Statistical Multiplexing; Layered Network Architecture; End-to-end Arguments

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http://zoo.cs.yale.edu/classes/cs433/

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Outline

- Admin. and recap
- A taxonomy of communication networks
- Layered network architecture

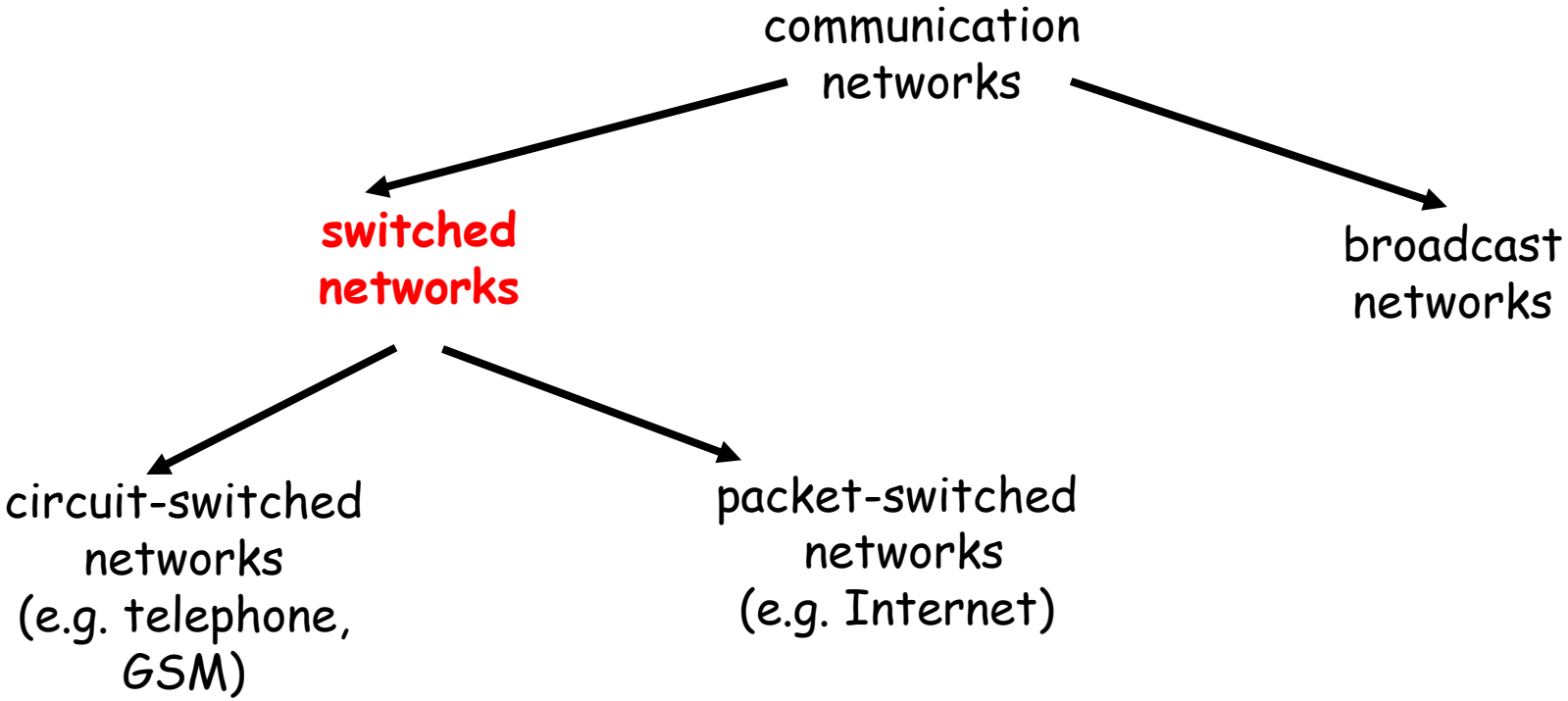
Admin.

- Readings from the textbook and additional suggested readings
  - All are highly recommended
  - Some are marked as required

- Assignment one is linked on the schedule page
  - Due Sept. 14, in class
  - if you type it in, you can upload to canvas

Recap: A Taxonomy of Comm. Networks

- Basic question: how are data (the bits) transferred through communication networks?



Recap: Circuit Switching vs. Packet Switching

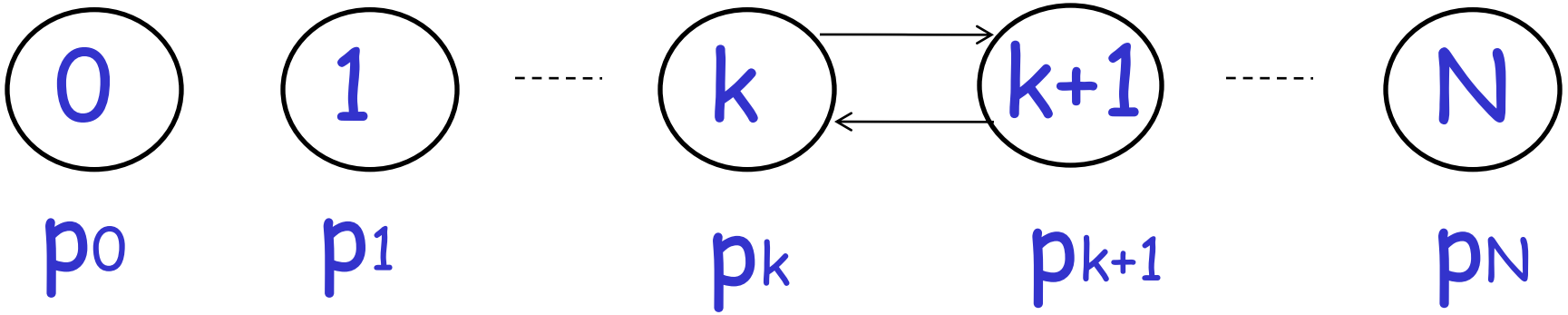
	circuit switching	packet switching
resource usage	use a single partition bandwidth	use whole link bandwidth
reservation/setup	need reservation (setup delay)	no reservation
resource contention	busy signal (session loss)	congestion (long delay and packet losses)
charging	time	packet
header	no per-pkt header	per packet header
fast path processing	fast	per packet processing

Recap: Queueing Theory

- Model system state
- Introduce state transition diagram
- Focus on equilibrium: state trend neither growing nor shrinking

Recap: Queueing Theory Analysis of Circuit-Switching

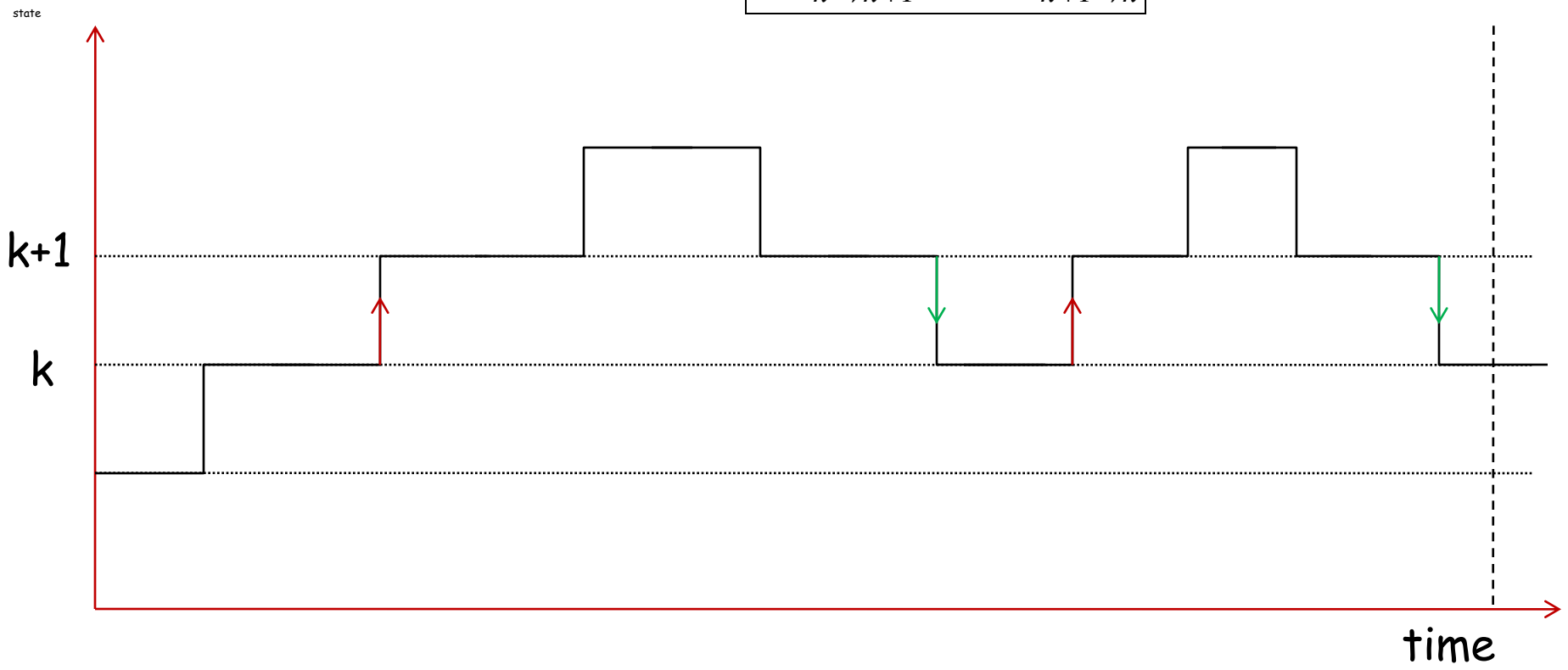
system state: # of busy lines



Equilibrium = Time Reversibility

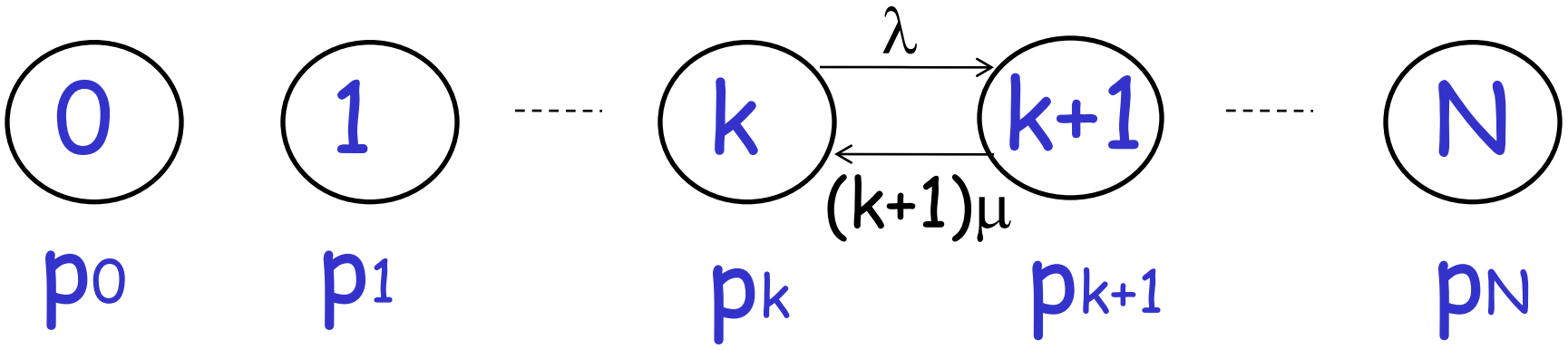
- Cannot distinguish $\#f_{k\to k+1}, \quad \#f_{k+1\to k}$

