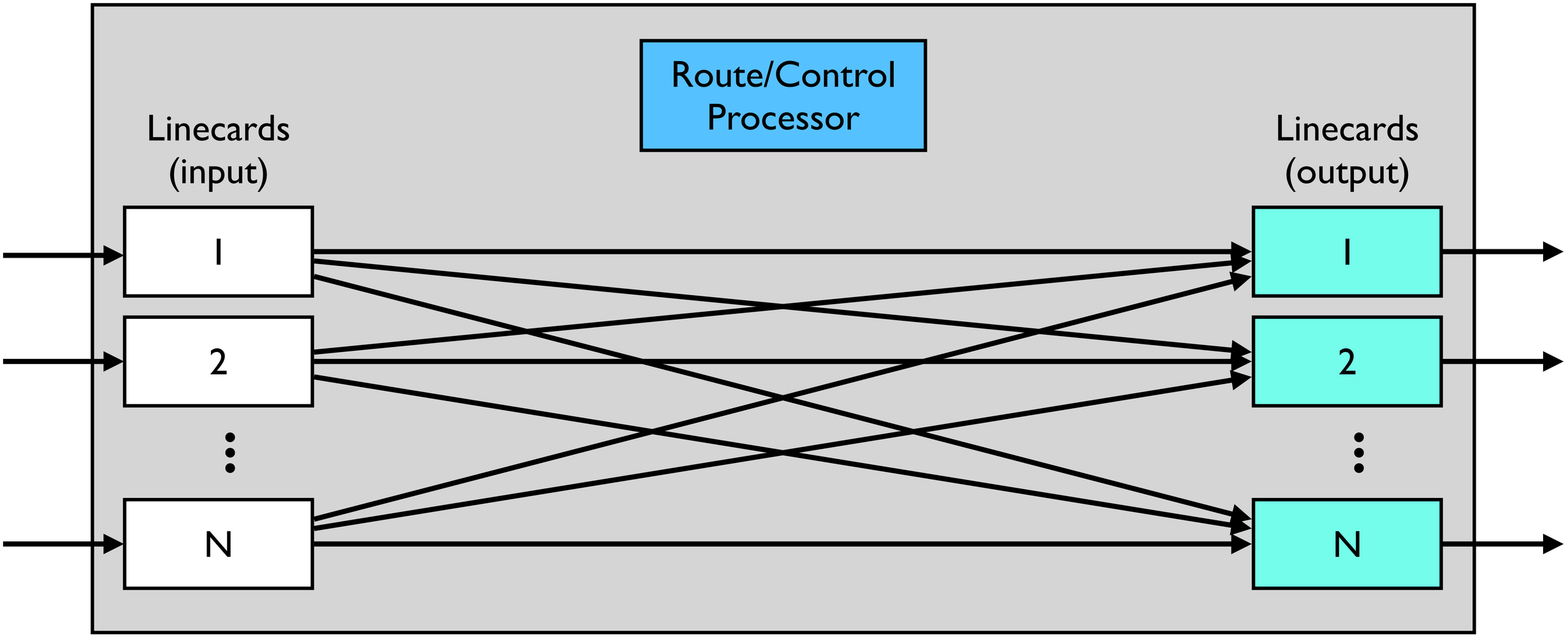
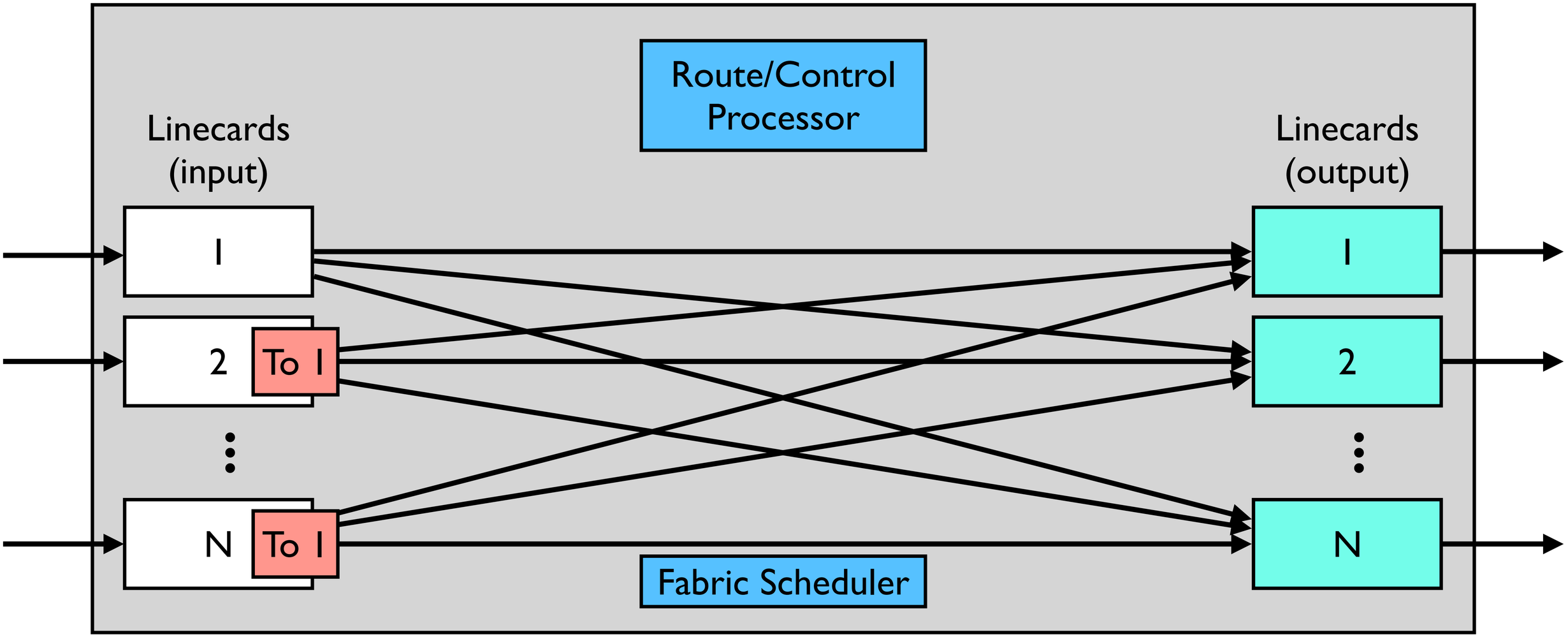


Input Queueing: Challenges



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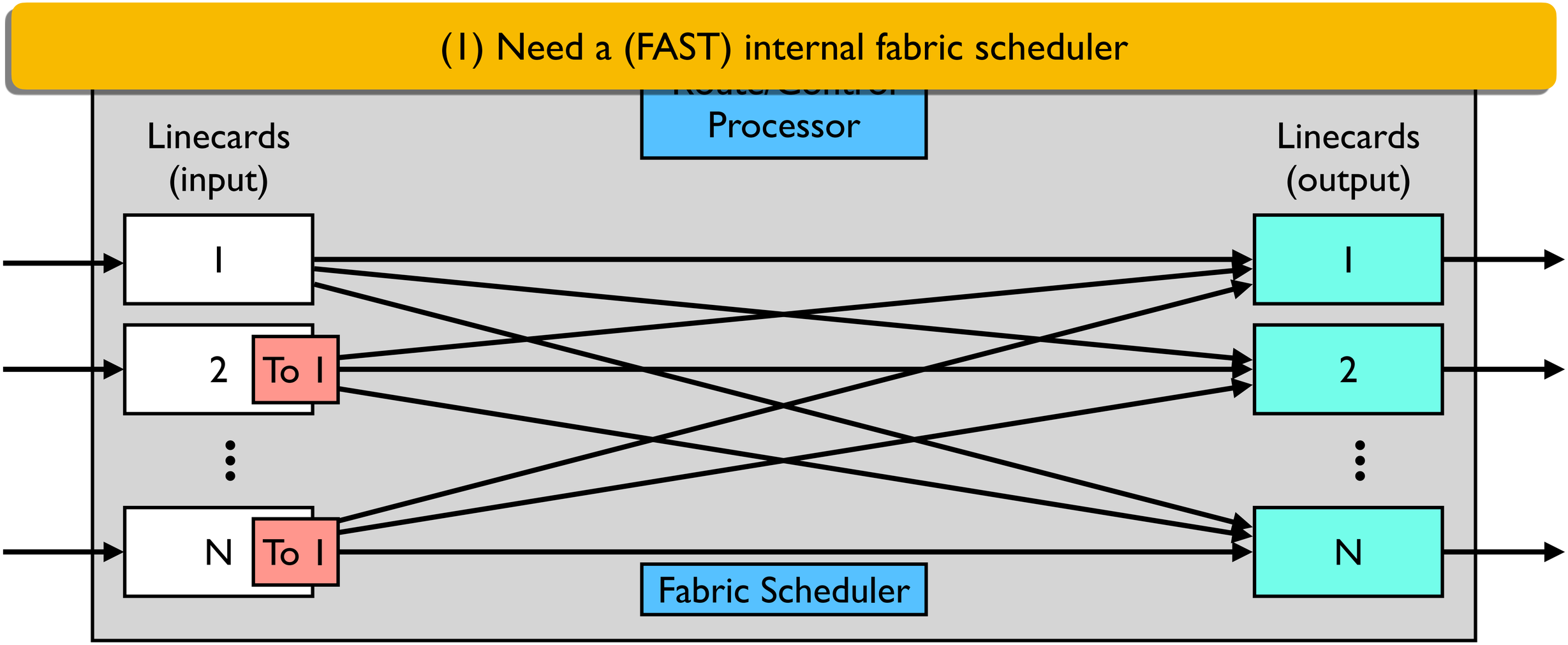

