CS 168
Lecture 4

Designing the Internet

Sylvia Ratnasamy
Spring 2022

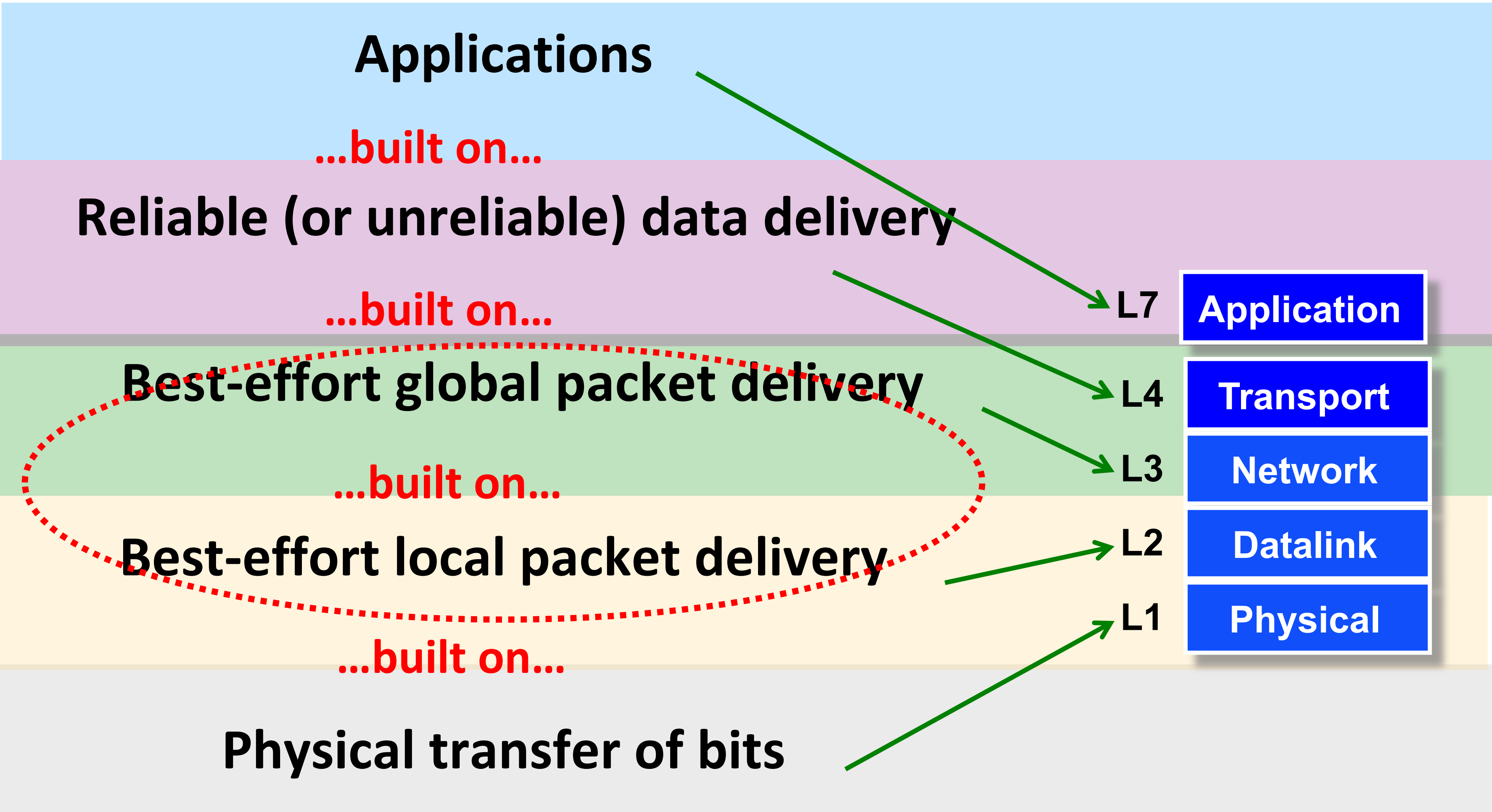
Recall: How do you solve a problem?

1. Define the problem (and why you’re solving it!)

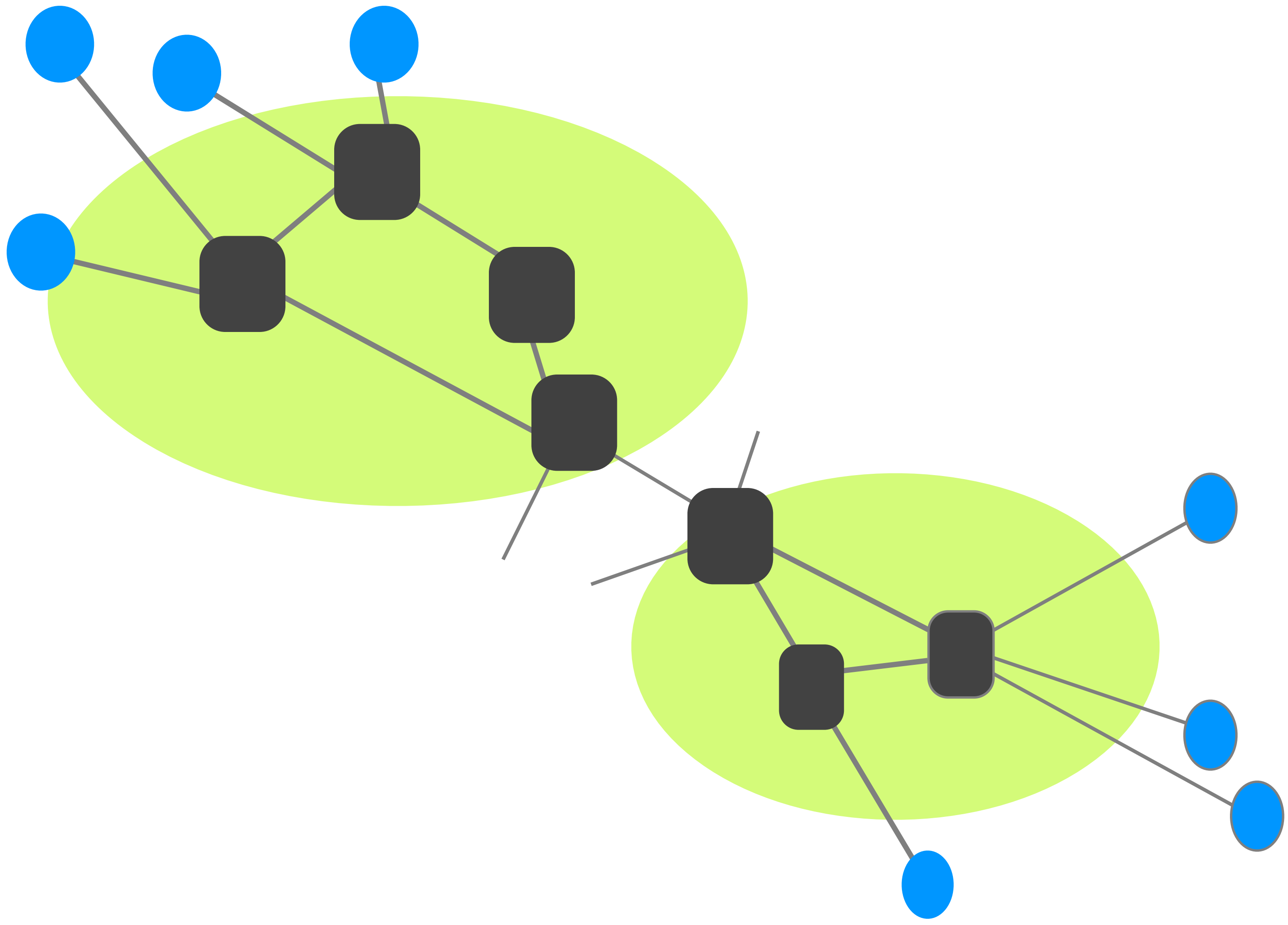
2. Decompose it (into tasks and abstractions)