$\#b_{k\to k+1}, \quad \#b_{k+1\to k}$



Recap: Queueing Theory
Analysis of Circuit-Switching

system state: # of busy lines



at equilibrium (time reversibility) in one unit time:

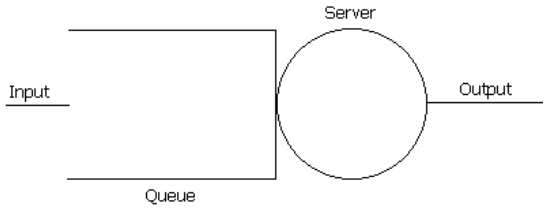
#(transitions k → k+1) = #(transitions k+1 → k)

$$p_k \lambda = p_{k+1}(k+1)\mu$$

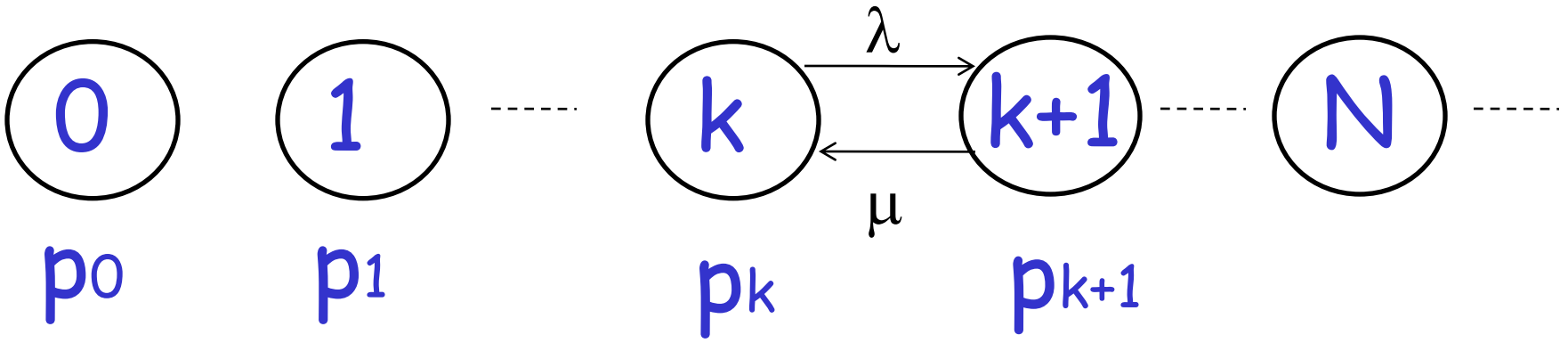
$$p_{k+1} = \frac{1}{k+1}\frac{\lambda}{\mu} p_k = \frac{1}{(k+1)!}\left(\frac{\lambda}{\mu}\right)^{k+1} p_0$$

$$p_0 = \frac{1}{1 + \frac{1}{1!}\frac{\lambda}{\mu} + \frac{1}{2!}\left(\frac{\lambda}{\mu}\right)^2 + \ldots + \frac{1}{N!}\left(\frac{\lambda}{\mu}\right)^N}$$

Recap: Queueing Theory Analysis of Packet Switching



system state: #packets in queue



at equilibrium (time reversibility) in one unit time:

#(transitions k → k+1) = #(transitions k+1 → k)

$$p_k \lambda = p_{k+1} \mu$$

$$p_{k+1} = \frac{\lambda}{\mu} p_k = \left(\frac{\lambda}{\mu}\right)^{k+1} p_0 = \rho^{k+1} p_0$$

$$p_0 = 1 - \rho$$

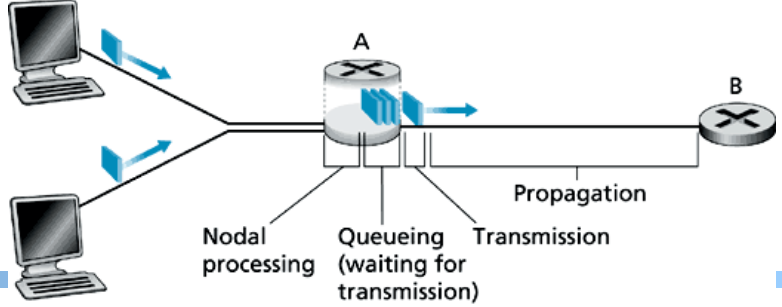
$$\rho = \frac{\lambda}{\mu}$$

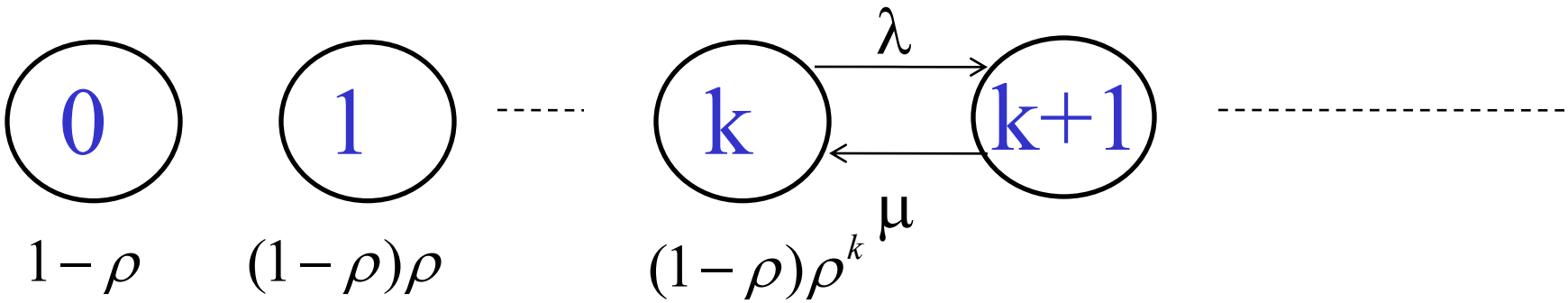
Example

- Assume requests (packets) come in at a rate of one request per 50 ms
- Each request (packet) takes on average 20 ms

- What is the fraction of time that the system is empty?
- What is the chance that a packet newly arrived needs to wait for 3 early packets?

Analysis of Delay (cont')





- Average queueing delay:
- Transmission delay:
- Queueing + transmission:

Delay

$$\rho = \frac{\lambda}{\mu}$$

$$S = \frac{1}{\mu}$$

$$\text{average queueing delay: } w = S\frac{\rho}{1-\rho}$$

$$queueing + trans = S\frac{\rho}{1-\rho} + S = S\frac{1}{1-\rho}$$

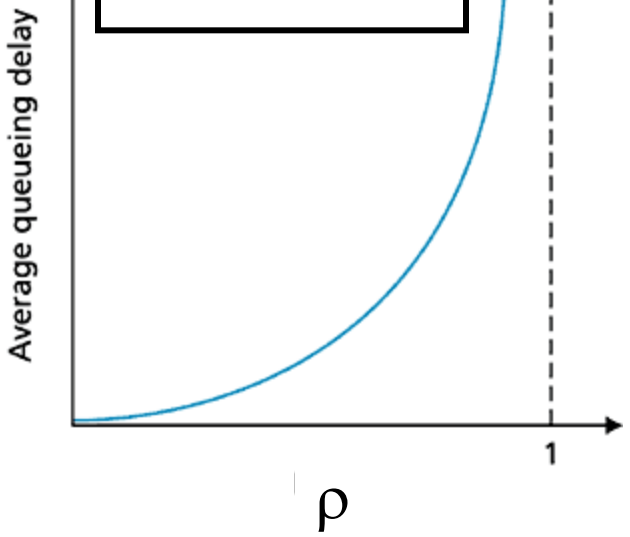
For a demo of M/M/1, see:
http://www.dcs.ed.ac.uk/home/jeh/Simjava/queueing/mm1_q/mm1_q.html

Queueing Delay as a Function of Utilization

Assume:
R = link bandwidth (bps)
L = packet length (bits)
S = L / R
a = average packet arrival rate (pkt/sec)

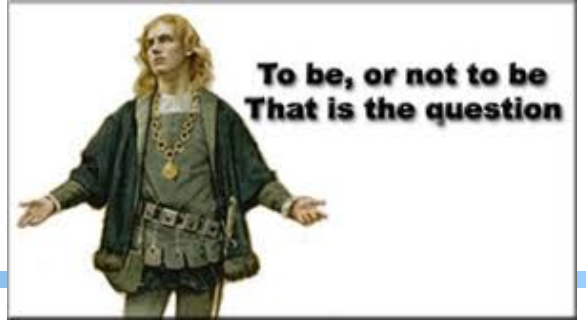
$$utilization: \ \rho = \frac{a}{1/S} = aS$$

$$w = S\frac{\rho}{1-\rho}$$



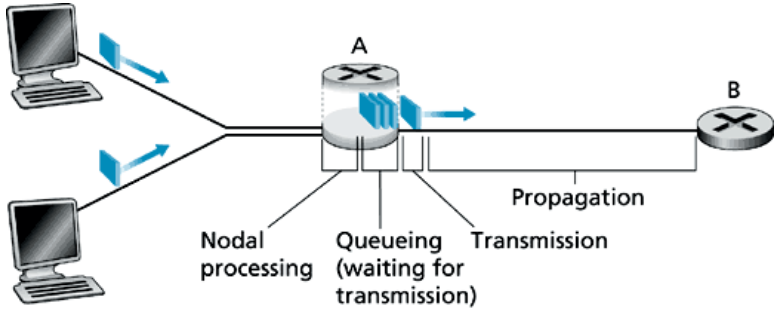
- ρ ~ 0: average queueing delay small
- ρ -> 1: delay becomes large
- ρ > 1: more "work" arriving than can be serviced, average delay infinite !

