1. Introduction: roadmap

1.1 what *is* the Internet?

1.2 network edge

- end systems, access networks, links

1.3 network core

- packet switching, circuit switching, network structure

1.4 delay, loss, throughput in networks

1.5 protocol layers, service models

1.6 networks under attack: security

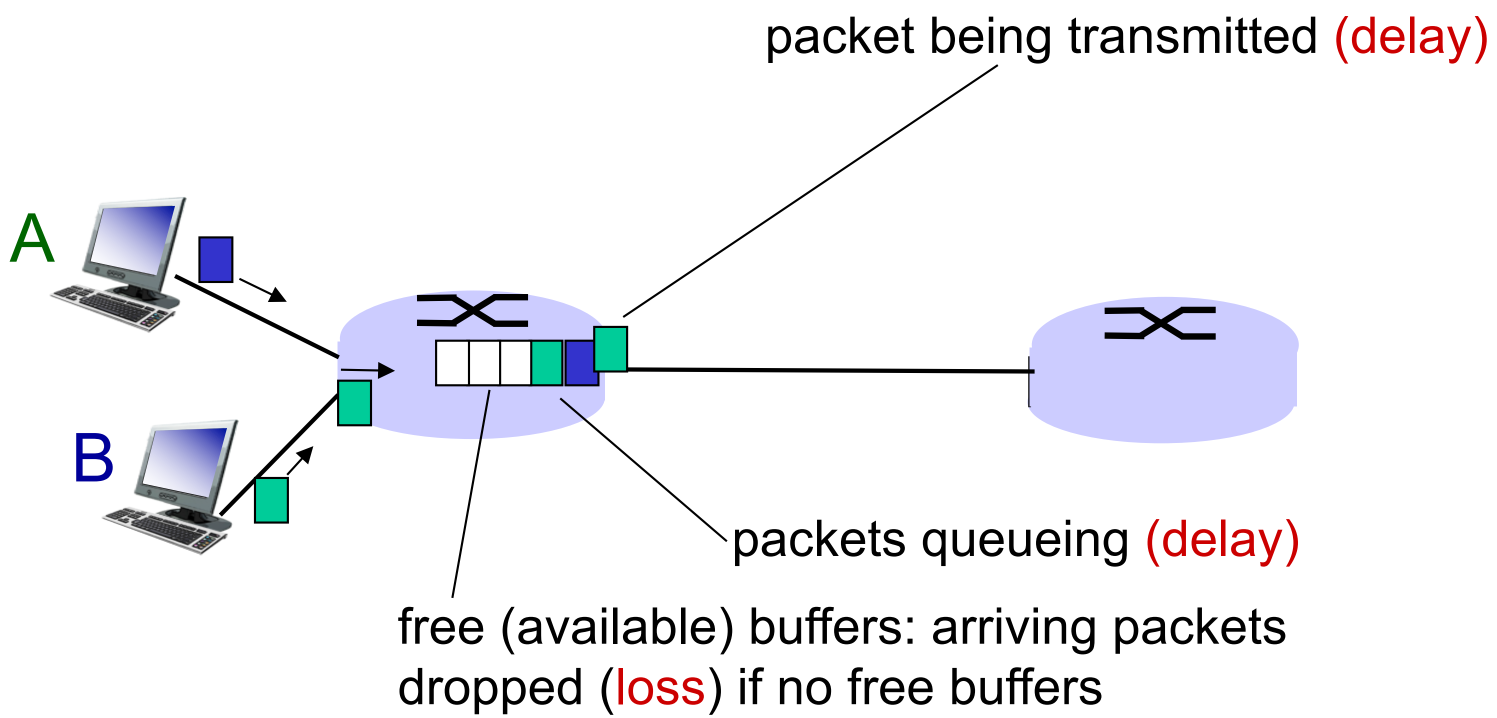
1.7 history

Self study

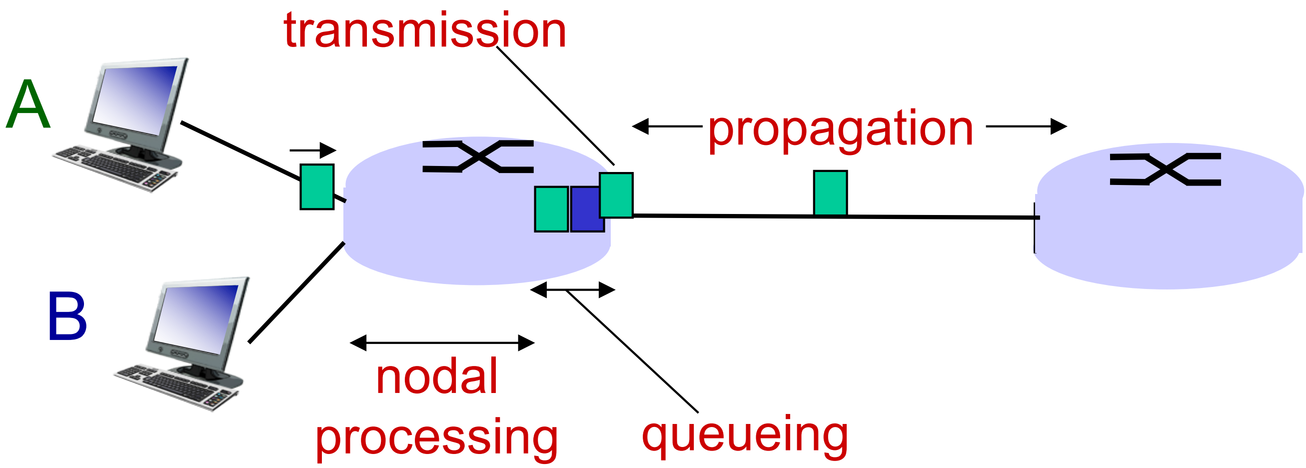
How do loss and delay occur?

Packets *queue* in router buffers

- Packet arrival rate to link (temporarily) exceeds output link capacity
- Packets queue, wait for turn



Four sources of packet delay



$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

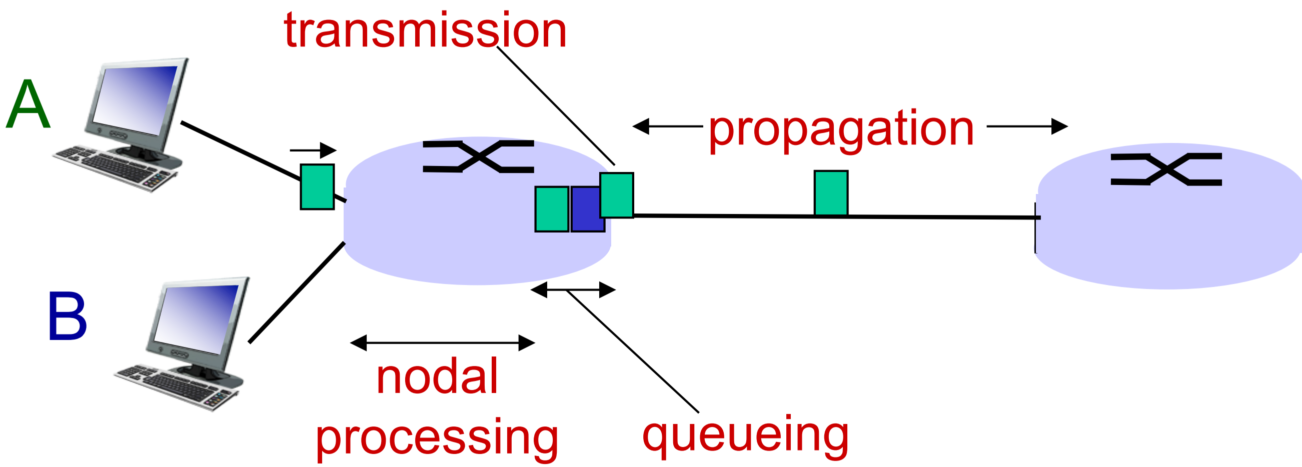
d_{proc}: nodal processing

- check bit errors
- determine output link
- typically < msec

d_{queue}: queueing delay

- time waiting at output link for transmission
- depends on congestion level of router

Four sources of packet delay



$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

d_{trans}: transmission delay:

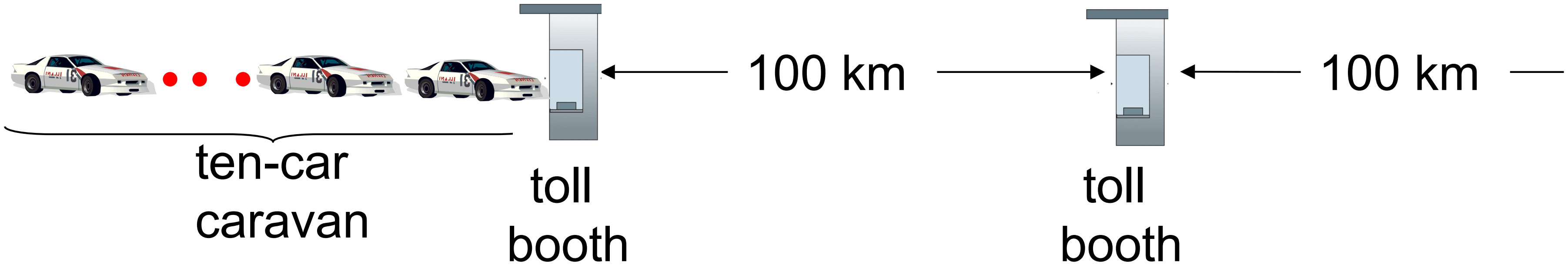
- *L*: packet length (bits)
- *R*: link *bandwidth (bps)*
- $d_{trans} = L/R$

d_{trans} and d_{prop}
very different

d_{prop}: propagation delay:

