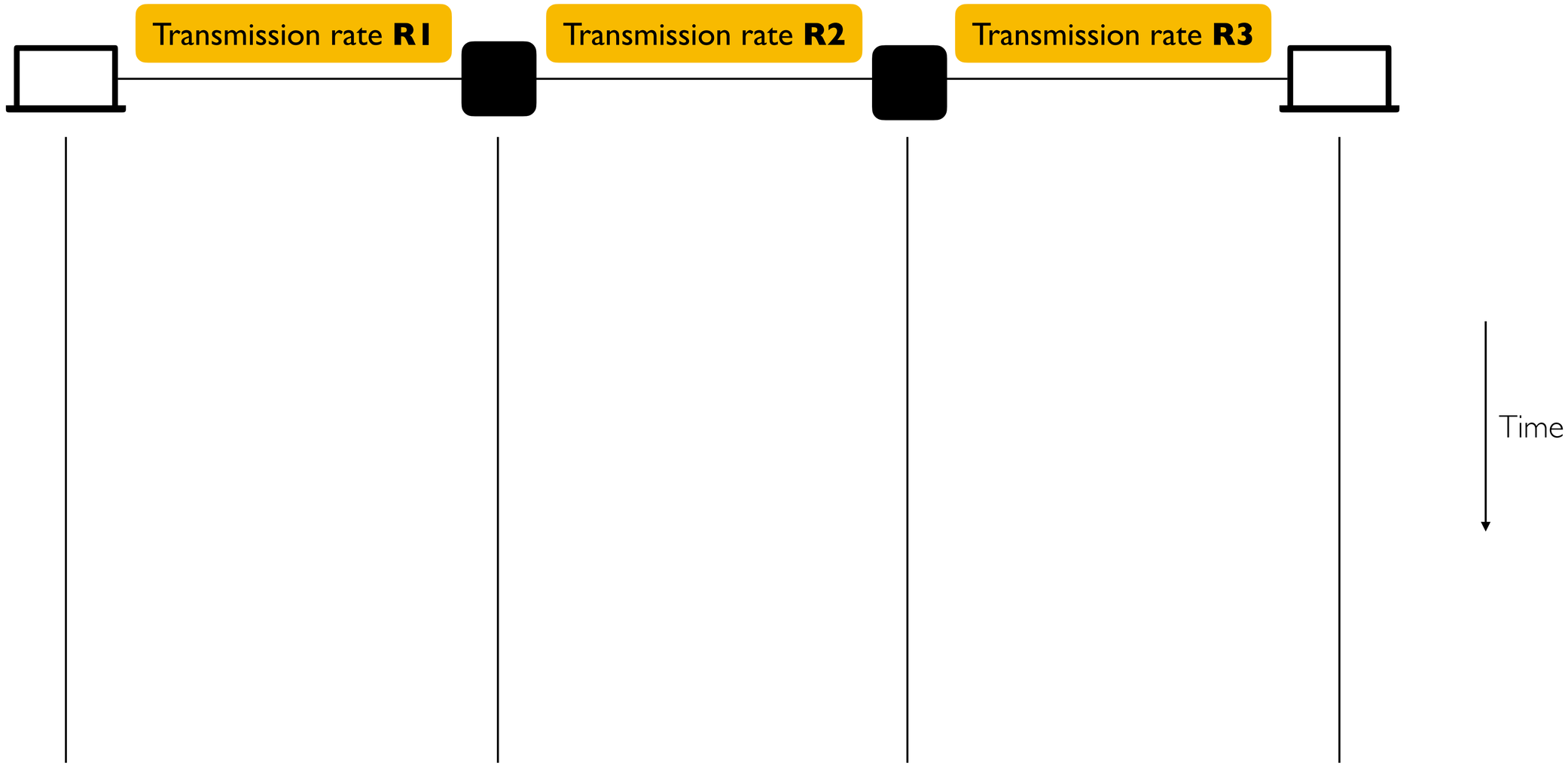
How is communication organized? (Contd.)

CPSC 433/533, Spring 2021

Anurag Khandelwal

But before that… Throughput Calculation



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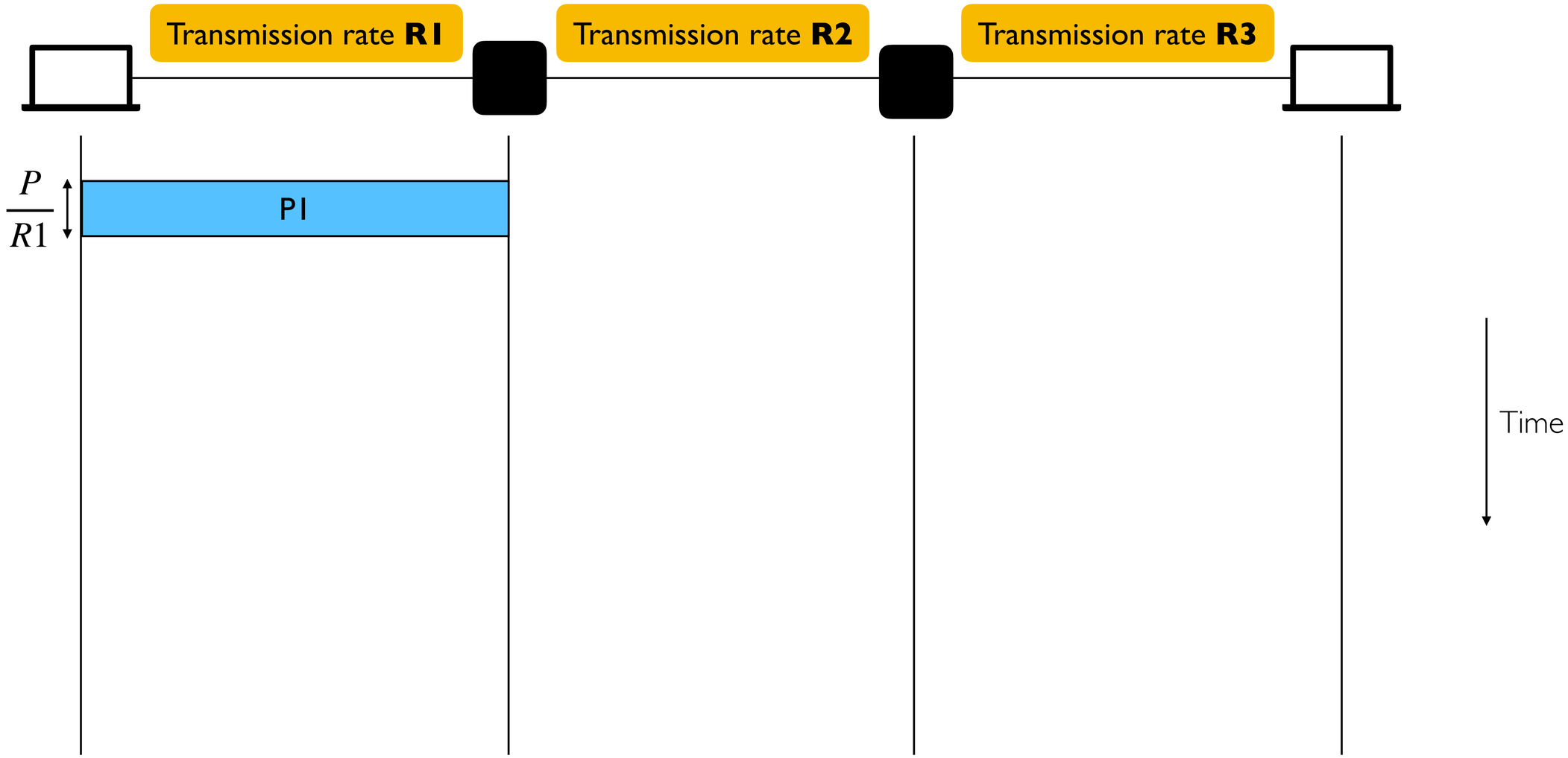

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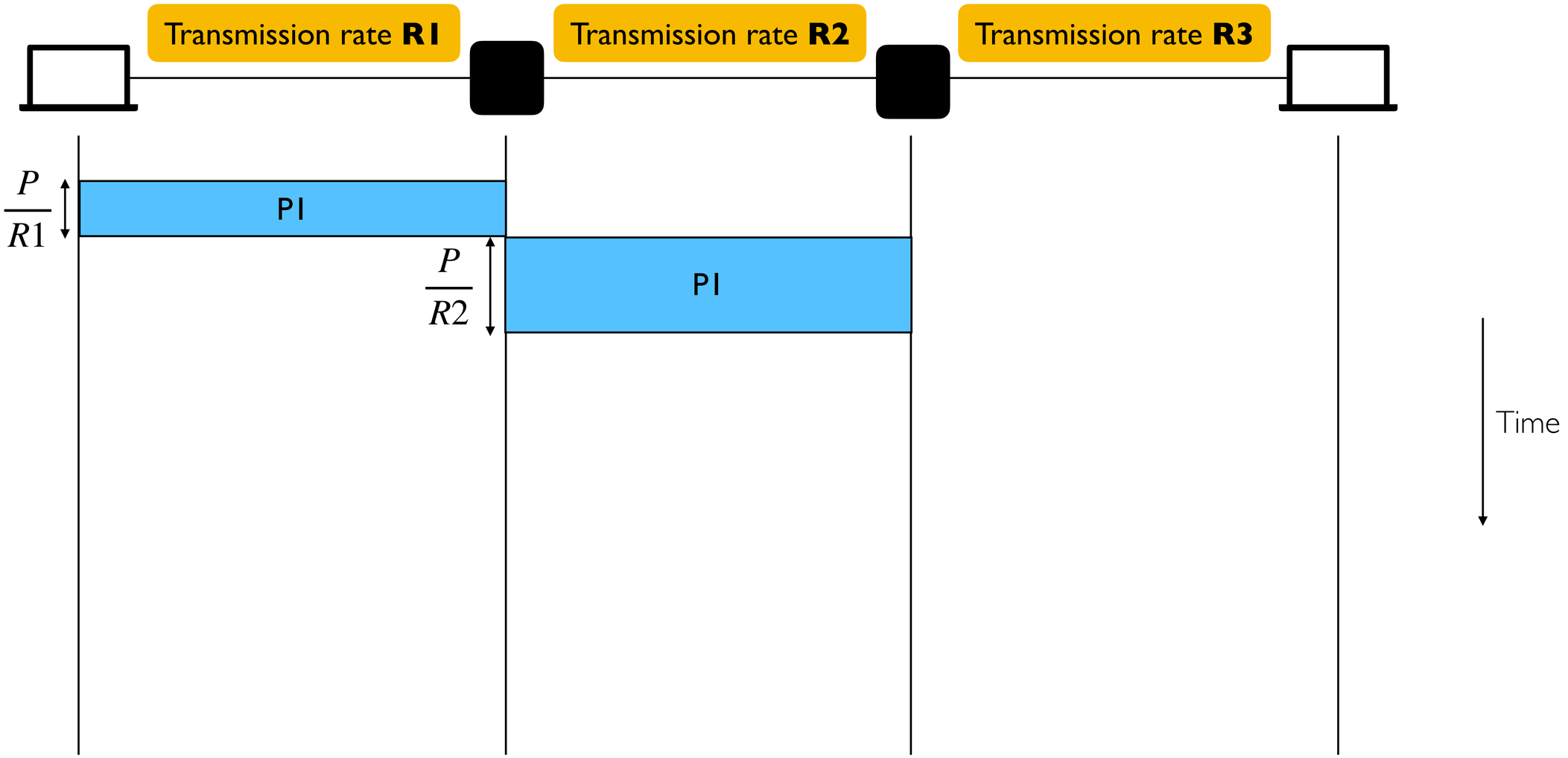

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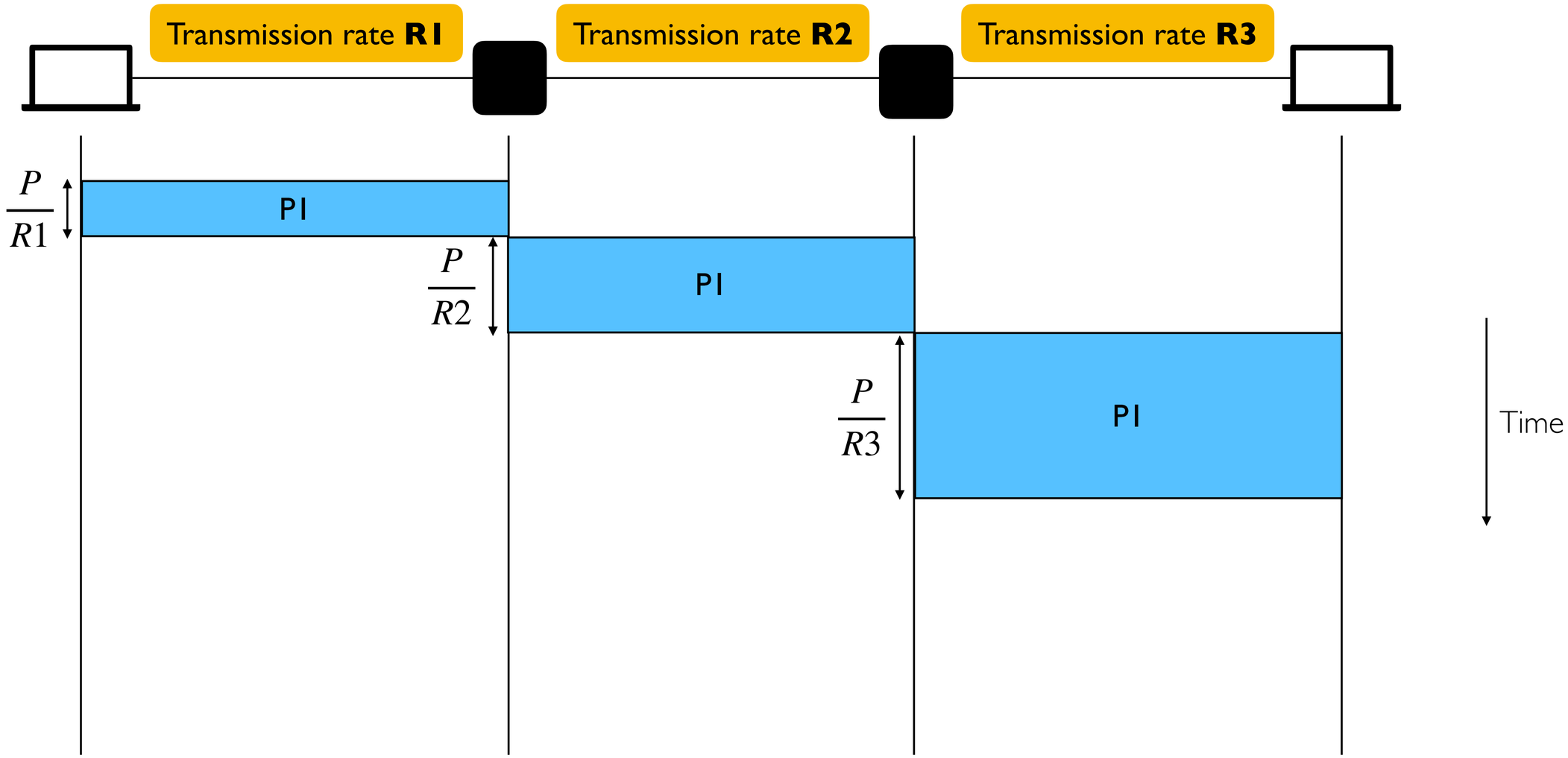

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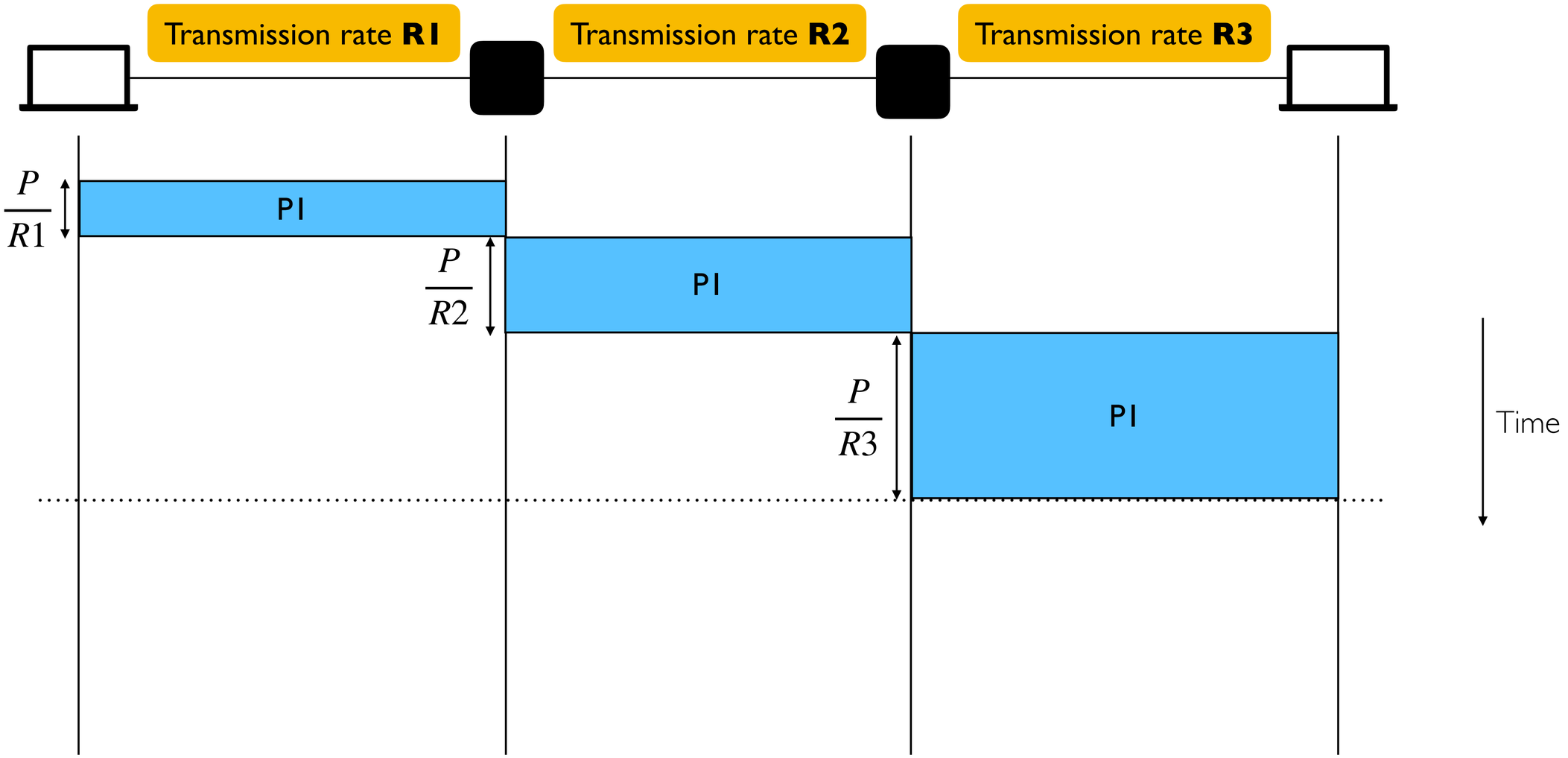

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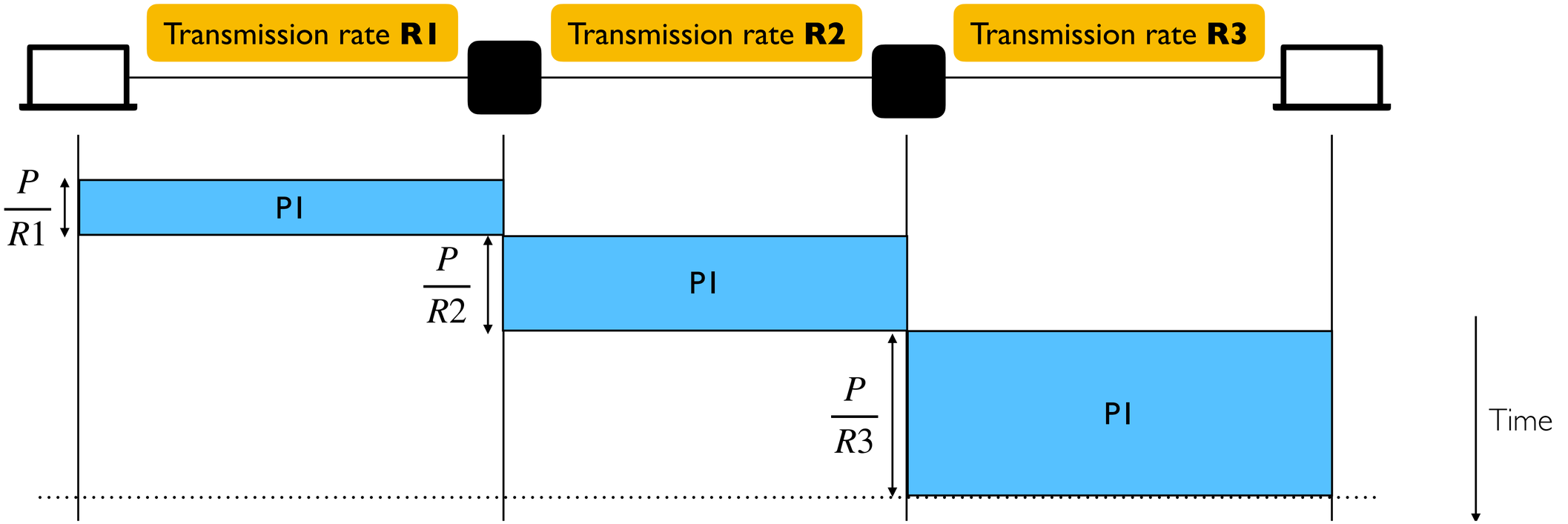

Ignoring propagation, queueing and processing delays, packet delay for a packet of P bits $= \frac{P}{R1} + \frac{P}{R2} + \frac{P}{R3}$

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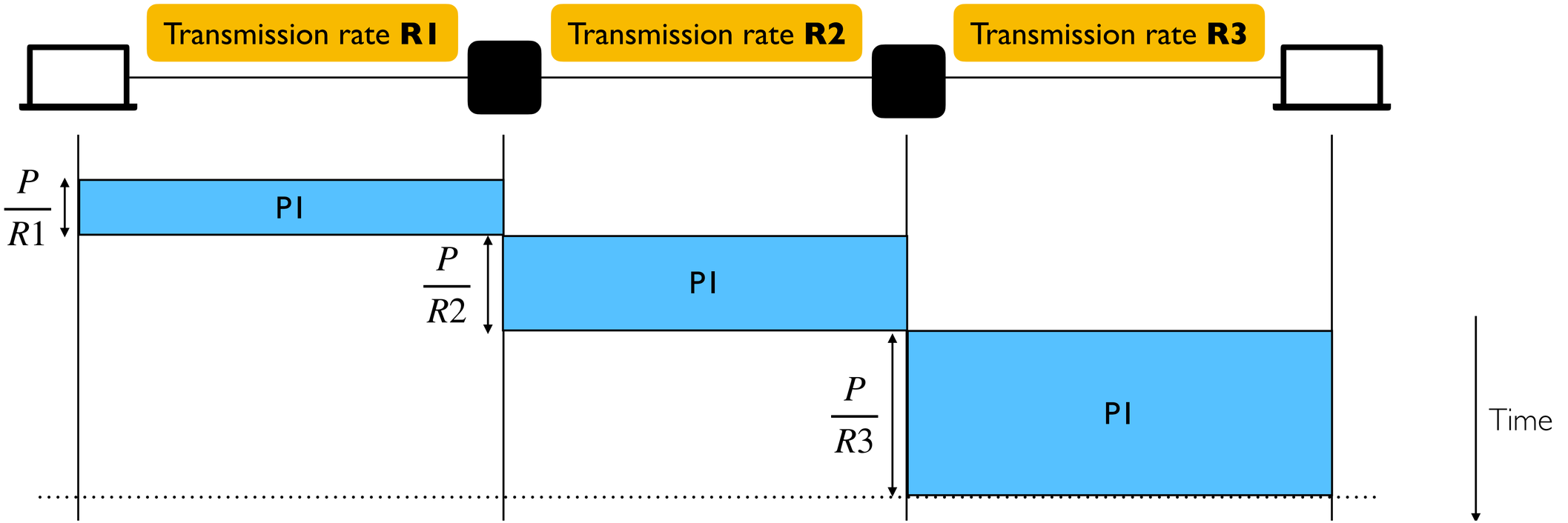
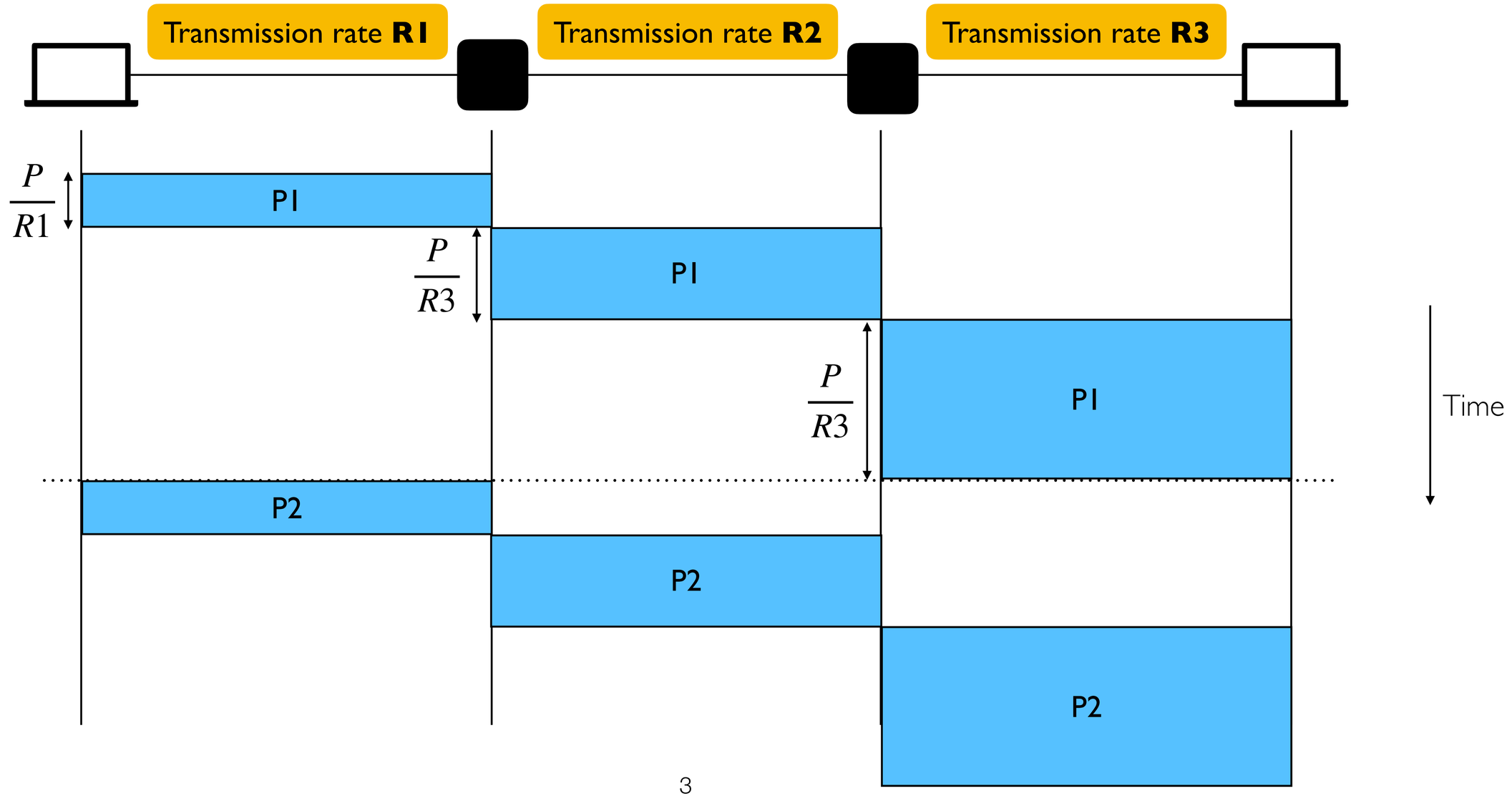


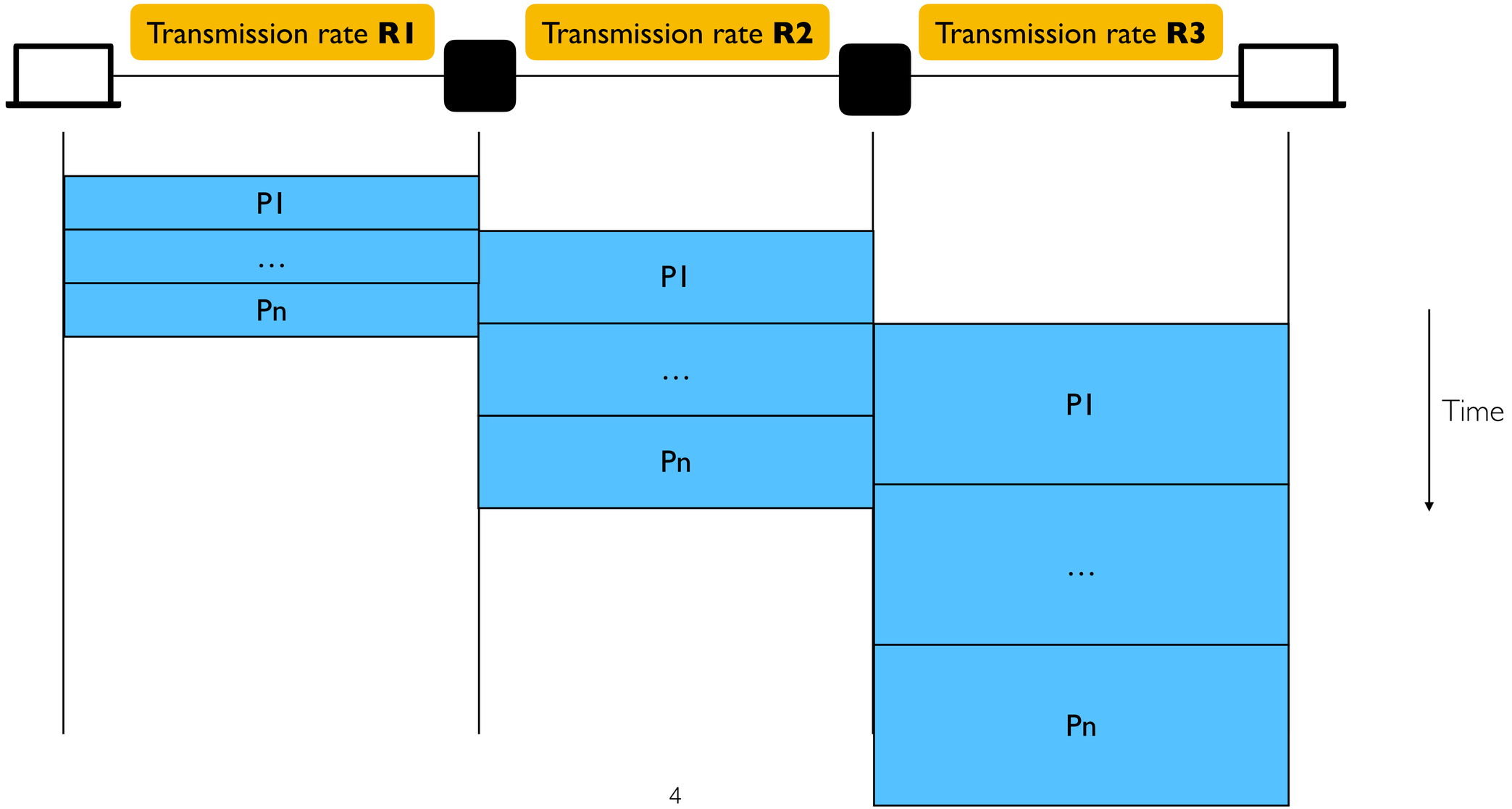
Ignoring propagation, queueing and processing delays, packet delay for a packet of P bits $= \frac{P}{R1} + \frac{P}{R2} + \frac{P}{R3}$

Shouldn't the throughput of a file of F bits sent in P bit packets be $\frac{F}{P} \cdot \frac{P}{\frac{P}{R1} + \frac{P}{R2} + \frac{P}{R3}} = \frac{F}{\frac{P}{R1} + \frac{P}{R2} + \frac{P}{R3}}$?