Statistical Multiplexing



A simple model to compare bandwidth efficiency of
- reservation/dedication (aka circuit-switching) vs
- no reservation (aka packet switching)

setup
- a single bottleneck link w/ u
- n flows; each flow has an arrival rate of a/n



- no reservation: all arrivals into the single link, the queueing delay + transmission delay:

$$S\frac{1}{1-\rho}$$

- reservation: each flow uses its own reserved (sub)link with rate u/n, the queueing delay + transmission delay:

$$n\,S\frac{1}{1-\rho}$$

Summary: Packet Switching vs. Circuit Switching

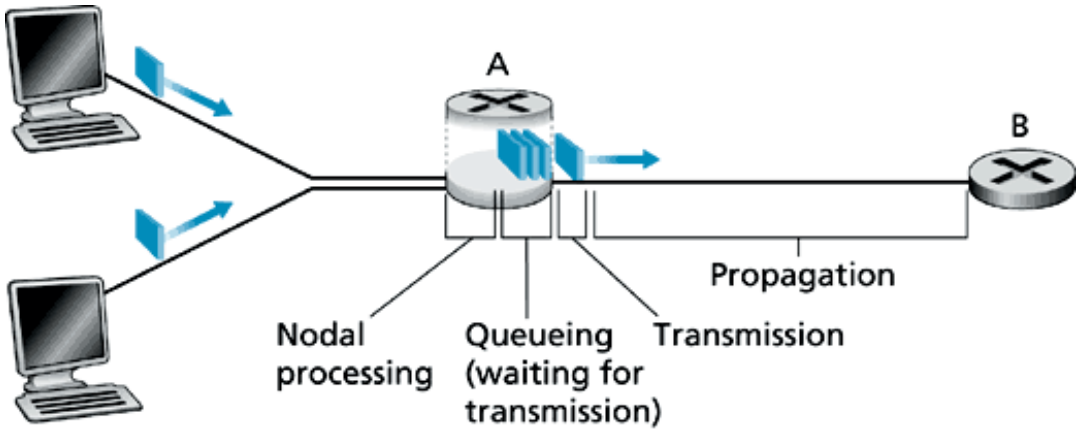
- Advantages of packet switching over circuit switching
  - most important advantage of packet-switching over circuit switching is statistical multiplexing, and therefore more efficient bandwidth usage
- Disadvantages of packet switching
  - potential congestion: packet delay and high loss
    - protocols needed for reliable data transfer, congestion control
    - it is possible to guarantee quality of service (QoS) in packet-switched networks and still gain statistical multiplexig, but it adds much complexity
  - packet header overhead
  - per packet processing overhead

Outline

- Admin. and recap
- *A taxonomy of communication networks*
  - circuit switched networks
  - packet switched networks
  - circuit switching vs. packet switching
  - *datagram and virtual circuit packet switched networks*

A Taxonomy of Packet-Switched Networks According to Routing

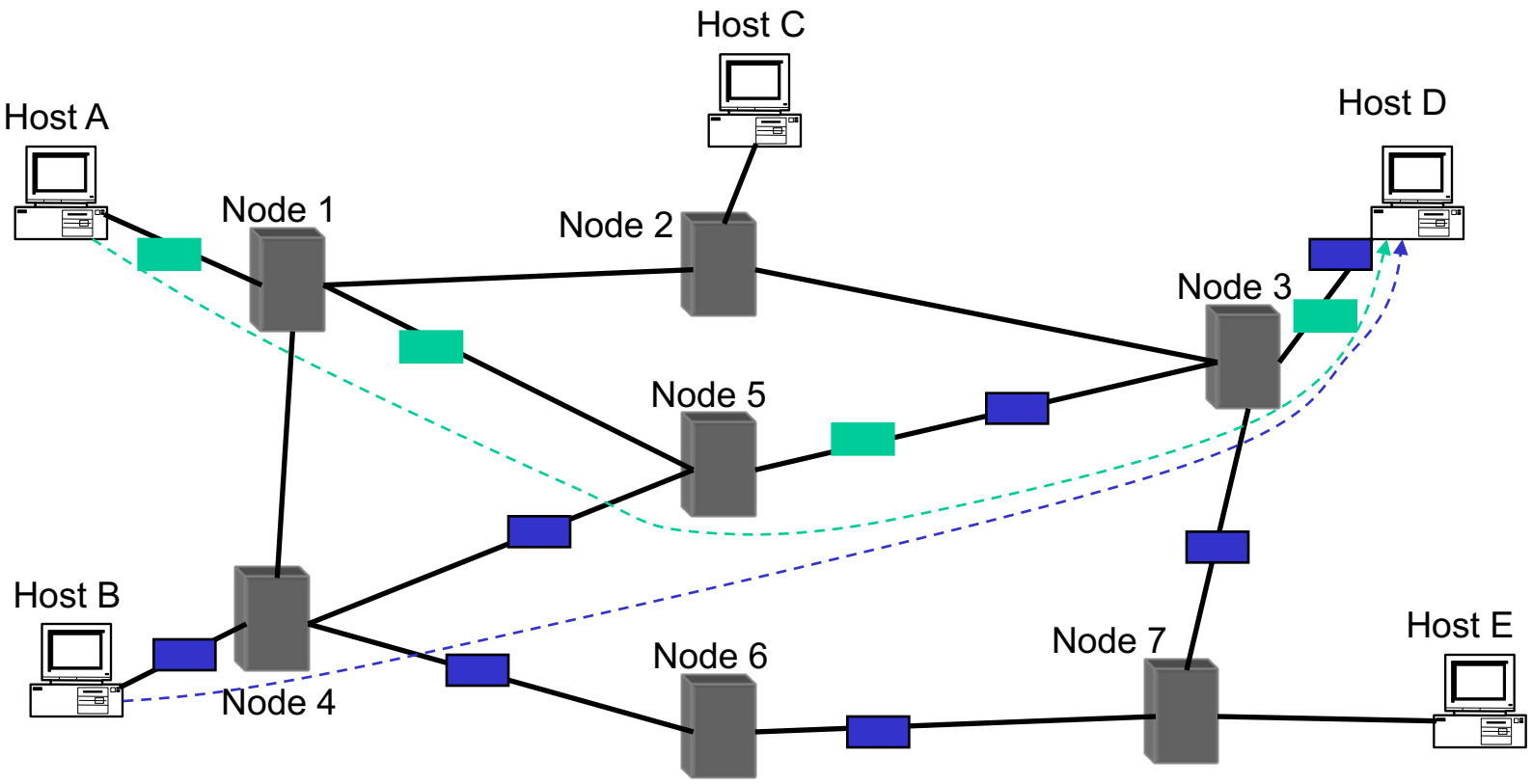
- Two types of packet switching
  - datagram network
    - each packet of a flow is switched **independently**
  - virtual circuit network:
    - all packets from one flow are sent along a **pre-established** path (= virtual circuit)



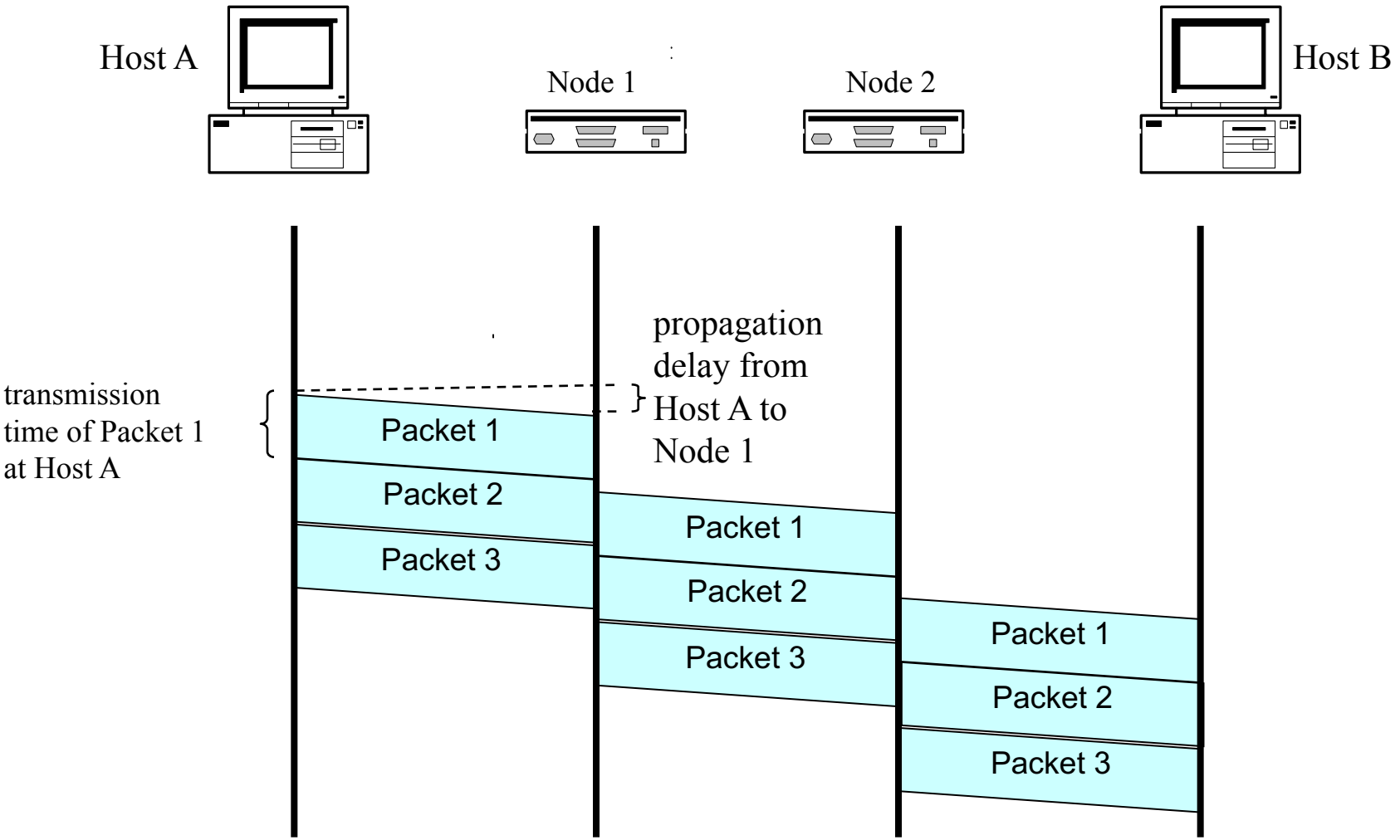
Datagram Packet Switching

- Commonly when we say packet switching we mean datagram switching
- Example: IP networks
- Each packet is independently switched
  - each packet header contains *complete destination address*
  - receiving a packet, a router looks at the packet's destination address and *searches* its current routing table to determine the possible next hops, and pick one
- Analogy: postal mail system

