Computer Networks and the Internet
- Overview -

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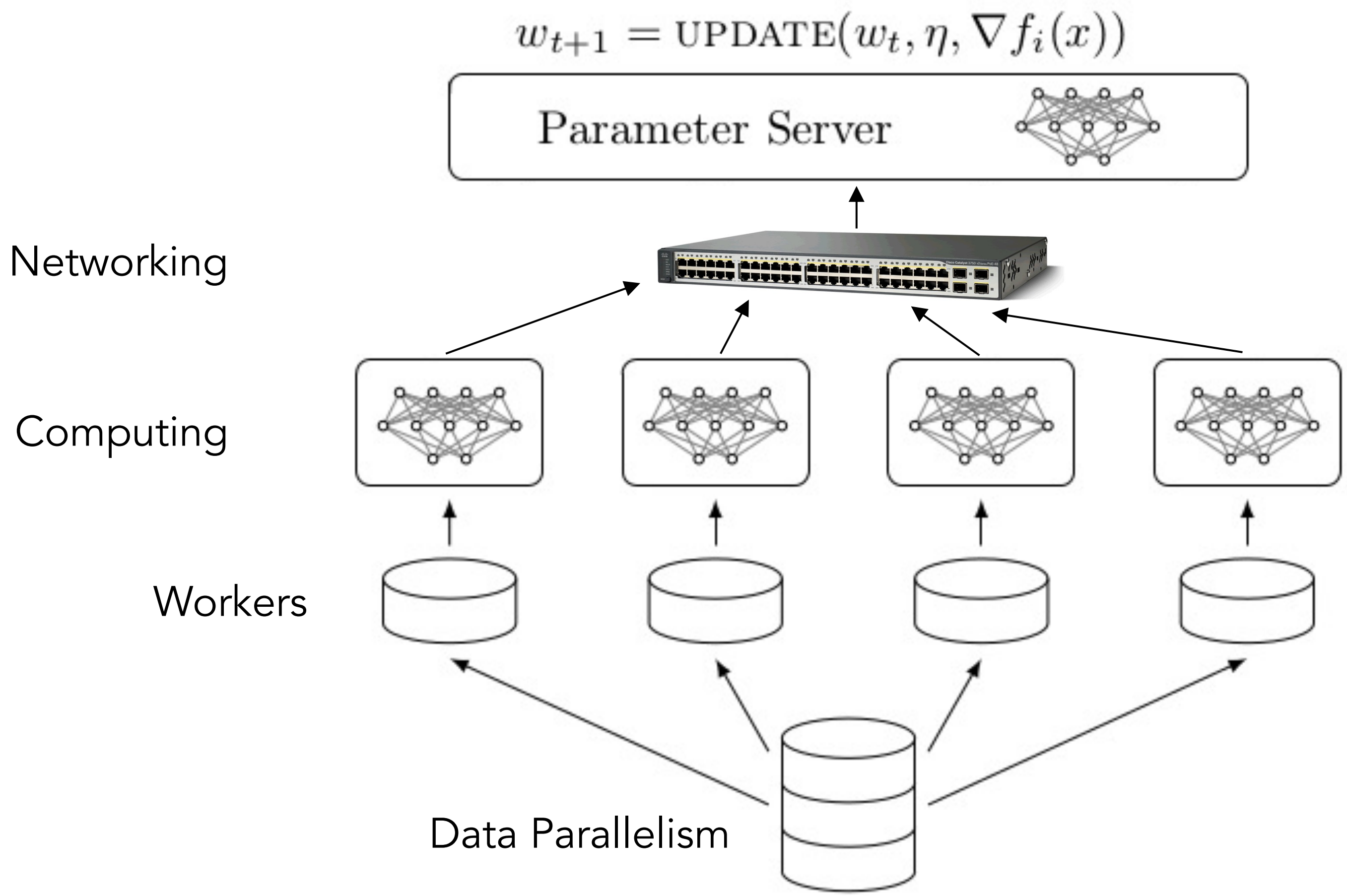
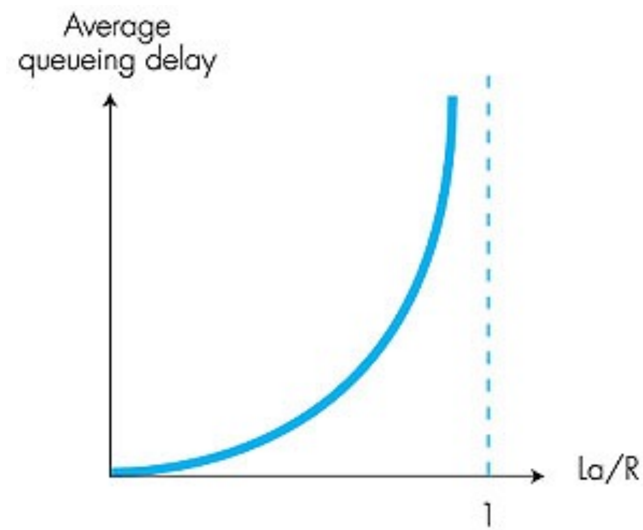
Why Should We Learn Networking?