3. Assign tasks to entities (who does what)

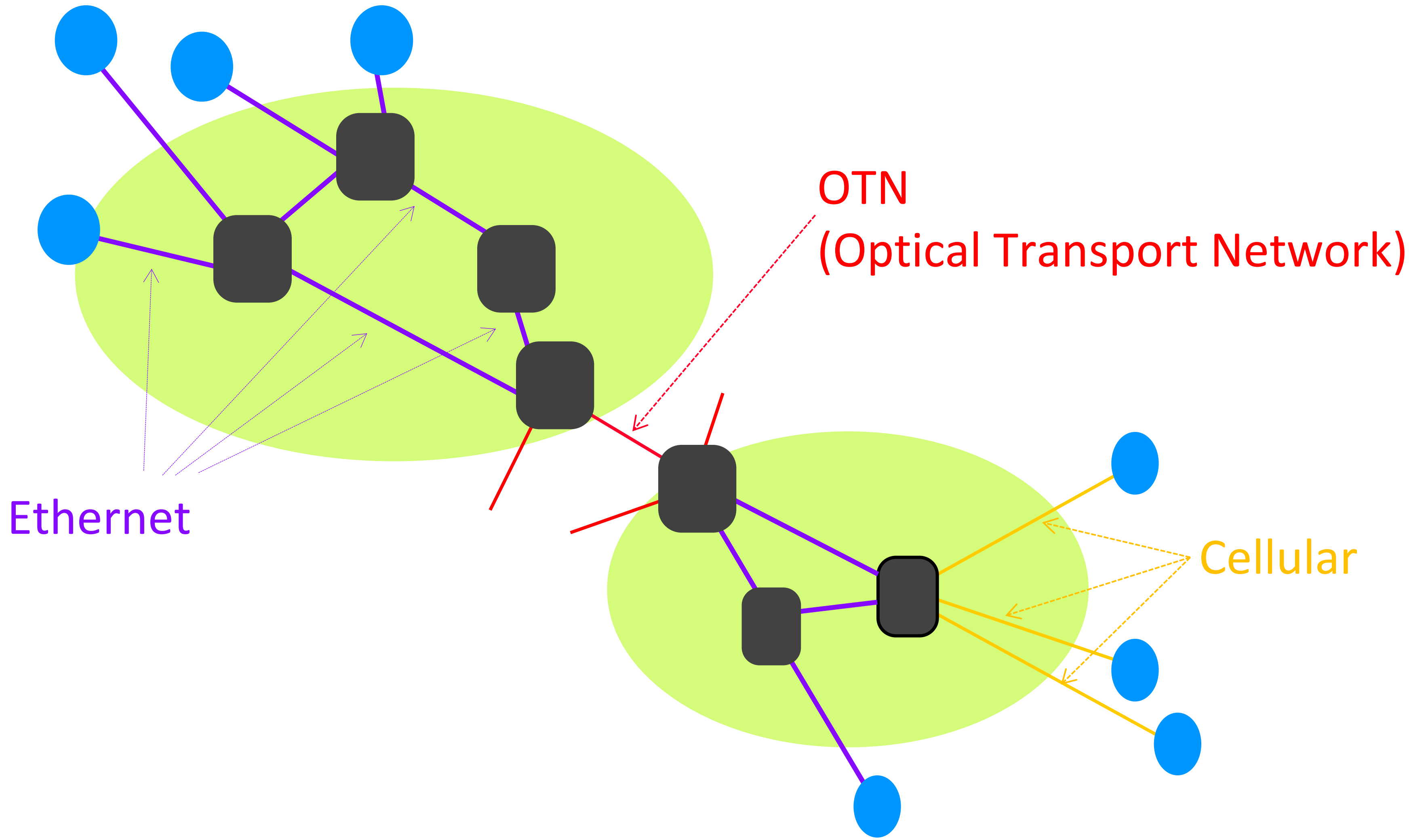
Recall: a layered architecture



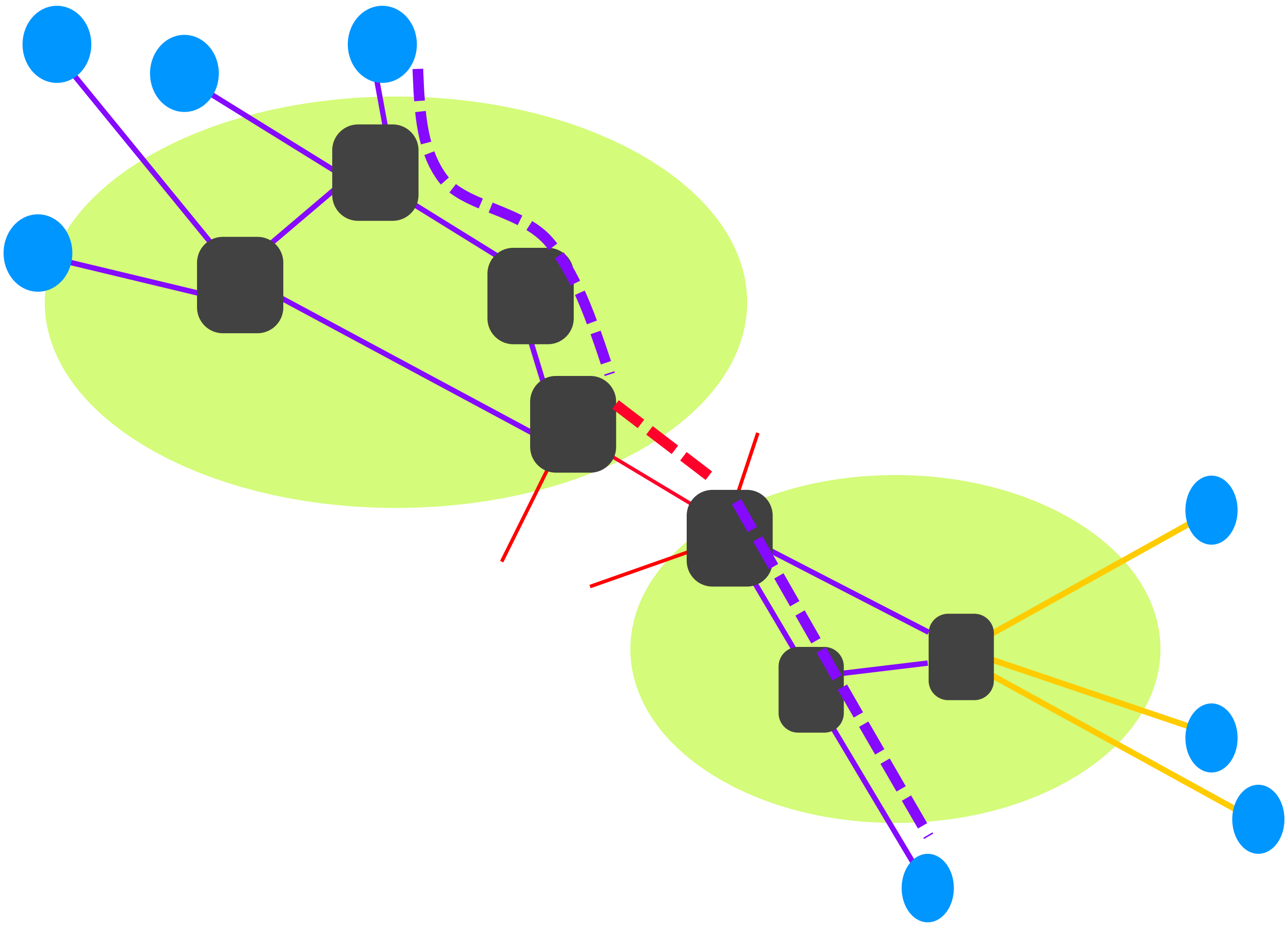
Local *vs.* Global Delivery



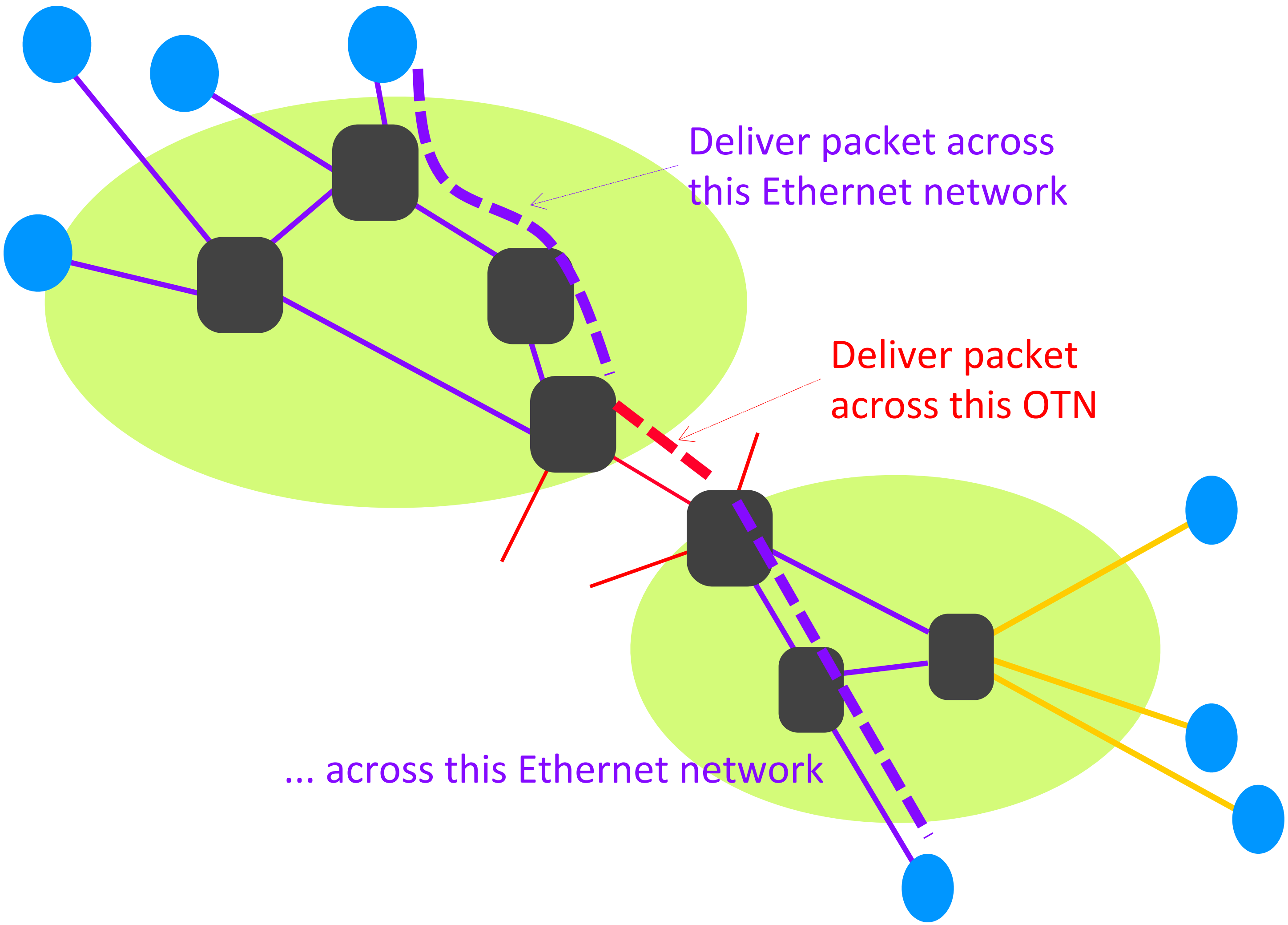
Local *vs.* Global Delivery



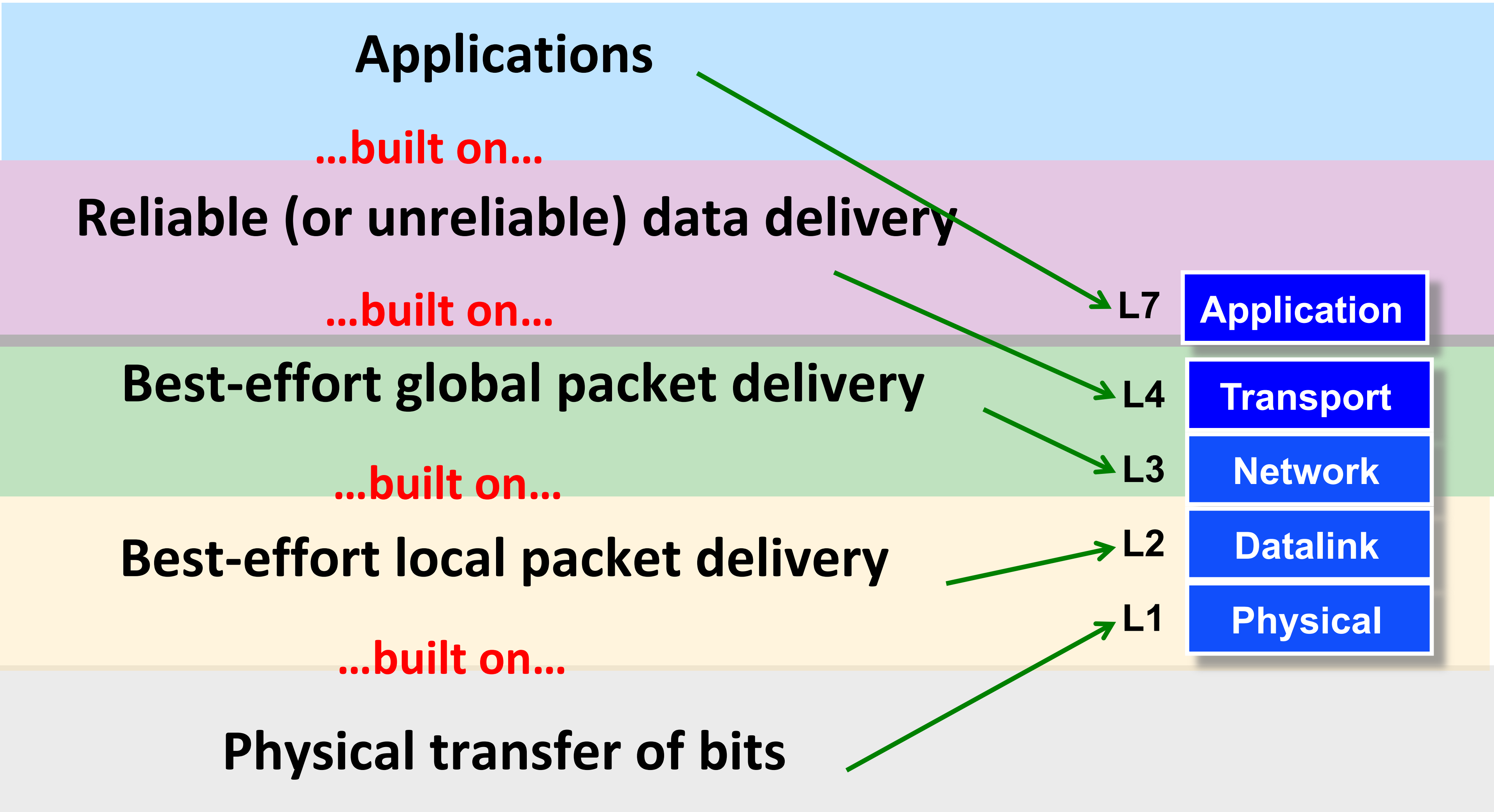
Local *vs.* Global Delivery



Local *vs.* Global Delivery



Recall: a layered architecture



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

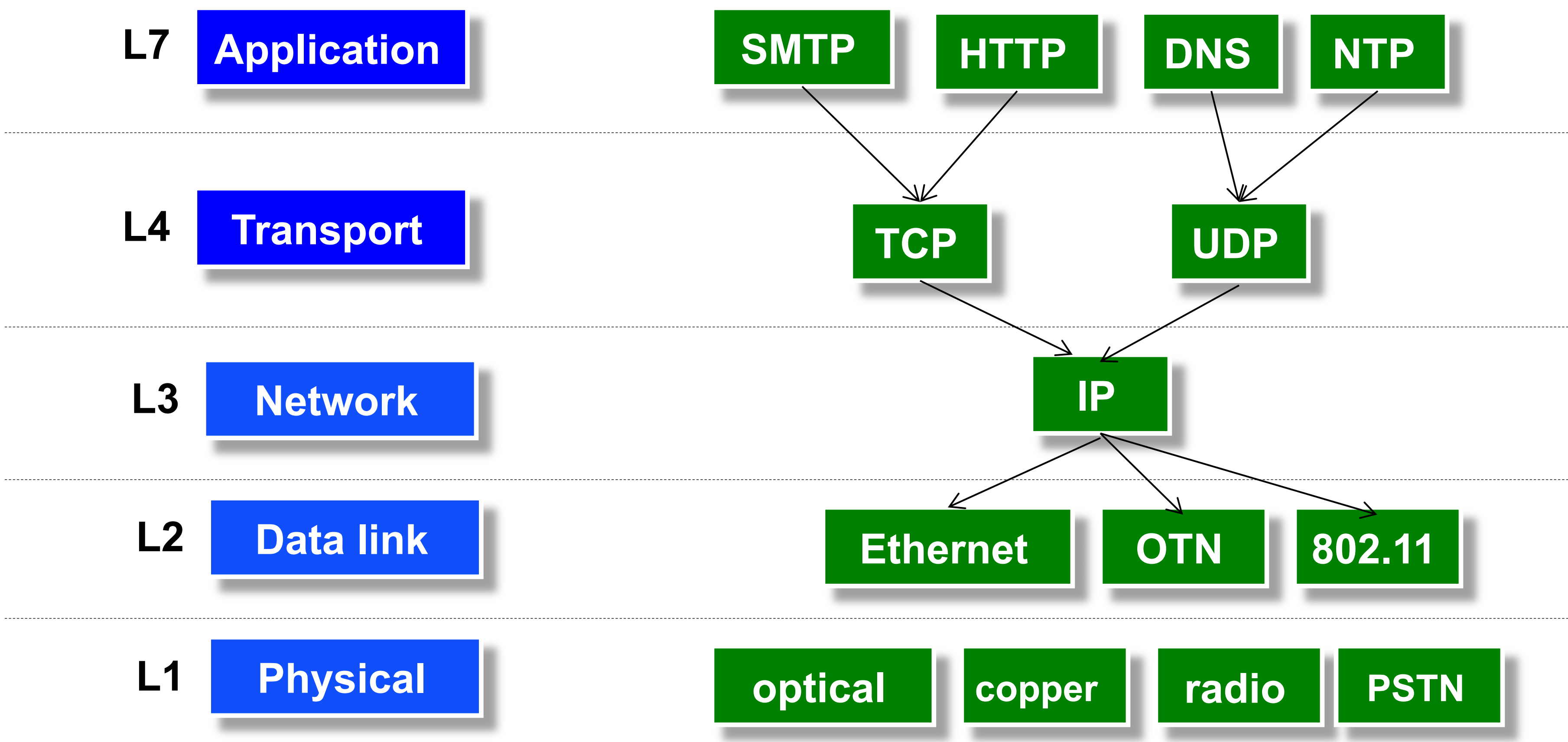
What is a Protocol?

- A specification of how parties communicate
- Defines the syntax of communication
  - Each protocol defines the format of its packet **headers**
    - *e.g. "the first 32 bits carry the destination address"*

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

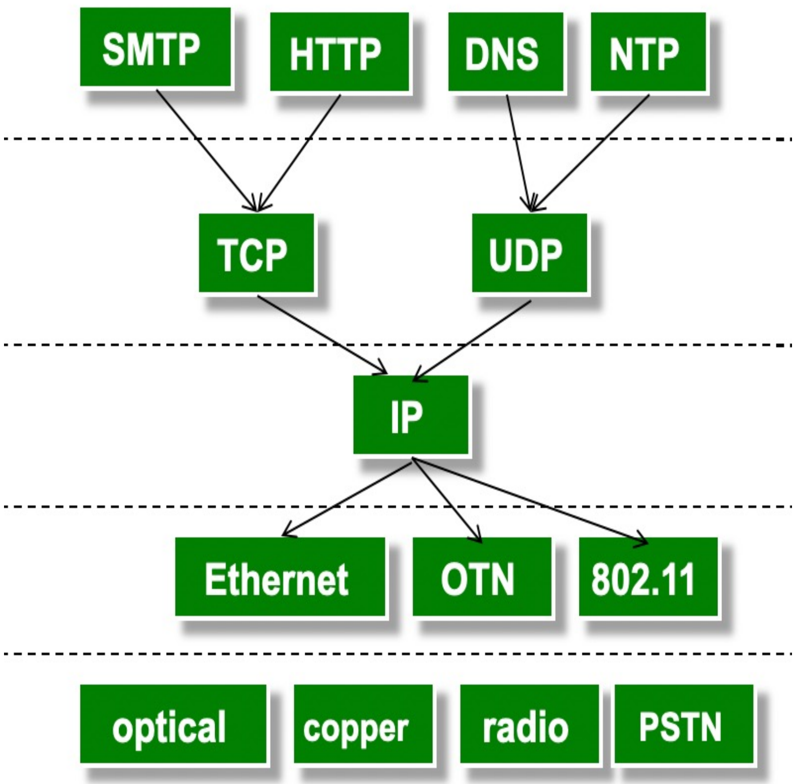
Protocols at different layers



There is just one network-layer protocol!

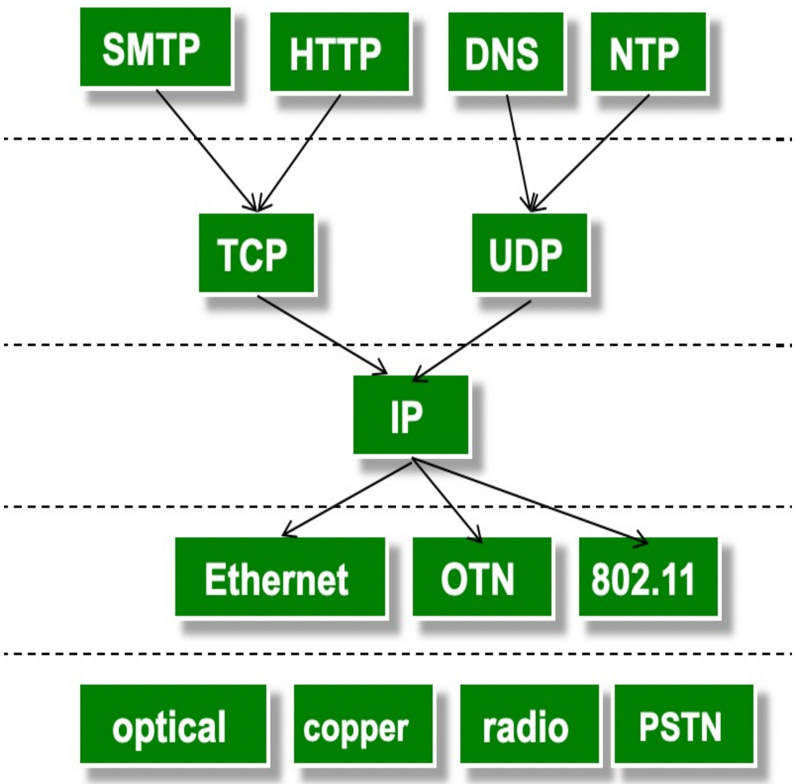
Recap: Three important properties

- Each layer:
  - Depends on layer below
  - Supports layer above
  - Independent of others
- Multiple versions in a layer