Datagram Packet Switching



Timing Diagram of Datagram Switching



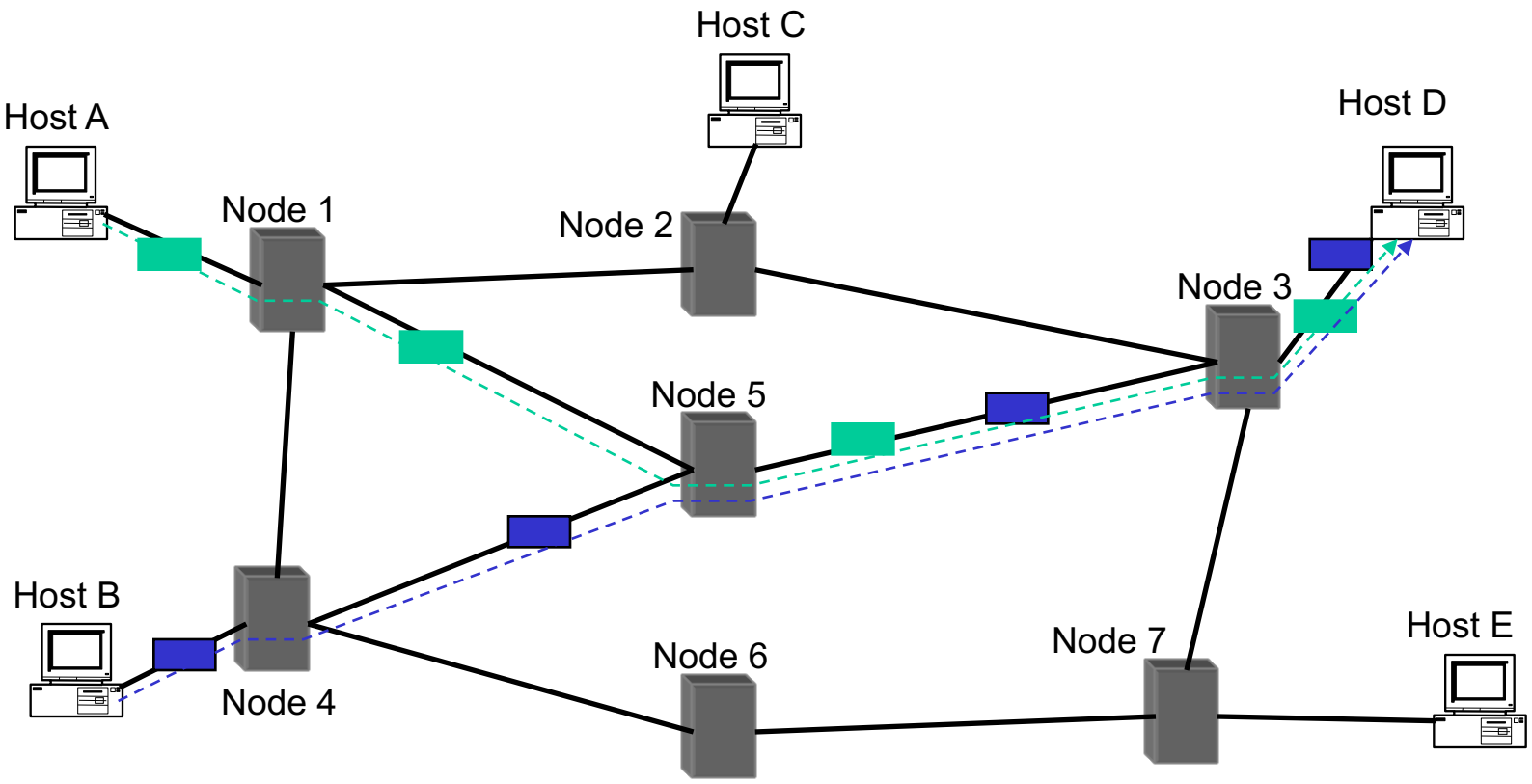
Virtual-Circuit Packet Switching

- Example: Multiple Label Packet Switching (MPLS) in IP networks

- Hybrid of circuit switching and datagram switching
  - fixed path determined at *virtual circuit setup time*, remains fixed thru flow
  - Implementation:
    1. each packet carries a short local, tag (virtual-circuit (VC) #); tag determines next hop

Incoming VC#	Outgoing Interface	QoS
12	2	
16	3	
20	3	
…		

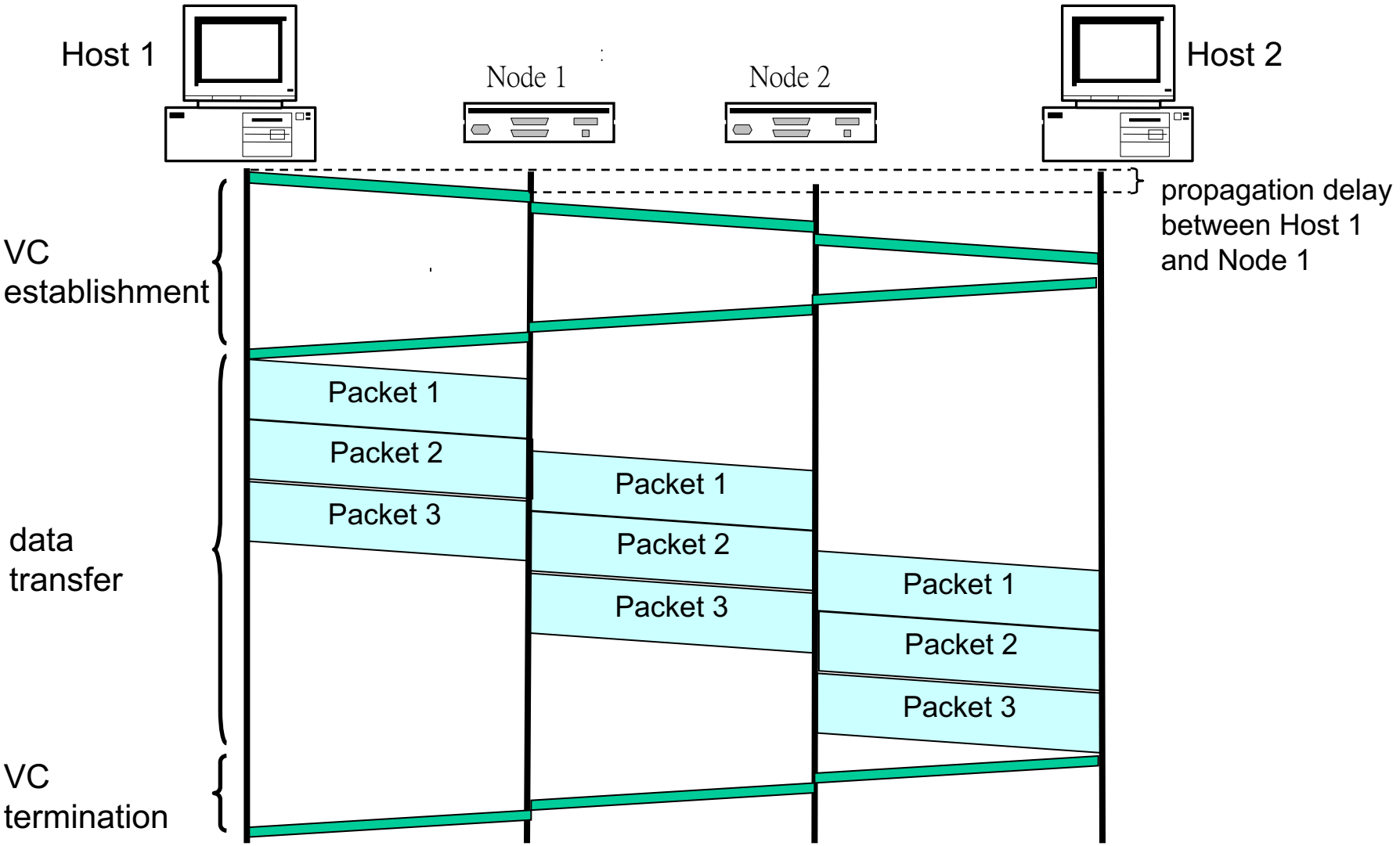
Virtual-Circuit Switching



Virtual-Circuit Packet Switching

- Three phases
  1. VC establishment
  2. Data transfer
  3. VC disconnect

Timing Diagram of Virtual-Circuit Switching

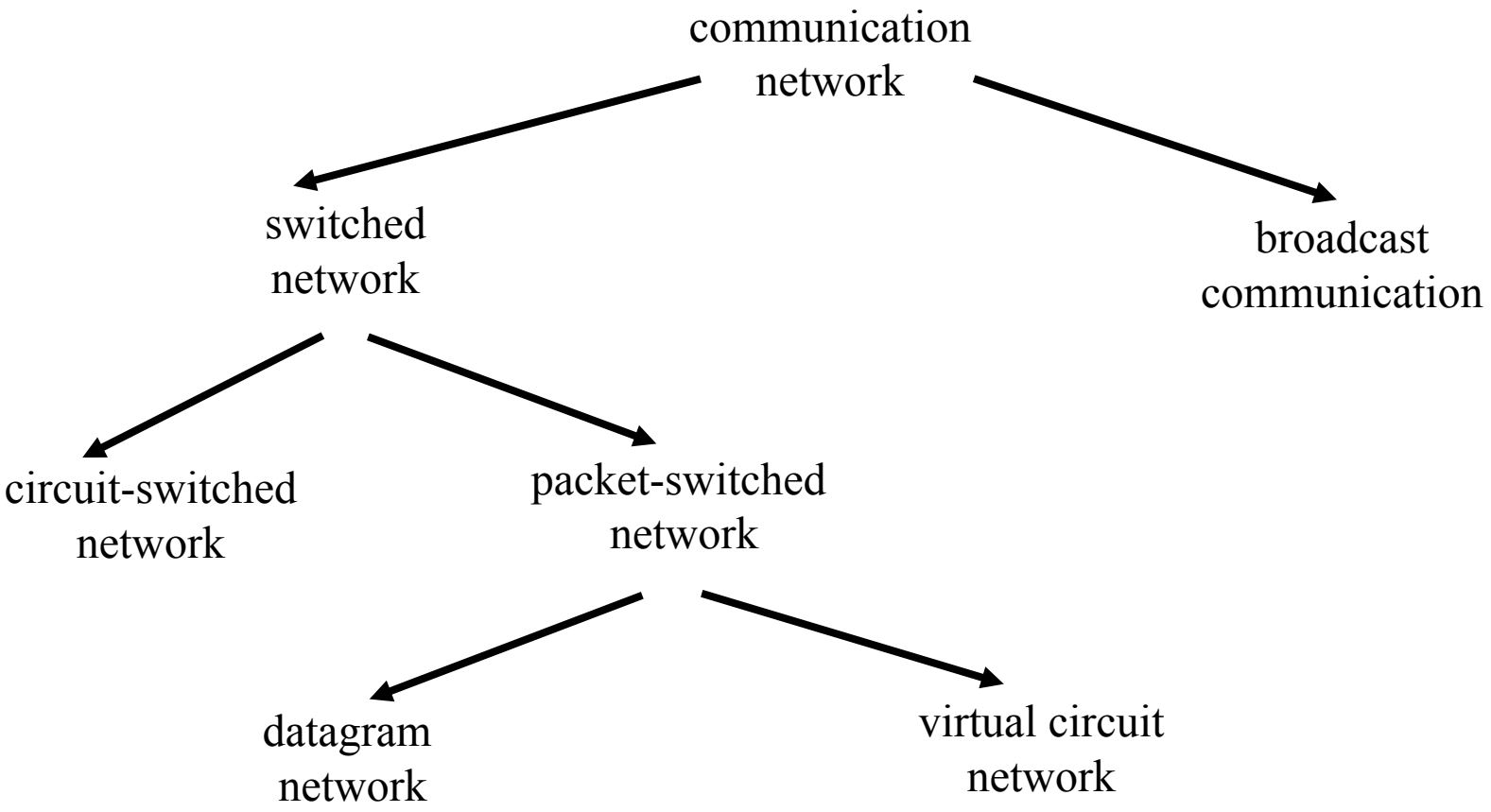


Discussion: Datagram Switching vs. Virtual Circuit Switching

- What are the benefits of datagram switching over virtual circuit switching?

- What are the benefits of virtual circuit switching over datagram switching?