- *d*: length of physical link
- *s*: propagation speed in medium ($\sim 2 \times 10^8$ m/sec)
- $d_{prop} = d/s$

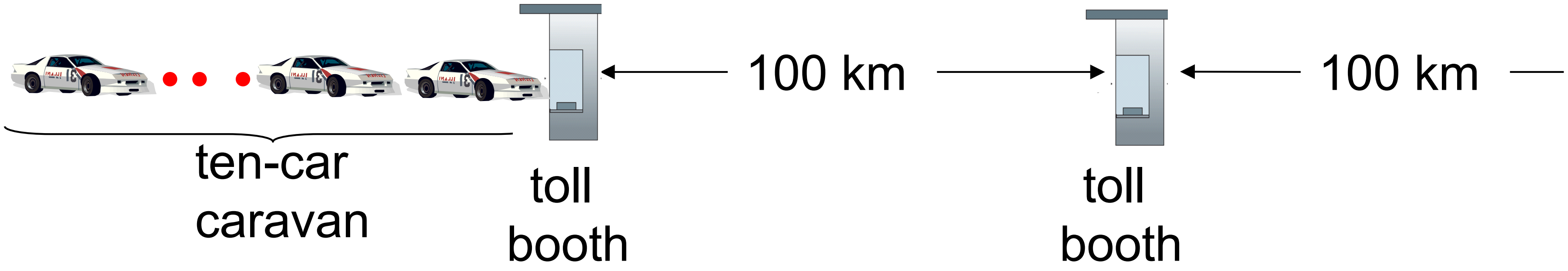
Caravan analogy



- Car ~bit; Caravan ~ packet
- Cars "propagate" at 100 km/hr
- Toll booth takes 12 sec to service car (bit transmission time)
- *Q: How long until caravan is lined up before 2nd toll booth?*

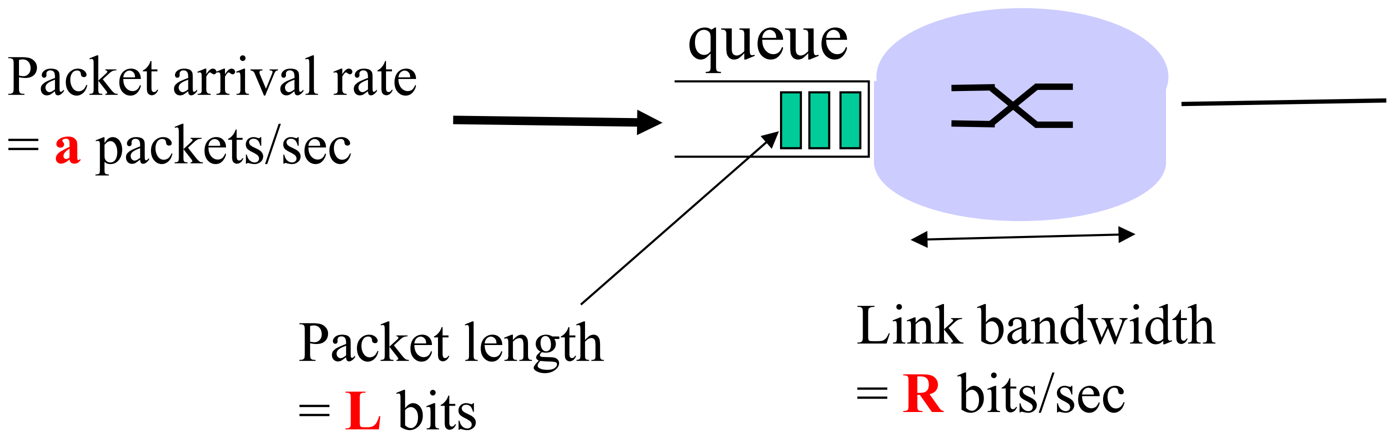
- time to "push" entire caravan through toll booth onto highway = 12*10 = 120 sec
- time for last car to propagate from 1st to 2nd toll both: 100km/(100km/hr)= 1 hr
- *A: 62 minutes*

Caravan analogy (more)



- Suppose cars now "propagate" at 1000 km/hr
- And suppose toll booth now takes one min to service a car
- *Q:* Will cars arrive to 2nd booth before all cars serviced at first booth?
  - *A: Yes!* after 7 min, 1st car arrives at second booth; three cars still at 1st booth.

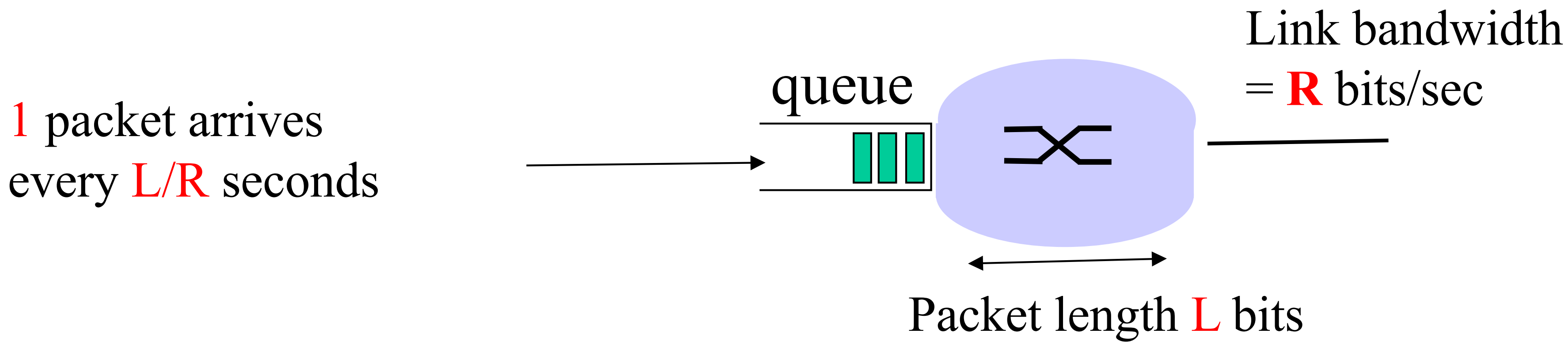
Queueing delay (more insight)



- Every second: aL bits arrive to queue
- Every second: R bits leave the router
- Question: what happens if $aL > R$?
- Answer: queue will fill up, and packets will get dropped!!

aL/R is called traffic intensity

Queueing delay: illustration

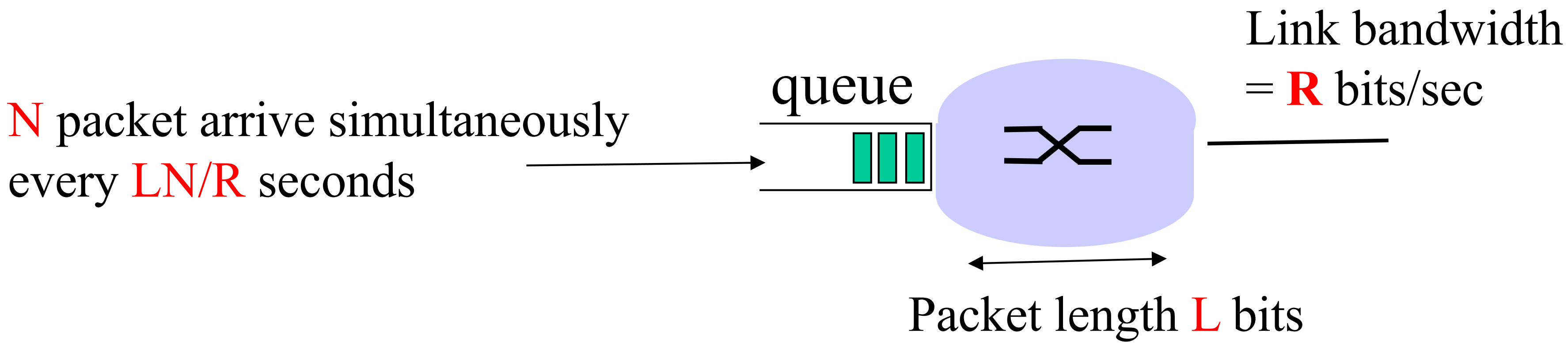


Arrival rate: a = 1/(L/R) = R/L (packet/second)

Traffic intensity = aL/R = (R/L) (L/R) = 1

Average queueing delay = 0
(queue is initially empty)