  - Interfaces differ somewhat
  - Components at one layer pick which lower-level protocol to use
- But only one IP layer
  - Unifying protocol



Why is layering important?

- Innovation can proceed largely in parallel!
- Pursued by very different communities
  - App devs (L7), chip designers (L1/L2)
- Leading to innovation at most levels
  - Applications (lots)
  - Transport (some)
  - Network (few)
  - Physical (lots)



Questions?

How do you solve a problem?

1. Define the problem (and why you’re solving it!)
2. Decompose it (into tasks and abstractions)
3. Assign tasks to entities (who does what)

Distributing Layers Across Network

- Layers are simple if only on a single machine
  - Just stack of modules interacting with those above/below
- But we need to implement layers across:
  - Hosts
  - Routers (switches)
- What gets implemented where?

What gets implemented at the end host?

- Bits arrive on wire ... → must implement L1
- ... must make it up to app → must implement L7

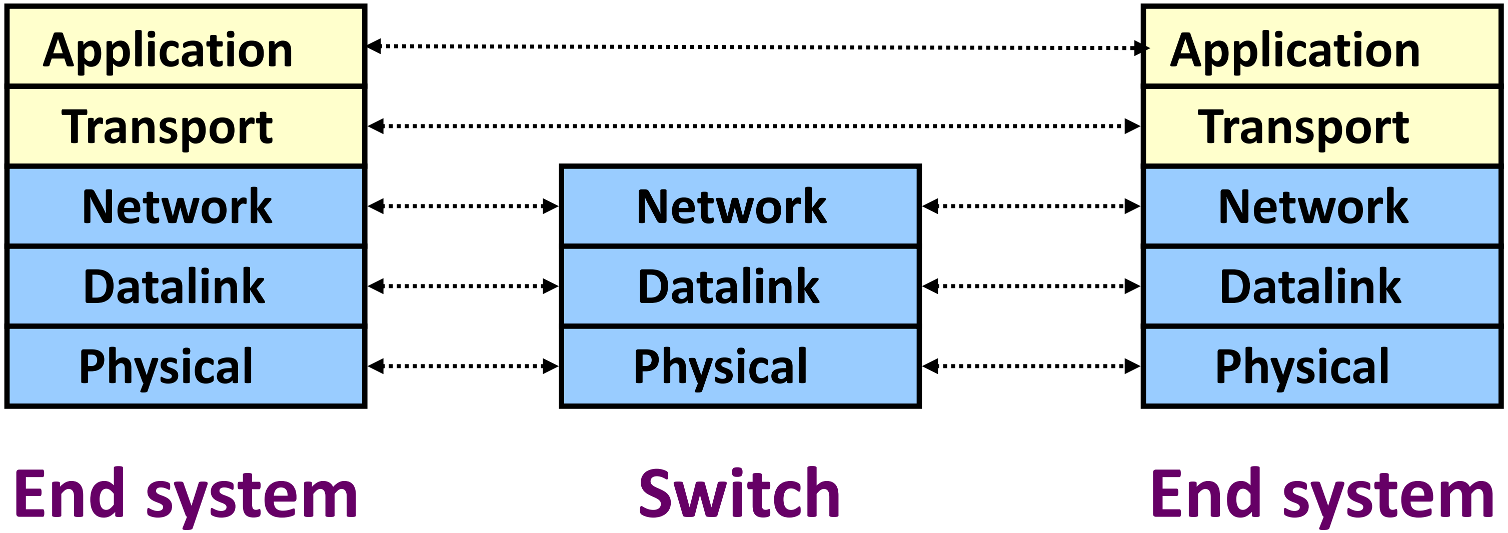
- Therefore, all layers must exist at host!