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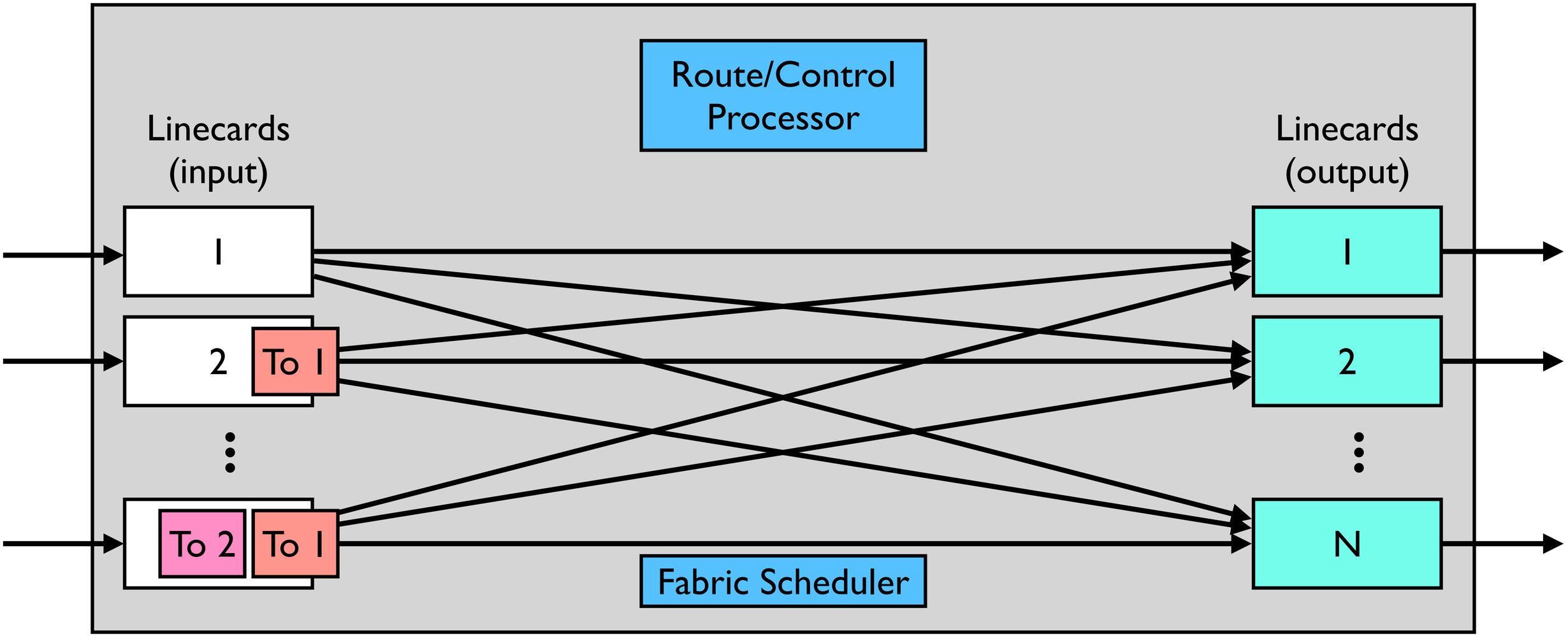

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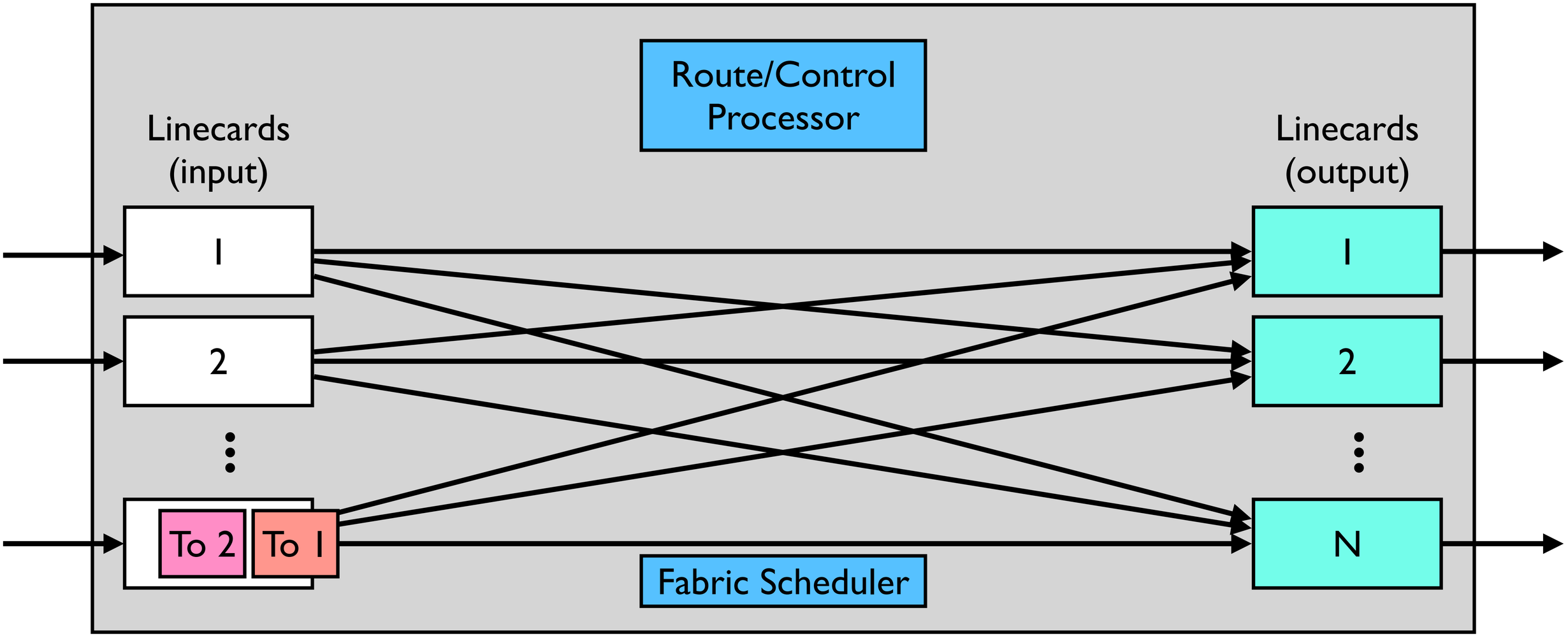