Queueing delay: illustration



Arrival rate: $a = N/(LN/R) = R/L$ packet/second

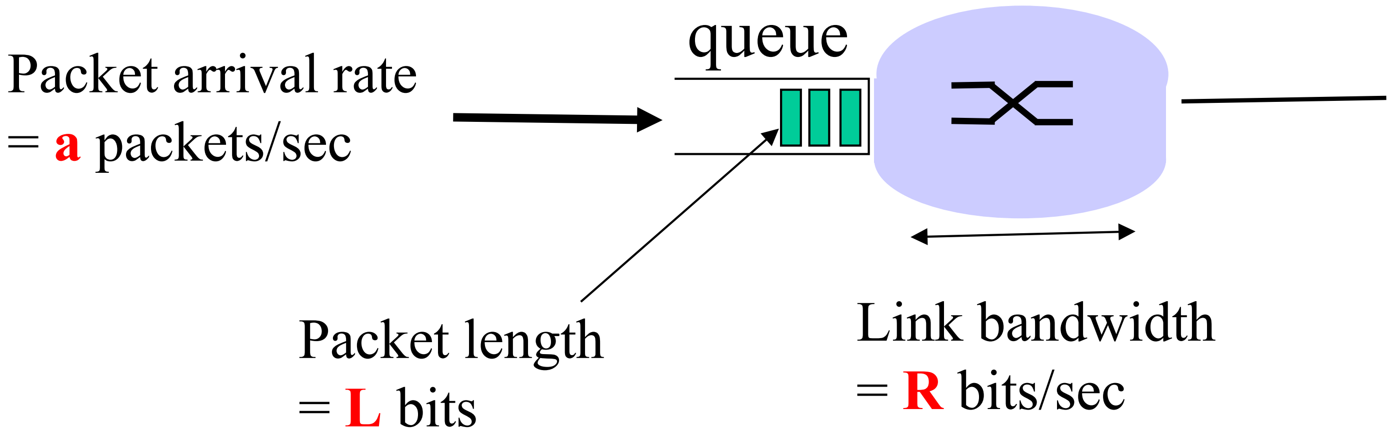
Traffic intensity $= aL/R = (R/L)(L/R) = 1$

Average queueing delay (queue is empty at time 0) ?

$\{0 + L/R + 2L/R + \ldots + (N-1)L/R\}/N = L/(RN)\{1+2+\ldots+(N-1)\} = L(N-1)/(2R)$

Note: traffic intensity is same as previous scenario, but queueing delay is different

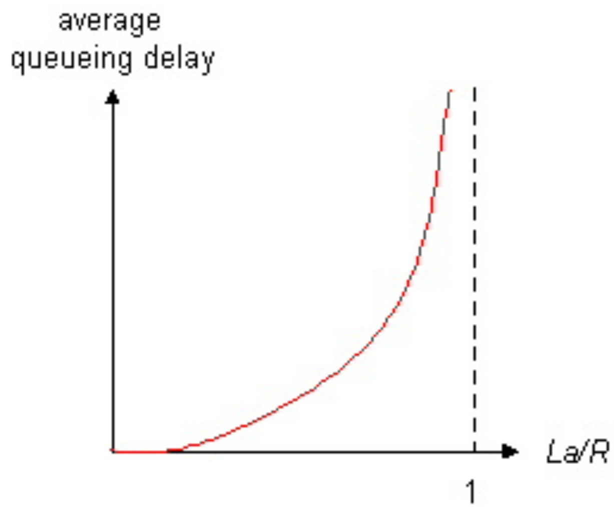
Queueing delay: behaviour



Interactive Java Applet:
http://media.pearsoncmg.com/aw/aw_kurose_network_2/applets/queuing/queuing.html

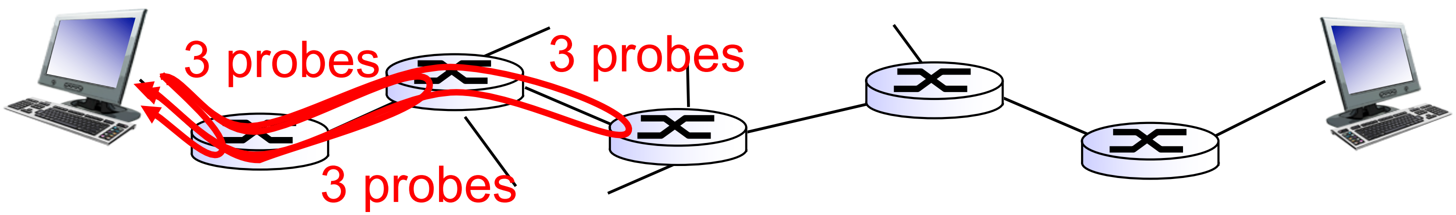
- La/R ~ 0: avg. queueing delay small
- La/R -> 1: delays become large
- La/R > 1: more "work" than can be serviced, average delay infinite!

(this is when **a** is random!)



"Real" Internet delays and routes

- what do "real" Internet delay & loss look like?
- `traceroute` program: provides delay measurement from source to router along end-end Internet path towards destination. For all *i:*
  - sends three packets that will reach router *i* on path towards destination
  - router *i* will return packets to sender
  - sender times interval between transmission and reply.



"Real" Internet delays, routes

traceroute: gaia.cs.umass.edu to www.eurecom.fr

3 delay measurements from gaia.cs.umass.edu to cs-gw.cs.umass.edu

1 cs-gw (128.119.240.254) 1 ms 1 ms 2 ms
2 border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145) 1 ms 1 ms 2 ms
3 cht-vbns.gw.umass.edu (128.119.3.130) 6 ms 5 ms 5 ms
4 jn1-at1-0-0-19.wor.vbns.net (204.147.132.129) 16 ms 11 ms 13 ms
5 jn1-so7-0-0-0.wae.vbns.net (204.147.136.136) 21 ms 18 ms 18 ms
6 abilene-vbns.abilene.ucaid.edu (198.32.11.9) 22 ms 18 ms 22 ms
7 nycm-wash.abilene.ucaid.edu (198.32.8.46) 22 ms 22 ms 22 ms
8 62.40.103.253 (62.40.103.253) 104 ms 109 ms 106 ms
9 de2-1.de1.de.geant.net (62.40.96.129) 109 ms 102 ms 104 ms
10 de.fr1.fr.geant.net (62.40.96.50) 113 ms 121 ms 114 ms
11 renater-gw.fr1.fr.geant.net (62.40.103.54) 112 ms 114 ms 112 ms
12 nio-n2.cssi.renater.fr (193.51.206.13) 111 ms 114 ms 116 ms
13 nice.cssi.renater.fr (195.220.98.102) 123 ms 125 ms 124 ms
14 r3t2-nice.cssi.renater.fr (195.220.98.110) 126 ms 126 ms 124 ms
15 eurecom-valbonne.r3t2.ft.net (193.48.50.54) 135 ms 128 ms 133 ms
16 194.214.211.25 (194.214.211.25) 126 ms 128 ms 126 ms
17 * * *
18 * * *
19 fantasia.eurecom.fr (193.55.113.142) 132 ms 128 ms 136 ms

trans-oceanic link

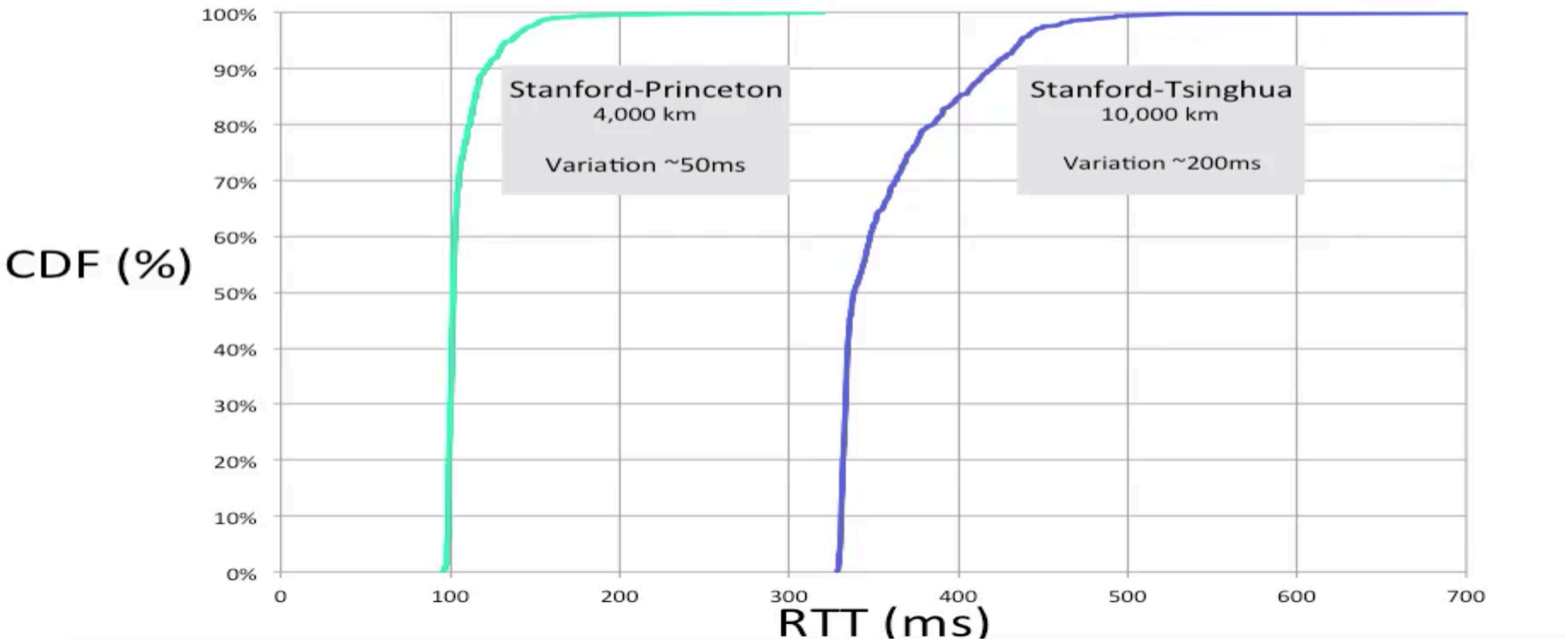
* means no response (probe lost, router not replying)