What gets implemented in the network?

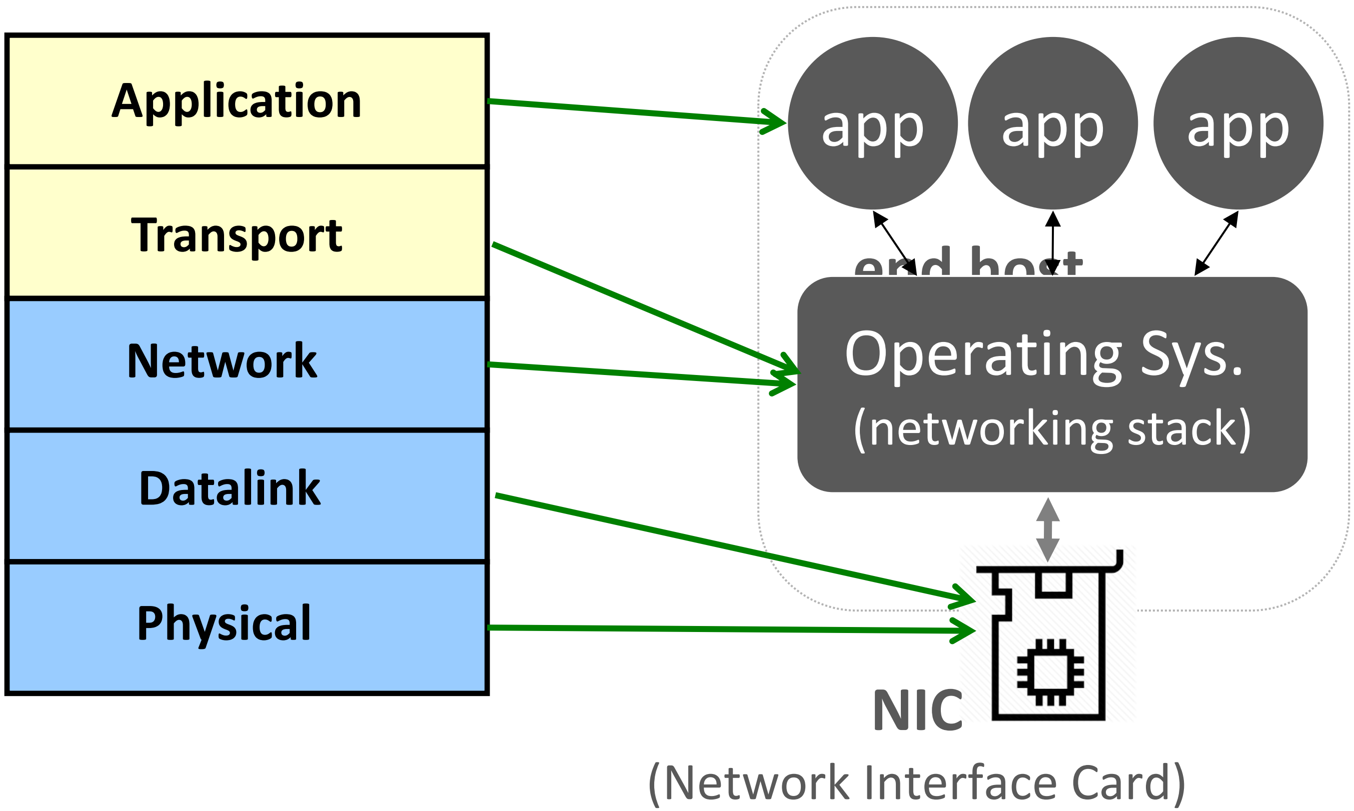
- Bits arrive on wire → physical layer (L1)
- Packets must be delivered across links and local networks → datalink layer (L2)
- Packets must be delivered between networks for global delivery → network layer (L3)
- The network does not support reliable delivery
  - Transport layer (and above) ***not*** supported

Simple Diagram

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

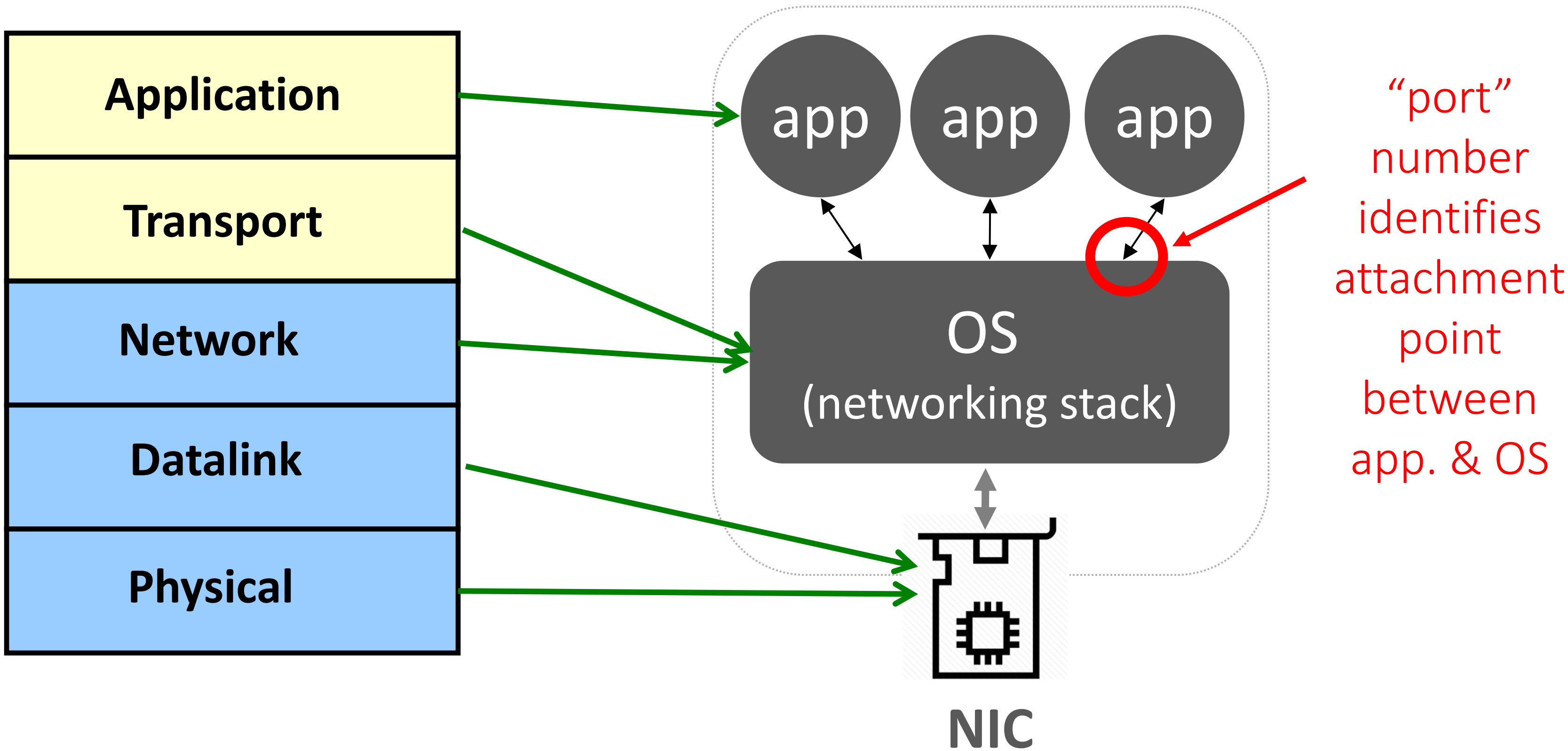


A closer look: end host



Note: addressing *within* the end host

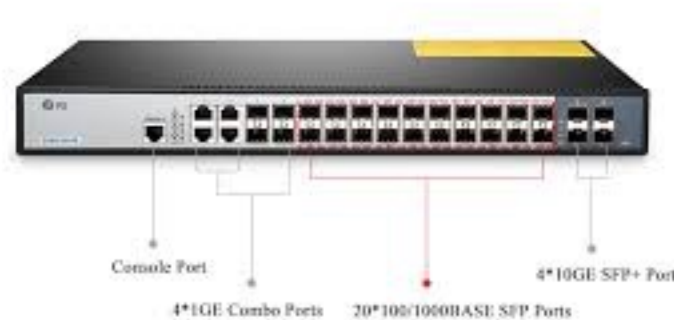
Recall: packet contains the destination host's address



When a packet arrives at the host, how does the OS know which app to send the packet to?

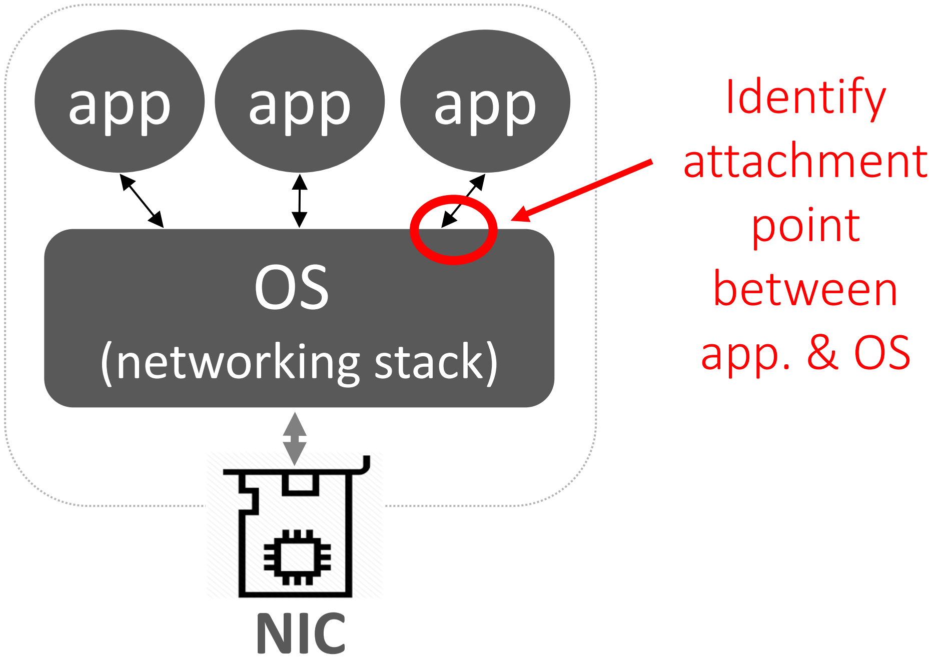
Network “ports”: two types

- Switches/routers have **physical ports**:
  - Places where links connect to switches



Network "ports": two types

- Switches/routers have **physical ports**:
  - Places where links connect to switches
- The OS supports **logical ports**:
  - Place where app connects to OS network stack



Of Sockets and Ports

- **Socket:** an OS mechanism that connects app processes to the networking stack
- When an app wants access to the network, it opens a **socket**, which is associated with a **port**
  - *This is not a physical port, just a logical one*
- The **port number** is used by the OS to direct incoming packets to its associated socket

Details about sockets in next week's section!