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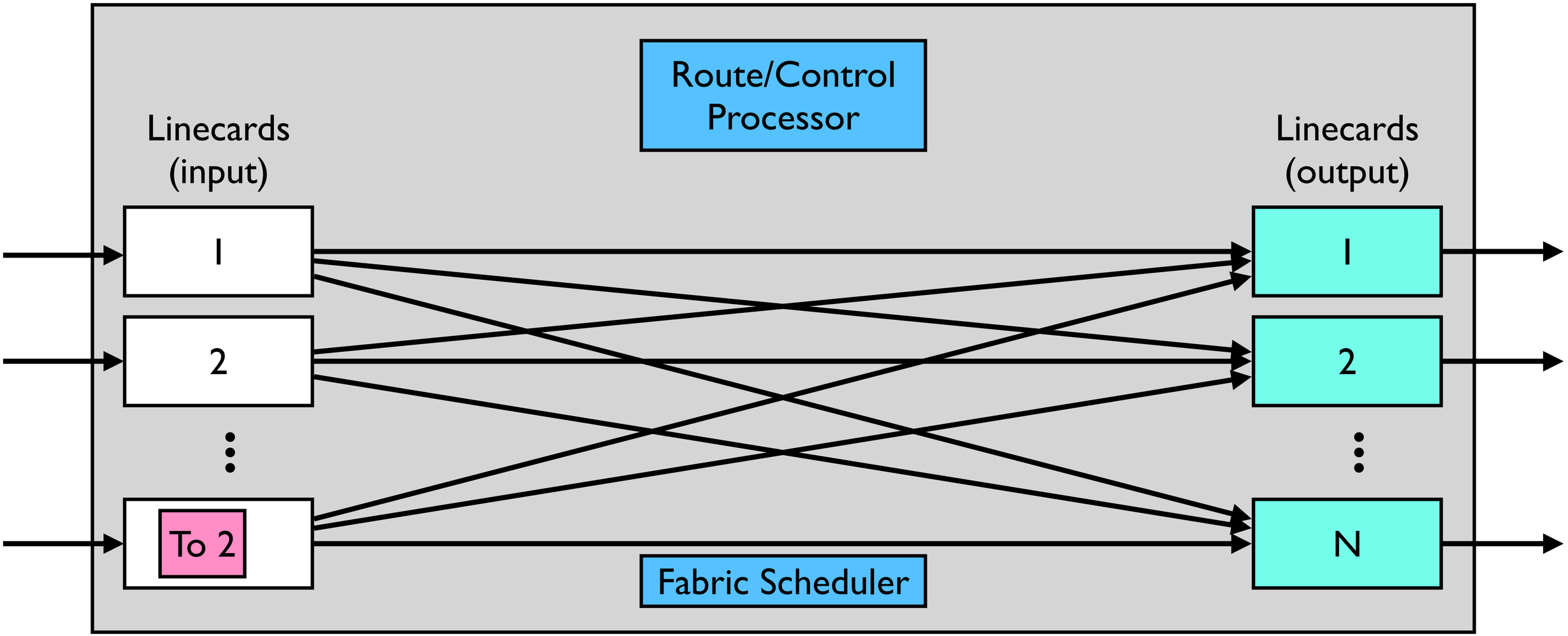
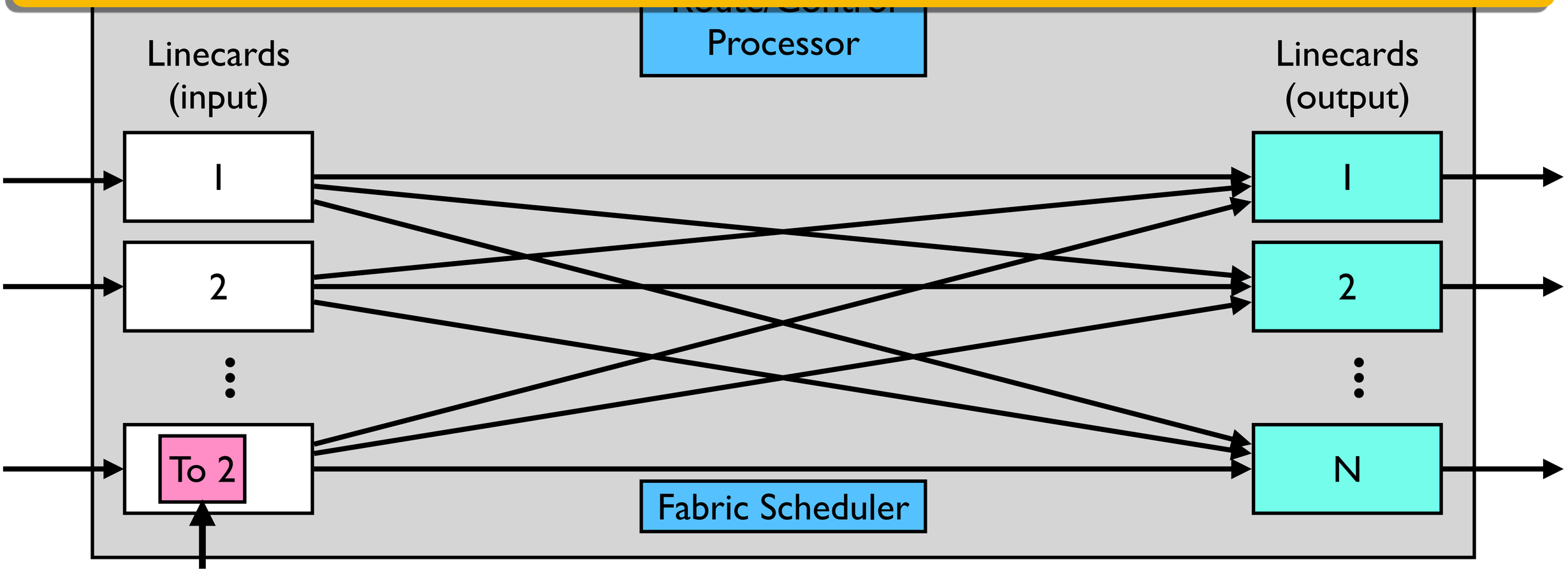
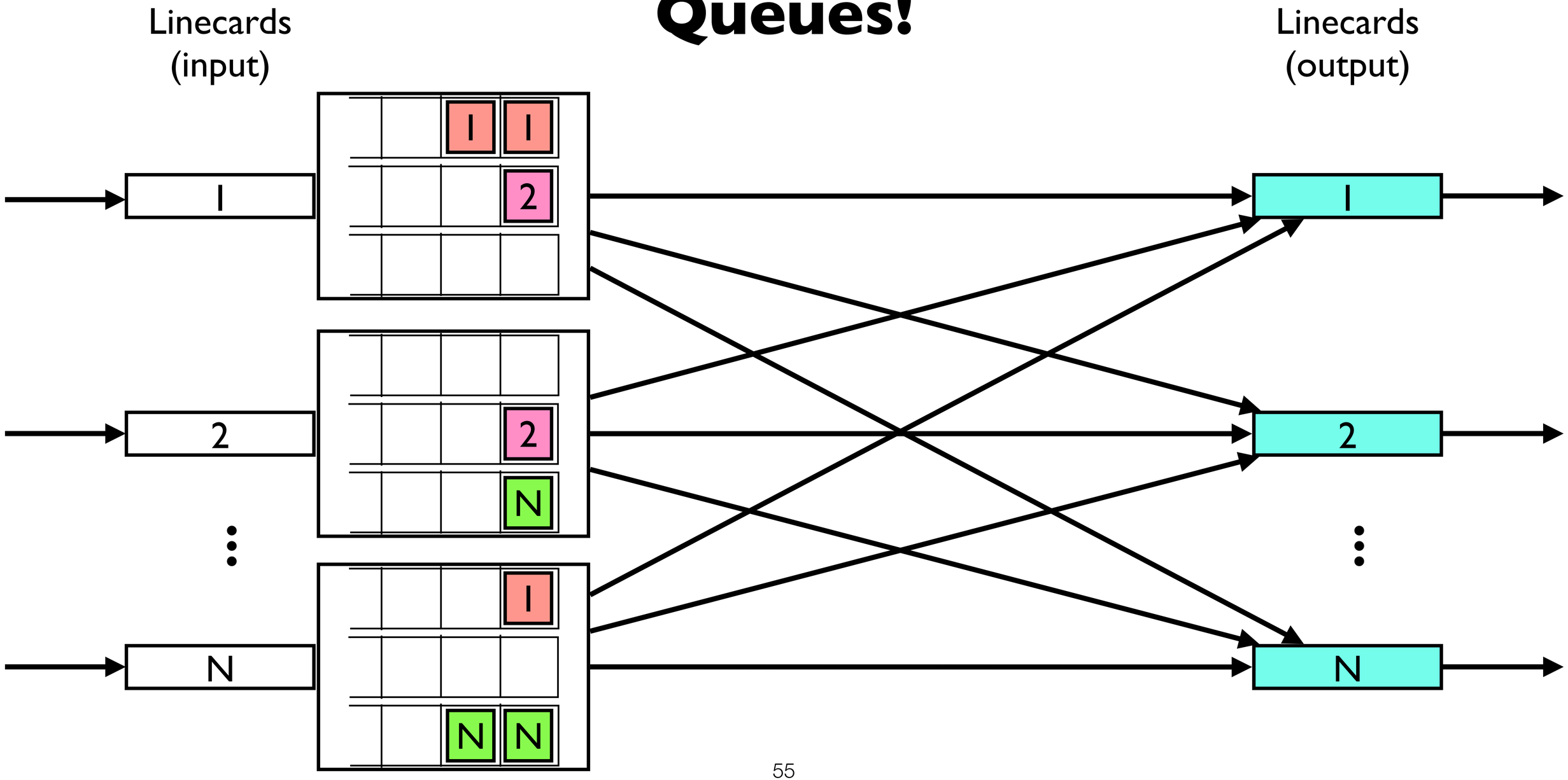


Input Queueing: Challenges

(2) Head of line blocking — **limits throughput to approximately 58% of capacity!**



Fixing head of line blocking: **Virtual Output Queues!**



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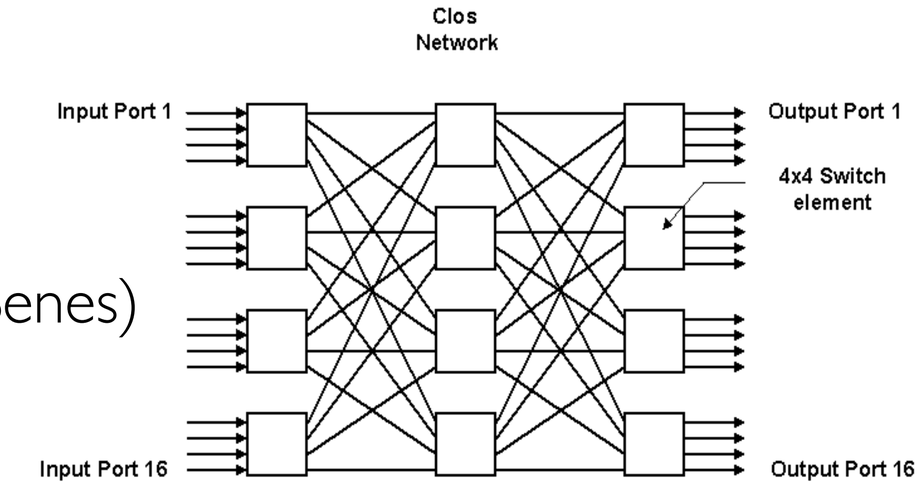

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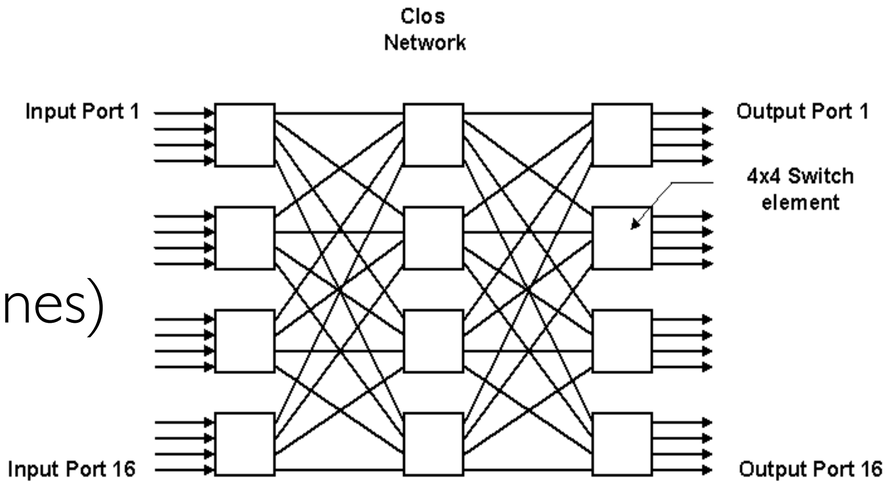

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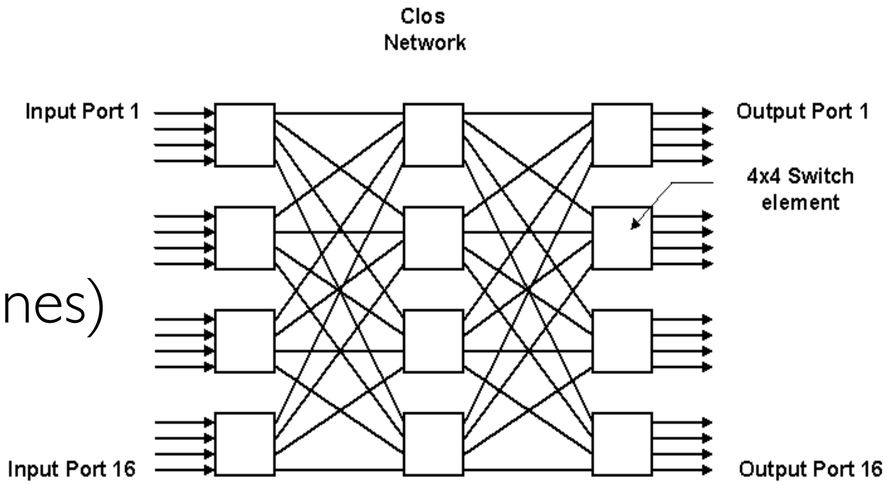