Summary of the Taxonomy of Communication Networks



Summary of Progress

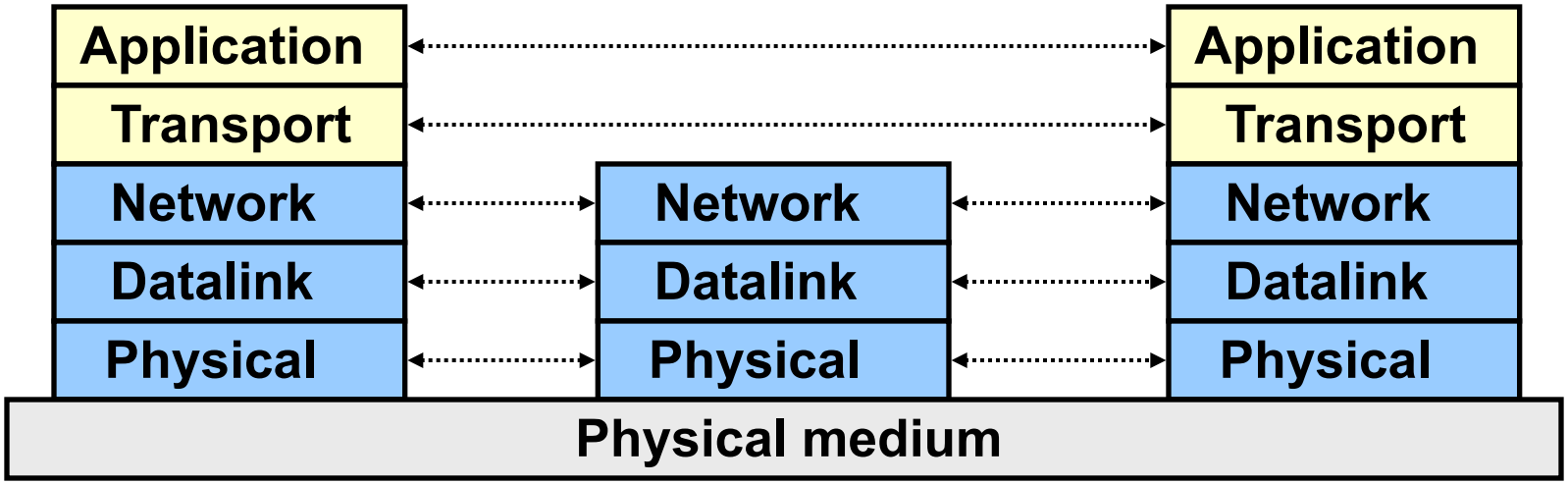
- We have seen the hardware infrastructure, the basic communication scheme, a next key question is how to develop the software system.

Outline

- Admin. and recap
- A taxonomy of communication networks
- Layered network architecture
  - *what is layering?*
  - why layering?
  - how to determine the layers?
  - ISO/OSI layering and Internet layering

What is Layering?

- A technique to organize a networked system into a succession of logically distinct entities, such that the service provided by one entity is solely based on the service provided by the previous (lower level) entity.



Outline

- Admin. and recap
- A taxonomy of communication networks
- Layered network architecture
  - what is layering?
  - *why layering?*

Why Layering?

Networks are complex !

- many "pieces":
  - hardware
    - hosts
    - routers
    - links of various media
  - software
    - applications
    - infrastructure

Dealing with complex systems:

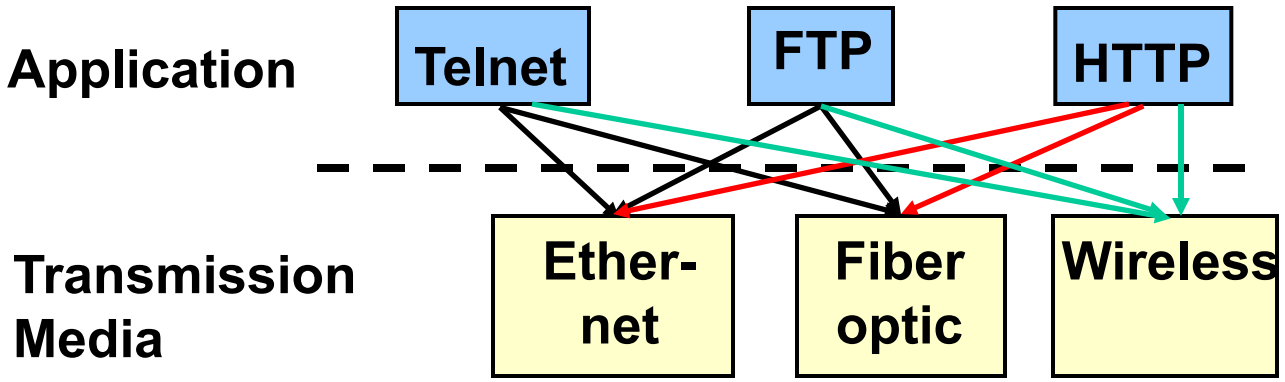
explicit structure allows identification of the relationship among a complex system's pieces

- layered reference model for discussion

Modularization eases maintenance, updating of system:

- change of implementation of a layer's service transparent to rest of system, e.g., changes in routing protocol doesn't affect rest of system

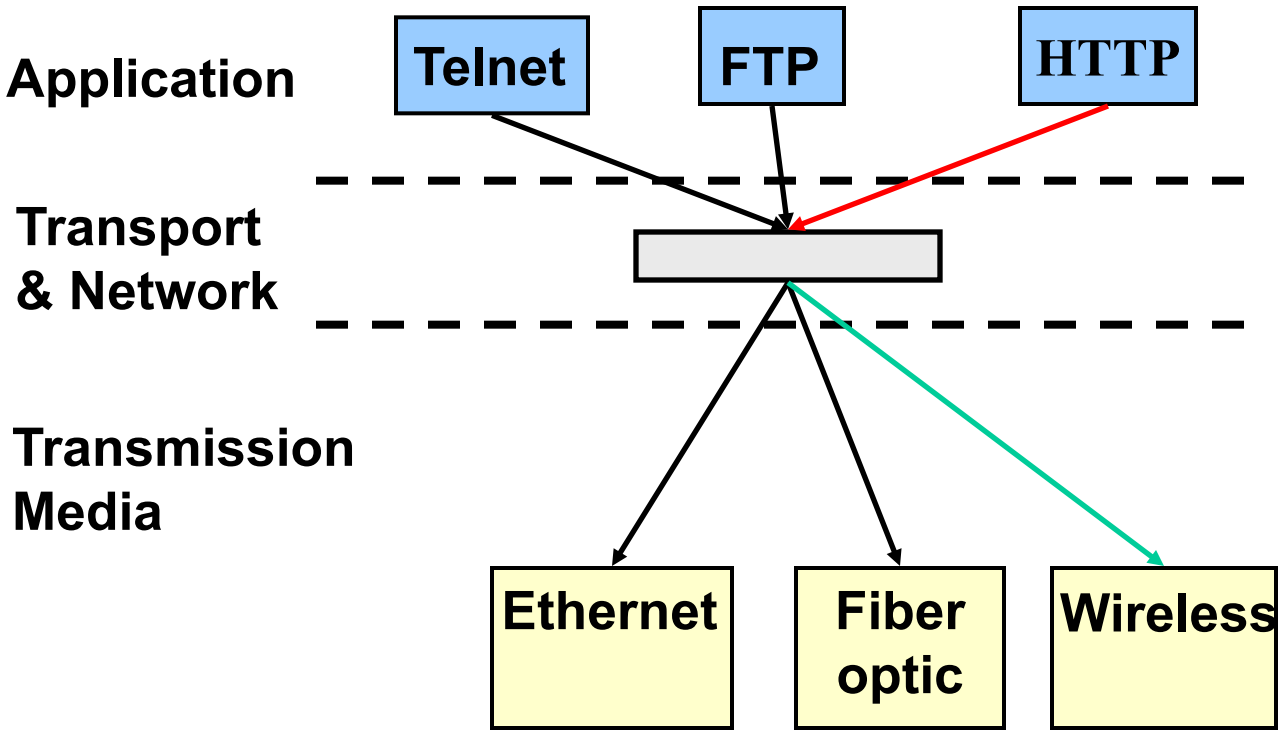
An Example: No Layering



- No layering: each new application has to be re-implemented for every network technology !

An Example: Benefit of Layering

- Introducing an intermediate layer provides a common abstraction for network technologies