Implications for Packet Header

- Packet header must include:
  - Destination host address (used by network to reach host)
  - Destination port (used by host OS to reach app) [new!]

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

OS Network Stack Is An Intermediary

- Application has very clear task (w.r.t. network)
  - Thinks about data
- NIC/driver has very clear task
  - Thinks about packets
- Network stack in the intermediary between them
  - Translates between their abstractions

Recap: layers at the end host

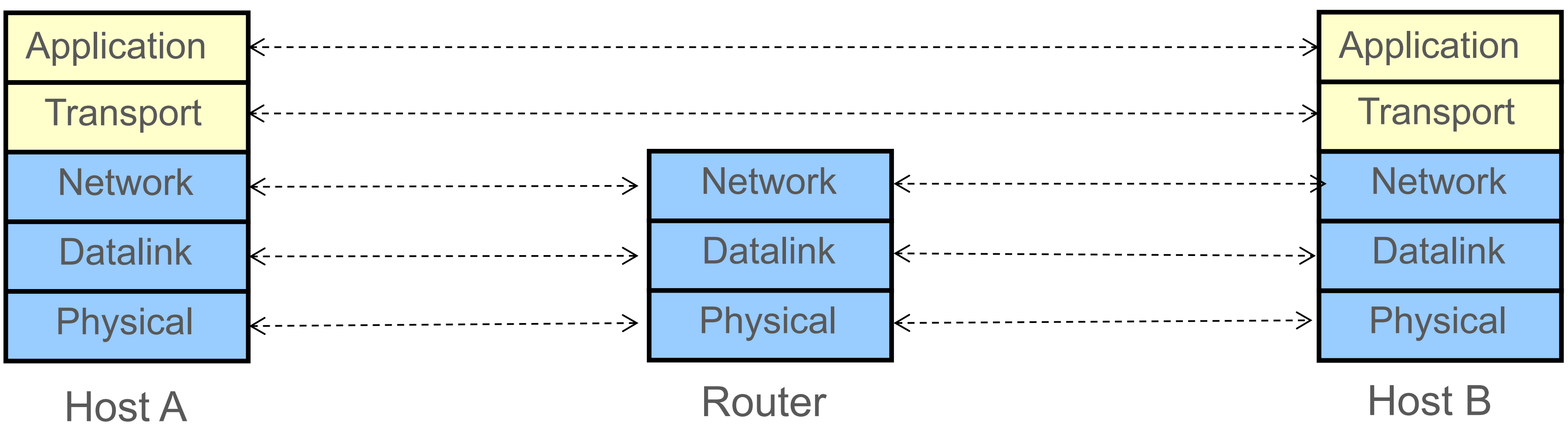
- **Application layer (L7)**
  - part of the app: browser, mail client,…
- **Transport and network layer (L3, L4)**
  - typically part of the OS
- **Datalink and physical layer (L1, L2)**
  - hardware/firmware/drivers

A closer look: network

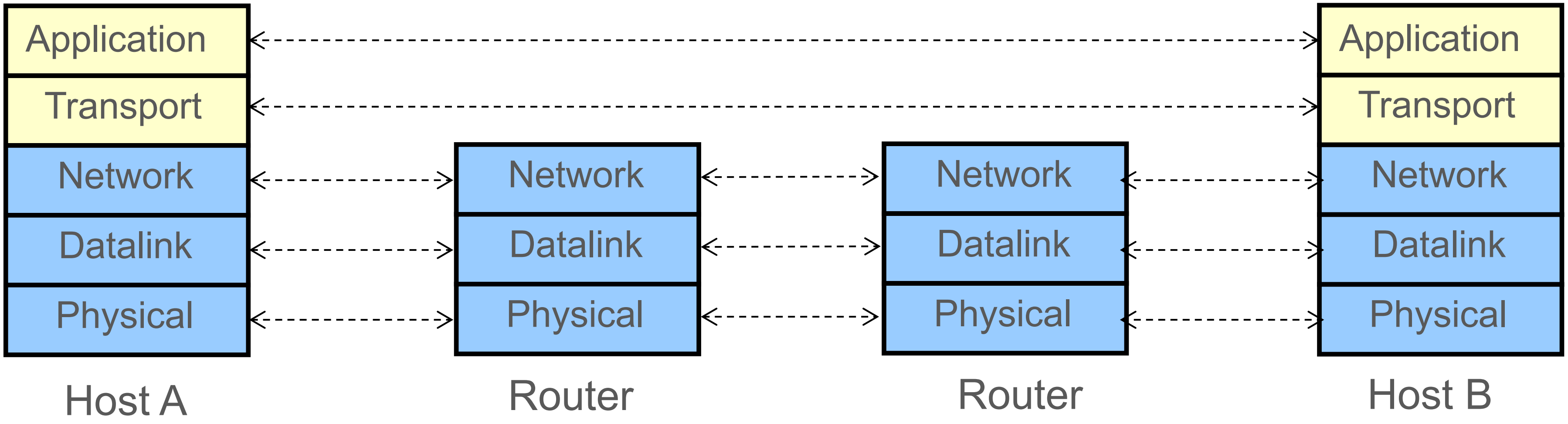
- Bits on wire → physical layer (L1)
- Local delivery of packets → datalink layer (L2)
- Global delivery of packets → network layer (L3)

Recall: Logical Communication

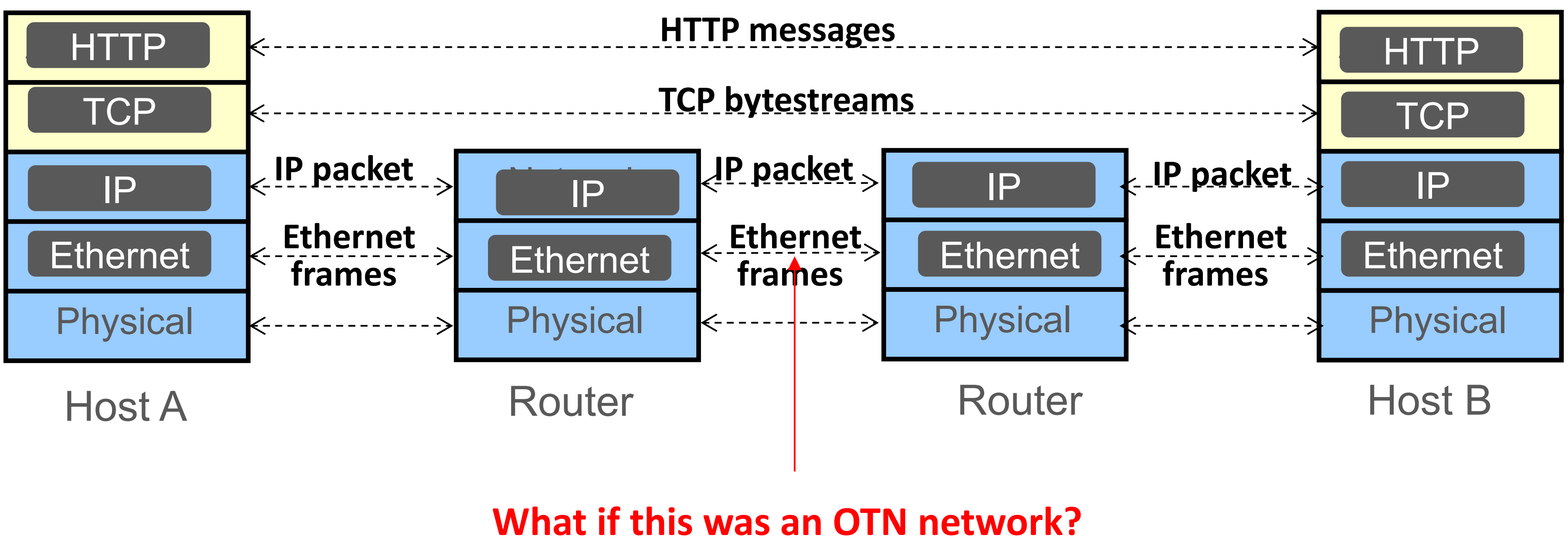
- Layers interact with peer's corresponding layer
- Lower three layers implemented everywhere
- Top two layers implemented only at hosts