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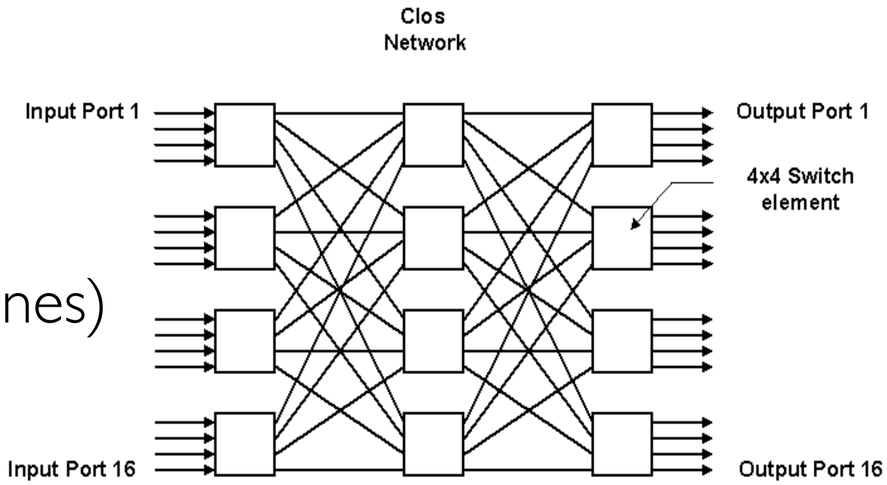

- **We'll consider one simple context**
  - De-facto architecture for a long time and still used in lower-speed routers

Context

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- **Centralized scheduler**

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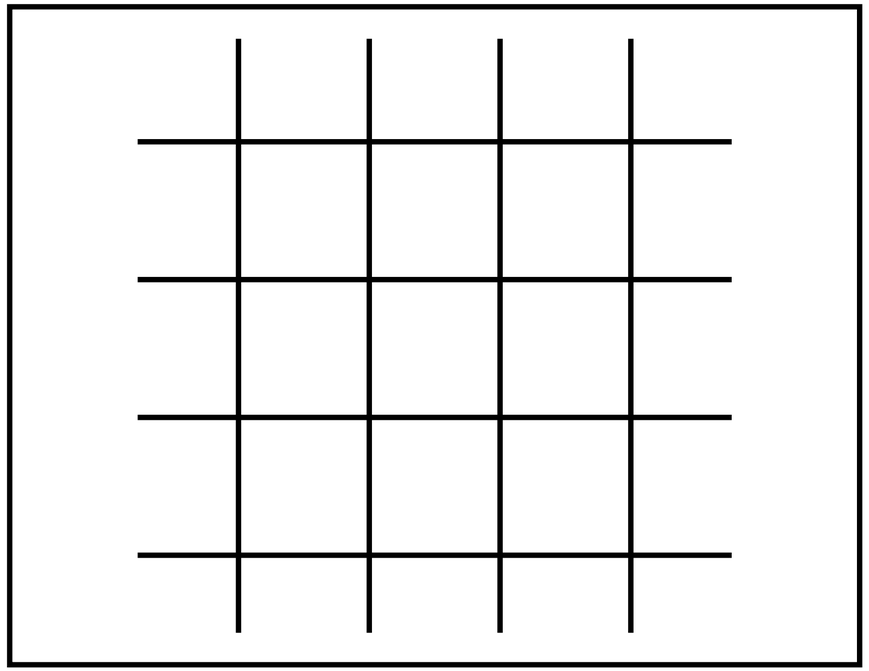

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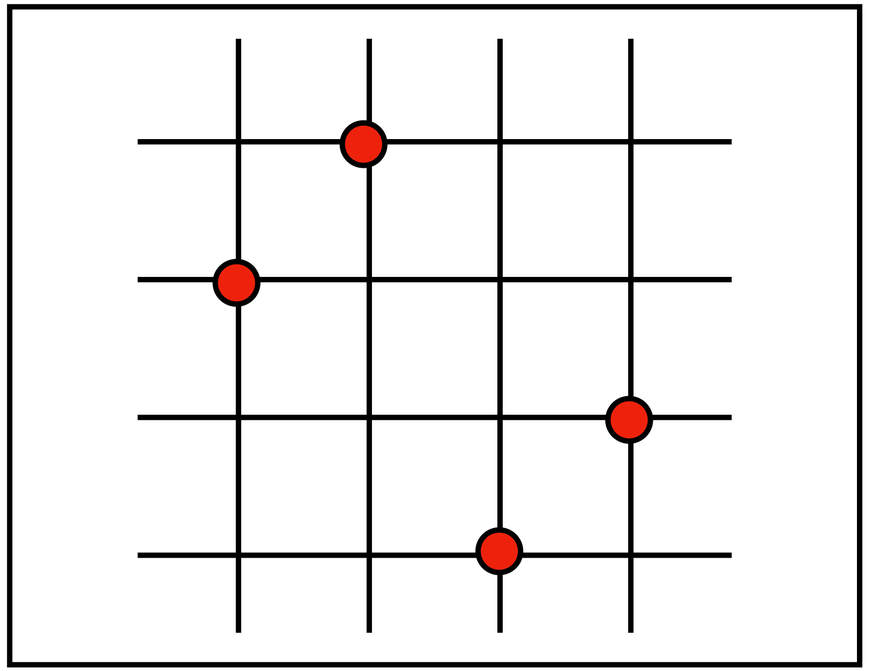
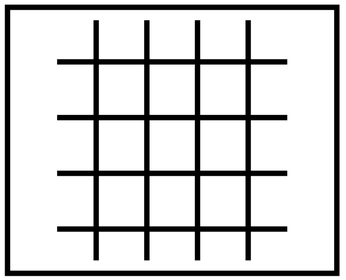
- **Crossbar fabric**
- **Centralized scheduler**



Scheduling



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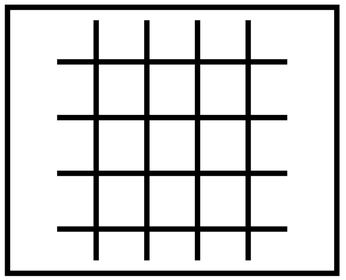

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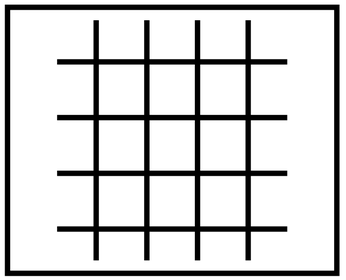
Scheduling



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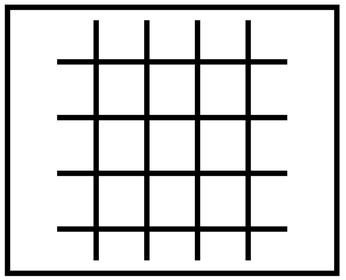

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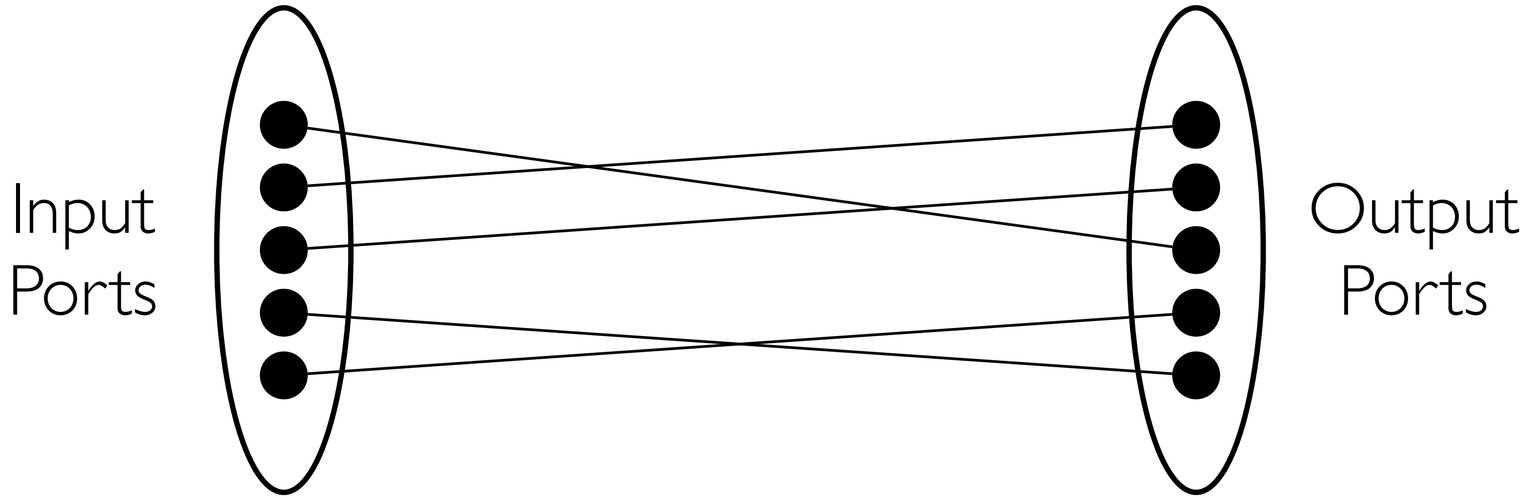
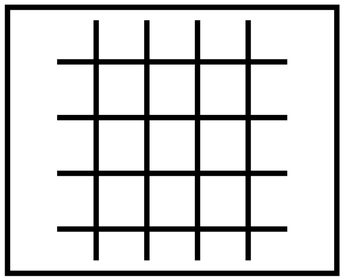