* Do some traceroutes from countries at www.traceroute.org

"Real" delay variations

$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

End-to-end delay = sum of all d_{nodal} along the path



Quiz: Switching

- Packet switching, instead of circuit switching, is generally used to transfer data in the Internet. True or false?

A. True

B. False

Quiz: Delays

- Propagation delay depends on the size of the packet. True or false?

  A. True

  B. False

Quiz: Delays

- Which of the following delays is significantly affected by the load in the network?

  A. Processing delay

  B. Queuing delay

  C. Transmission delay

  D. Propagation delay

Quiz: Delays

- Consider a packet that has just arrived at a router. What is the correct order of the delays encountered by the packet until it reaches the next-hop router?

A. Transmission, processing, propagation, queuing

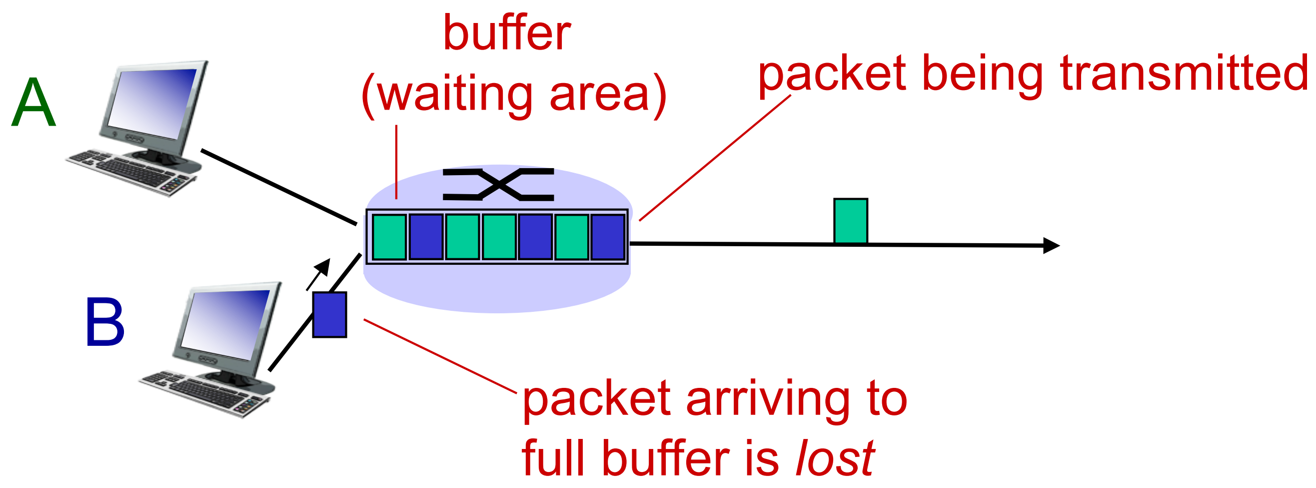
B. Propagation, processing, transmission, queuing

C. Processing, queuing, transmission, propagation

D. Queuing, processing, propagation, transmission

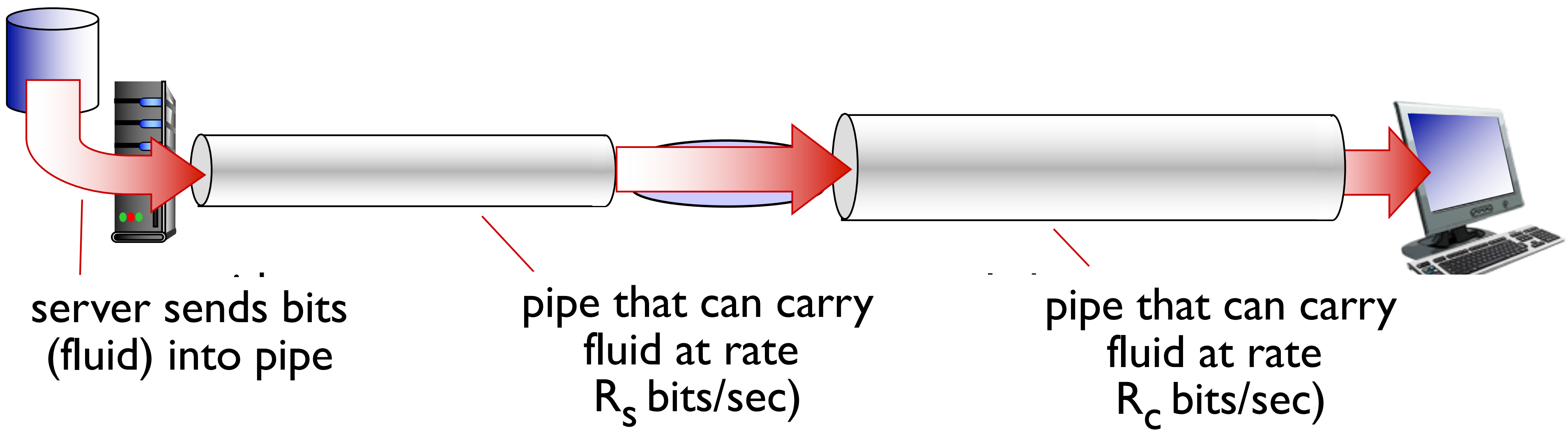
Packet loss

- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted



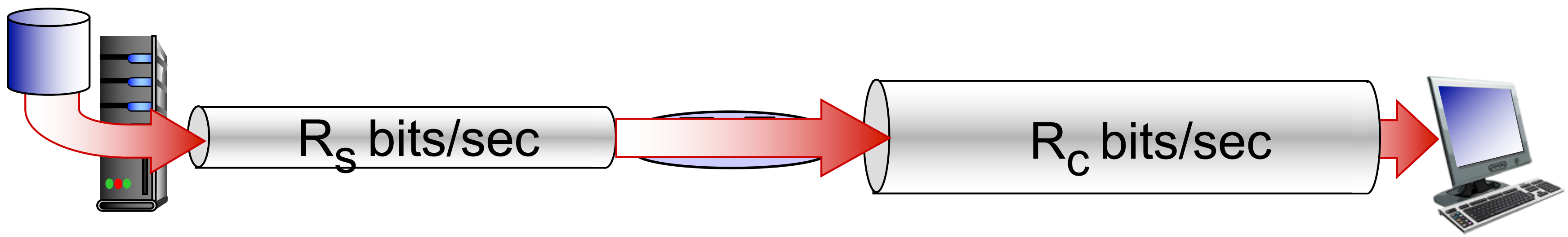
Throughput

- *throughput:* rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time

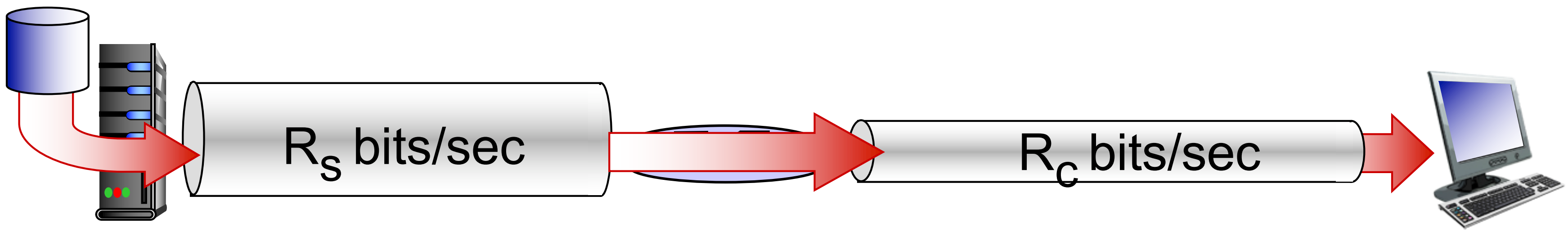


Throughput (more)

- $R_s < R_c$ What is average end-end throughput?



- $R_s > R_c$ What is average end-end throughput?

