CS168
How the Internet Works (contd.)

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Spring 2026

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Last week:
Building the Internet Bottom-Up

- Packets
  - Consisting of payloads and headers
  - Payloads are meaningful only to the endpoints
  - Headers are meaningful to the network *and* endpoint

- Links
  - Characterized by bandwidth, propagation delay and bandwidth-delay product
  - Packet transfer involves transmission delay and propagation delay
  - Circuit switching vs packet switching

Last week: Sharing Network Resources

- Statistical multiplexing, which can be implemented as:
  - Reservations (e.g., circuit switching)
  - Best-effort (packet switching)

- Detailed analysis of the trade-offs involved
  - As an abstraction to applications
  - Network efficiency
  - Handling failures (at scale)
  - Complexity of implementation (at scale)

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  - More predictable and understandable (w/o failures)

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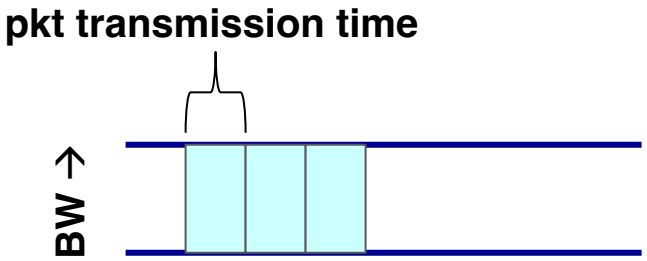
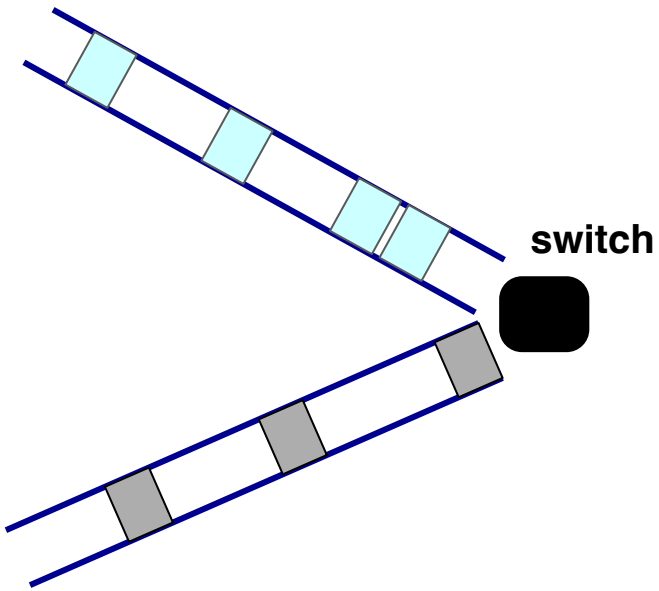
- **Pros for packet switching**:
  - Better efficiency
  - Faster startup to first packet delivered
  - Easier recovery from failure
  - Simpler implementation (avoids dynamic per-flow state management in switches)

Let’s take a closer look at packet switching ….

Recall, packets in flight: “pipe” view

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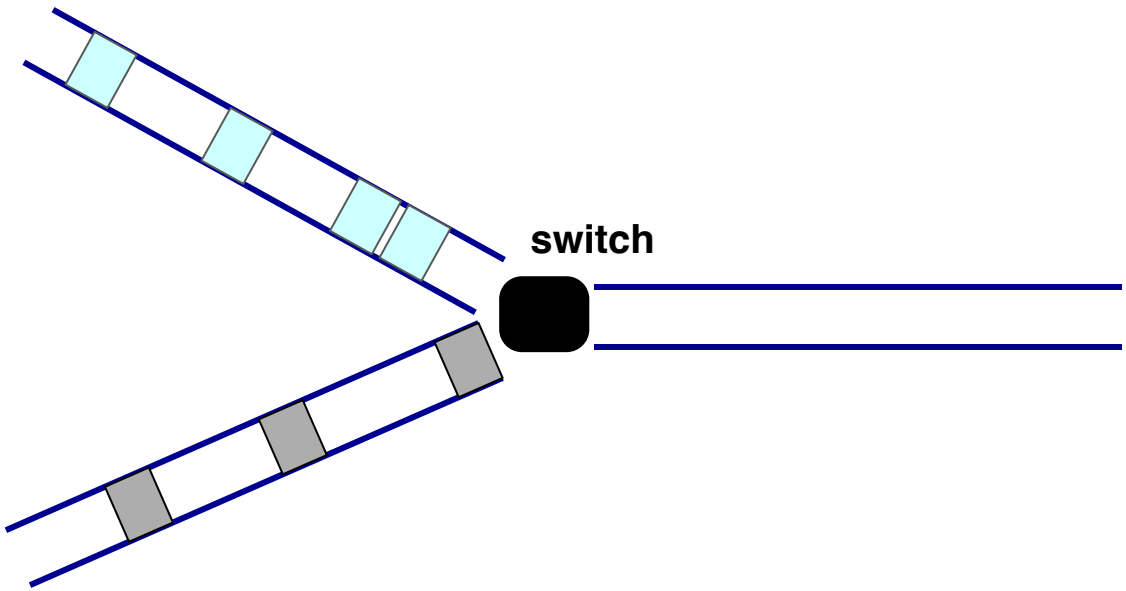
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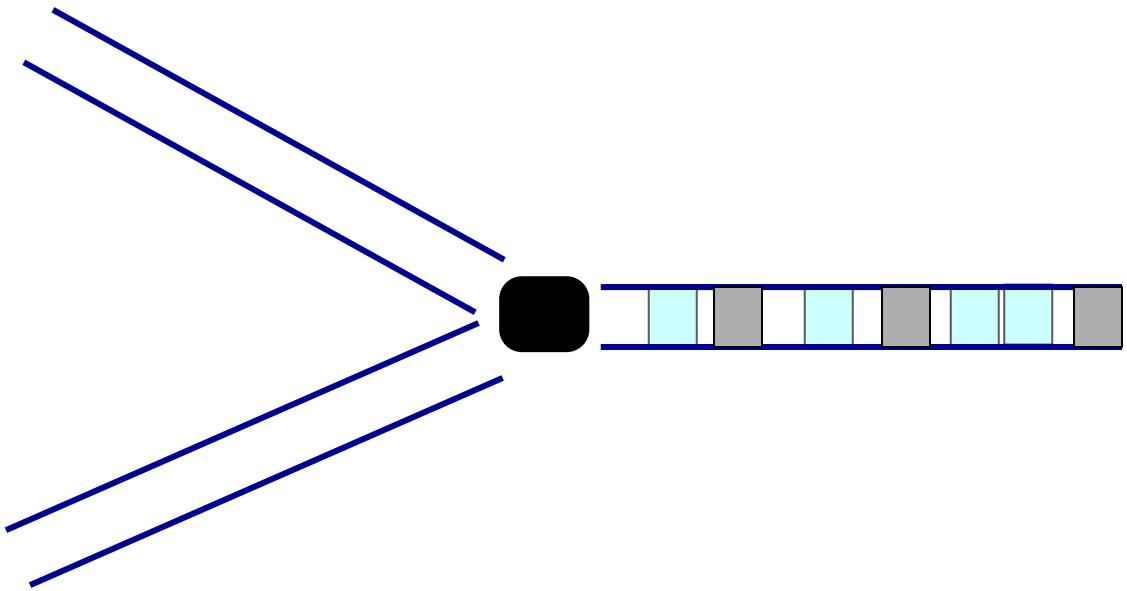

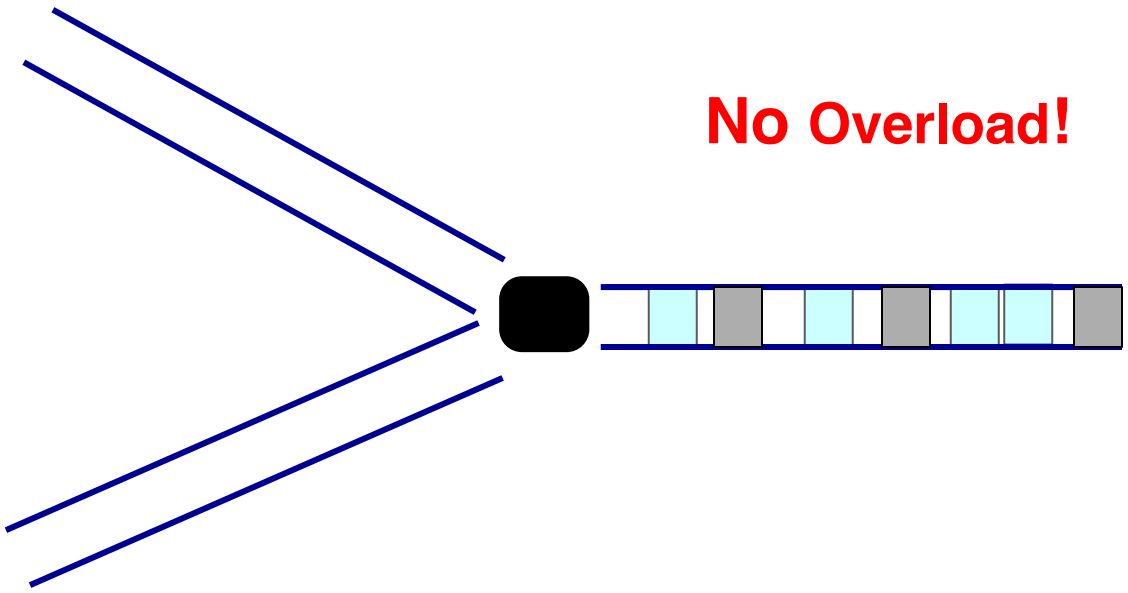
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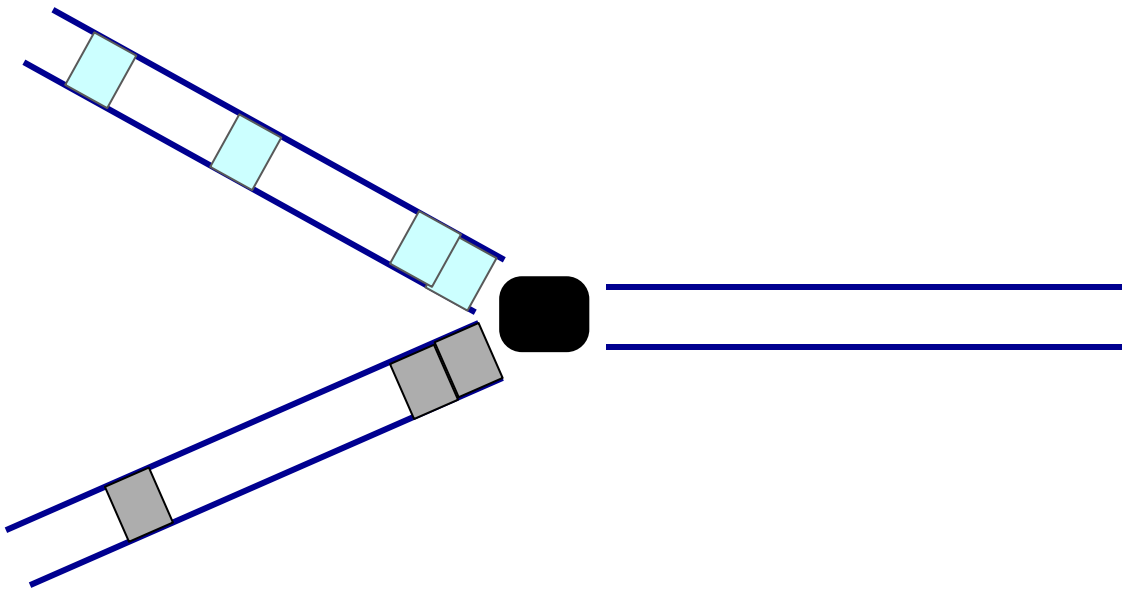
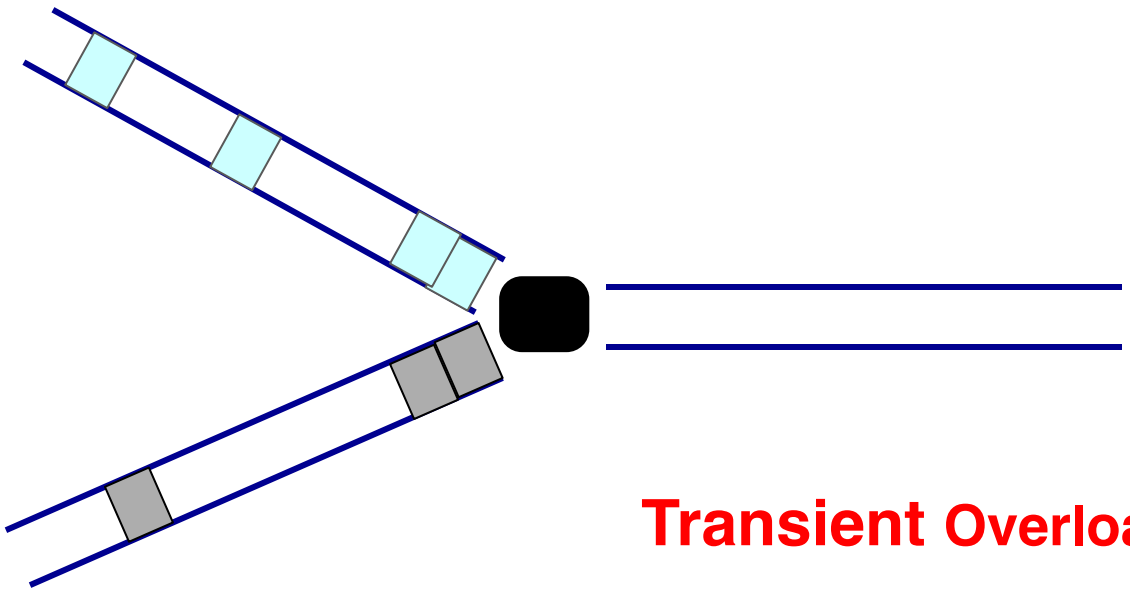
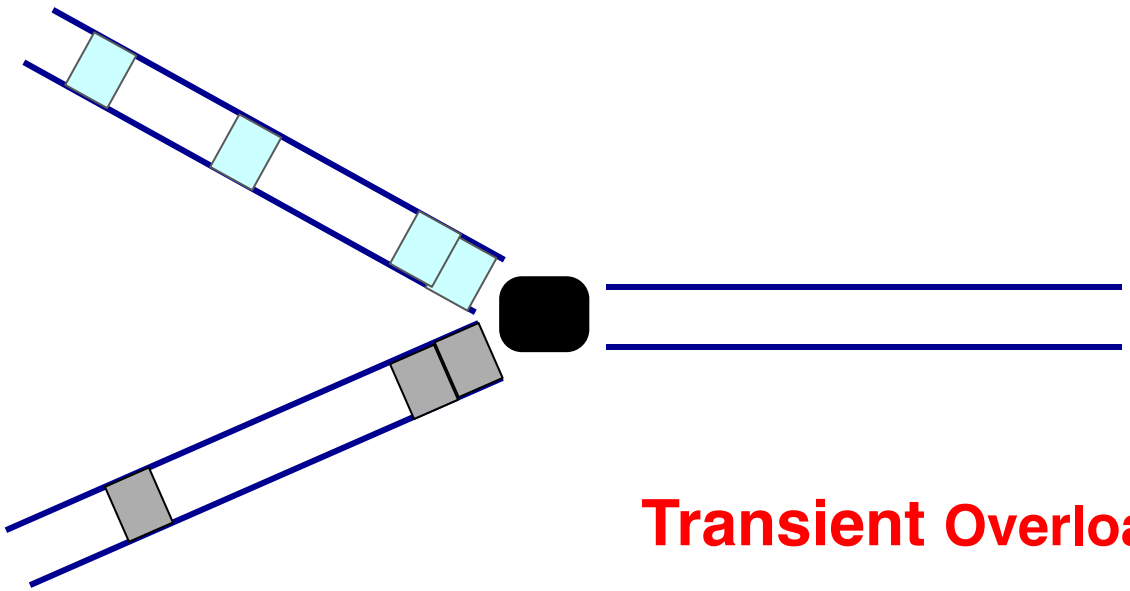




Transient Overload



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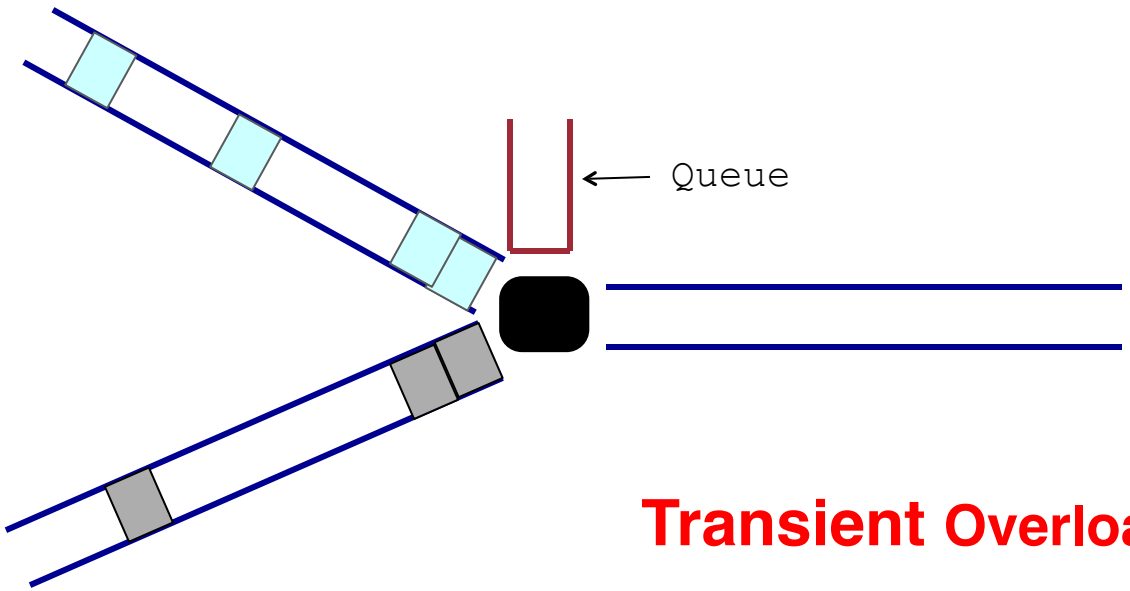

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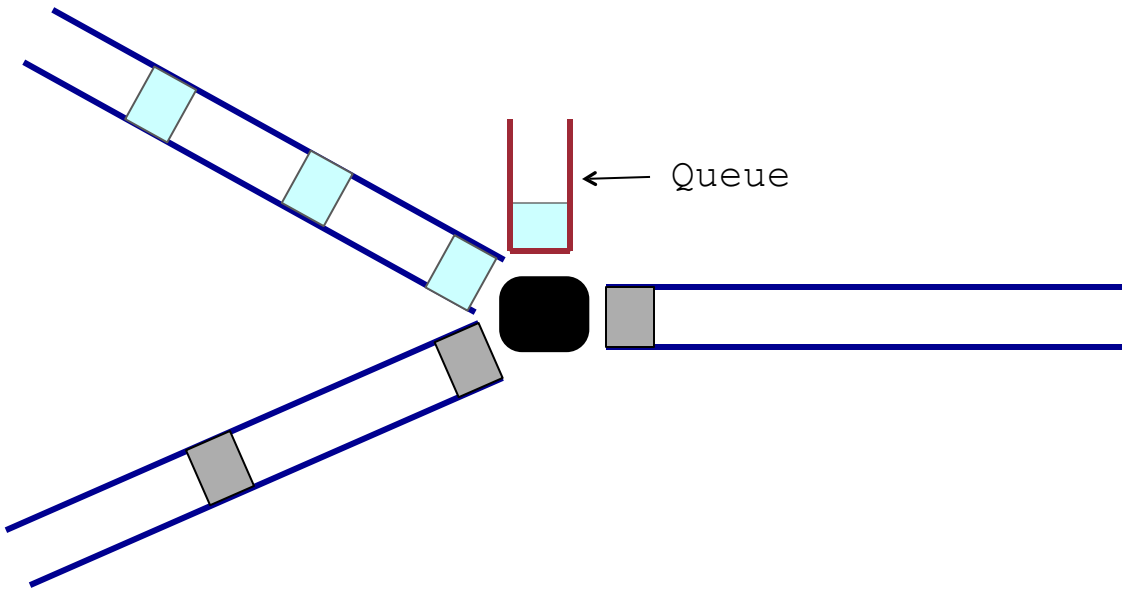
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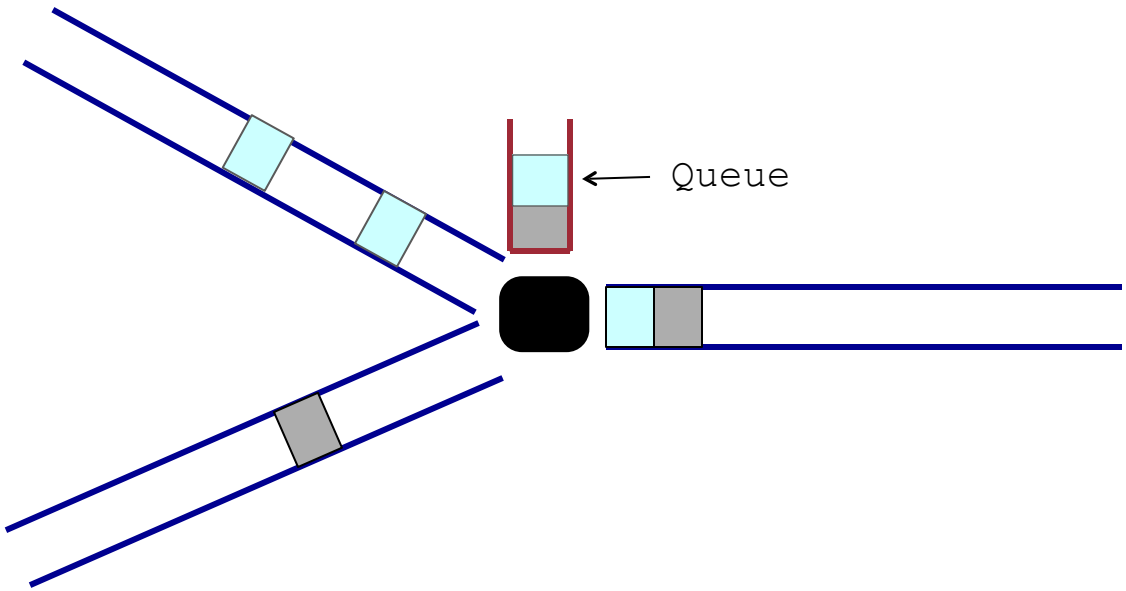
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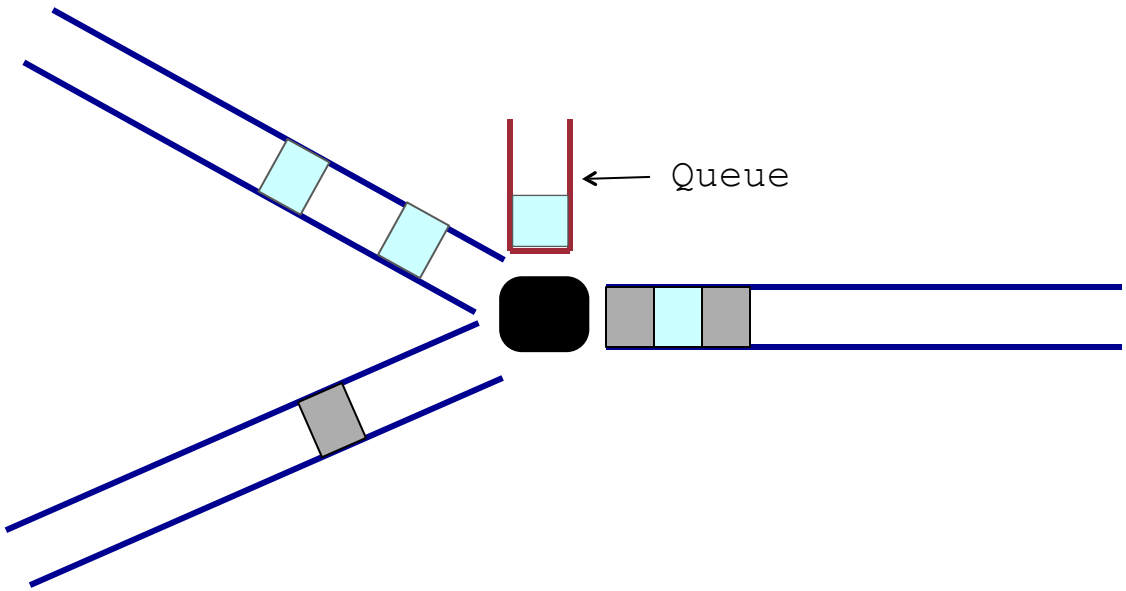
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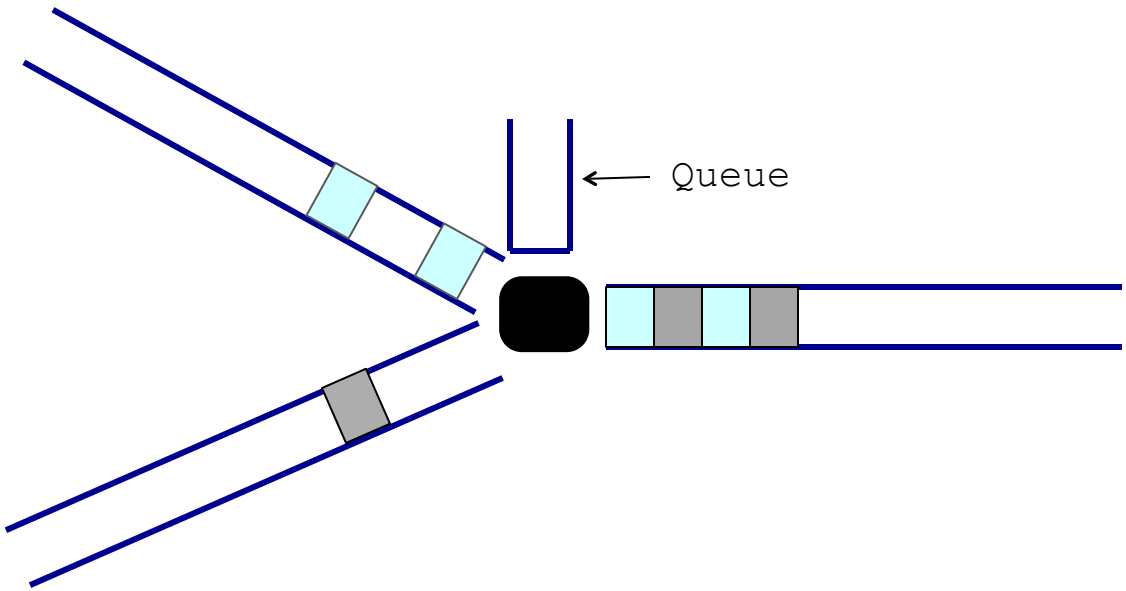
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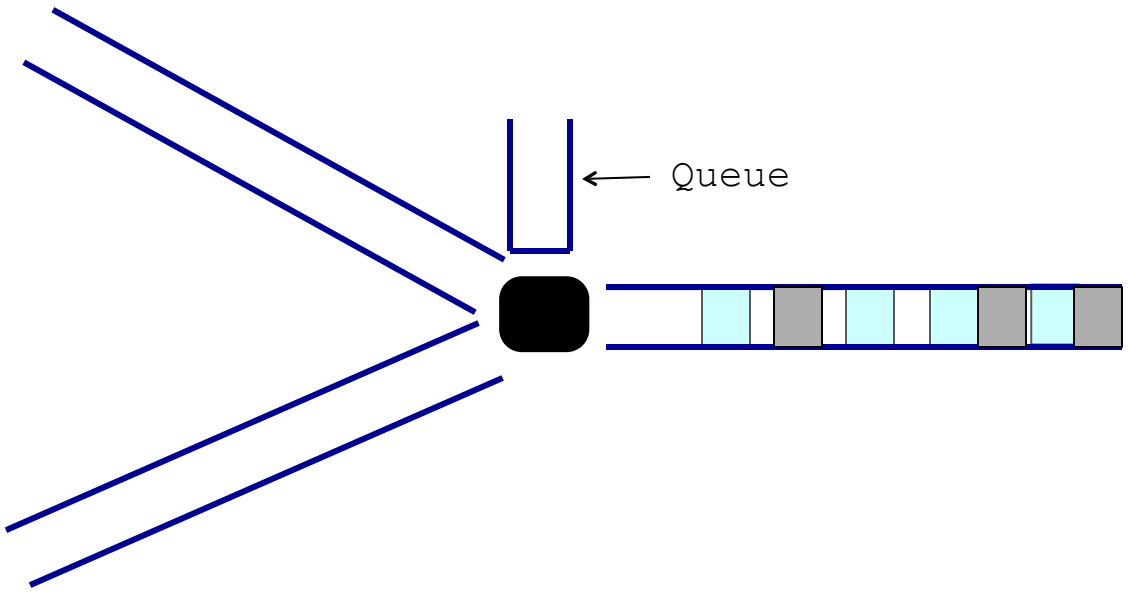
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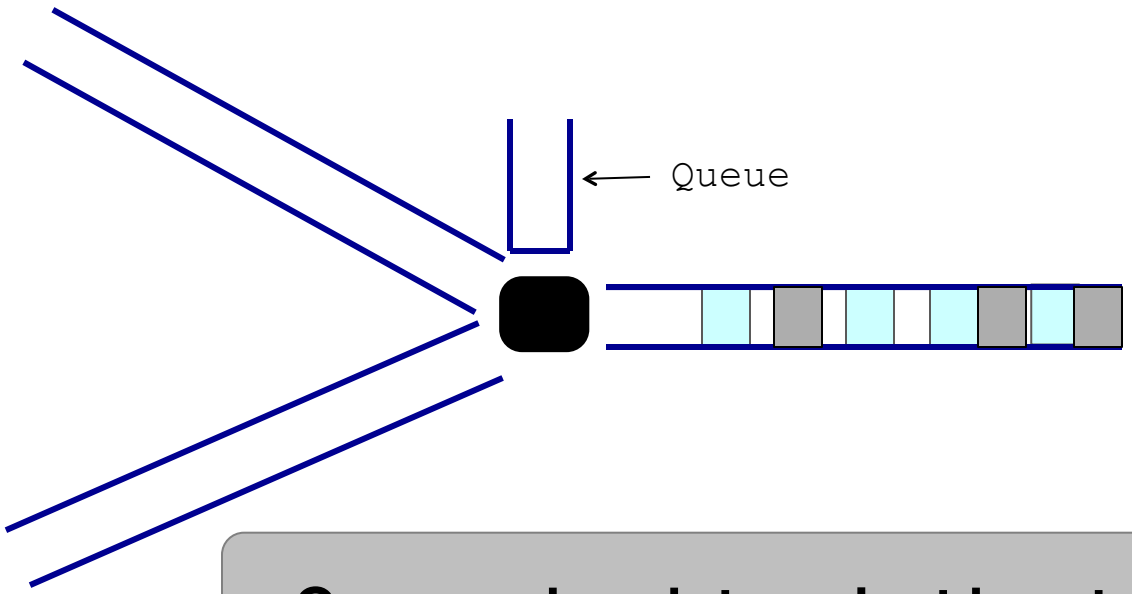
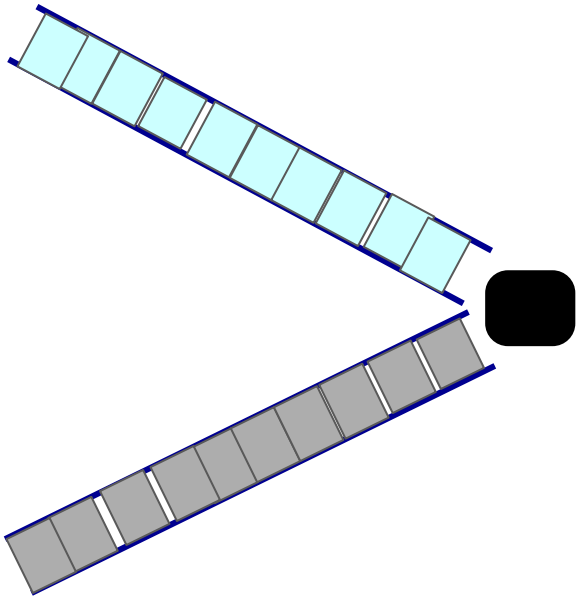
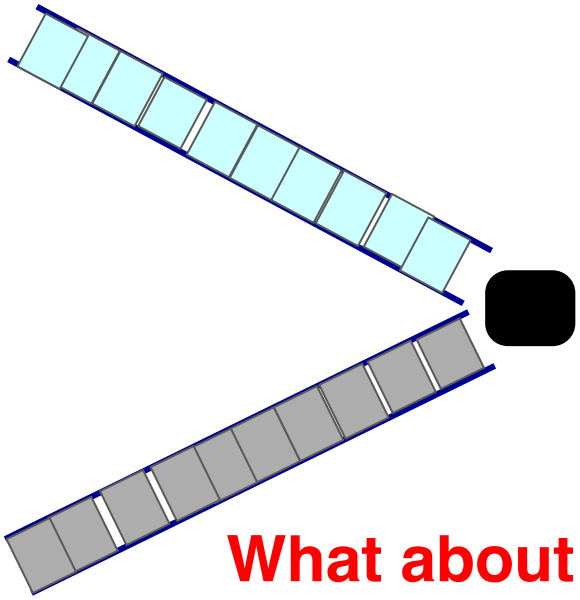


Queues absorb transient bursts!





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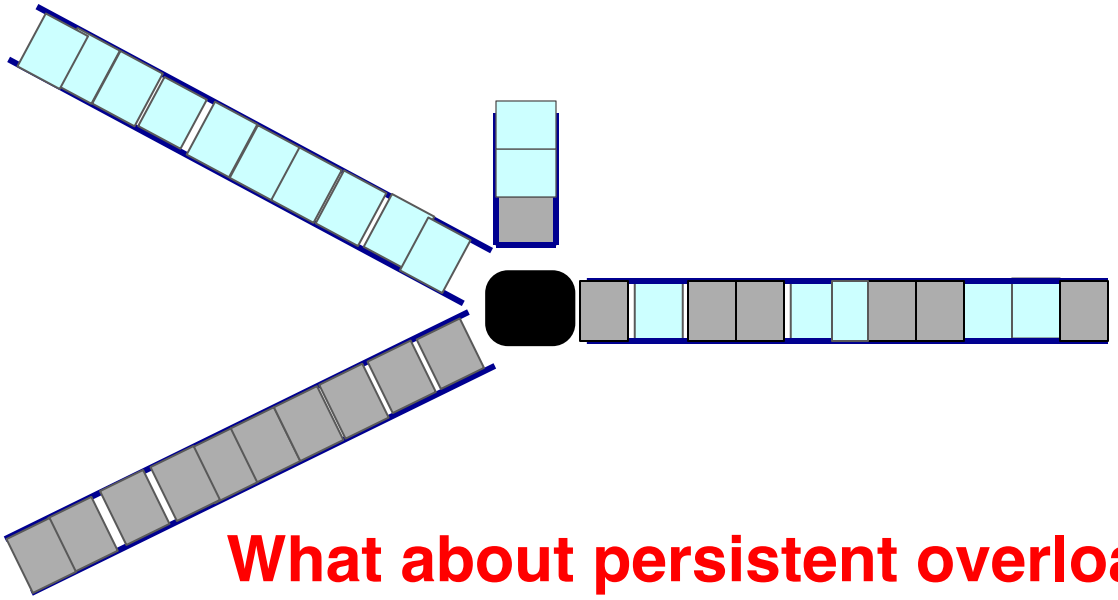

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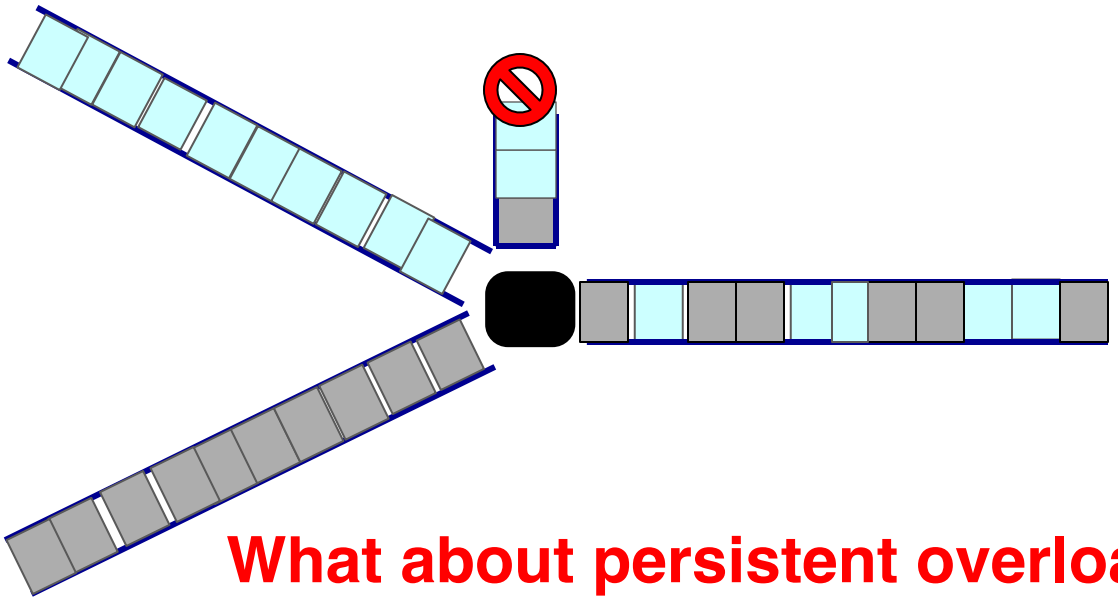

What about persistent overload?

Will eventually drop packets

Queues introduce queuing delays

- **Recall, packet delay = transmission delay + propagation delay**
- **With queues: packet delay = transmission delay + propagation delay + queueing delay**

Recall: life of a packet so far…

- Source has some data to send to a destination
- Chunks it up into packets: each packet has a payload and a header
- Packet travels along a link
- Arrives at a switch; switch forwards the packet to its next hop
- And the last step repeats until we reach the destination …

Recall: life of a packet so far… [updated]

- Source has some data to send to a destination
- Chunks it up into packets: each packet has a payload and a header
- Packet travels along a link
- Arrives at a switch; switch forwards the packet to its next hop
  - switch may buffer, or even drop, the packet
- And the last step repeats until we reach the destination …
  - or the packet is dropped

Challenge: Reliable packet delivery

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- **Packets can be dropped along the way**
  - Buffers in switch can overflow
  - Switch can crash while buffering packets
  - Links can garble/corrupt packets

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- **Packets can be dropped along the way**
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  - Links can garble/corrupt packets
- **Given an unreliable network, how do we make sure the destination receives its packets?**
  - Or at least know if they are delivered….

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- But endhosts independently decide at what rate they will send packets!
- This can be tricky!
  - How fast I send packets impacts whether *your* packets are dropped
  - What's a good rate at which I should send my packets?
- Hence, congestion control:
  - How do we ensure that (endhosts') independent decisions lead to a good outcome?

Hence, our fundamental topics [updated]

- How do we name endhosts on the Internet? **(naming)**
- How do we address endhosts? **(addressing)**
- How do we map names to addresses? **(mapping names to addresses)**
- How do we compute forwarding tables? **(routing control plane → project 1)**
- How do we forward packets? **(routing data plane)**
- How do hosts communicate reliably? **(reliable packet delivery → project 3)**
- How do sources know at what rate they can send packets? **(congestion control)**

Hence, our fundamental topics [updated]

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- How do sources know at what rate they can send packets? **(congestion control)**
- **How do our solutions change in modern environments (clouds, wifi, cellular)**

Recap: key takeaways from our bottom-up overview

- **What is a packet?**
- **Approaches to sharing the network – circuit vs. packet switching -- and their tradeoffs**
- **An overall sense of the life of a packet**
  - We'll continue to refine this picture over the course of the semester

Questions??

Changing Perspective

- Designing the Internet: a top-down approach
- In the process, discuss a few enduring ideas:
  - Layering
  - The end-to-end principle
  - Fate sharing

The Internet's problem definition

- Support the transfer of data between endhosts
- ... across multiple networks
  - The Internet

How do you solve a problem?

1. Decompose it (into tasks and abstractions)

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2. Assign tasks to entities (who does what)

Modularity

Modularity based on abstraction is the way things are done

– Barbara Liskov, Turing lecture

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- Decomposing systems into smaller units
  - Providing a “separation of concerns”
- Plays a crucial role in computer science…
- The challenge is to find the *right* modularity

Network Modularity

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  - **And is even more important!**
- Normal modularity organizes code
- But network implementations are not just distributed across many lines of code…
  - Also distributed across many devices (hosts, routers)
  - … *and* different players (clients, server, ISPs)

How do we decompose the job of transferring data between end-hosts?