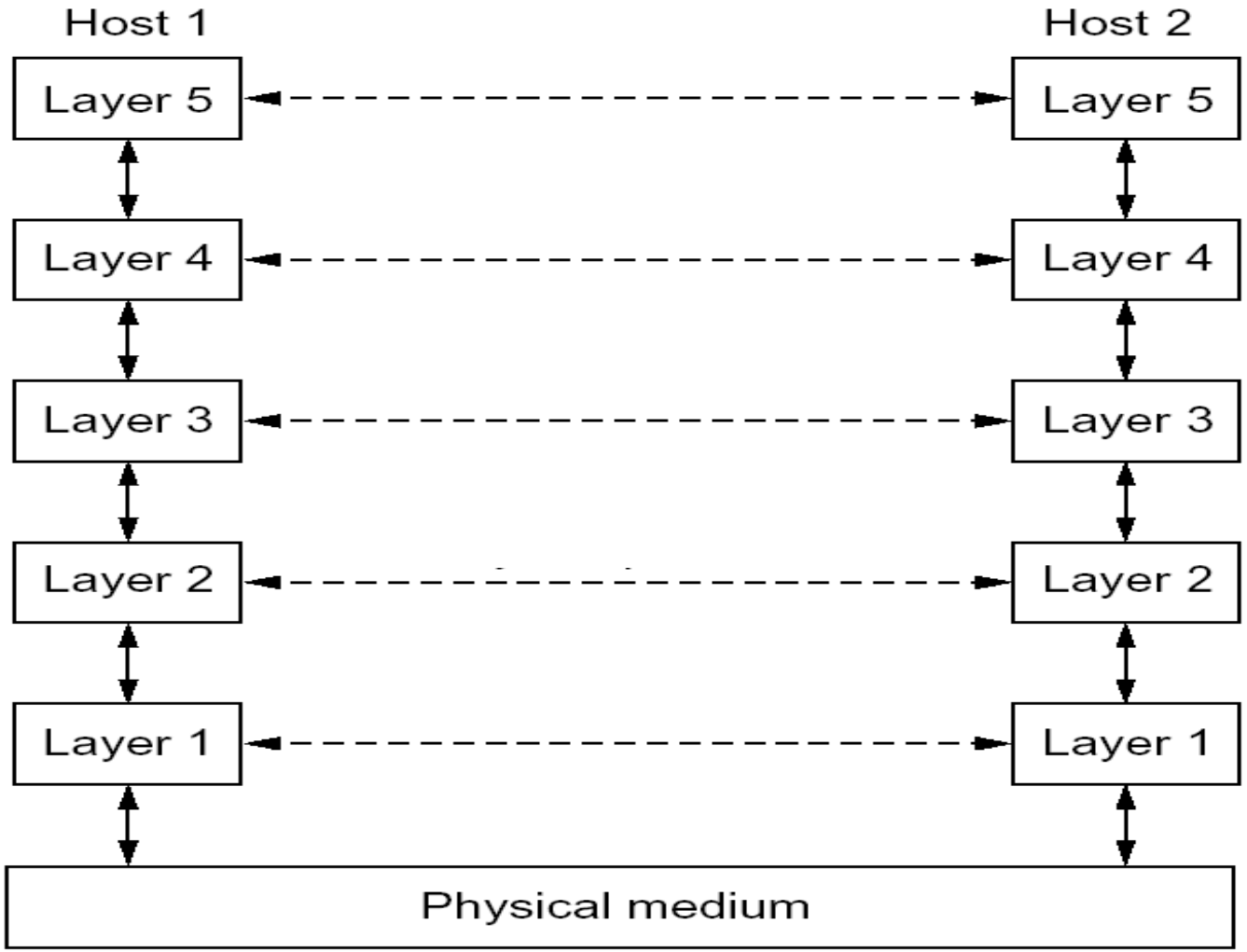


ISO/OSI Concepts

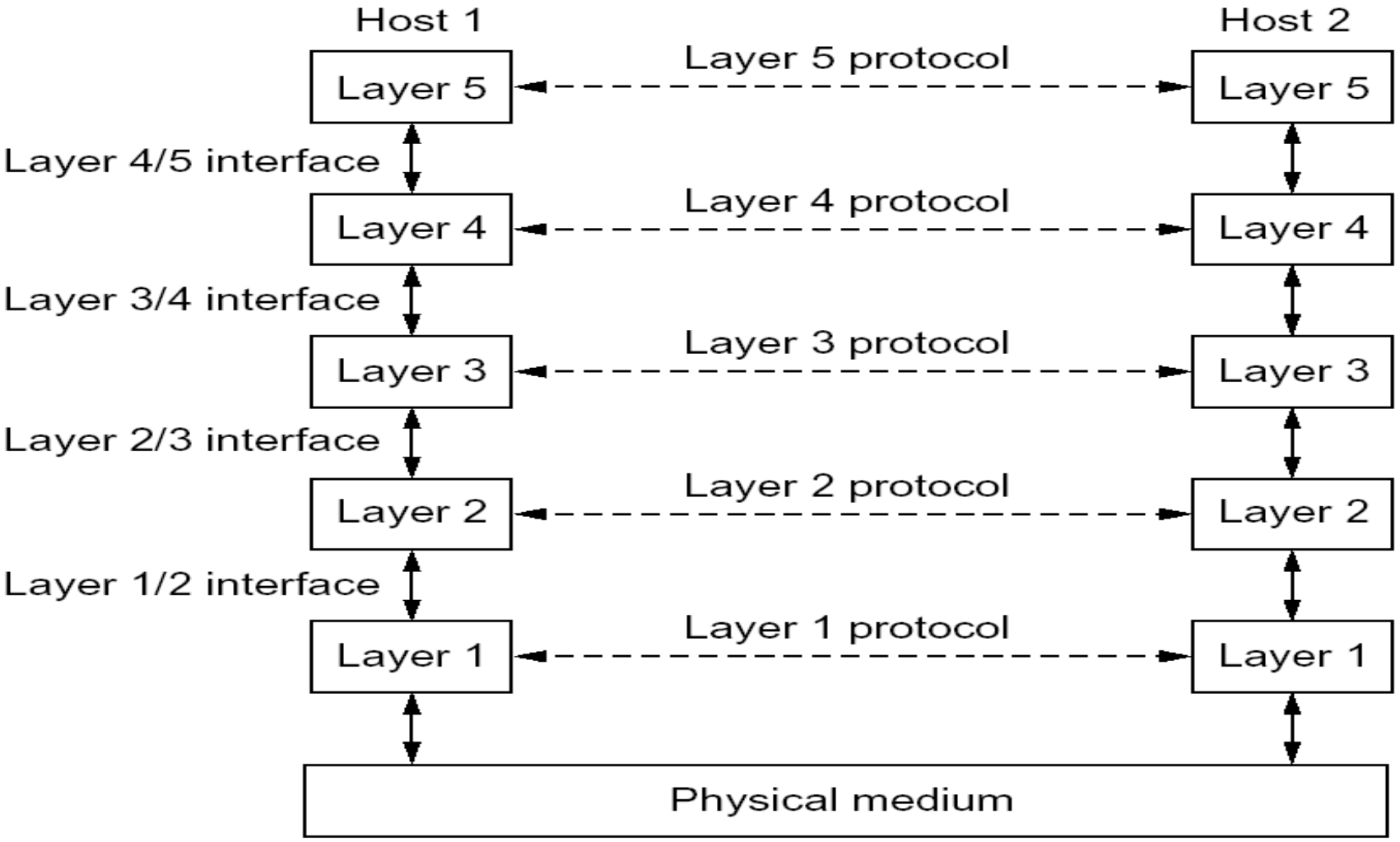
- ISO – International Standard Organization
- OSI – Open System Interconnection

- Service – says what a layer does
- Interface – says how to access the service
- Protocol – specifies how the service is implemented
  - a set of rules and formats that govern the communications between two or more peers

An Example of Layering



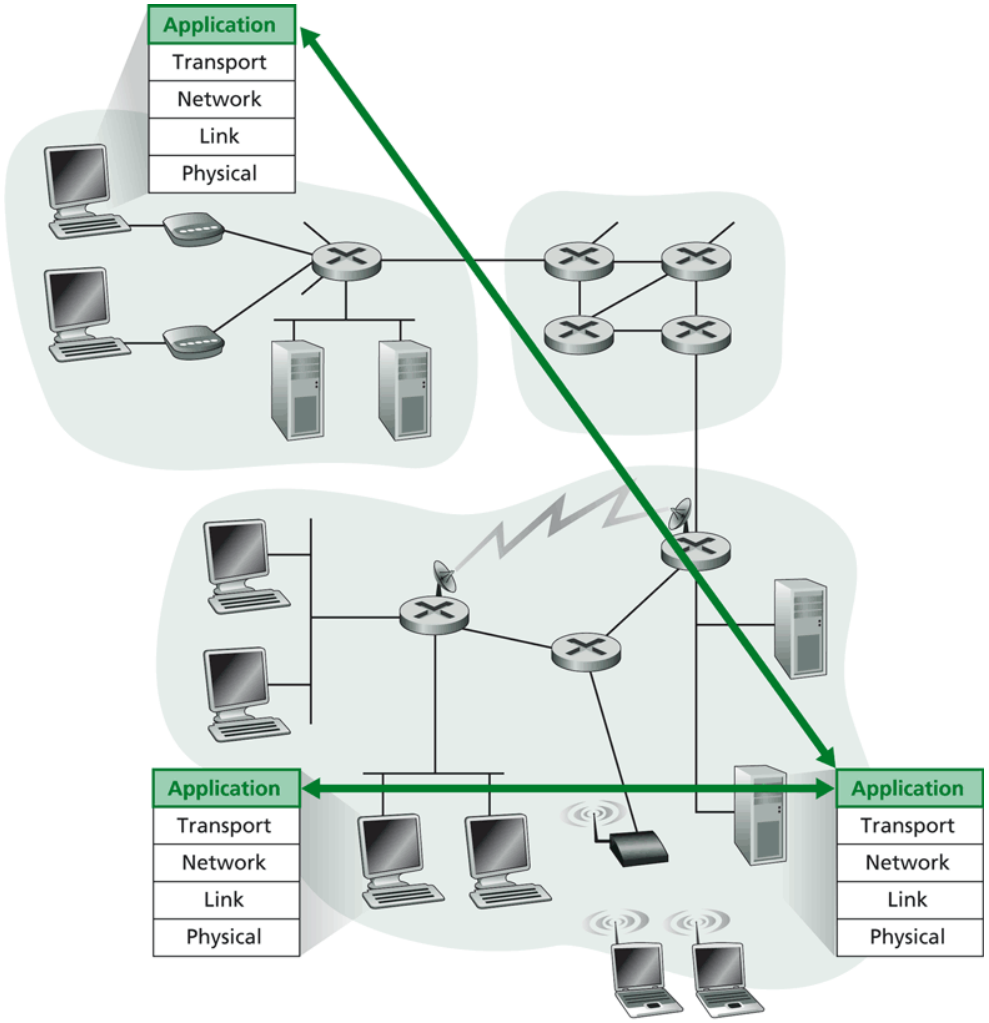
An Example of Layering



Layering -> *Logical* Communication

E.g.: application

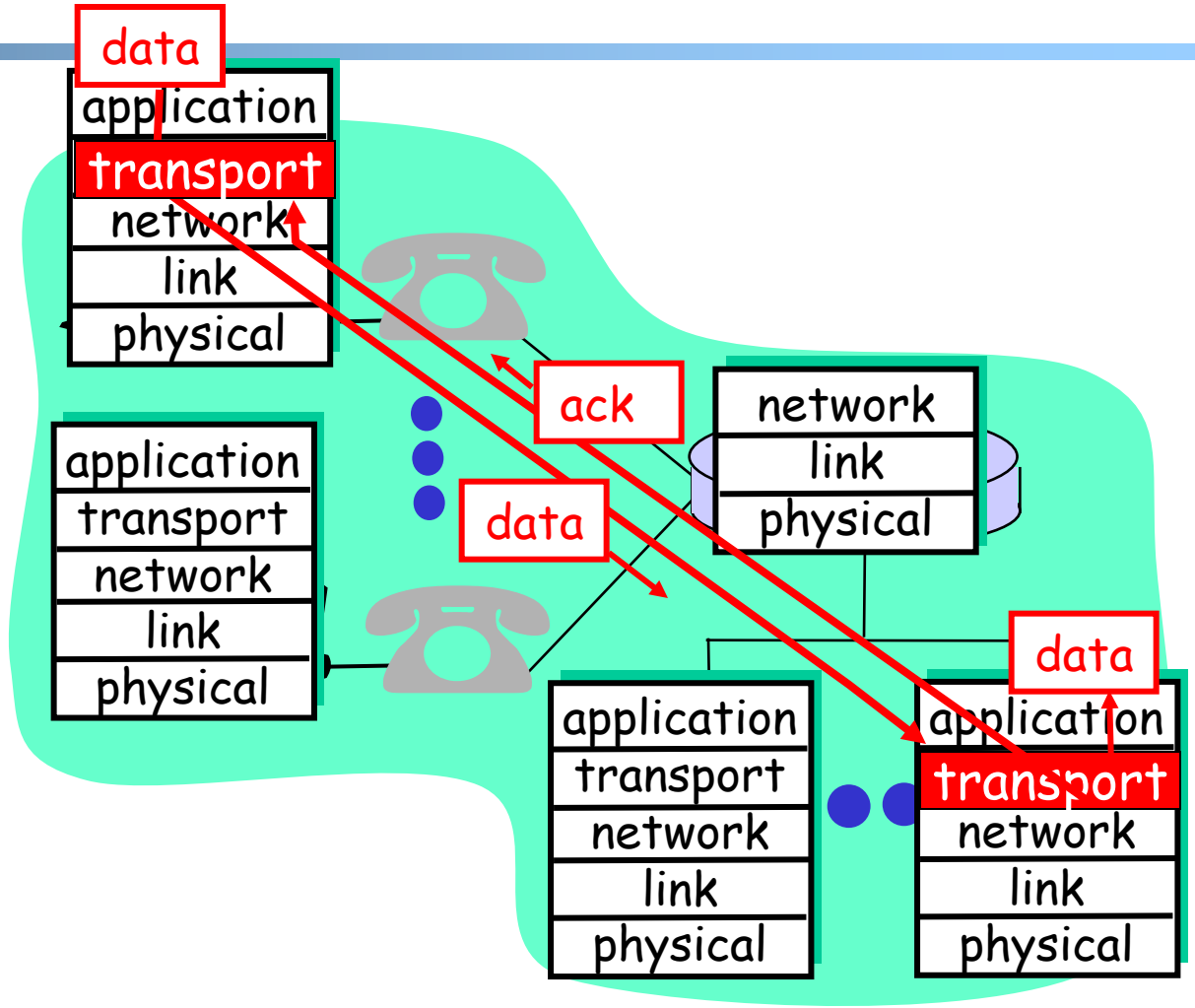
- provide services to users
- application protocol:
  - send messages to peer
  - for example, HELO, MAIL FROM, RCPT TO are messages between two SMTP peers