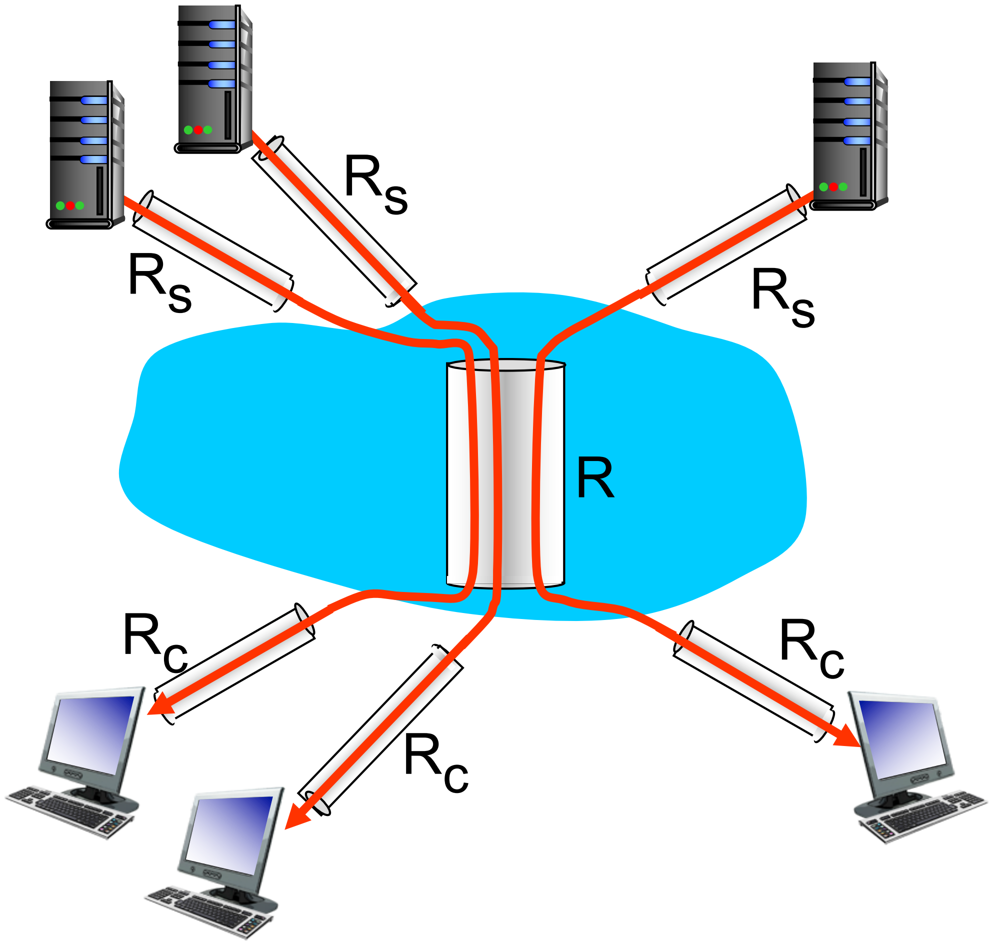


bottleneck link

link on end-end path that constrains end-end throughput

Throughput: Internet scenario

- per-connection end-end throughput: $\min(R_c, R_s, R/10)$
- in practice: R_c or R_s is often bottleneck



10 connections (fairly) share backbone bottleneck link R bits/sec

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Self study

How Both PCs with different OS are Communicating???

Three (networking) design steps

- Break down the problem into tasks
- Organize these tasks
- Decide who does what

Tasks in Networking

- What does it take to send packets across?
- Simplistic decomposition:
  - Task 1: send along a single wire

  - Task 2: stitch these together to go across country/globe

- This gives idea of what I mean by decomposition

Resulting Modules

- Bits / Packets on wire (Physical)
- Delivery packets within local network (Datalink)
- Deliver packets across global network (Network)
- Ensure that packets get to the dst process. (Transport)
- Do something with the data (Application)

This is decomposition…

Now, how do we organize these tasks?

Let us have an example

Inspiration…

- CEO A writes letter to CEO B
  - Folds letter and hands it to administrative aide
    - » Aide:
      - » Puts letter in envelope with CEO B's full name
      - » Takes to FedEx

```
Dear John,

Your days are numbered.

            --Pat
```

- FedEx Office
  - Puts letter in larger envelope
  - Puts name and street address on FedEx envelope
  - Puts package on FedEx delivery truck
- FedEx delivers to other company

The Path of the Letter

"Peers" on each side understand the same things

No one else needs to (abstraction)

Lowest level has most packaging

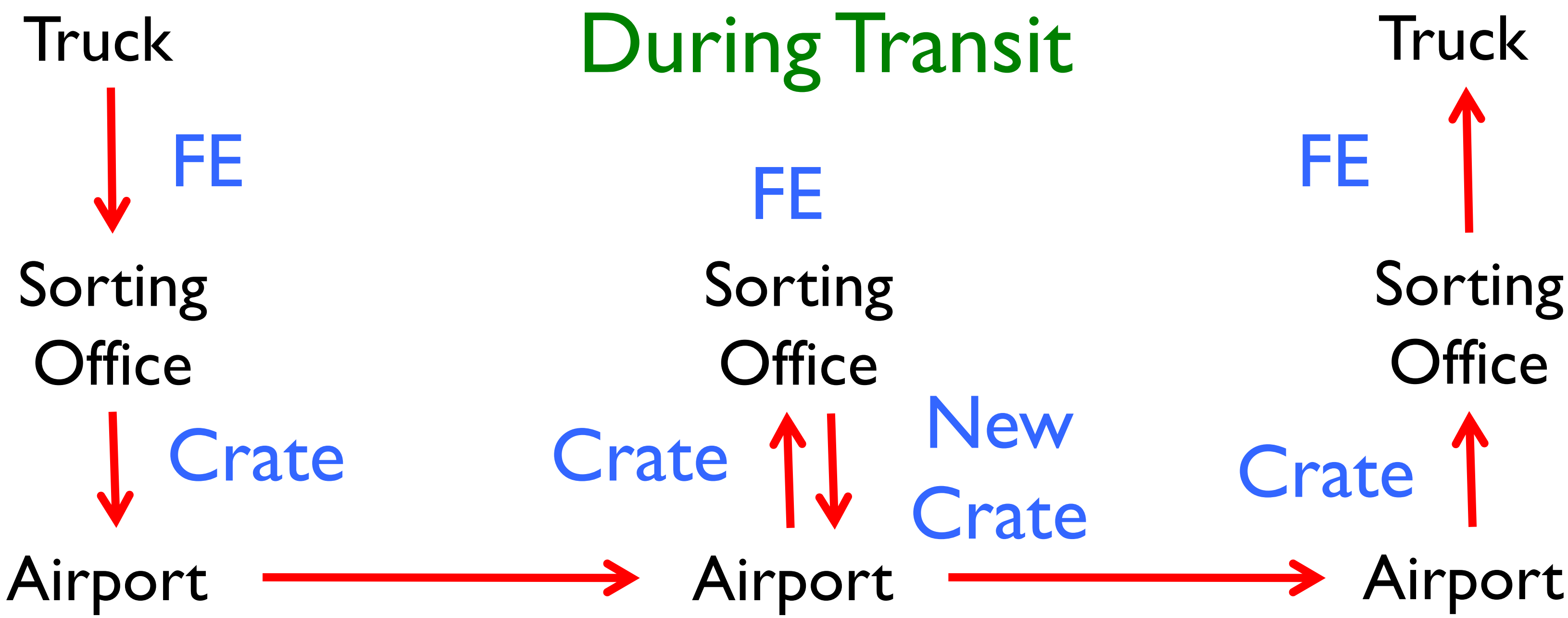
CEO	Semantic Content Letter	CEO
Aide	Identity Envelope	Aide
FedEx	Location Fedex Envelope (FE)	FedEx