Inspiration…

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- **CEO A writes letter to CEO B**
  - Folds letter and hands it to administrative aide

Dear Sam,

Your days are numbered.

-- Sundar

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  - Puts package on FedEx delivery truck
- **FedEx delivers to other company**

The Path of the Letter

CEO

Aide

FedEx

CEO

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The Path of the Letter

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The Path of the Letter

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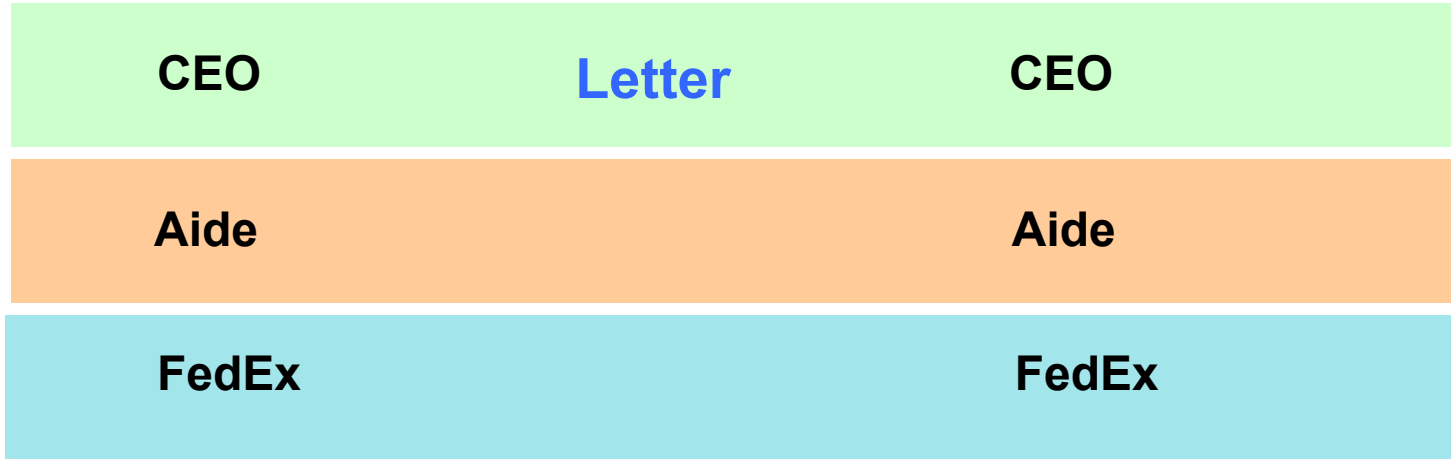
The Path of the Letter

- “Peers” understand the same things



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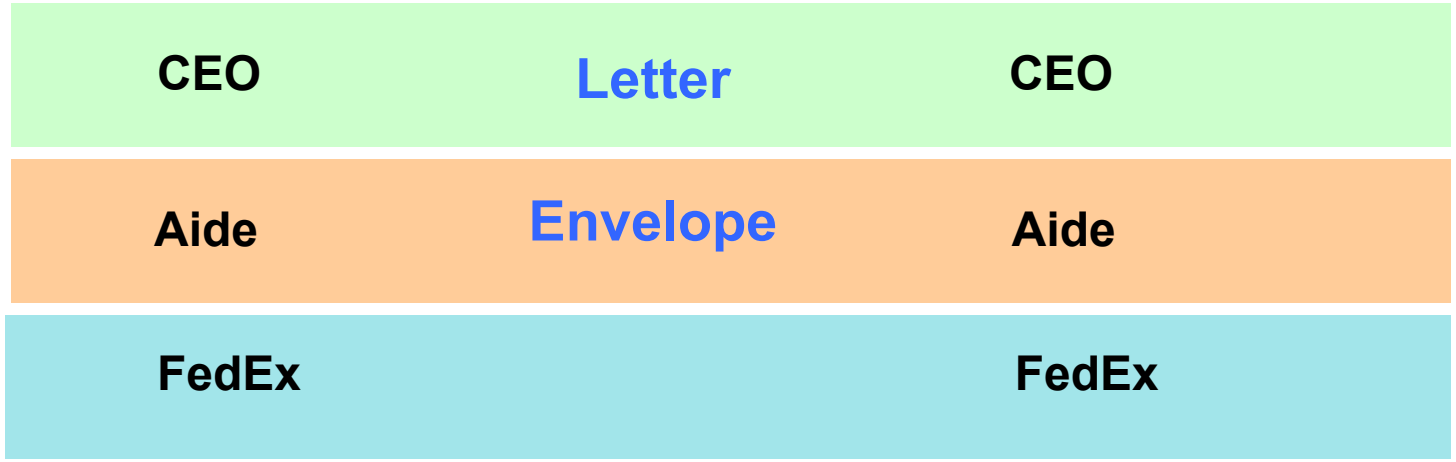

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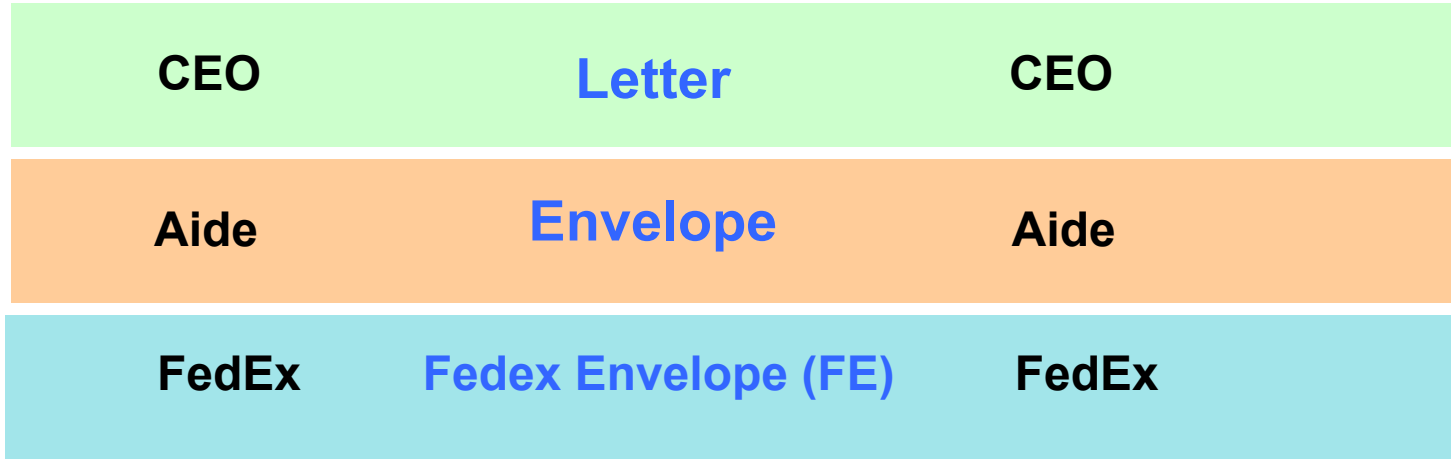

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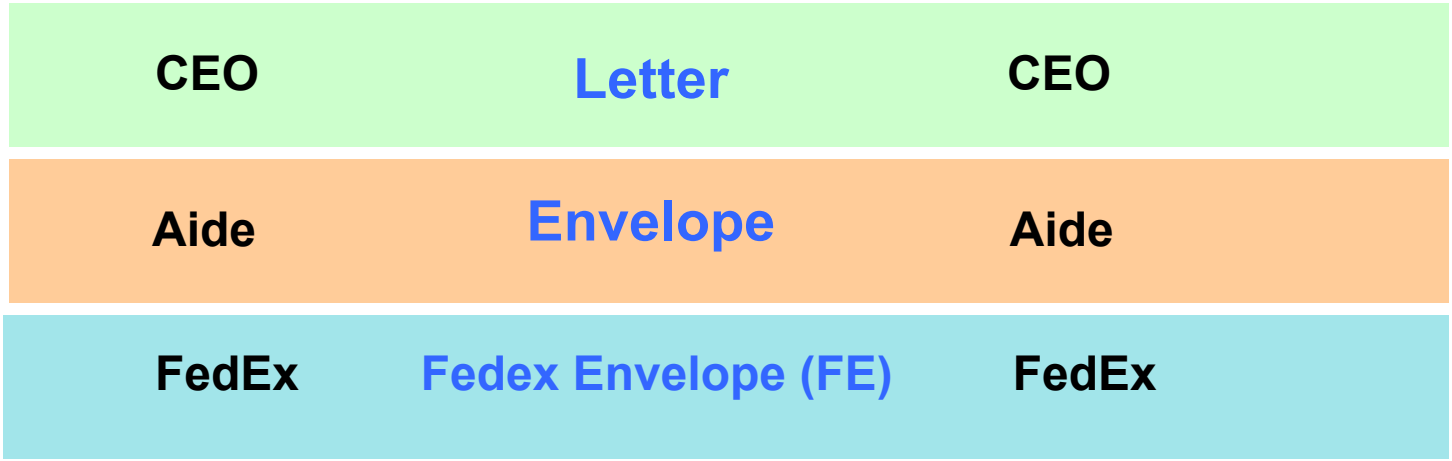
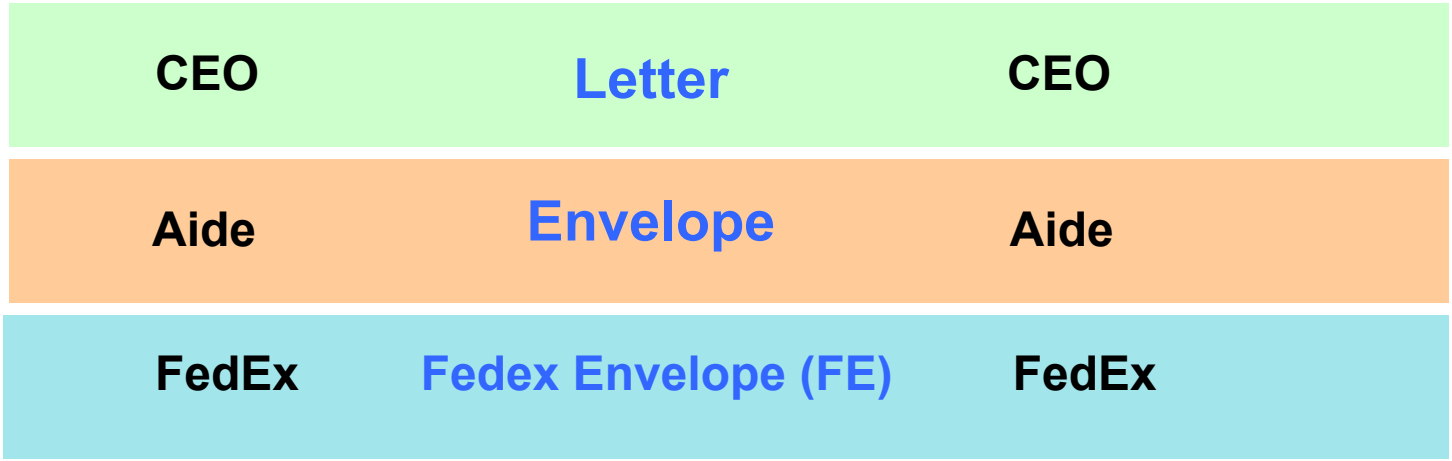


The Path of the Letter

- “Peers” understand the same things
- No one else needs to
- Lowest level has most “packaging”



Thought Experiment

- How would ***you*** break the Internet into tasks?
- Just focus on what is needed to get packets between processes on different hosts….
- Do not consider application or control tasks
  - Naming, computing forwarding tables, etc.

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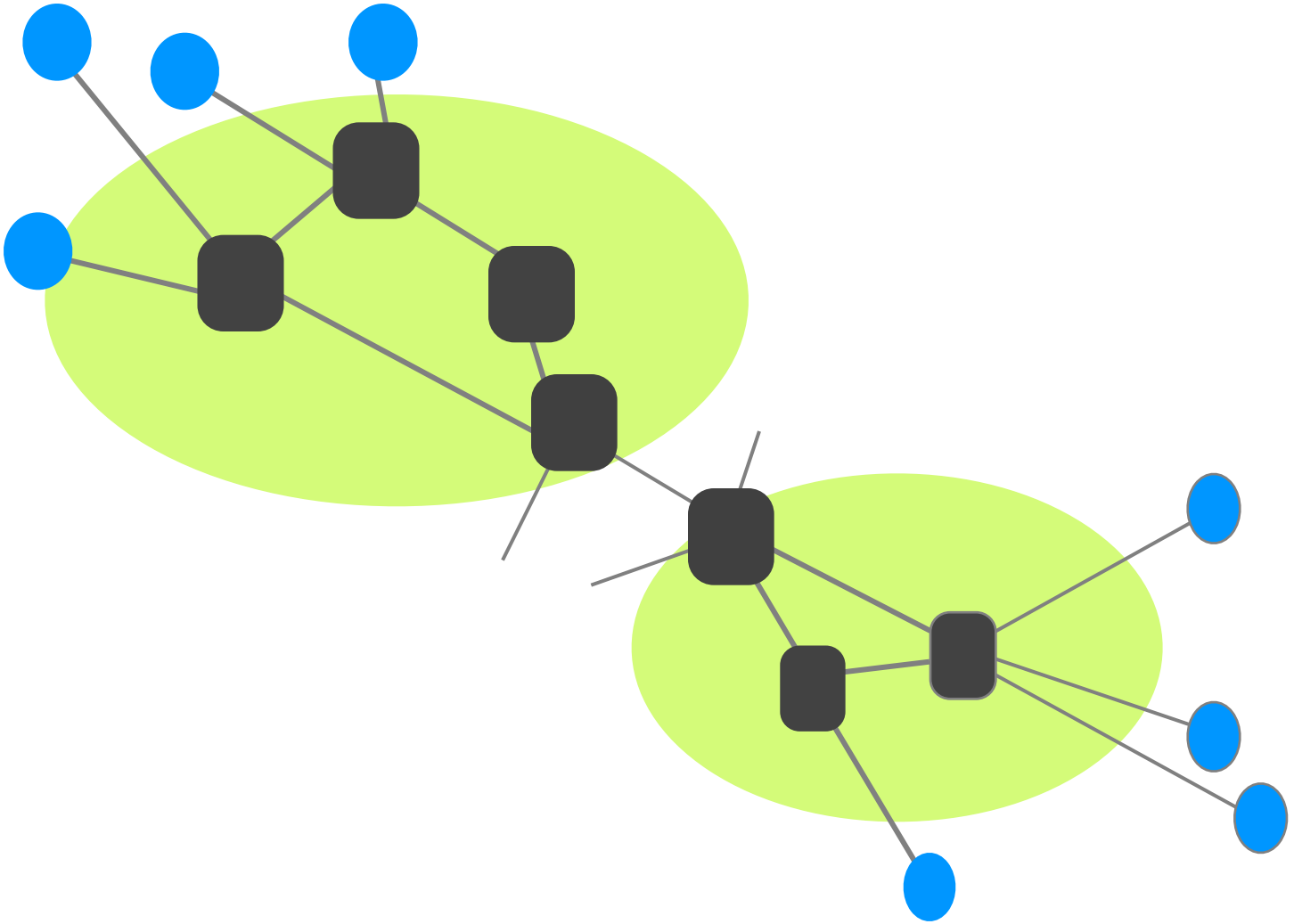

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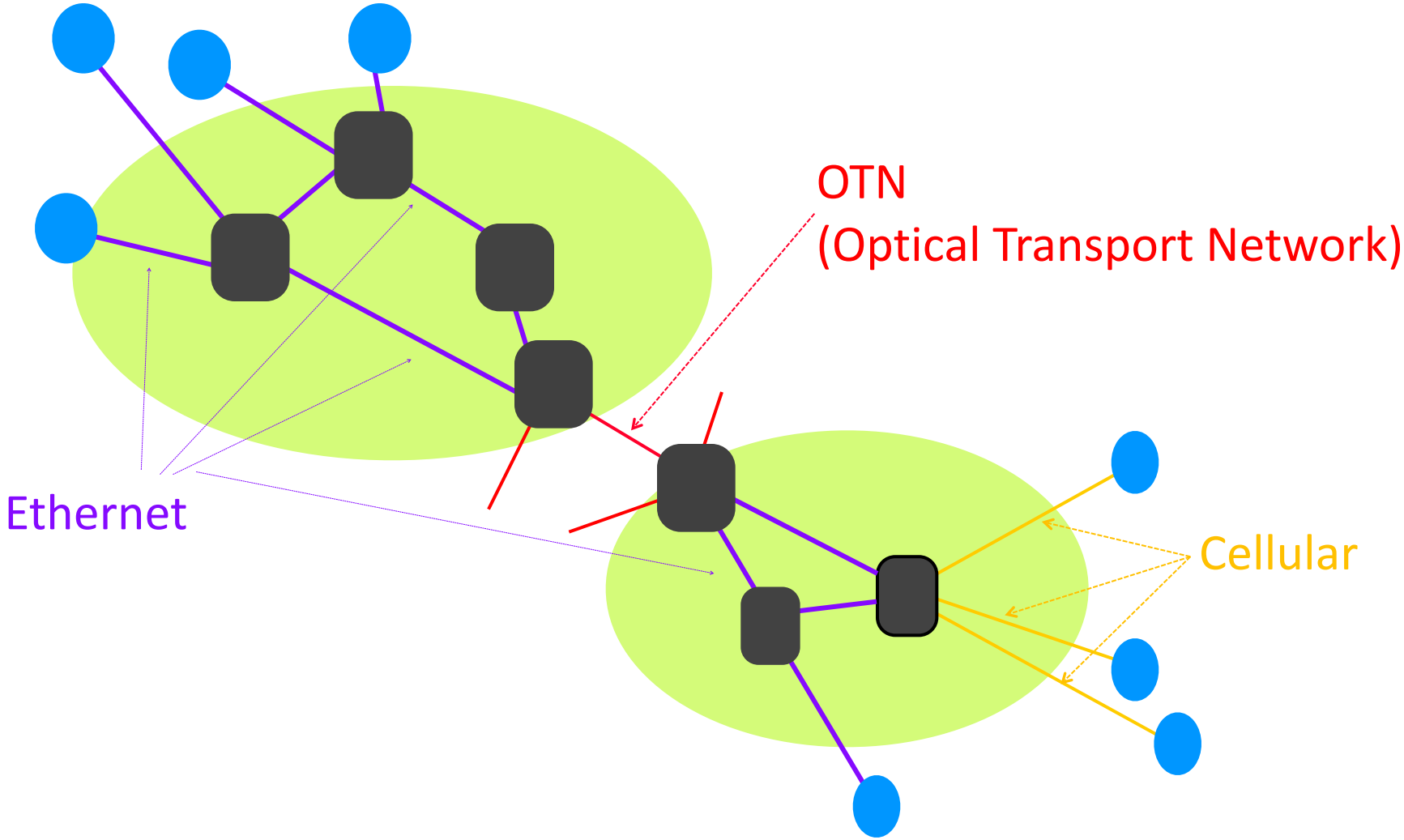

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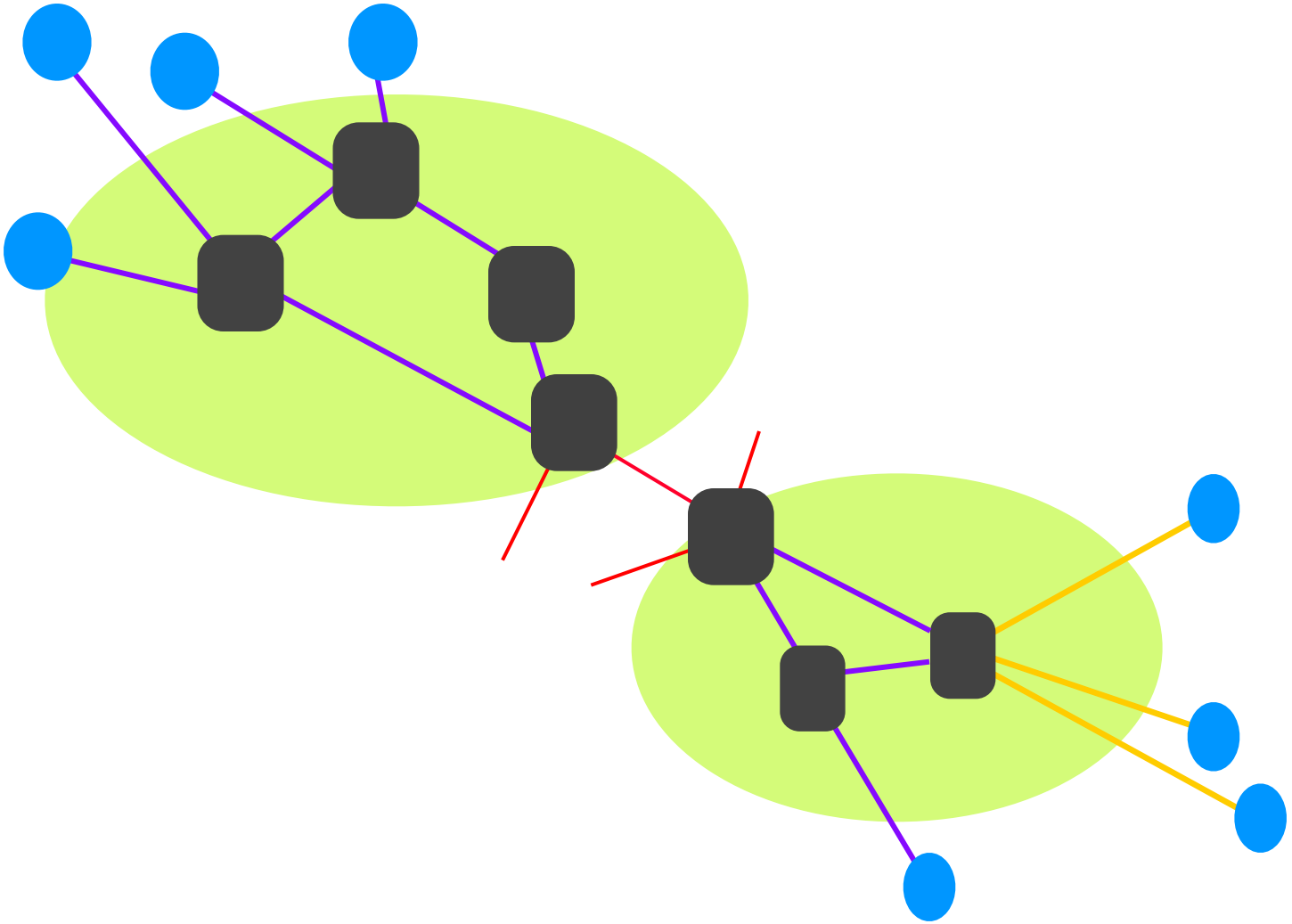

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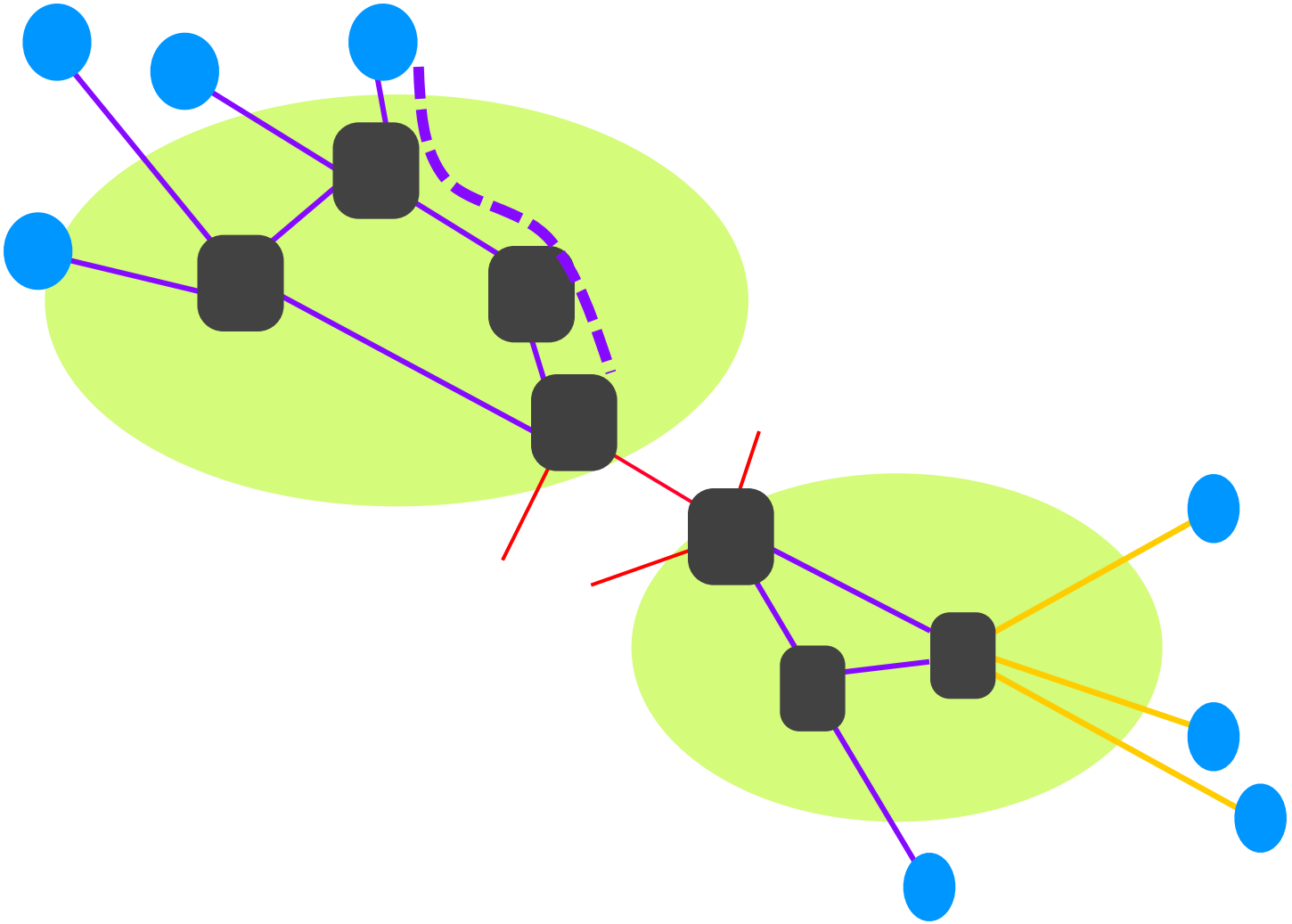

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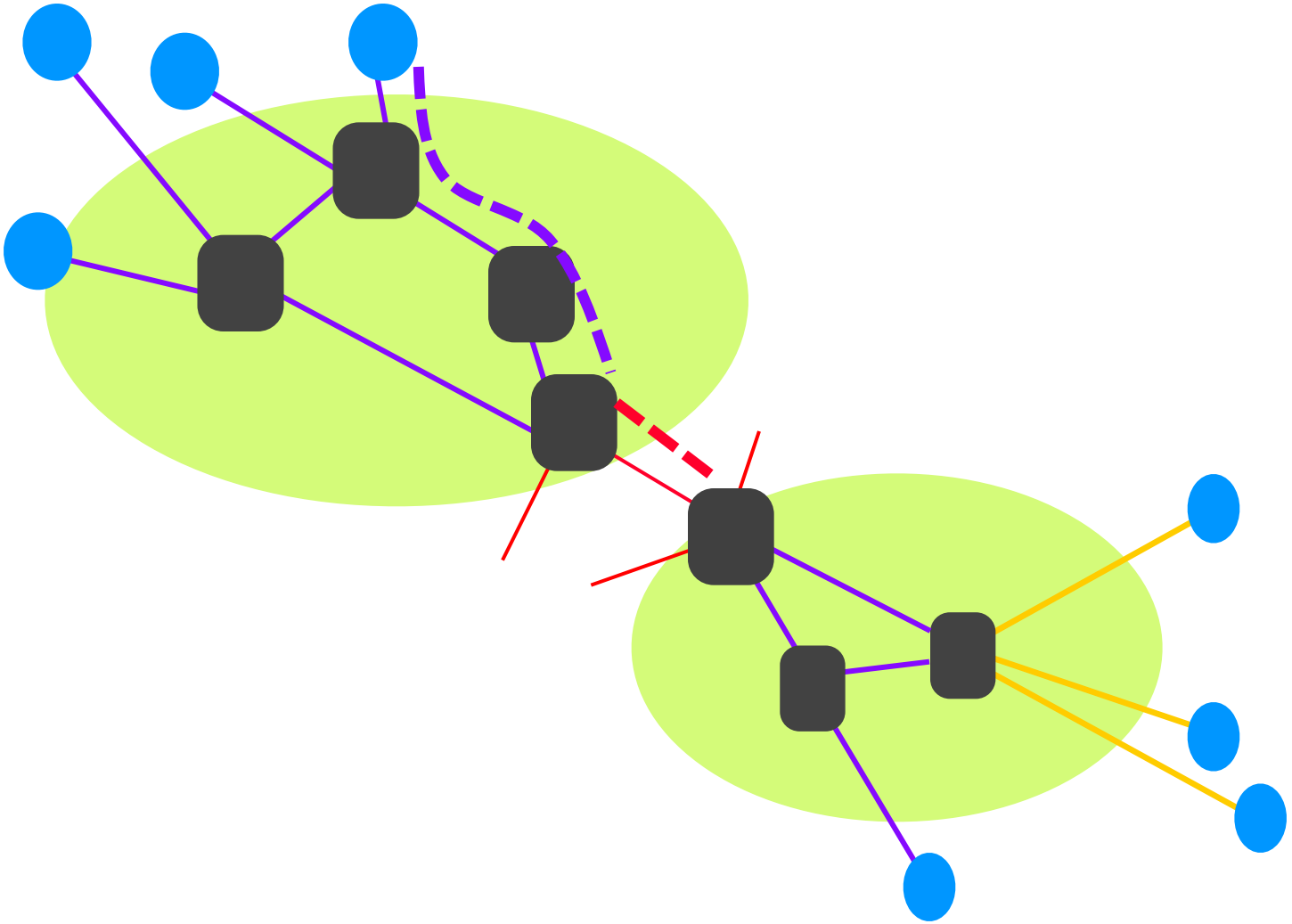

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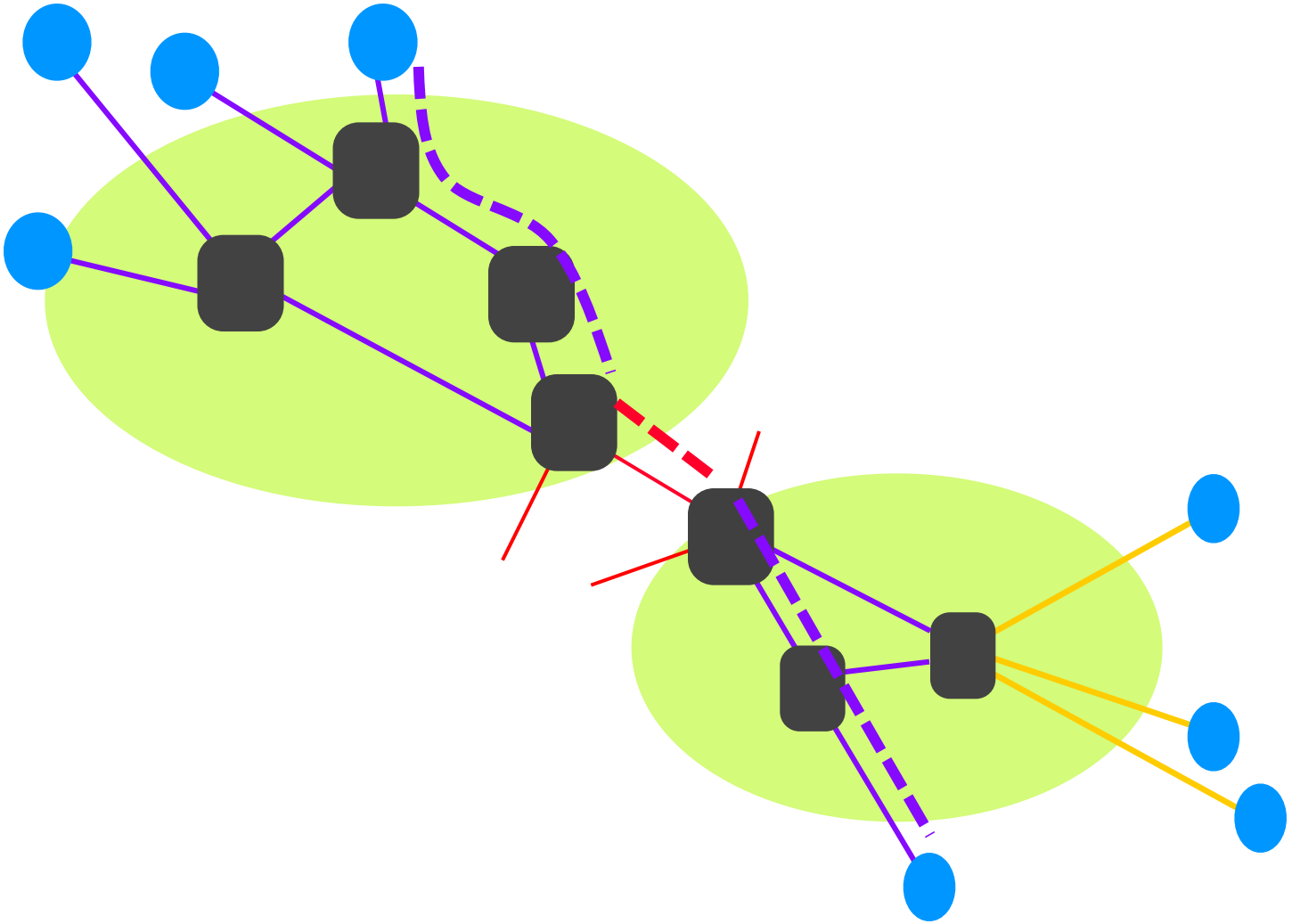

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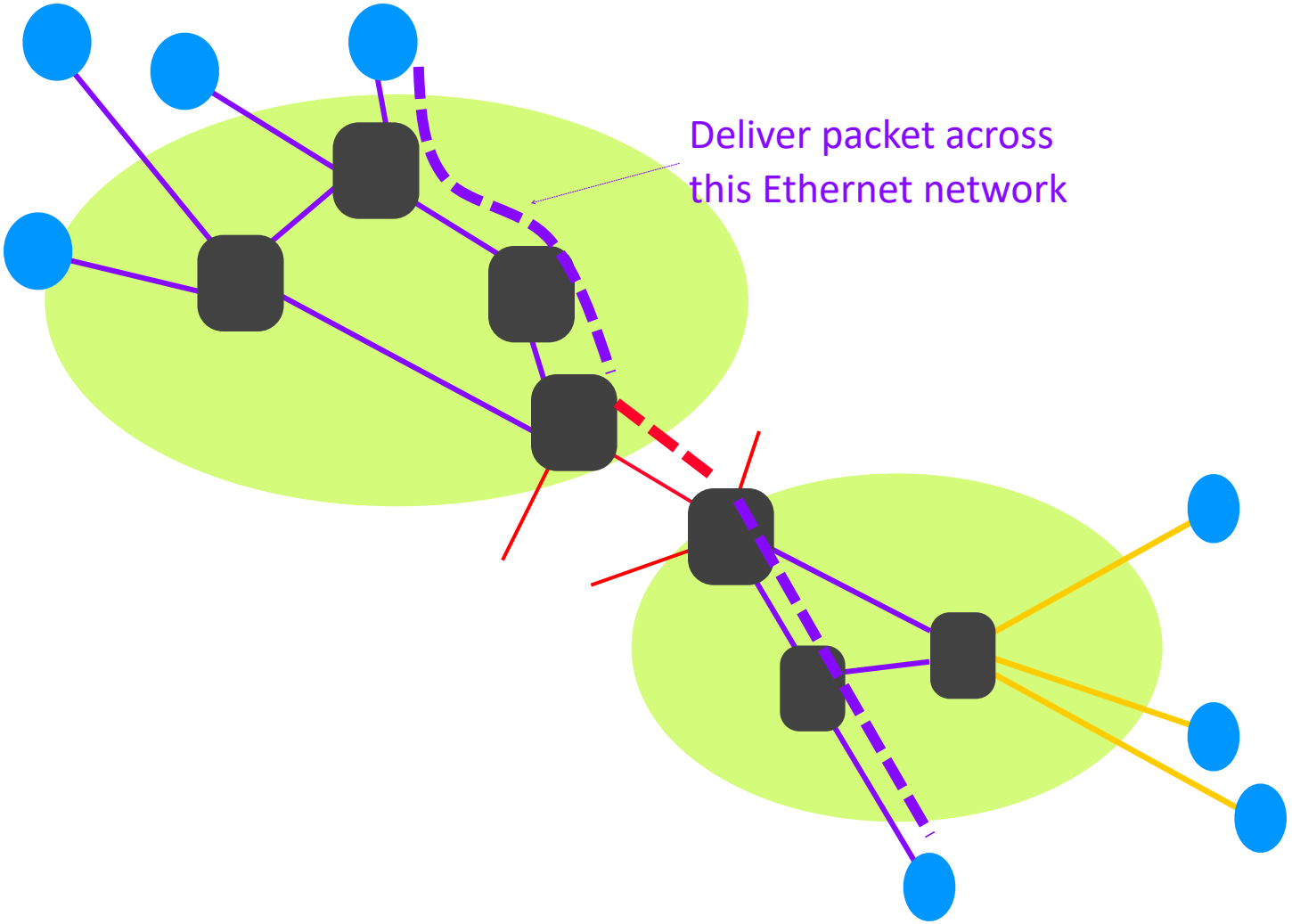

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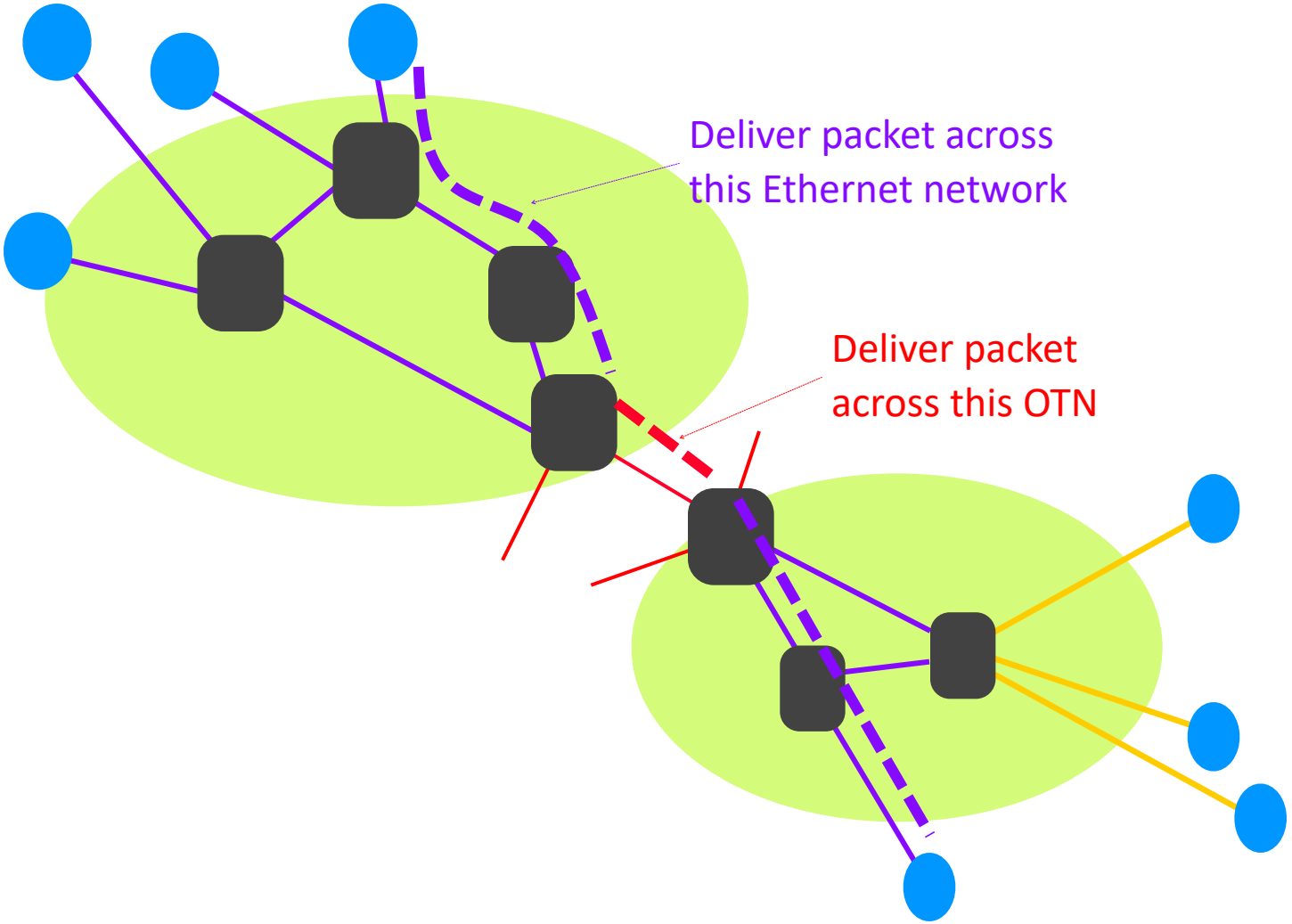