Throughput Calculation: Packet by packet



Throughput Calculation: In Reality



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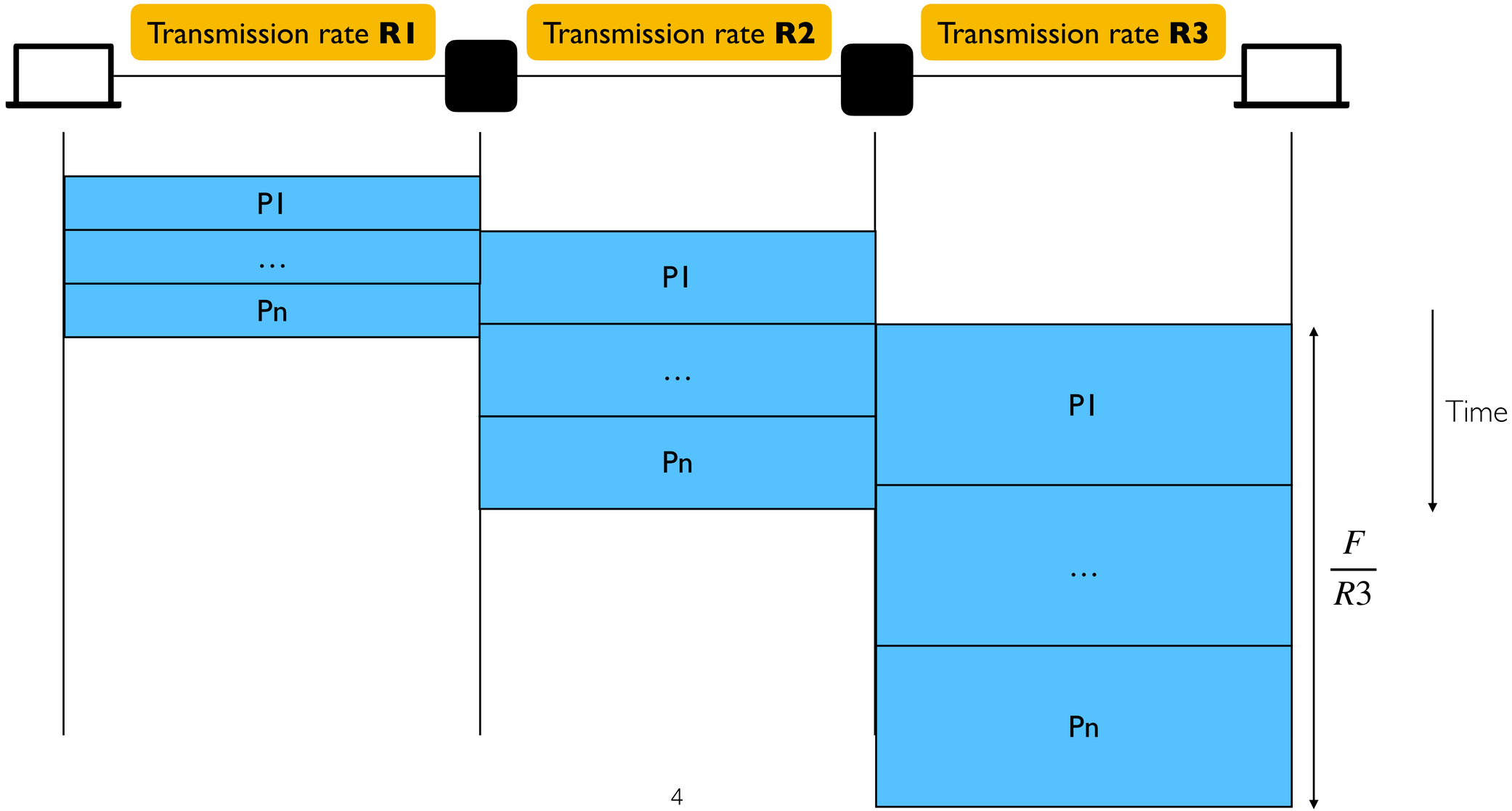

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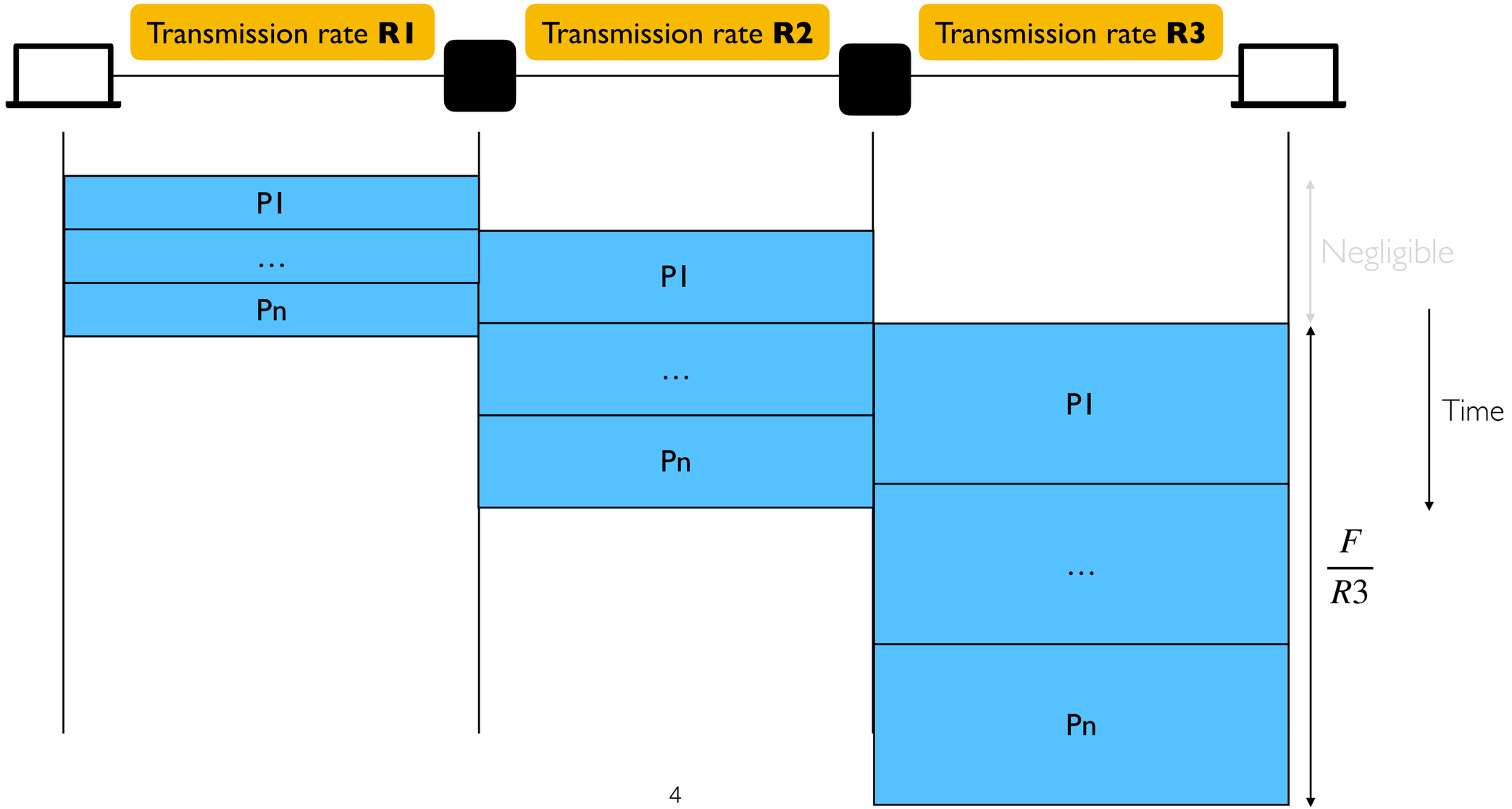

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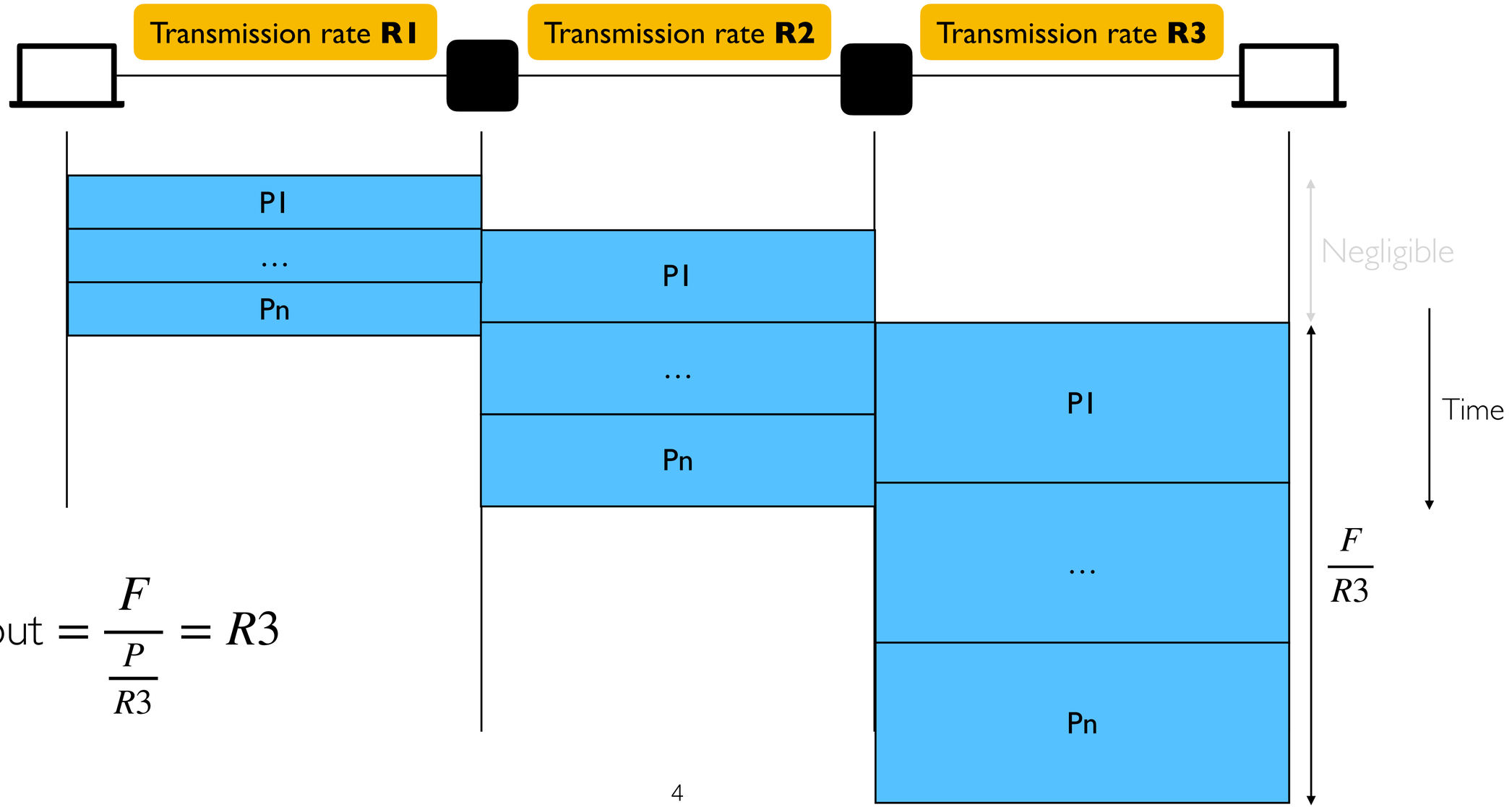

$$\text{Throughput} = \frac{F}{\frac{P}{R3}} = R3$$

Three steps

- **Decompose** the problem into tasks
- **Organize** these tasks
- **Assign** tasks to entities (who does what)

Three steps

- **Decomposition**
- **Organization**
- **Assignment**

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Layering principle

Three steps

- **Decomposition**
- **Organization**
- **Assignment**

The Path through FedEx

FE = FedEx Envelope

Truck

Truck

Sorting Office

Sorting Office

Sorting Office

Airport

Airport

Airport

The Path through FedEx

FE = FedEx Envelope

Truck

Sorting Office

Airport

Sorting Office

Airport

Truck

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Airport

The Path through FedEx

FE = FedEx Envelope

Truck

Truck

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Crate

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The Path through FedEx

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Crate

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The Path through FedEx

FE = FedEx Envelope

Truck

Truck

FE

Sorting Office

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Airport

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The Path through FedEx

FE = FedEx Envelope

Truck

Truck

Sorting Office

Sorting Office

Sorting Office

New Crate

Airport

Airport

Airport

The Path through FedEx

FE = FedEx Envelope

Truck

Truck

Sorting Office

Sorting Office

Sorting Office

Airport

Airport

Airport

The Path through FedEx

FE = FedEx Envelope

Truck

Truck

Sorting Office

Sorting Office

Sorting Office

Crate

Airport

Airport

Airport

The Path through FedEx

FE = FedEx Envelope

Truck

Sorting Office

Airport

Sorting Office

Airport

Truck

FE

Sorting Office

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Airport

Airport

Airport

The Path through FedEx

FE = FedEx Envelope

Truck

Truck

Sorting Office

Sorting Office

Sorting Office

Airport

Airport

Airport

Deepest packaging (Envelope+FE+Crate) at Lowest level of transport

The Path through FedEx

FE = FedEx Envelope

Higher "Stack" at Ends

Truck

Truck

Sorting Office

Sorting Office

Sorting Office

Airport

Airport

Airport

Deepest packaging (Envelope+FE+Crate) at Lowest level of transport

The Path through FedEx

FE = FedEx Envelope

Higher "Stack" at Ends

Partial "Stack" during Transit

Truck

Truck

Sorting Office

Sorting Office

Sorting Office

Airport

Airport

Airport

Deepest packaging (Envelope+FE+Crate) at Lowest level of transport

Path through Internet

Path through Internet

What gets implemented where?

What layers get implemented at the end-systems?

What layers get implemented at the end-systems?

- Bits arrive on wire, must make it up to application

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- Bits arrive on wire, must make it up to application
- Therefore, all layers must exist at host!

What layers get implemented in the network?

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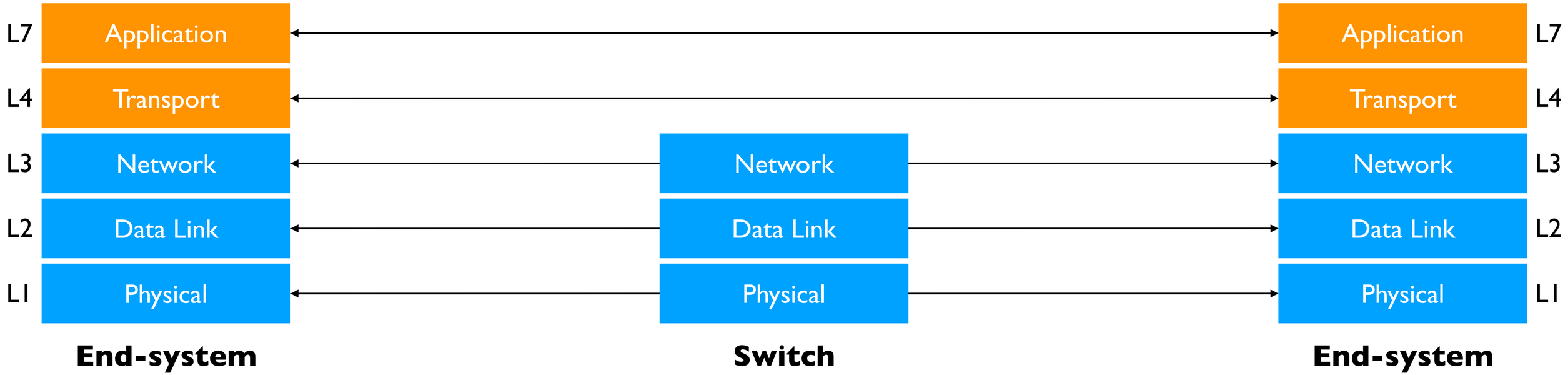
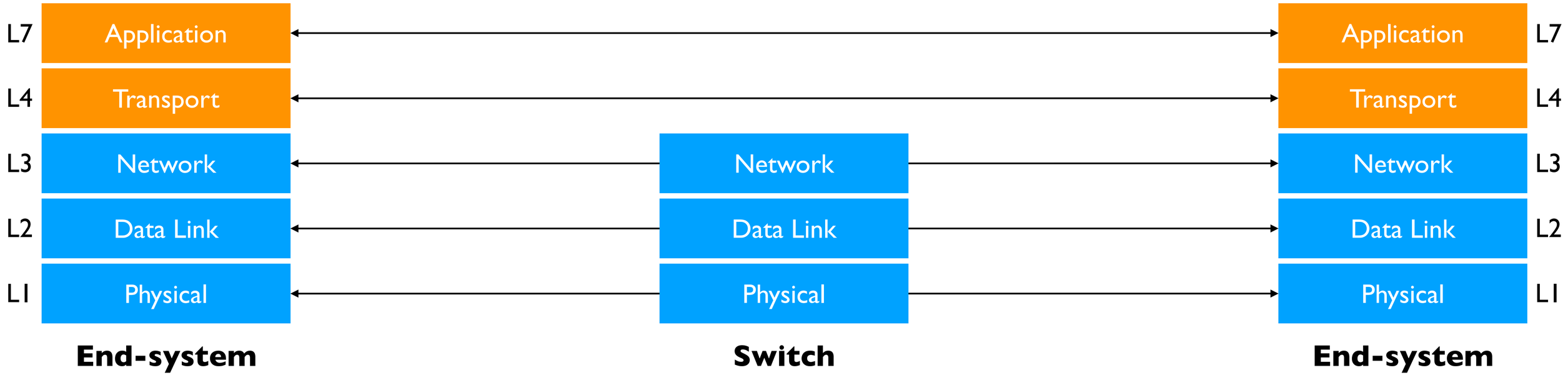
  - *Transport layer (and above) <u>not</u> supported* ***(Why?)***

Path through Internet



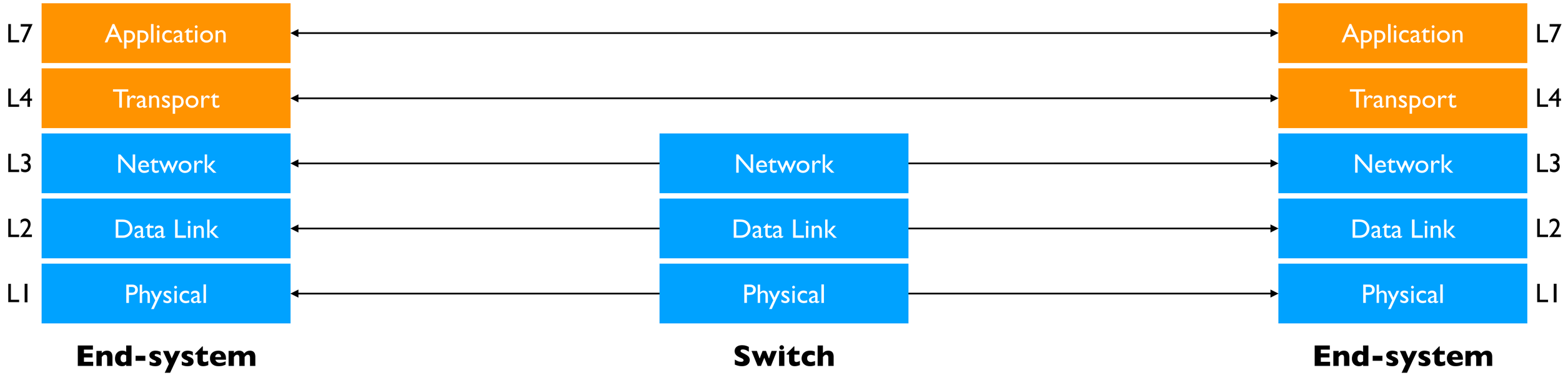
Path through Internet

- Lower three layers implemented everywhere



Path through Internet

- Lower three layers implemented everywhere
- Top two layers implemented only on hosts



A closer look: end-system

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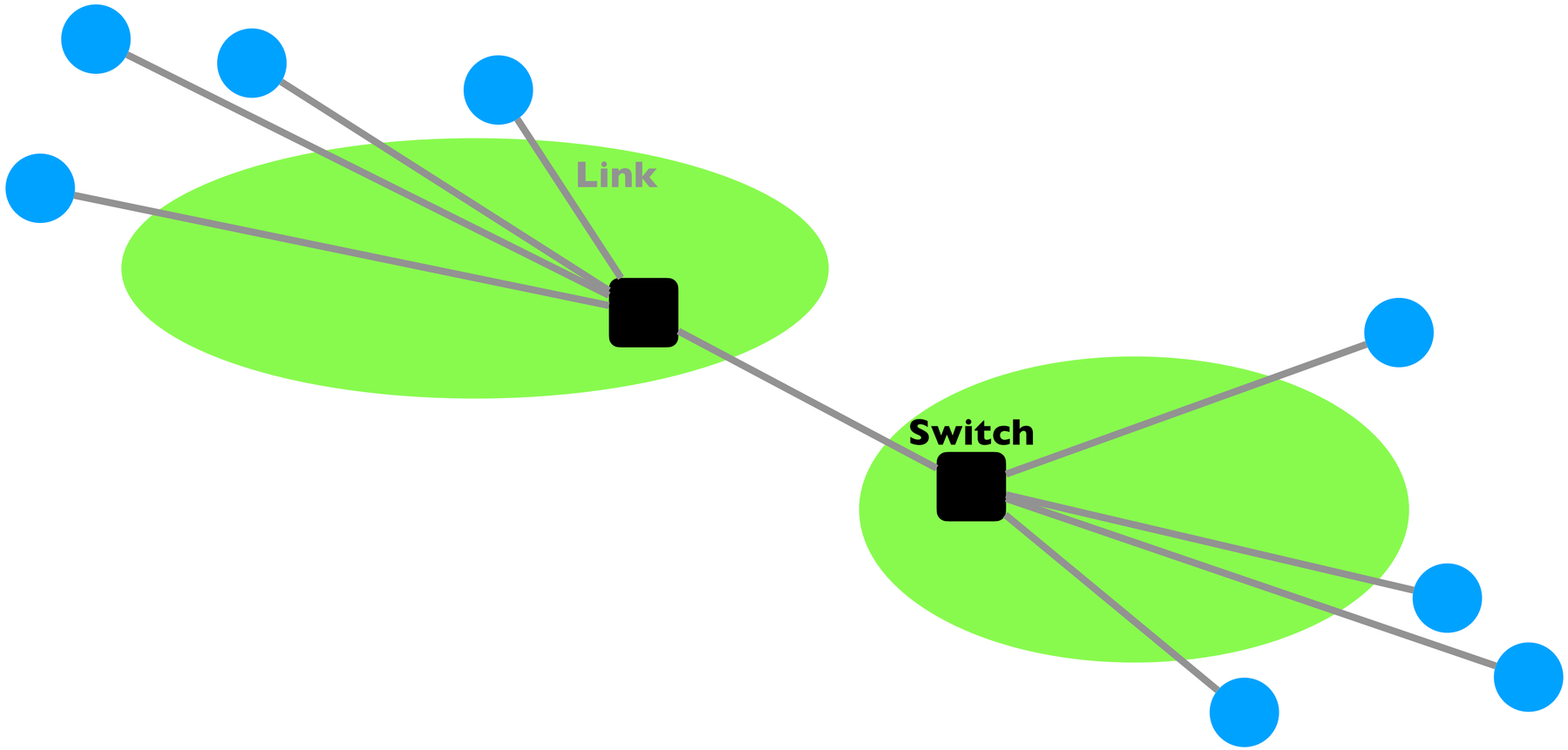
- Transport and network layer
  - *Typically part of the operating system*
- Datalink and physical layer
  - *Hardware/firmware/drivers*

A closer look: Network



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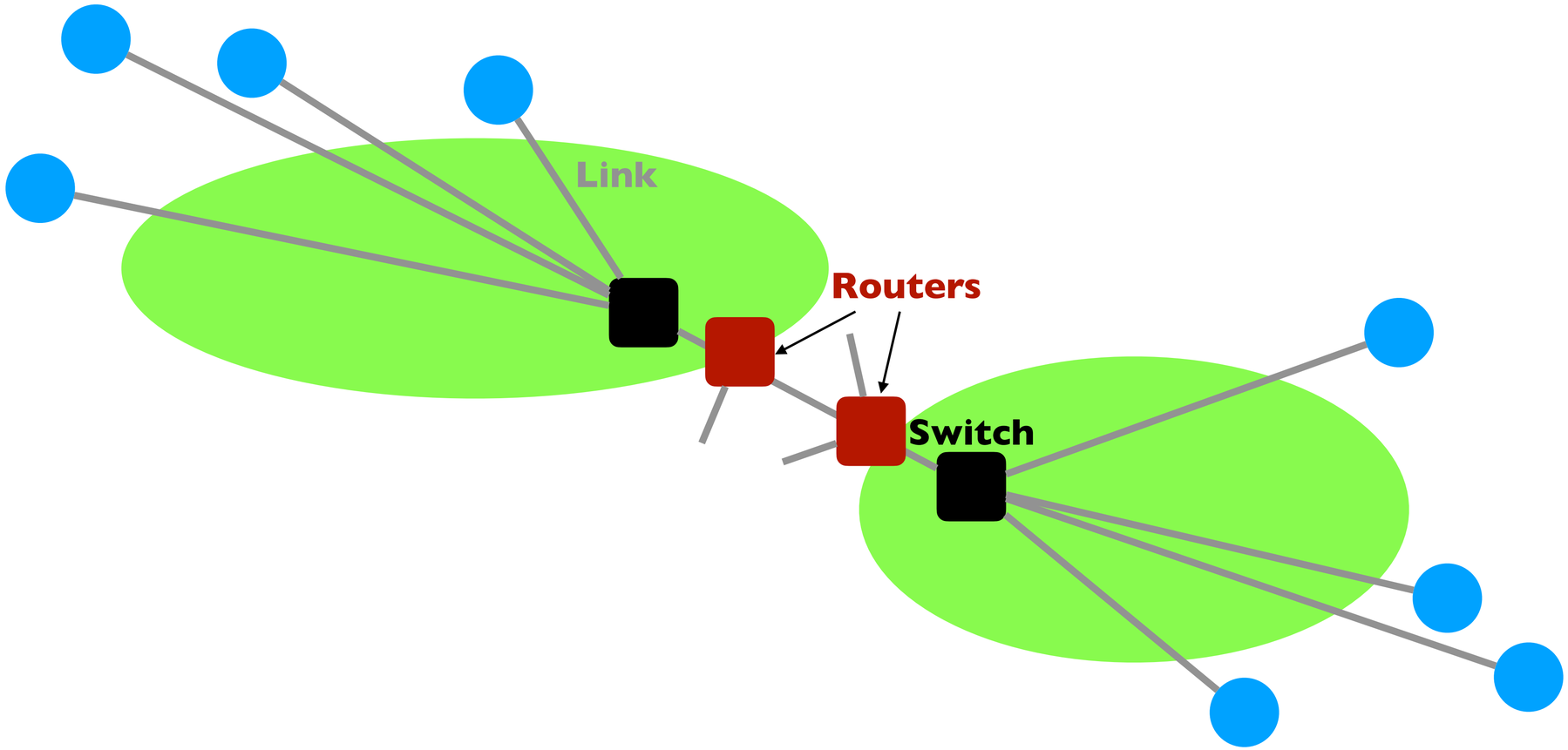

Switches vs. Routers

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- Switches do what routers do, but don't participate in global delivery, just local delivery
  - *Switches only need to support L1, L2*
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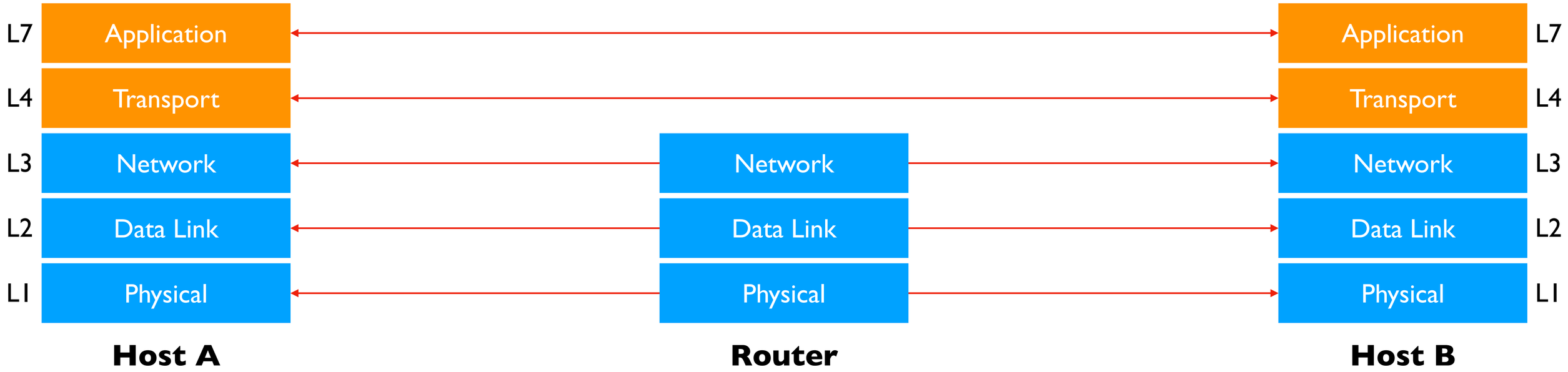
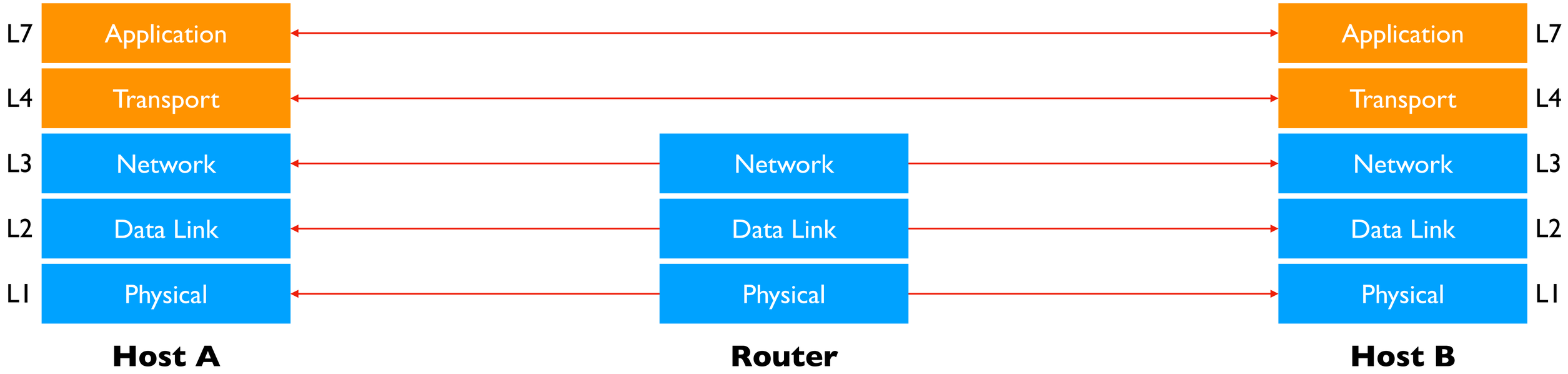
  - *Switches only need to support L1, L2*
  - *Routers support L1-L3*
- Won't focus on the router/switch distinction
  - *When I say switch, I almost always mean router*
  - *Almost all boxes support network layer these days*

Logical Communication

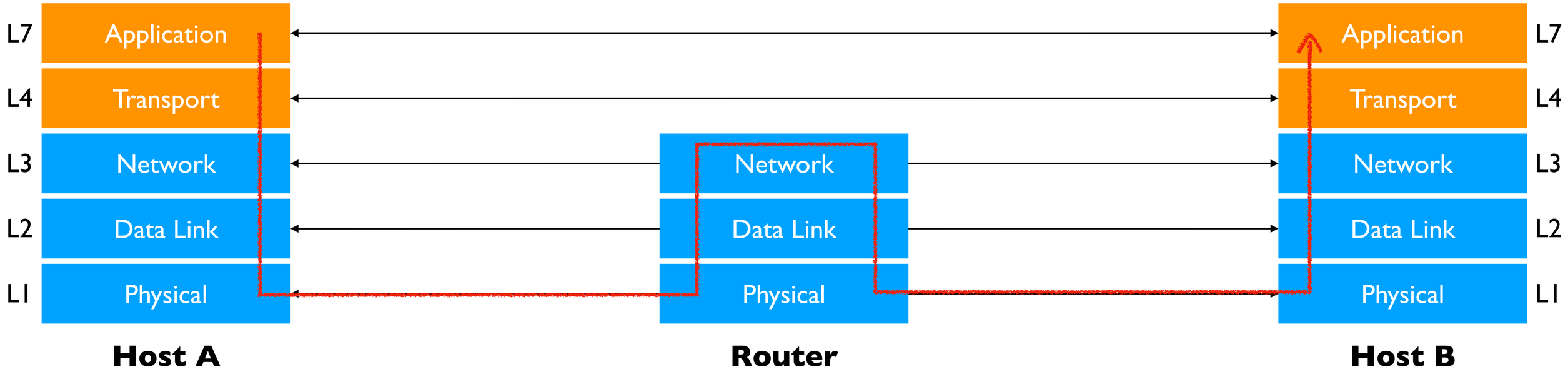


Logical Communication

- Layers interact with peer's corresponding layer

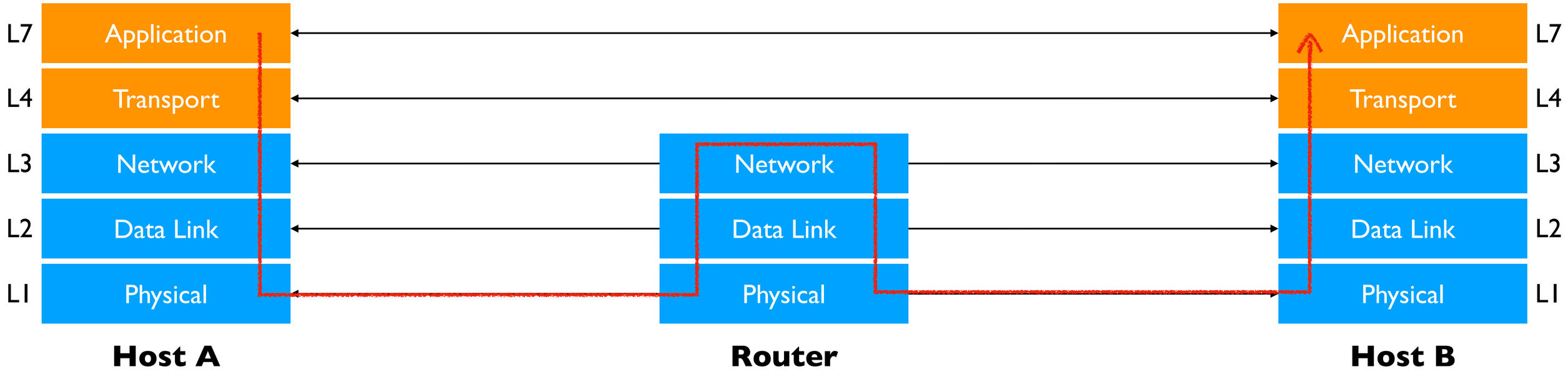


Physical Communication



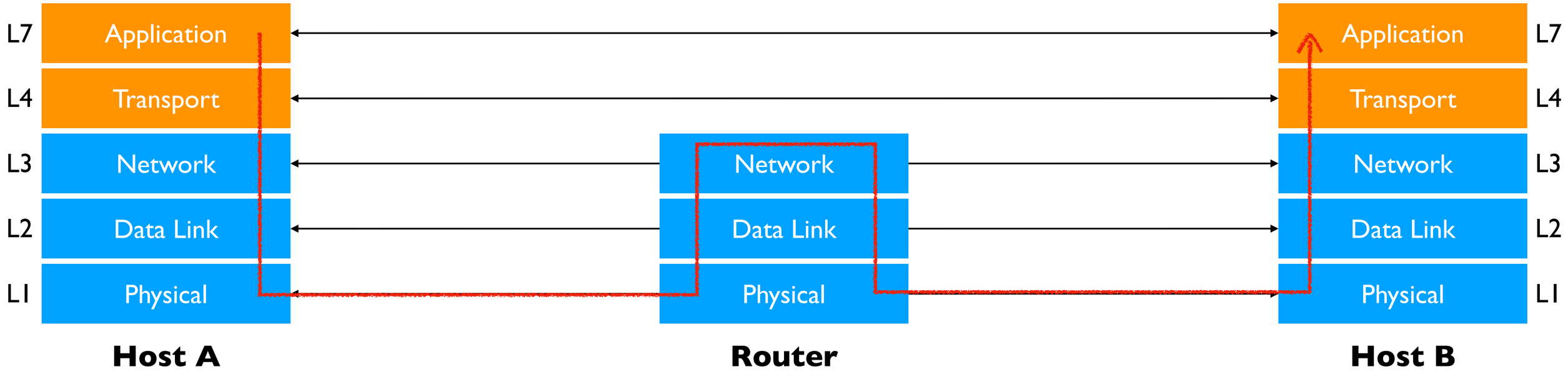
Physical Communication

- Communication goes down to the physical network

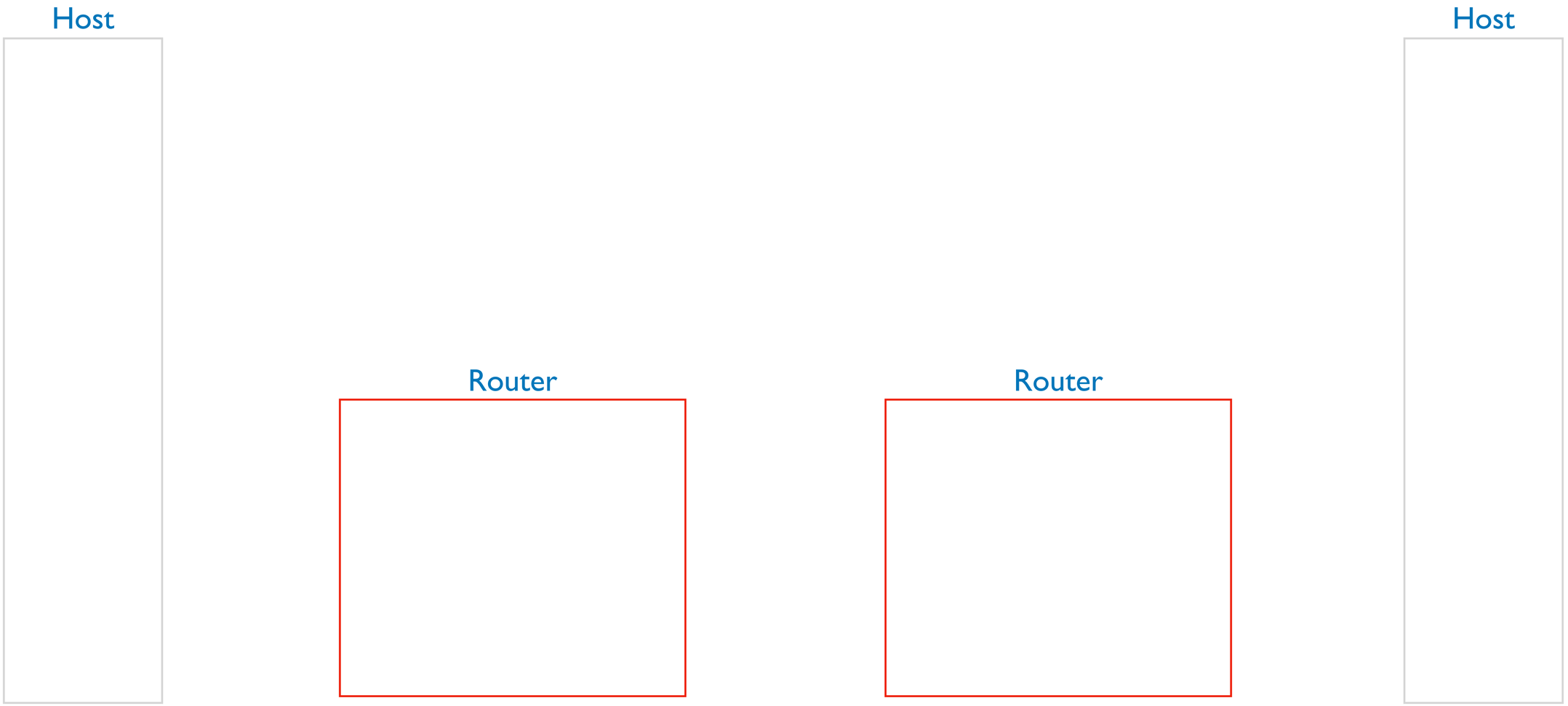


Physical Communication

- Communication goes down to the physical network
- Then up to relevant layer



A Protocol-centric Diagram



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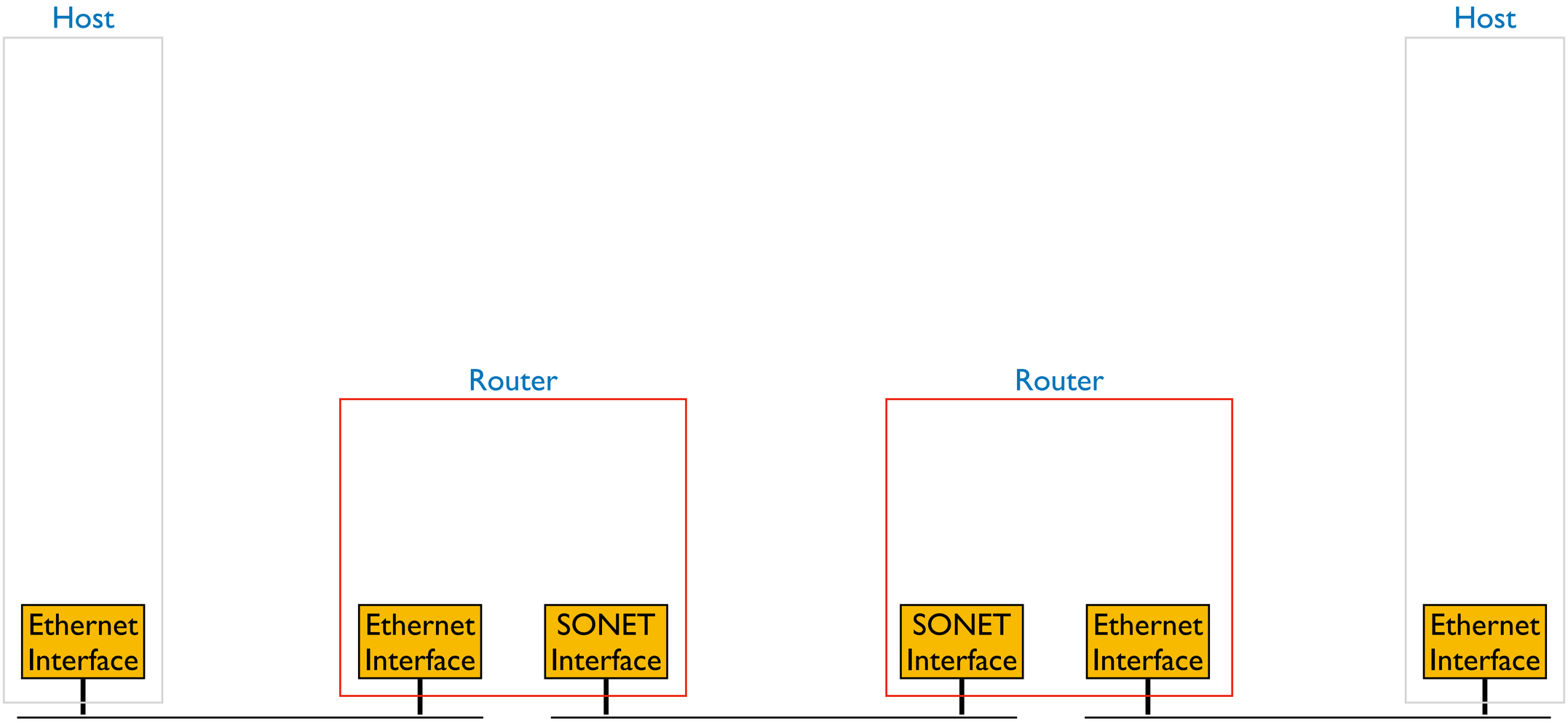