Scheduling



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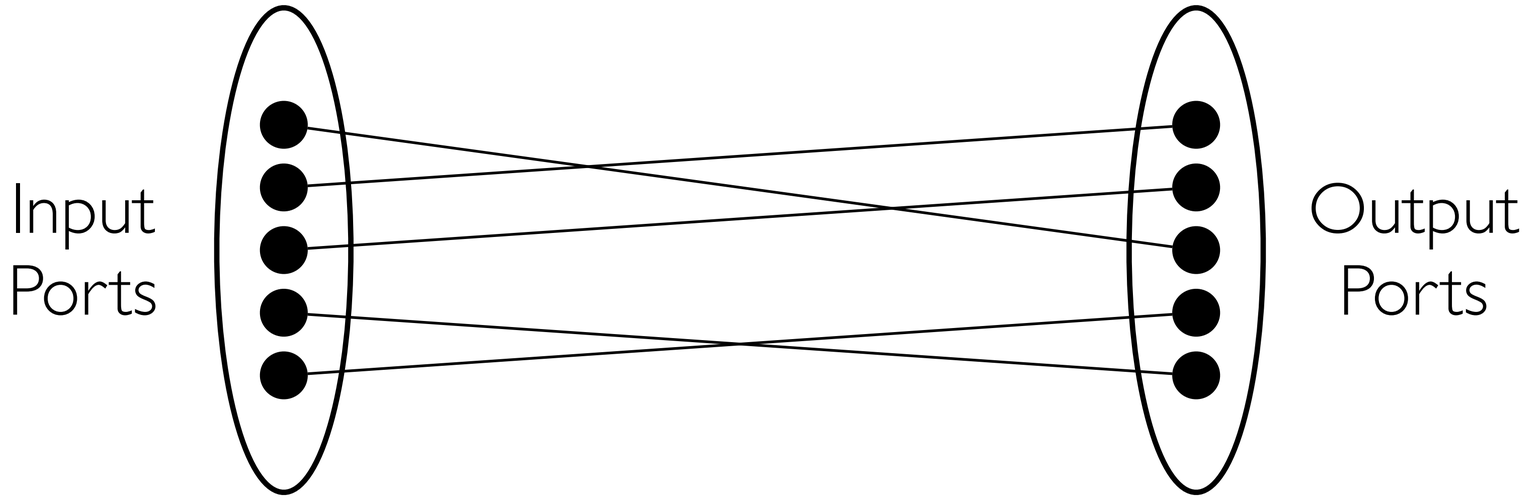

- **Practical solutions look for a good *maximal* matching (fast)**

Summary: IP Routers

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- **$$$**

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Summary: IP Routers

- **$$$**
- **Core building block of Internet**
- **Line cards receive packets, change headers**
- **Scalable addressing → Longest Prefix Matching**
- **Need fast implementations for:**
  - Longest prefix matching
  - Switch fabric scheduling

Taking Stock: Network Layer

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- ***Best-effort global delivery of packets***

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- **Control Plane:** Routing

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- ***Best-effort global delivery of packets***
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- **Key enabler of scalability:** Addressing

Addressing: Hierarchical for Scalability

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- **Hierarchical address structure**

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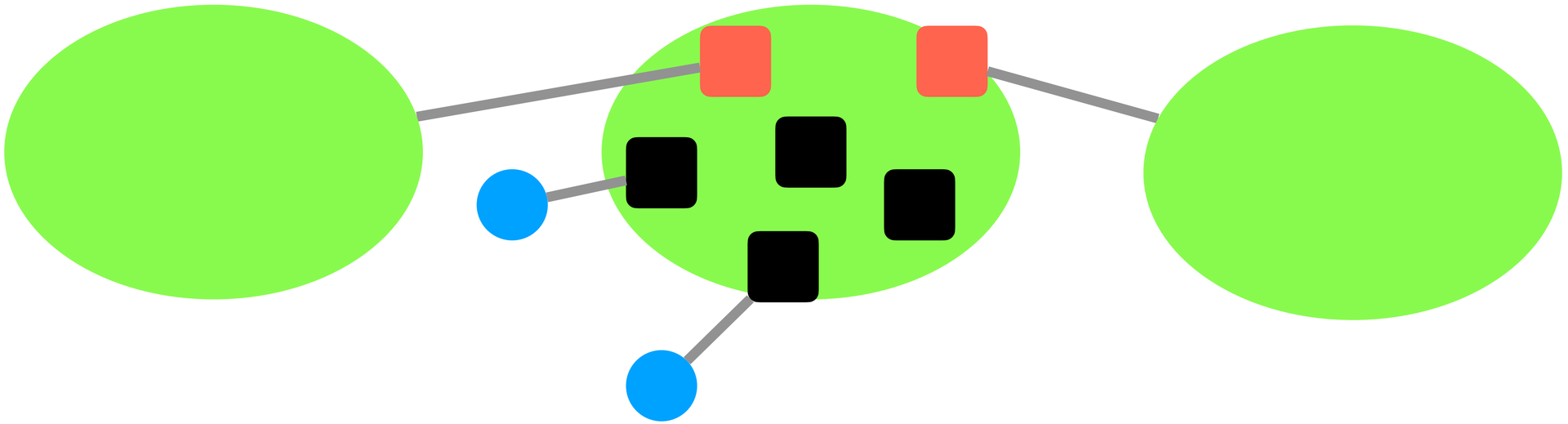
- **Hierarchical addresses and routing scalability**

Control Plane: **Routing**



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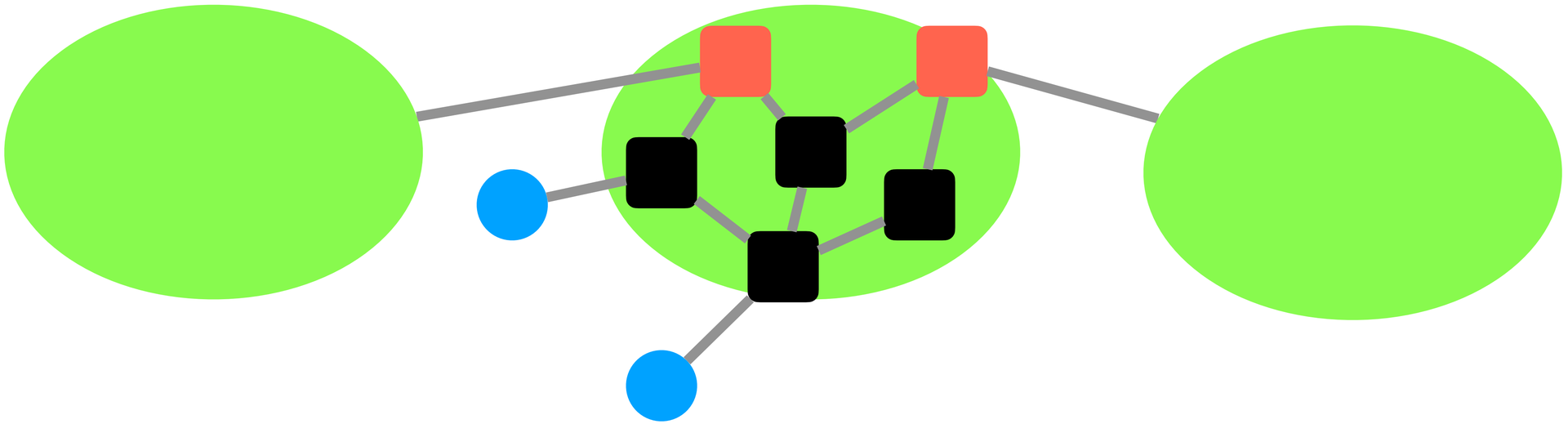
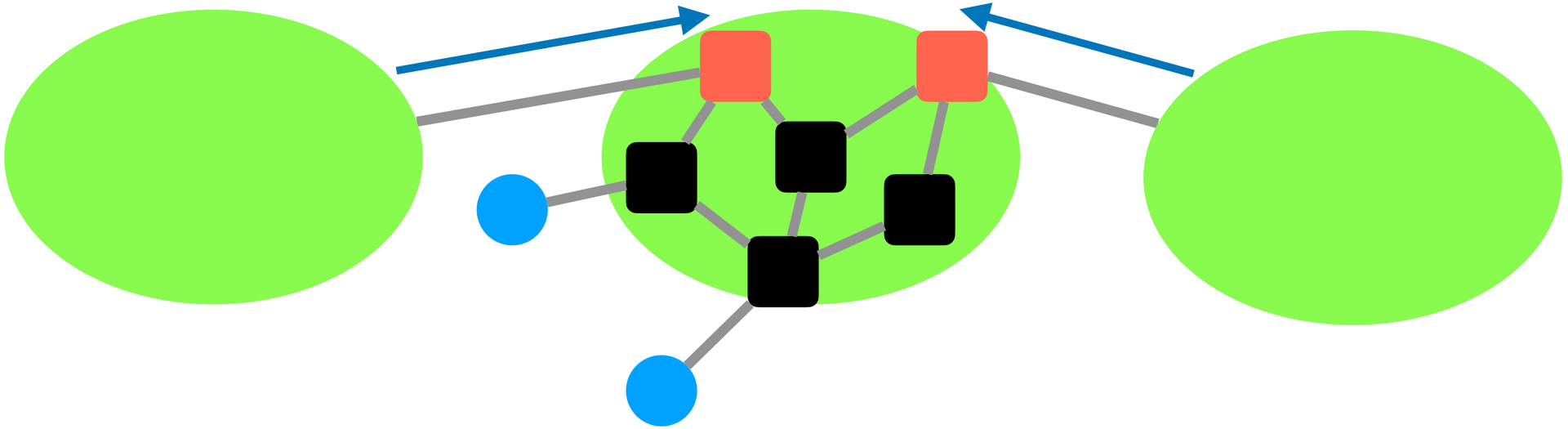