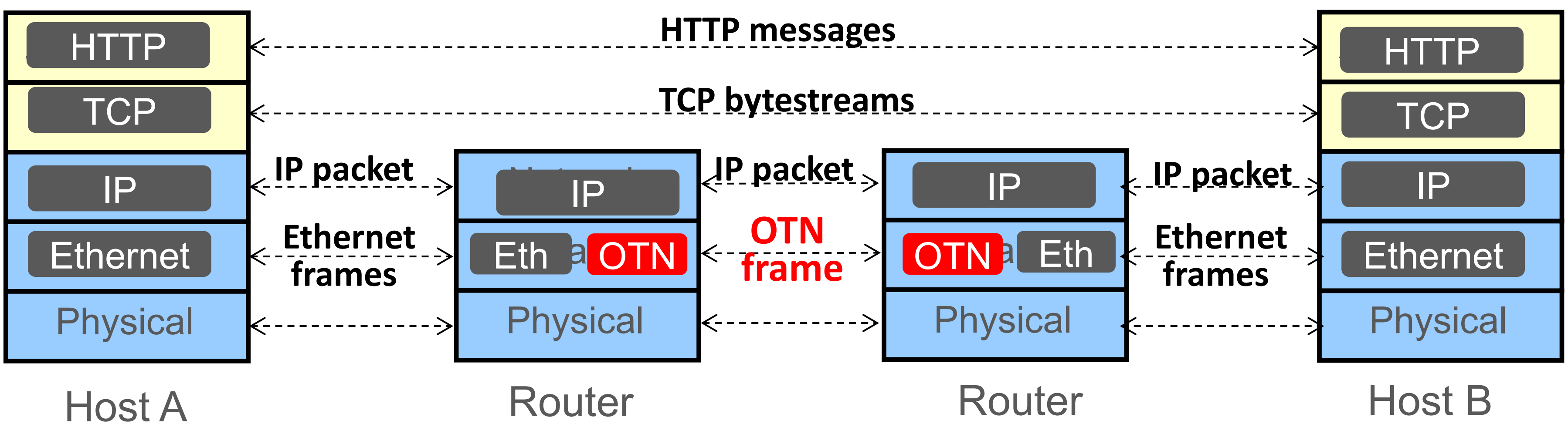
A closer look: network



Example: simple protocol diagram



Example: simple protocol diagram



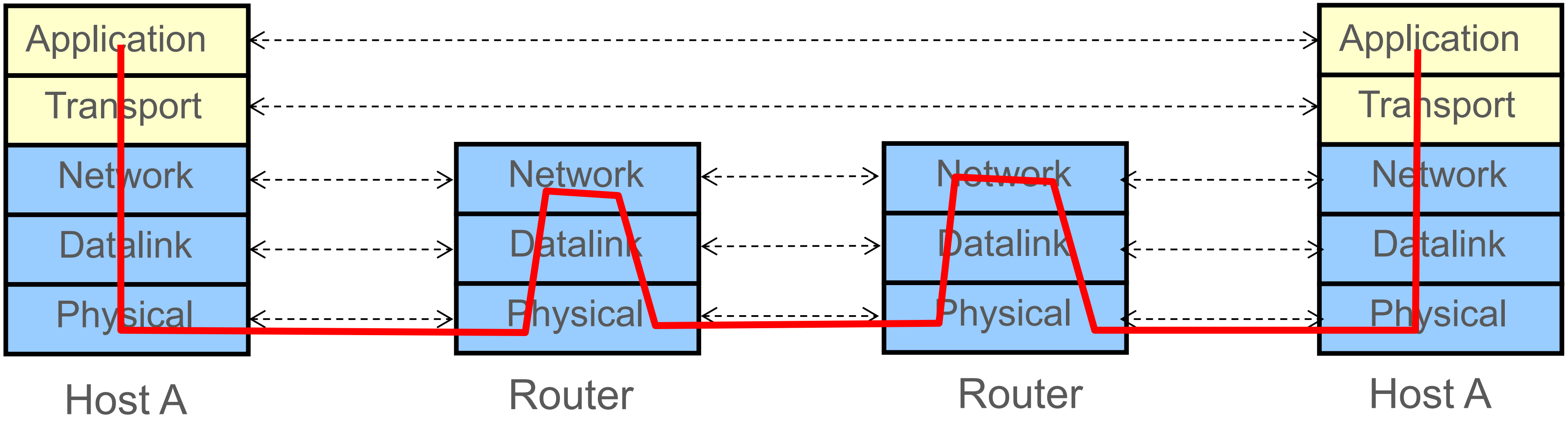
Recap: Physical Communication

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

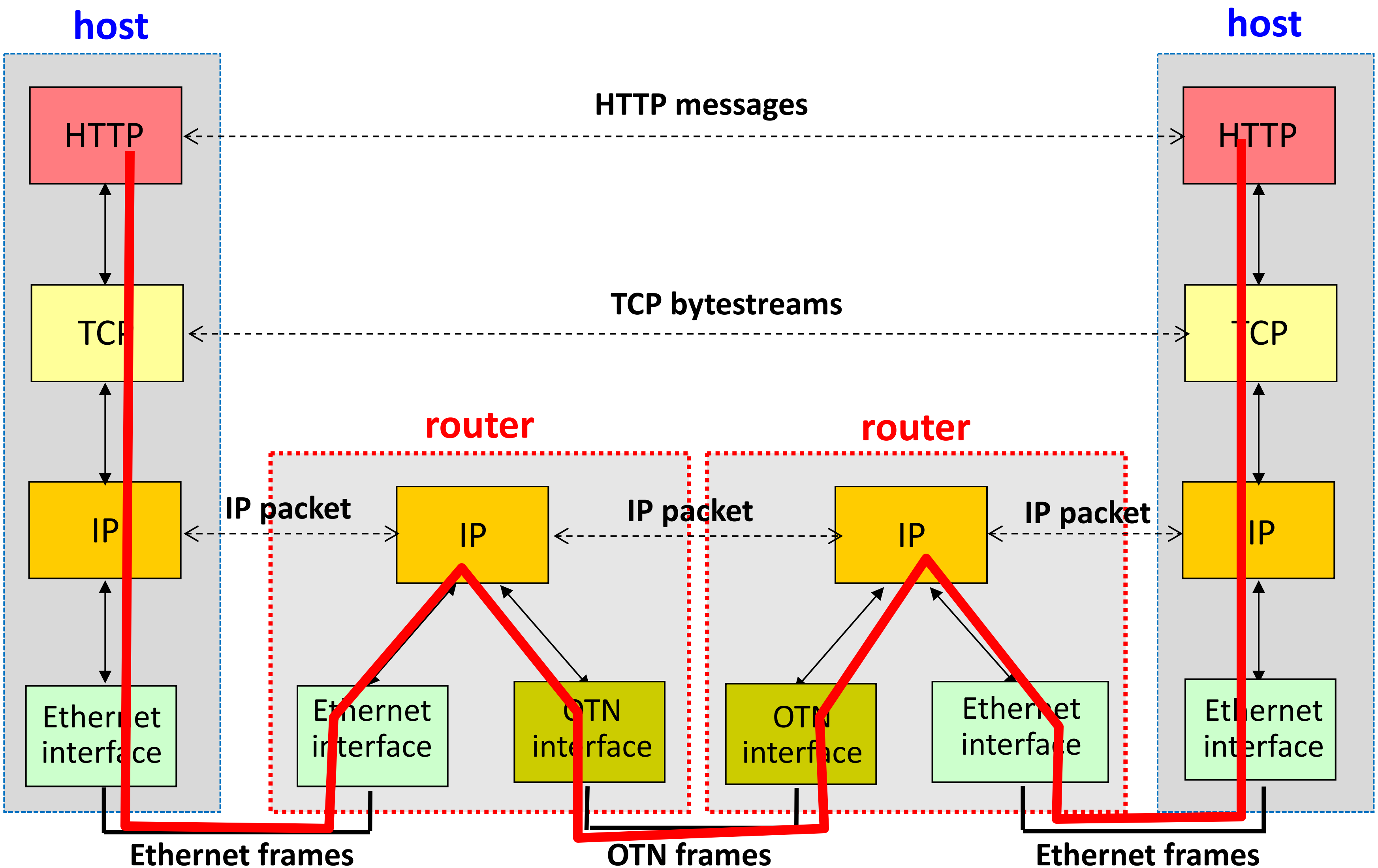
Recall: the path of the letter

Recap: Physical Communication

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

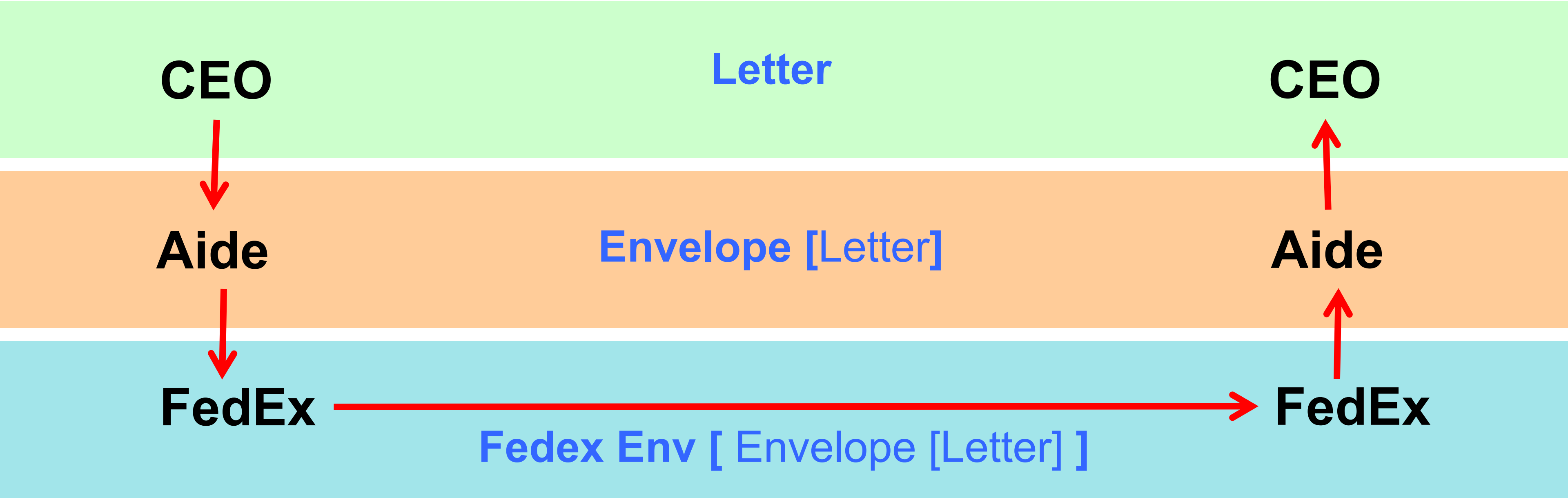


Complicated protocol diagram

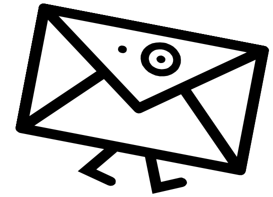


Recap: Physical Communication

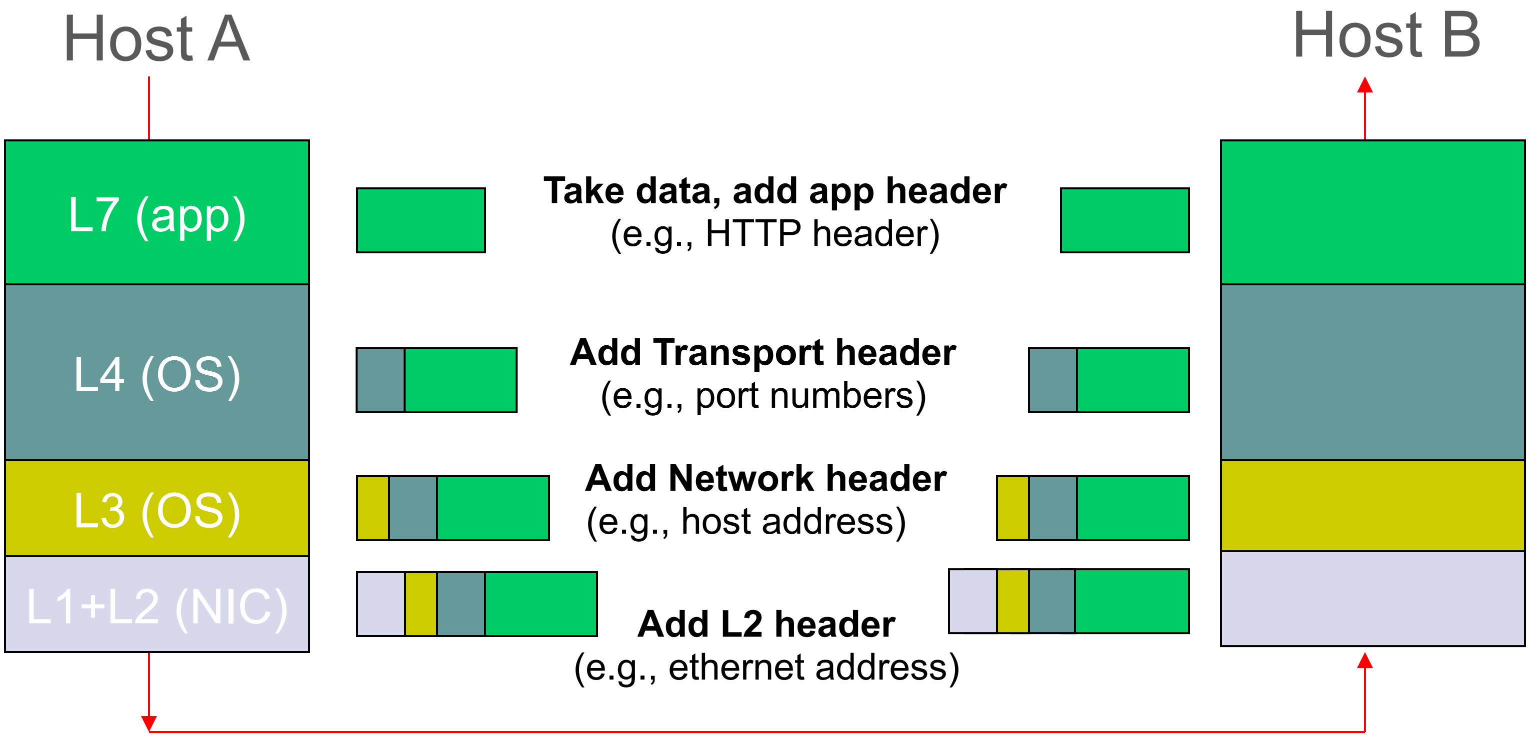
- Communication goes down to physical network
- Then up to relevant layer
- Lowest layer has the most “packaging”