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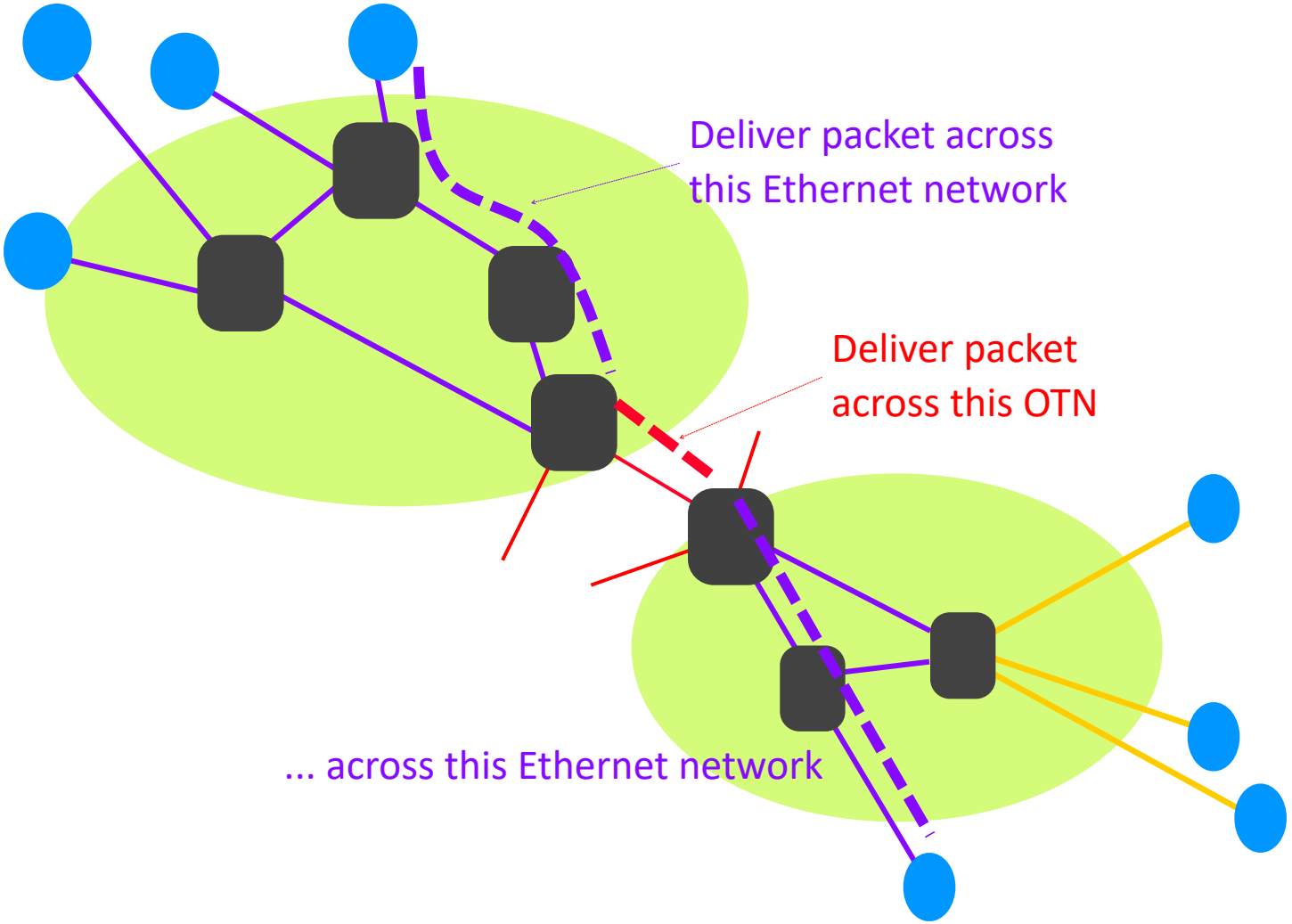

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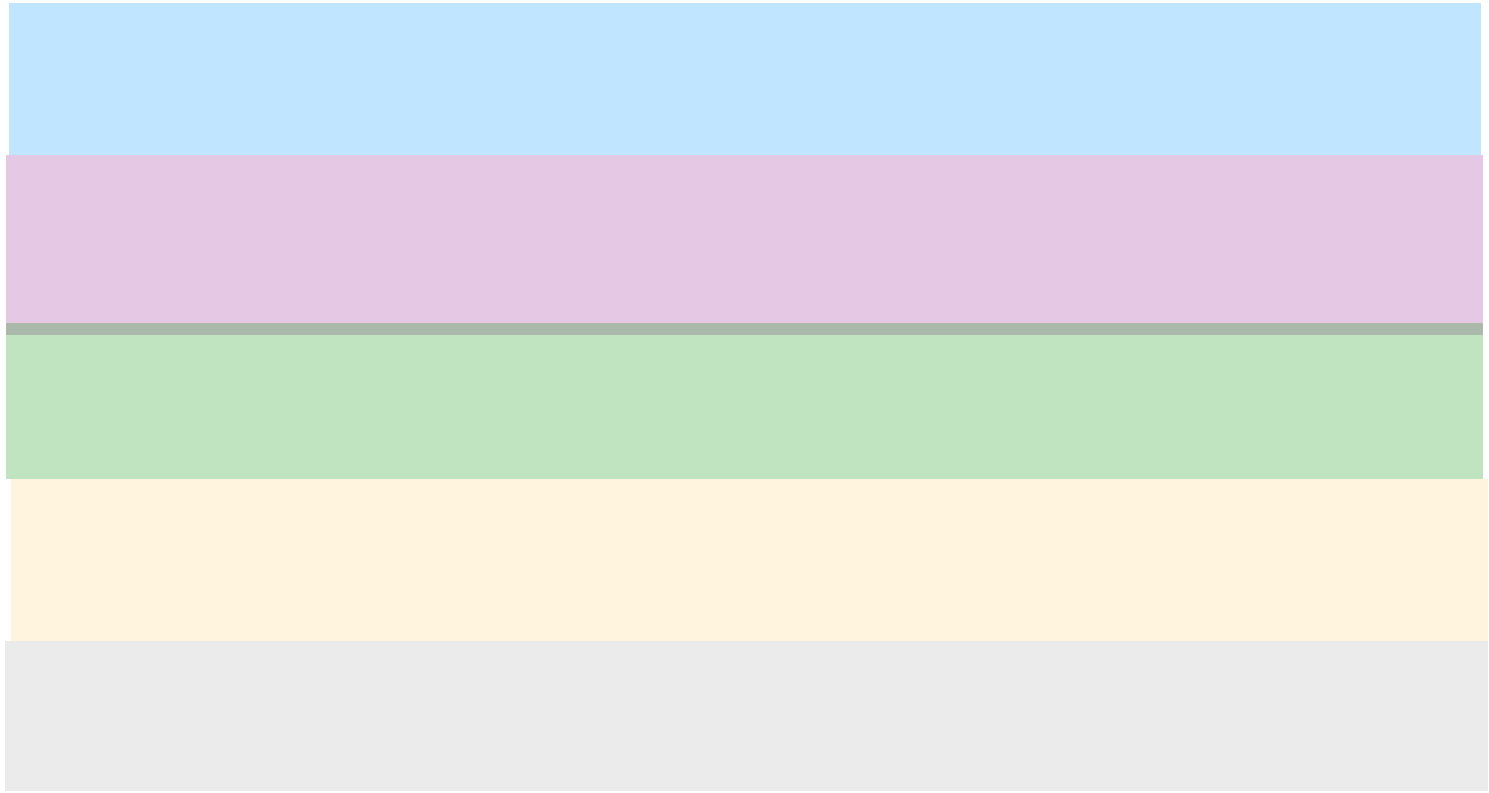

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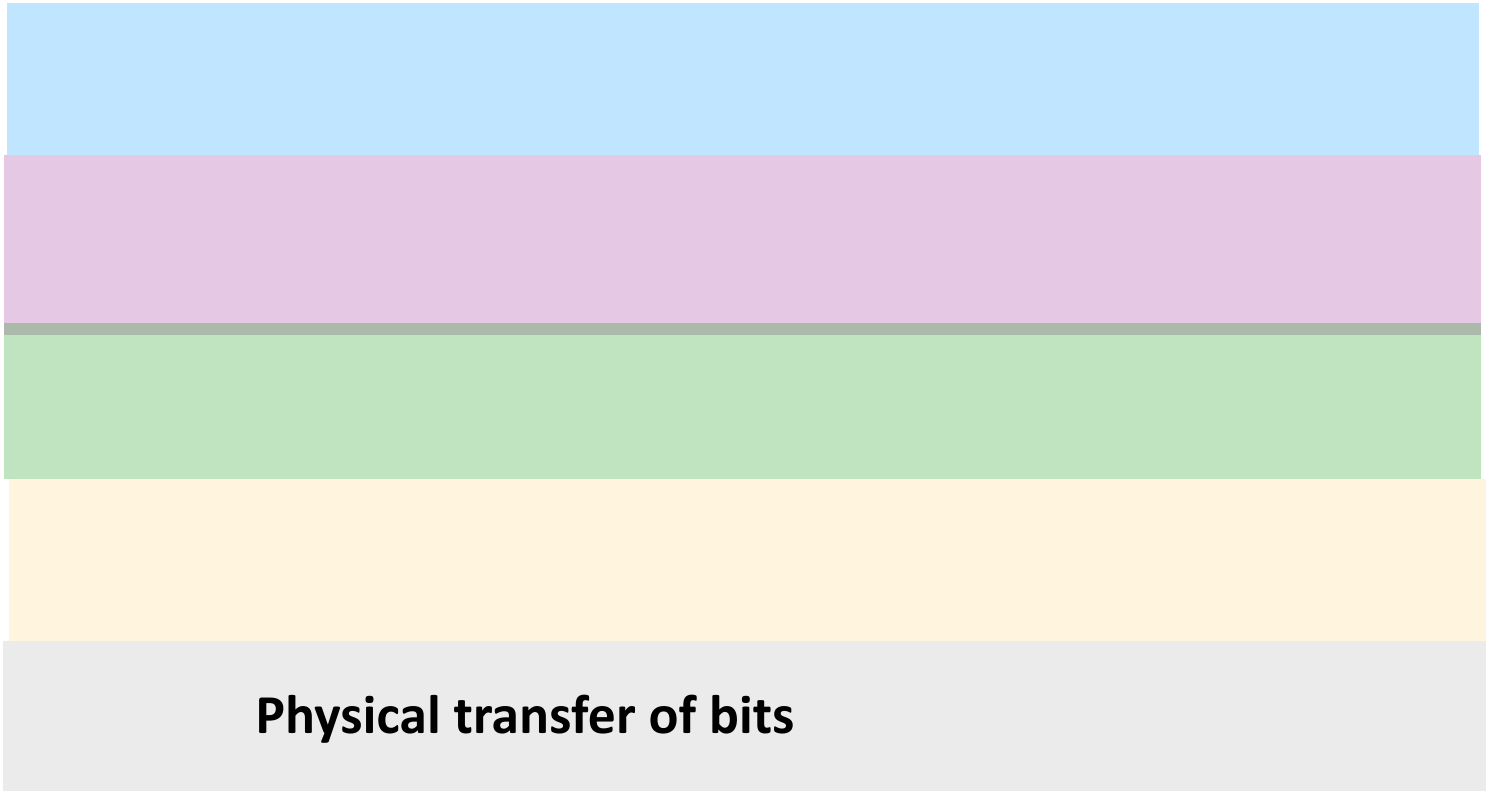

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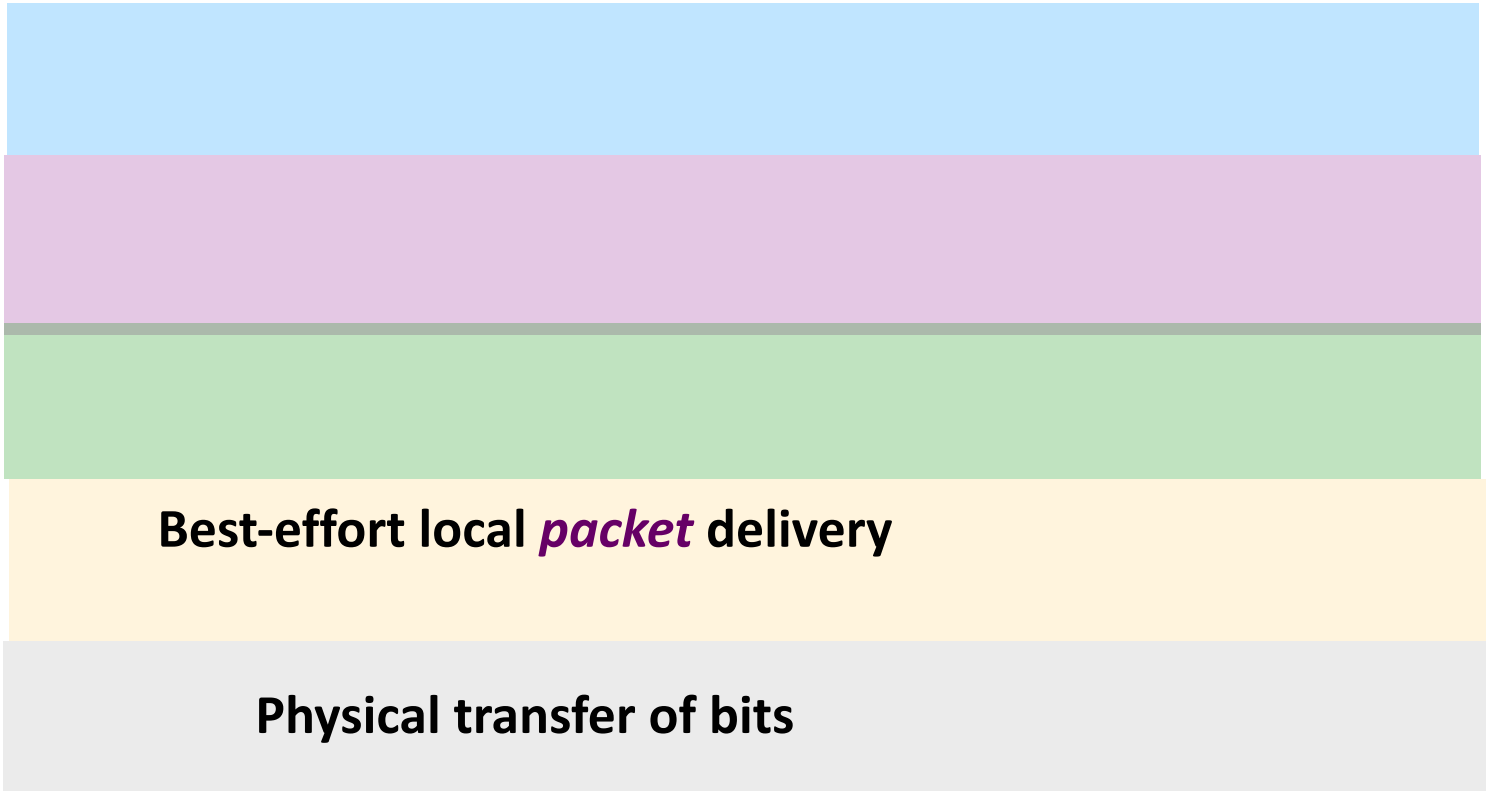

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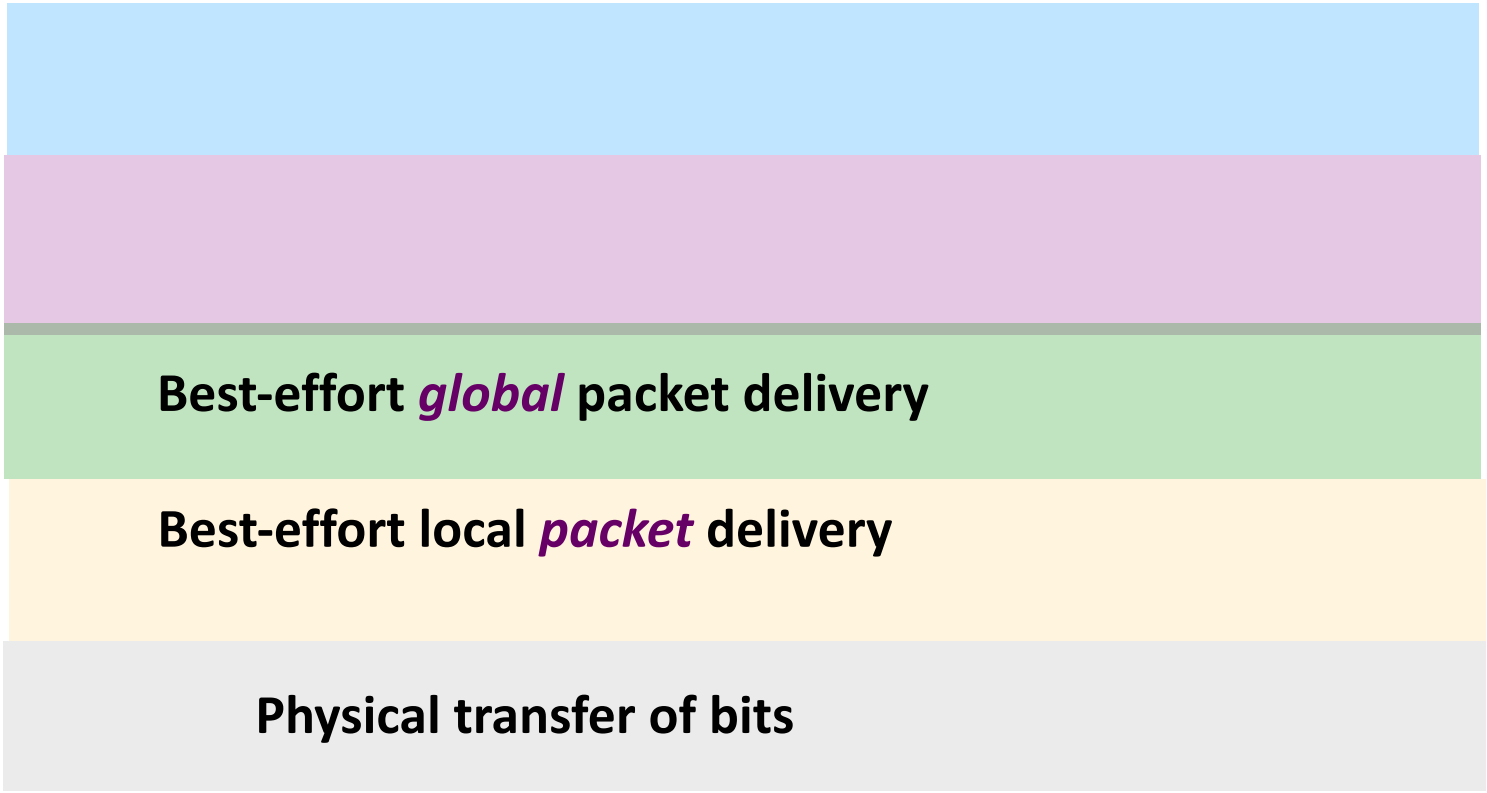

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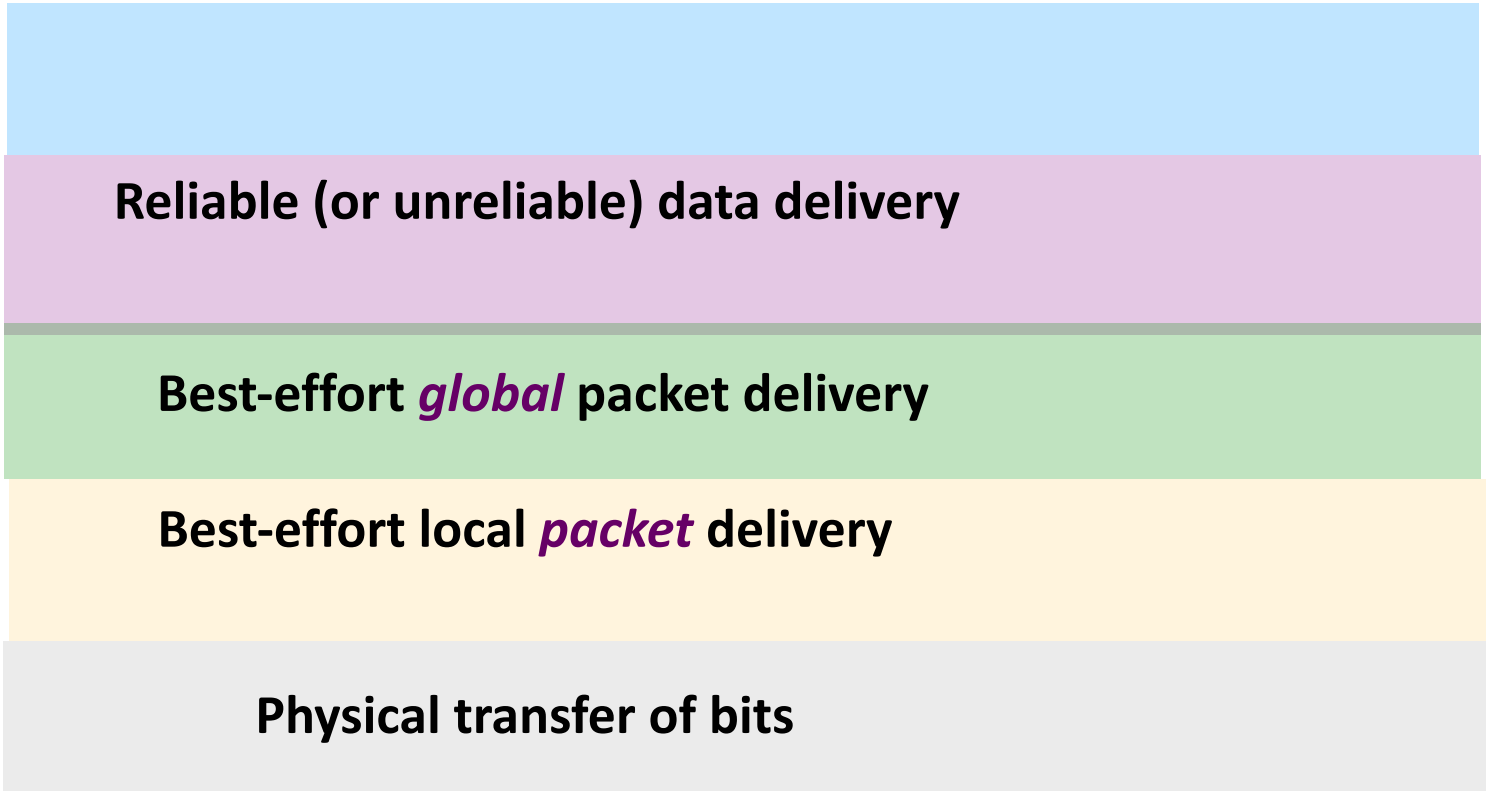

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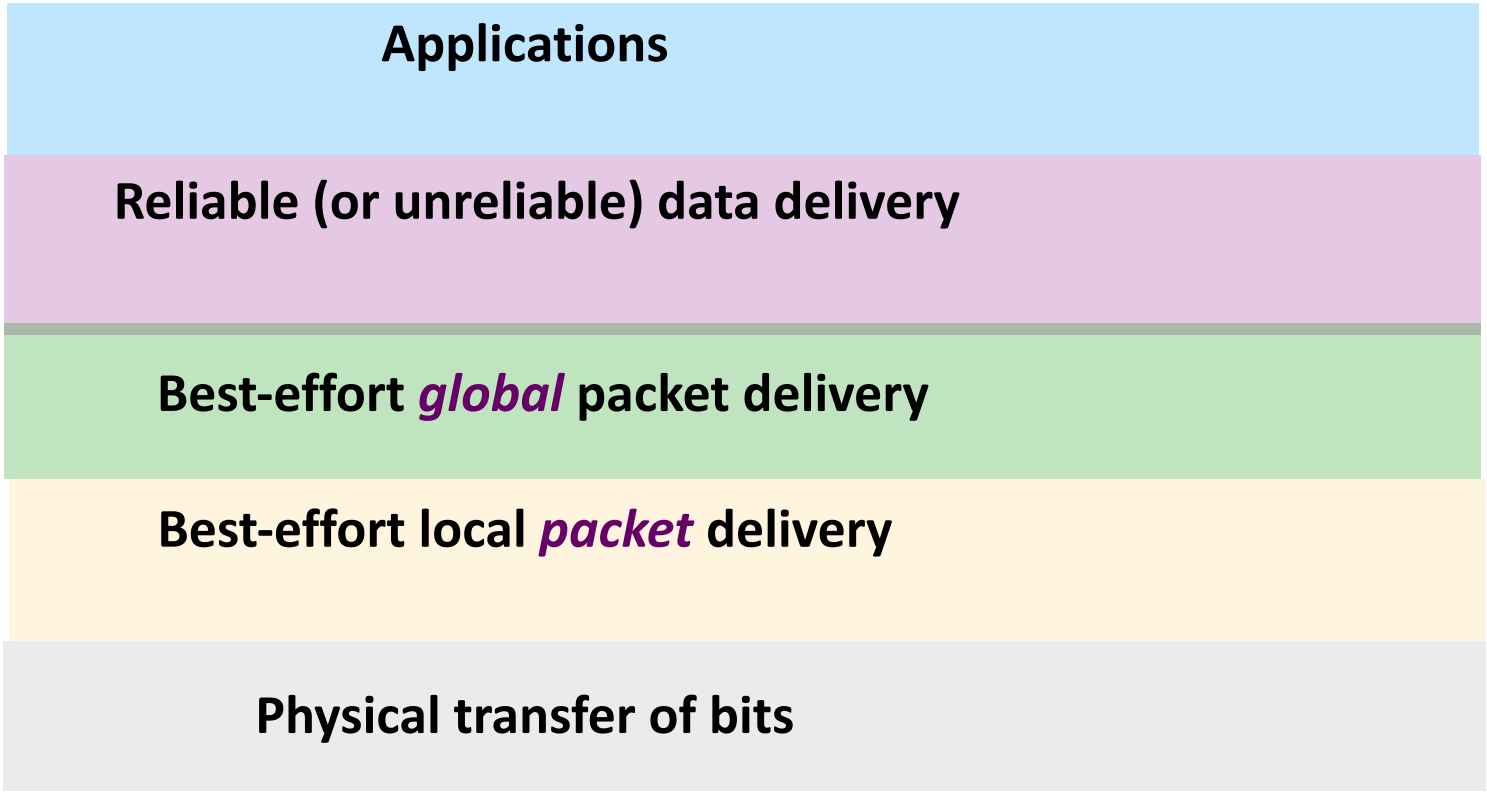

A layered architecture

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- Two layers interact only through the interface between them

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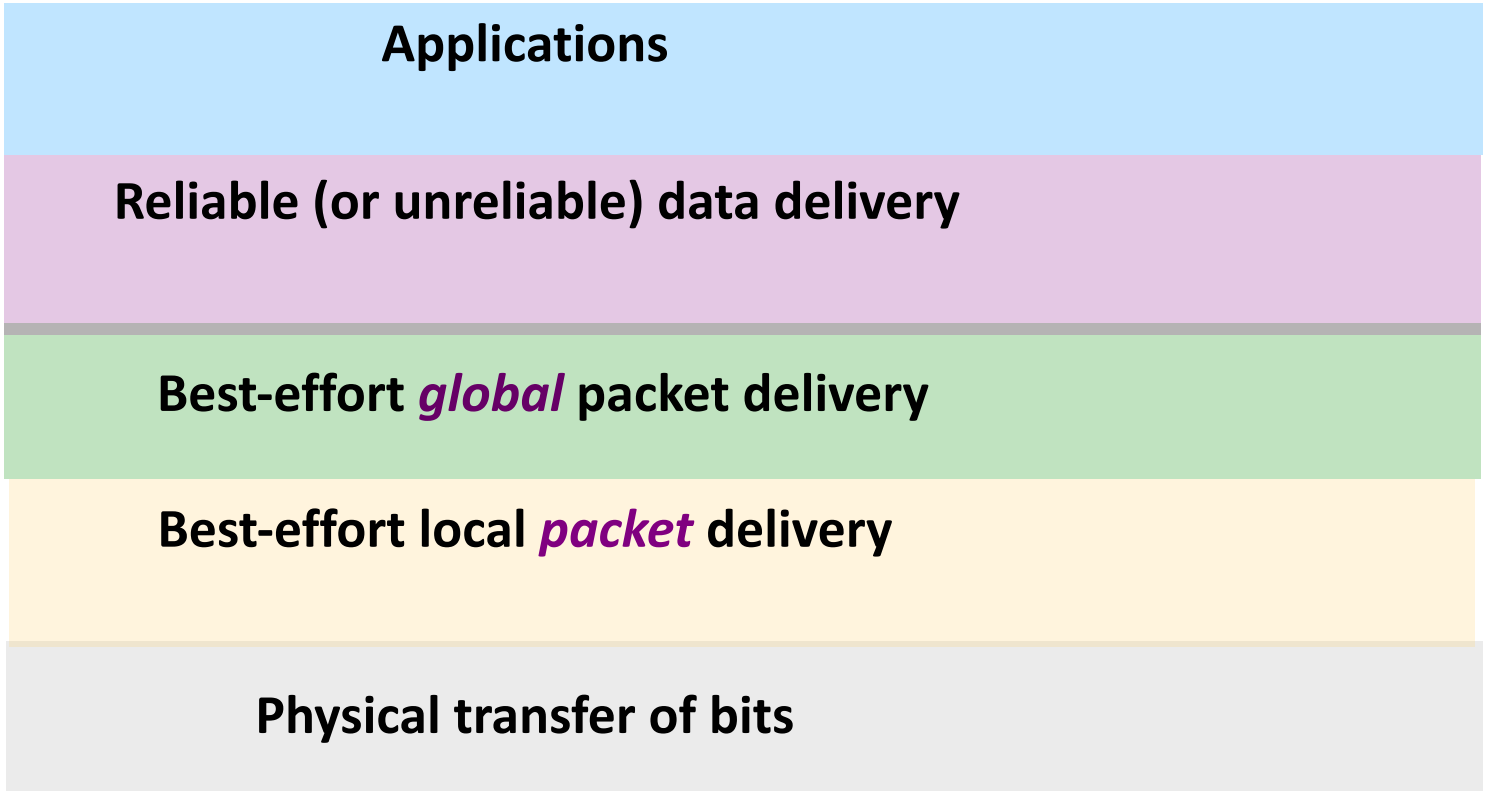

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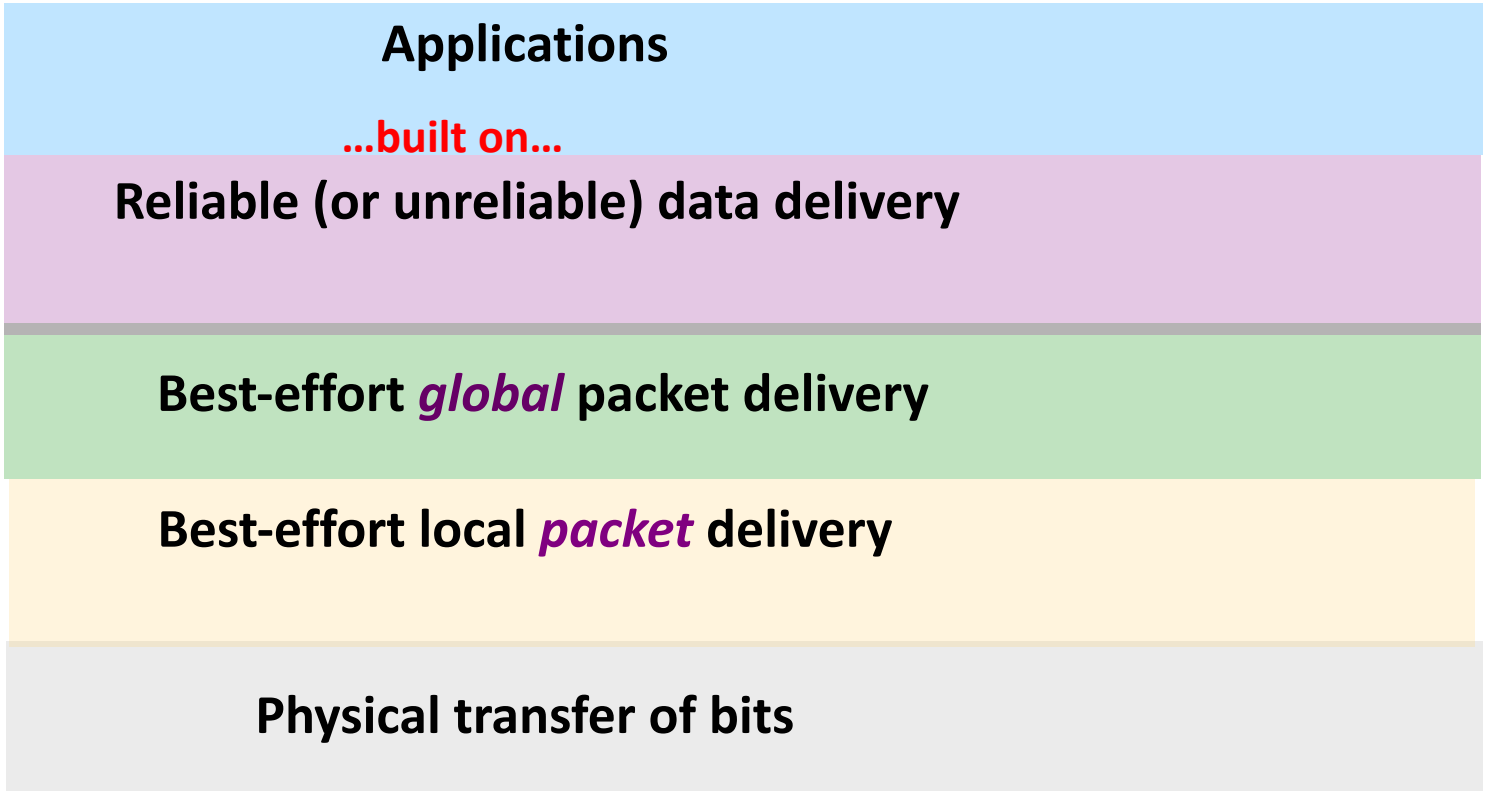

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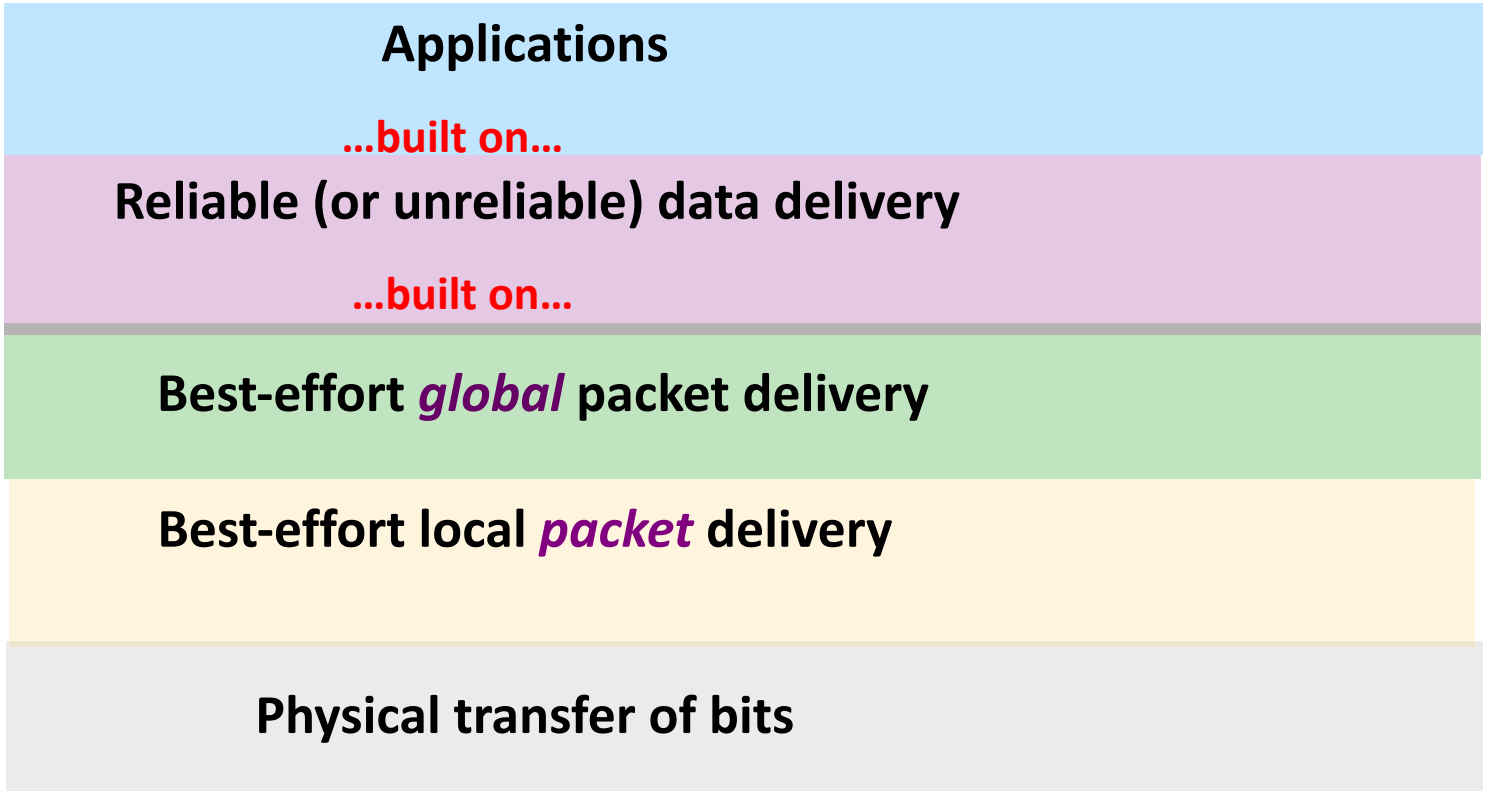

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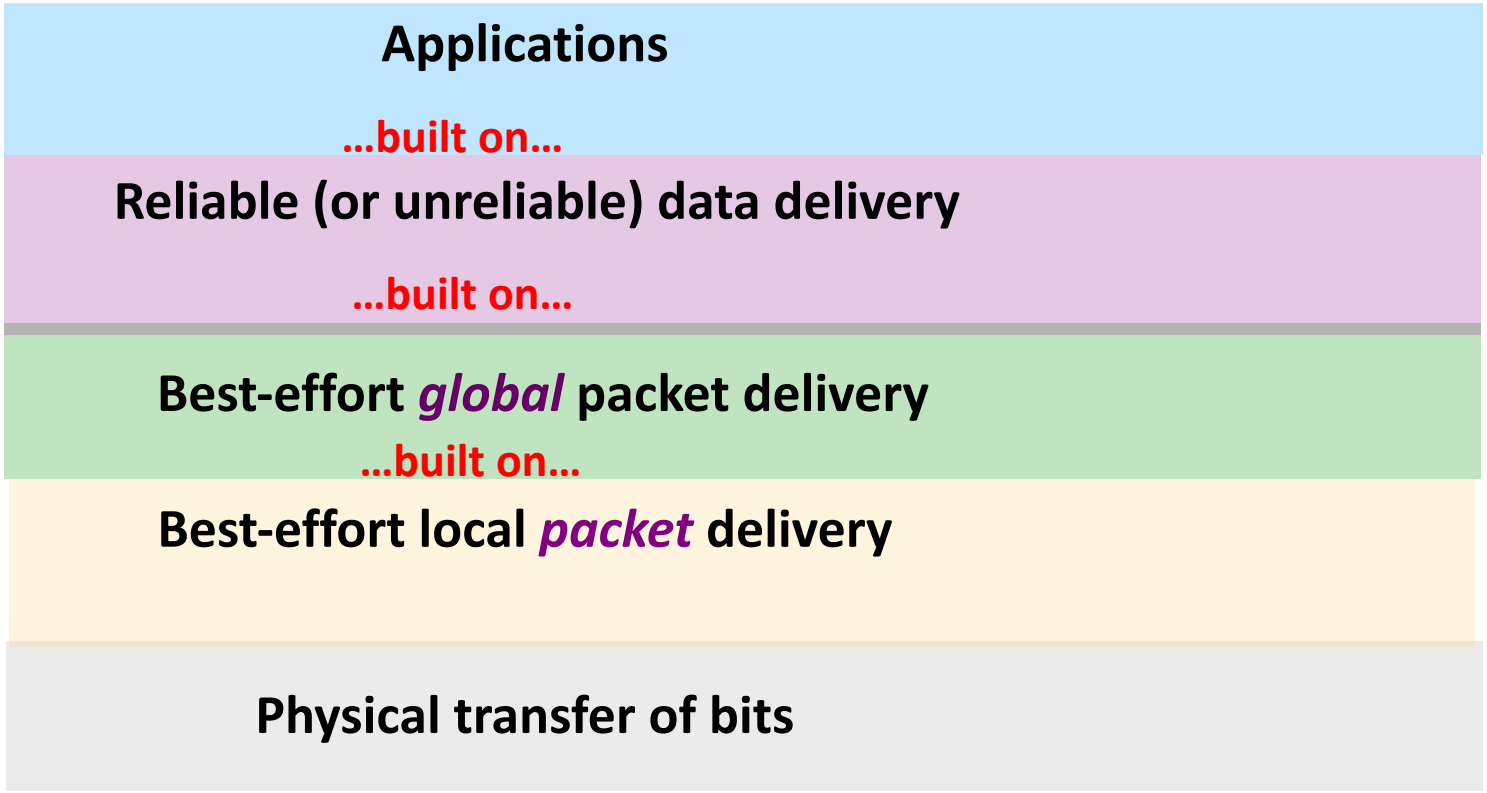