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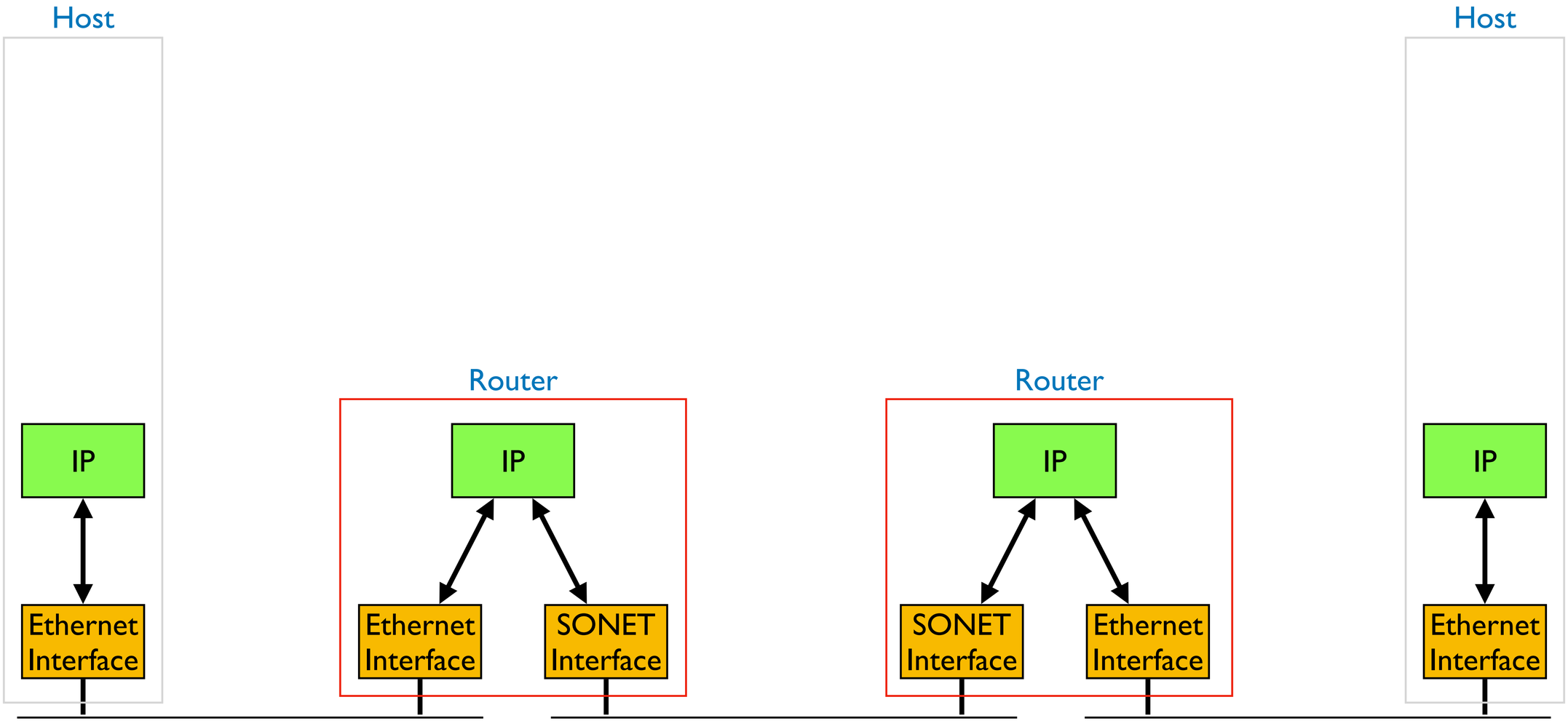

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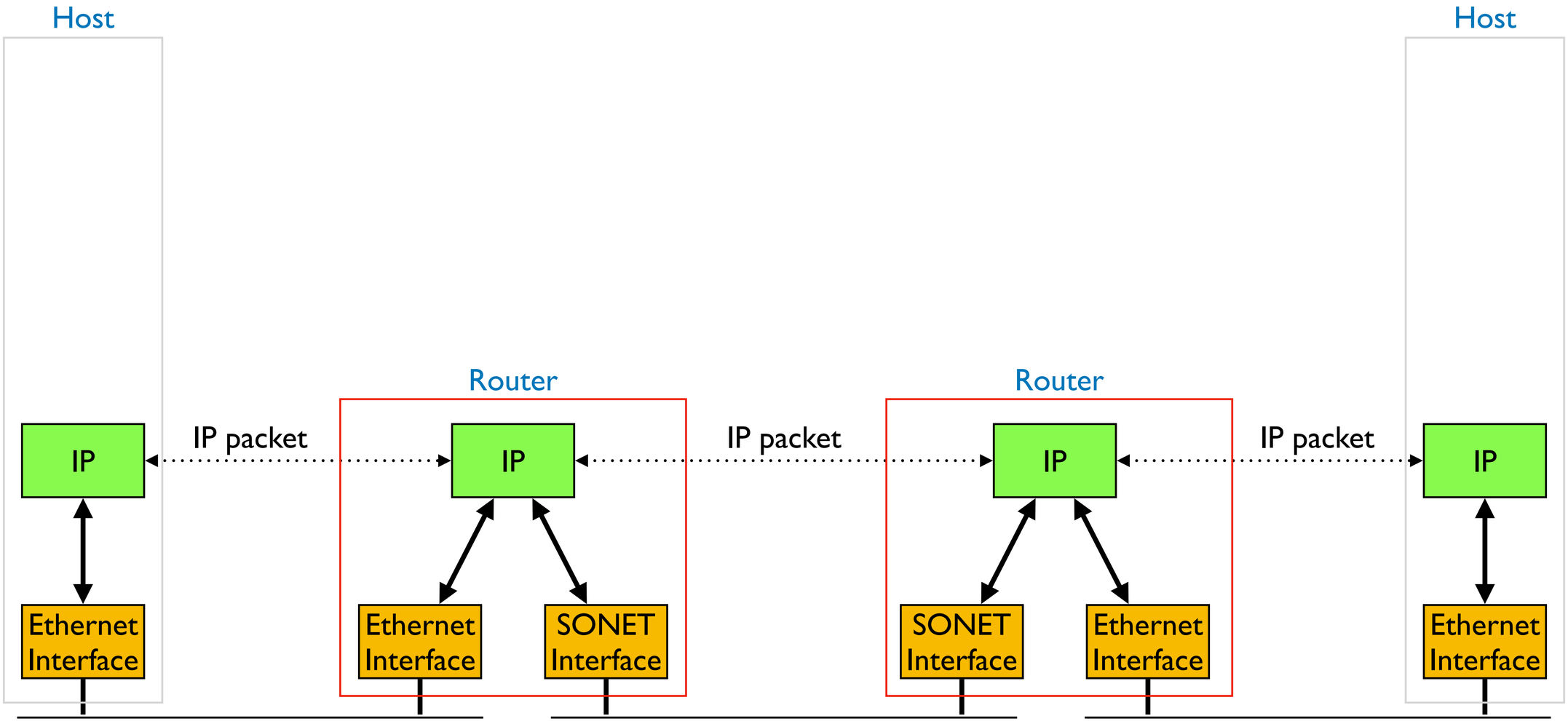

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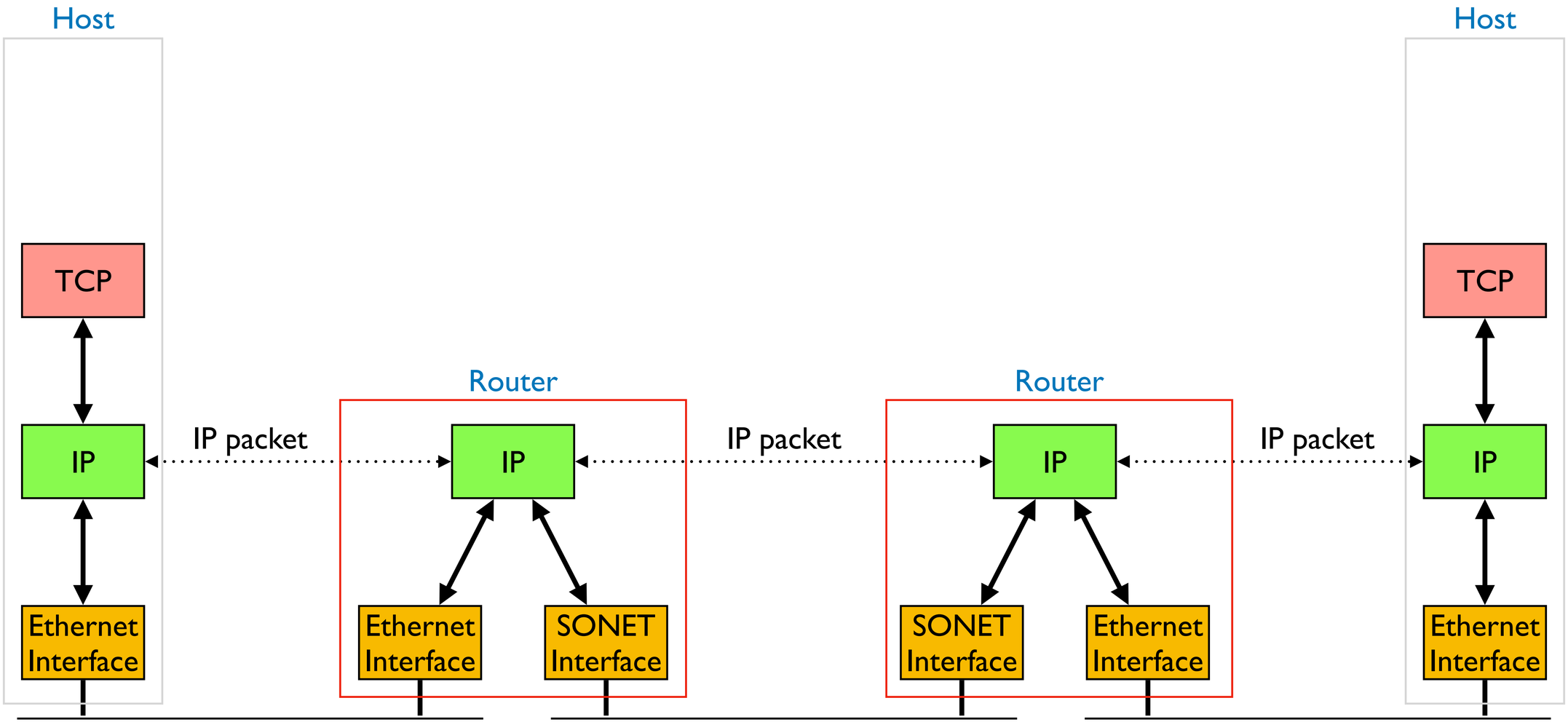

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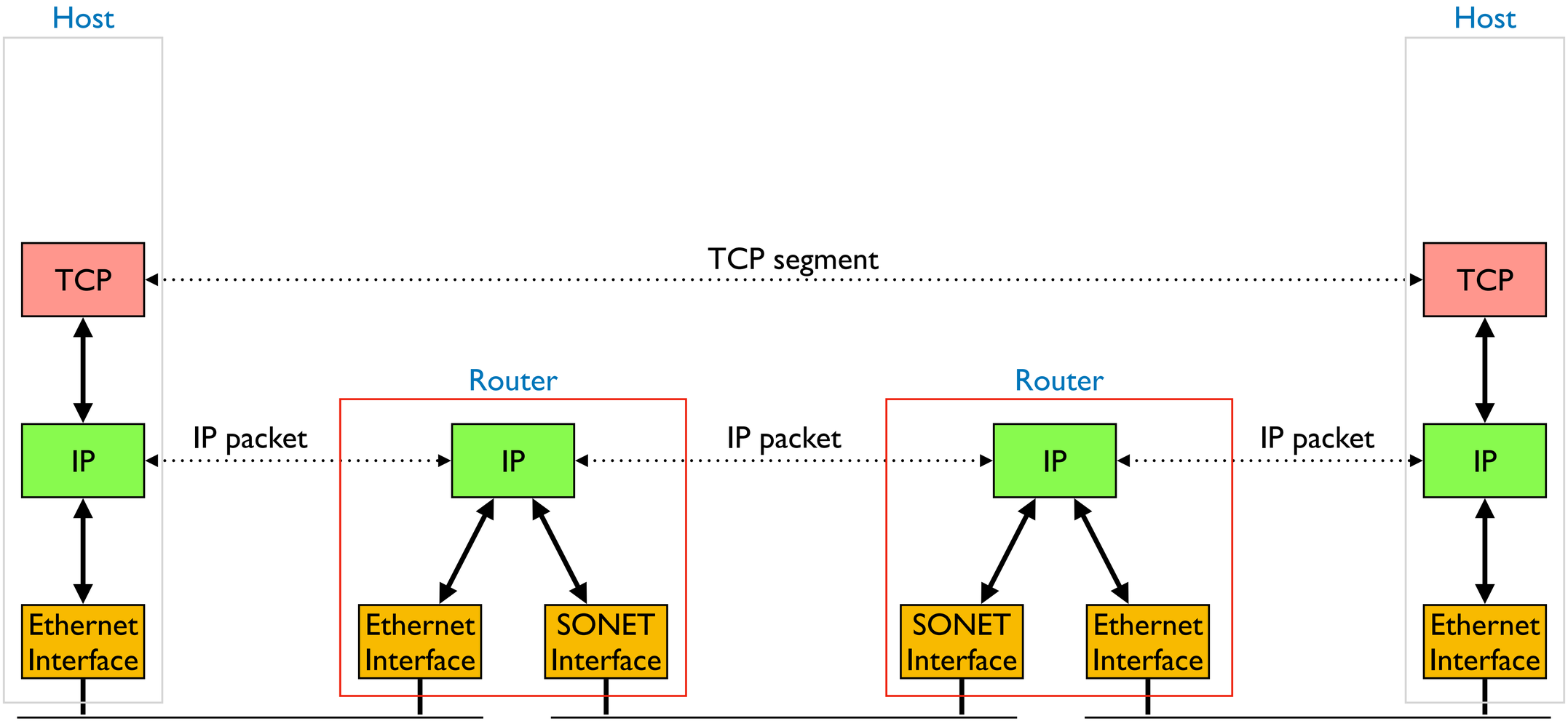

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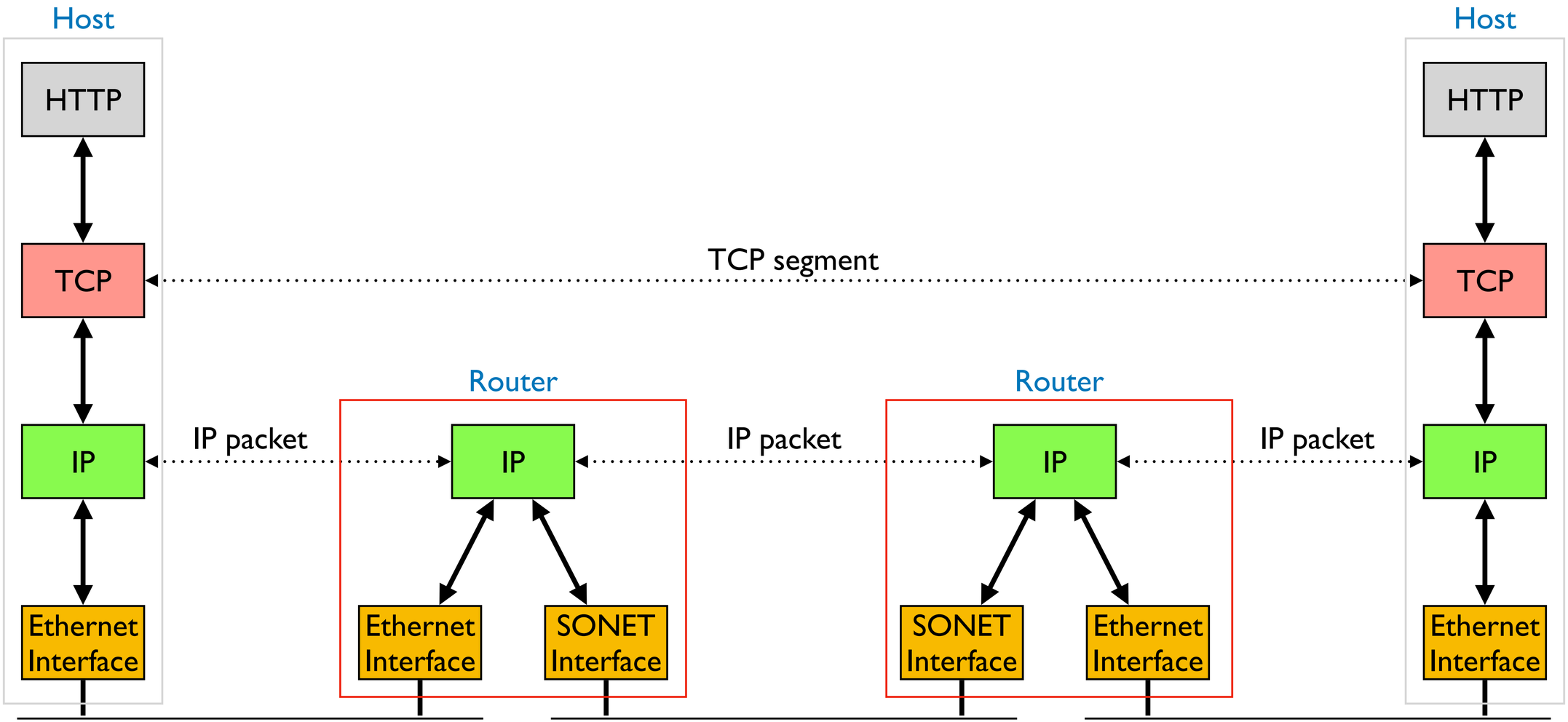

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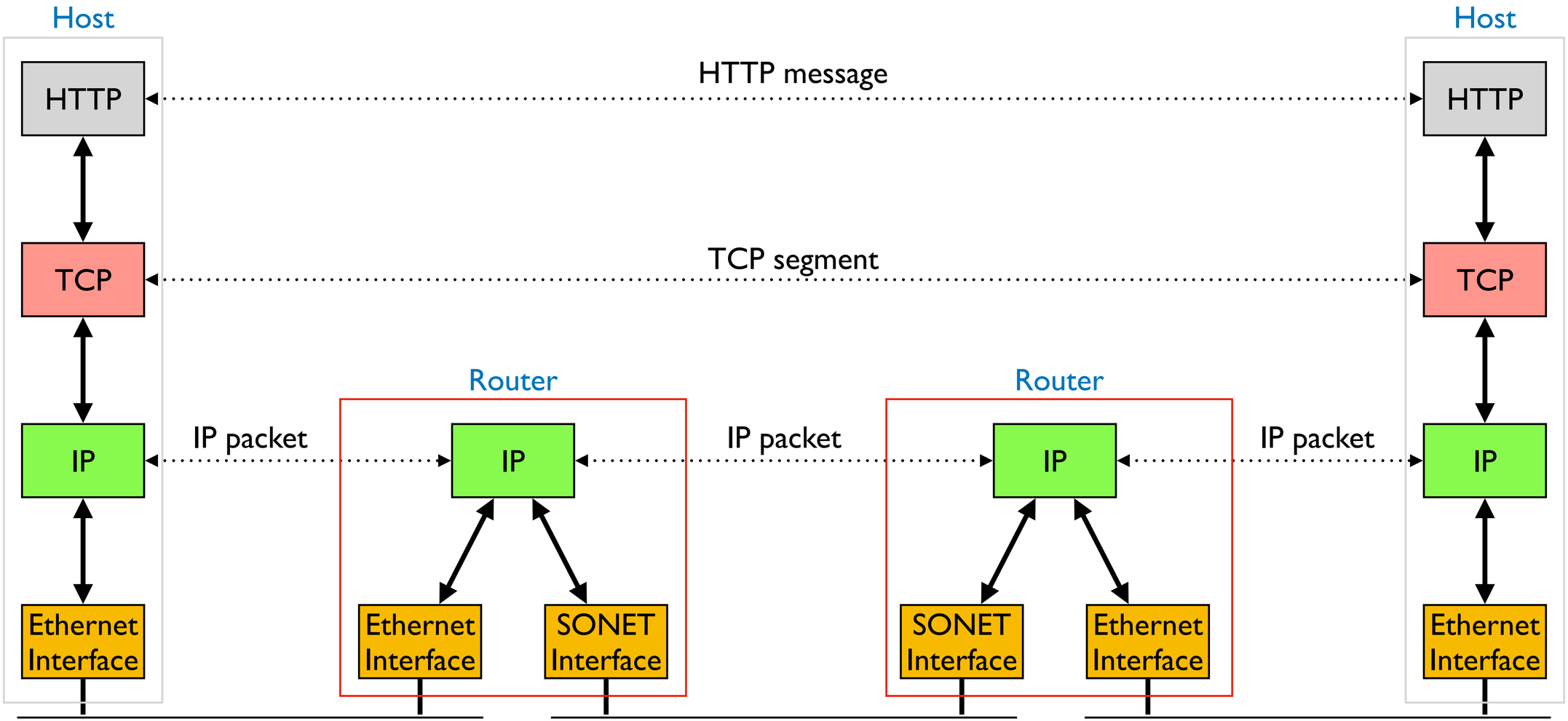

Questions?

Three steps

- **Decomposition**
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End-to-end principle

Placing Network Functionality

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- Endless debate over what it means
- Many have used their own interpretation to support their position
- But core argument holds value, esp. in understanding its impact on Internet design

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- **Sometimes** an **incomplete version of the function** provided by the communication system **may be useful as a performance enhancement**

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- Implementing these completely in the network may not only be hard, but impossible
- End-systems:
  - ***Can*** *satisfy the requirement without network's help*
  - ***Will/must*** *do so, since they cannot rely on the network*

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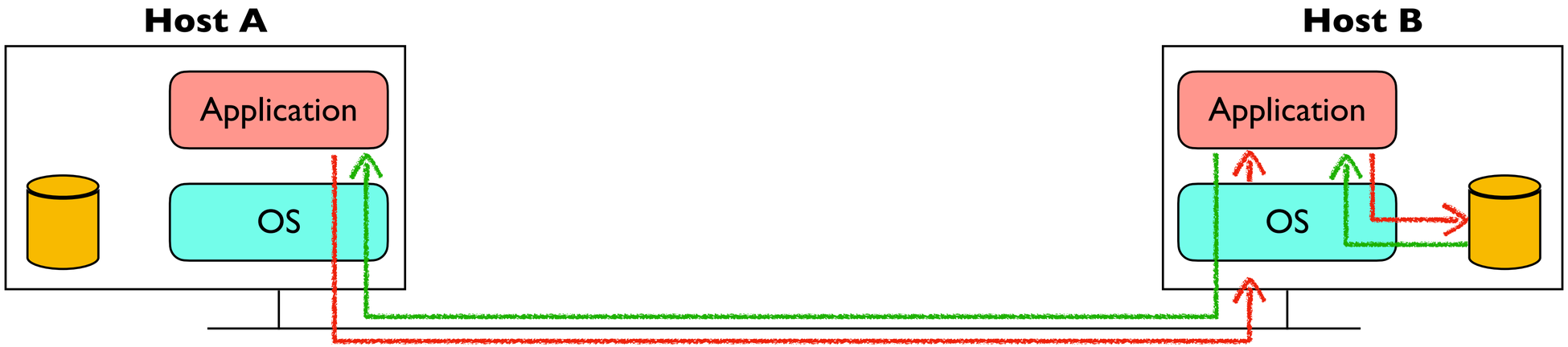

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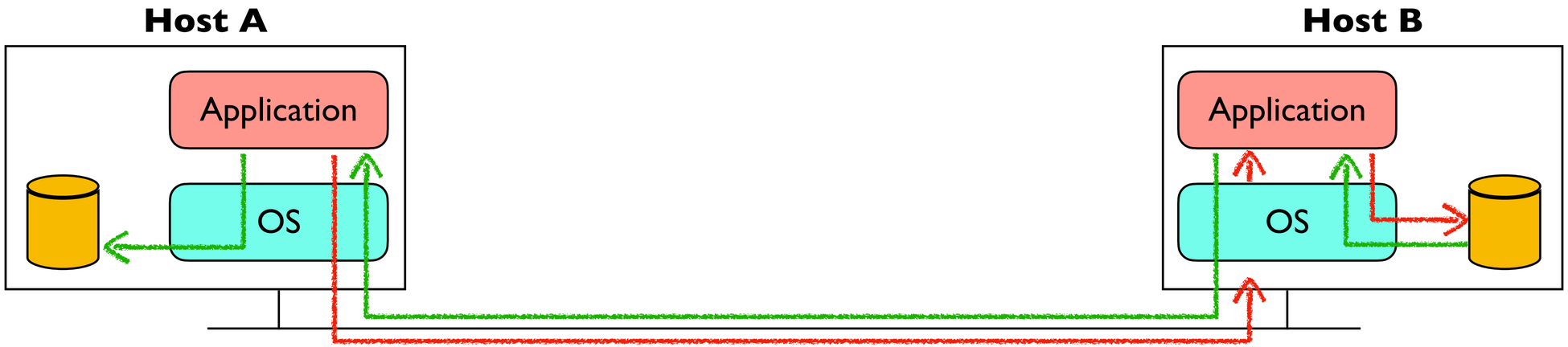

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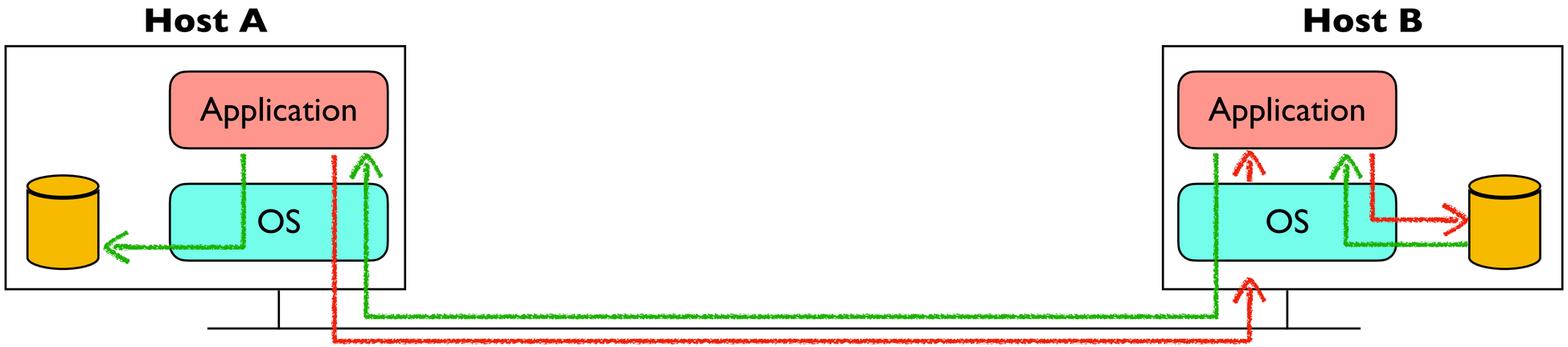

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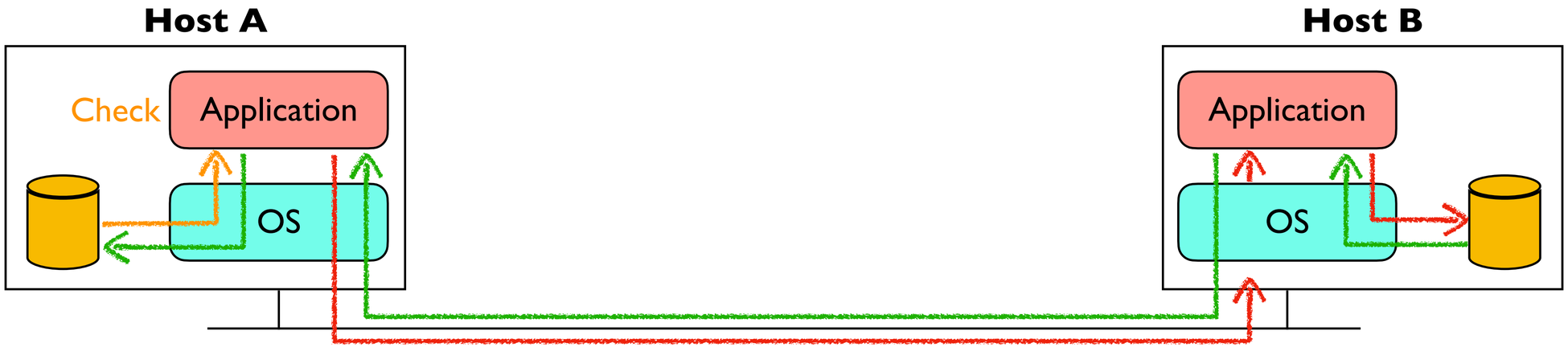

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Discussion

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  - *Receiver has to do the check anyway!*
- **Solution 2** is complete
  - *Full functionality can be entirely implemented at application layer with no need for reliability from lower layers*
- Is there any **need** to implement reliability at lower layers?