1. Provide internal reachability (**IGP**)

Control Plane: **Routing**



1. Provide internal reachability (**IGP**)
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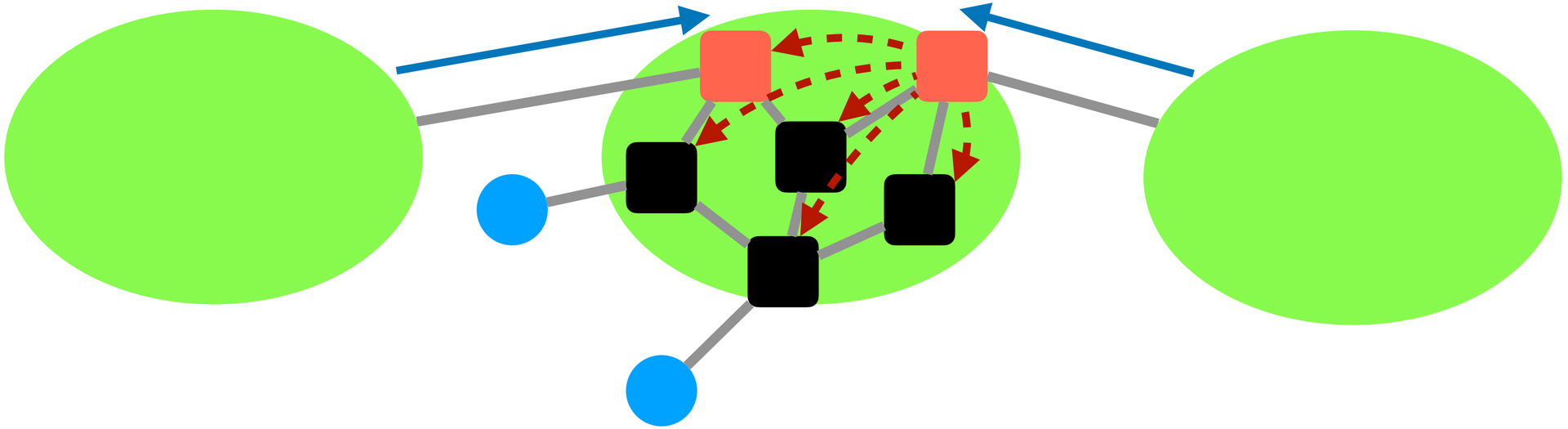

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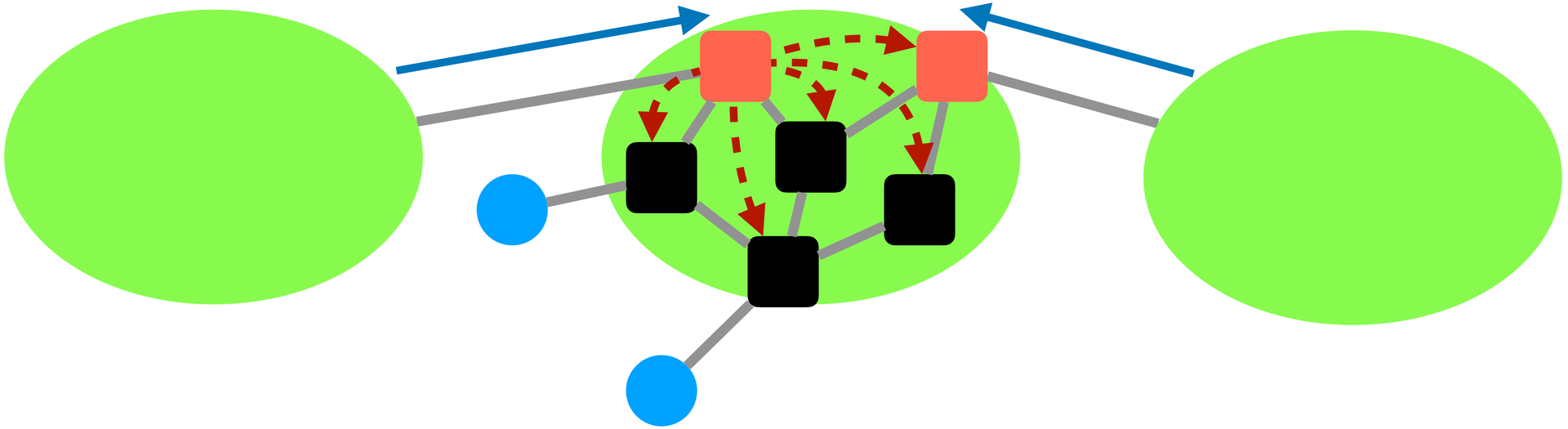

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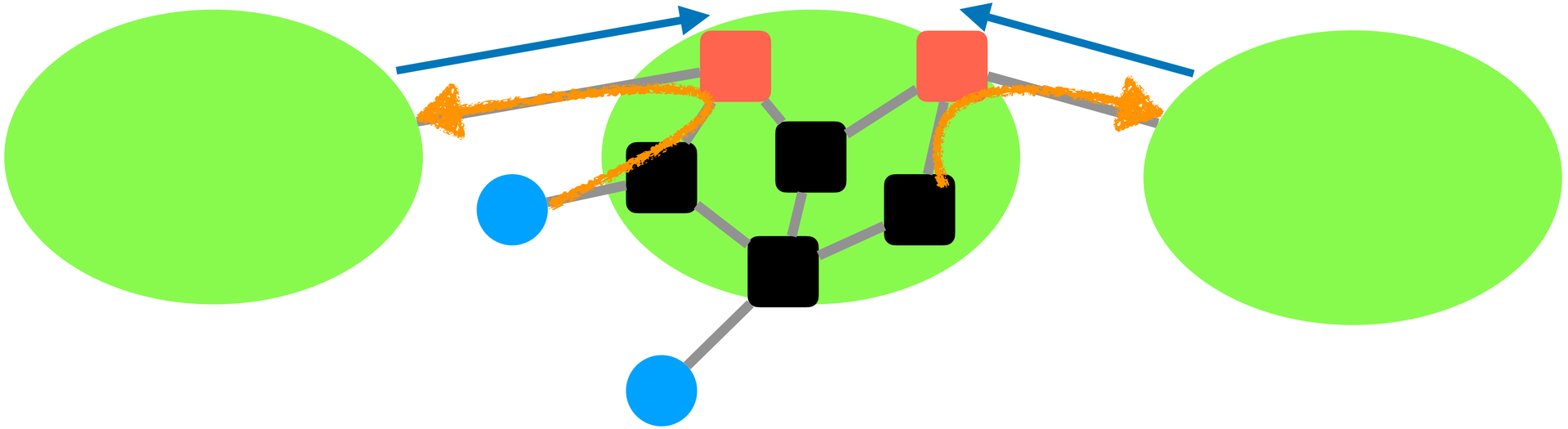

1. Provide internal reachability (**IGP**)
2. Learn routes to external destinations (**eBGP**)
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4. Travel shortest path to egress (**IGP**)

Data Plane: **Forwarding**

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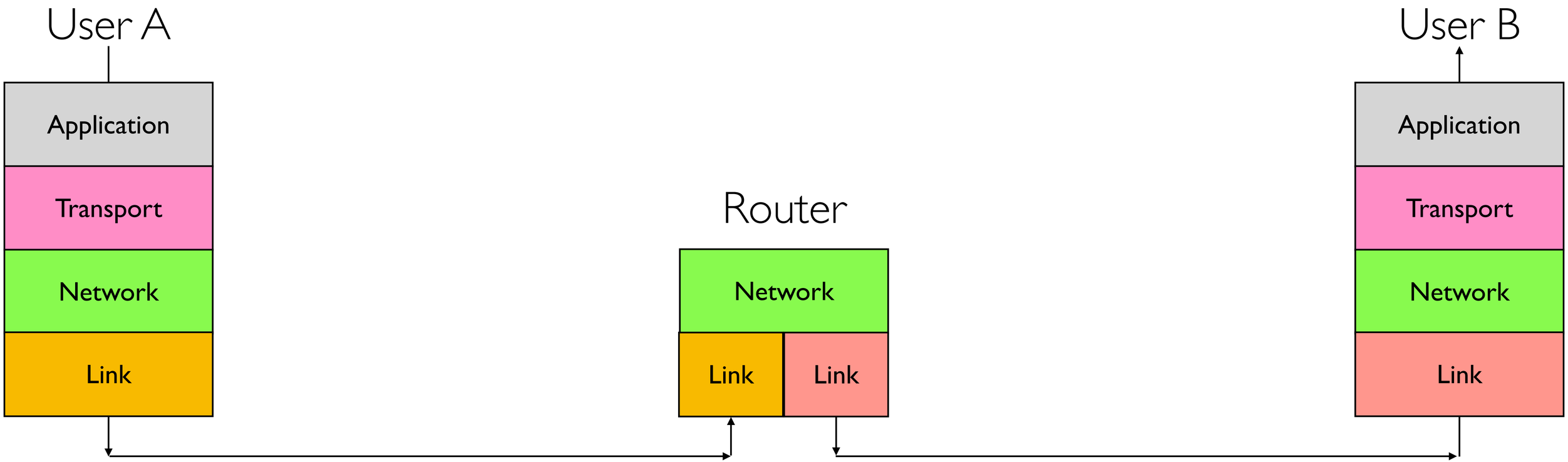