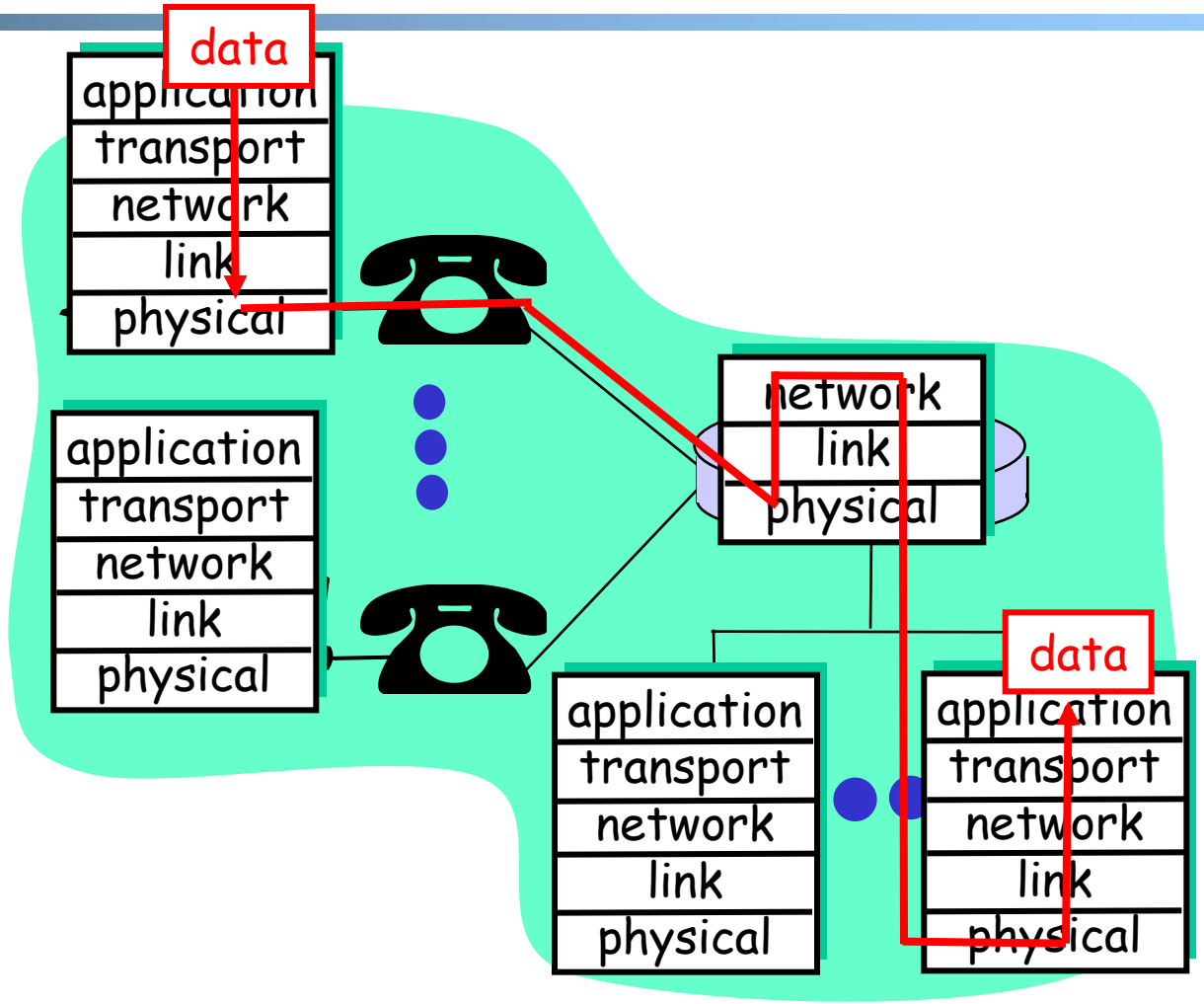
Layering: *Logical* Communication

E.g.: transport

- Trans. msg for app
- Transport protocol
  - add control info to form "datagram"
  - send datagram to peer
  - wait for peer to ack receipt; if no ack, retransmit



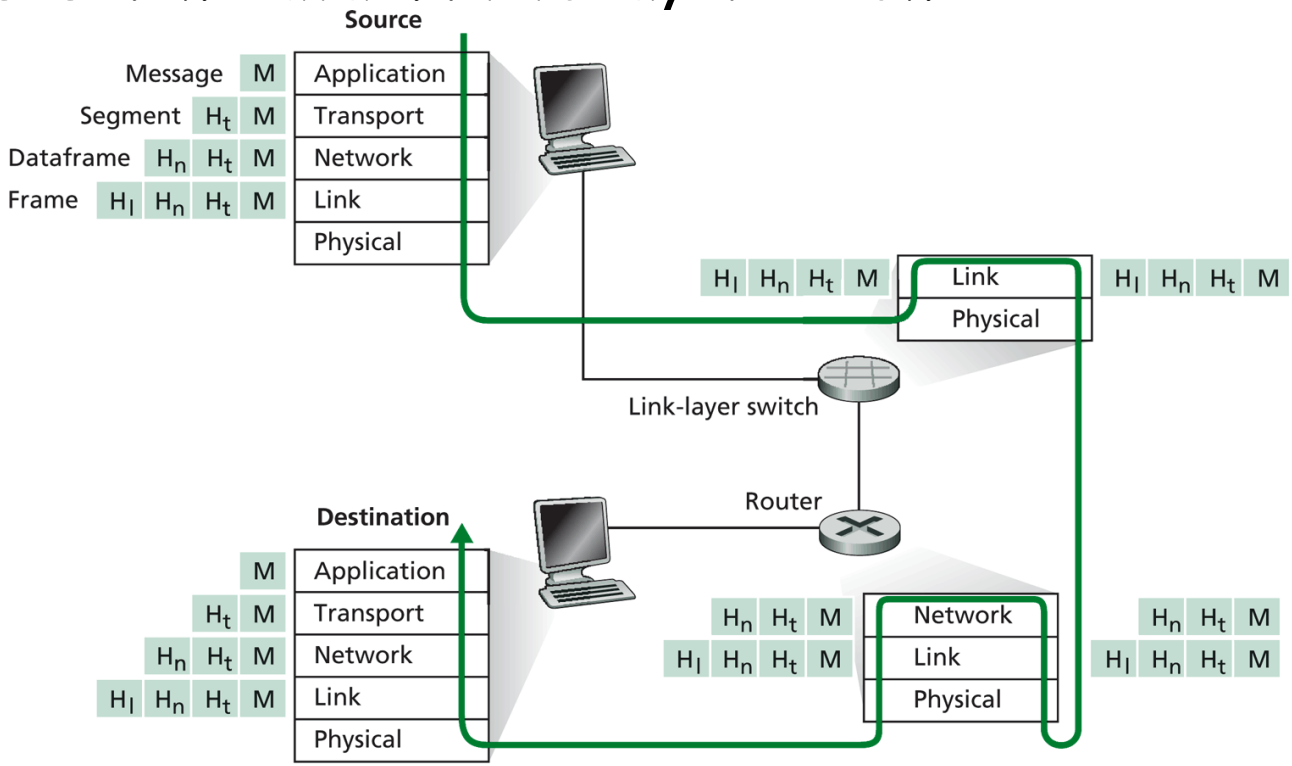
Layering: *Physical* Communication



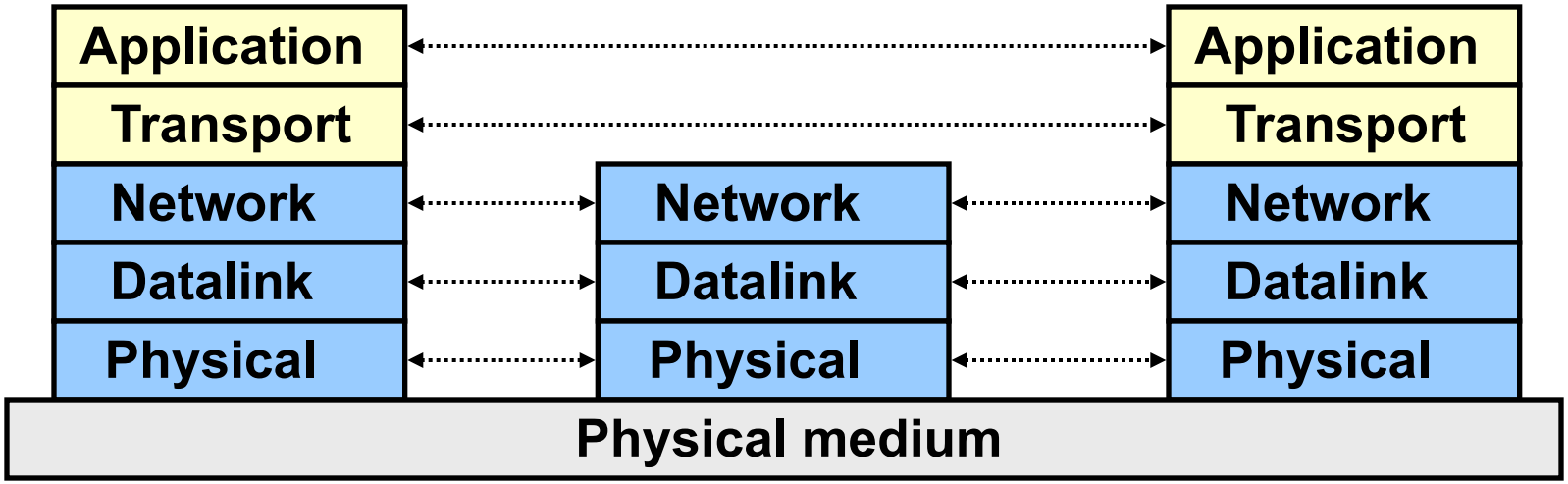
Protocol Layering and Meta Data

Each layer takes data from above

- adds header (meta) information to its peer to create new data unit
- passes new data unit to layer below



Packet as a Stack in a Layered Architecture



Key design issue:

How do you *divide* functionalities among the layers?

Outline

- Review
- A taxonomy of communication networks
- Layered network architecture
  - what is layering?
  - why layering?
  - *how to determine the layers?*

The End-to-End Arguments

The function in question can completely and correctly be implemented only with the knowledge and help of the application standing at the endpoints of the communication systems. Therefore, providing that questioned function as a feature of the communications systems itself is not possible.