Except…

Sometimes an **incomplete version of the function** provided by the communication system may be useful as a **performance enhancement**

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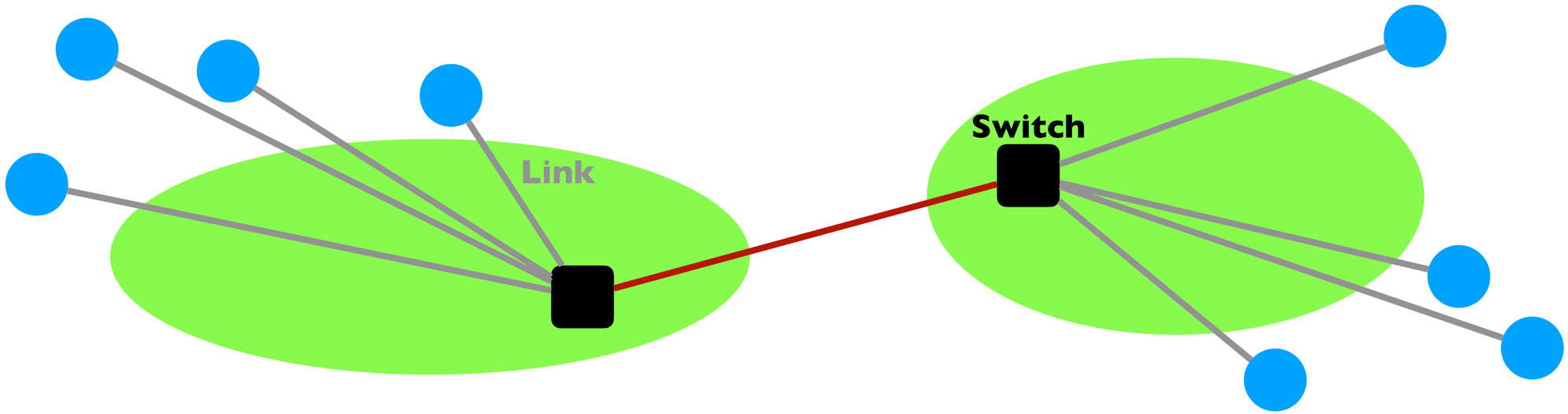

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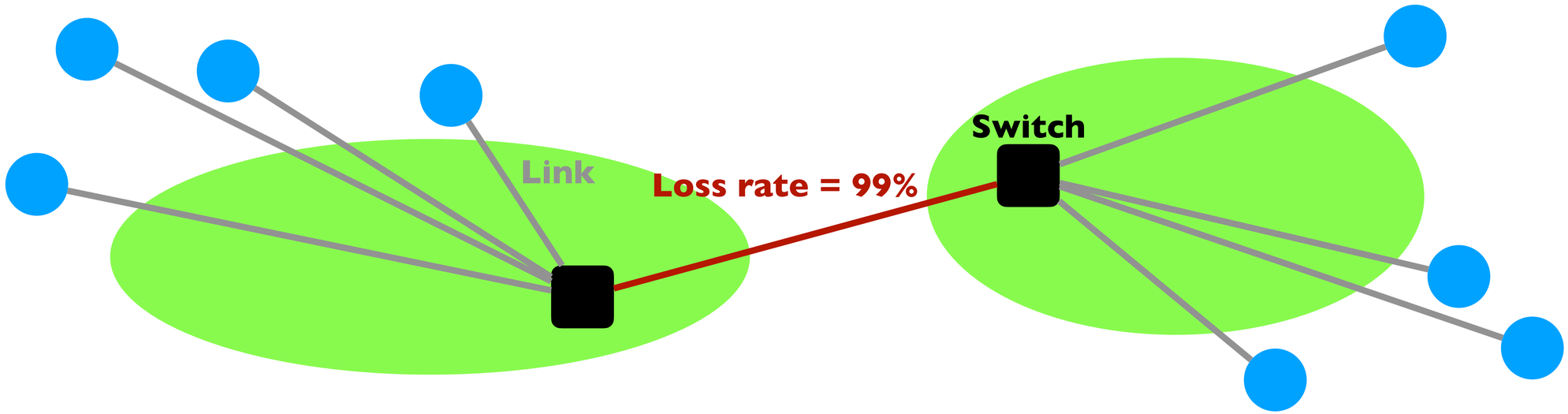

Summary of the E2E principle

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- Implementing functionality (e.g., reliability) in the network
  - *Doesn't reduce host implementation complexity*
  - *Does increase network complexity*
  - *Probably increases delay and overhead on all applications even if they don't need the functionality (e.g., reliable data transfer vs. VoIP)*

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- Implementing functionality (e.g., reliability) in the network
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  - *Does increase network complexity*
  - *Probably increases delay and overhead on all applications even if they don't need the functionality (e.g., reliable data transfer vs. VoIP)*
- However, implementing in the network can improve performance in some cases
  - *E.g., consider a very lossy link*

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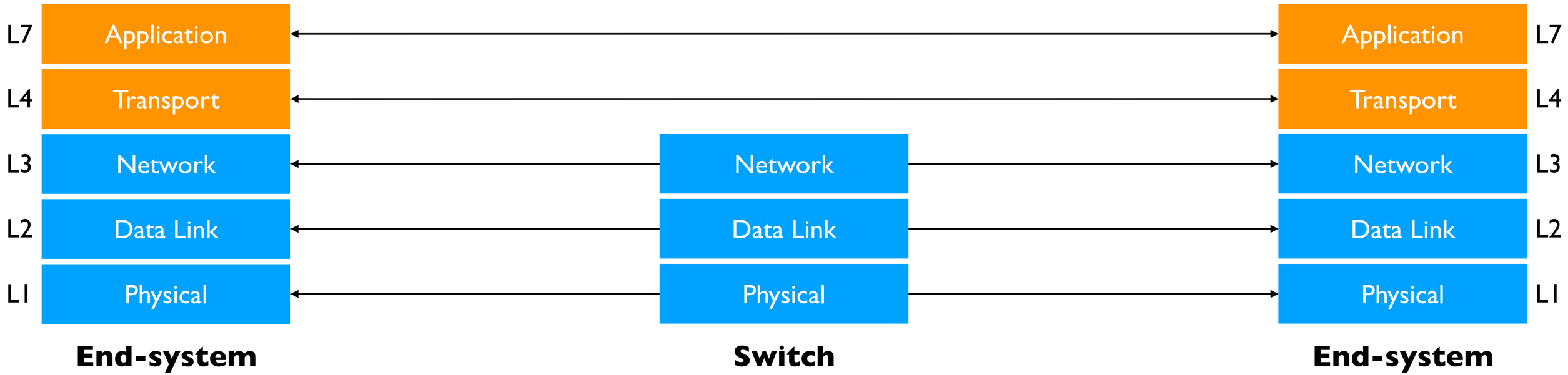
- In layered design, the E2E principle provides guidance on which layers are implemented where
- "Dumb" network and "smart" end-systems
  - *Often credited as a key to the Internet's success!*
- "Fate-sharing"
  - *Store state at the system entities that rely on the state*
  - *Often translated to keep end-host state out of routers*

E2E meets Layering



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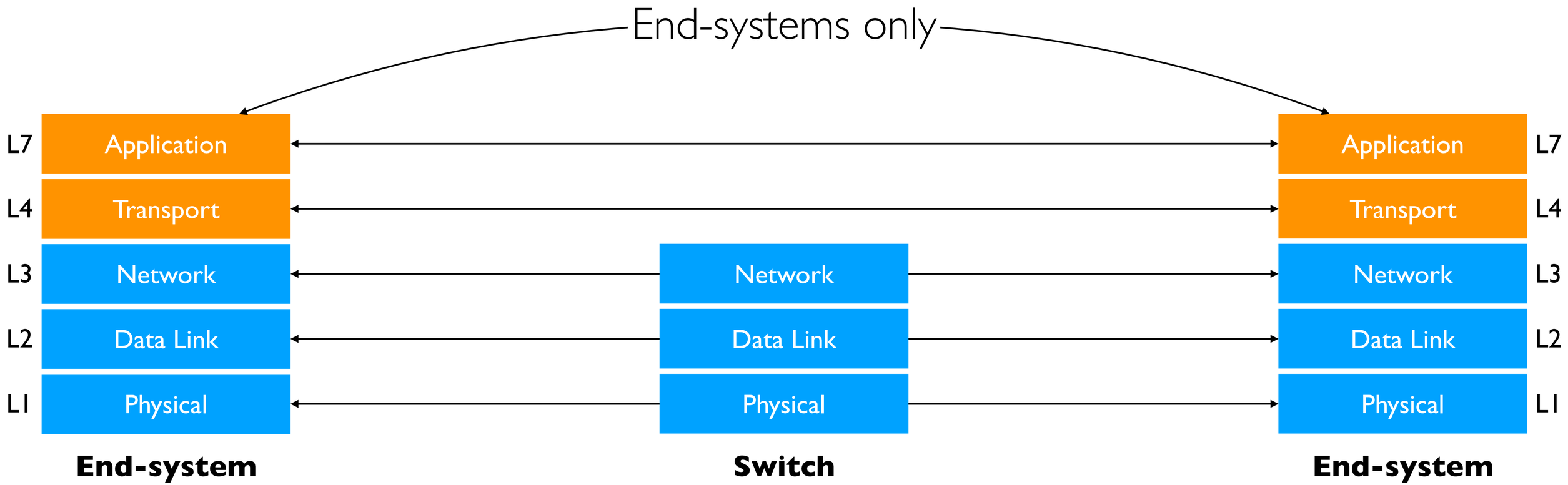

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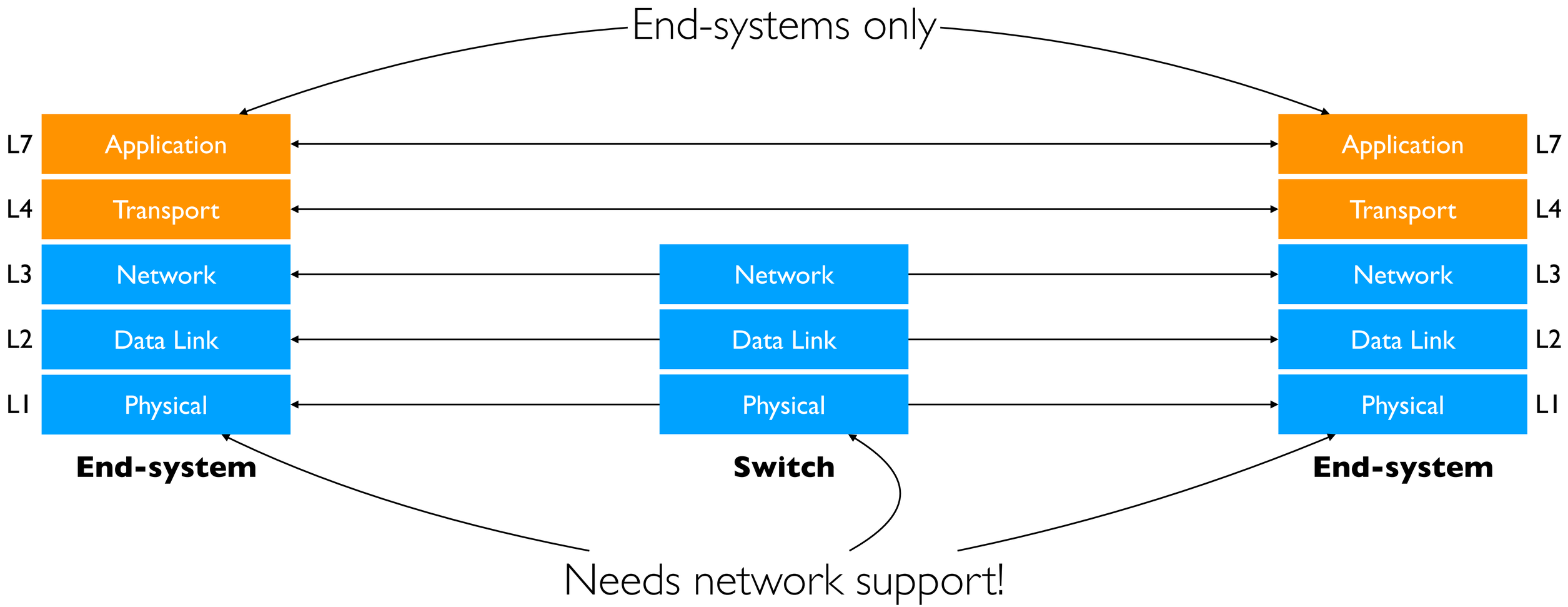

Cracks in the E2E argument?

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  - *e.g., ISP looking for new revenue-generating services*
  - *e.g., users looking for a performance boost*
- Sometimes we don't trust end-systems to do the job
  - *e.g., firewalls, intrusion detection systems*

Questions?

Asking the right architectural questions…

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- How to break system into modules?

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  - *Classic decomposition into tasks*

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… leads to three design principles

- How to break system into modules?
  - *Layering*
- Where are modules implemented?
  - *End-to-end principle*
- Where is state stored?
  - *Fate-sharing*

Taking Stock

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Taking Stock: So Far…

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- What is a network made of?
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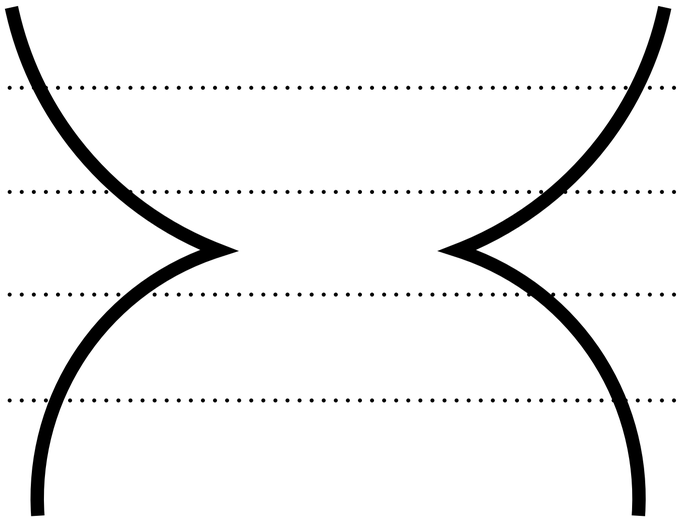
Taking Stock

- **Basic concepts**
  - Components: end-systems, links, switches, routers
  - Performance: delay, loss, throughput
- **Basic design choices**
  - Packets vs circuit switching
  - Best-effort vs guaranteed service
  - Layering
  - "Dumb" network, "smart" ends
    - E2E principle, fate-sharing

Coming up next…

- How, in detail, layer by layer (we will obsess a lot over "why" too…)



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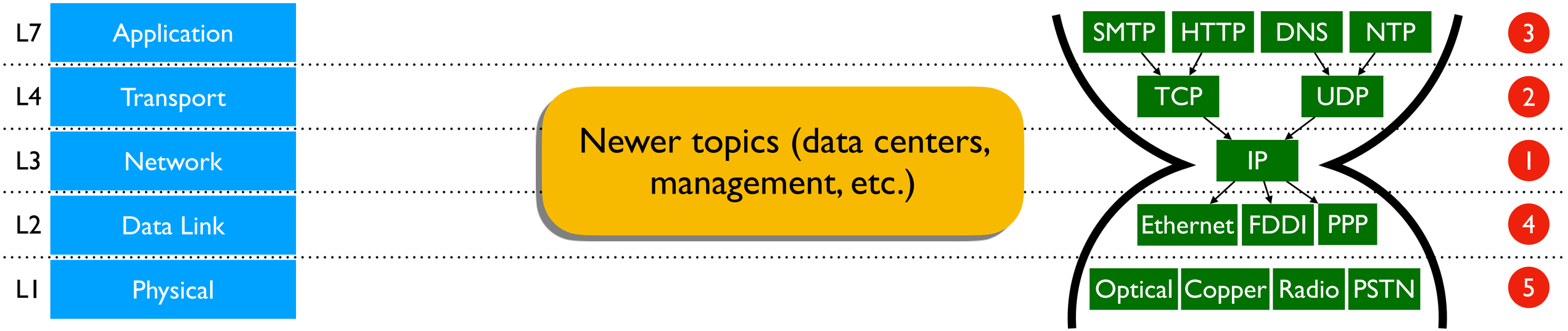


The Network Layer

CPSC 433/533, Spring 2021

Anurag Khandelwal

What does the Network Layer do?

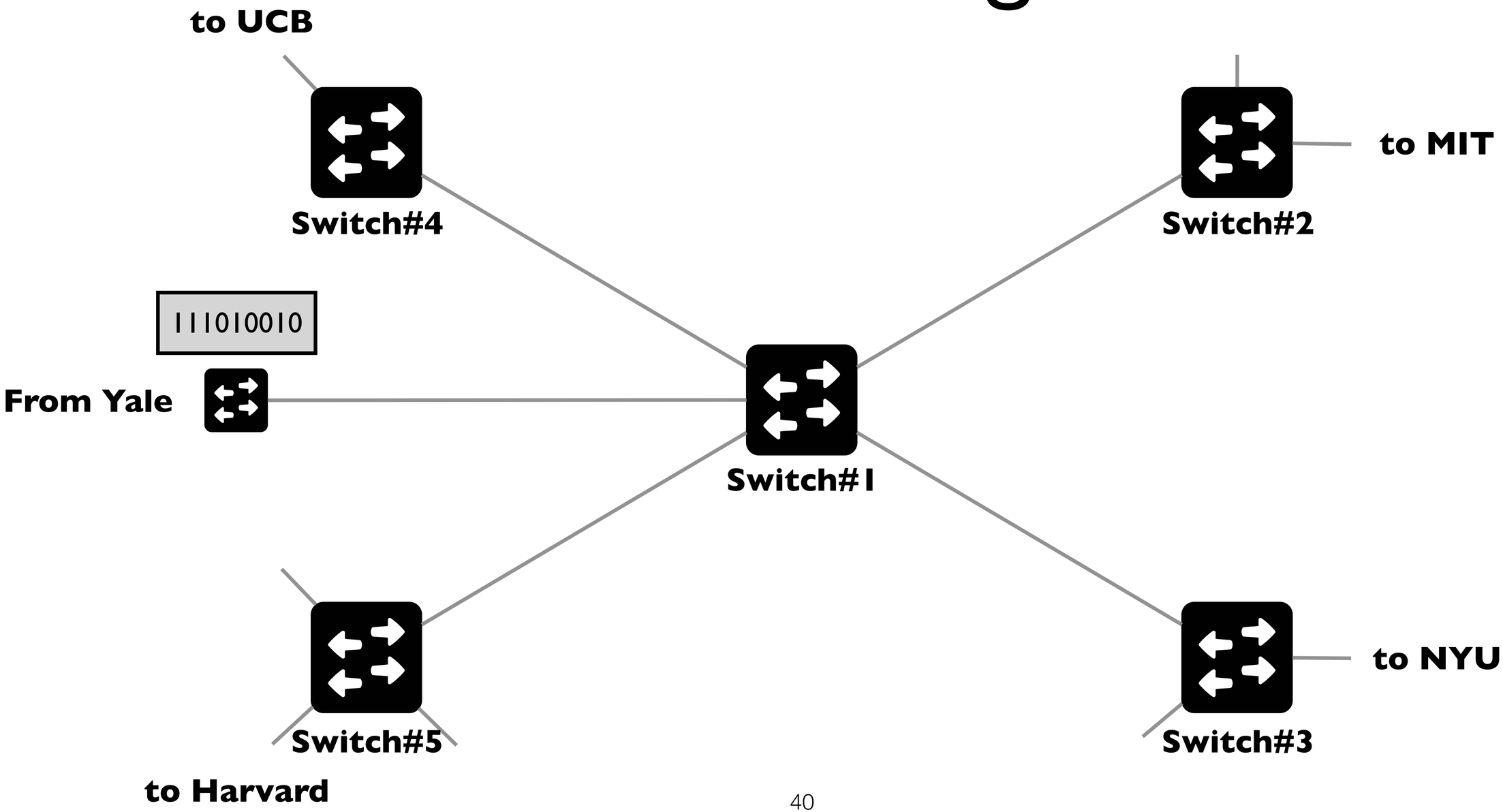
What does the Network Layer do?

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

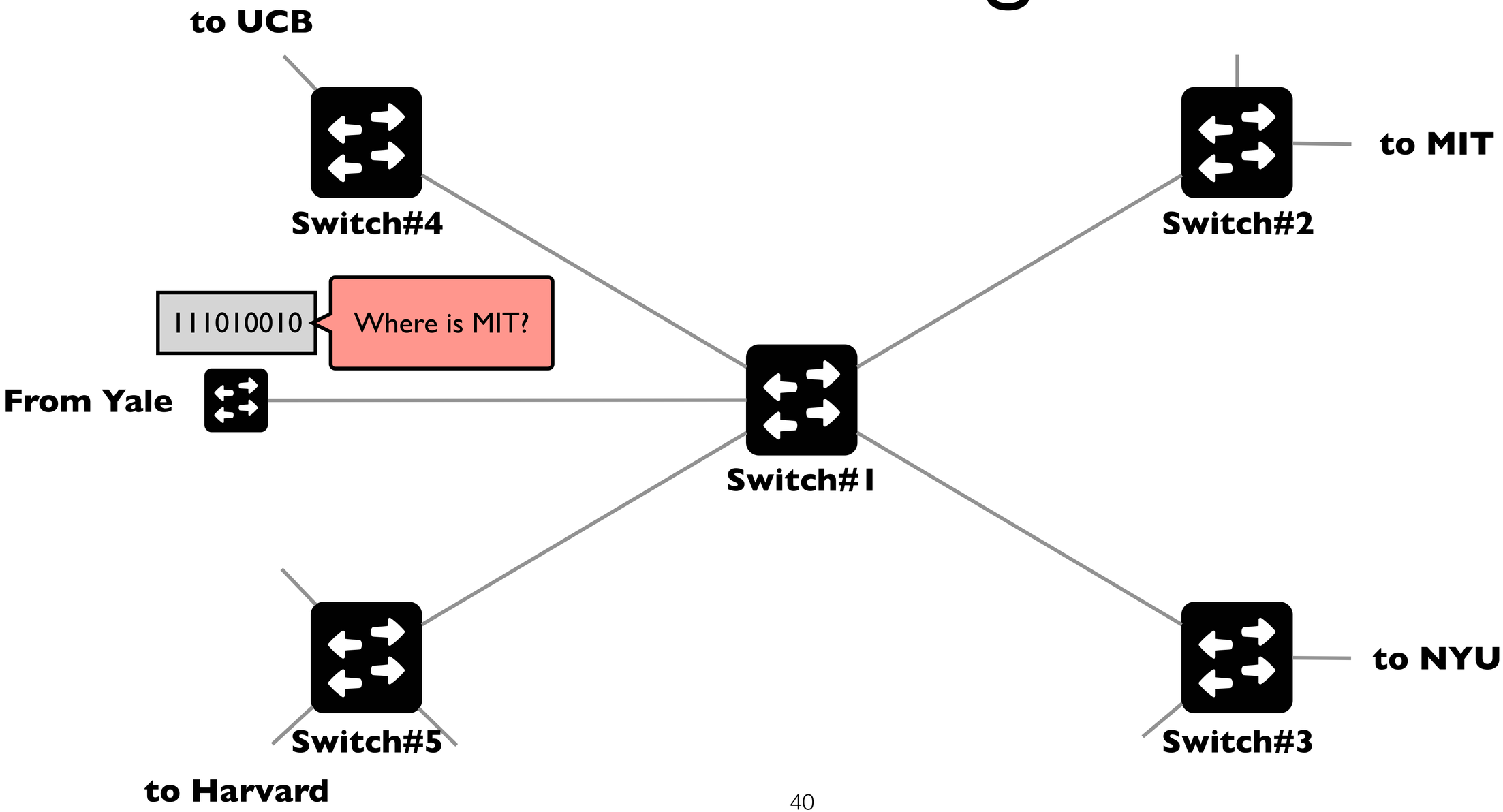
What does the Network Layer do?

- ***Best-effort global delivery of packets***
- Ok, but what does that entail?

Addressing


to UCB
Switch#4
Switch#2
to MIT
111010010
From Yale
Switch#1
Switch#5
Switch#3
to NYU
to Harvard

Addressing


to UCB
Switch#4
Switch#2
to MIT
111010010
Where is MIT?
From Yale
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Switch#5
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Addressing (for now)

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- Assume each end-host has a unique address

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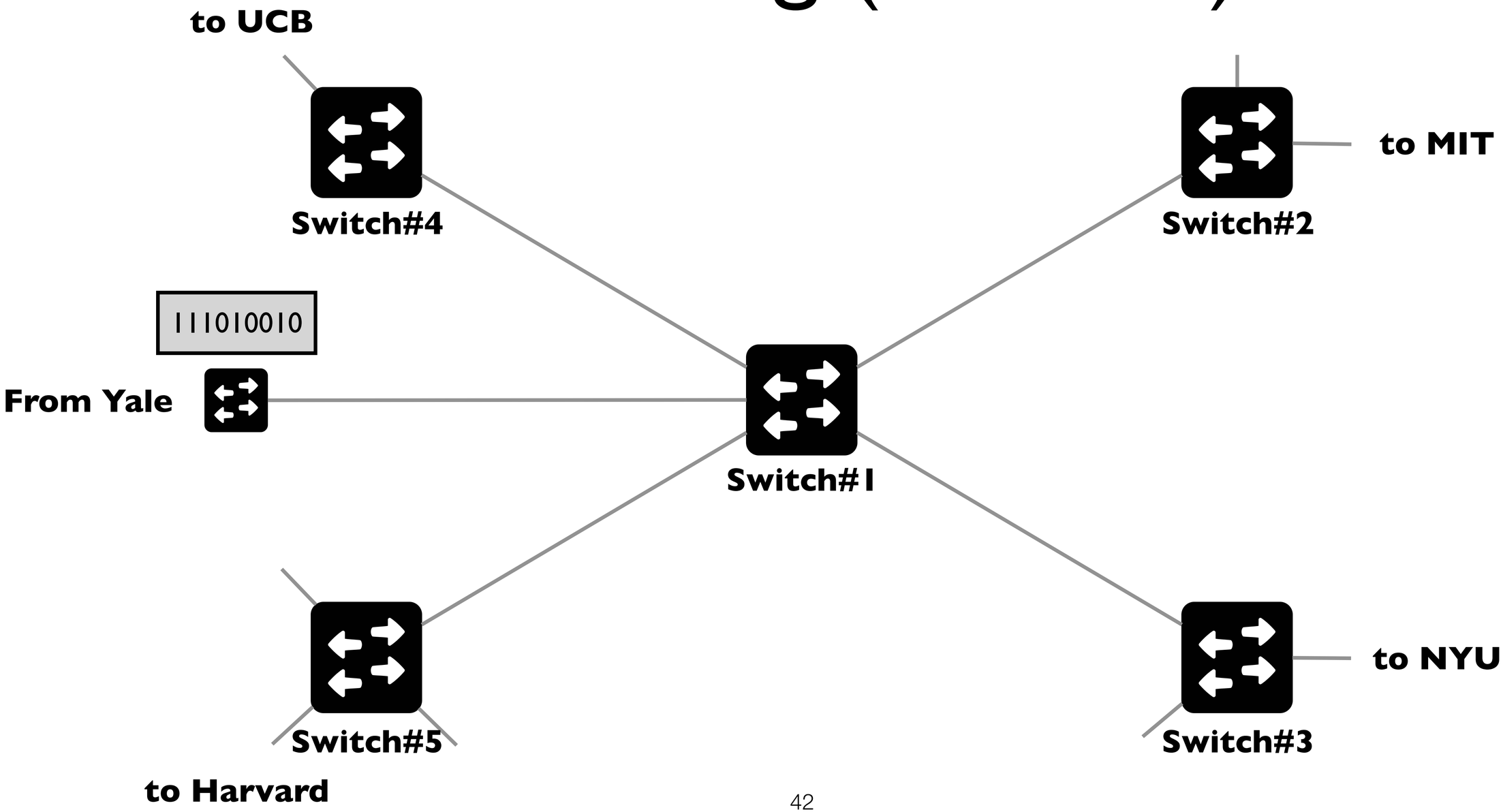
- No particular structure to these addresses
- Will cover IP addresses later in the course

Addressing (for now)



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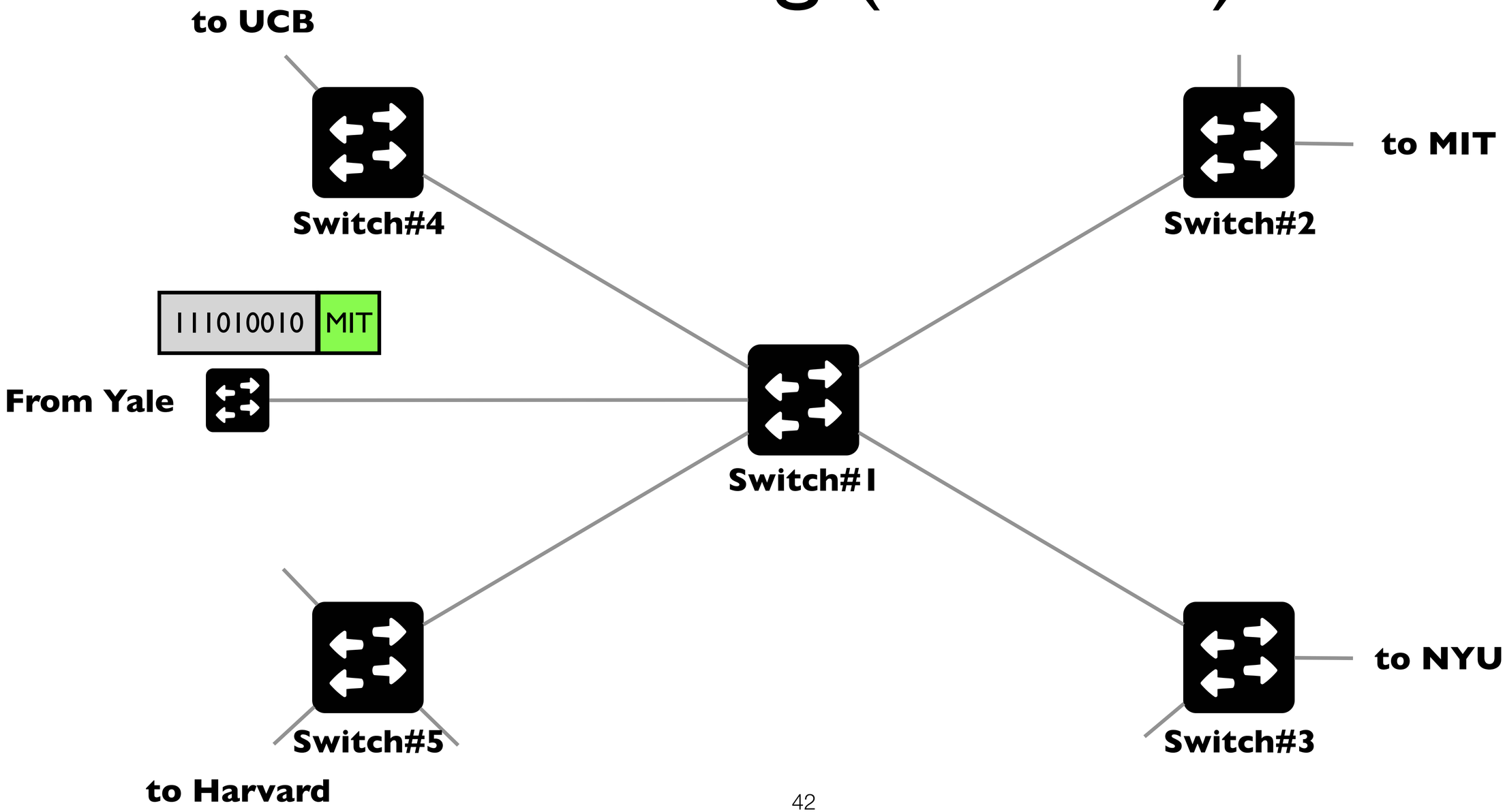

Forwarding

Forwarding

- **Local** router process that determines the output link (aka "next hop") for each packet

Forwarding

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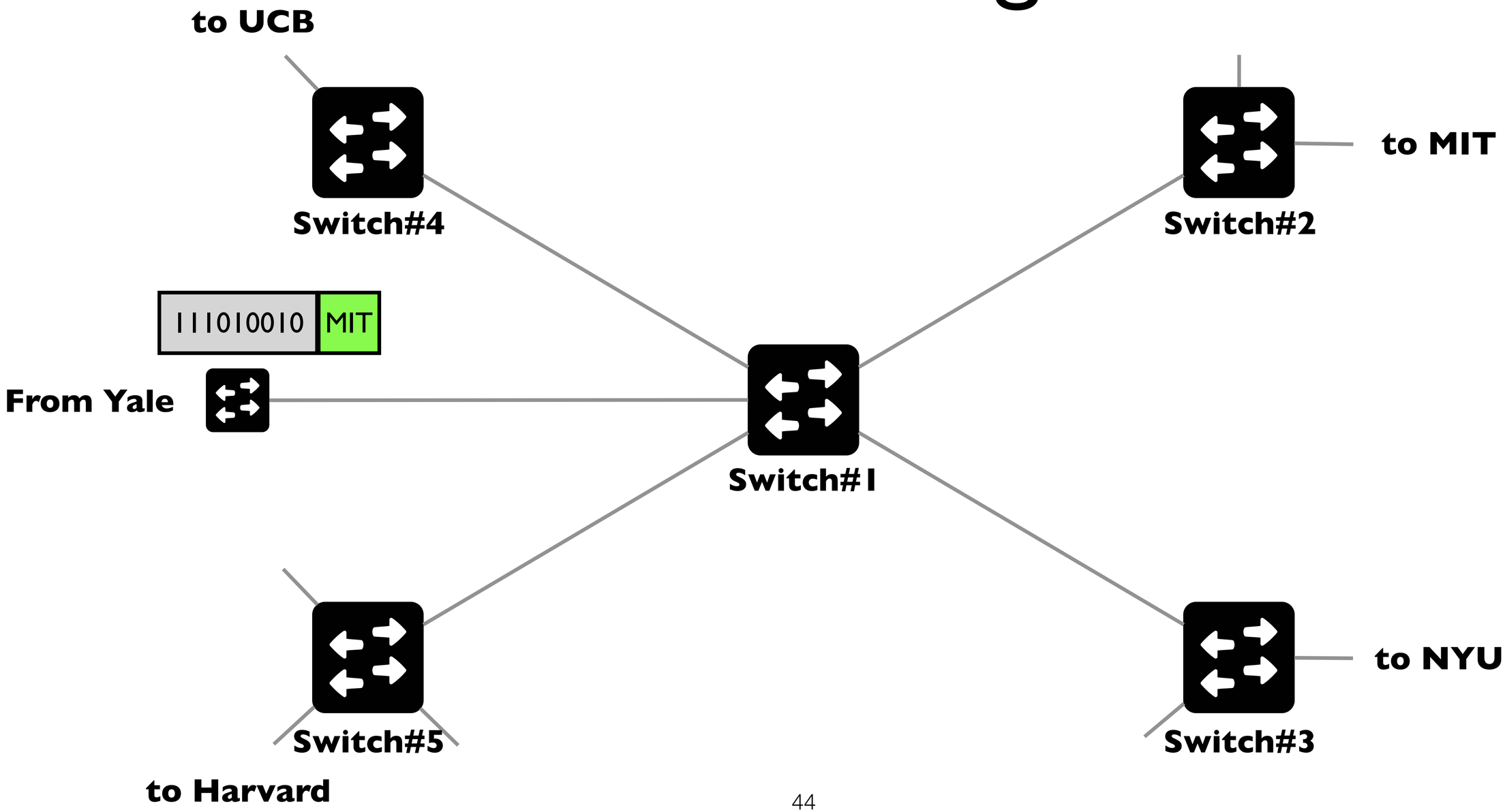
- **How?**
  - Read address from packet's network layer header
  - Search forwarding table

Forwarding


to UCB
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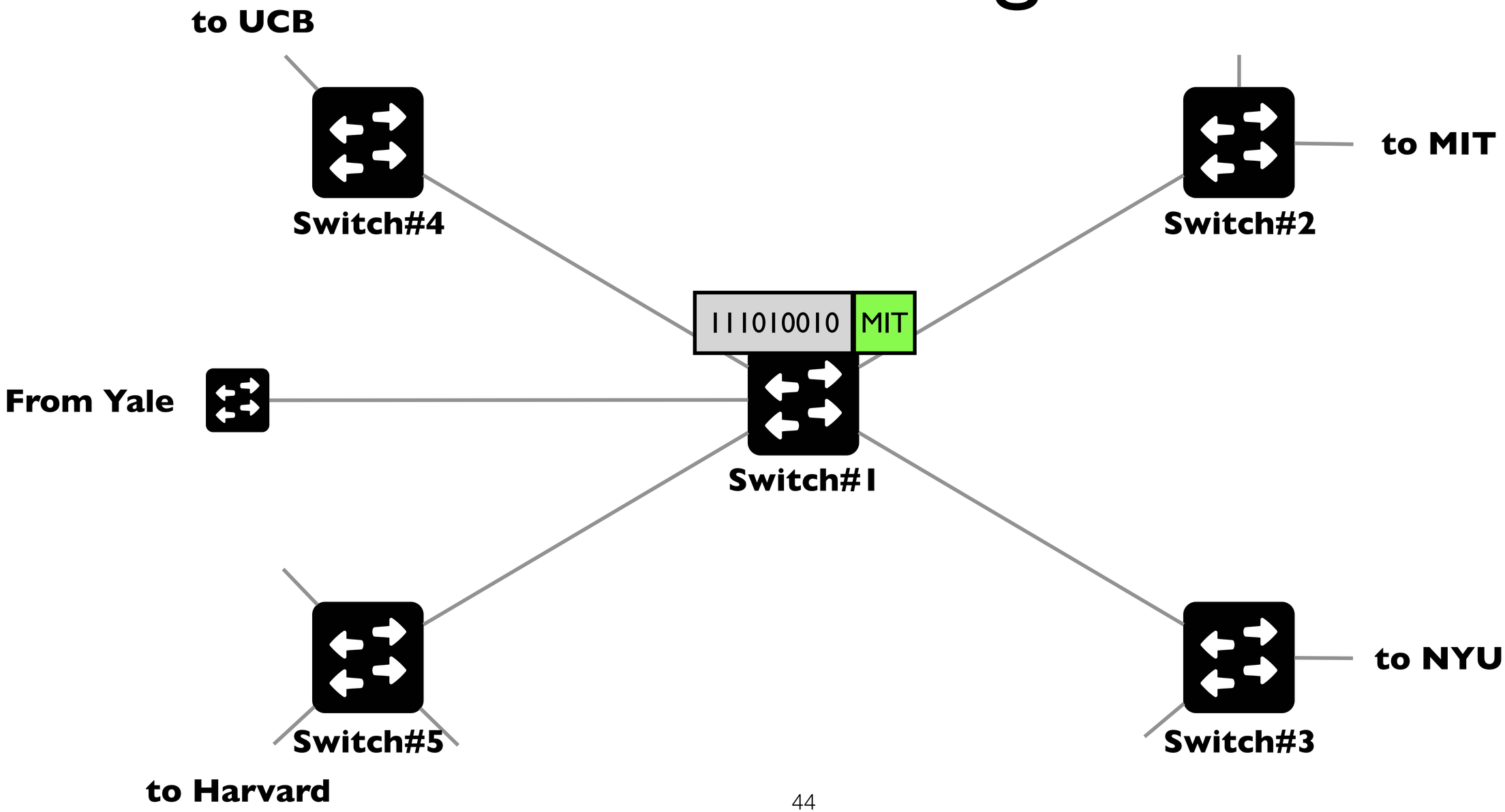
Forwarding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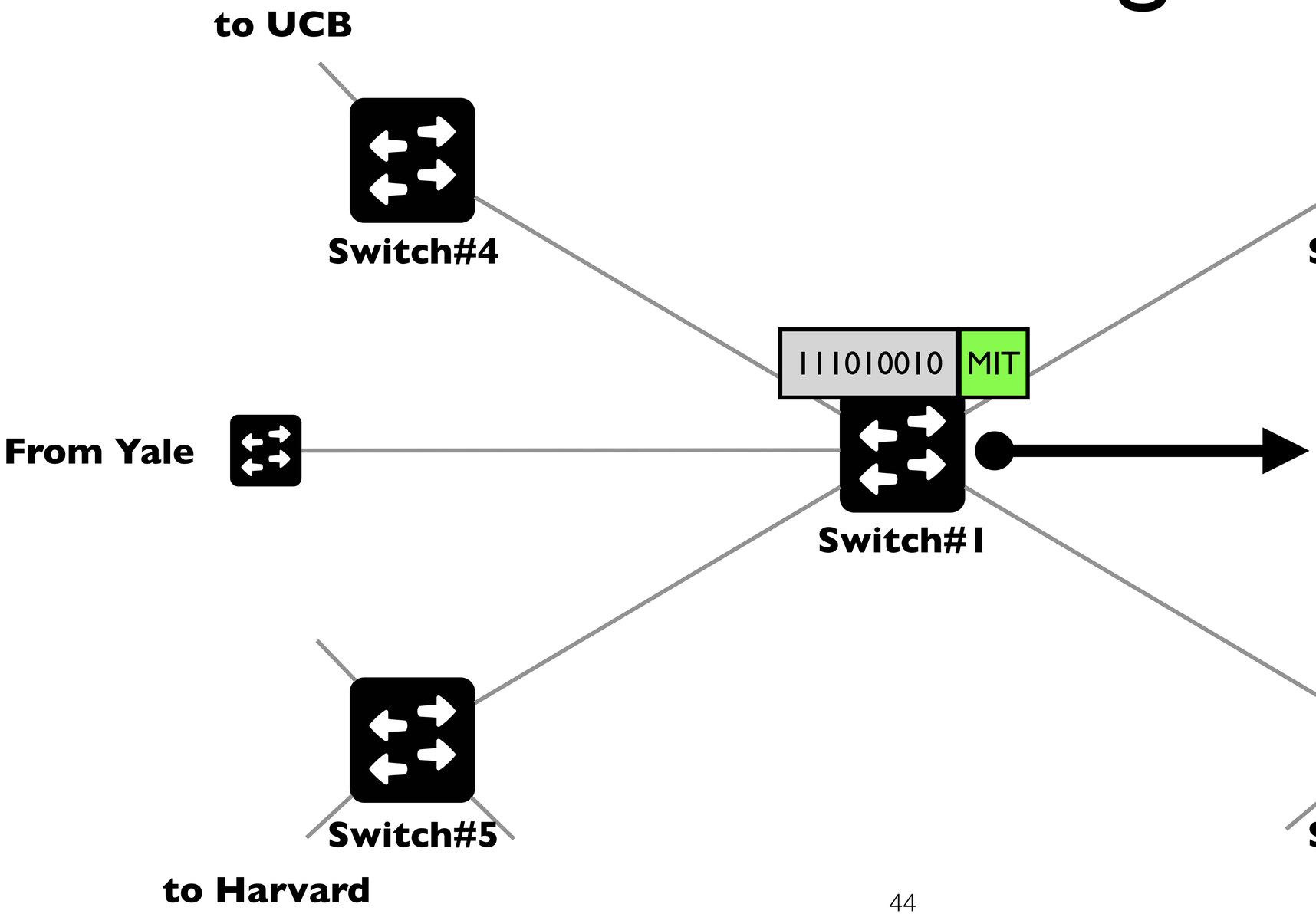
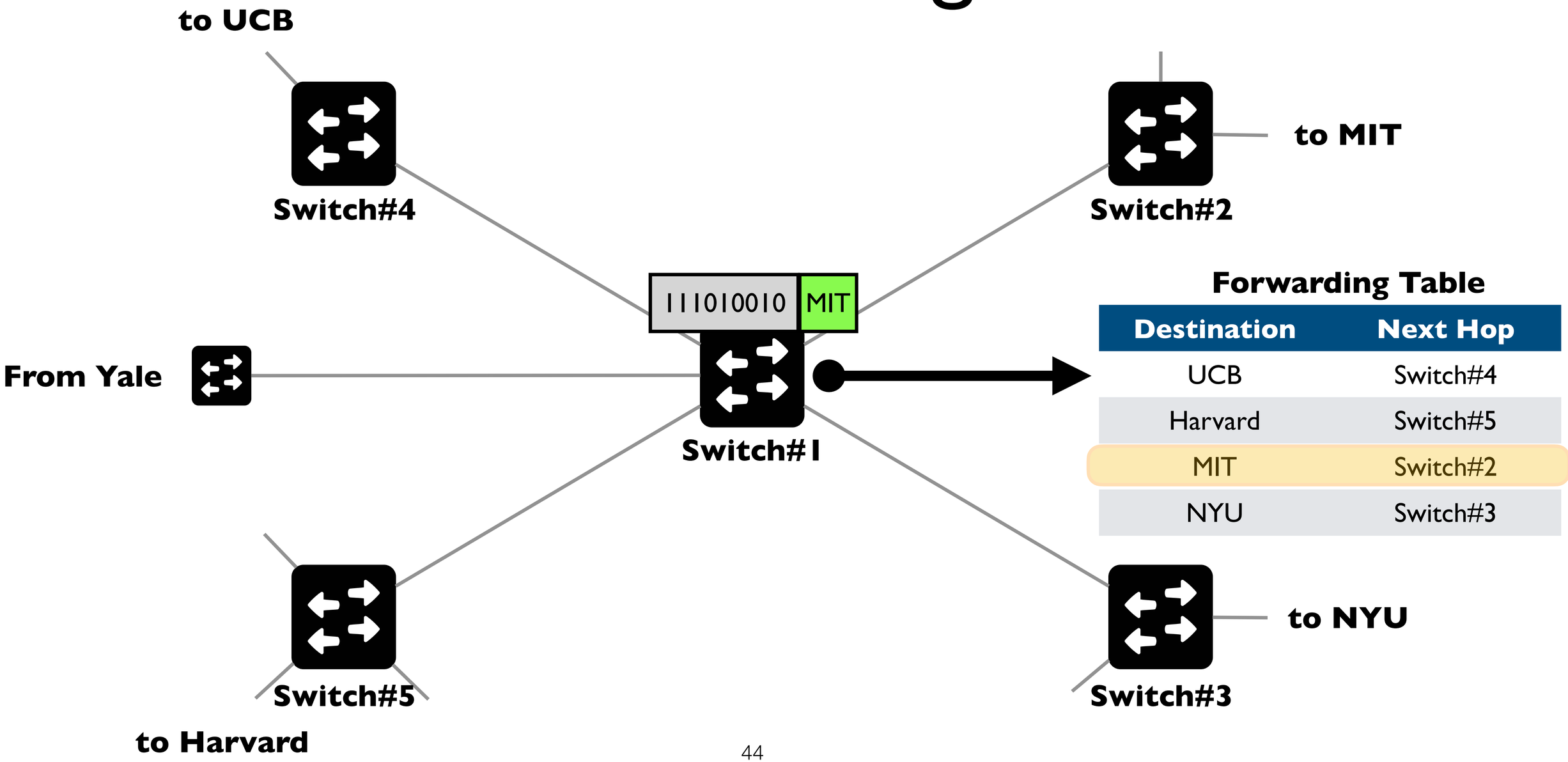
Forwarding