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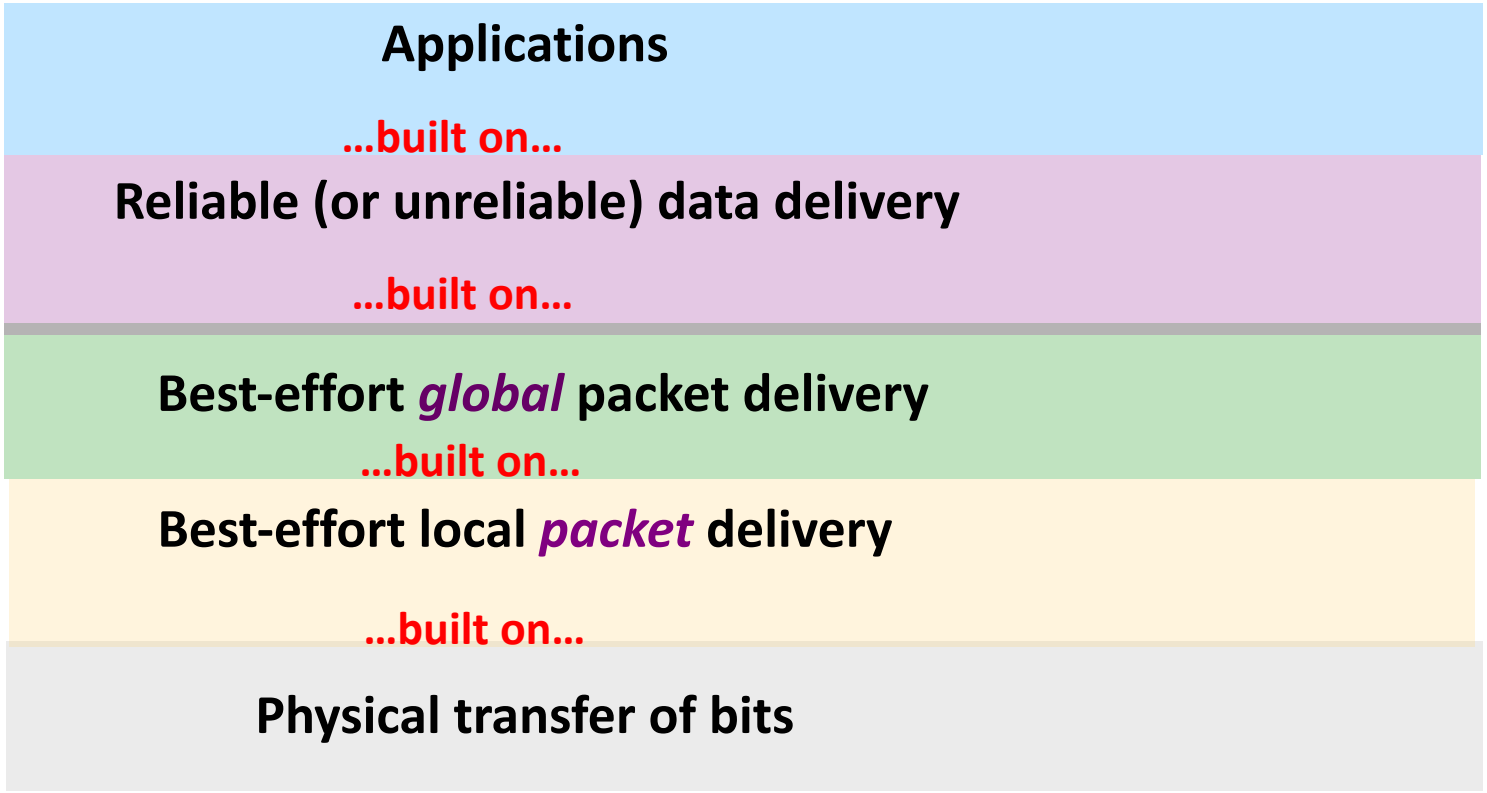

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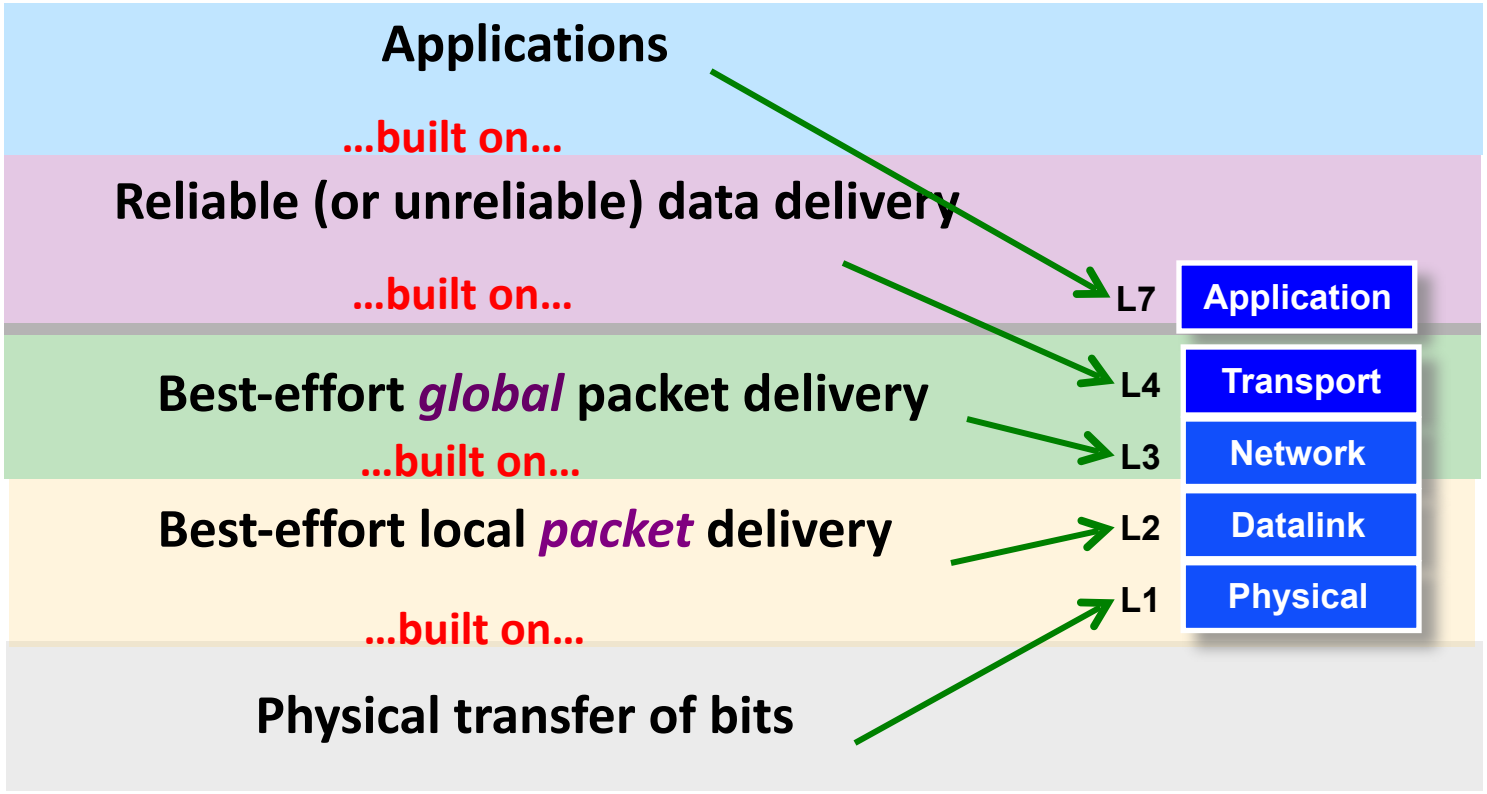

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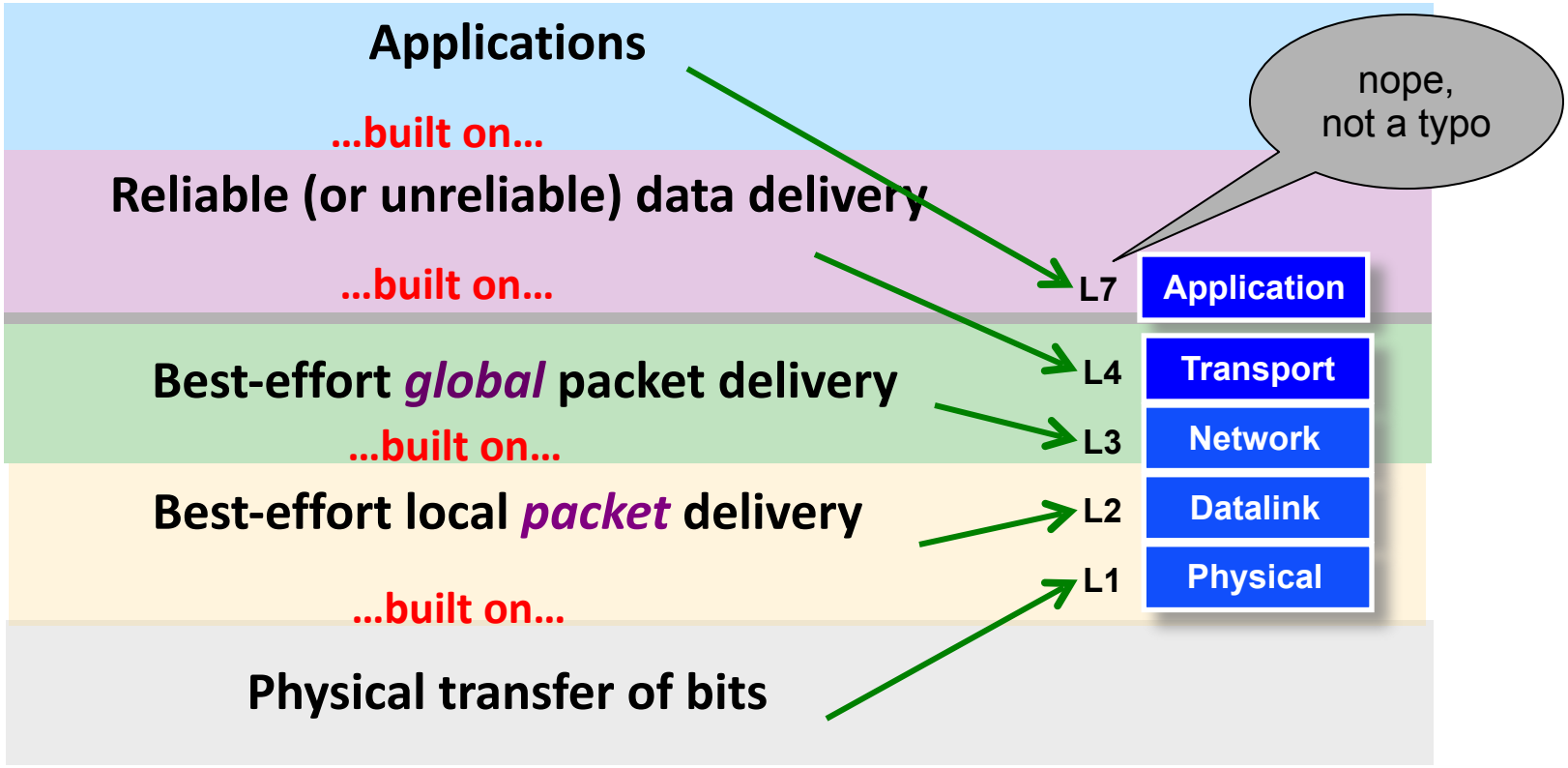
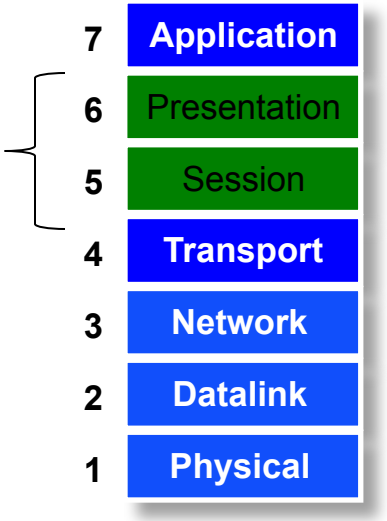


Ancient history (late 1970s)

The Open Systems Interconnect (OSI) model developed by the International Organization for Standardization (ISO) included two additional layers that are often implemented as part of the application

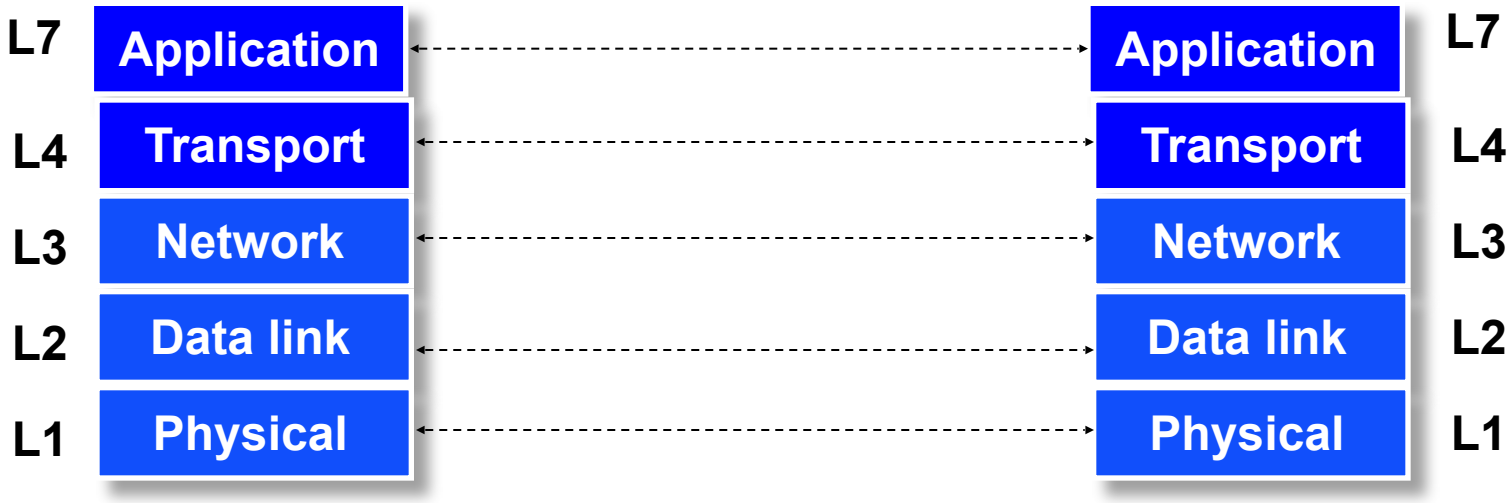


Questions?

Recall: peers understand the same things

CEO	Letter	CEO
Aide	Envelope	Aide
FedEx	Fedex Envelope (FE)	FedEx

Protocols and Layers



Communication between peer layers on different systems is defined by protocols

What is a Protocol?

- An agreement between parties on how to communicate
- Defines the syntax of communication
- And semantics
  - “first a hullo, then a request…”
  - essentially, a state machine
  - we’ll study many protocols later in the semester

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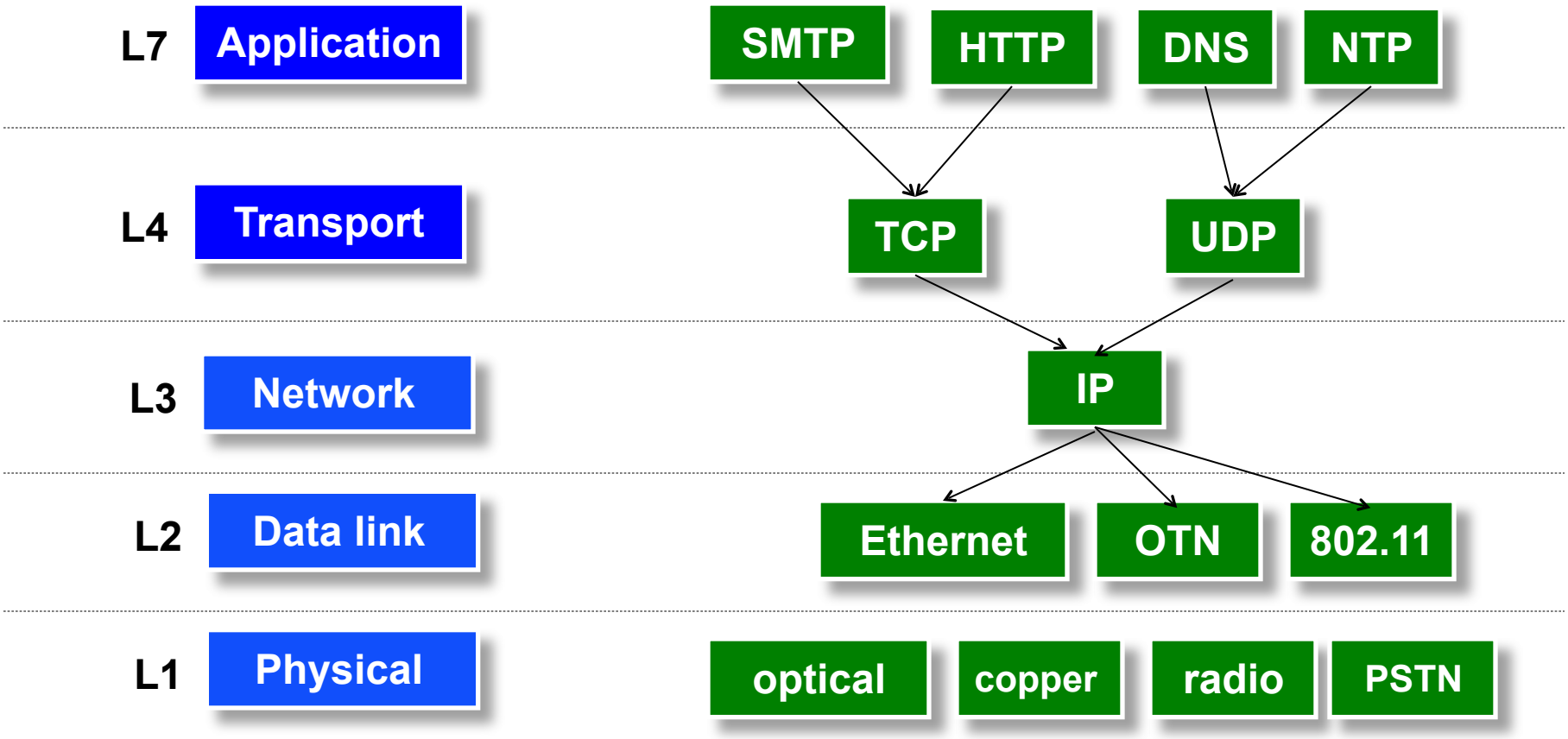
- Protocols exist at many layers
  - defined by a variety of standards bodies (IETF, IEEE, ITU)

Protocols at different layers



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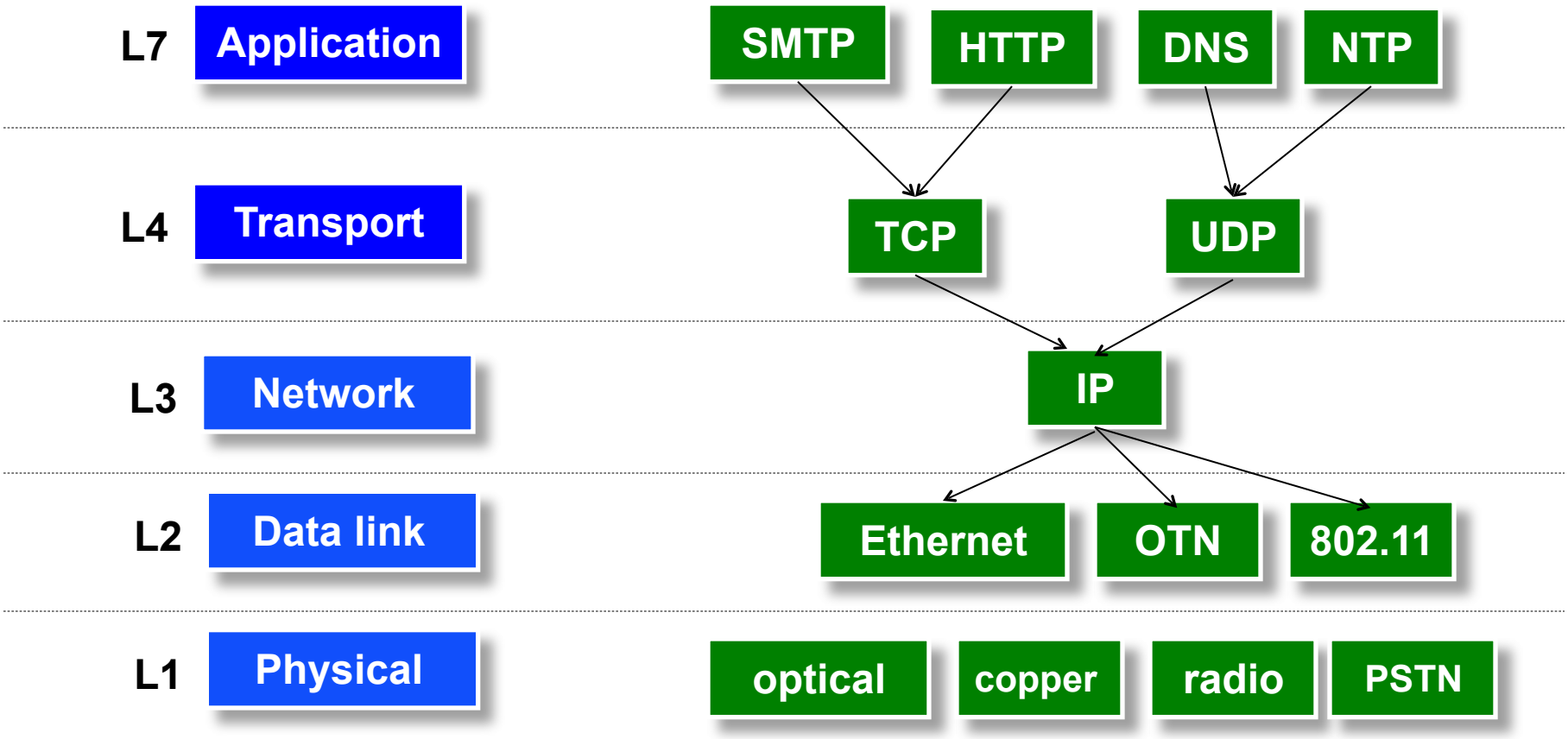
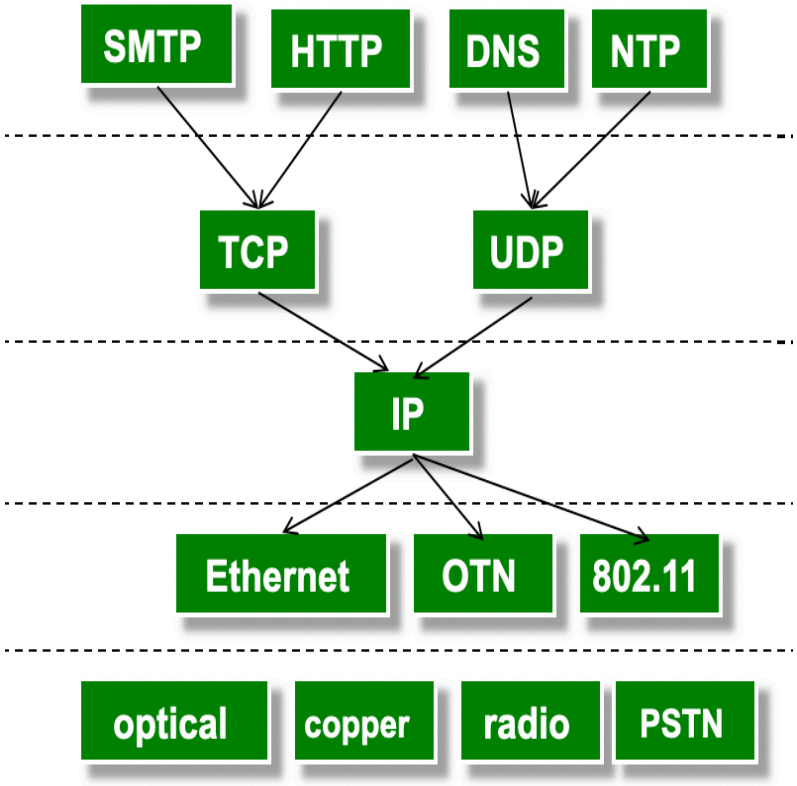


There is just one network-layer protocol!

Recap: Three important properties



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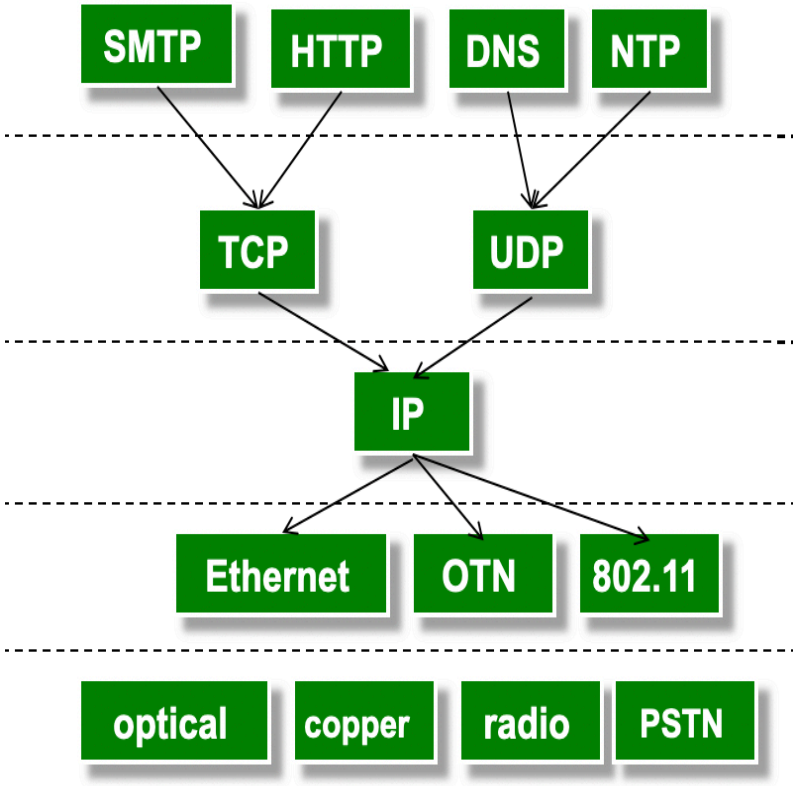
- Each layer:
  - Depends on layer below
  - Supports layer above
  - Independent of others



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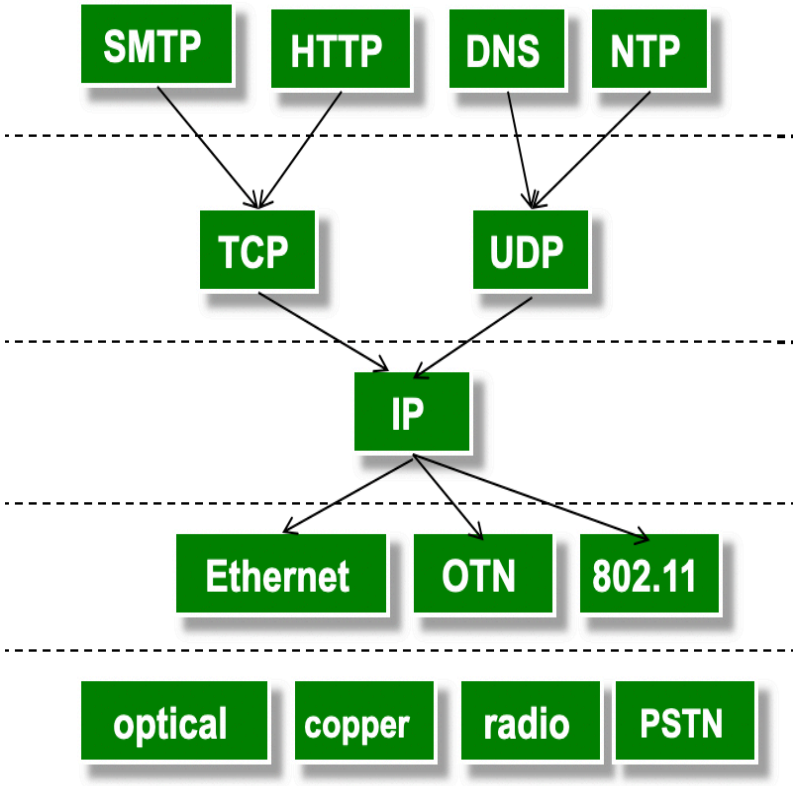

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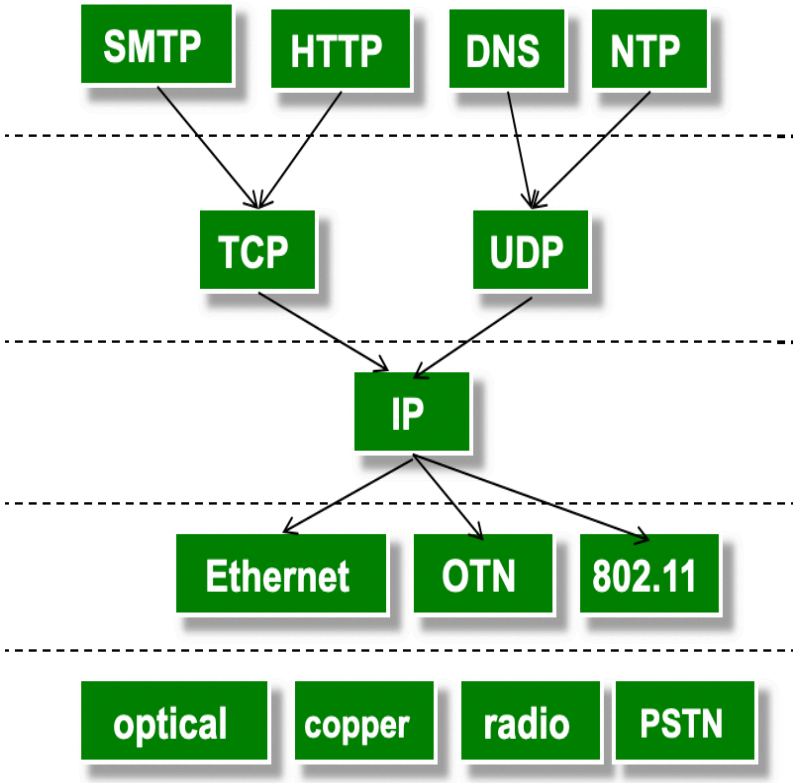
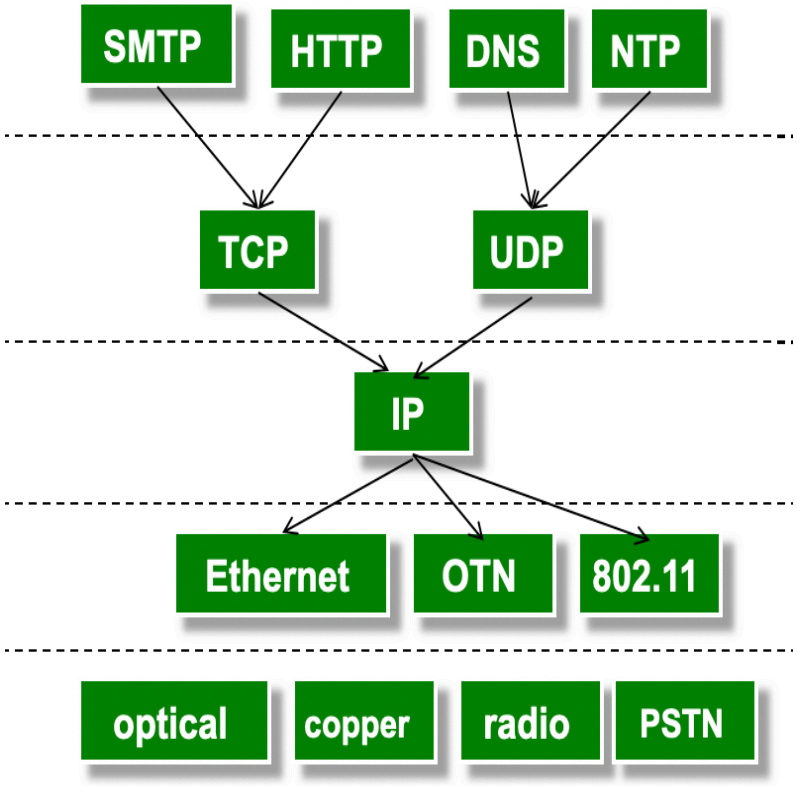
- But only one IP layer
  - Unifying protocol



Why is layering important?



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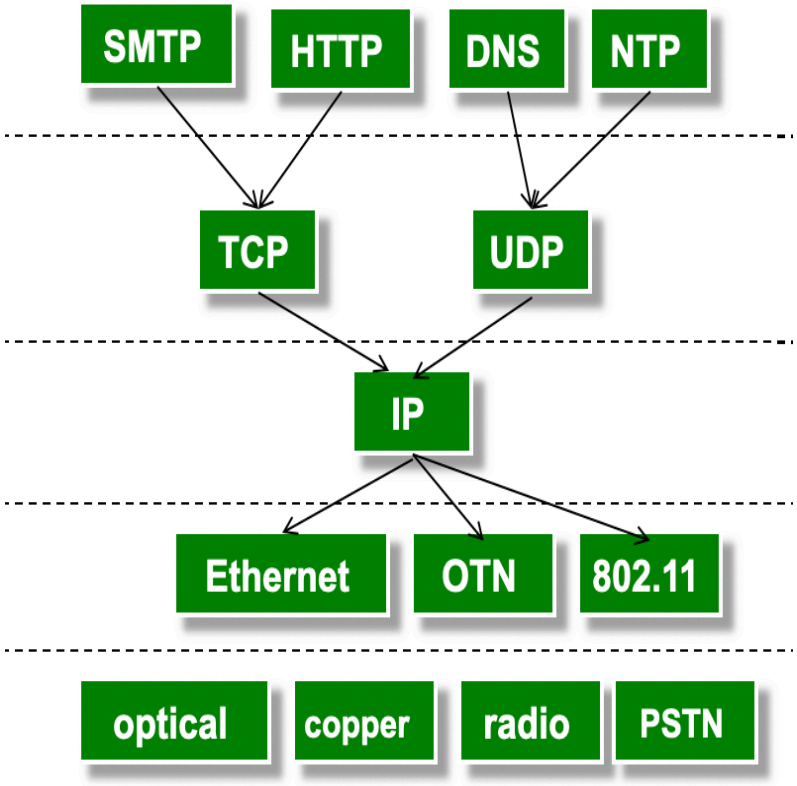
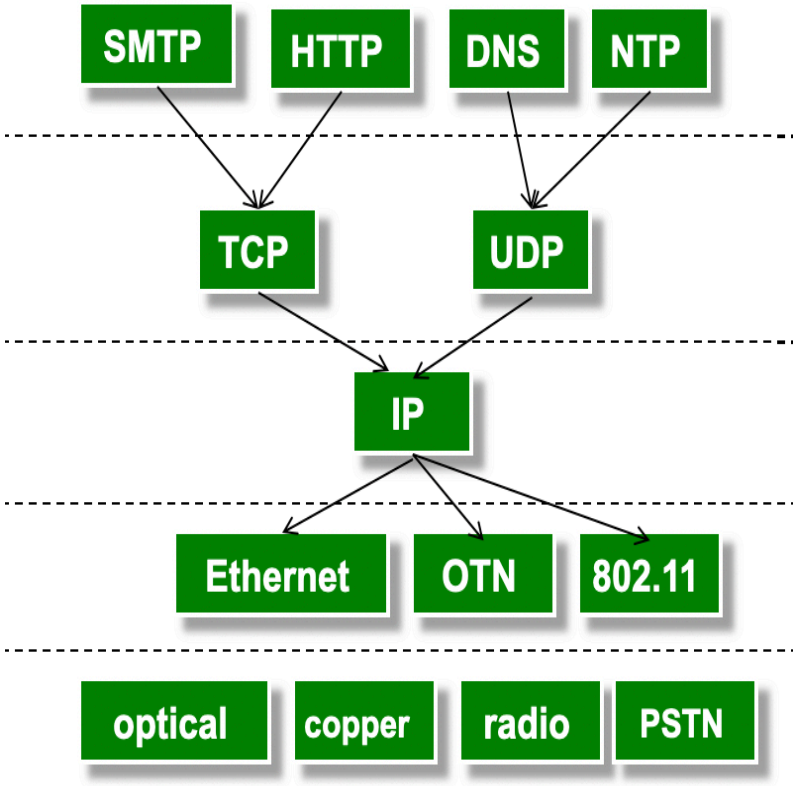


Why is layering important?

- Innovation can proceed largely in parallel!
- Pursued by very different communities
  - App devs (L7), chip designers (L1/L2)



Questions?

How do you solve a problem?

1. Decompose it (into tasks and abstractions)

2. Assign tasks to entities (who does what)

Distributing Layers Across Network

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- What gets implemented where?

What gets implemented at the end host?

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- Therefore, all layers must exist at host!

What gets implemented in the network?