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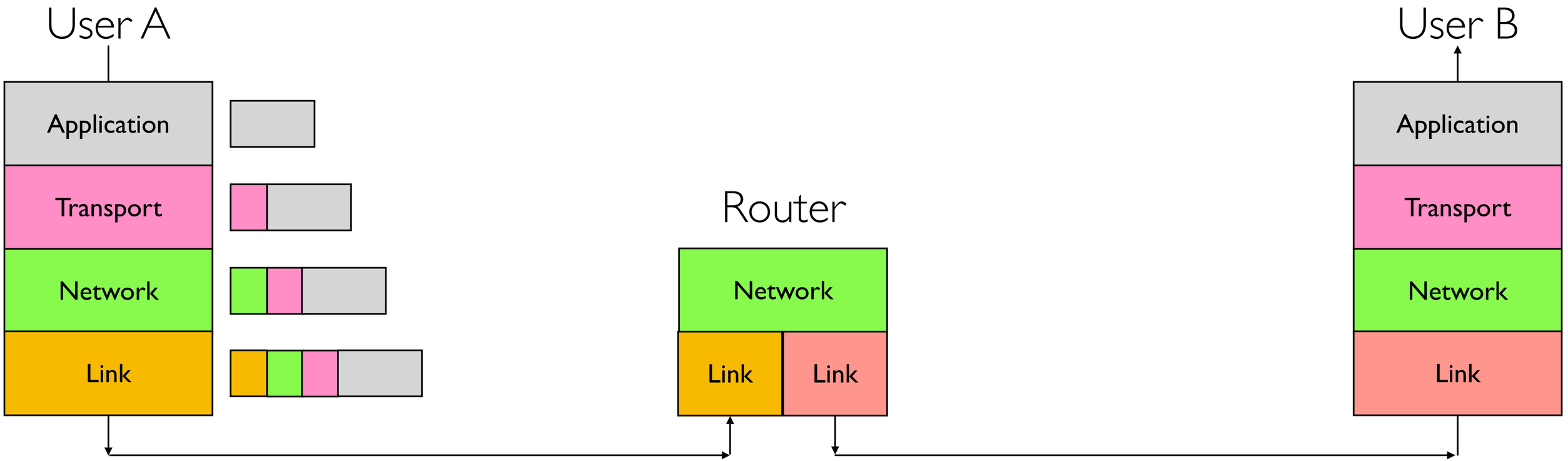

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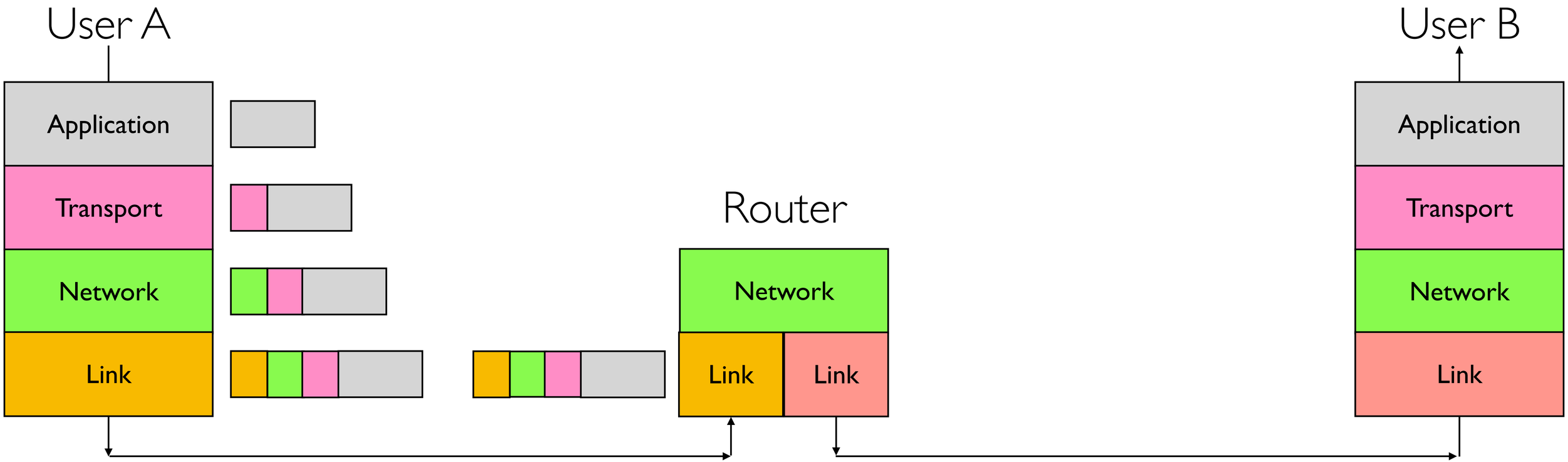

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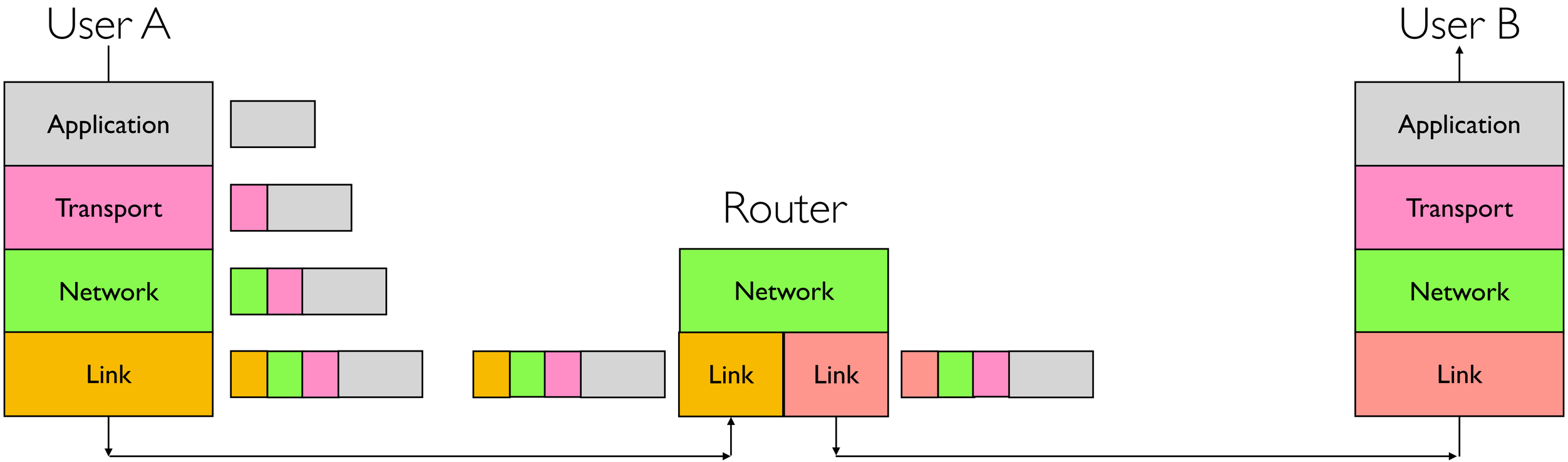

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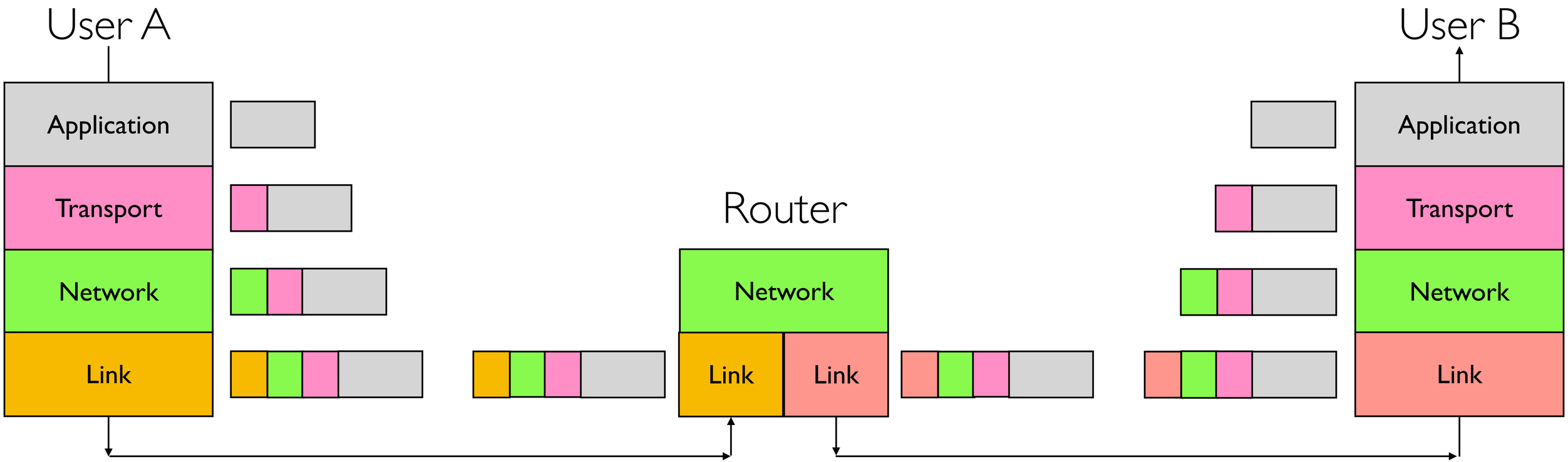