The Path Through FedEx

Higher "Stack" at Ends

Highest Level of "Transit Stack" is Routing

Partial "Stack" During Transit



Deepest Packaging (Envelope+FE+Crate) at the Lowest Level of Transport

In the context of the Internet

Applications

…built on…

Reliable (or unreliable) transport

…built on…

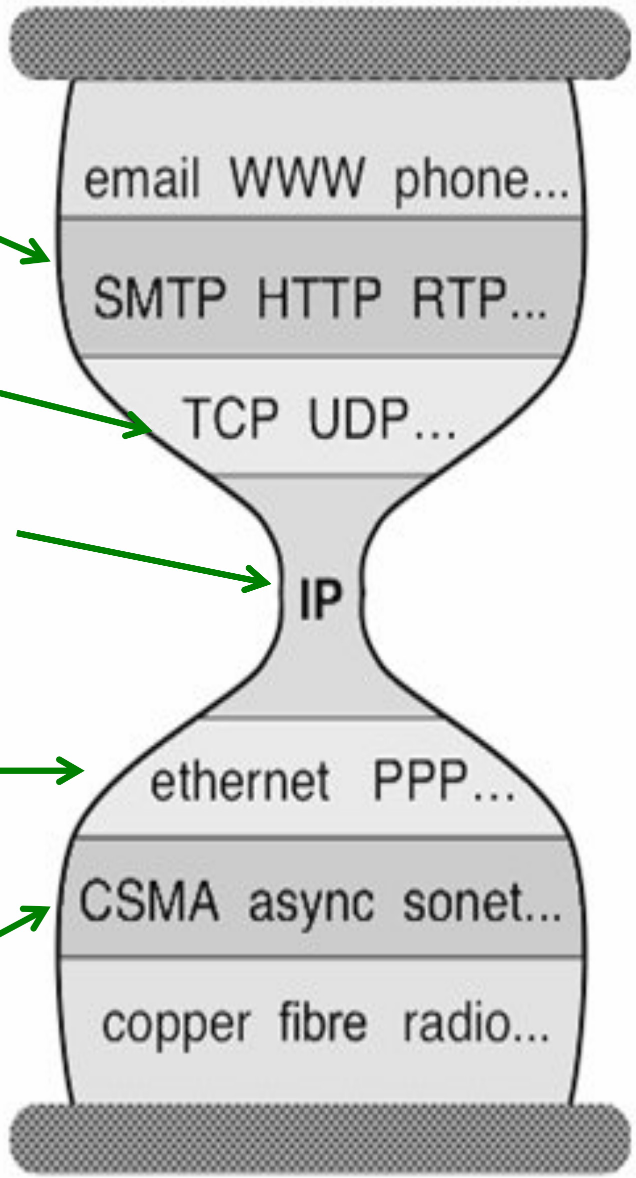
Best-effort global packet delivery

…built on…

Best-effort local packet delivery

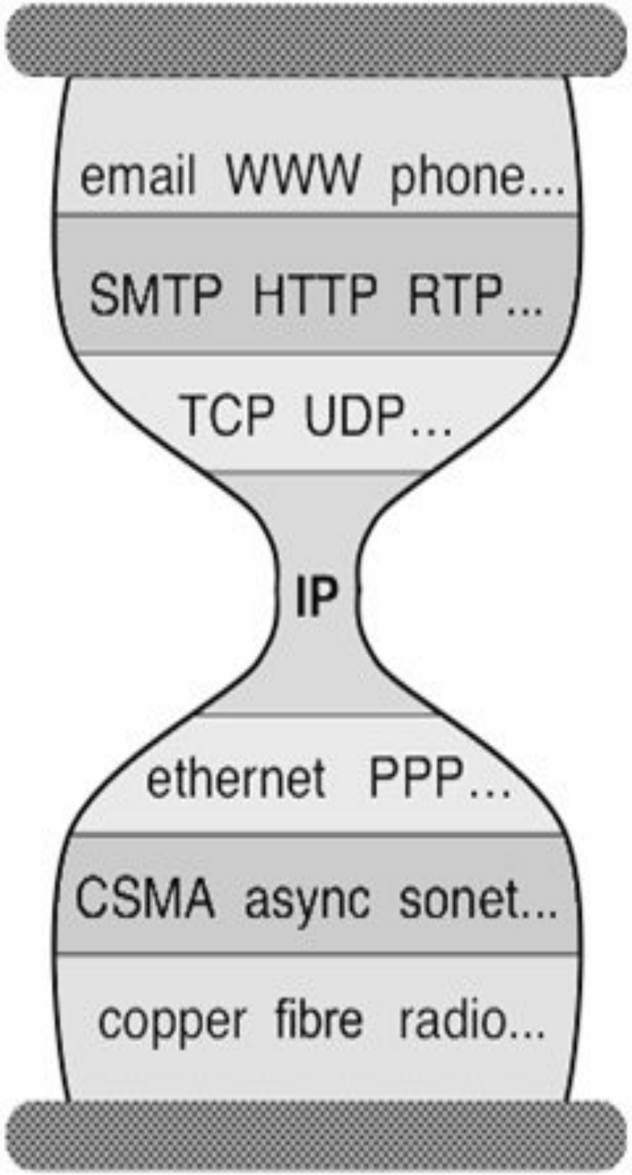
…built on…

Physical transfer of bits



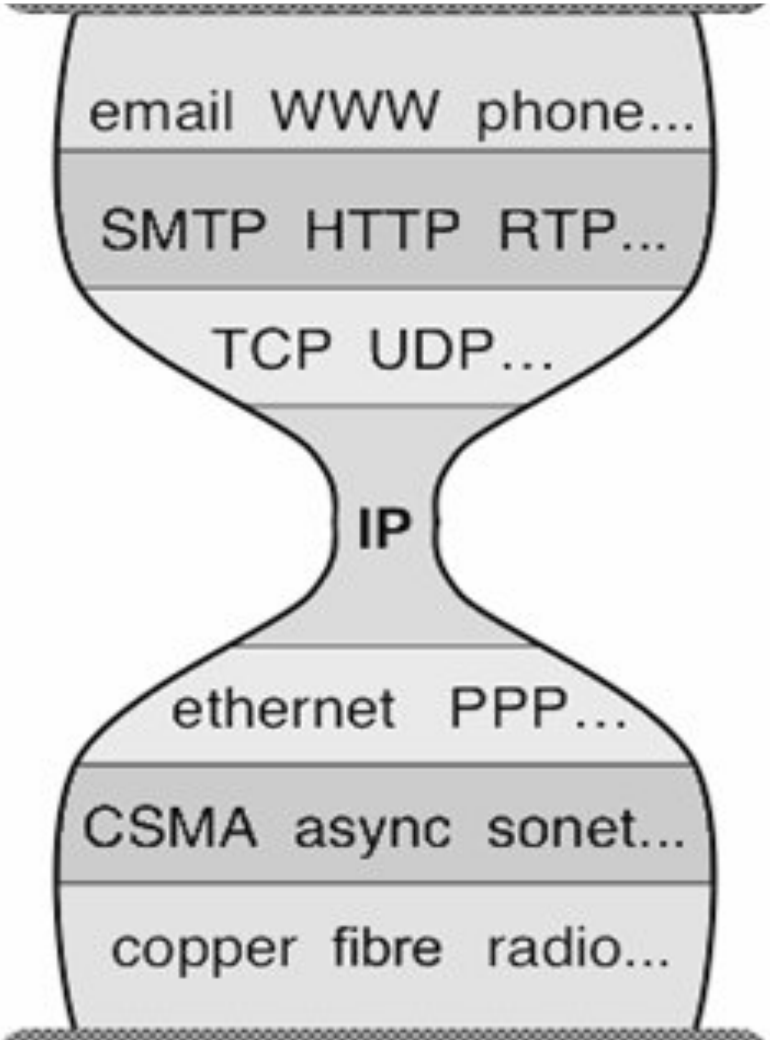
Internet protocol stack

- *application:* supporting network applications
  - FTP, SMTP, HTTP, Skype, ..
- *transport:* process-process data transfer
  - TCP, UDP
- *network:* routing of datagrams from source to destination
  - IP, routing protocols
- *link:* data transfer between neighboring network elements
  - Ethernet, 802.111 (WiFi), PPP
- *physical:* bits "on the wire"