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- Packets must be delivered across links and local networks → datalink layer (L2)
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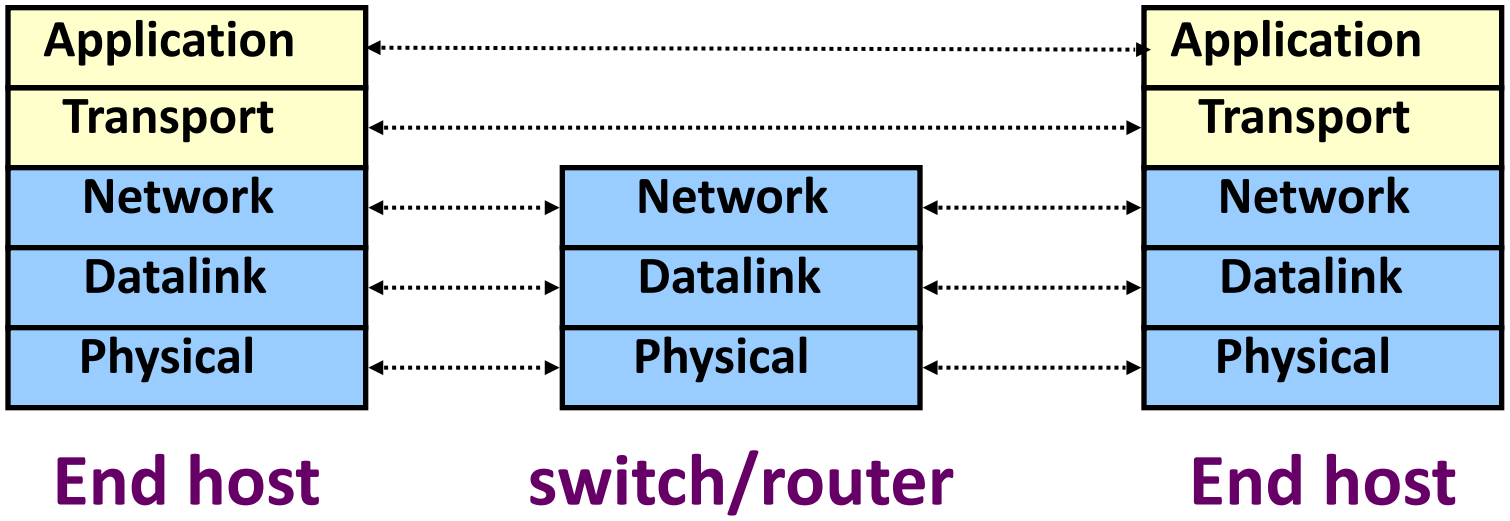
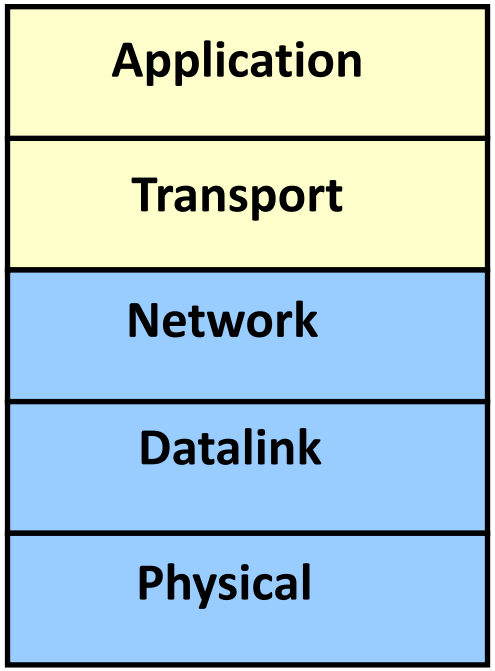
- The network does not support reliable delivery
  - Transport layer (and above) ***not*** supported

Simple Diagram

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



A closer look: end host



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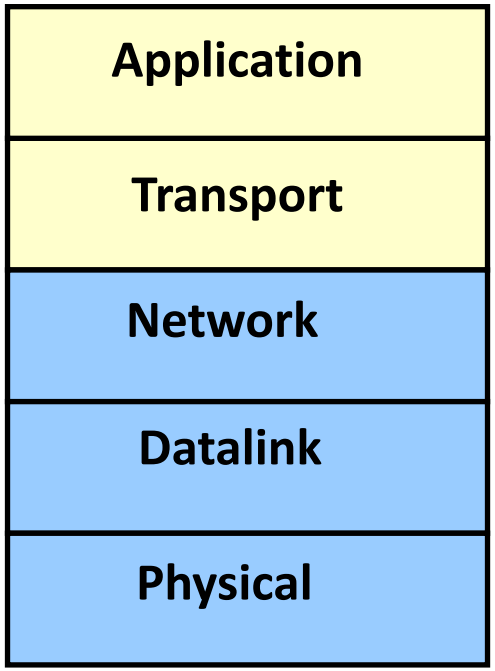
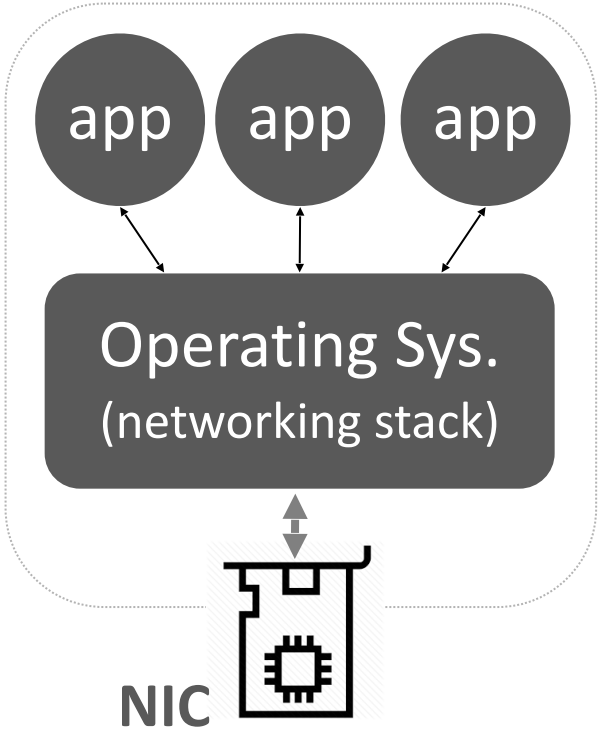
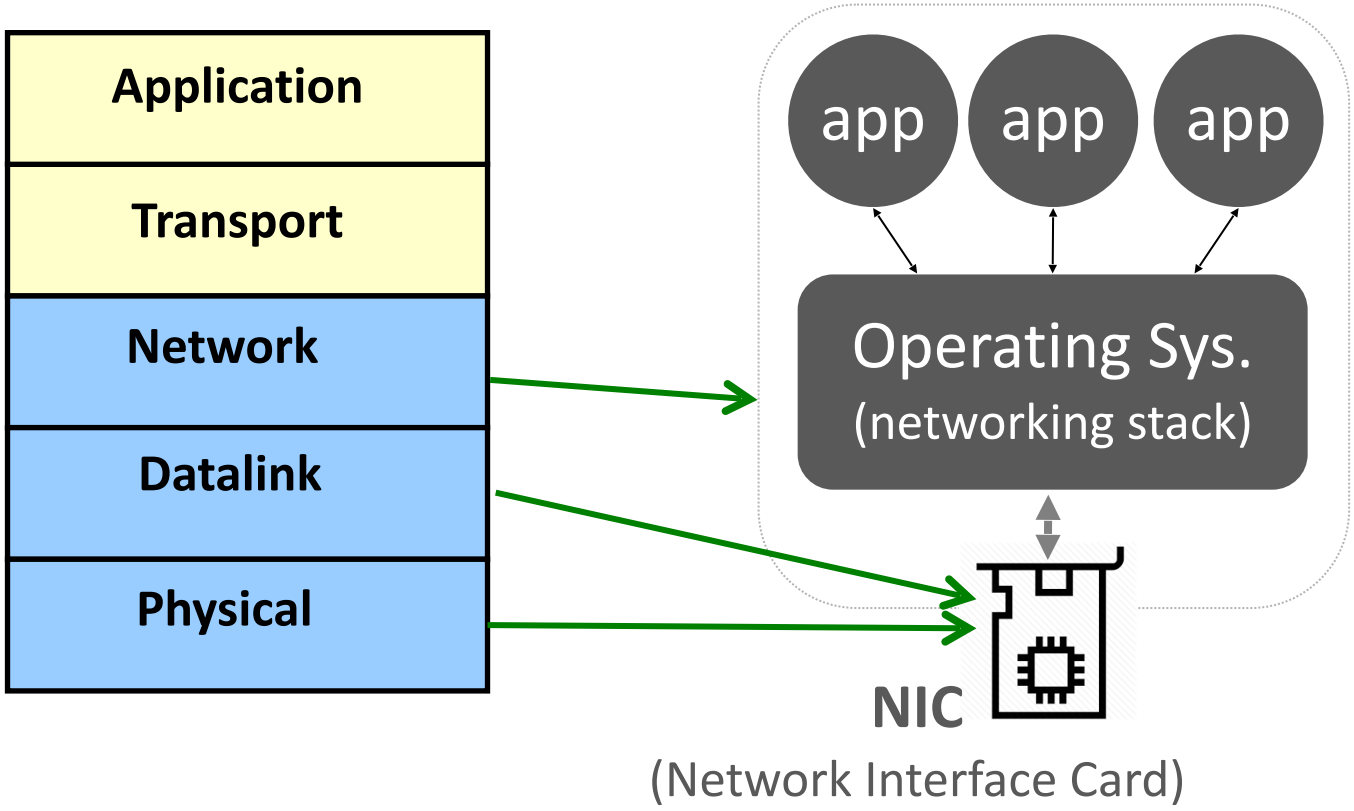




(Network Interface Card)

A closer look: end host



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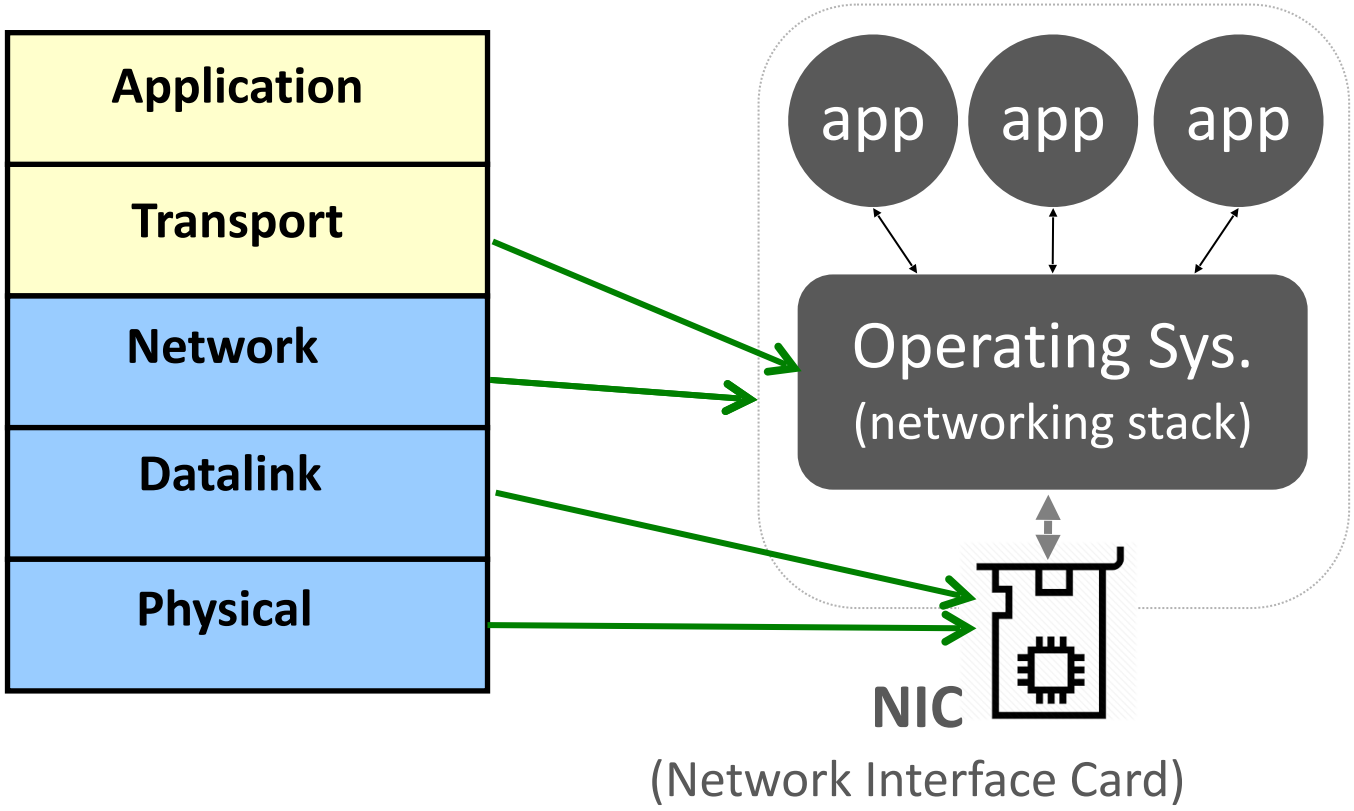
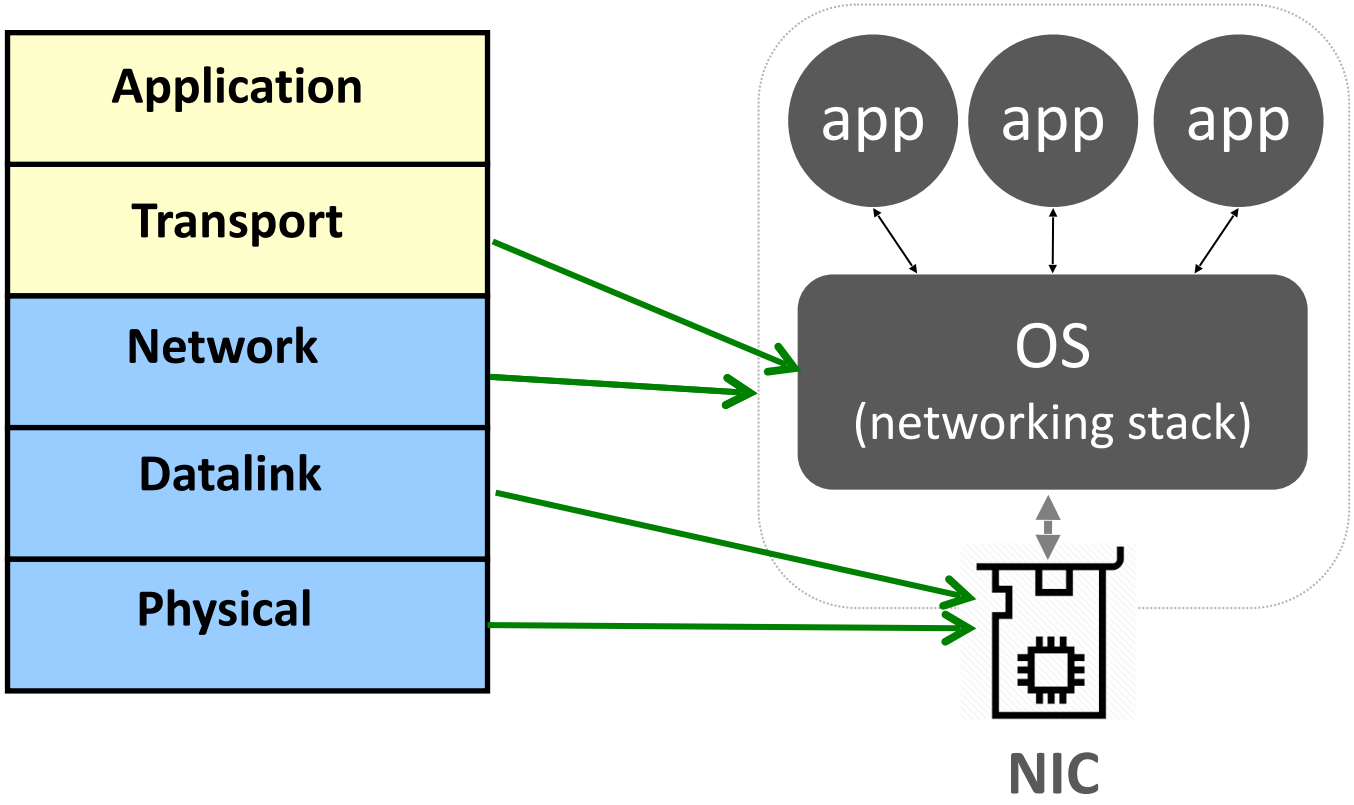


Note: addressing *within* the end host



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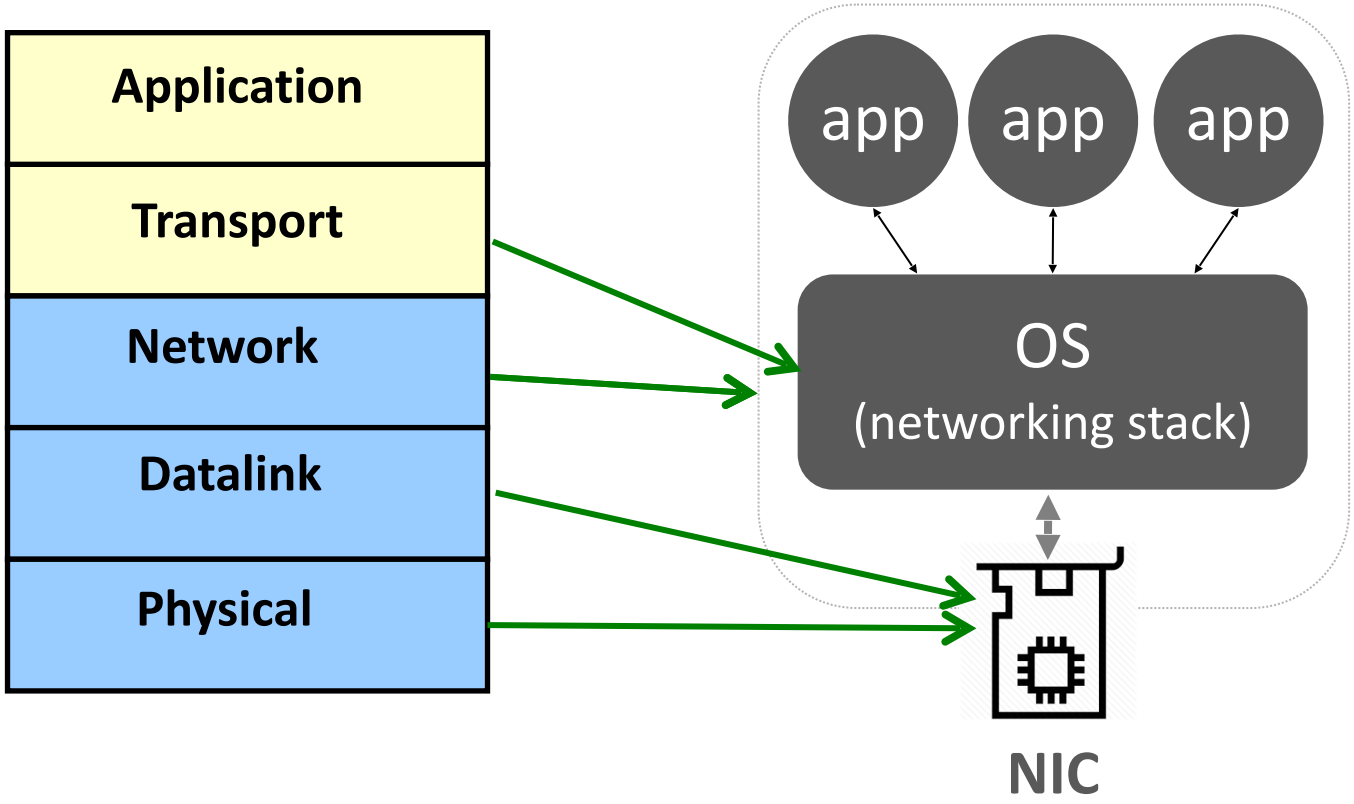
Recall: packet contains the destination host's address



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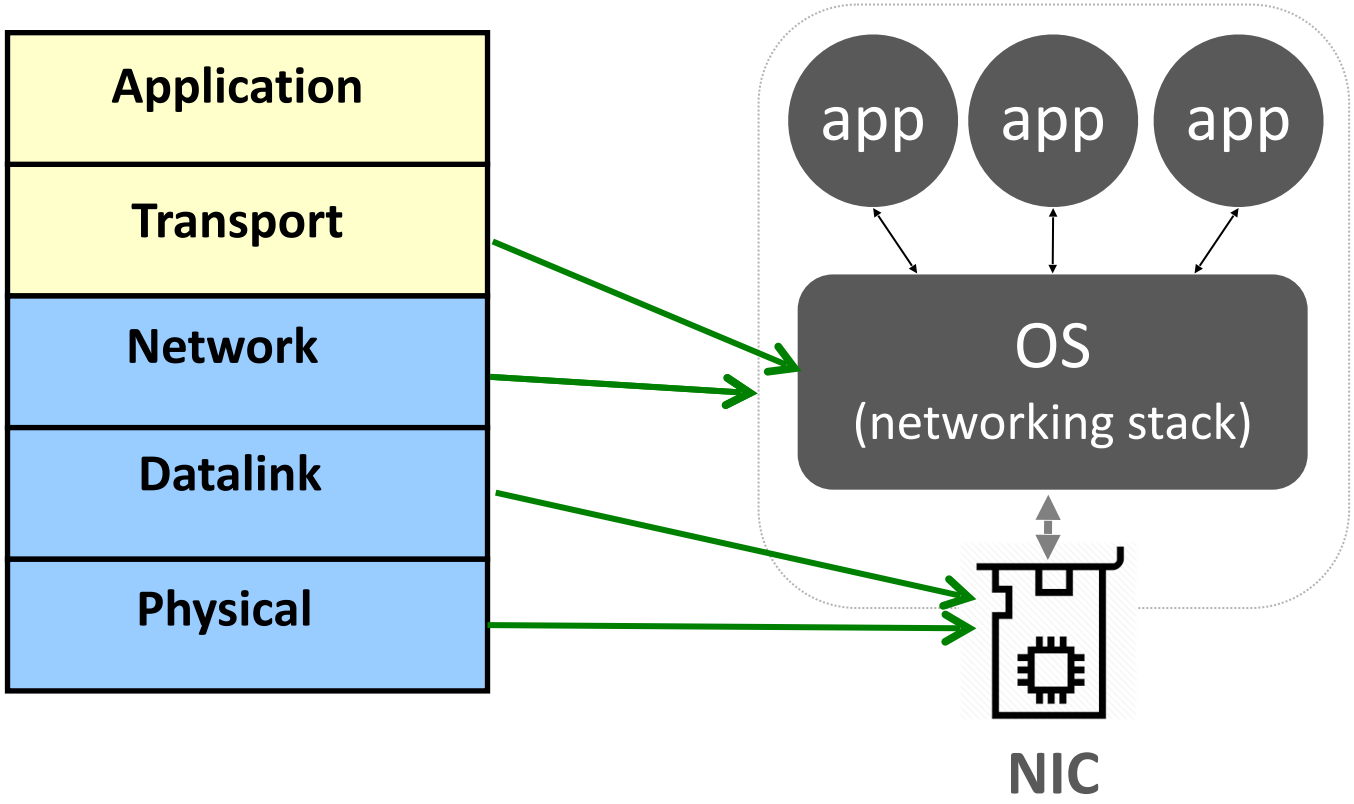

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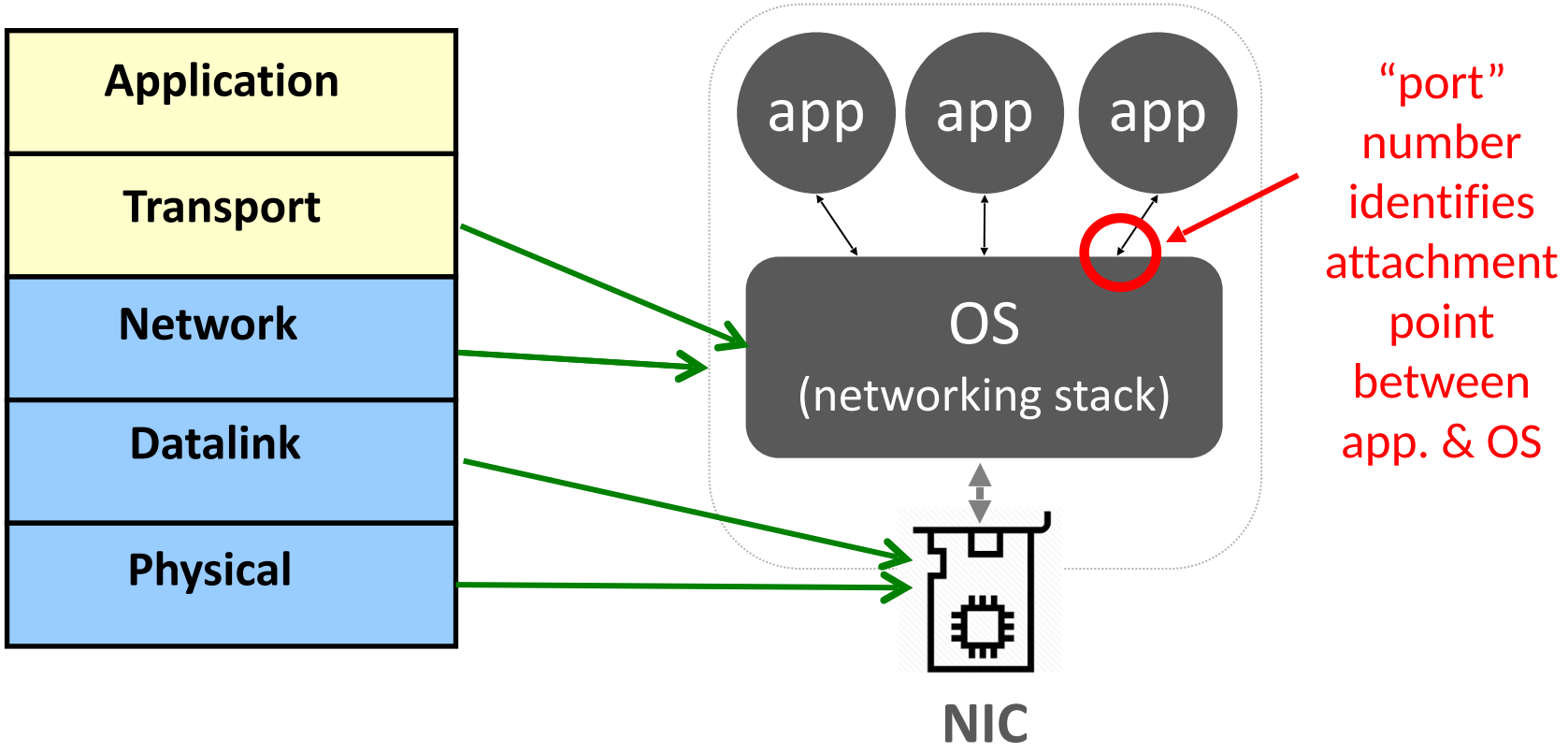

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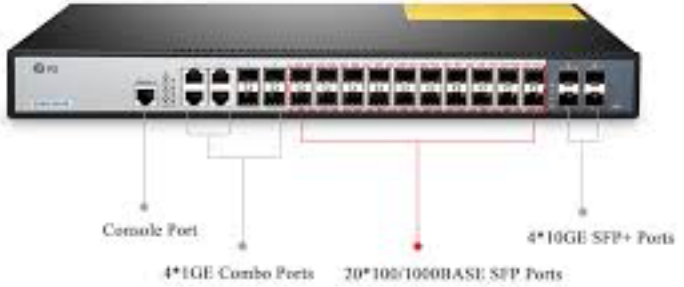

Network “ports”: two types

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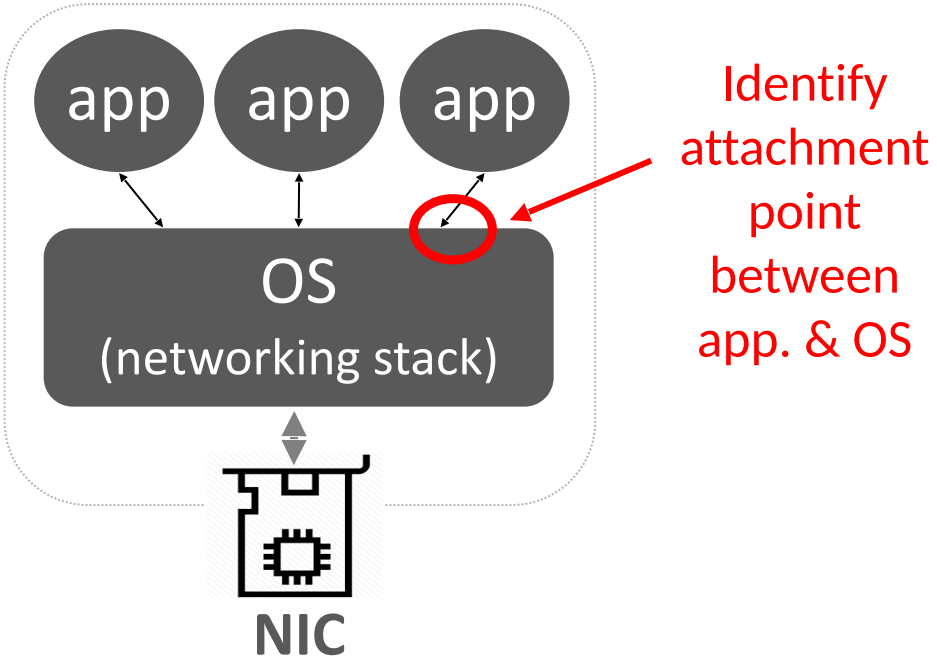
- The OS supports **logical ports**:
  - Place where app connects to OS network stack



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Section will cover sockets in detail

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- The **port number** is used by the OS to direct incoming packets to its associated socket

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- When a packet arrives at the destination end-host, it is delivered to the socket (process) associated with the packet's destination port

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  - Thinks about data

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- Network stack in the intermediary between them
  - Translates between their abstractions

Recap: layers at the end host

- **Application layer (L7)**
  - part of the app: browser, mail client,…
- **Transport and network layer (L3, L4)**
  - typically part of the OS
- **Datalink and physical layer (L1, L2)**
  - hardware/firmware/drivers

A closer look: network

- Bits on wire → physical layer (L1)
- Local delivery of packets → datalink layer (L2)
- Global delivery of packets → network layer (L3)

Recall: Logical Communication

- Layers interact with peer's corresponding layer
- Lower three layers implemented everywhere
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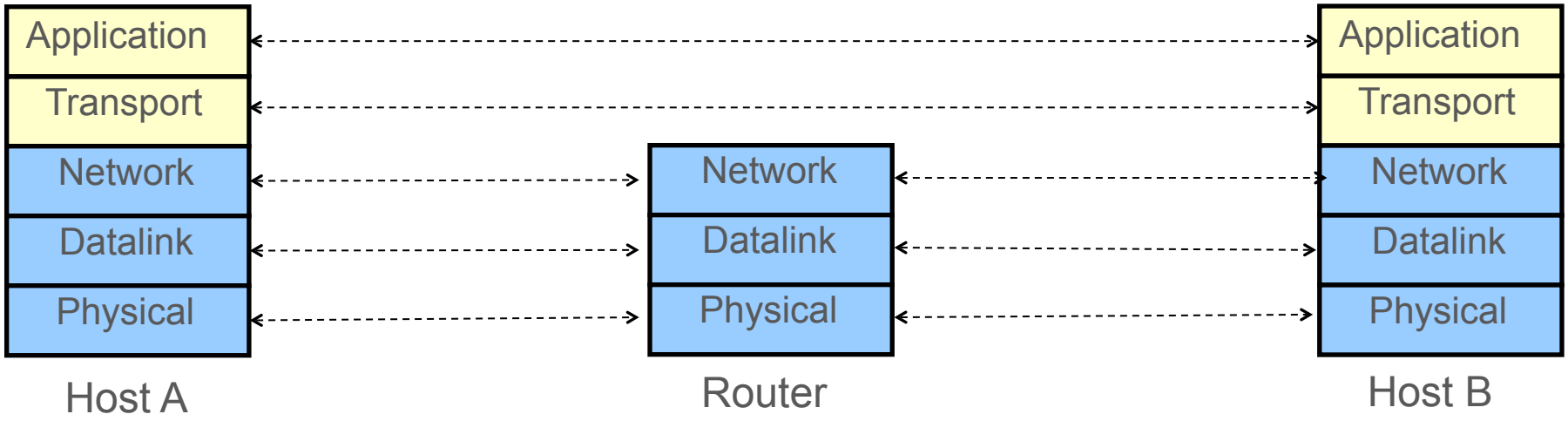

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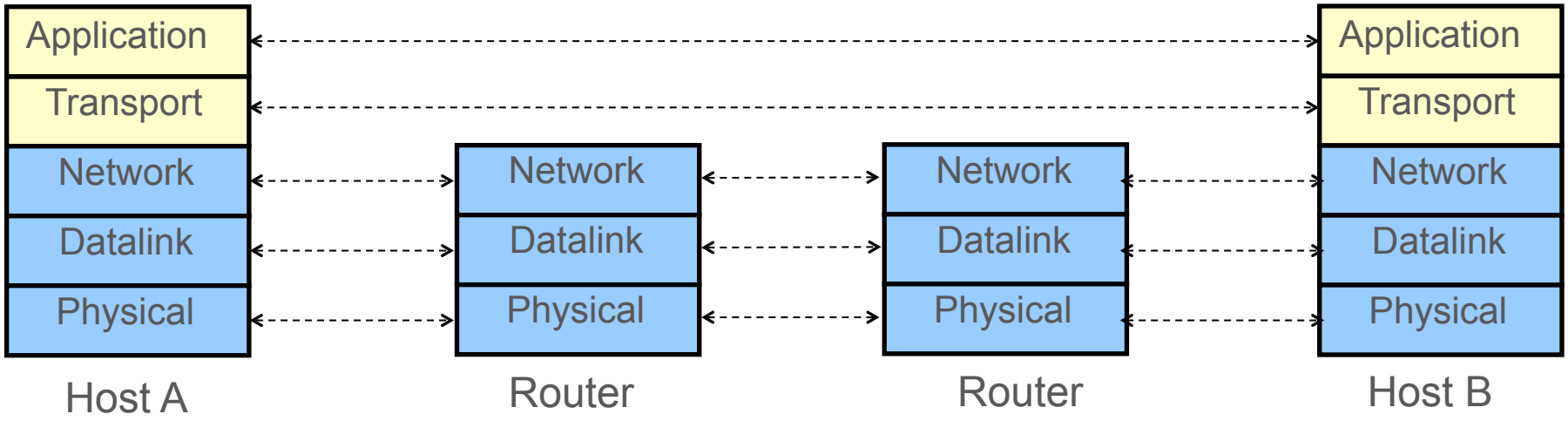
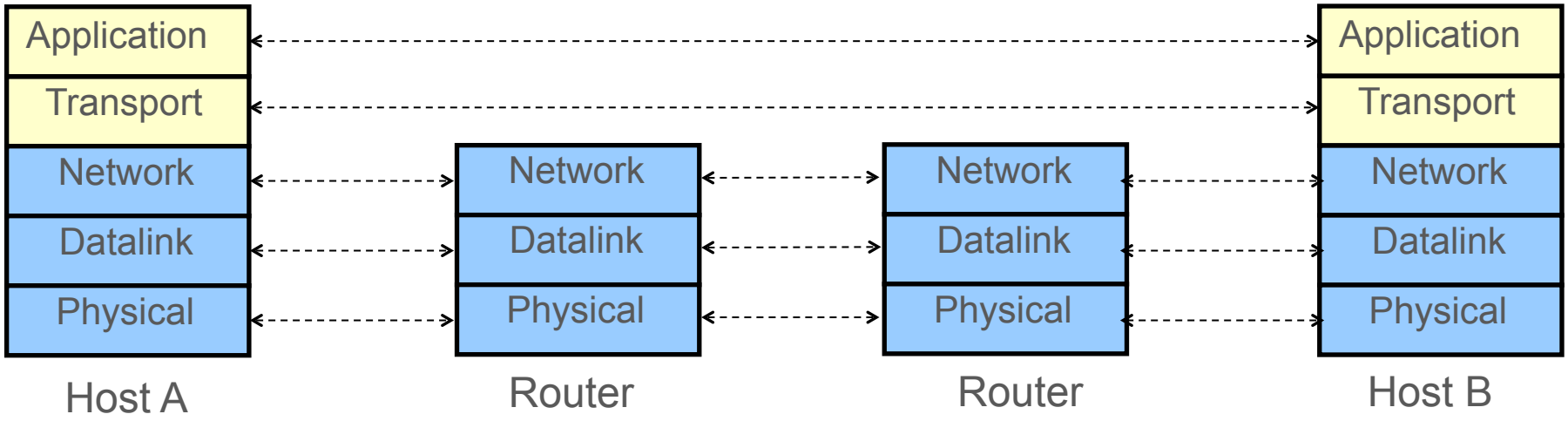


Example: simple protocol diagram



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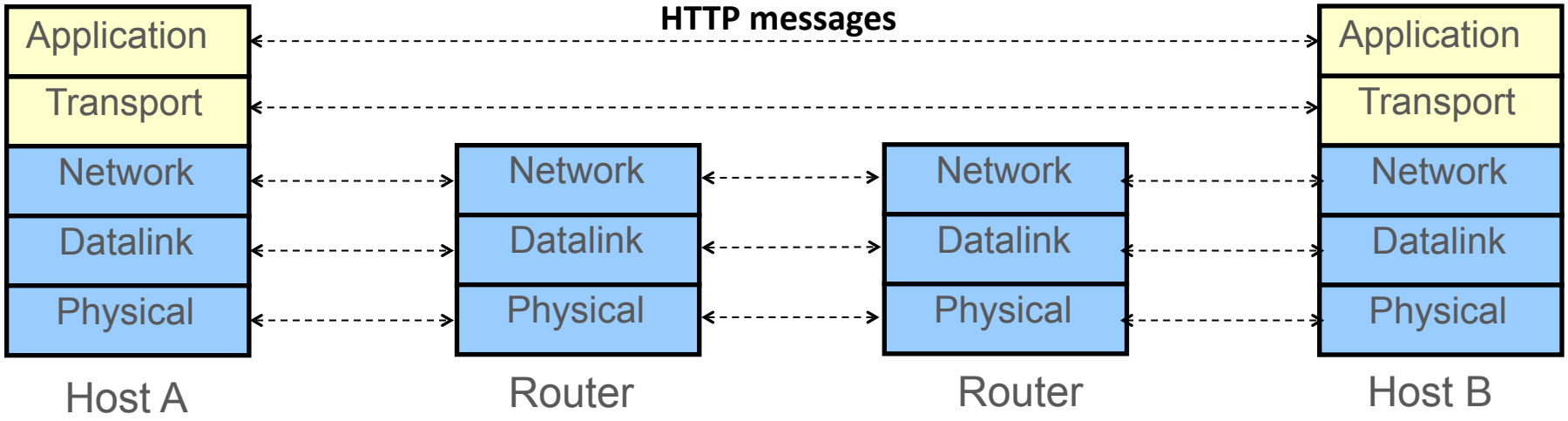

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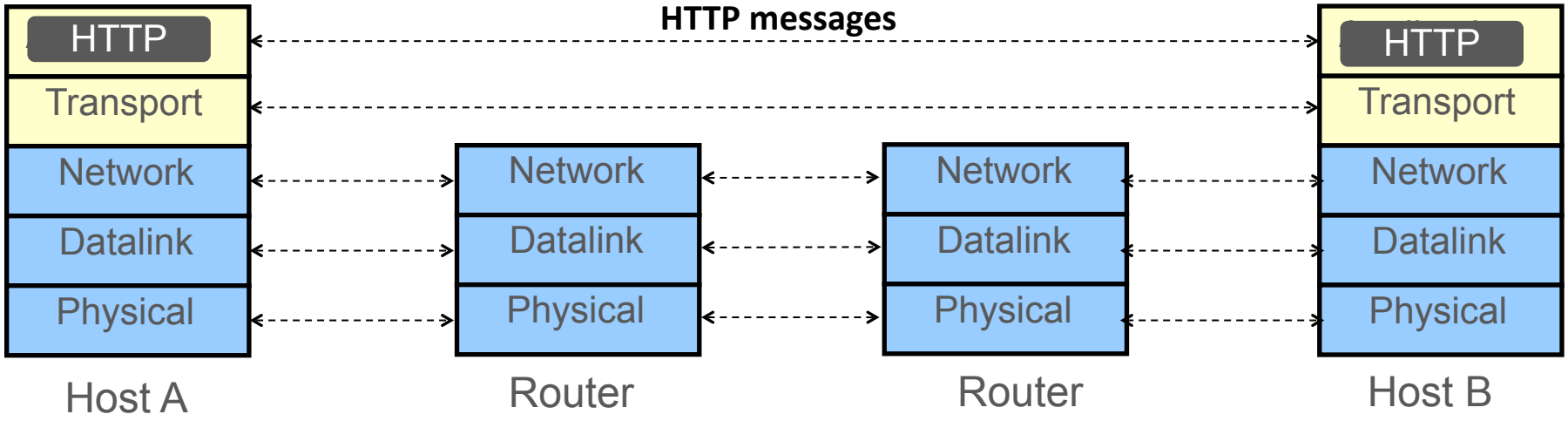