Layer Encapsulation

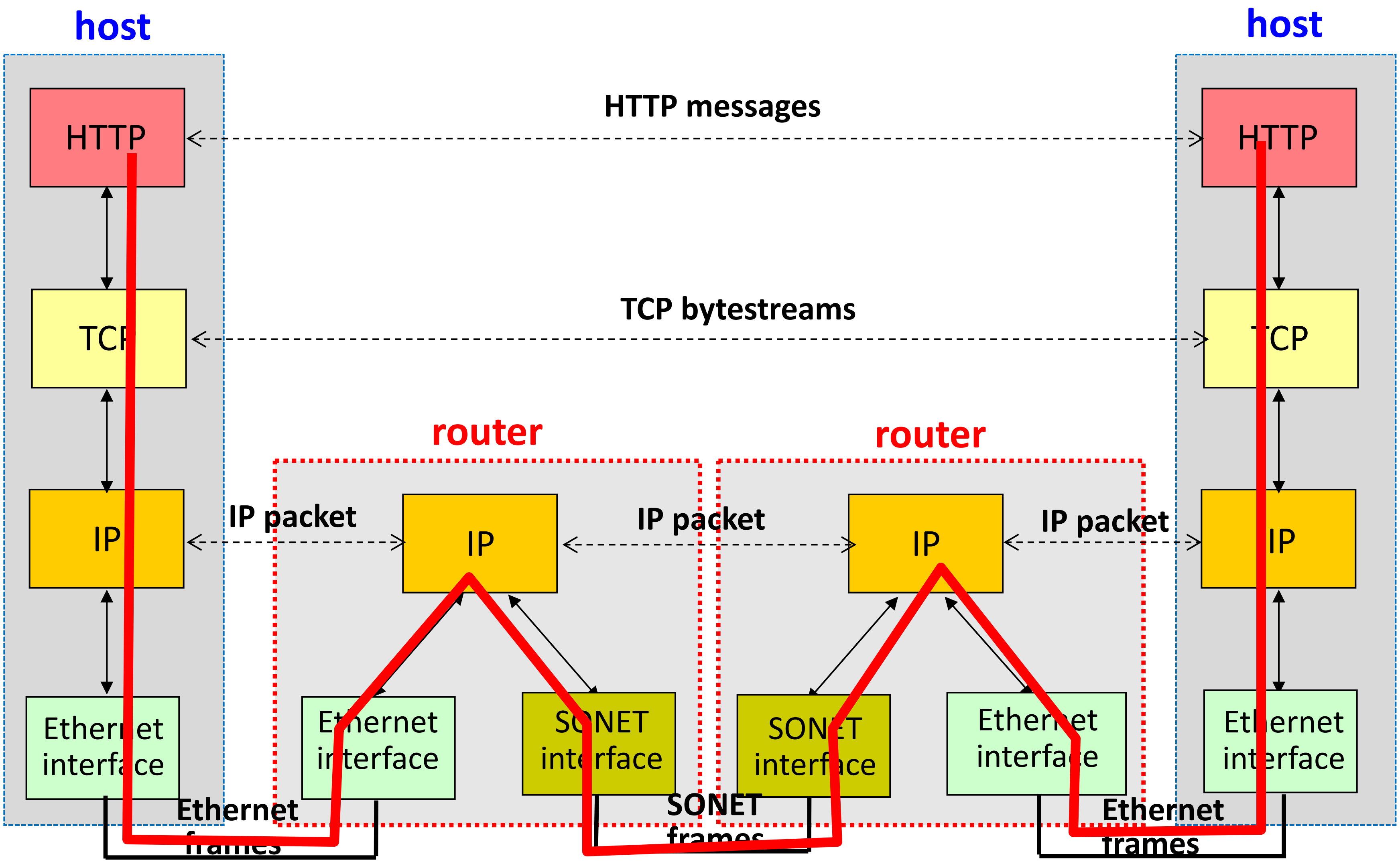


Packets contain multiple headers!

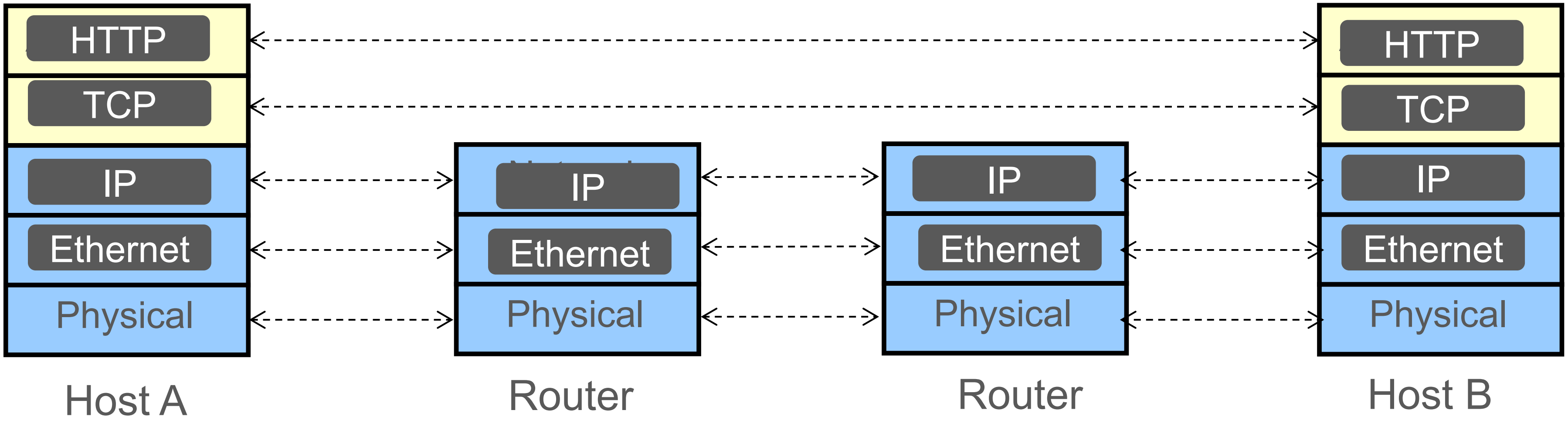


On wire: packet has data + headers from <u>all layers</u>!

Complicated protocol diagram

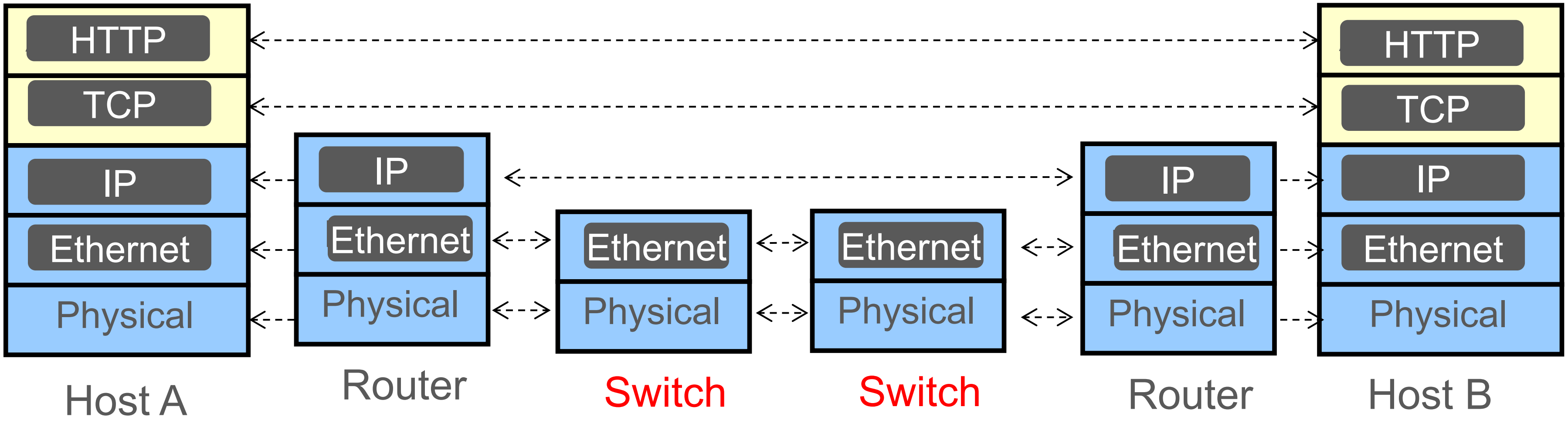


A side note: switches vs. routers

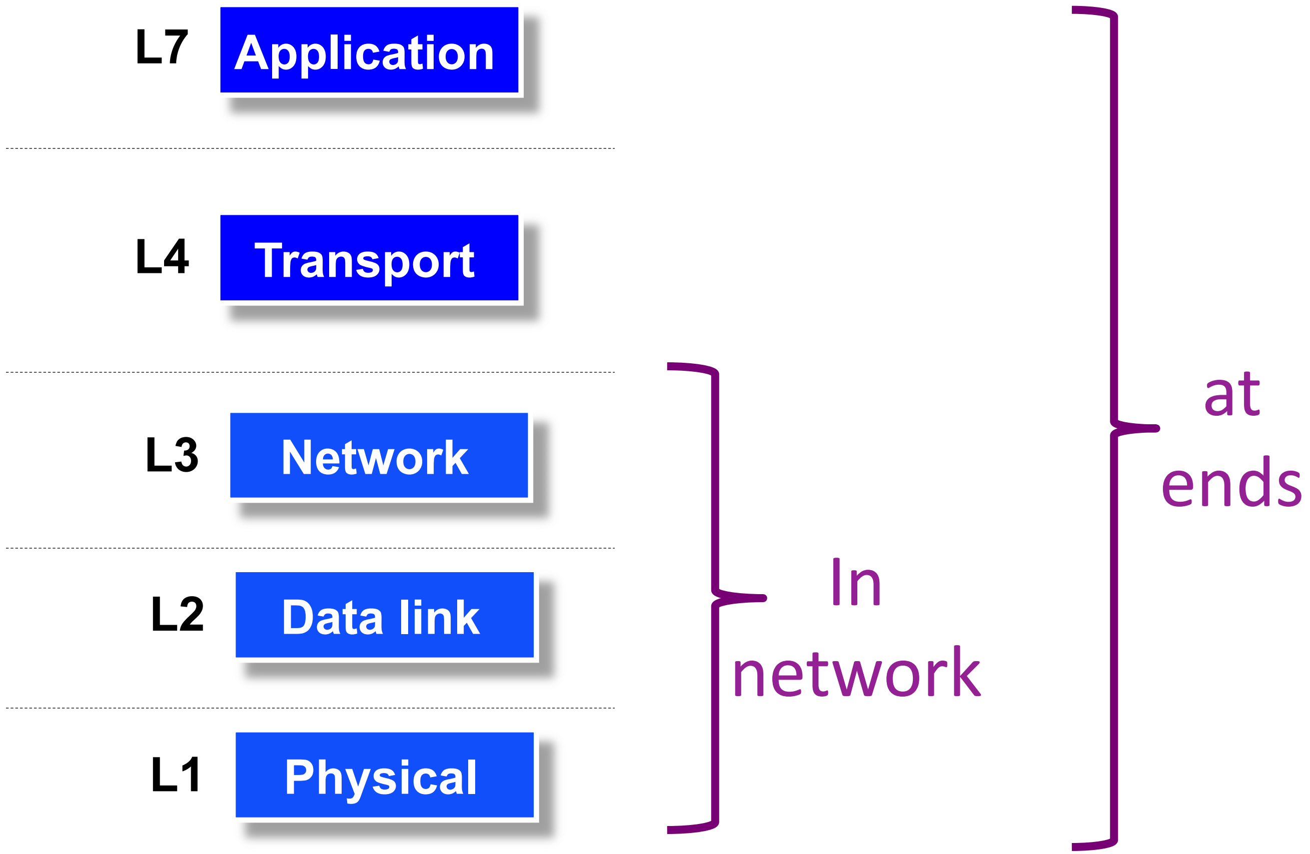


A side note: switches vs. routers

- 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



Why is *this* assignment of tasks good?