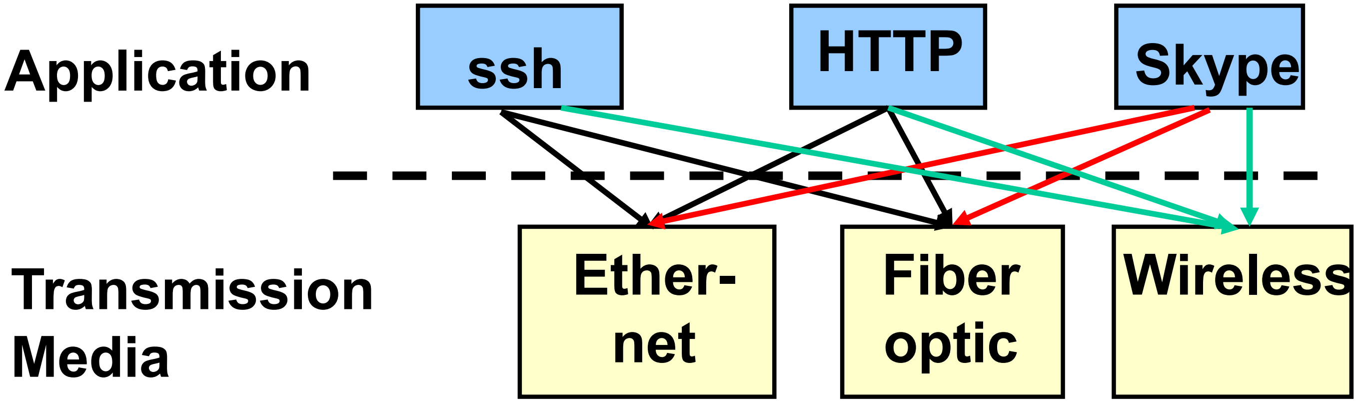


Three Observations

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



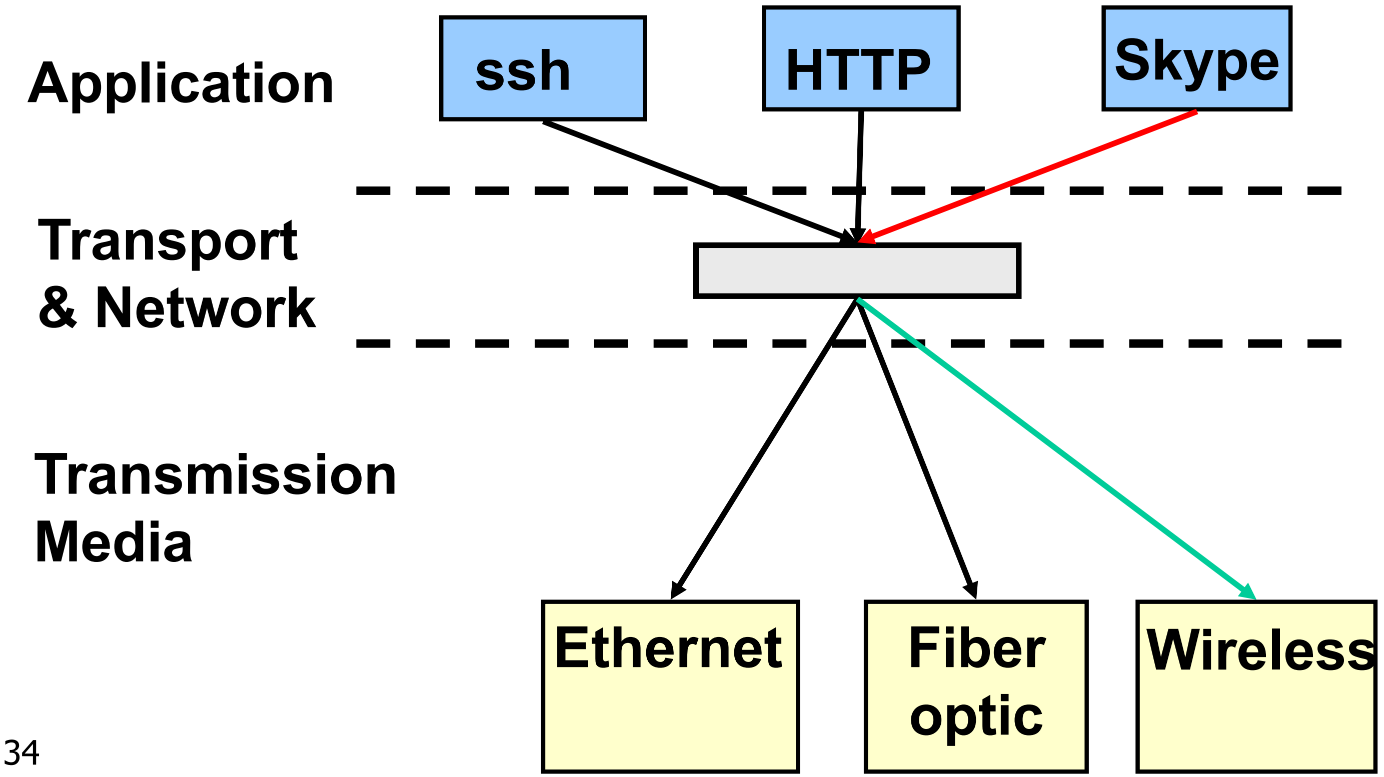
An Example: No Layering



- 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 various network technologies



Why layering?

dealing with complex systems:

- explicit structure allows identification, relationship of complex system's pieces
  - layered *reference model* for discussion
- modularization eases maintenance, updating of system
  - change of implementation of layer's service transparent to rest of system
  - e.g., change in gate procedure doesn't affect rest of system
- layering considered harmful?

Is Layering Harmful?

- Layer N may duplicate lower level functionality
  - E.g., error recovery to retransmit lost data
- Information hiding may hurt performance
  - E.g. packet loss due to corruption vs. congestion
- Headers start to get really big
  - E.g., typically TCP + IP + Ethernet headers add up to 54 bytes
- Layer violations when the gains too great to resist
  - E.g., TCP-over-wireless
- Layer violations when network doesn't trust ends
  - E.g., Firewalls

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 machines
  - Hosts
  - Routers
  - Switches
- What gets implemented where?

What Gets Implemented on Host?

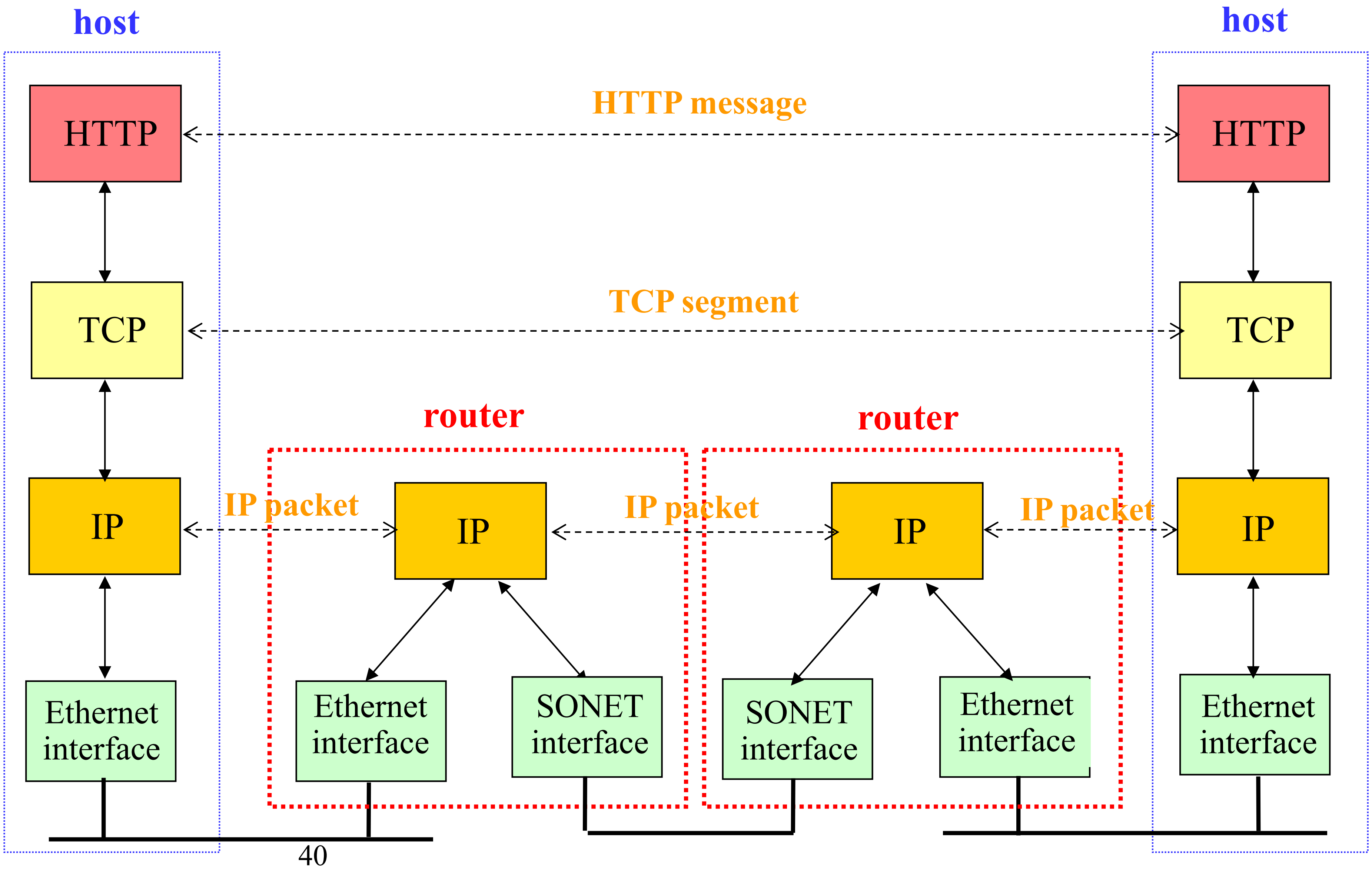
- Bits arrive on wire, must make it up to application

- Therefore, all layers must exist at host!

What Gets Implemented on Router?