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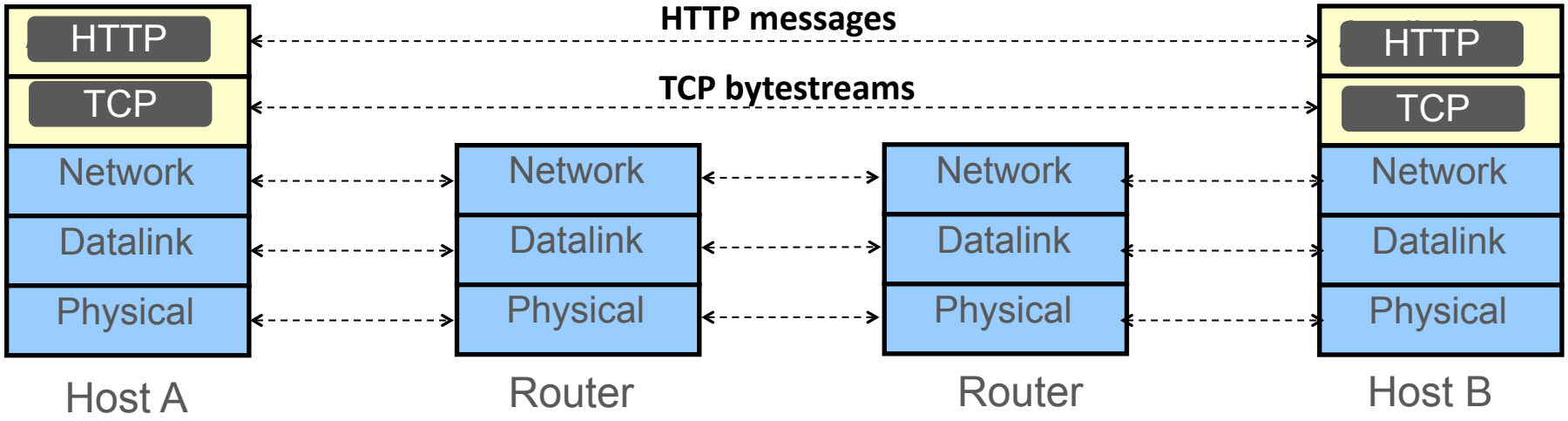

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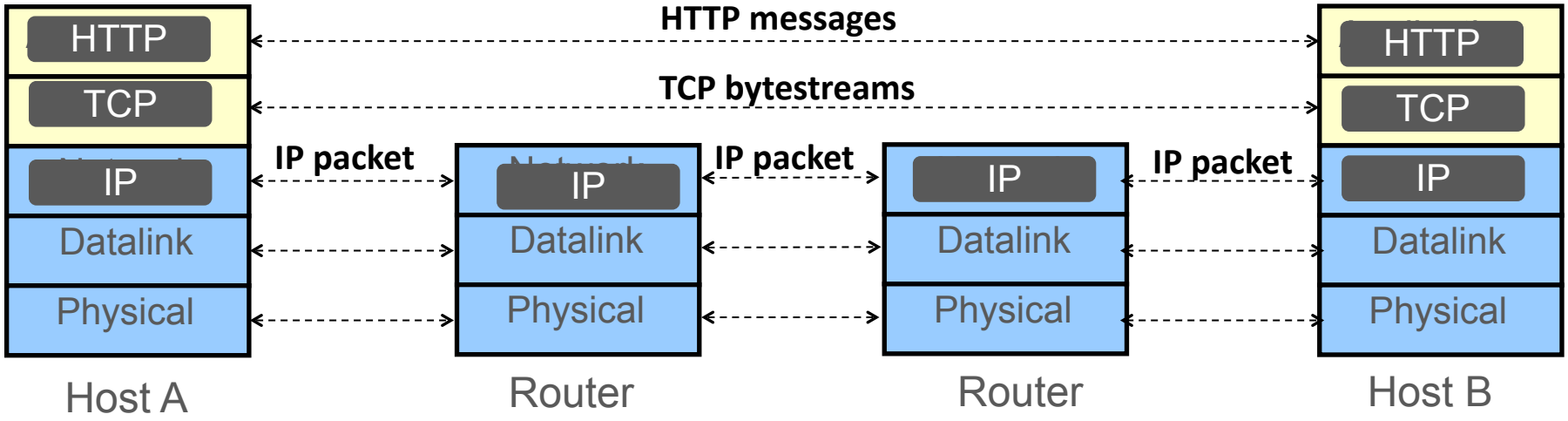

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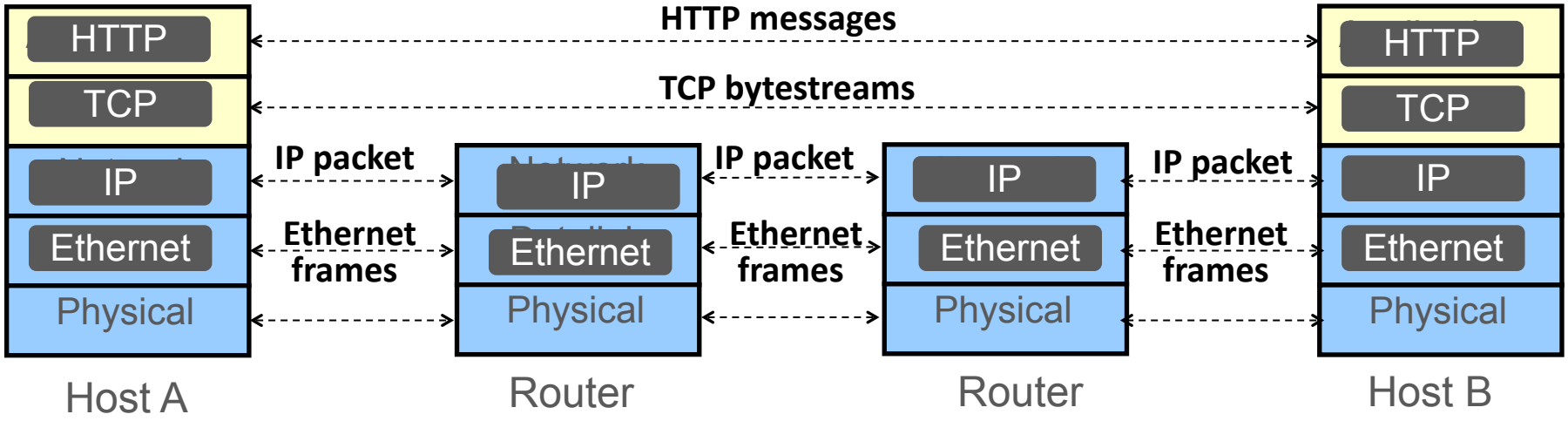

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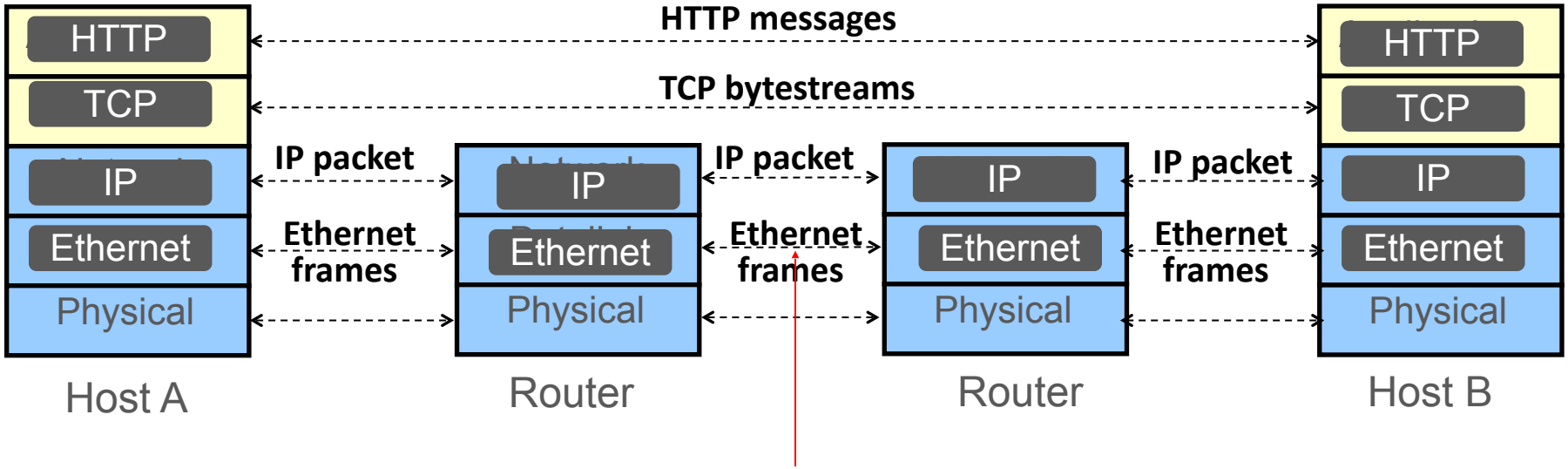

What if this was an OTN network?

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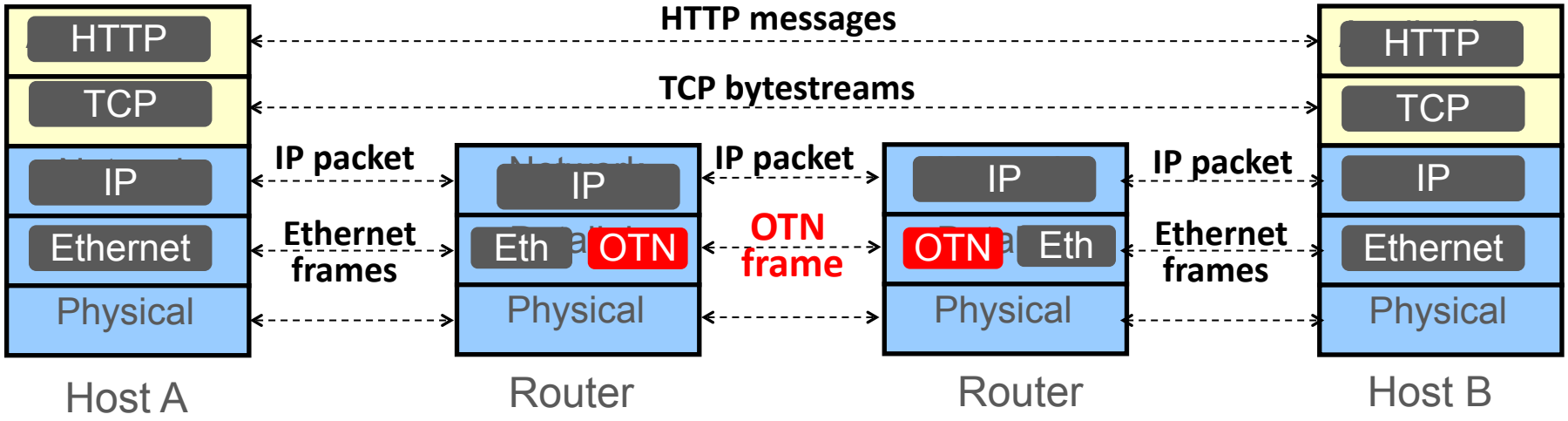
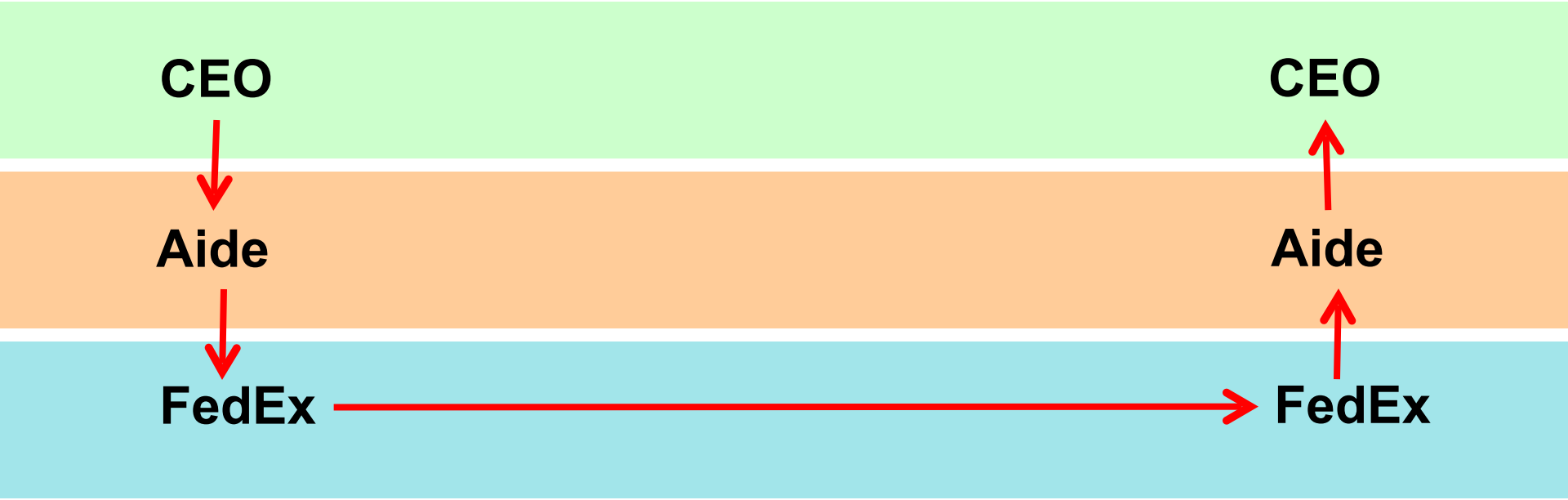


Recap: Physical Communication

- Communication goes down the layers
- Then up to relevant layer



Recall: the path of the letter

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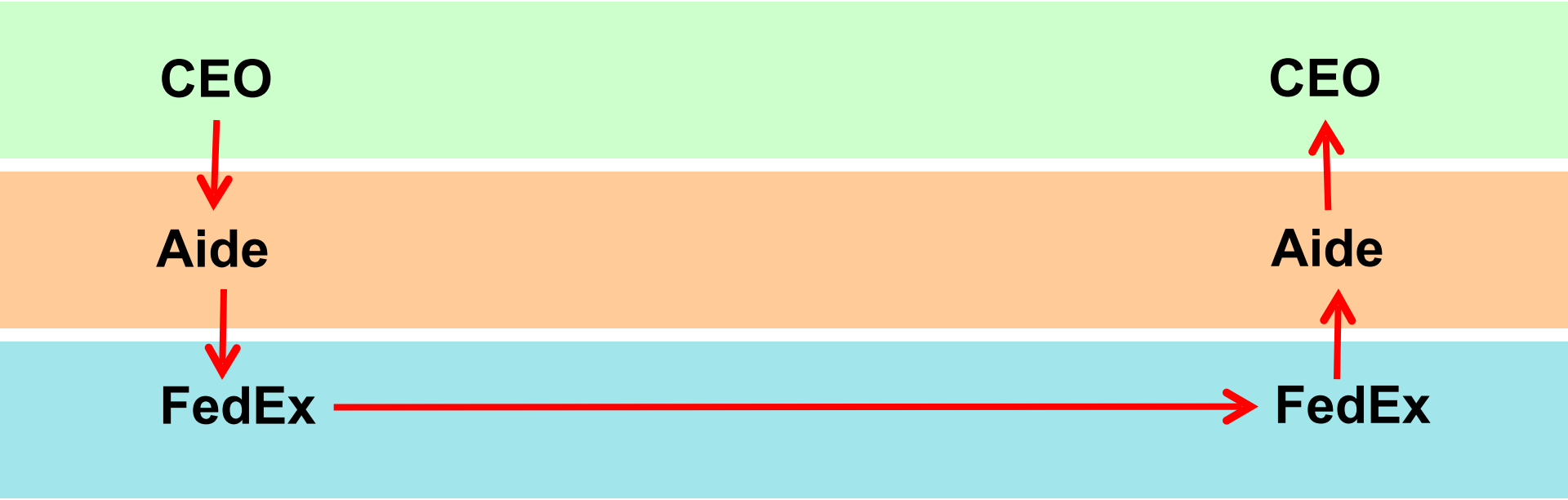

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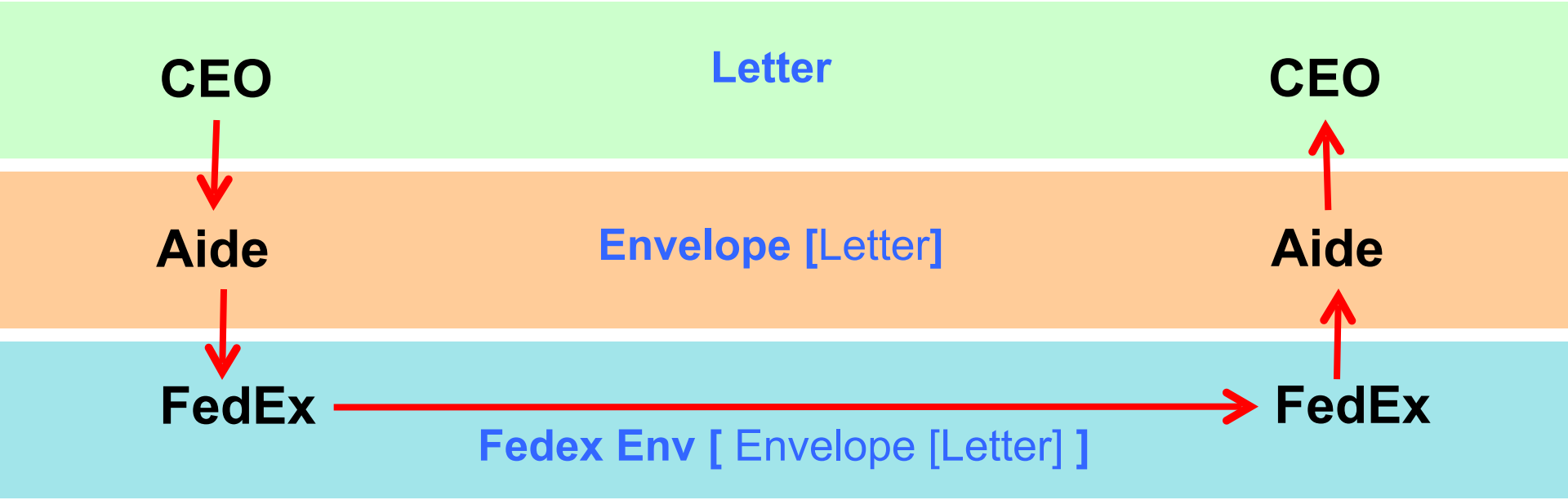
Recap: Physical Communication

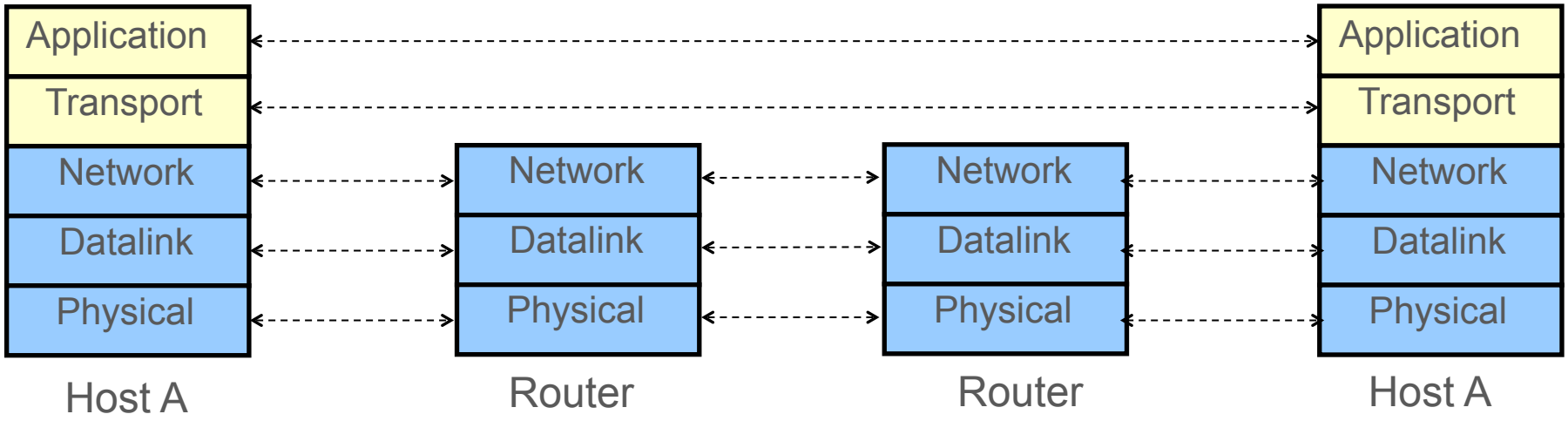
- Communication goes down the layers
- Then up to relevant layer
- Lowest layer has the most “packaging”



Recall: the path of the letter

Recap: Physical Communication

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



Recap: Physical Communication

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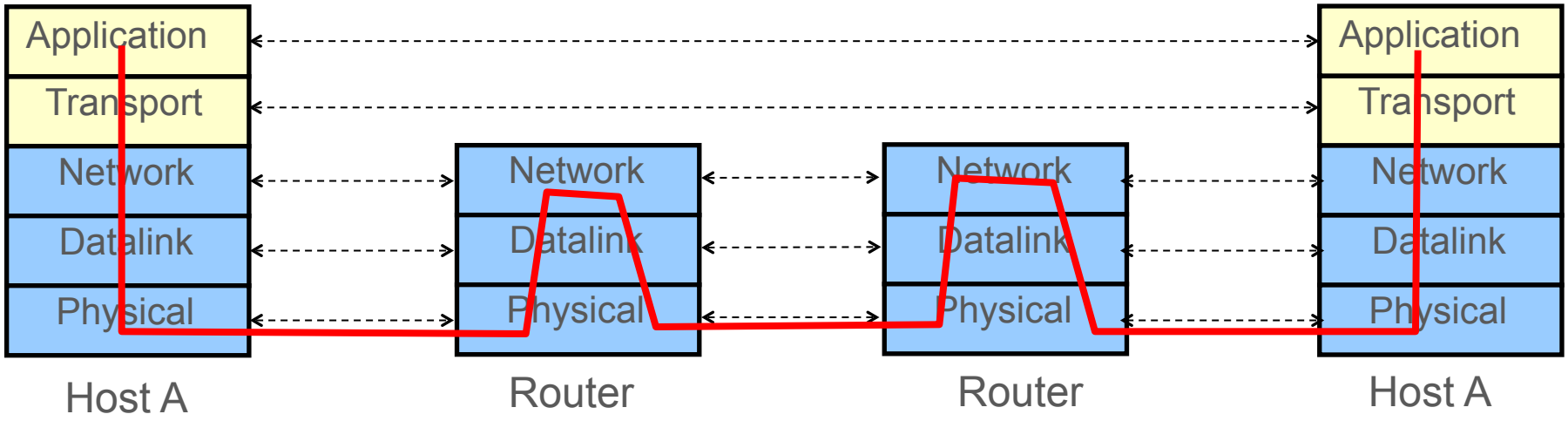
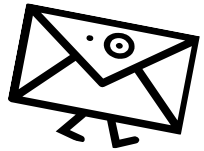
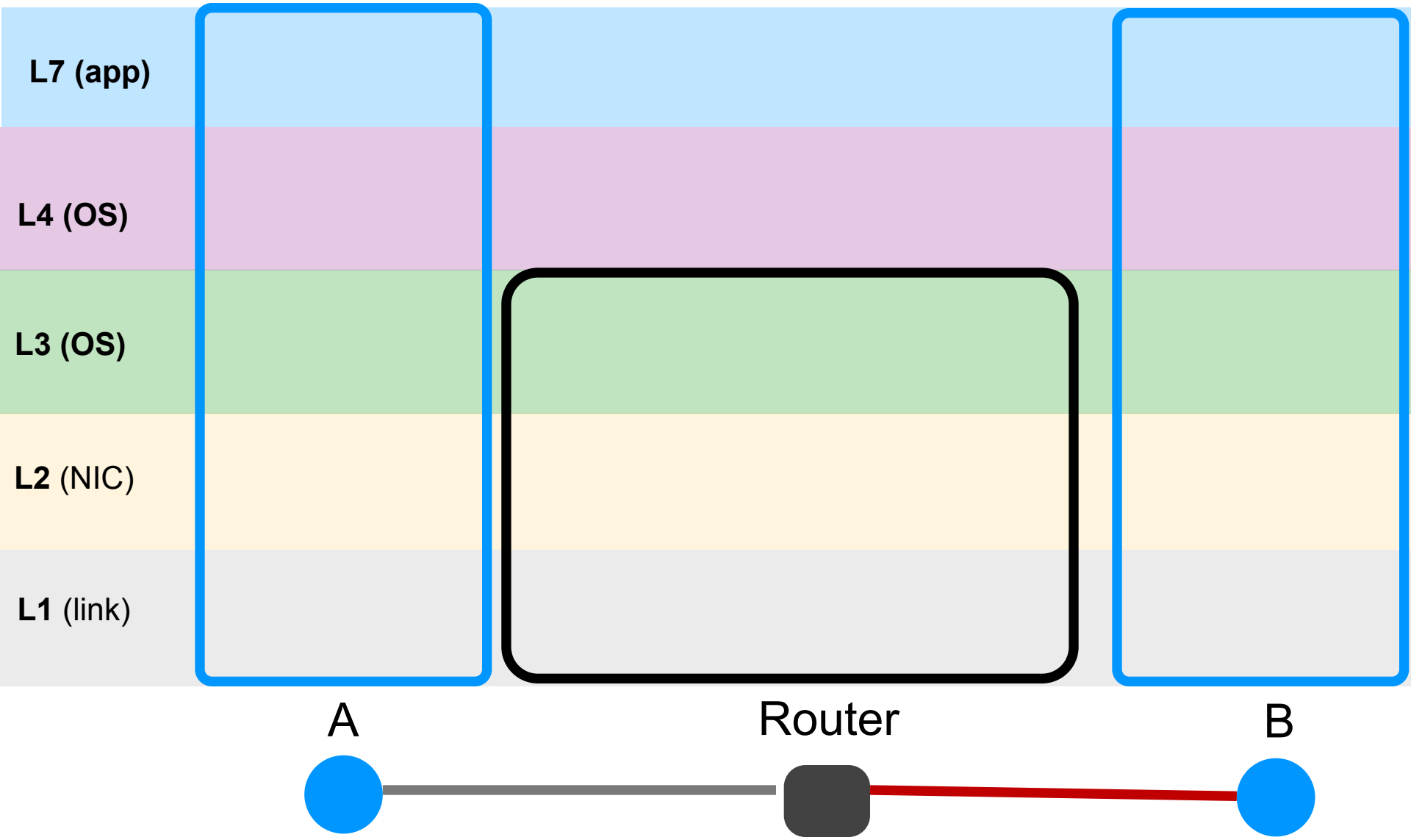
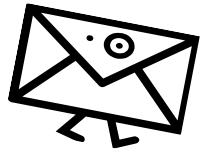


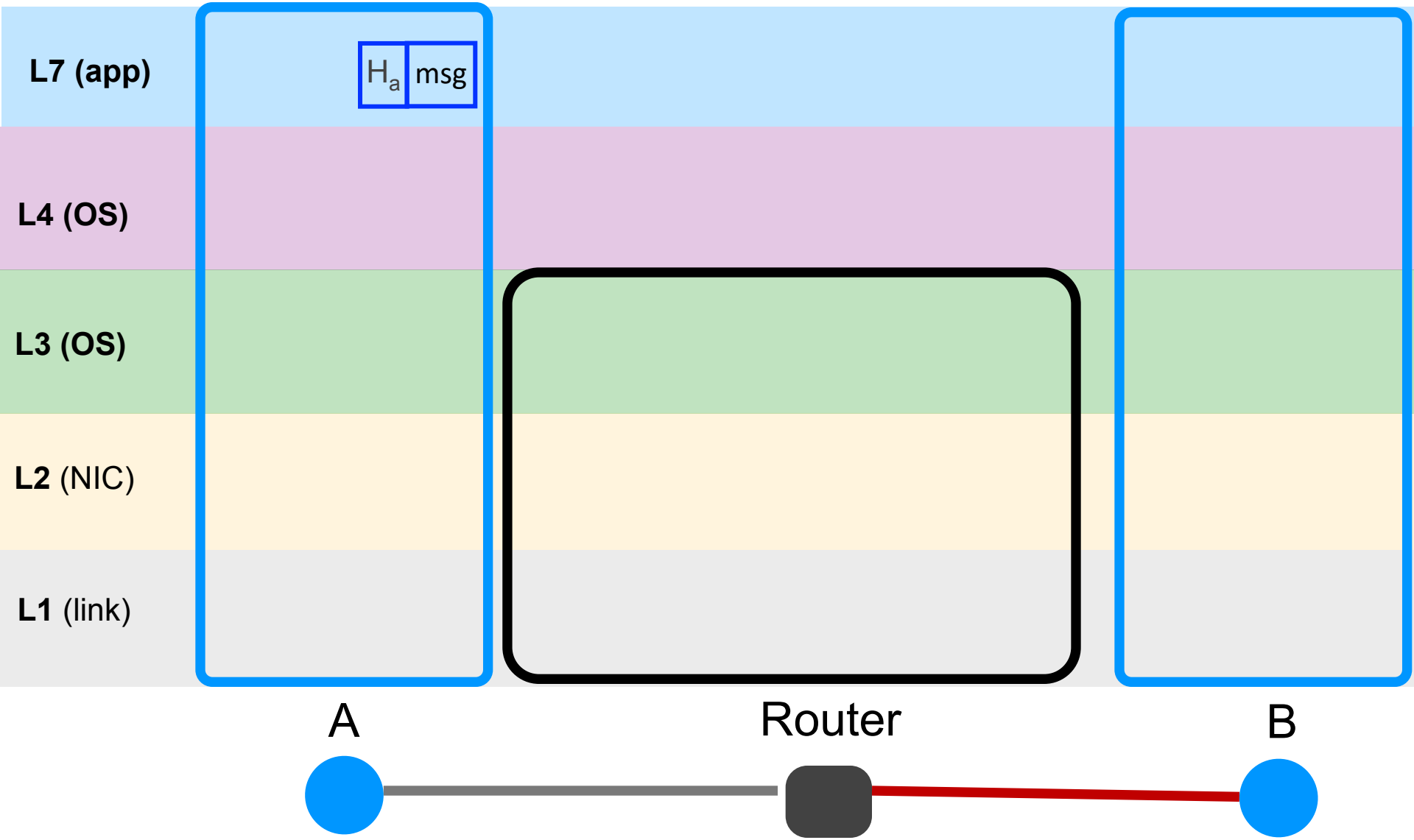
Layer Encapsulation



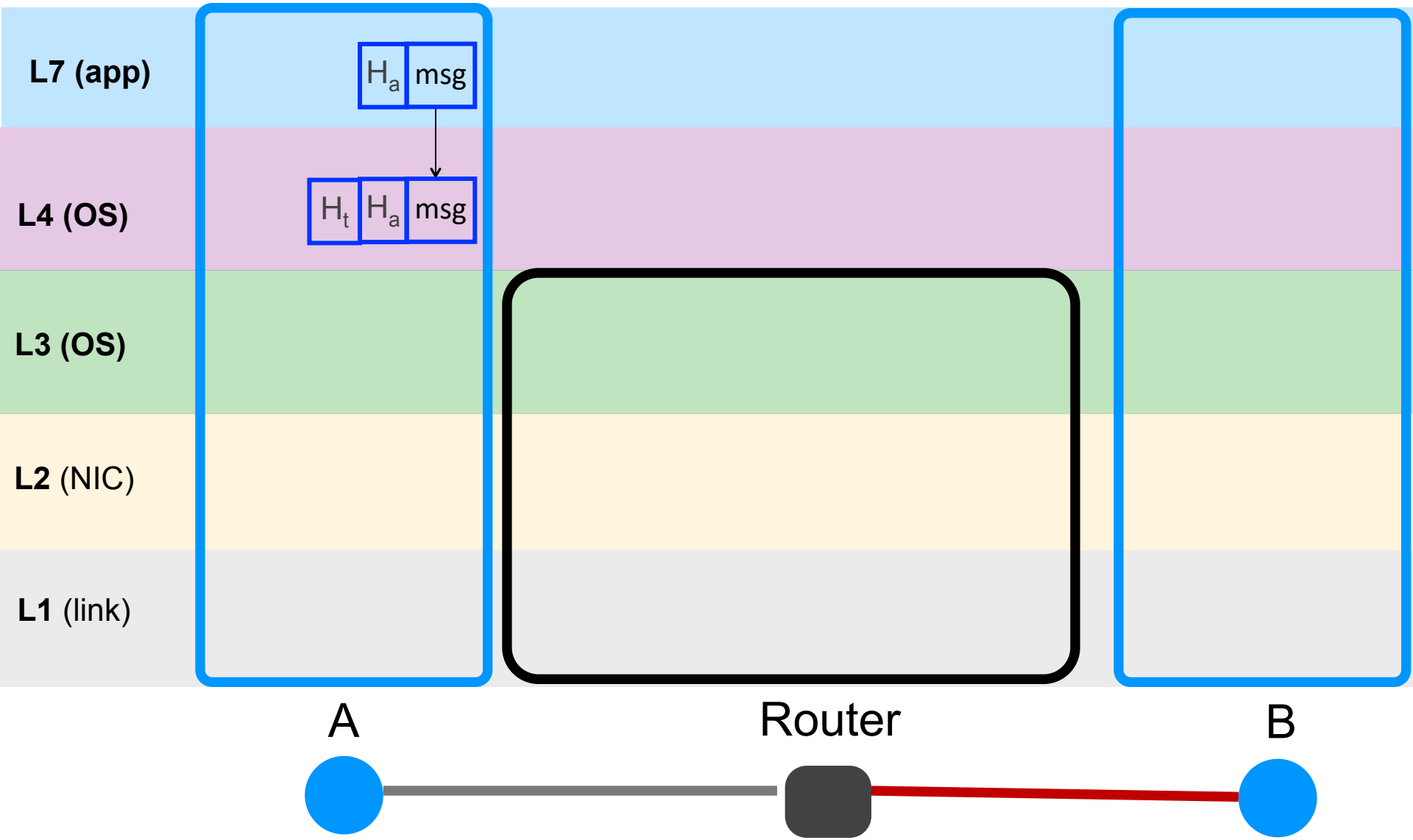


Layer Encapsulation

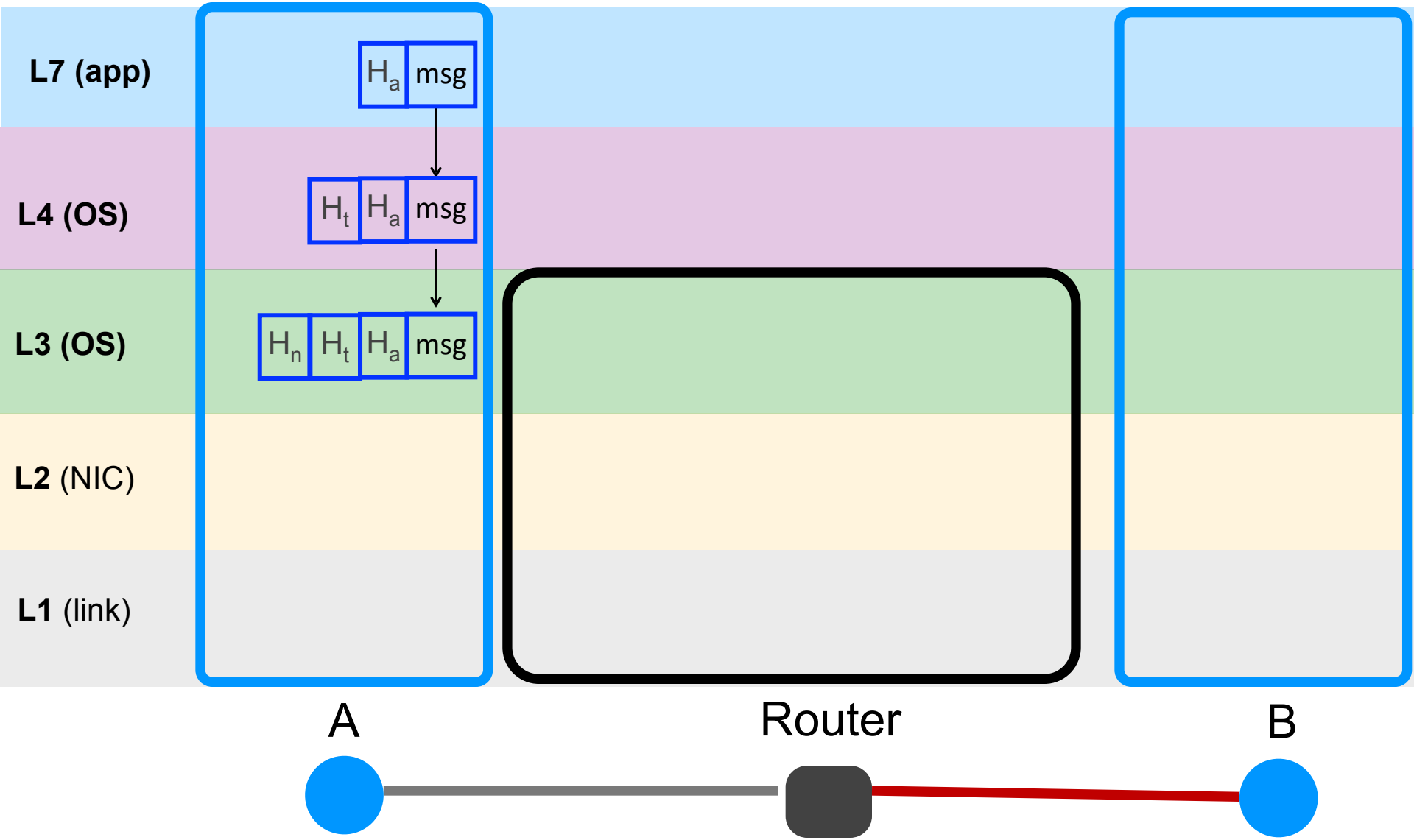




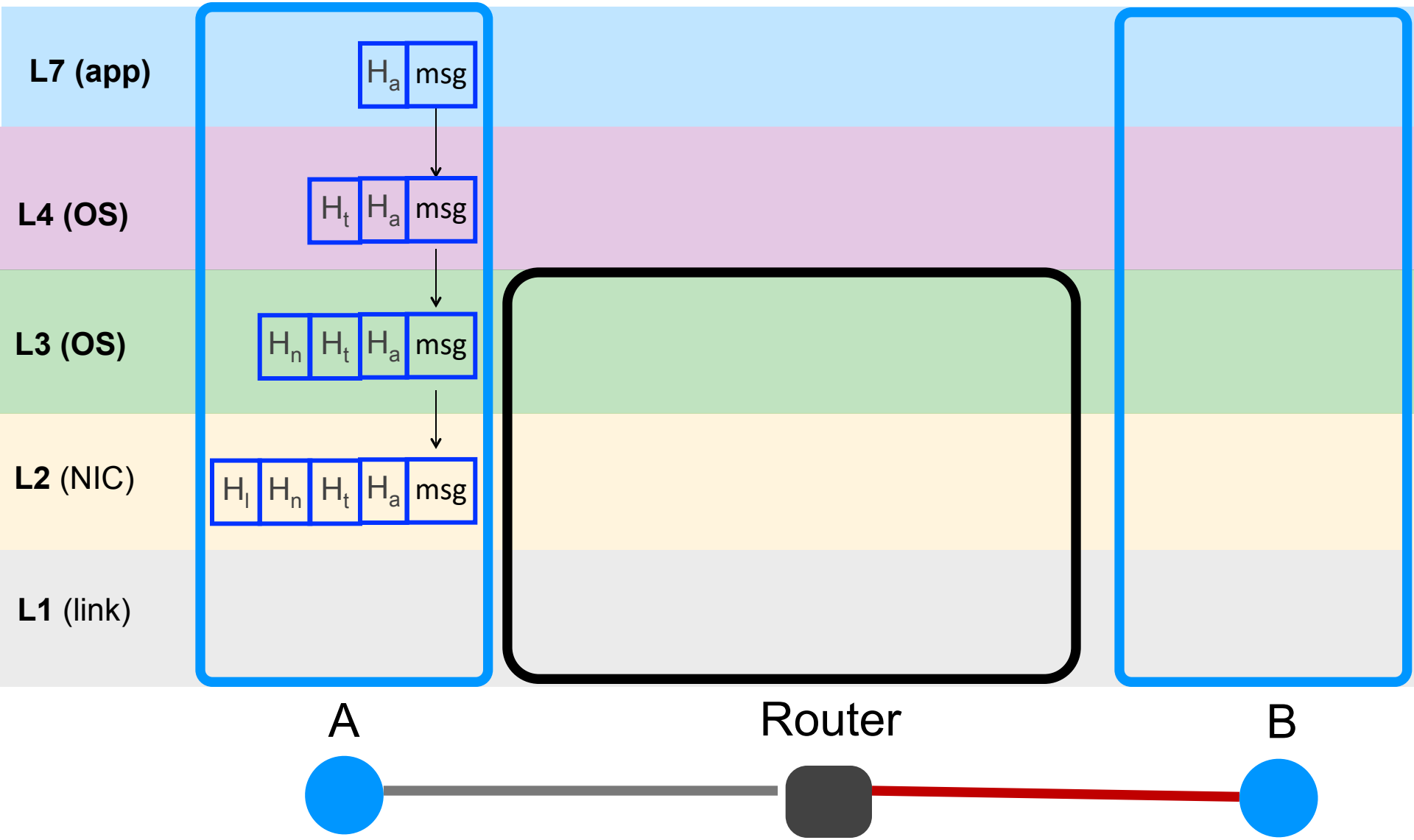
Layer Encapsulation



Layer Encapsulation



Layer Encapsulation



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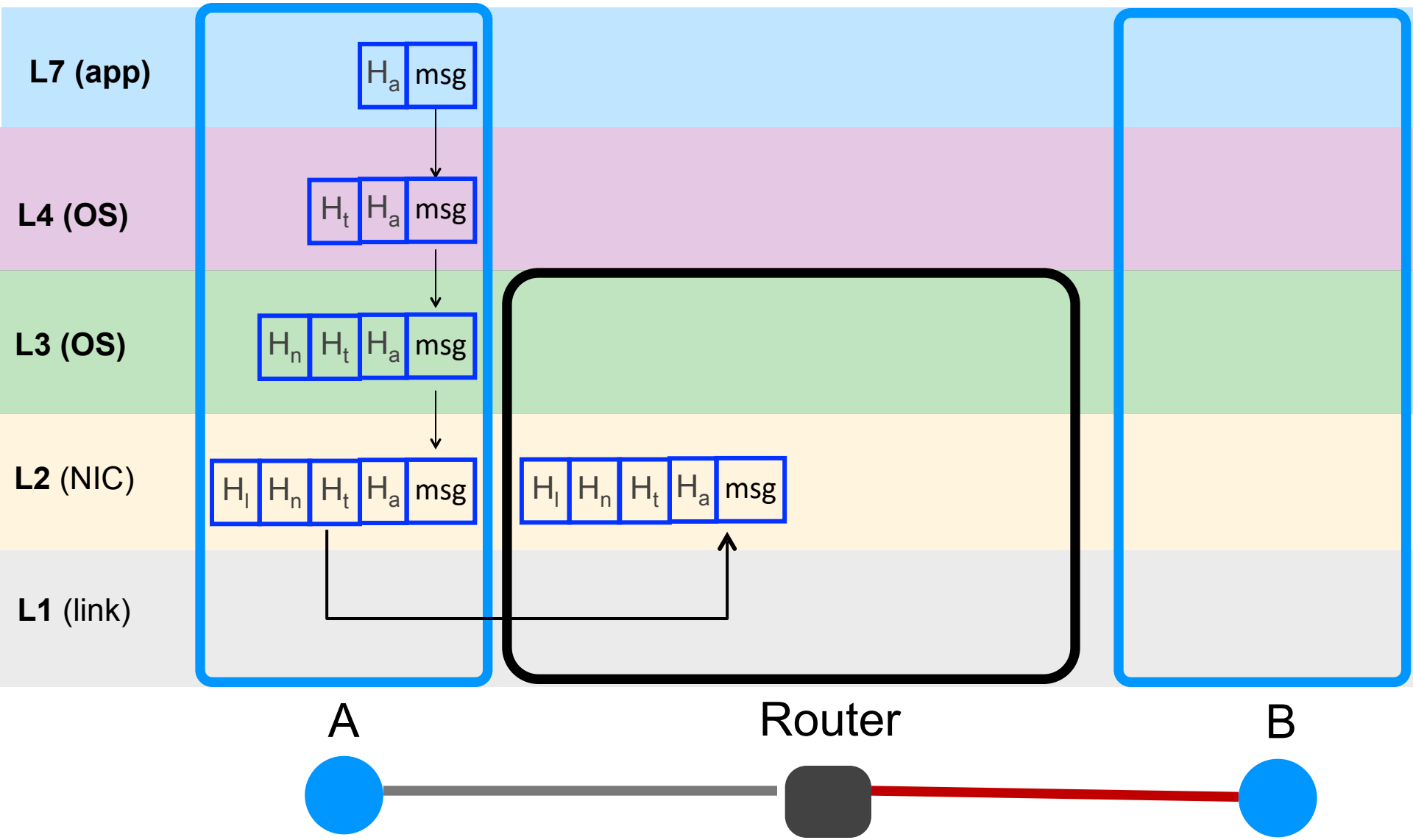