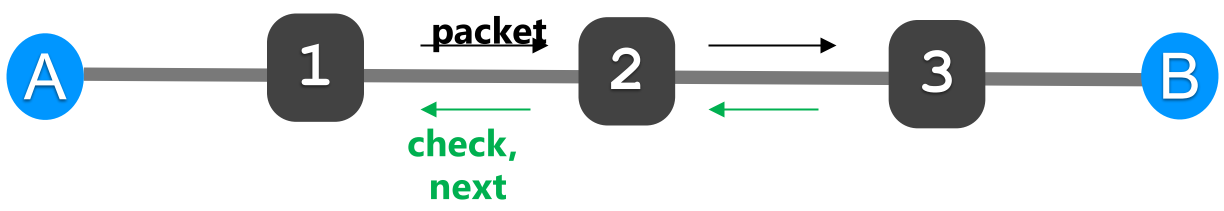
Architectural Wisdom

- David D. Clark
  - Chief protocol architect for the Internet in the 80s
- Co-authored two classics
  - "End-to-End Arguments in System Design" (1981)
  - "The Design Philosophy of the DARPA Internet Protocols" (1988)
- Articulates the rationale underlying the Internet's arch.

https://people.eecs.berkeley.edu/~sylvia/cs268-2019/

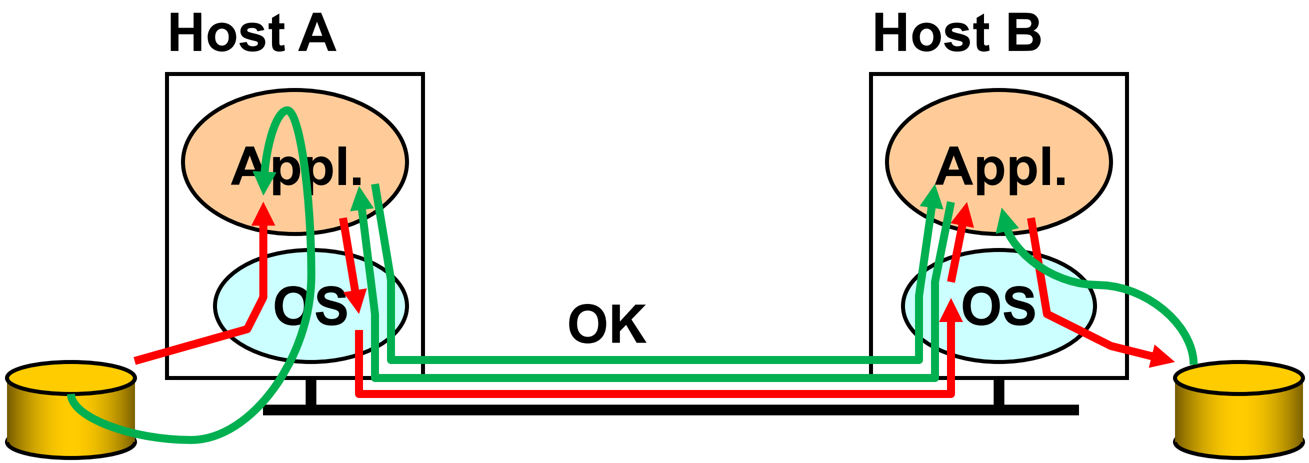
The End-to-End Principle

- Guides the debate about what functionality the network does or doesn't implement
- Today: should we implement reliability in the network?



What does it mean for the network to implement reliability?

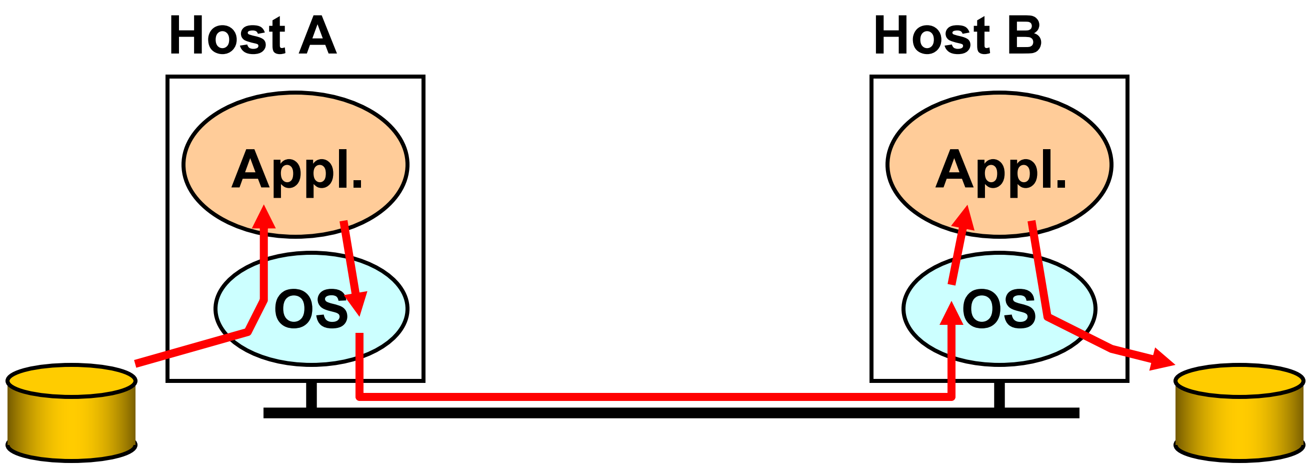
Example: Reliable File Transfer



- Solution 1: implement reliability at each step
  (→ network implements reliability)
- Solution 2: **end-to-end check** and retry
  (→ does not assume network is reliable)

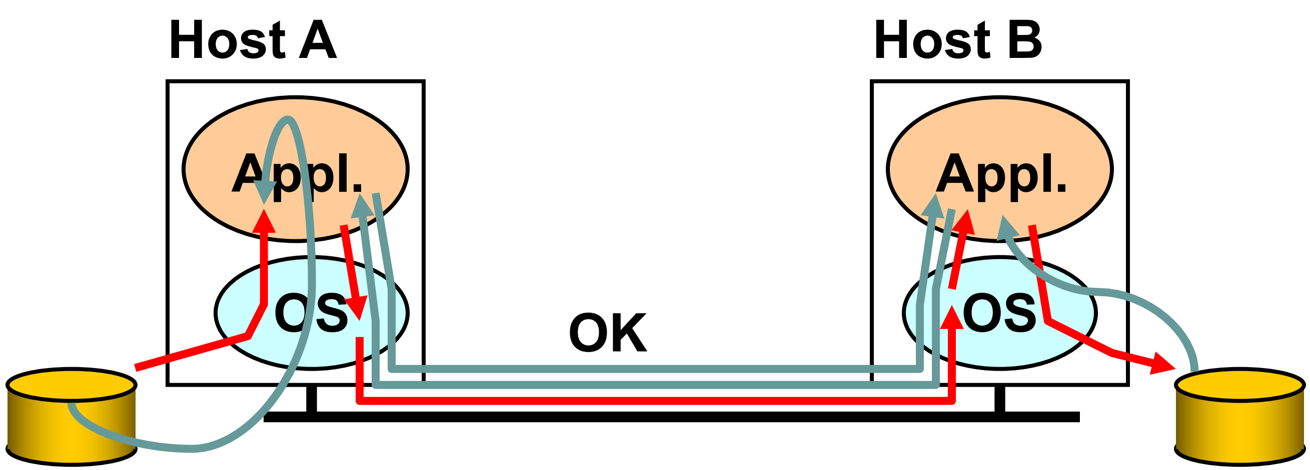
Correctness

- Solution 1 cannot be made perfectly reliable
  - What happens if a component fails between two steps?
  - What happens if a component has a bug?



Correctness

- Solution 1 cannot be made perfectly reliable
  - Receiver has to do the end-to-end check anyway
  - If not, the endpoints might be left in an incorrect state
- Solution 2 can also fail but will never leave the endpoints in an incorrect state
  - Host B will never accept a corrupted file



Impact of Network Failures

- Solution 1
  - Network failures/bugs impact endpoint *semantics*
  - Requires endpoints trust other elements!
- Solution 2
  - Endpoint semantics decoupled from network failure
  - Endpoint only relies on what it can control!

End-to-end argument: Intuition

- Some application requirements can only be correctly implemented **end-to-end**
  - reliability, security, *etc.*

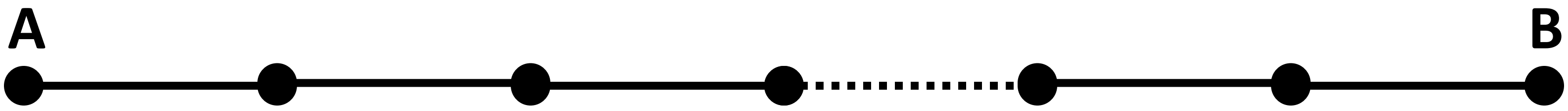
- End-systems
  - **Must** do so, for correctness
  - **Can** satisfy the requirement without network's help

- Implementing these functions in the network is unnecessary and adds complexity to the network

So...

- Should you ever implement reliability in network?
  - I.e., in <u>addition</u> to doing so in the hosts

Performance



- If each link drops packets 10% of the time, and we have 10 links, then E2E failure rate is ~65%
- What if the link implemented two retransmissions?
  - Per-link drop rate reduced to 0.1%, E2E error rate is ~1%

Performance

- Should you ever implement reliability in network?
  - I.e., in addition to doing so in the hosts
- Perhaps, as a performance optimization
  - Need for it must be evaluated on a case-by-case basis

Recap: End-to-End Principle

Implementing this function (reliability) in the network:

- Doesn’t reduce host implementation complexity
- Does increase network complexity
- Imposes overhead on <u>all</u> applications
- However, implementing in network *can* enhance performance in some cases
  - E.g., very lossy link

The end-to-end argument in Clark's words

"The function in question can completely and correctly be implemented only with the knowledge and help of the application at the end points. Therefore, providing that function as a feature of the communication system itself is not possible. (Sometimes an incomplete version of the function provided by the communication system may be useful as a performance enhancement.)"

Recap: architectual wisdom (the ”how")

- How to decompose system into modules?
  - Layering
- Where are layers implemented?
  - End hosts implement all layers (L1-L7)
  - Network implements only layers (L1-L3)
- One unifying protocol at the network layer
  - Internet Protocol (IP)

Recap: architectural wisdom (the "why")

- **Layering** provided a clean separation of concerns
  - And hence enabled innovation!
- **End-to-end principle** kept unnecessary state and functionality out of the network
  - And hence allowed the Internet to scale!

Questions?