Forwarding Table

Destination	Next Hop
UCB	Switch#4
Harvard	Switch#5
MIT	Switch#2
NYU	Switch#3

Forwarding


to UCB
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Forwarding Table
Destination
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to NYU
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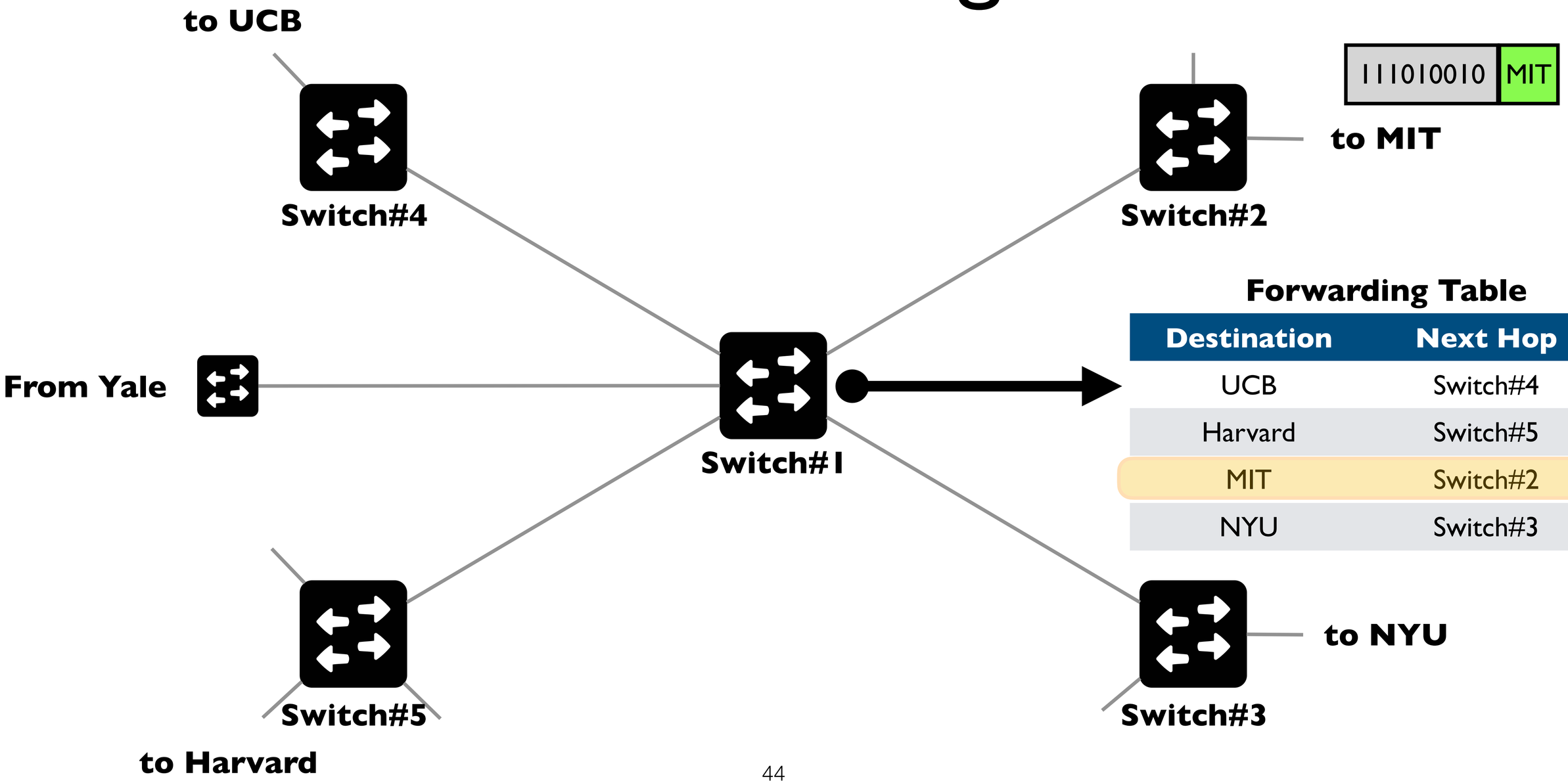
Forwarding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Forwarding Table
Destination
Next Hop
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Switch#4
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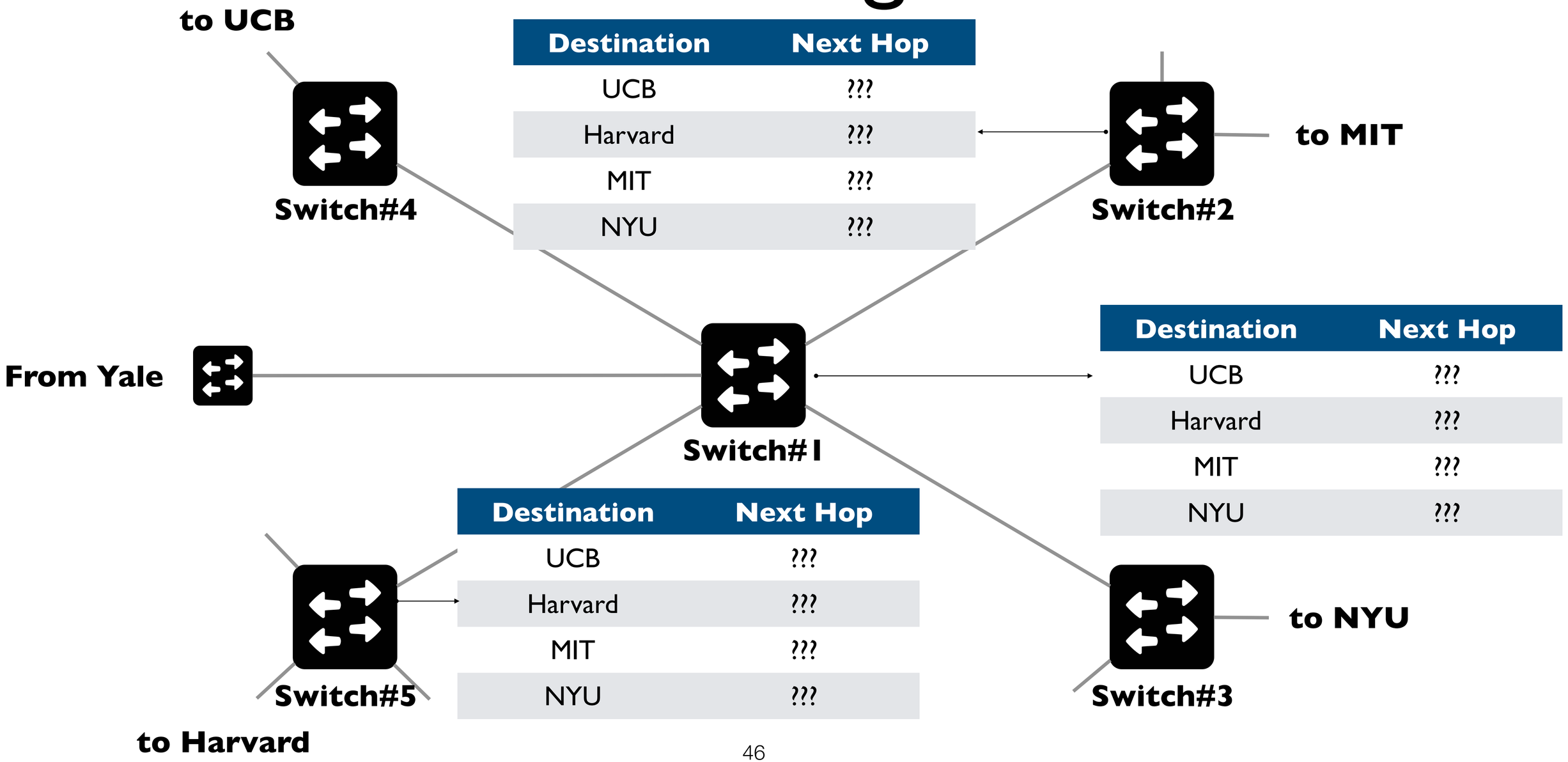
to Harvard
to NYU
Switch#3

Routing

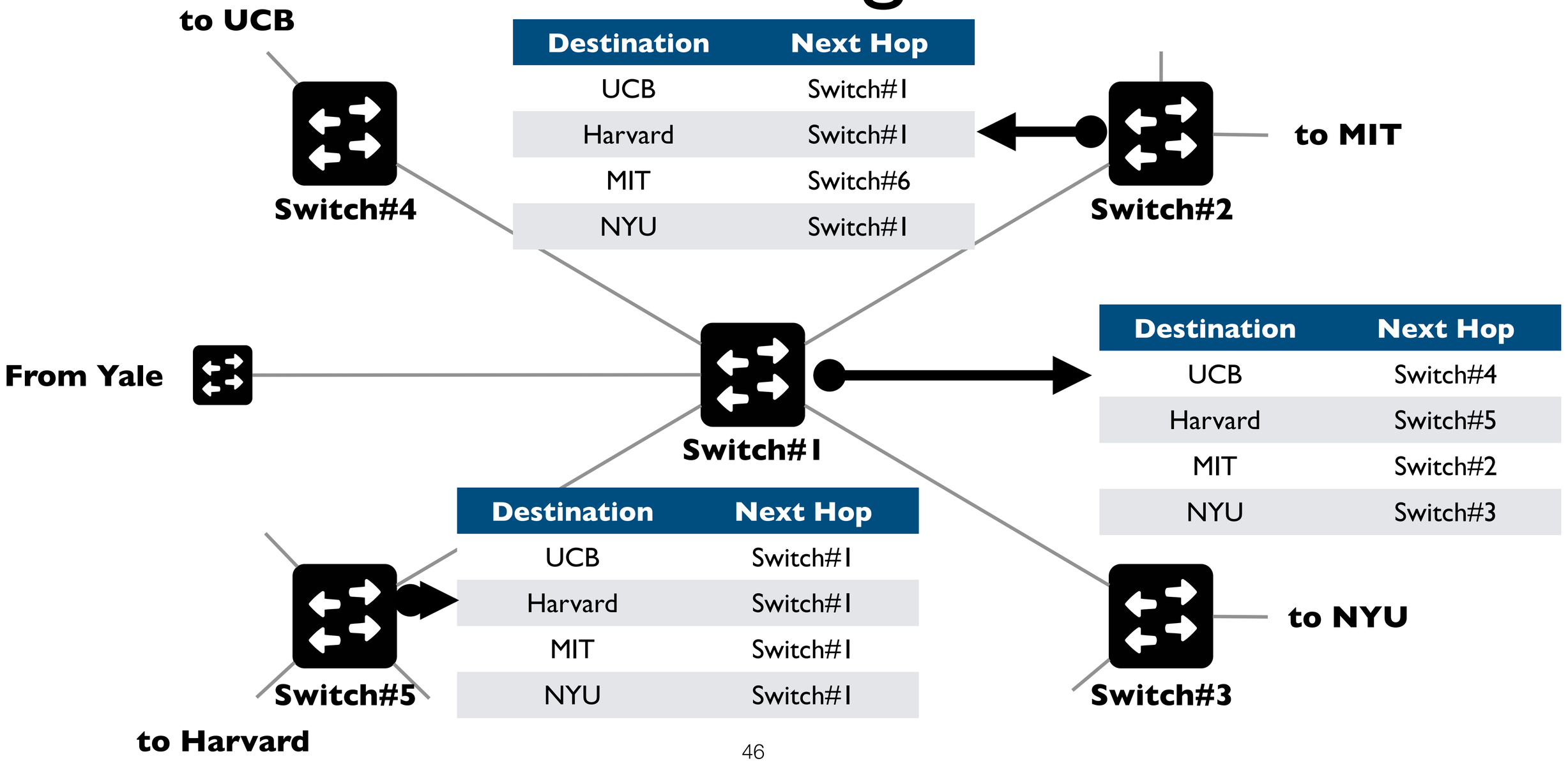
Routing

- **Network-wide** process that determines the content of forwarding tables
  - Determines the end-to-end path for each destination

Routing


to UCB
Switch#4
Destination
Next Hop
UCB
???
Harvard
???
MIT
???
NYU
???
Switch#2
to MIT
From Yale
Switch#1
Destination
Next Hop
UCB
???
Harvard
???
MIT
???
NYU
???
Switch#5
to Harvard
Destination
Next Hop
UCB
???
Harvard
???
MIT
???
NYU
???
Switch#3
to NYU

Routing



Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#6
NYU	Switch#1

Destination	Next Hop
UCB	Switch#4
Harvard	Switch#5
MIT	Switch#2
NYU	Switch#3

Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
NYU	Switch#1

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- **How?**
  - Coming up soon…

Forwarding vs. Routing

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  - Directing one data packet
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- Very different timescales!

Goals (for Routing)

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- **V1: Find a path to a given destination**

Goals (for Routing)

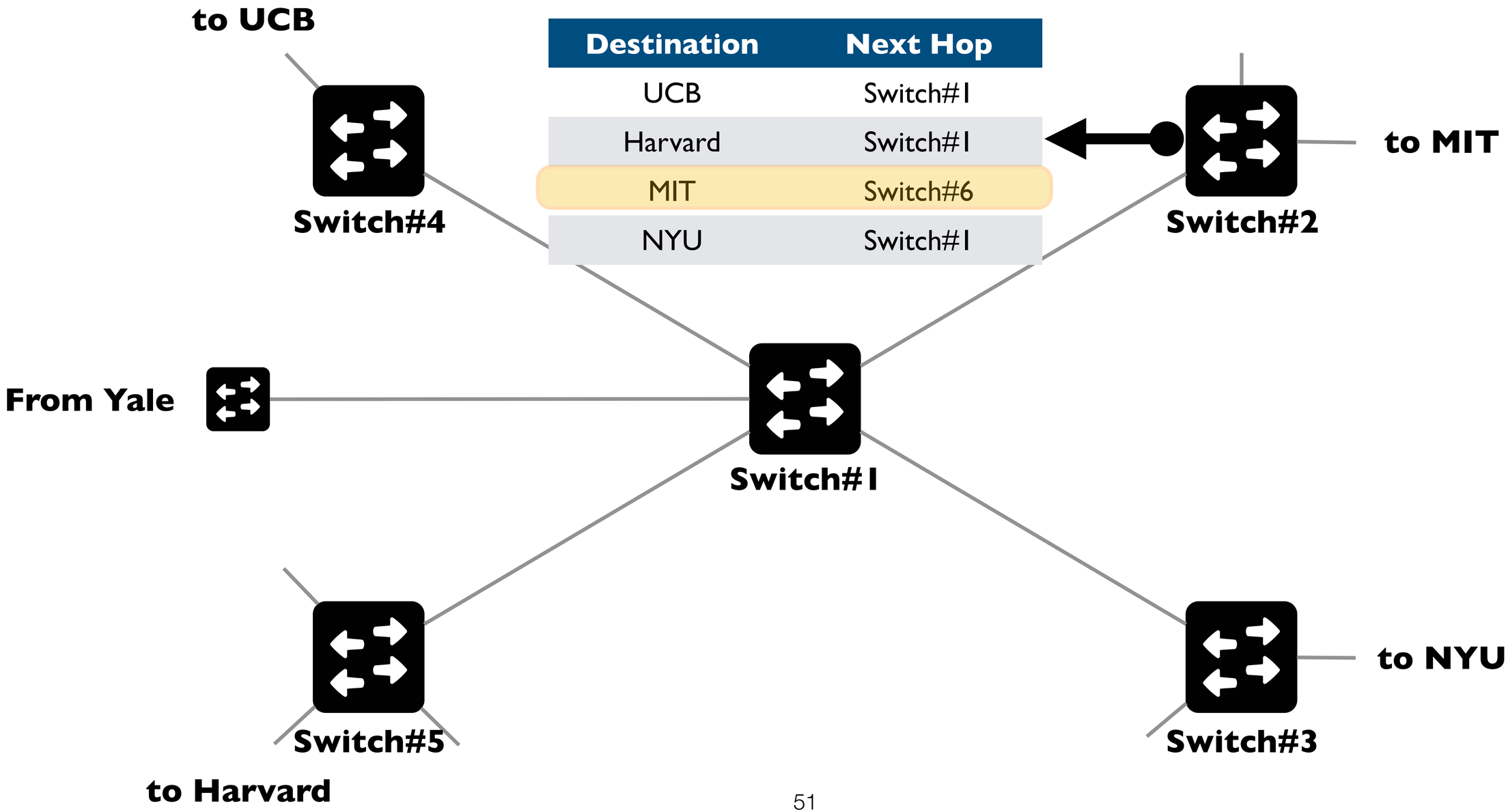
- **V1: Find a path to a given destination**
- How do we know that the state contained in forwarding tables meets our goal?
  - This is what "validity" of routing state tells us
  - [this is non-standard terminology]

Local vs. Global view of state

Local vs. Global view of state

- **Local** routing state is the forwarding table in a single router
  - By itself, the state in a single router cannot be evaluated for validity
  - It must be evaluated in terms of the global context

Local vs. Global view of state



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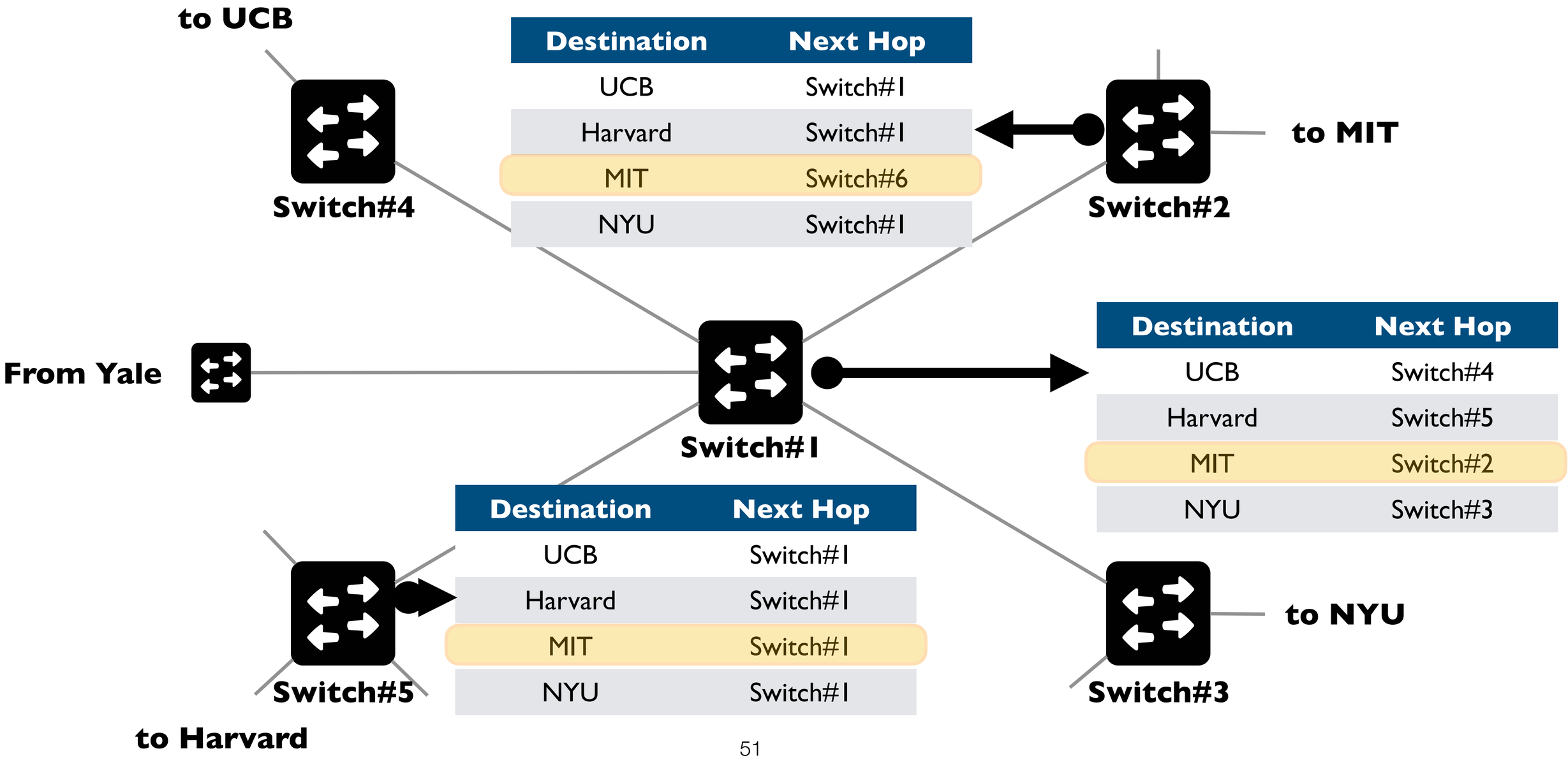

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- **Local** routing state is the forwarding table in a single router
  - By itself, the state in a single router cannot be evaluated for validity
  - It must be evaluated in terms of the global context
- **Global** state refers to the collection of forwarding tables in each of the routers
  - Global state determines which paths packet take

    (Will discuss later *where* the state comes from)

“Valid” Routing State

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- Global state is **“valid”** if it produces forwarding decisions that always deliver packets to their destinations

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“Valid” Routing State

- Global state is **“valid”** if it produces forwarding decisions that always deliver packets to their destinations
- **Goal of routing protocols:** compute valid state
  - But how can you tell if routing state is valid
- Need a **succinct** correctness condition for routing
  - *Suggestions?*

Necessary and Sufficient Condition

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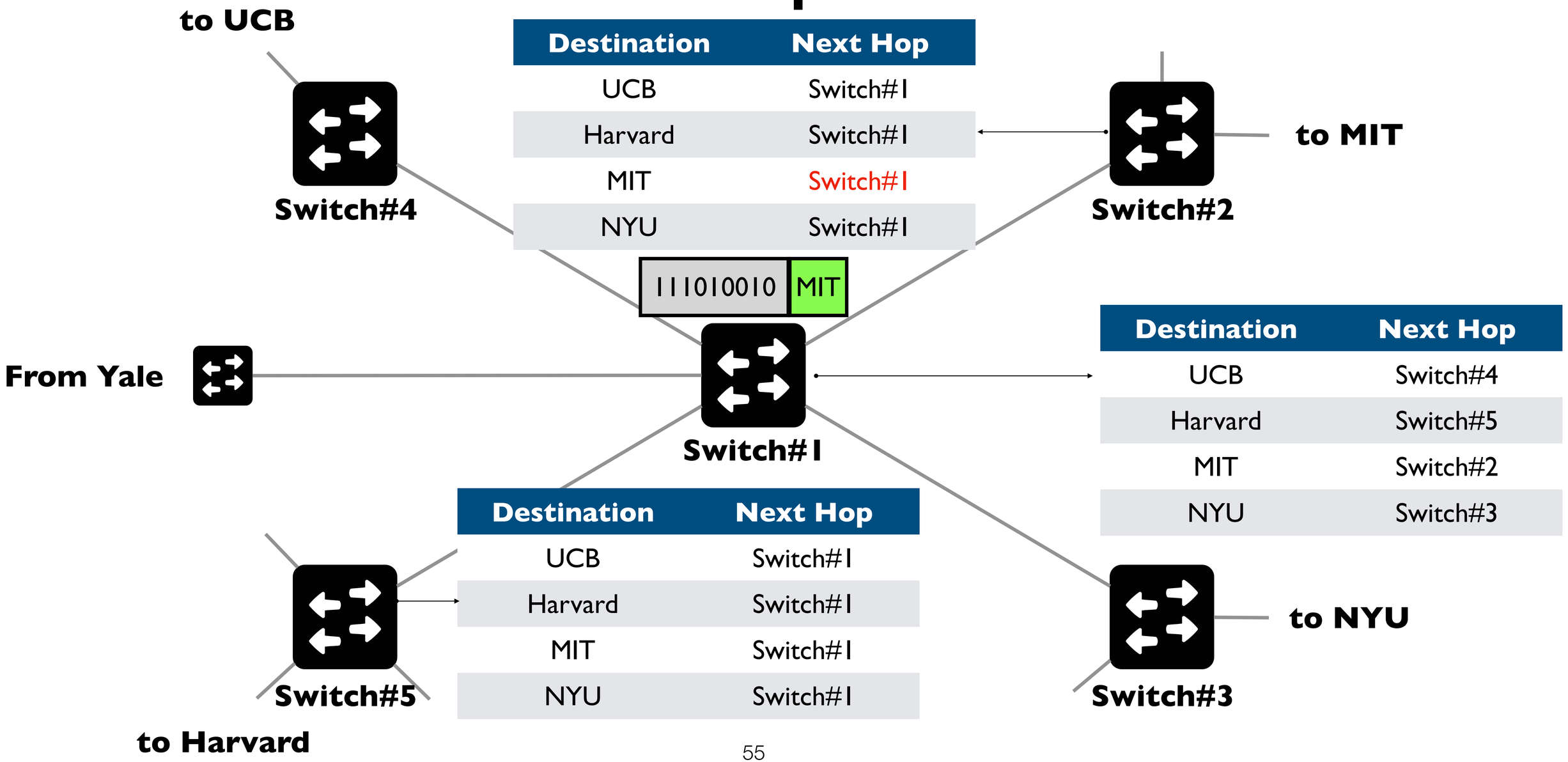
- Loop: when a packet cycles around the same set of nodes forever

Loops

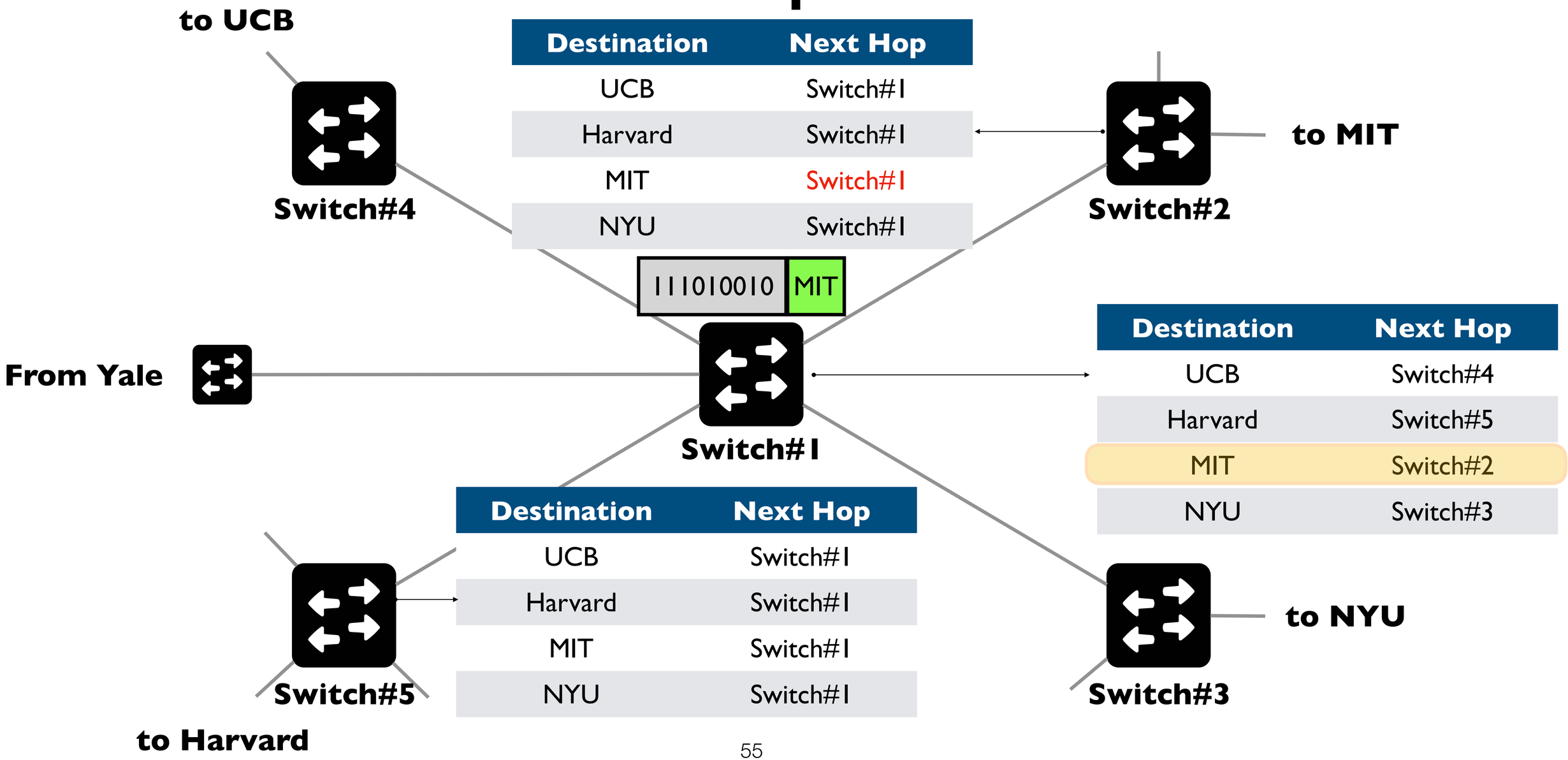


Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
NYU	Switch#1

Destination	Next Hop
UCB	Switch#4
Harvard	Switch#5
MIT	Switch#2
NYU	Switch#3

Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
NYU	Switch#1

Loops

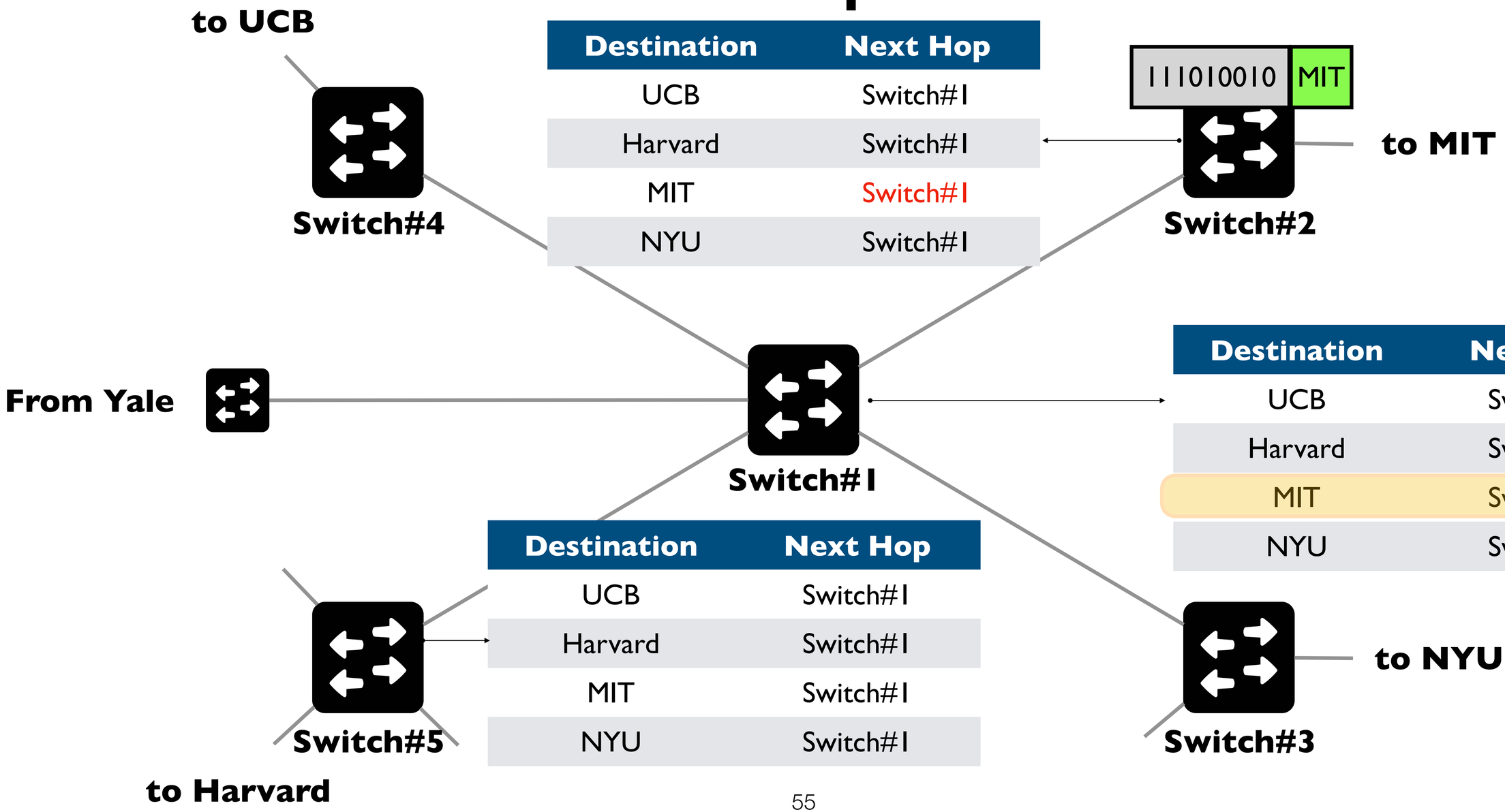


Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
NYU	Switch#1

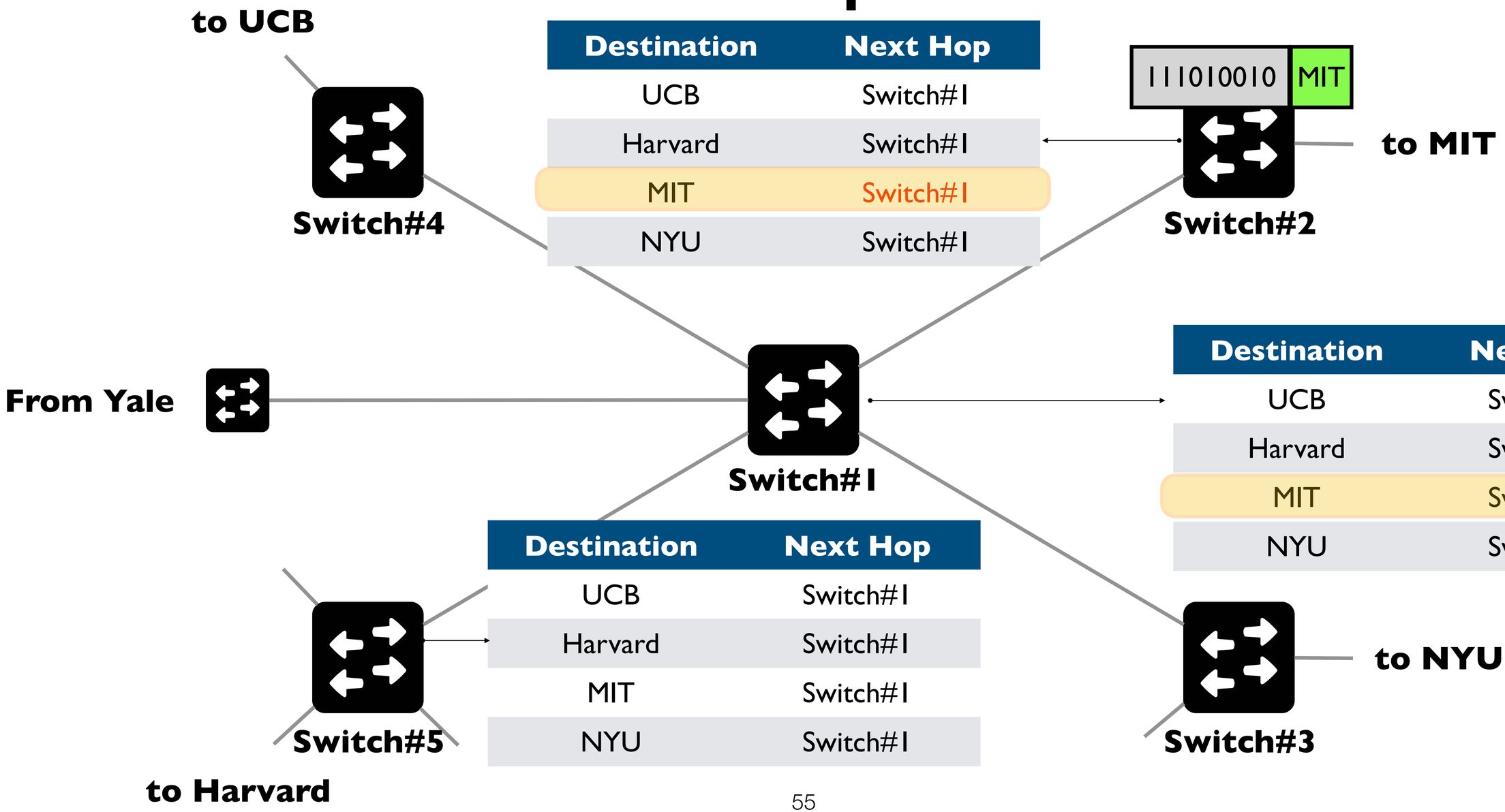
Destination	Next Hop
UCB	Switch#4
Harvard	Switch#5
MIT	Switch#2
NYU	Switch#3

Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
NYU	Switch#1

Loops


to UCB
Switch#4
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
111010010
MIT
Switch#2
to MIT
From Yale
Switch#1
Destination
Next Hop
UCB
Switch#4
Harvard
Switch#5
MIT
Switch#2
NYU
Switch#3
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
Switch#5
to Harvard
Switch#3
to NYU

Loops


to UCB
Switch#4
Destination
Next Hop
UCB
Switch#1
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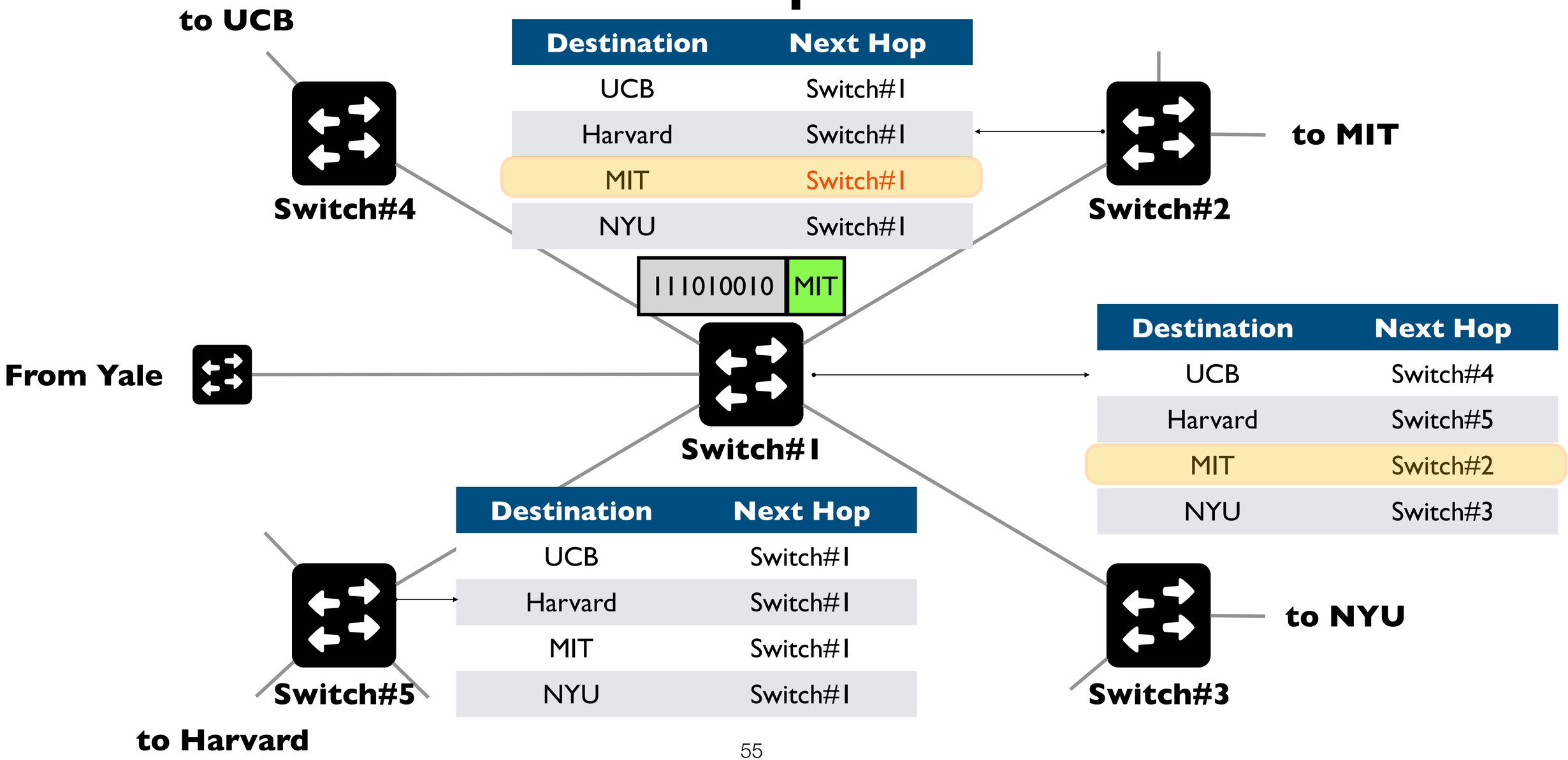
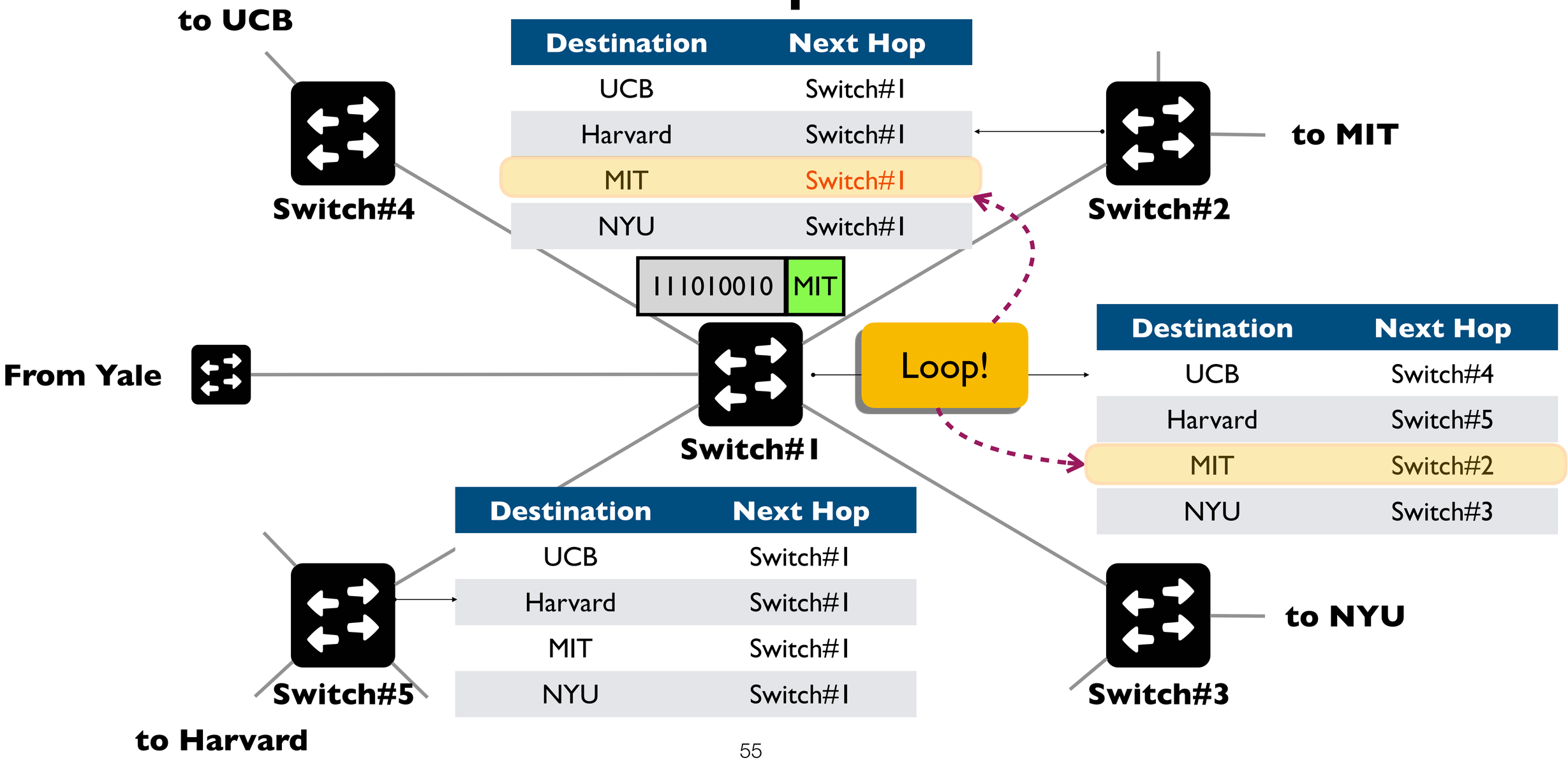
Switch#1
MIT
Switch#1
NYU
Switch#1
111010010
MIT
Switch#2
to MIT
From Yale
Switch#1
Destination
Next Hop
UCB
Switch#4
Harvard
Switch#5
MIT
Switch#2
NYU
Switch#3
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
Switch#5
to Harvard
Switch#3
to NYU

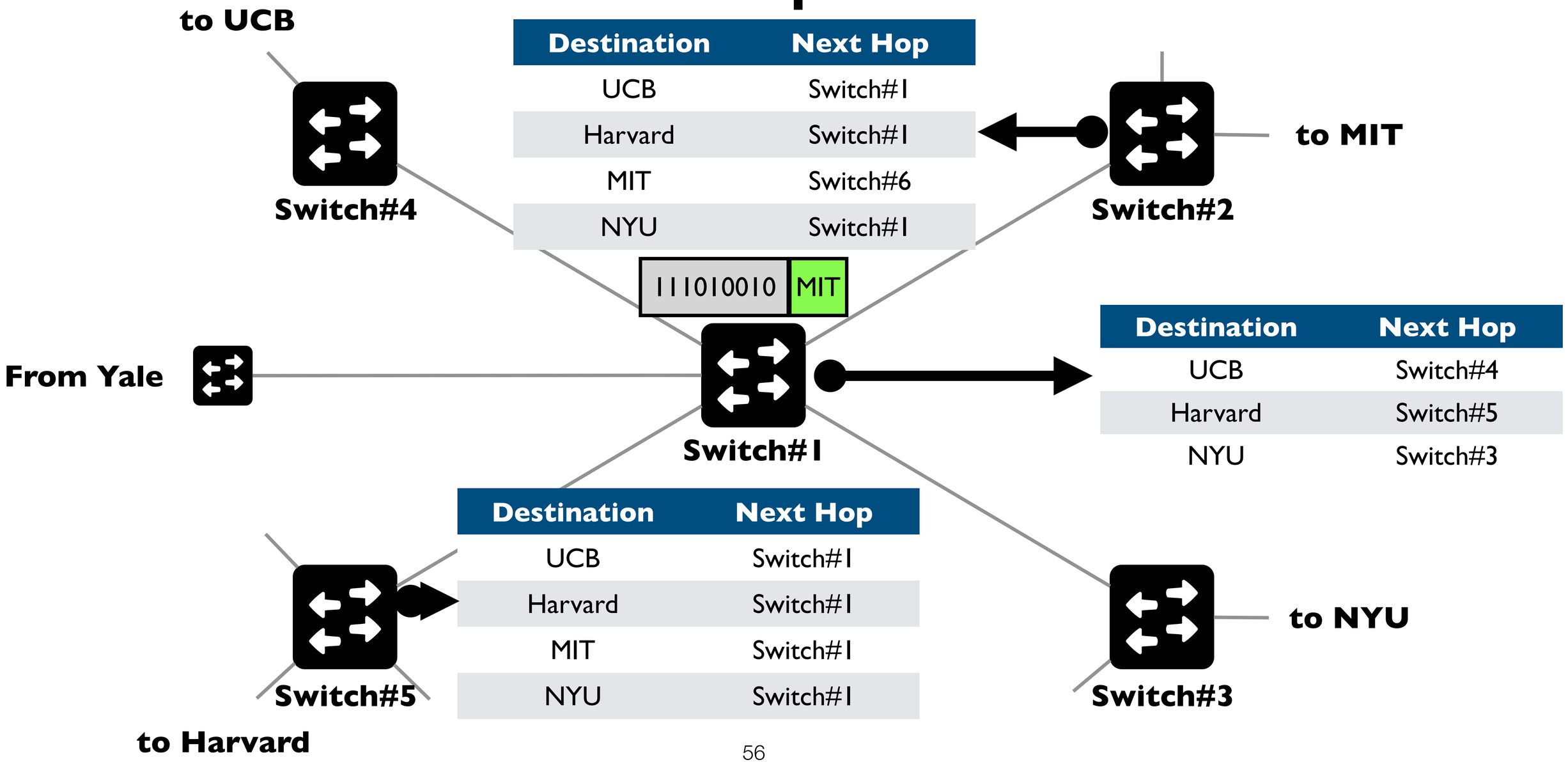
Loops


to UCB
Switch#4
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
111010010
MIT
Switch#2
to MIT
From Yale
Switch#1
Destination
Next Hop
UCB
Switch#4
Harvard
Switch#5
MIT
Switch#2
NYU
Switch#3
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
Switch#5
to Harvard
Switch#3
to NYU

Loops


to UCB
Switch#4
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
111010010
MIT
to MIT
Switch#2
From Yale
Switch#1
Loop!
Destination
Next Hop
UCB
Switch#4
Harvard
Switch#5
MIT
Switch#2
NYU
Switch#3
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
Switch#5
to Harvard
to NYU
Switch#3

Loops

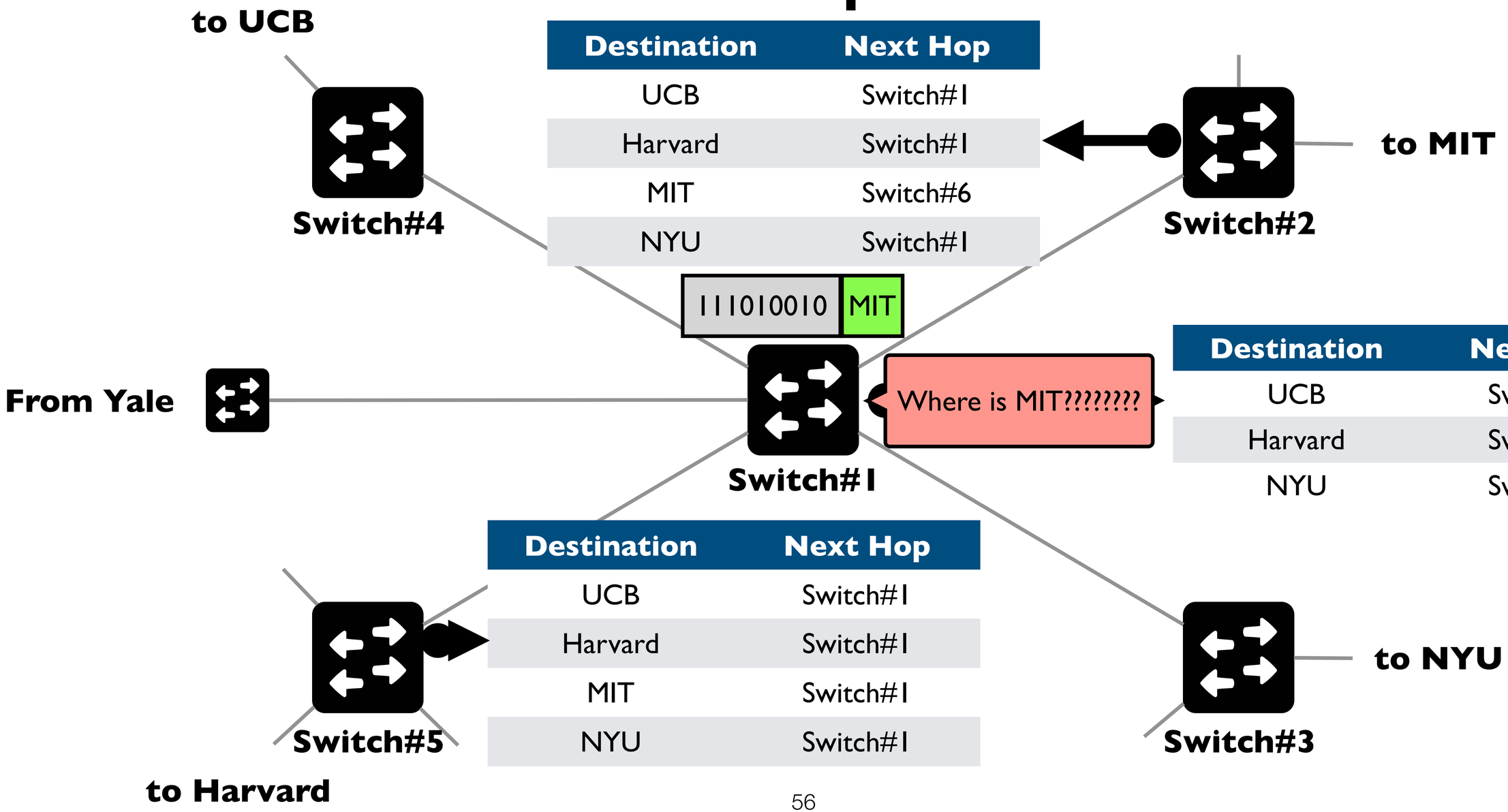


Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#6
NYU	Switch#1

Destination	Next Hop
UCB	Switch#4
Harvard	Switch#5
NYU	Switch#3

Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
NYU	Switch#1

Loops

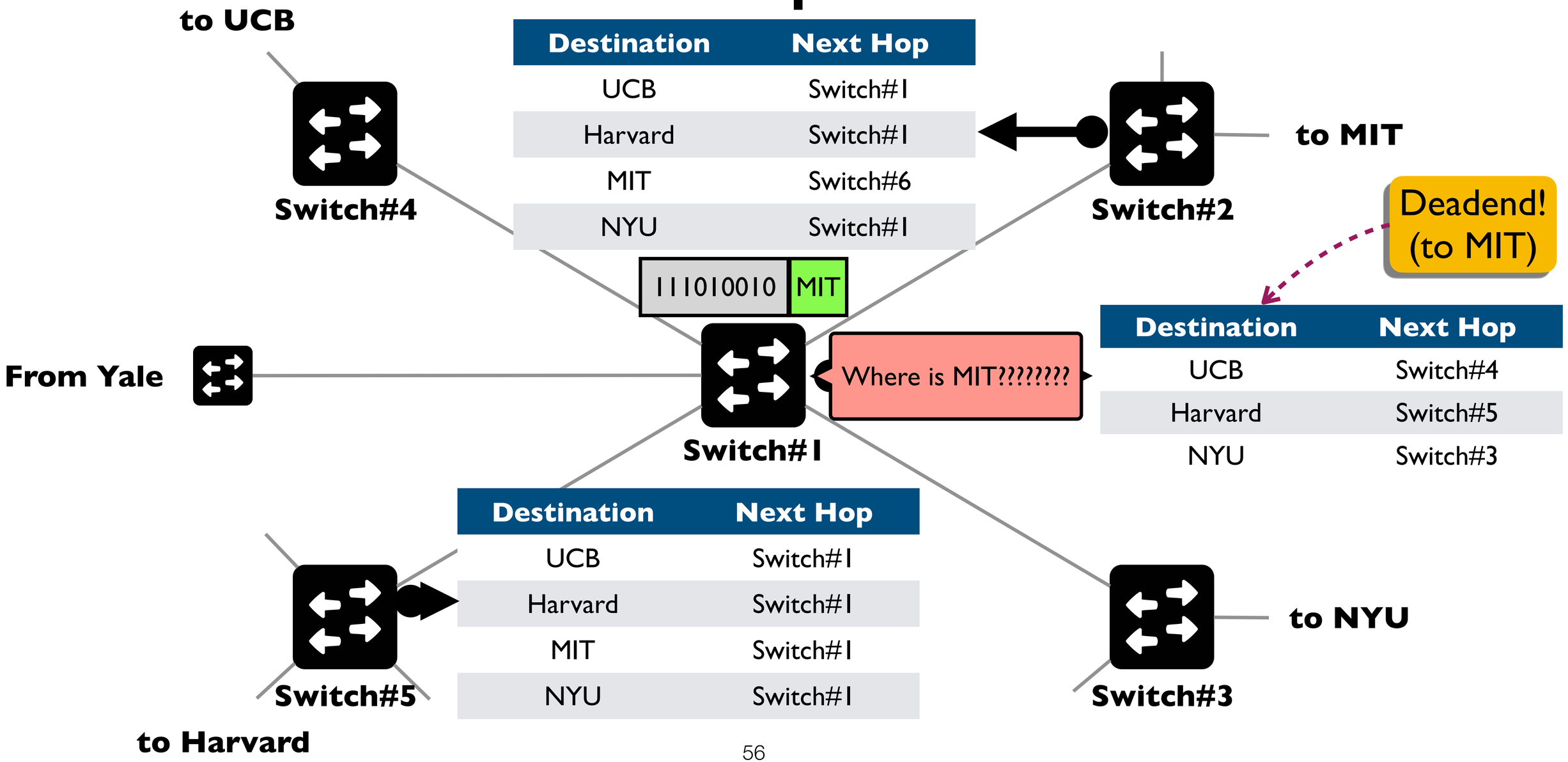


Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#6
NYU	Switch#1

Destination	Next Hop
UCB	Switch#4
Harvard	Switch#5
NYU	Switch#3

Destination	Next Hop
UCB	Switch#1
Harvard	Switch#1
MIT	Switch#1
NYU	Switch#1

Loops


to UCB
Switch#4
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#6
NYU
Switch#1
111010010
MIT
Switch#2
to MIT
Deadend!
(to MIT)
From Yale
Switch#1
Where is MIT????????
Destination
Next Hop
UCB
Switch#4
Harvard
Switch#5
NYU
Switch#3
Destination
Next Hop
UCB
Switch#1
Harvard
Switch#1
MIT
Switch#1
NYU
Switch#1
Switch#5
to Harvard
Switch#3
to NYU

Necessary and Sufficient Condition

Necessary and Sufficient Condition

- Global routing state is "valid" ***if and only if:***
  - There are no dead-ends (other than the destination)
  - There are no loops

Necessary (“only if”): Easy

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- If you run into a dead-end before reaching destination, you'll **never** reach the destination

Necessary (“only if”): Easy

- If you run into a dead-end before reaching destination, you’ll **never** reach the destination
- If you run into a loop before reaching destination, you’ll **never** reach the destination

Sufficient (“if”)

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- Assume no dead-ends, no loops

Sufficient (“if”)

- Assume no dead-ends, no loops
- Packets may keep wandering, but without repeating link
  - If ever a packet enters the same switch from the same link, there must be a loop

Sufficient ("if")

- **Assume no dead-ends, no loops**
- **Packets may keep wandering, but without repeating link**
  - If ever a packet enters the same switch from the same link, there must be a loop
- **Only a finite number of possible links for it to visit**
  - It cannot keep wandering forever without looping
  - Must eventually hit destination!

Checking Validity of Routing State

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- **Focus only on a single destination**
  - Ignore all other routing state

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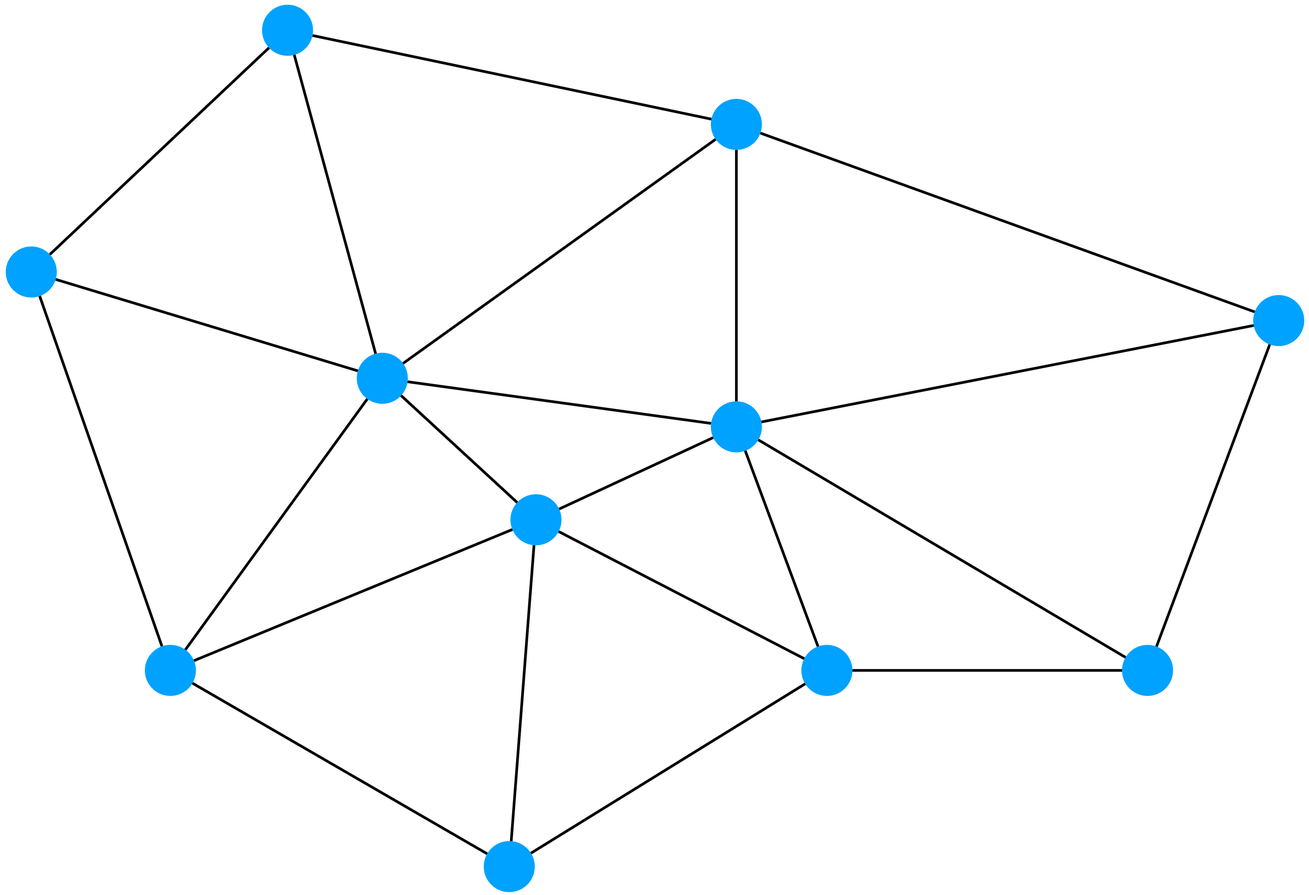
- **Mark outgoing link to that destination ("next hop") with arrow**
  - There is only one at each node

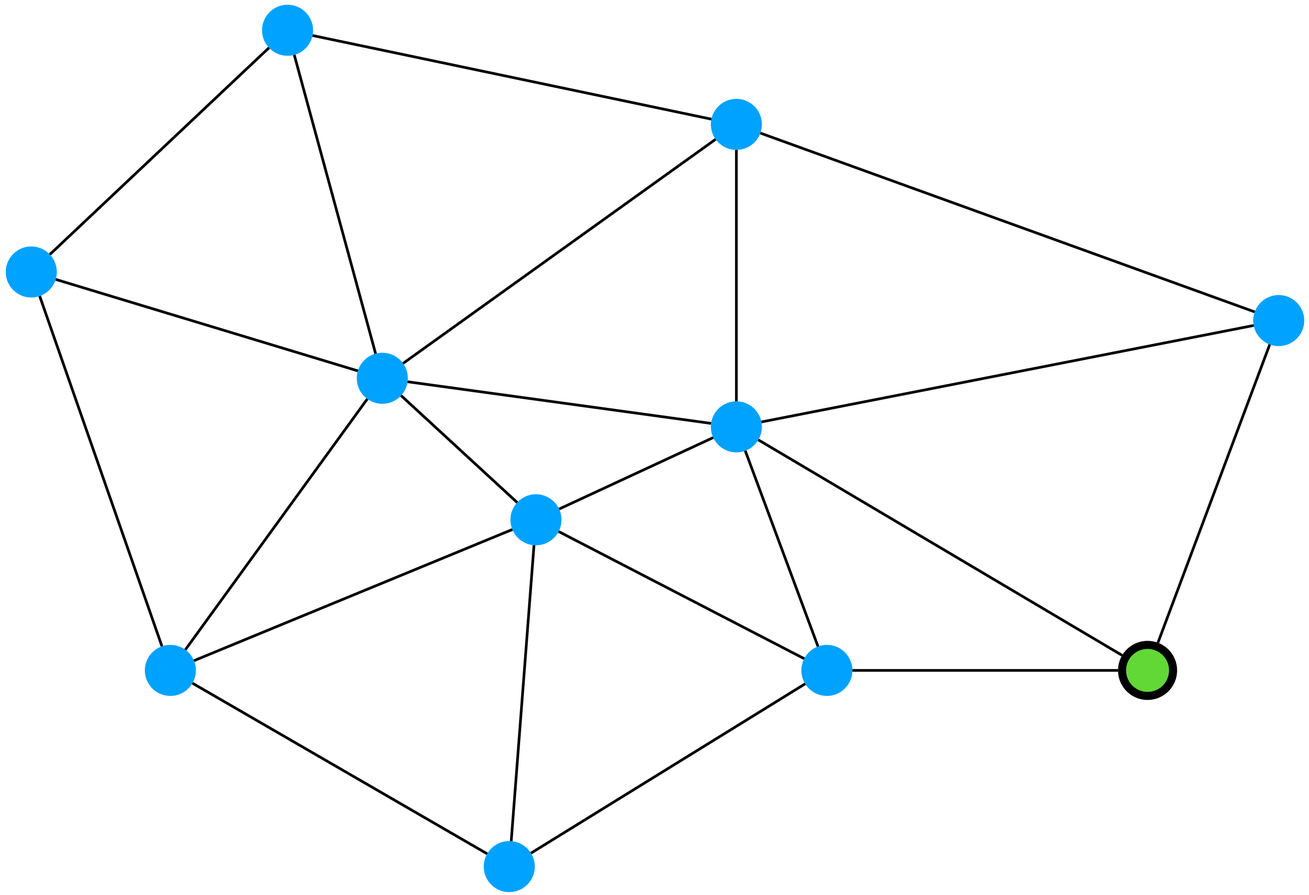
Checking Validity of Routing State

- **Focus only on a single destination**
  - Ignore all other routing state
- **Mark outgoing link to that destination ("next hop") with arrow**
  - There is only one at each node
- **Eliminate all links with no arrows**
  - Look at what's left…