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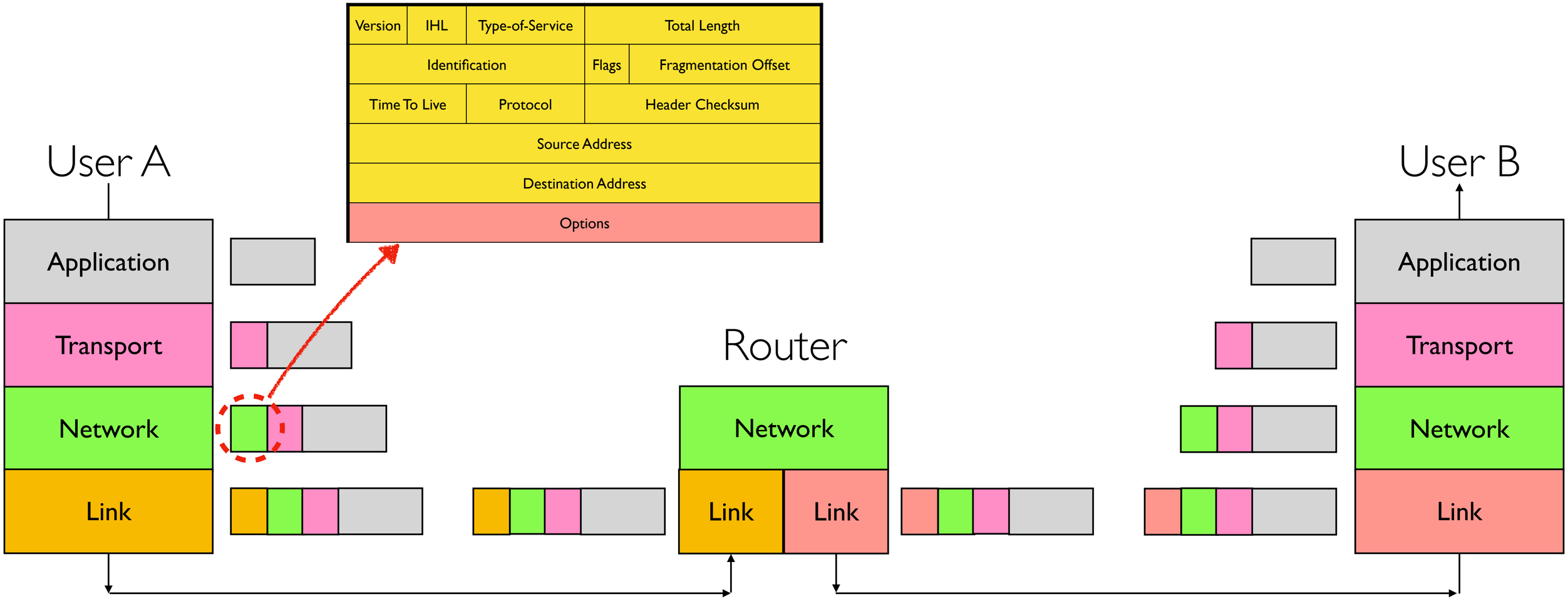

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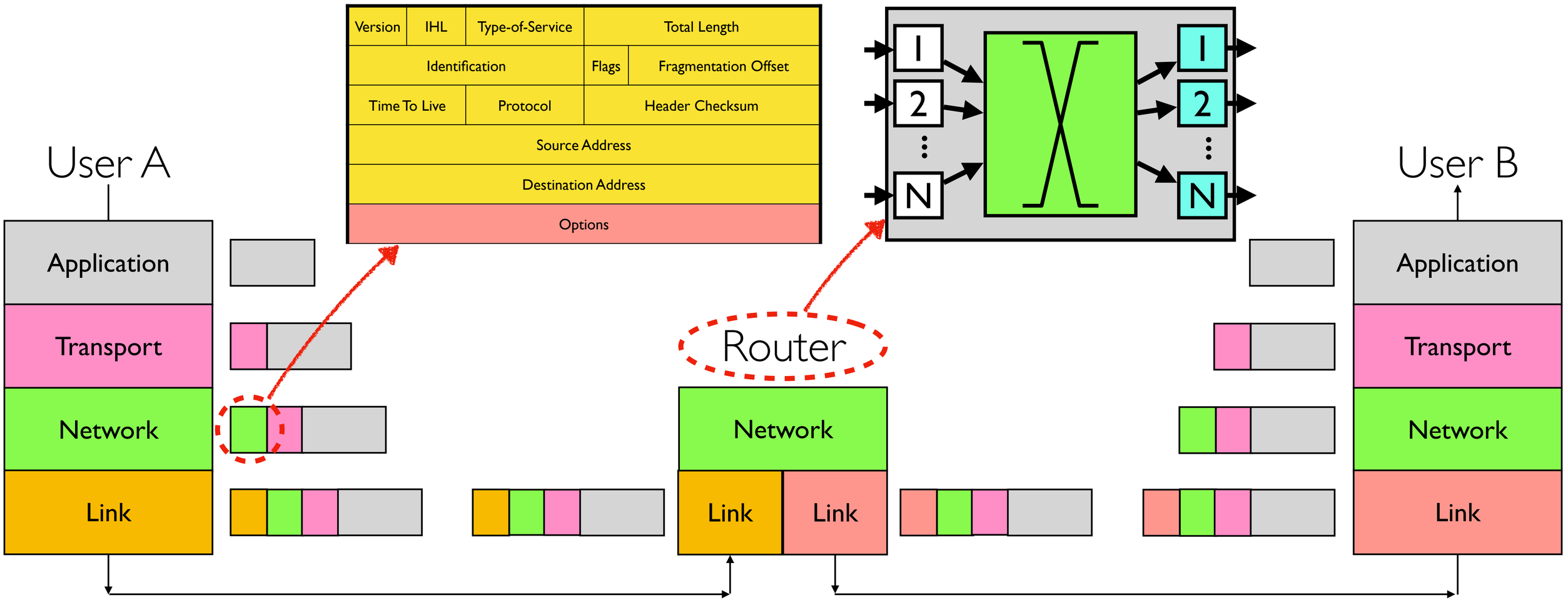
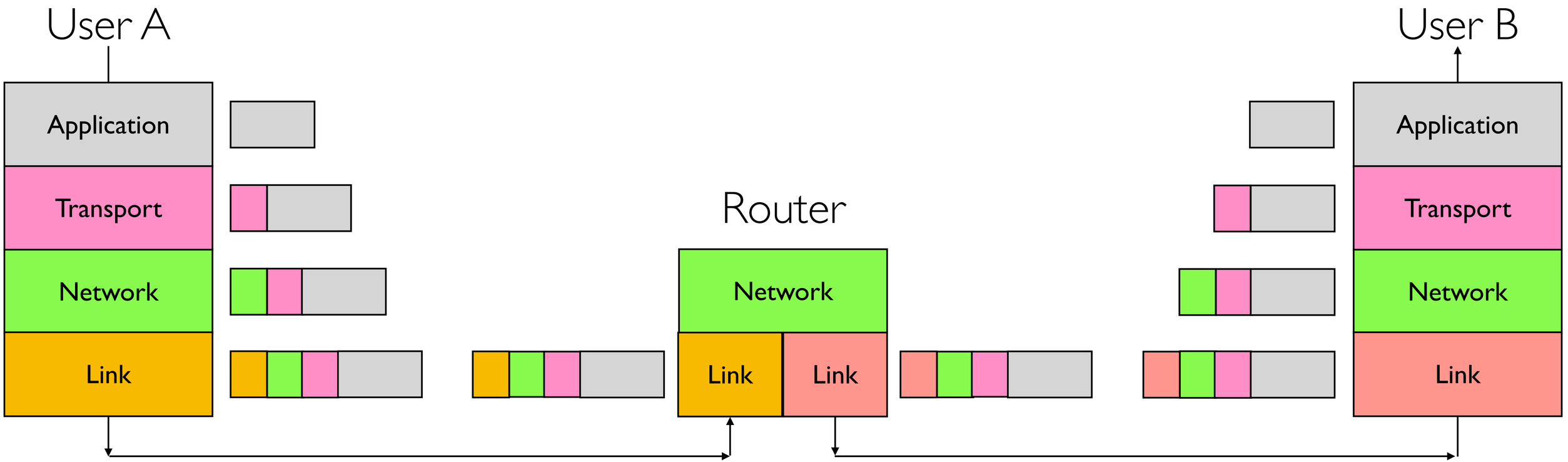
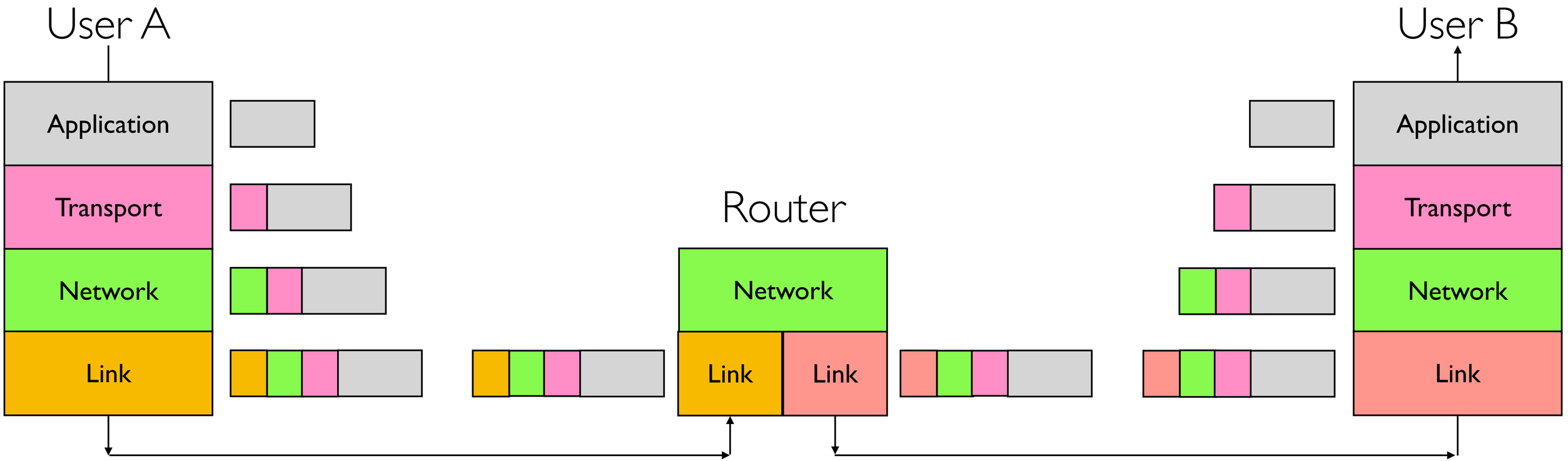


Looking Ahead



Looking Ahead

- **So far: Network Layer,** *Best-effort global delivery of packets*



Looking Ahead

- **So far: Network Layer,** *Best-effort global delivery of packets*
- **Next: Transport Layer,** *Reliable (or unreliable) delivery of data*