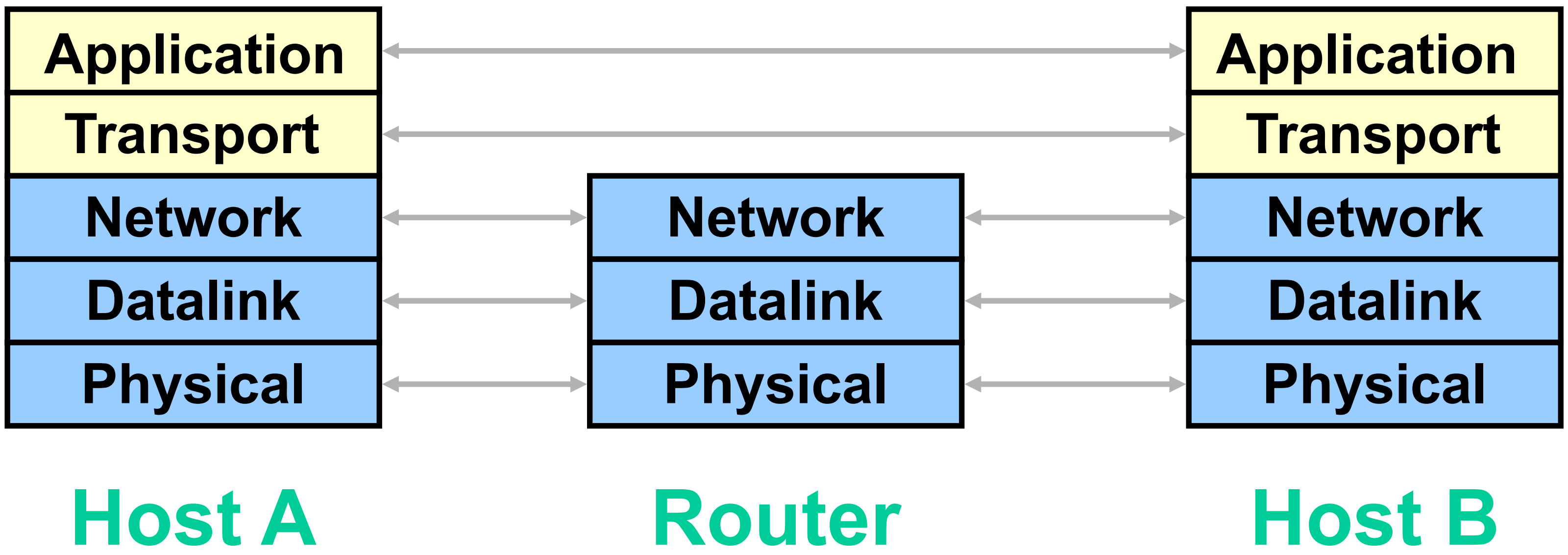
- Bits arrive on wire
  - Physical layer necessary
- Packets must be delivered to next-hop
  - datalink layer necessary
- Routers participate in global delivery
  - Network layer necessary
- Routers don't support reliable delivery
  - Transport layer (and above) ***not*** supported

Internet Layered Architecture



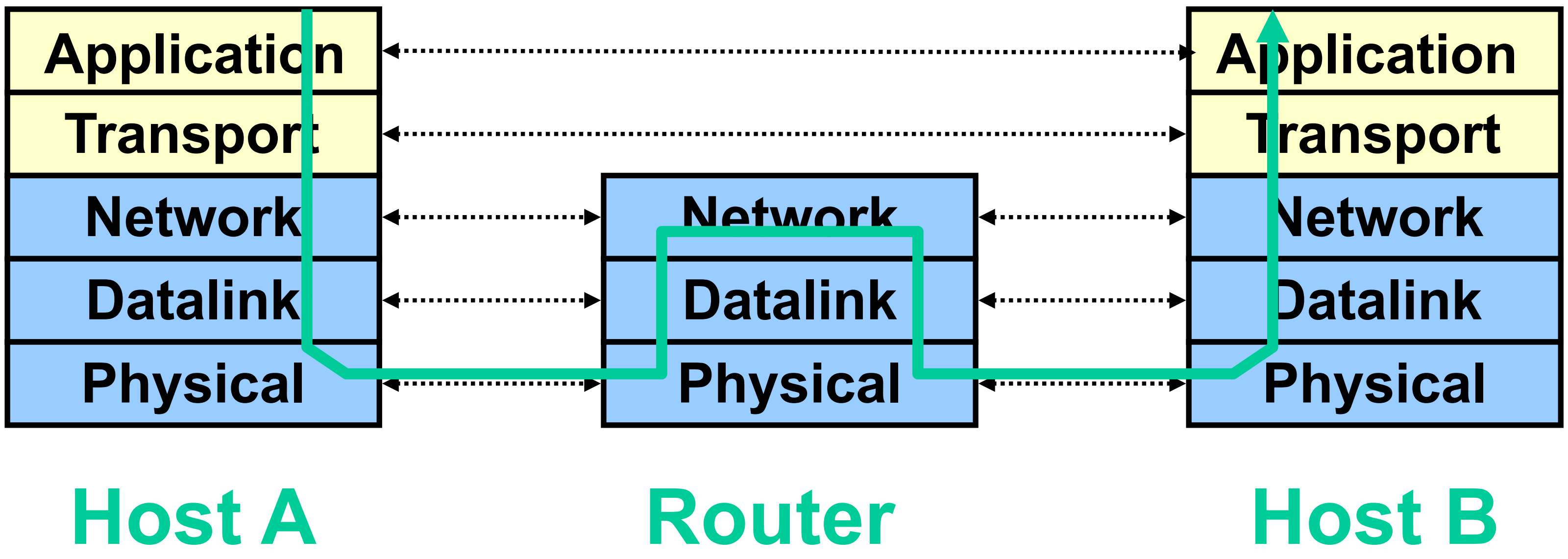
Logical Communication

- Layers interacts with peer’s corresponding layer

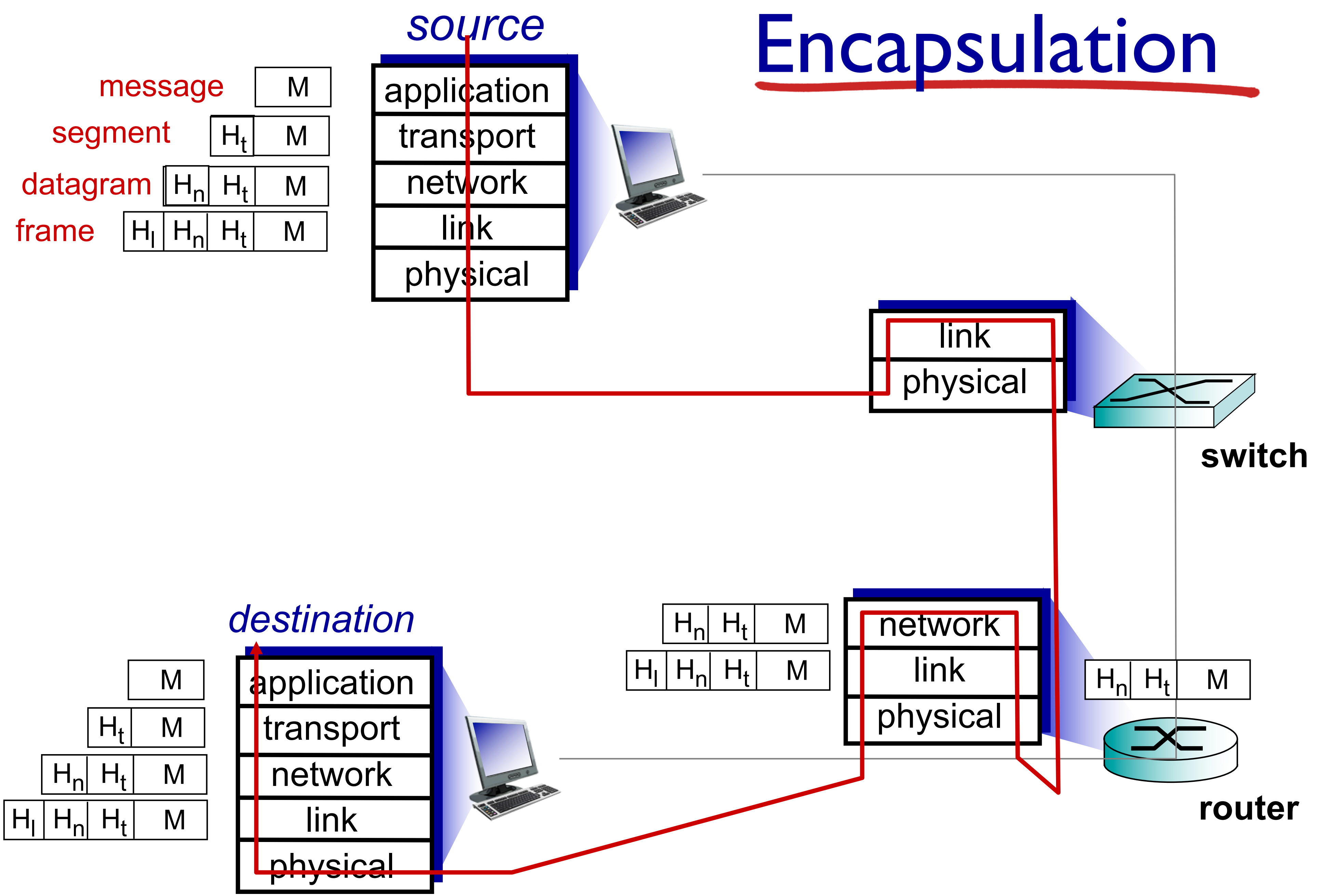


Physical Communication

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



Encapsulation



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Self study

Introduction: summary

covered a "ton" of material!

- Internet overview
- what's a protocol?
- network edge, core, access network
  - packet-switching versus circuit-switching
  - Internet structure
- performance: loss, delay, throughput
- layering, service models
- security
- history

you now have:

- context, overview, "feel" of networking
- more depth, detail *to follow!*