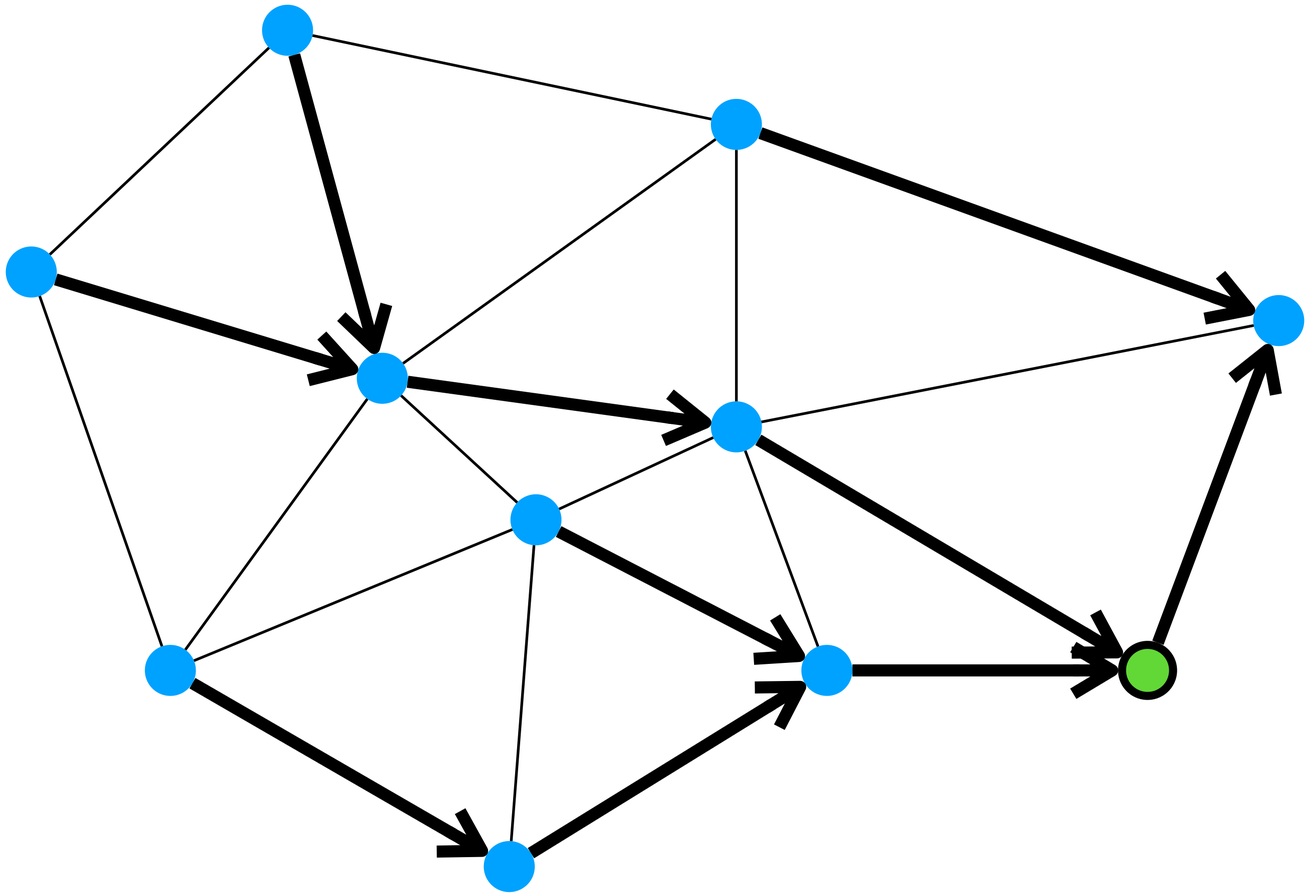
Example 1



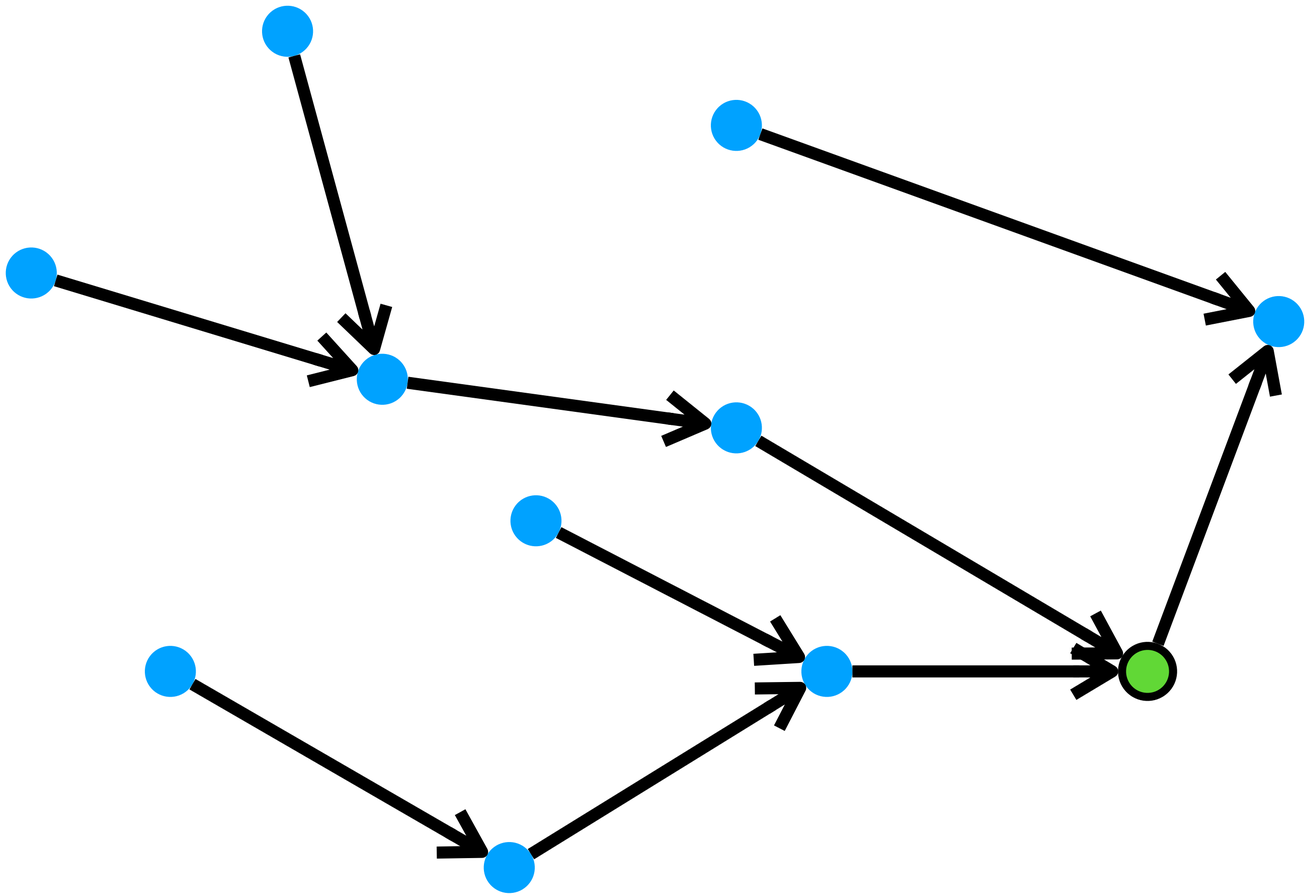
Pick Destination



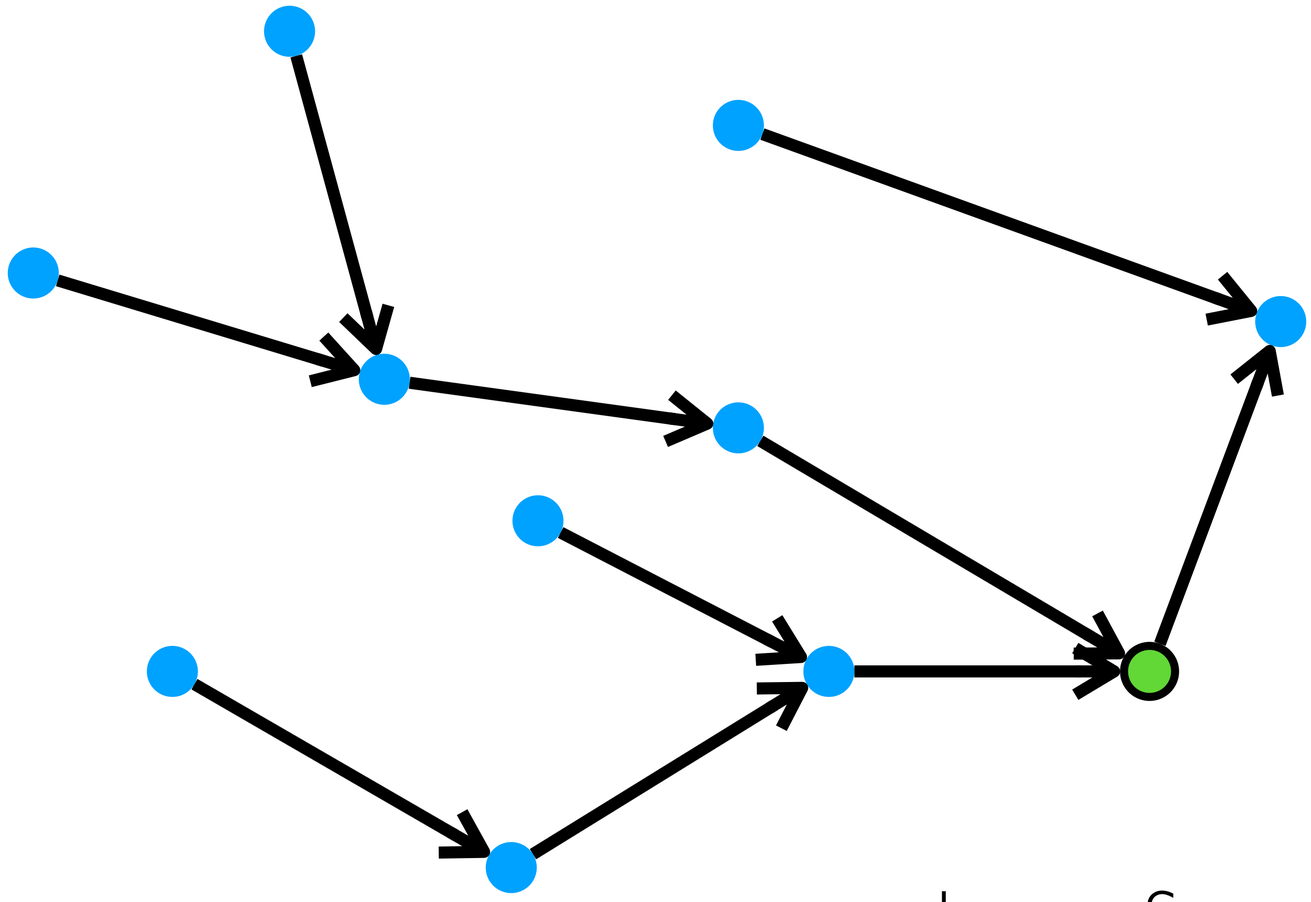
Put arrows on outgoing links (to green dot)



Remove Unused Links

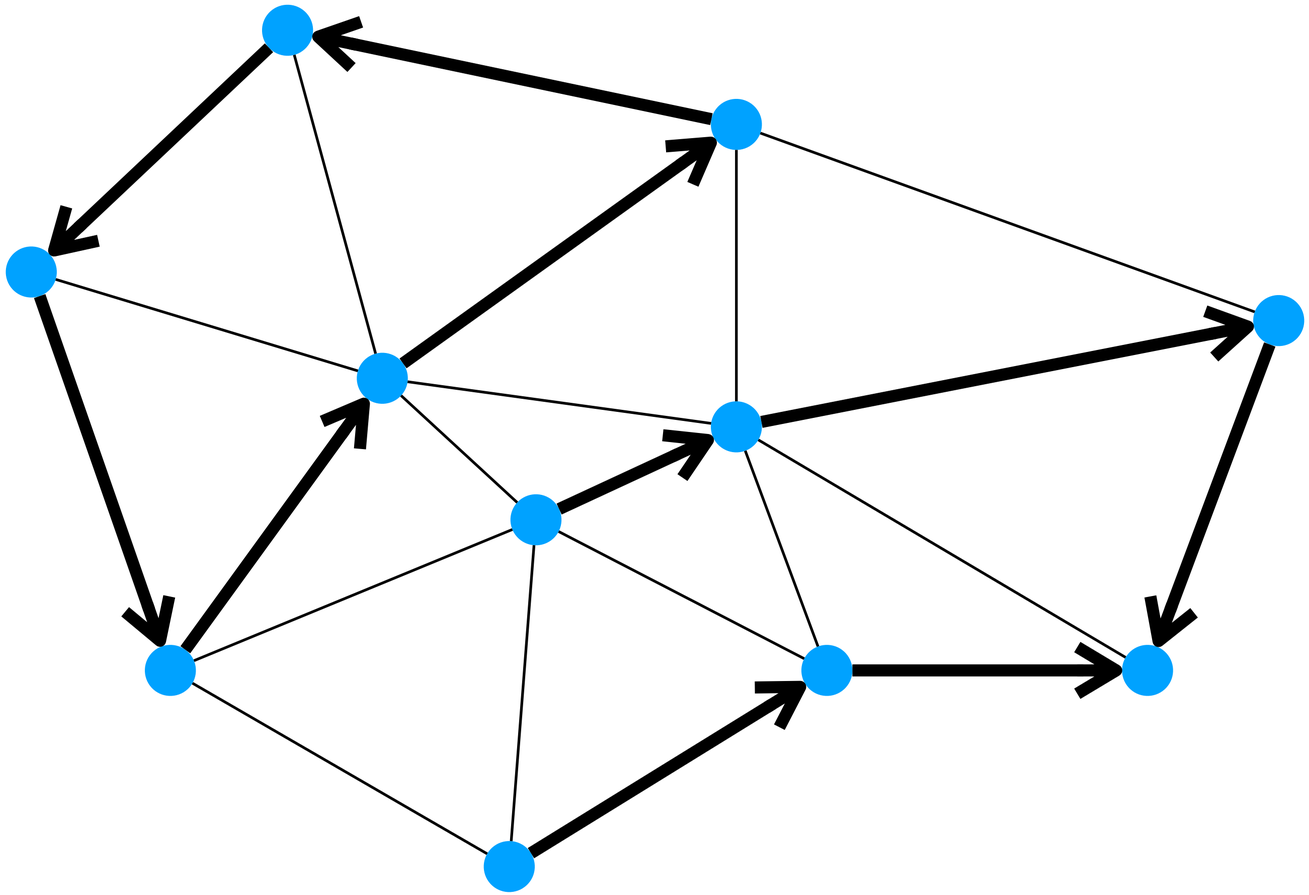


Remove Unused Links

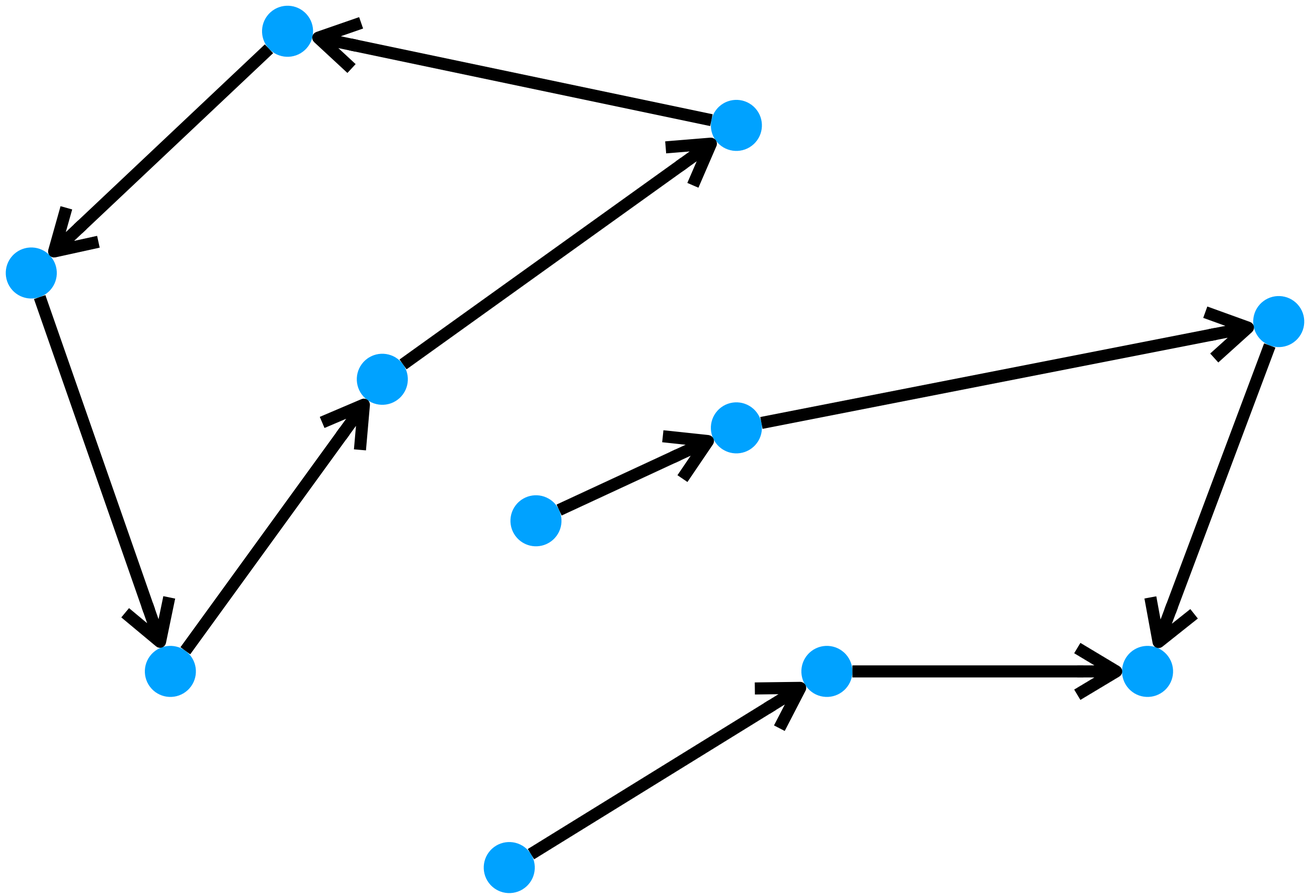


Leaves Spanning Tree: **Valid**

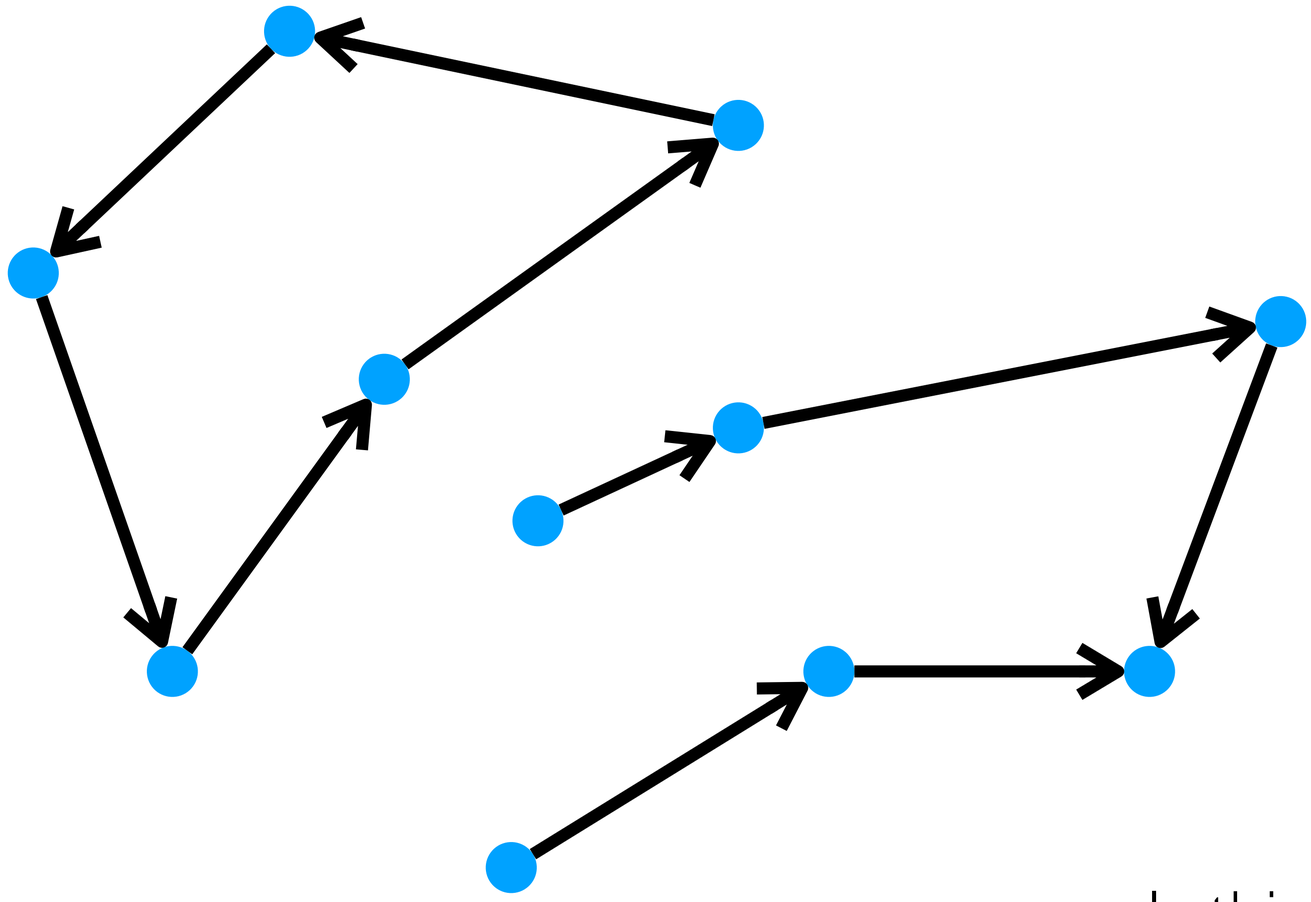
Example 2



Example 2



Example 2



Is this **Valid?**

Lesson?

- Very easy to check validity of routing state for a particular destination
- Dead-ends are obvious
  - Node without outgoing arrow
- Loops are obvious
  - Disconnected from the rest of the graph

Goal (for routing)

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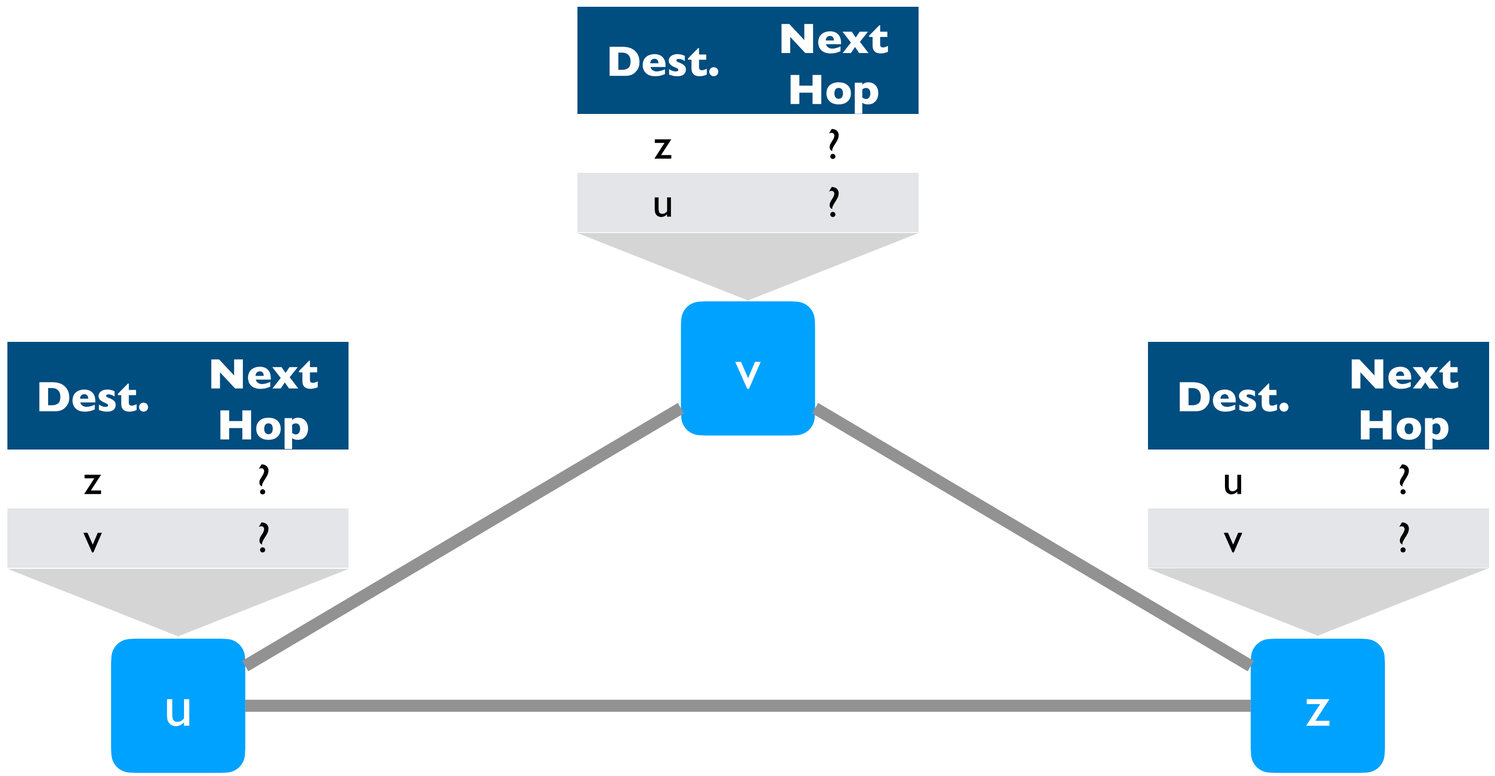
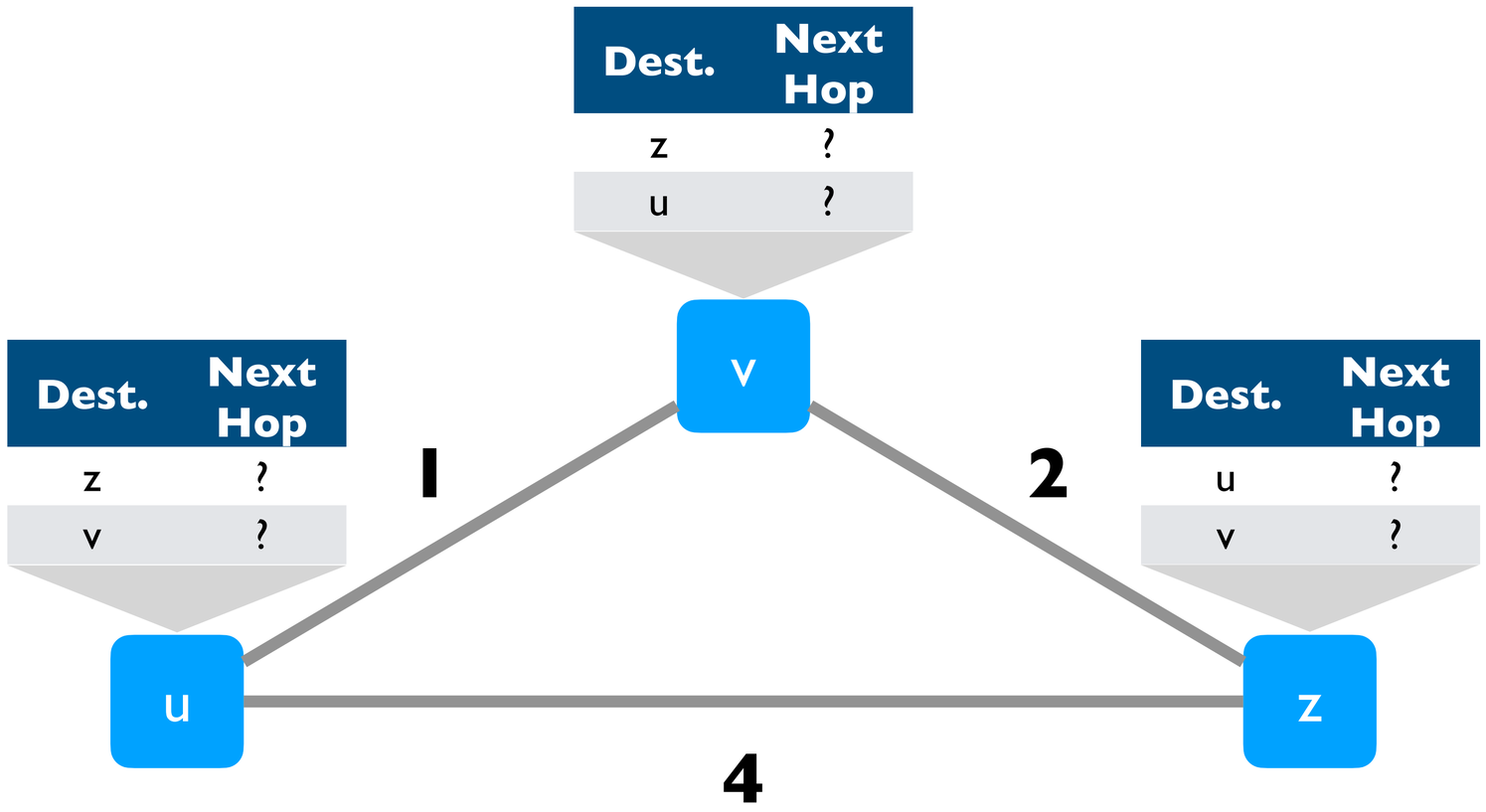
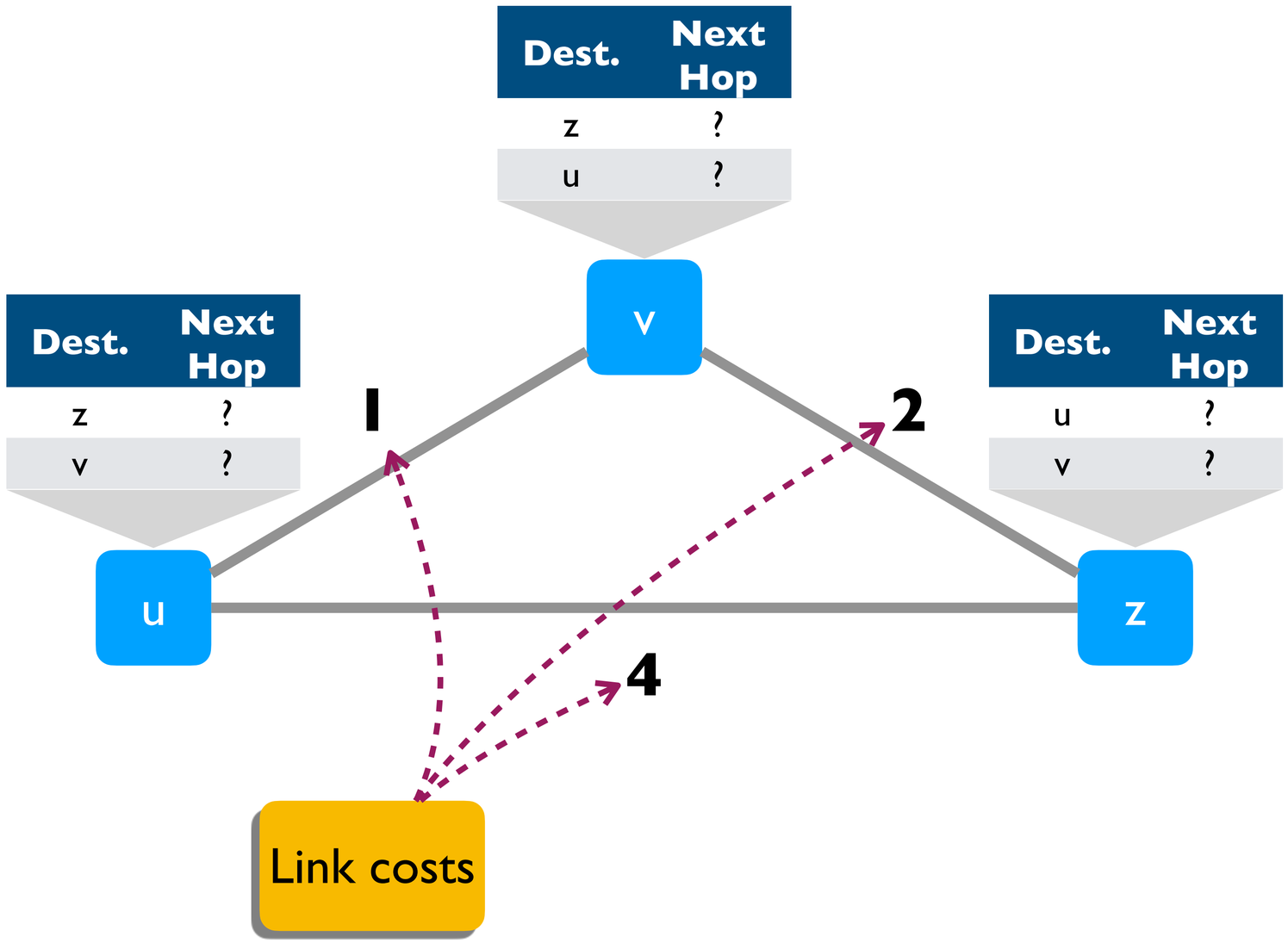
- **V1: Find a path to a given destination**

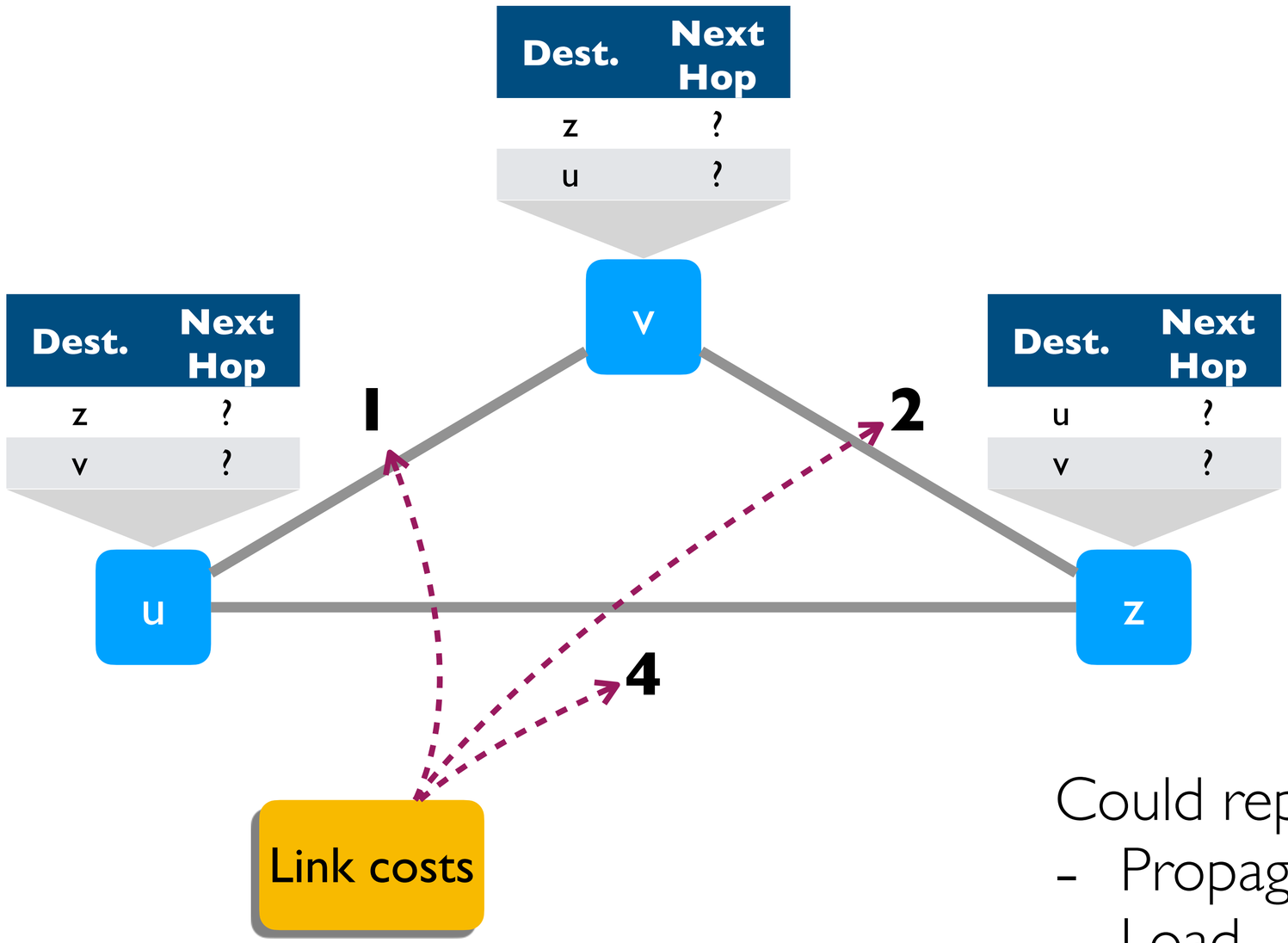
Goal (for routing)

- **V1: Find a path to a given destination**
- **V2: Find a *least cost path* to a given destination**


Dest.
Next Hop
z
?
u
?
v
Dest.
Next Hop
z
?
v
?
u
Dest.
Next Hop
u
?
v
?
u
z

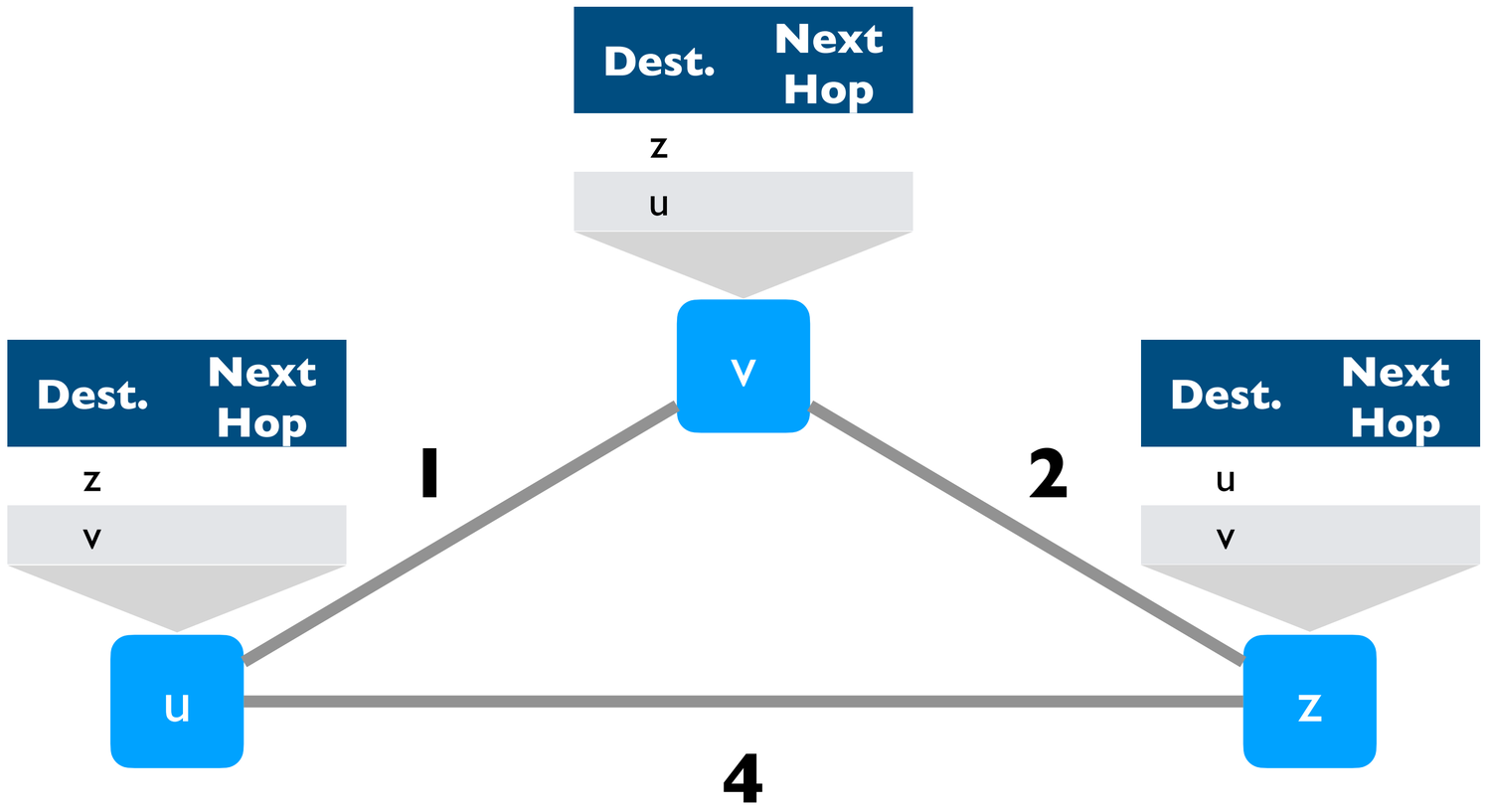

Dest.
Next Hop
z
?
u
?
v
Dest.
Next Hop
z
?
v
?
Dest.
Next Hop
u
?
v
?
1
2
4
u
v
z