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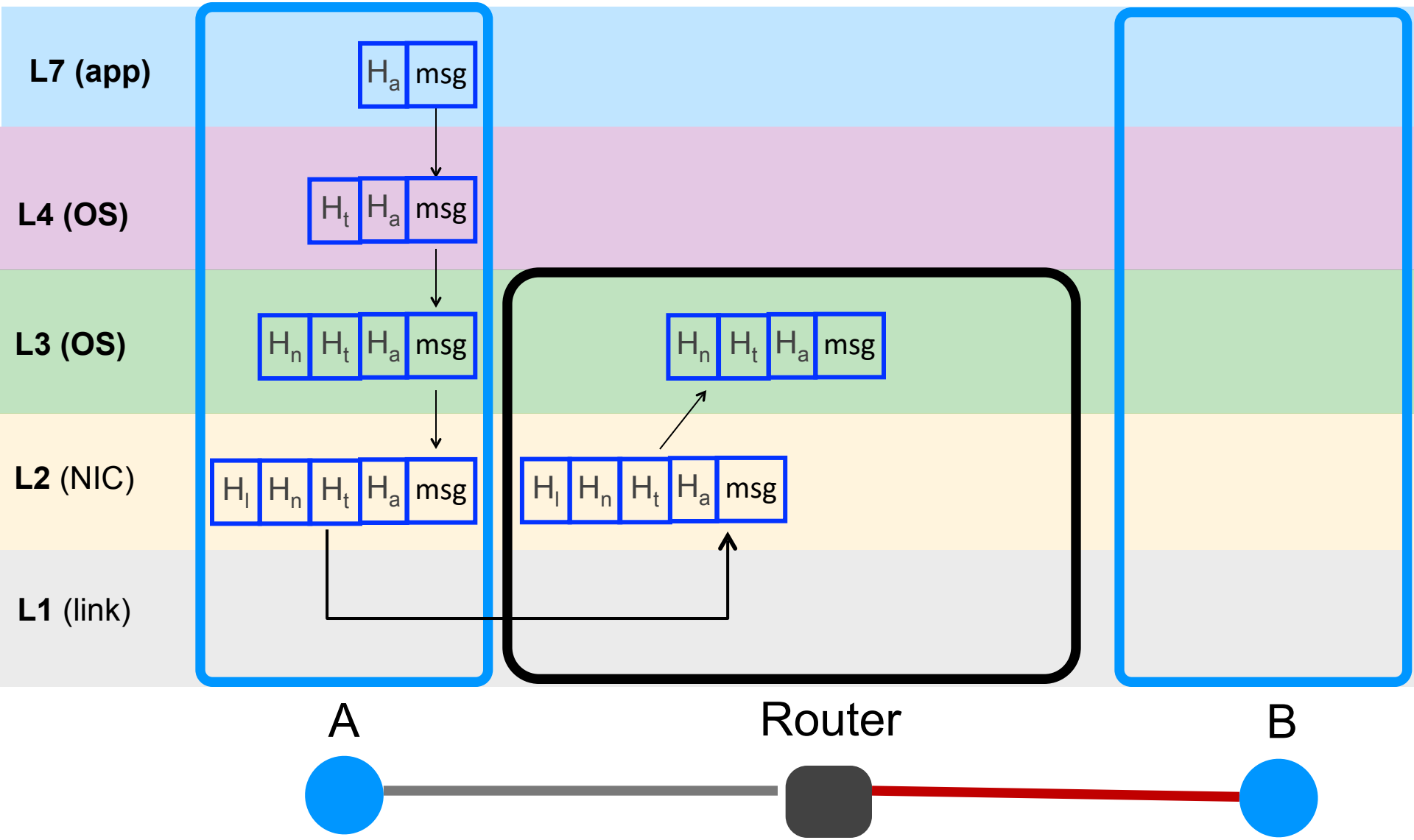
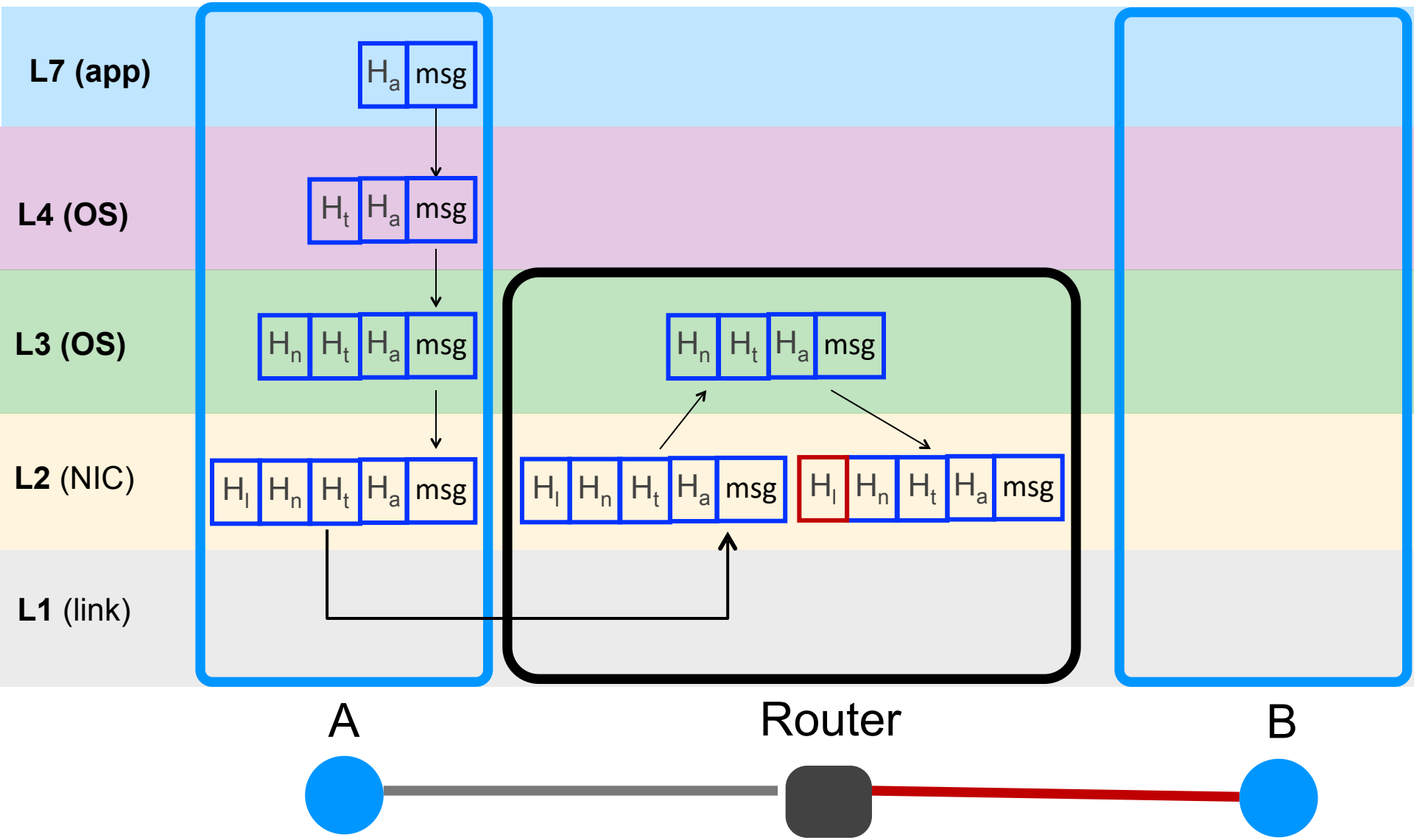
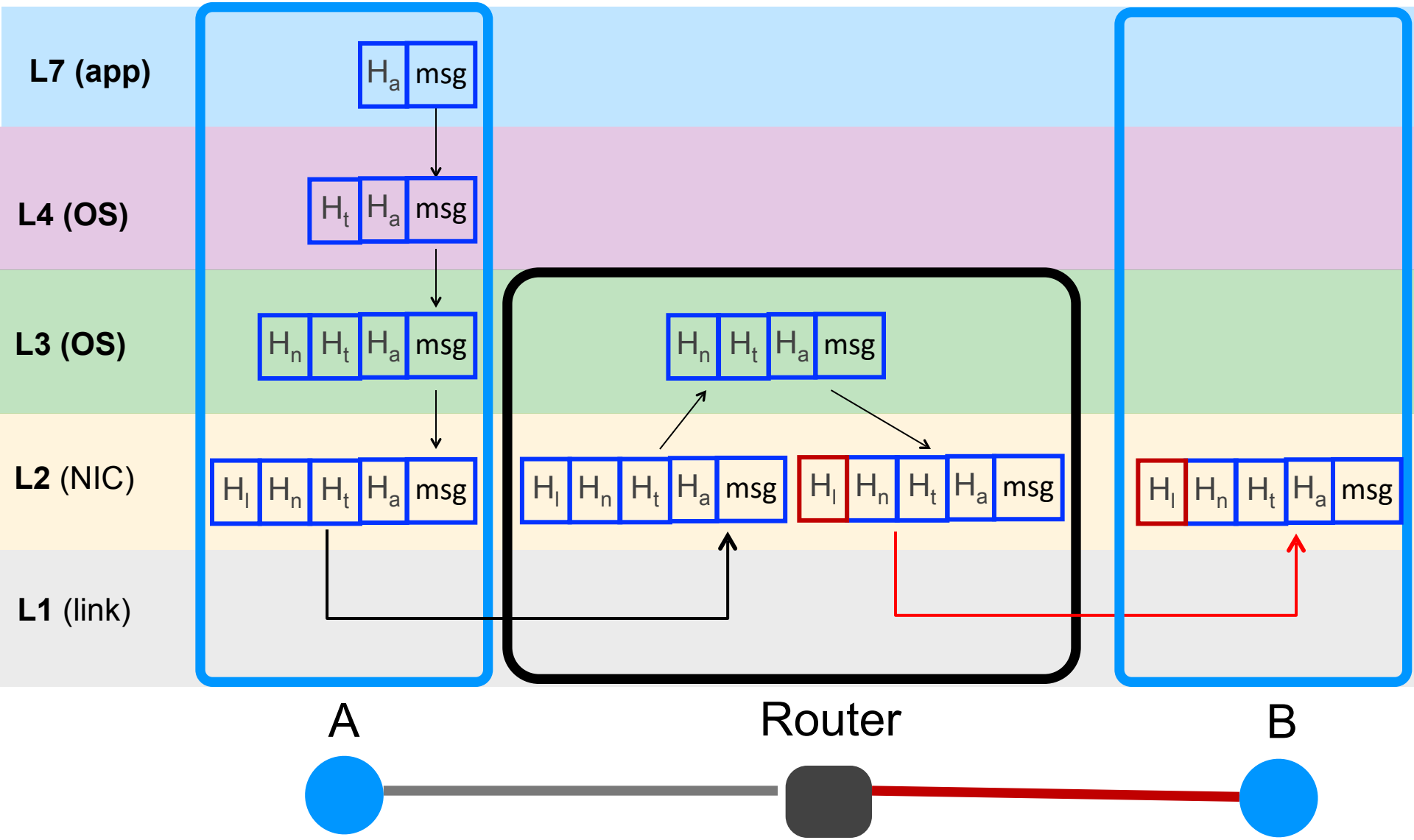


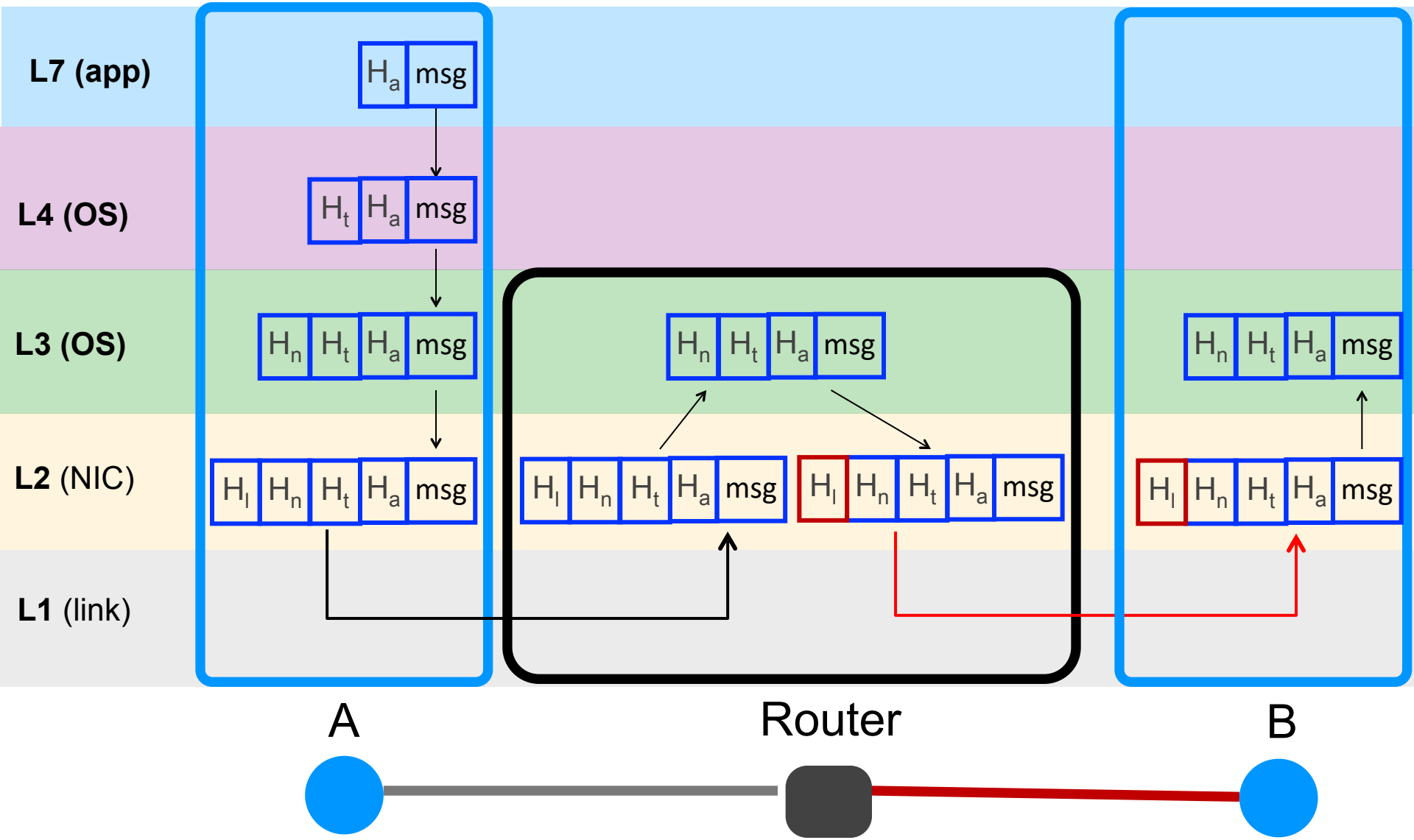
Layer Encapsulation



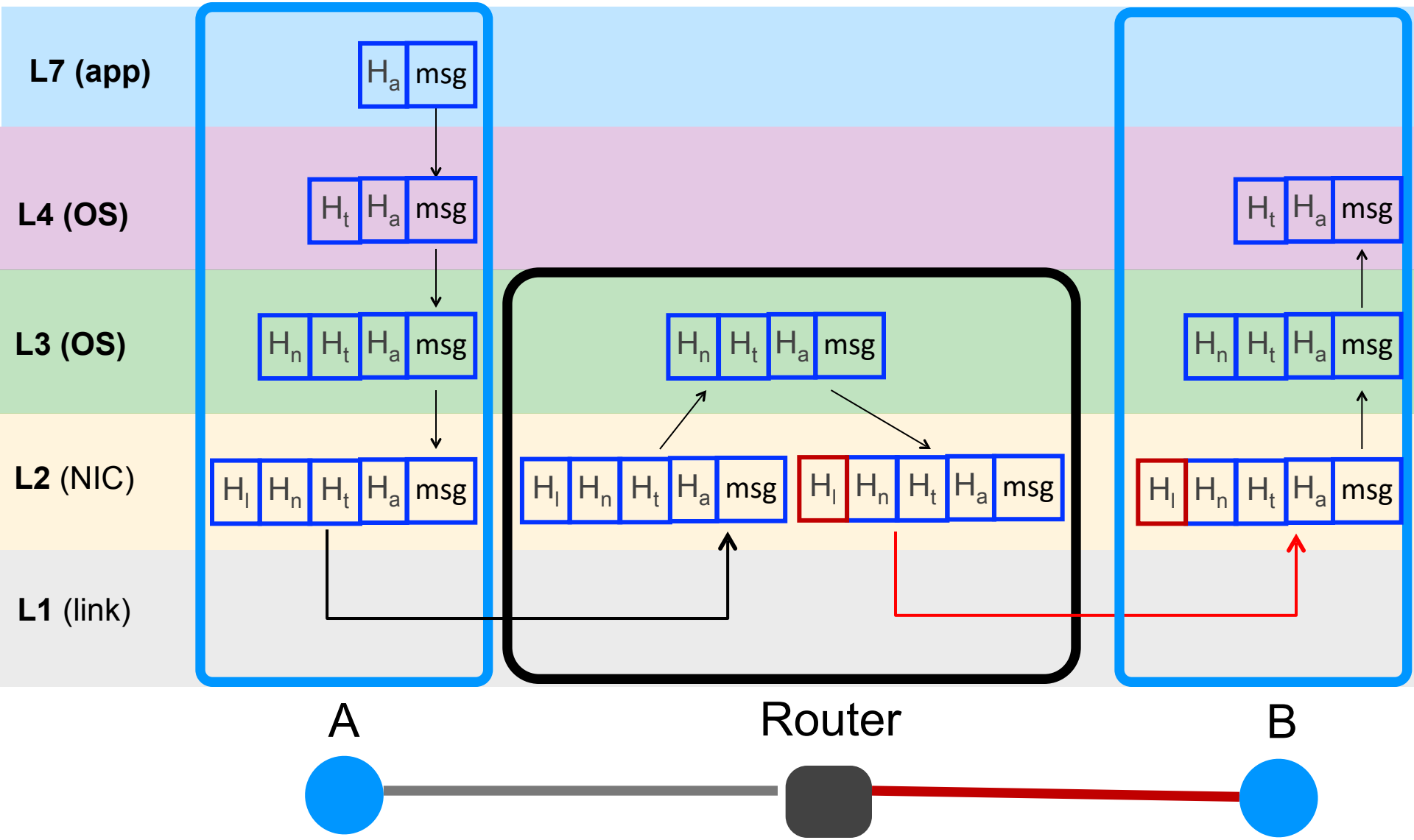
Layer Encapsulation



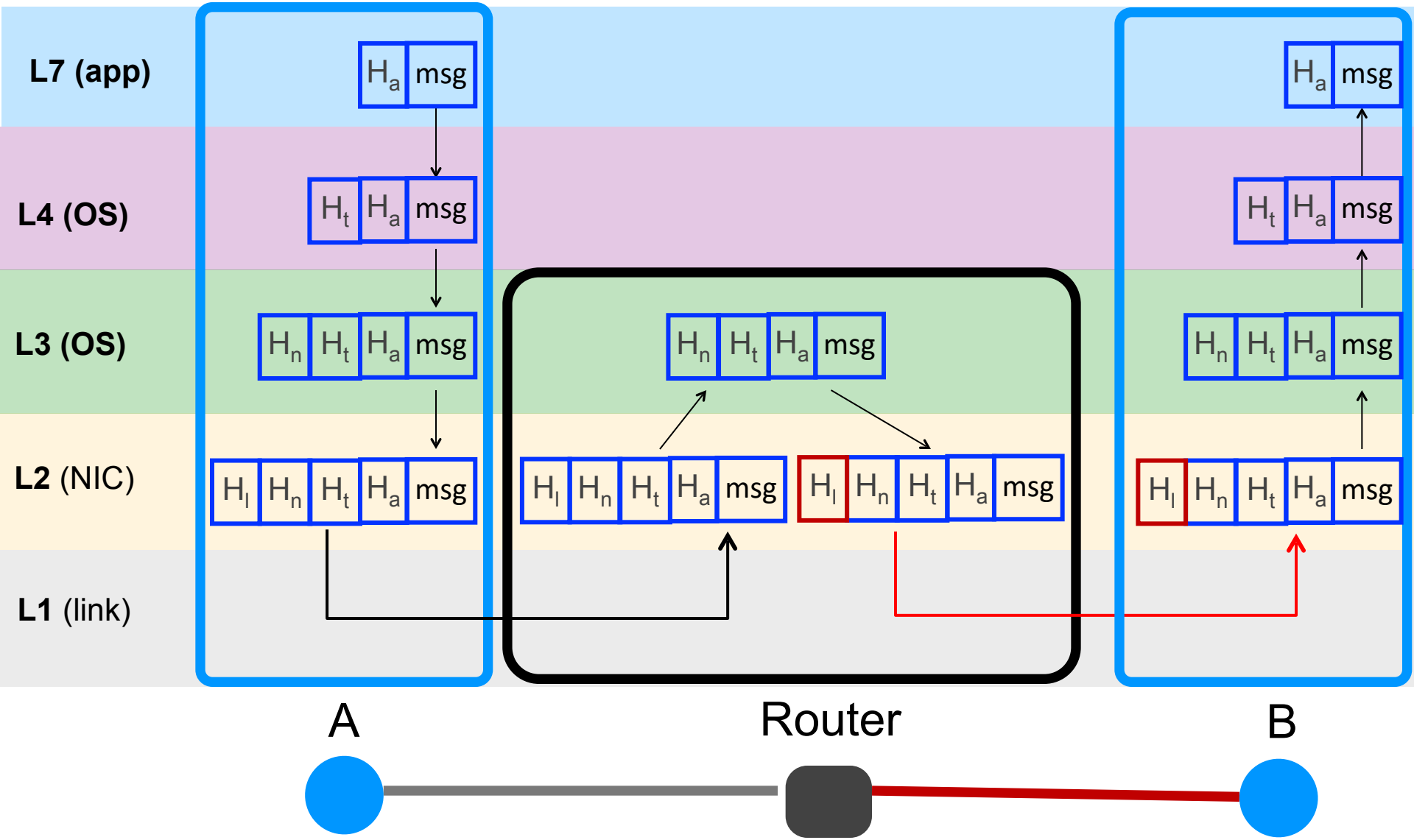
Layer Encapsulation



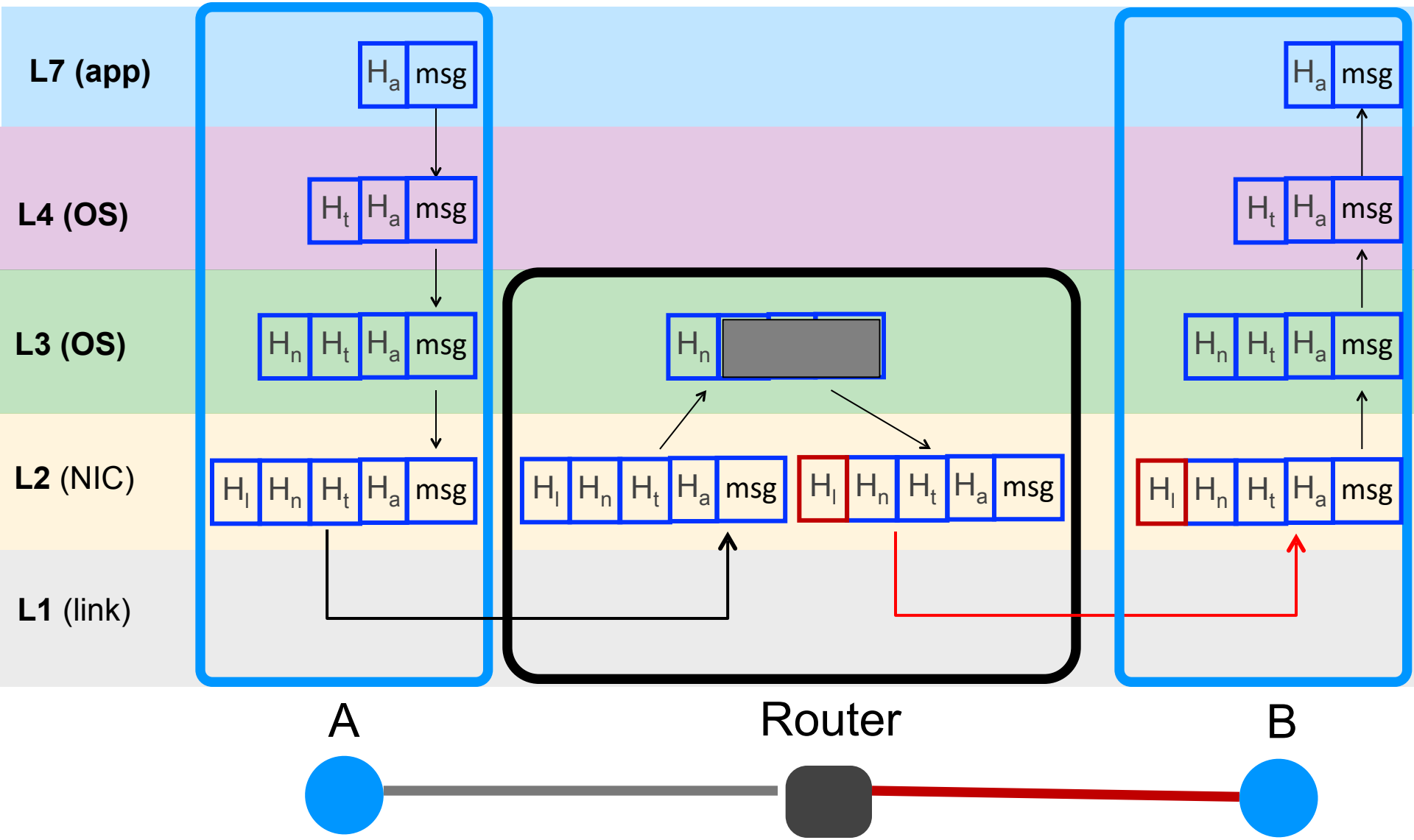
Layer Encapsulation



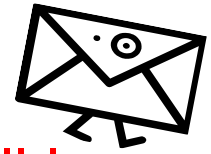
Layer Encapsulation



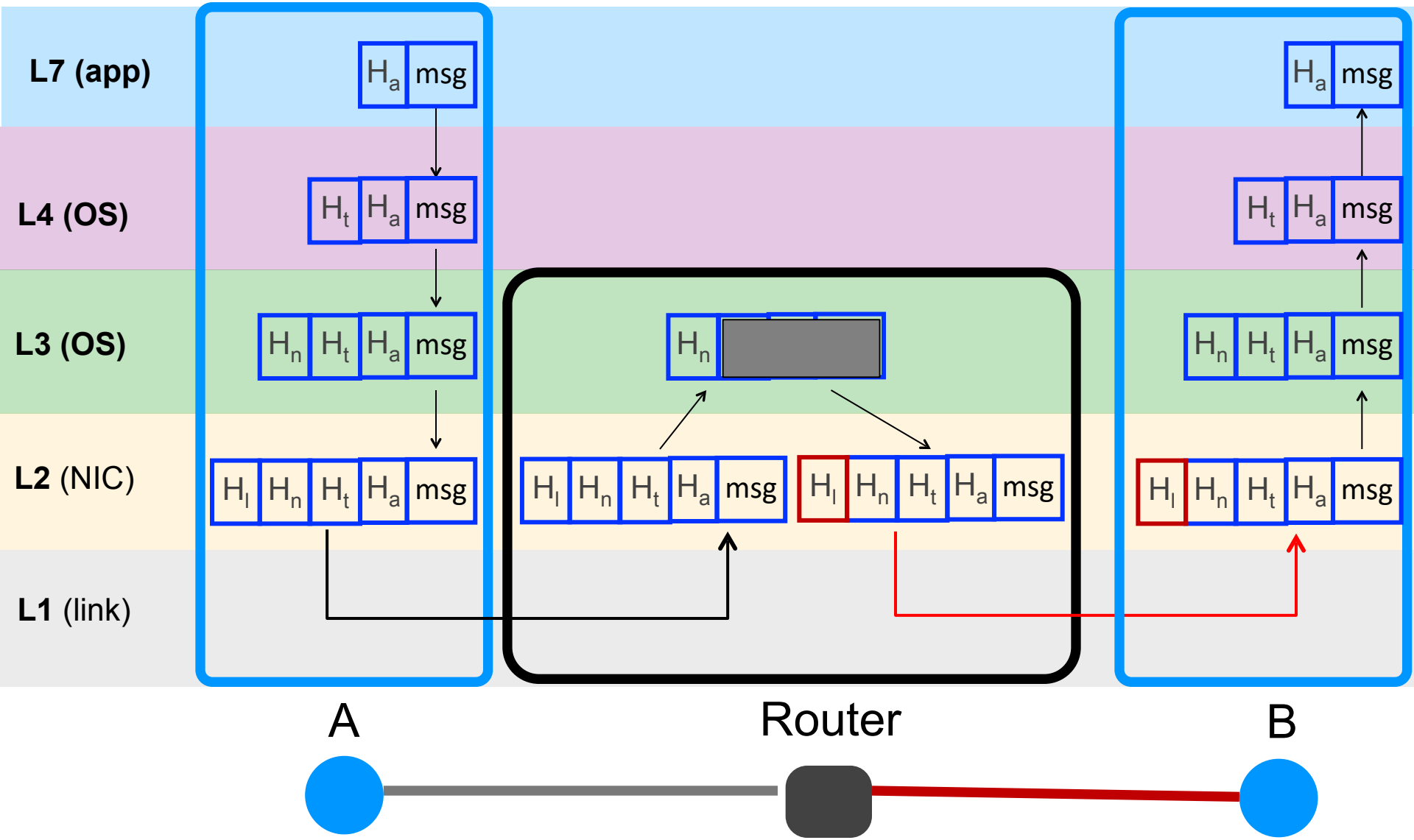
Layer Encapsulation



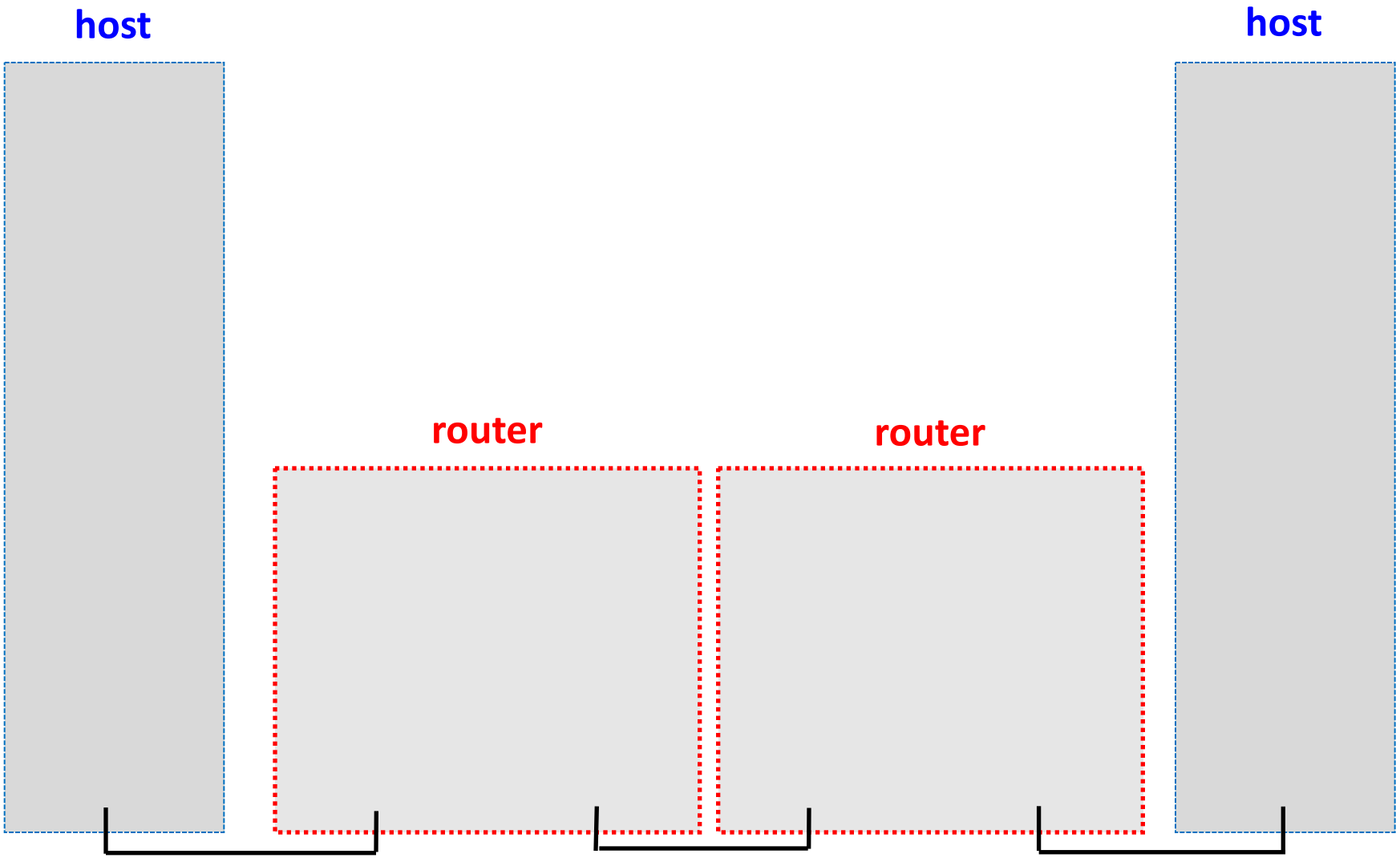
Layer Encapsulation



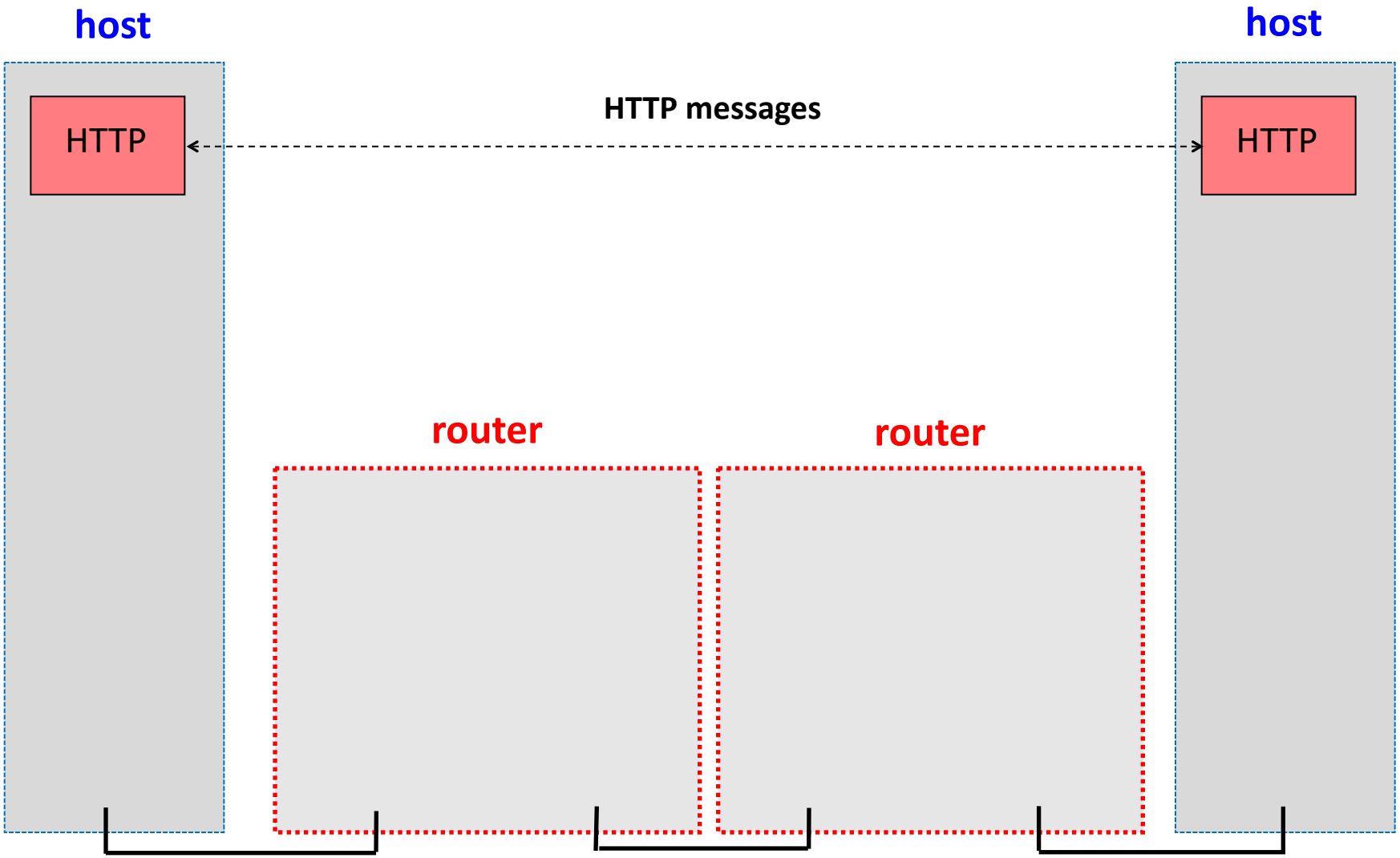
On the wire: packet has data + headers from all layers