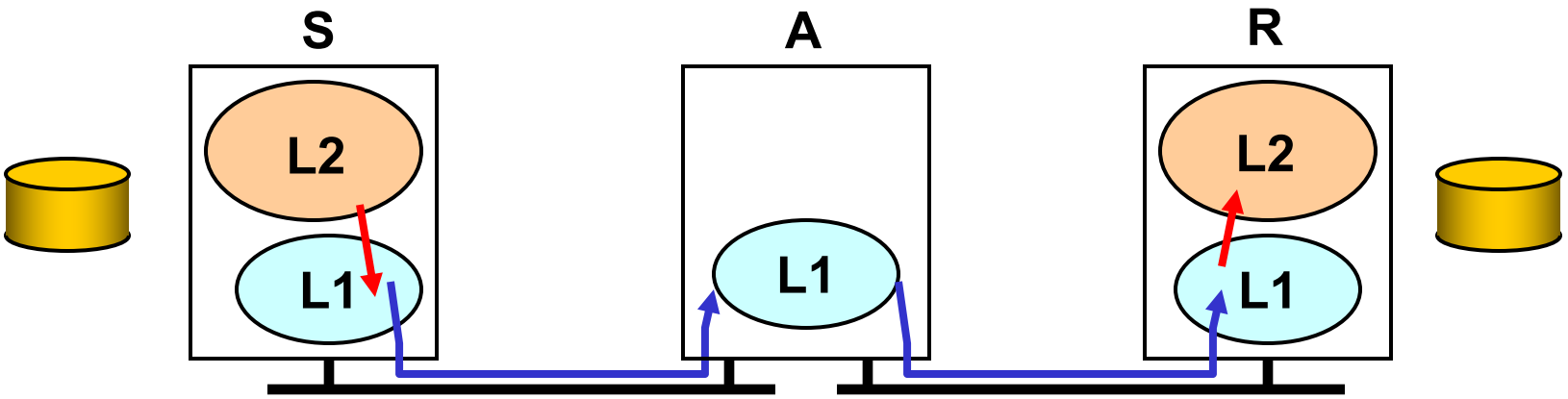
J. Saltzer, D. Reed, and D. Clark, 1984

What does the End-to-End Arguments Mean?

- The application knows the requirements best, place functionalities as high in the layer as possible

- Think twice before implementing a functionality at a lower layer, even when you believe it will be useful to an application

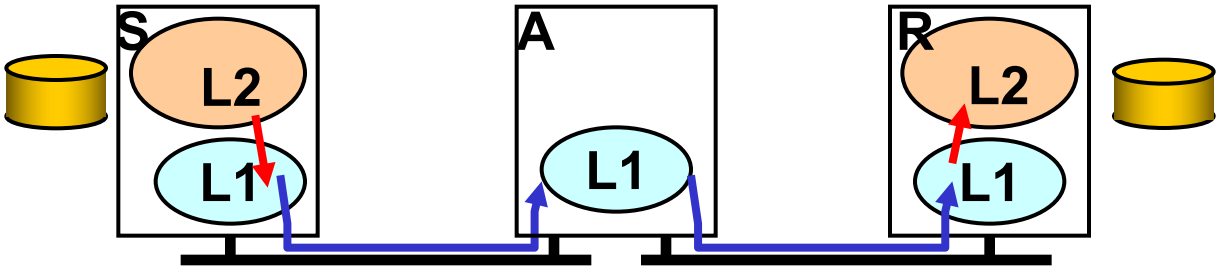
Example: Where to Provide Reliability ?



- Solution 1: the network (lower layer L1) provides reliability, i.e., each hop provides reliability
- Solution 2: the end host (higher layer L2) provides reliability, i.e., end-to-end check and retry

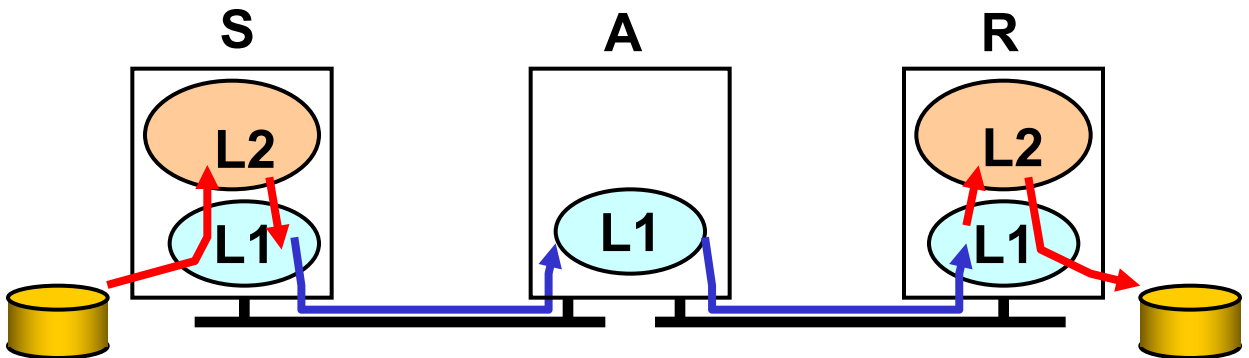
What are Reasons for Implementing Reliability at Higher Layer ?

- The lower layer cannot completely provide the functionality
  - the receiver has to do the check anyway !
- Implementing it at lower layer increases complexity, cost and overhead at lower layer
  - shared by all upper layer applications → everyone pays for it, even if you do not need it
- The upper layer
  - knows the requirements better and thus may choose a better approach to implement it



Are There Reasons Implementing Reliability at Lower Layer ?

- Improve performance, e.g., if high cost/delay/… on a local link
  - improves efficiency
  - reduces delay
- Share common code, e.g., reliability is required by multiple applications



Summary: End-to-End Arguments

- If a higher layer can do it, don't do it at a lower layer -- the higher the layer, the more it knows about the best what it needs
- Add functionality in lower layers iff it

  (1) is used by and improves performance of a large number of (current and potential future) applications,

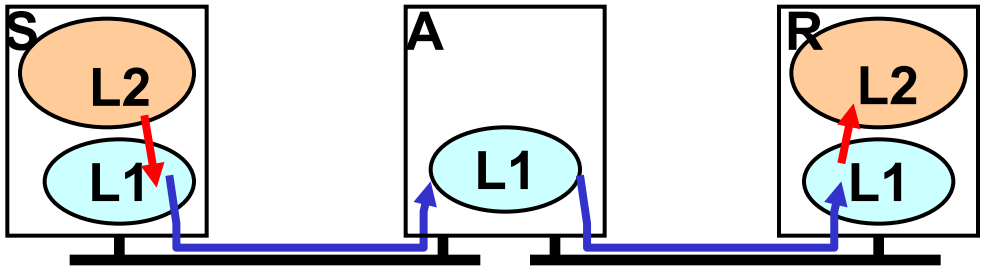
  (2) does not hurt (too much) other applications, and

  (3) does not increase (too much) complexity/overhead
- Practical tradeoff, e.g.,
  - allow multiple interfaces at a lower layer (one provides the function; one does not)

Examples

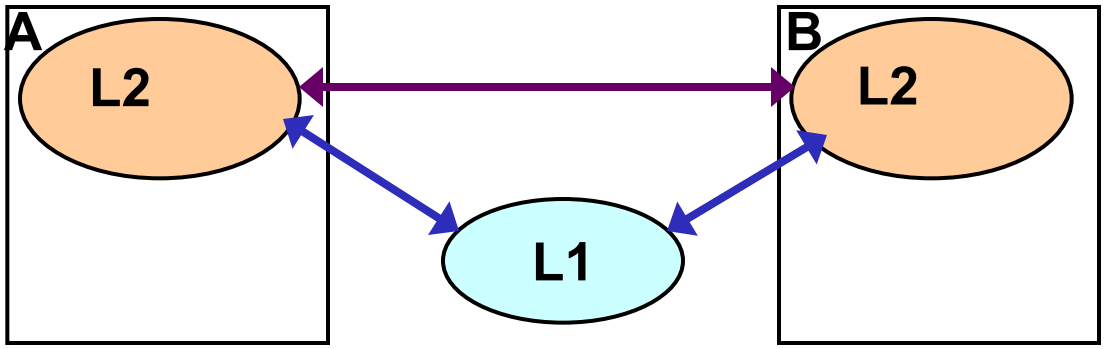
- We used reliability as an example

- Assume two layers (L1: network; L2: end-to-end). Where may you implement the following functions?
  - security (privacy of traffic)
  - quality of service (e.g., delay/bandwidth guarantee)
  - congestion control (e.g., not to overwhelm network links or receiver)



Example

- Consider the presence service in a social networking system: shows which contacts are online (e.g., skype)
  - implementing by end user's host app or through a third party service?



Challenges

- Challenges to build a good (networking) system: find the right balance between:

end-to-end arguments

performance ⟷ reuse, interoperability, implementation effort (apply layering concepts)

No universal answer: the answer depends on the goals and assumptions!

Discussion: Limitations of Layered Architecture

Backup Slides

The Design Philosophy of the DARPA Internet

Goals

0. **Connect different networks**

1. Survivability in the face of failure
2. Support multiple types of services
3. Accommodate a variety of networks

4. Permit distributed management of resources
5. Be cost effective
6. Permit host attachment with a low level of effort
7. Be accountable

Survivability in the Face of Failure: Questions

- What does the goal mean?
- Why is the goal important?
- How does the Internet achieve this goal?
- Does the Internet achieve this goal (or in what degree does the Internet achieve this goal)?

Survivability in the Face of Failure

- Continue to operate even in the presence of network failures (e.g., link and router failures)
  - as long as the network is not partitioned, two endpoints should be able to communicate…moreover, any other failure (excepting network partition) should be transparent to endpoints
- Decision: maintain state only at end-points (fate-sharing)
  - eliminate the problem of handling state inconsistency and performing state restoration when router fails
- Internet: stateless network architecture

Support Multiple Types of Service: Questions

- What does this goal mean?
- Why is the goal important?
- How does the Internet achieve this goal?
- Does the Internet achieve this goal (or in what degree does the Internet achieve this goal)?

Support Multiple Types of Service

- Add UDP to TCP to better support other types of applications
  - e.g., "real-time" applications
- This was arguably the main reason for separating TCP and IP
- Provide datagram abstraction: lower common denominator on which other services can be built: everything over IP
  - service differentiation was considered (remember ToS?), but this has never happened on the large scale (Why?)

Support a Variety of Networks: Questions

- What does the goal mean?
- Why is this goal important?
- How does the Internet achieve this goal?
- Does the Internet achieve this goal (or in what degree does the Internet achieve this goal)?

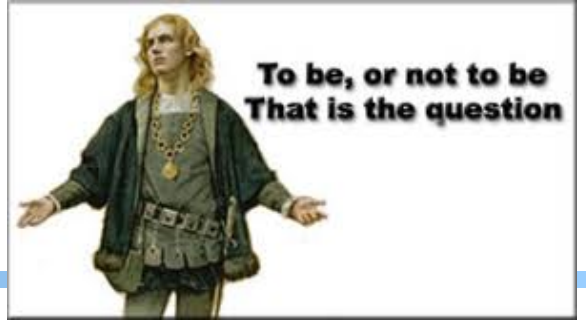
Support a Variety of Networks

- Very successful
  - because the minimalist service; it requires from underlying network only to deliver a packet with a "reasonable" probability of success
- …does not require:
  - reliability
  - in-order delivery
- The mantra: IP over everything
  - Then: ARPANET, X.25, DARPA satellite network..
  - Now: ATM, SONET, WDM…

Other Goals

- Permit distributed management of resources
- Be cost effective
- Permit host attachment with a low level of effort
- Be accountable

To Partition, or not to Partition: This is the Question.



Assume:

R = link bandwidth (bps)

L = packet length (bits)

S = L / R

a = average packet arrival rate (pkt/sec)

Setup: n streams; each stream has an arrival rate of a/n

Comparison: each stream reserves 1/n bandwidth or not

- Case 1 (not reserve): all arrivals into a single queue serving with rate R
- Case 2 (reserve): the arrivals are divided into n links with rate R/n each

Partition or Not