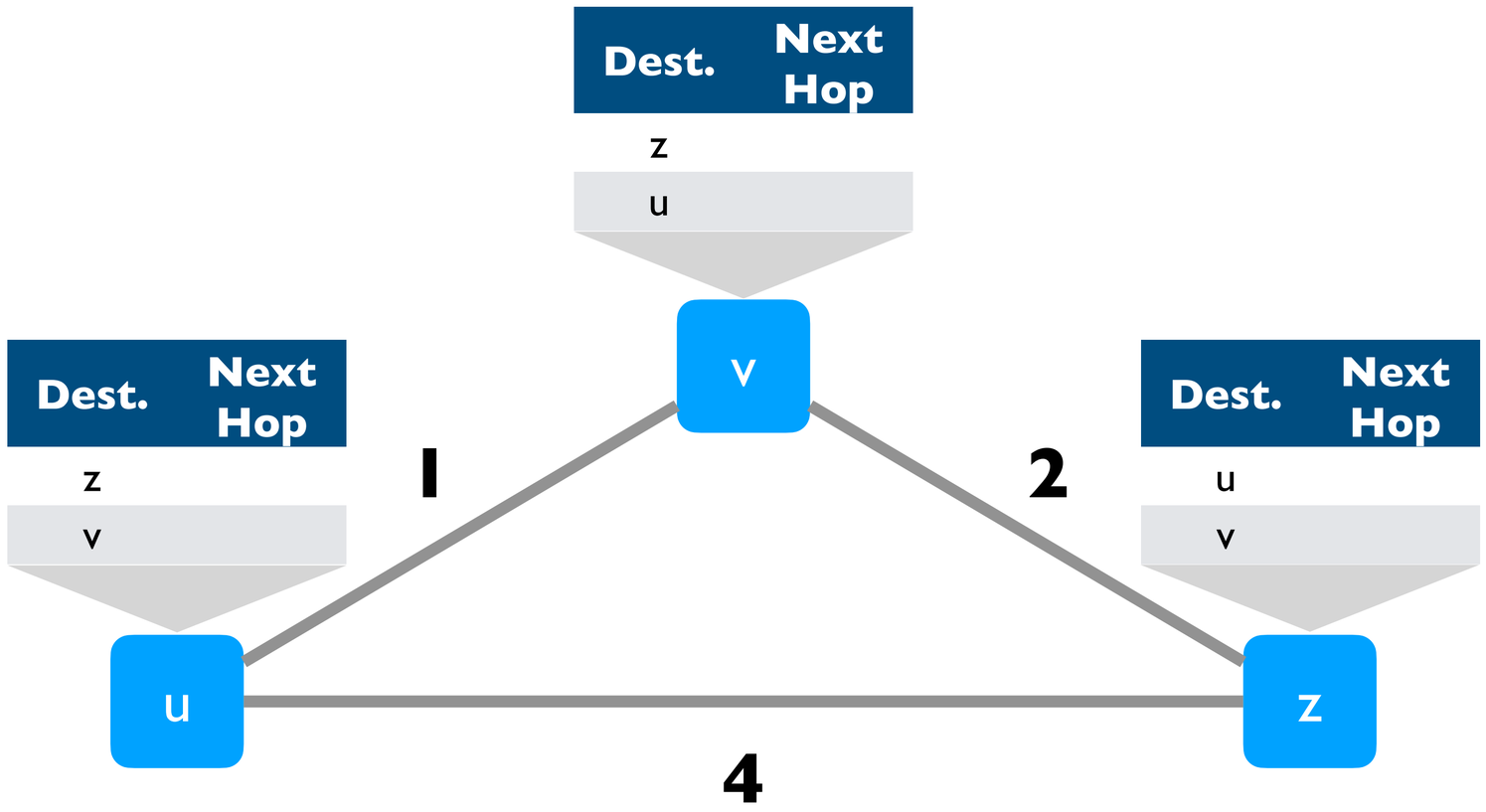

Dest.
Next Hop
z ?
u ?
v
Dest.
Next Hop
z ?
v ?
u
Dest.
Next Hop
u ?
v ?
z
1
2
4
u
z
Link costs



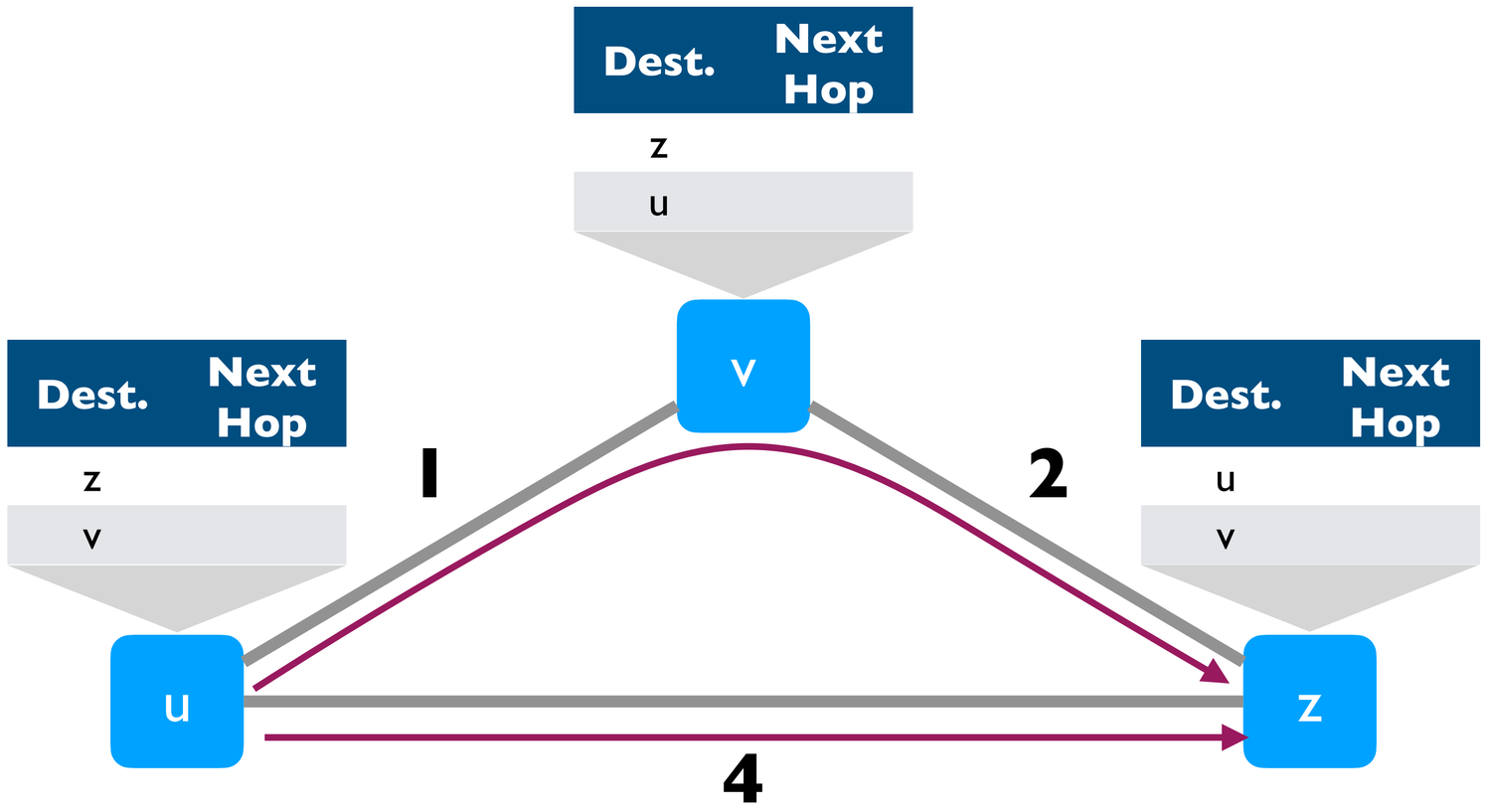
Could represent:

- Propagation delay
- Load
- Cost

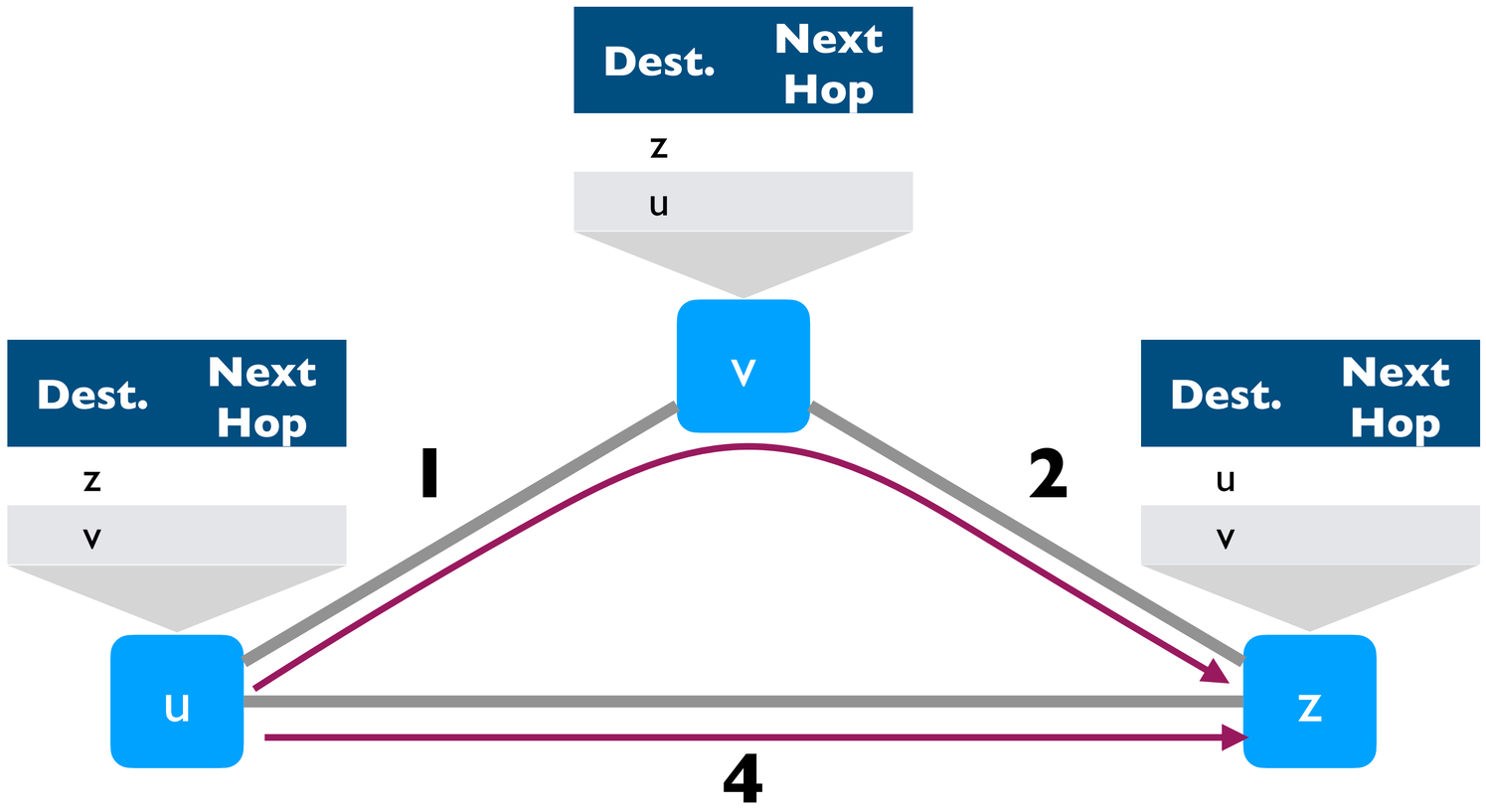

Dest.
Next Hop
z
u
v
Dest.
Next Hop
z
v
Dest.
Next Hop
u
v
1
2
4
u
v
z



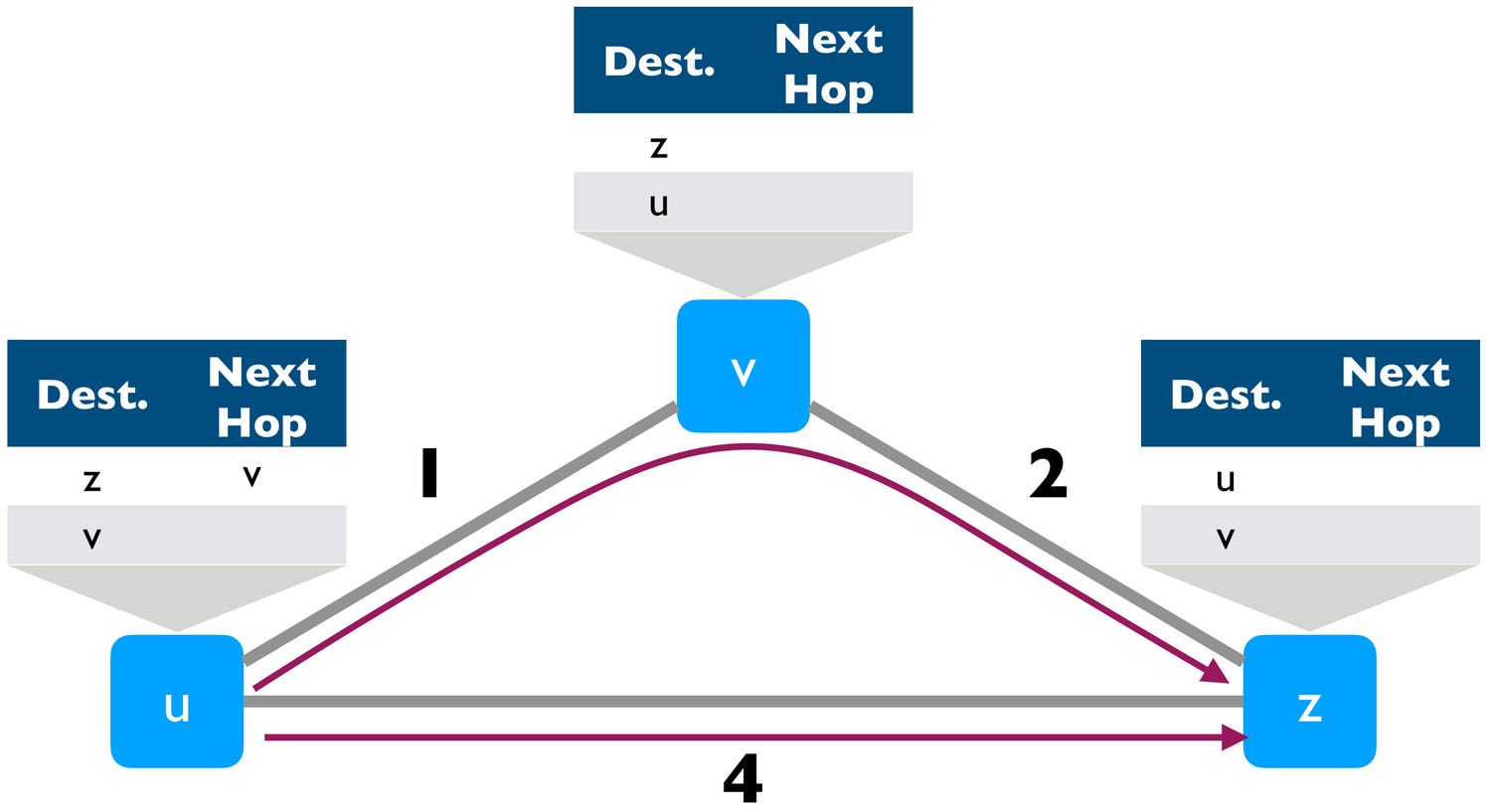
Least-cost path from **u** to **z**:



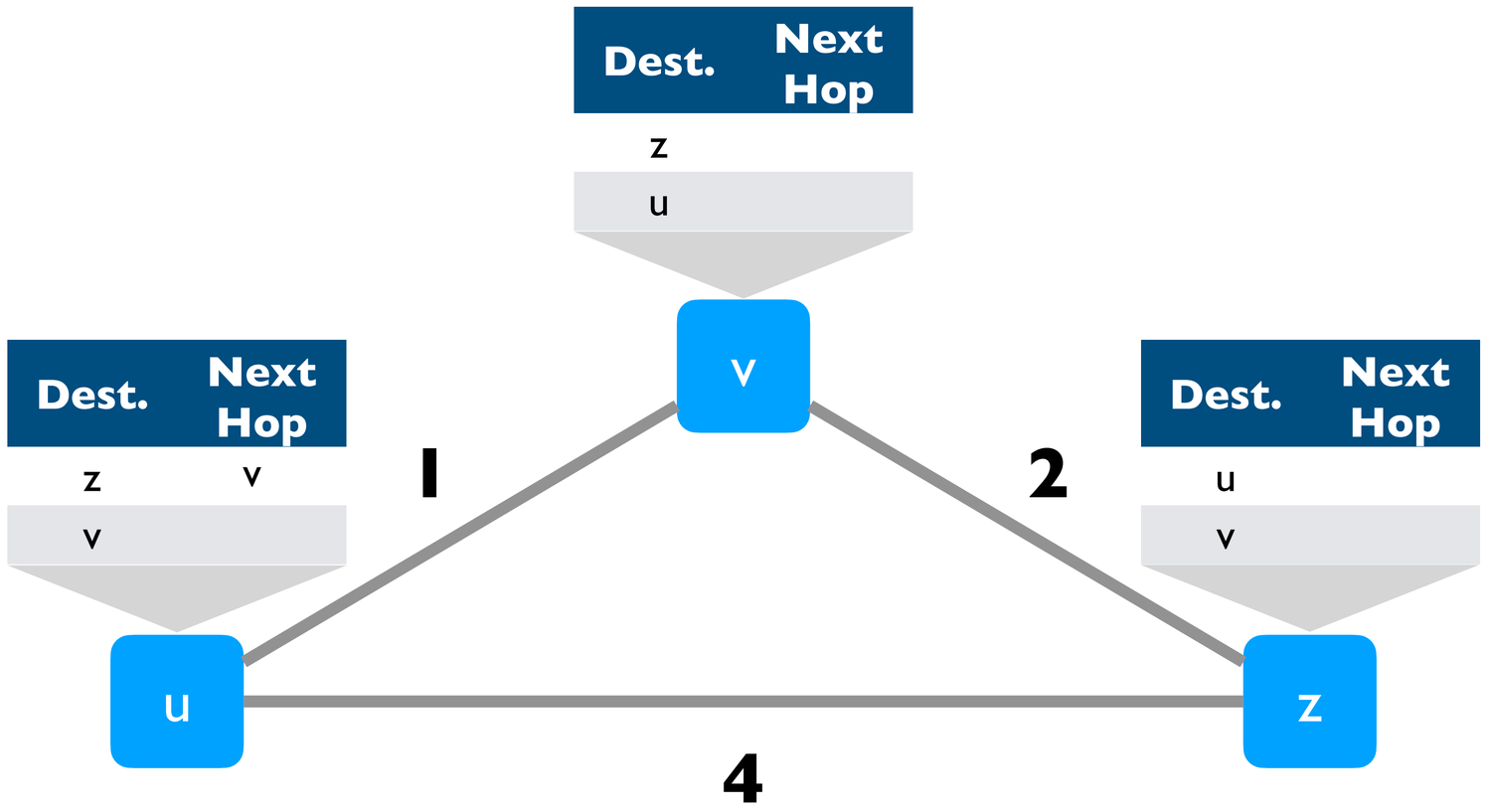
Least-cost path from **u** to **z**:



Least-cost path from **u** to **z**: **u v z**

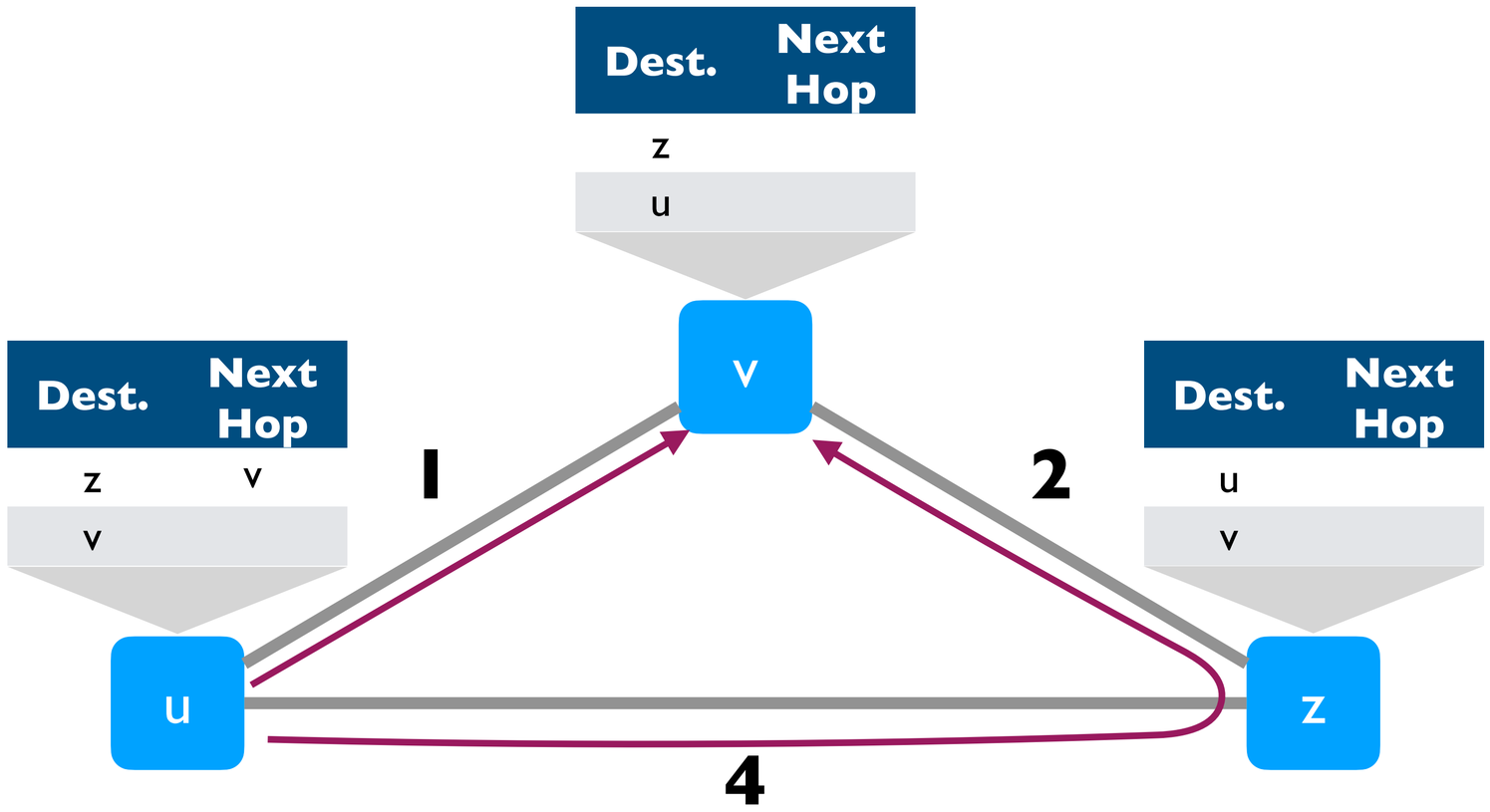


Least-cost path from **u** to **z**: **u v z**



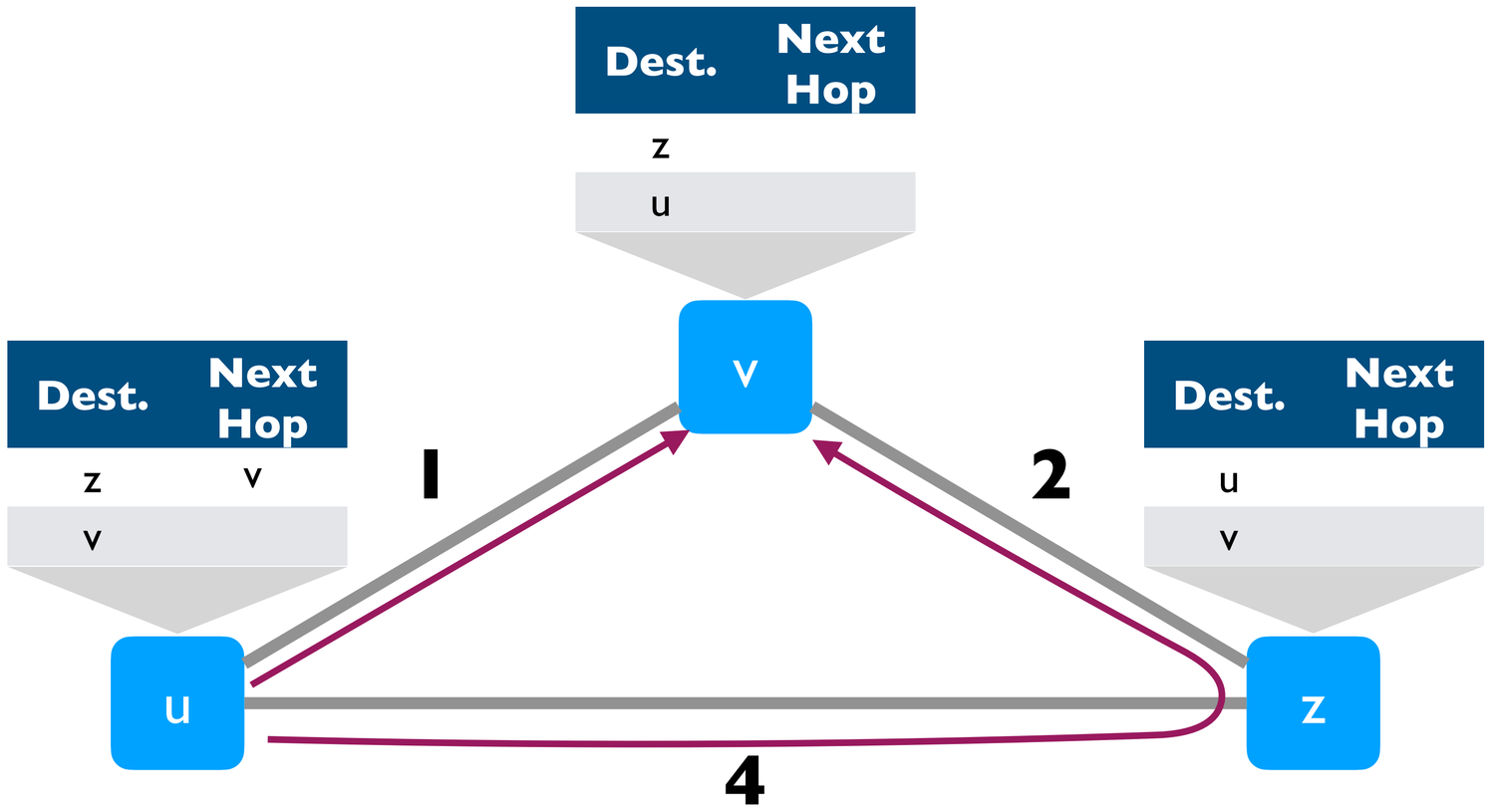
Least-cost path from **u** to **z**: **u v z**

Least-cost path from **u** to **v**:



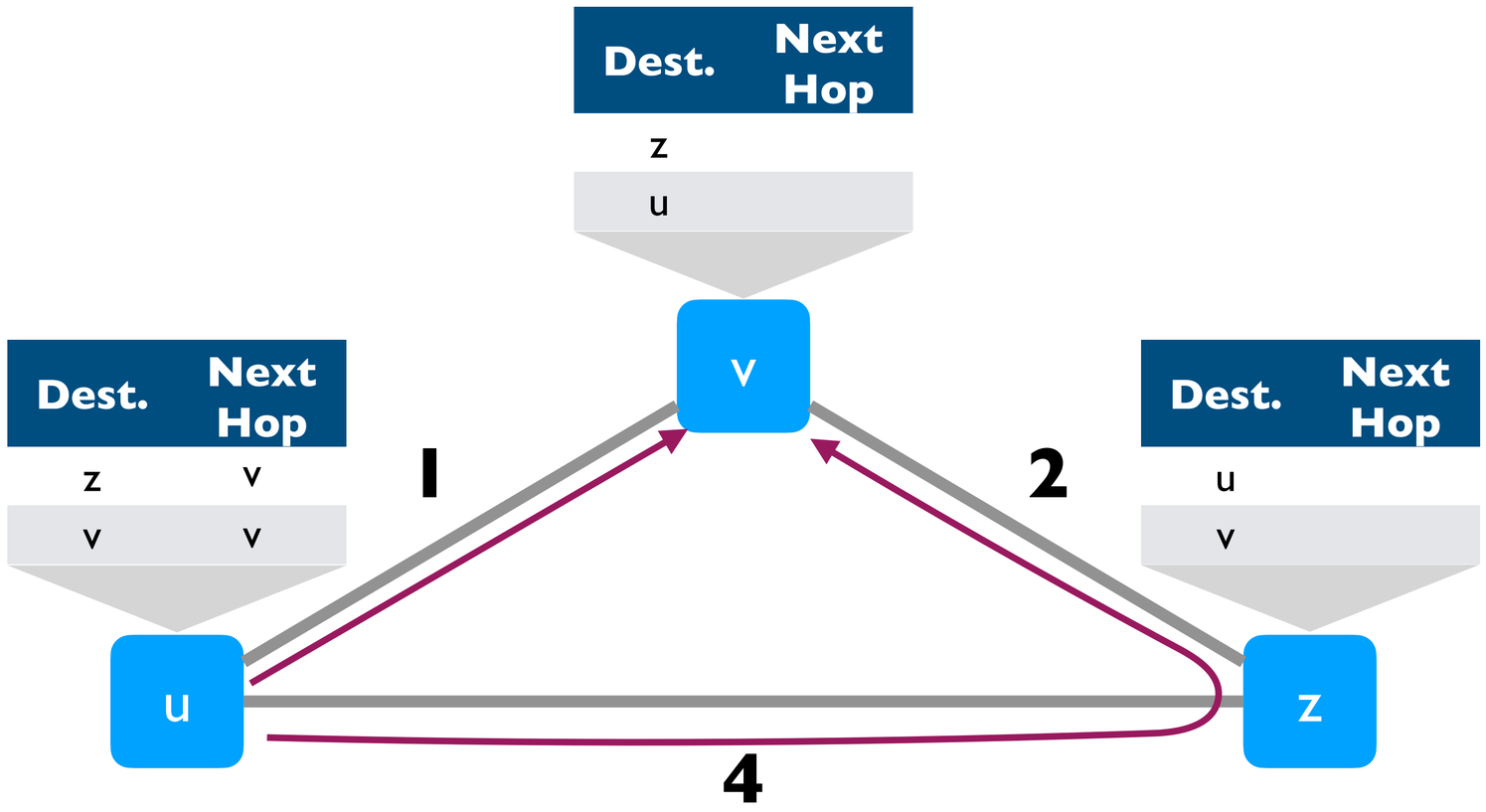
Least-cost path from **u** to **z**: **u v z**

Least-cost path from **u** to **v**:



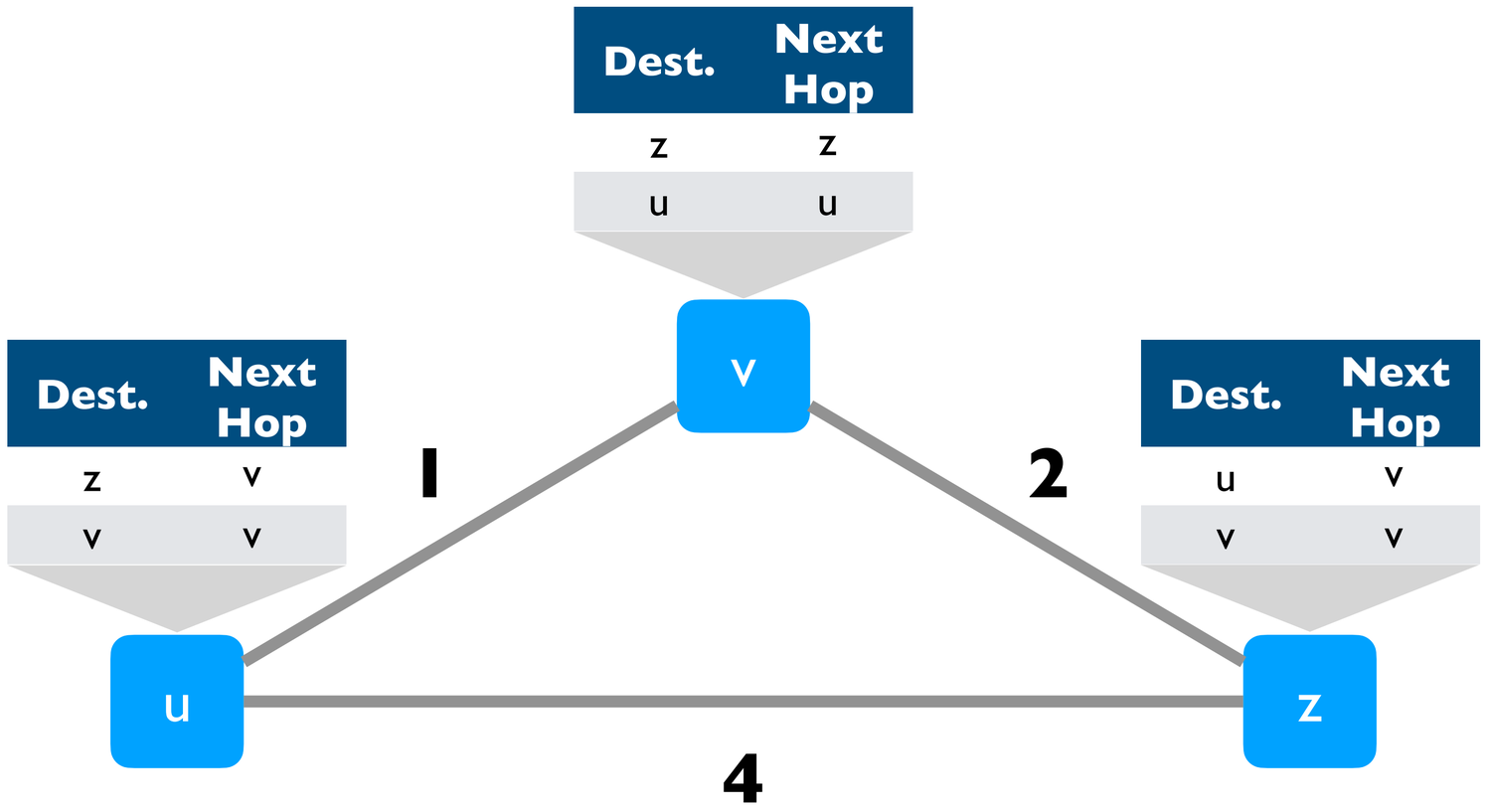
Least-cost path from **u** to **z**: **u v z**

Least-cost path from **u** to **v**: **u v**



Least-cost path from **u** to **z**: **u v z**

Least-cost path from **u** to **v**: **u v**



Least-cost path from **u** to **z**: **u v z**

Least-cost path from **u** to **v**: **u v**

Least-cost path routing

Least-cost path routing

- **Given:** Router graph & link costs

Least-cost path routing

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- **Goal:** find least-cost path
  from each source router
  to each destination router

Least-cost path routing

- **Given:** Router graph & link costs
- **Goal:** find least-cost path
  from each source router
  to each destination router
- **Next time on CPSC 433/533:** How we compute these!