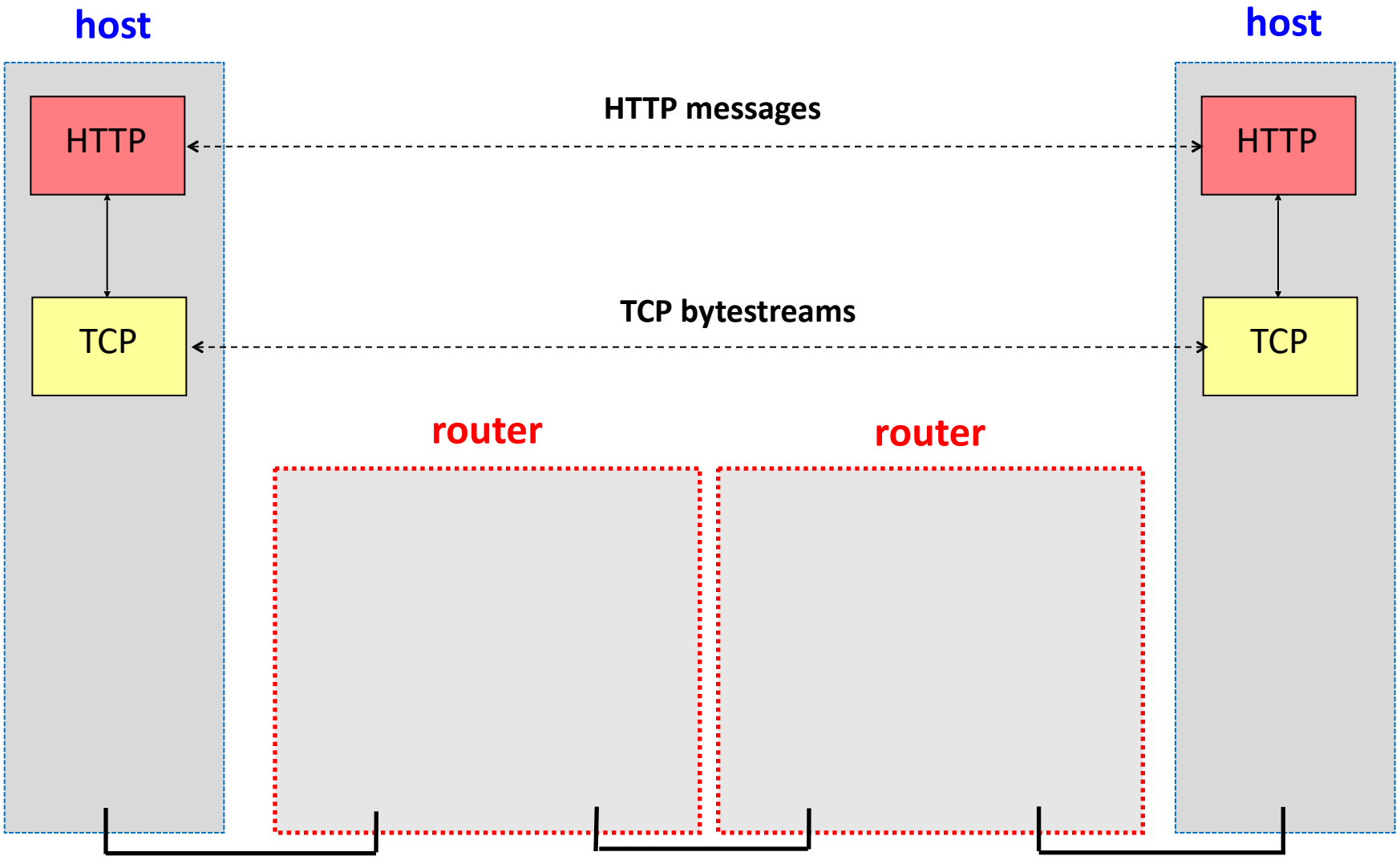
Complicated protocol diagram



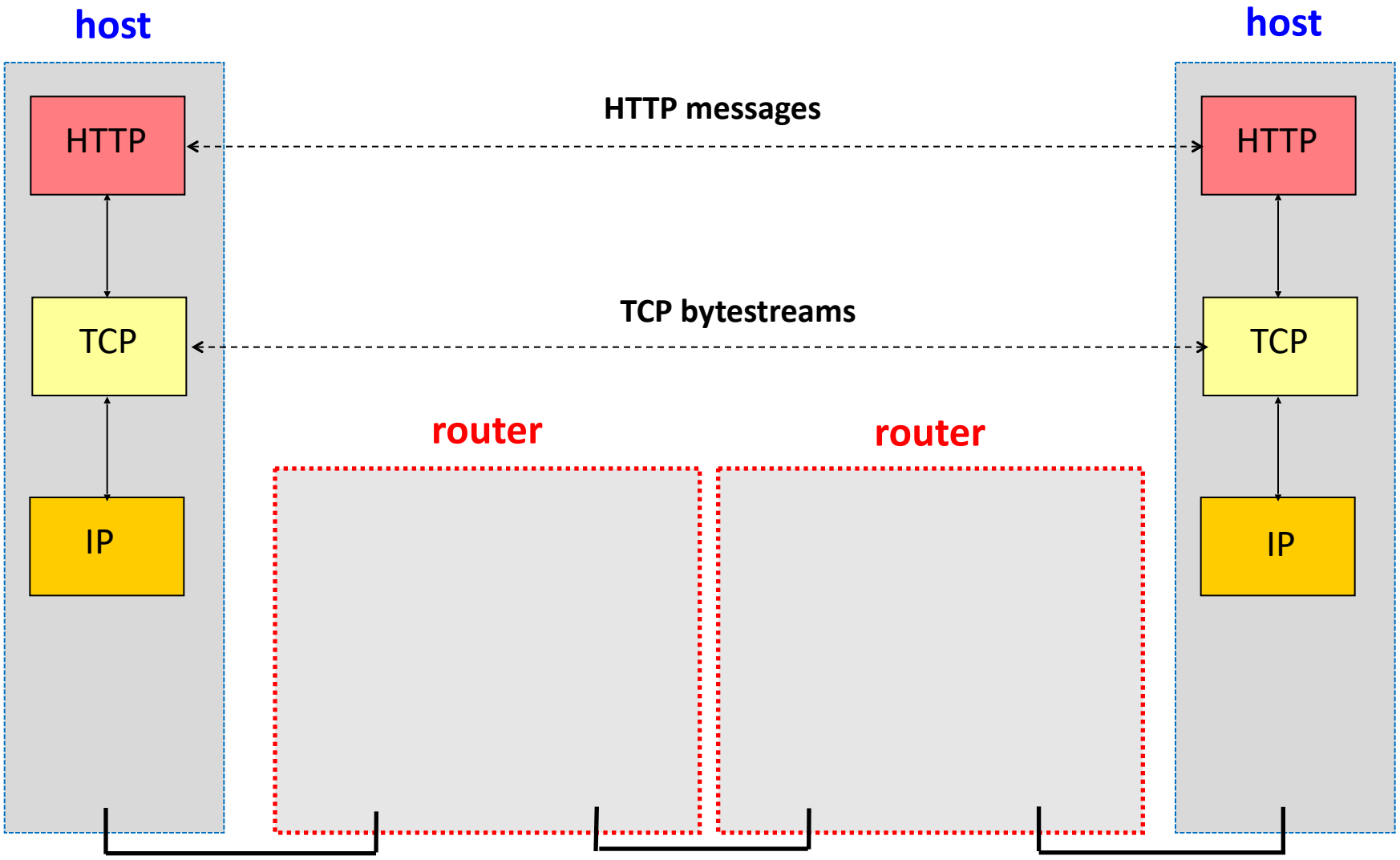
Complicated protocol diagram



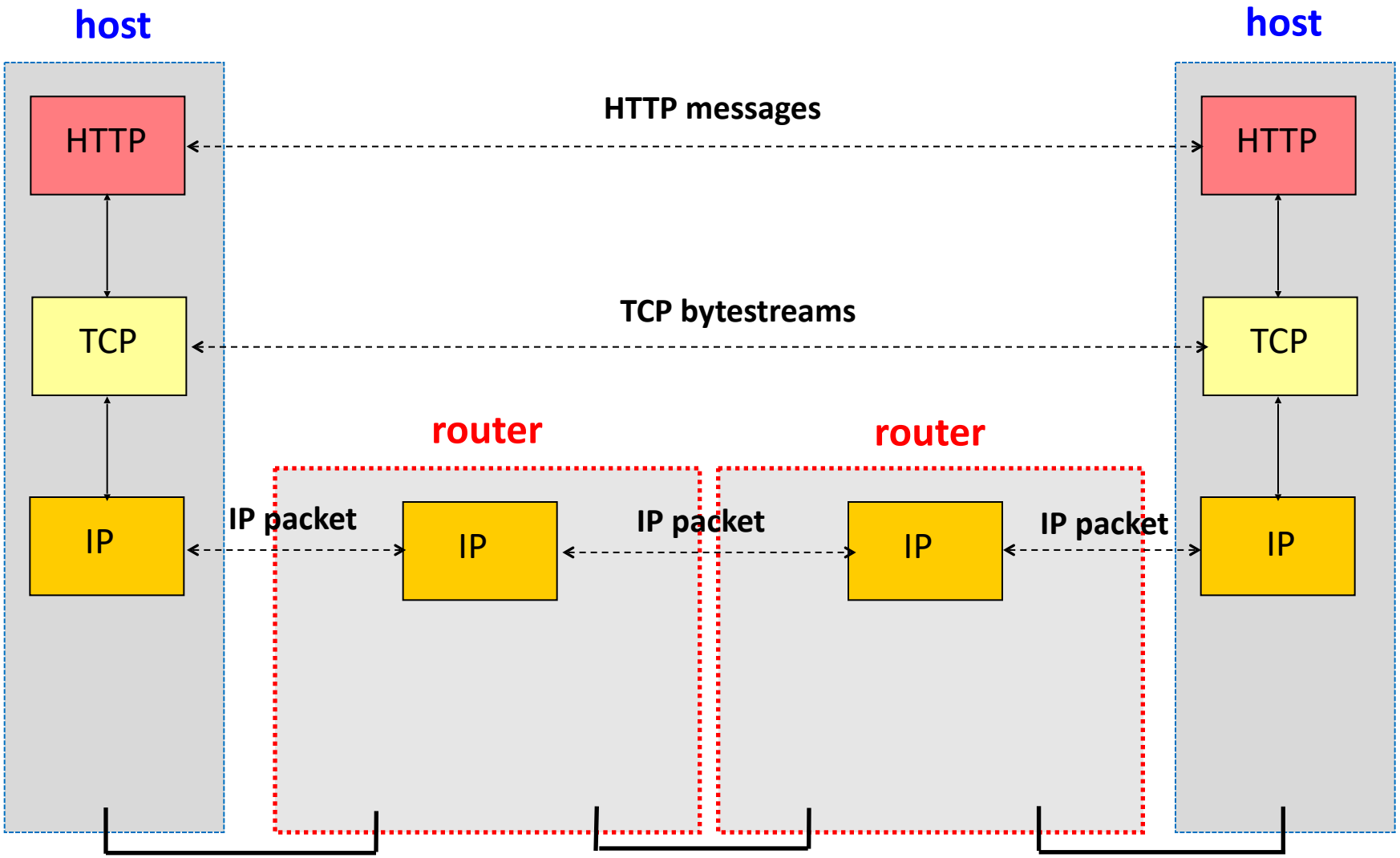
Complicated protocol diagram



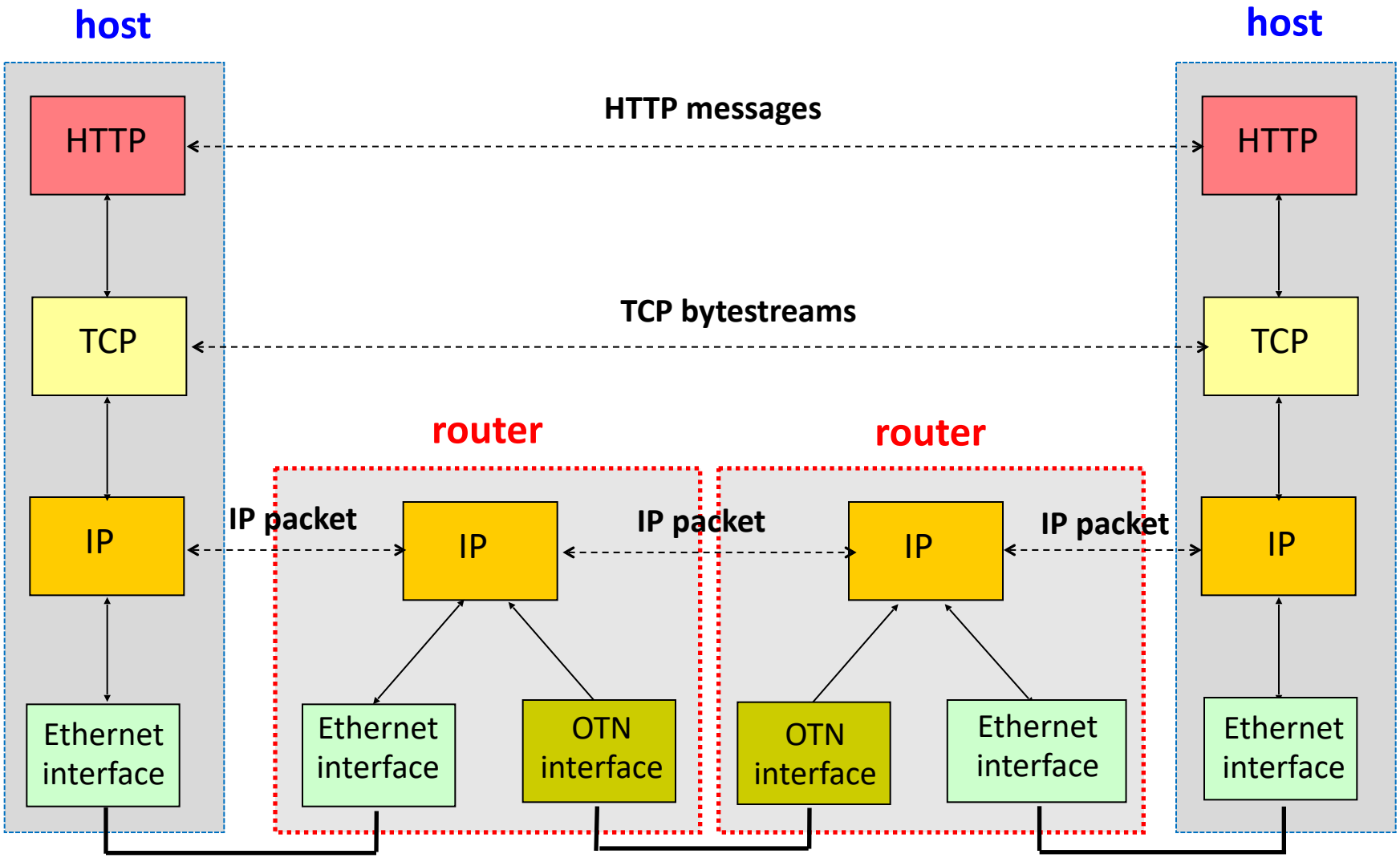
Complicated protocol diagram



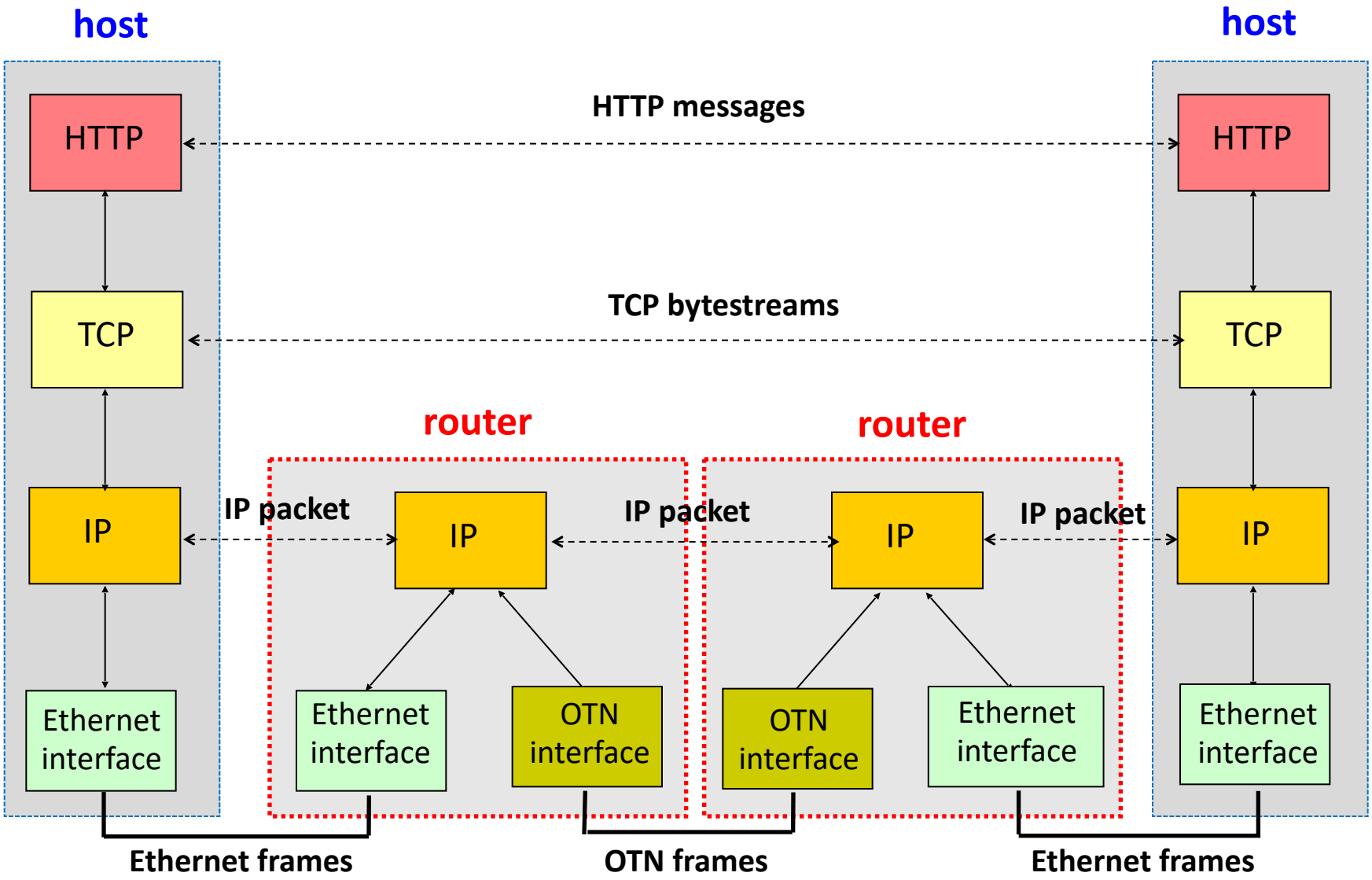
Complicated protocol diagram



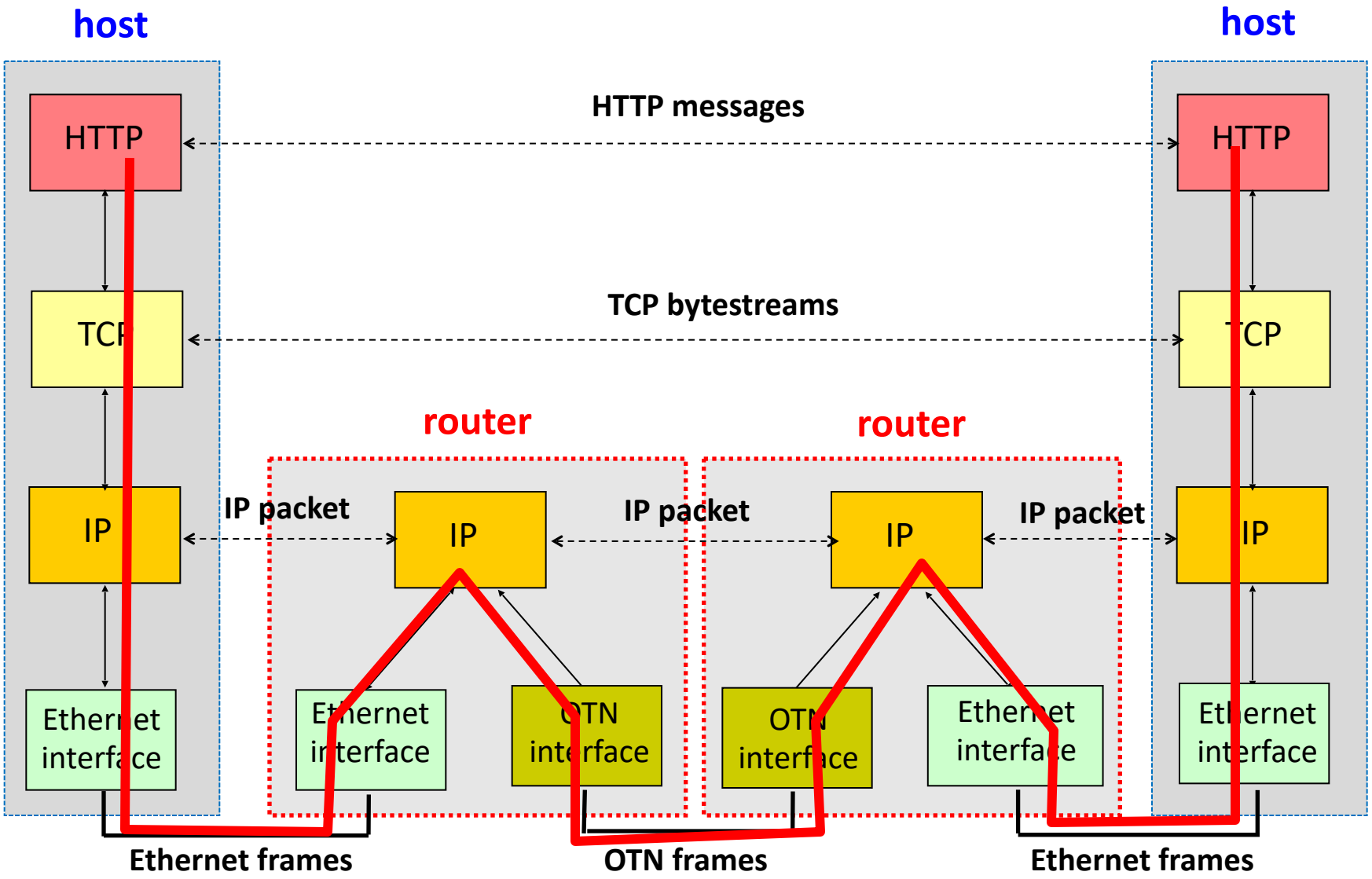
Complicated protocol diagram



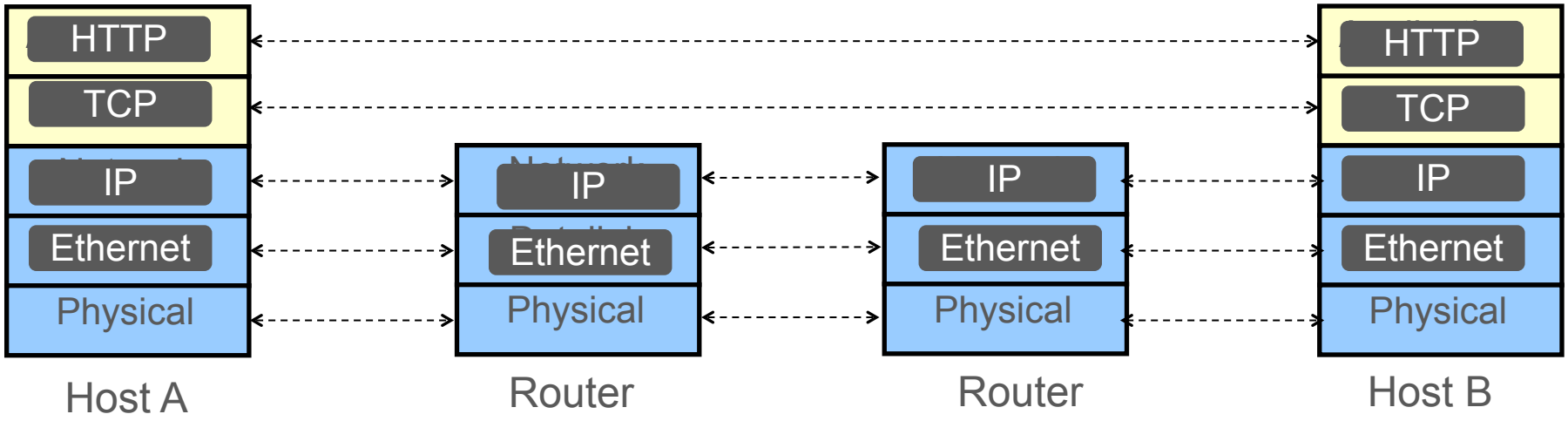
Complicated protocol diagram



Complicated protocol diagram

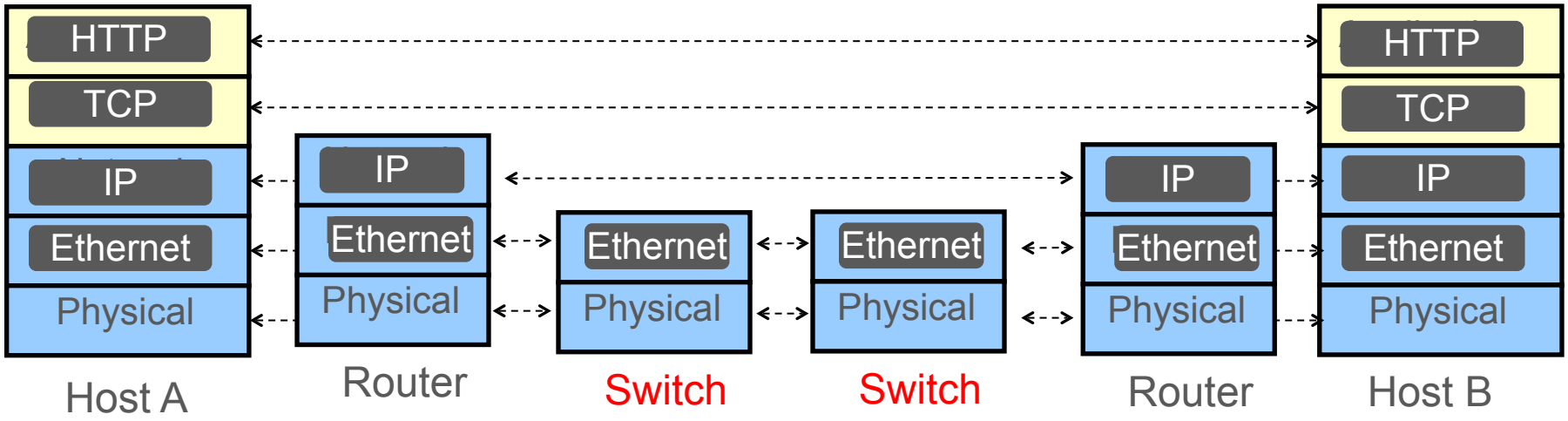


A side note: switches vs. routers

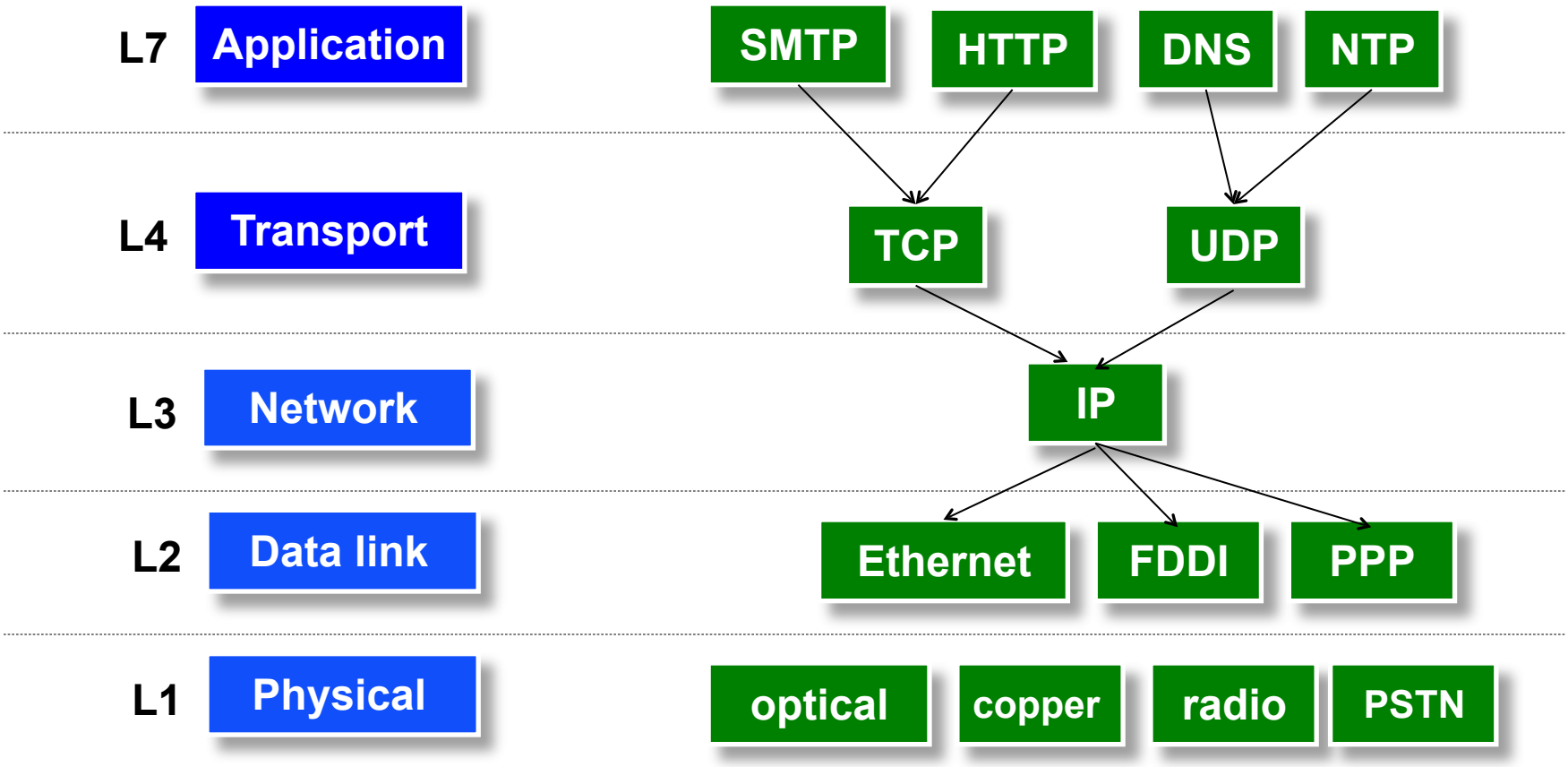


A side note: switches vs. routers

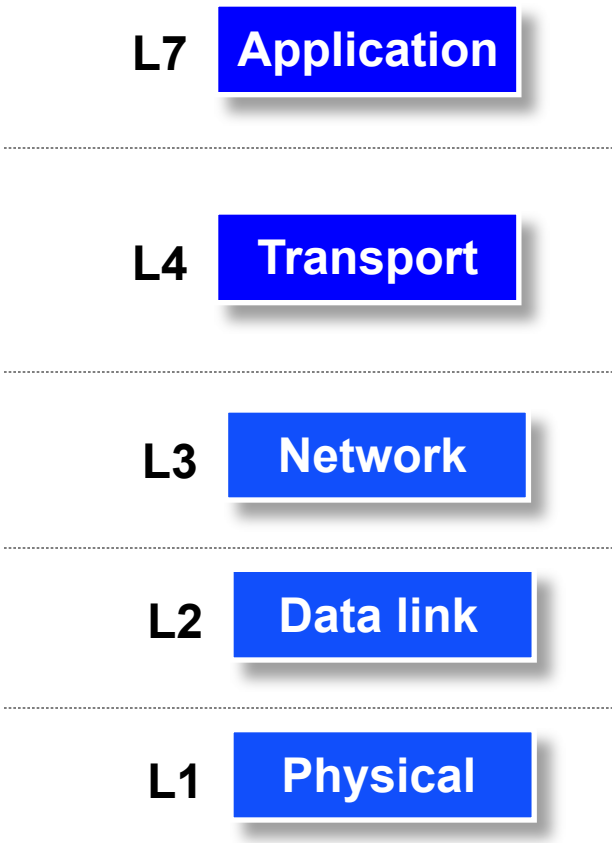
- Historically: switches implemented L1, L2 and routers L1, L2, L3
- These days, most switches also implement L3 hence we use the term switches and router interchangeably



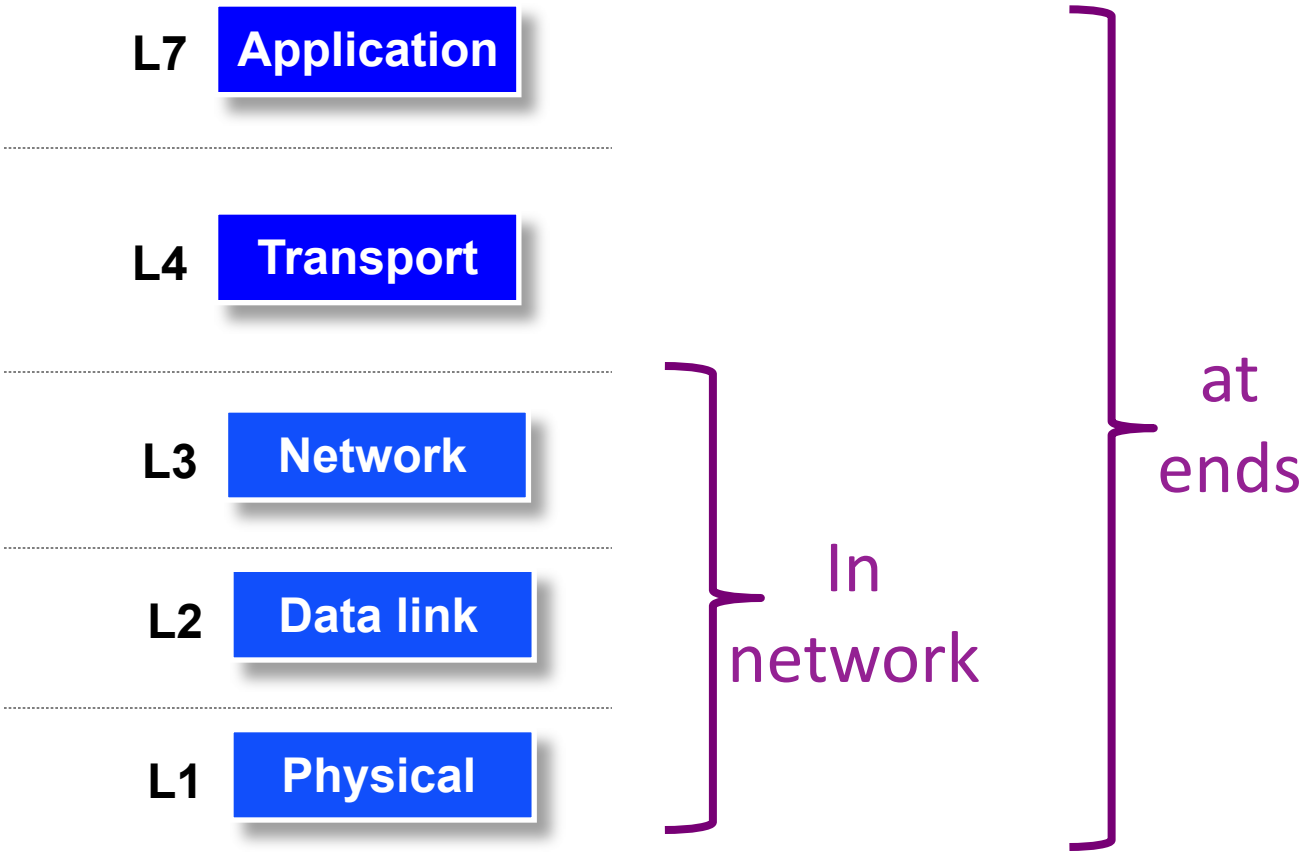
Review


L7
Application
L4
Transport
L3
Network
L2
Data link
L1
Physical
SMTP
HTTP
DNS
NTP
TCP
UDP
IP
Ethernet
FDDI
PPP
optical
copper
radio
PSTN

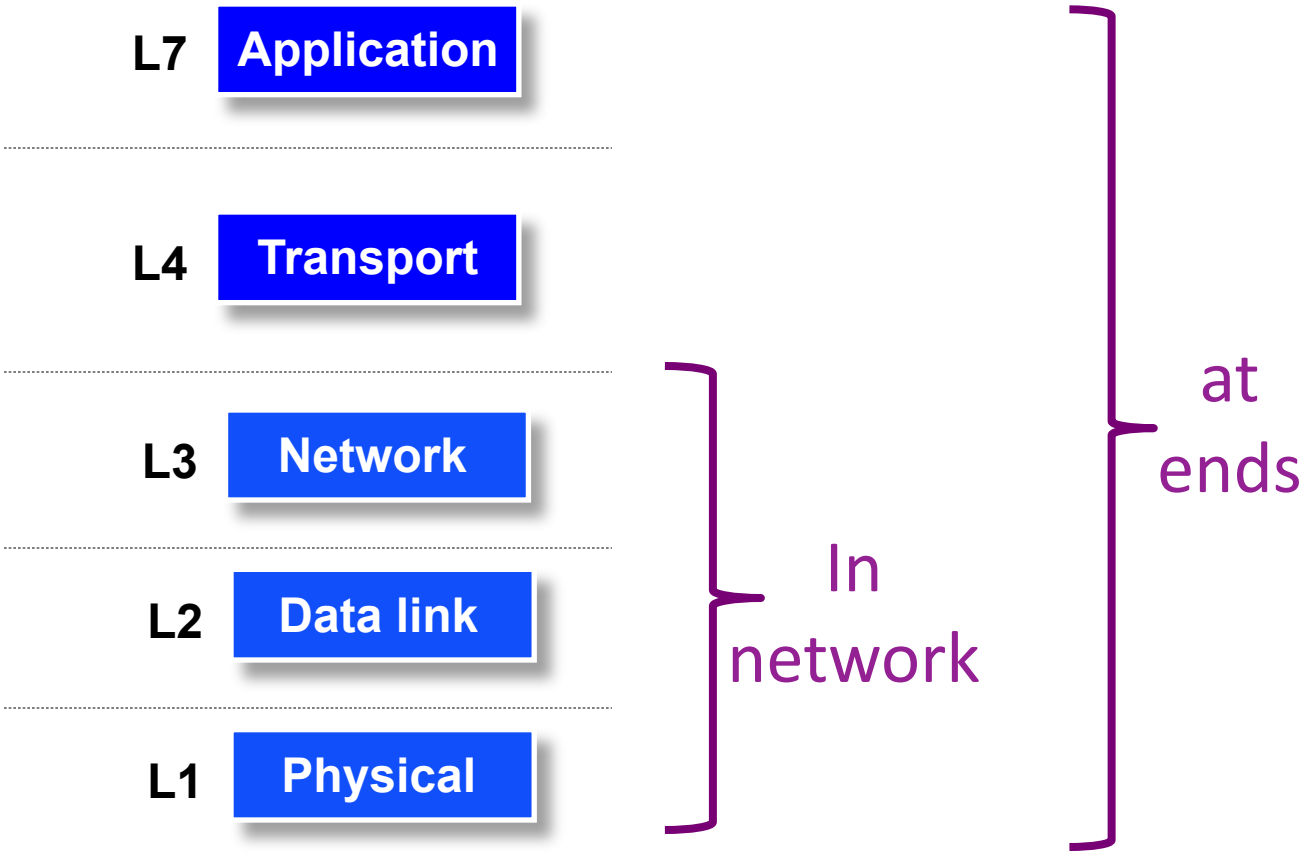
Review


L7
Application
L4
Transport
L3
Network
L2
Data link
L1
Physical

Review


L7
Application
L4
Transport
L3
Network
L2
Data link
L1
Physical
In network
at ends

Review



Next lecture: why is *this* a good assignment of tasks?