https://joerihermans.com/ramblings/distributed-deep-learning-part-1-an-introduction/

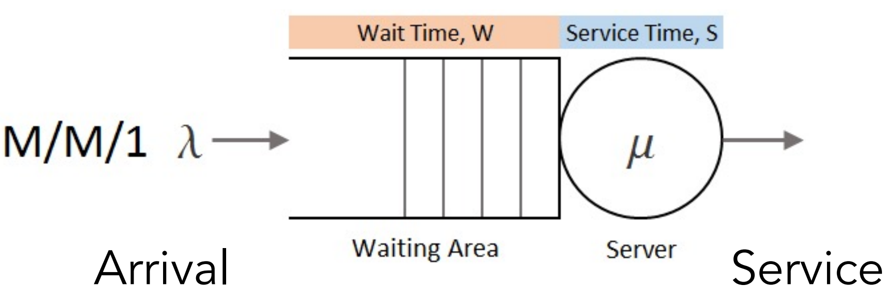
Queueing and Delay (and Throughput)

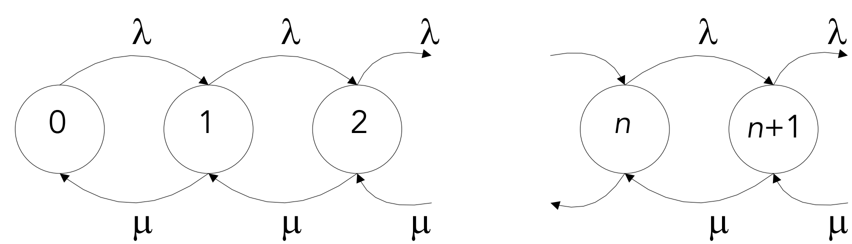


- □ *R:* link bandwidth (bps)
- □ *L:* packet length (bits)
- □ a: average packet arrival rate

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

Traffic intensity: La/R

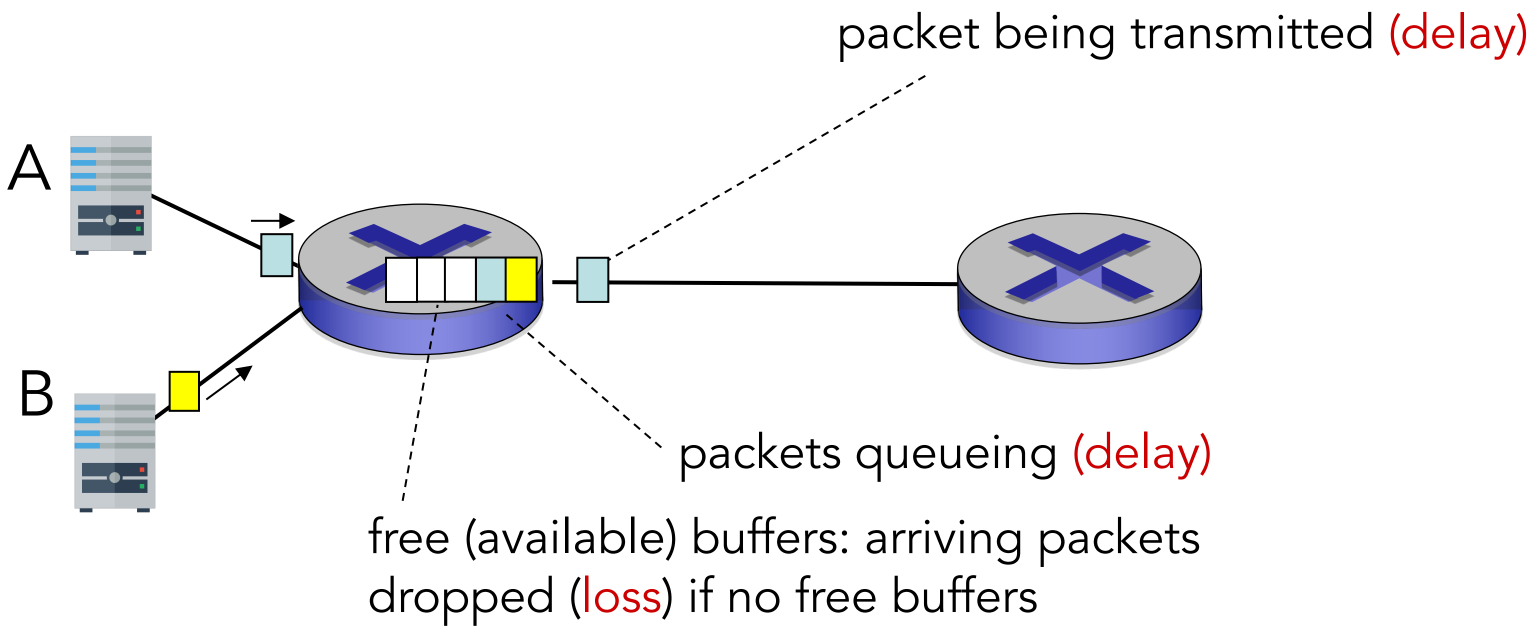




Expected # of packets in the queue: $E(N) = \sum_{n=1}^{\infty} nP_n$

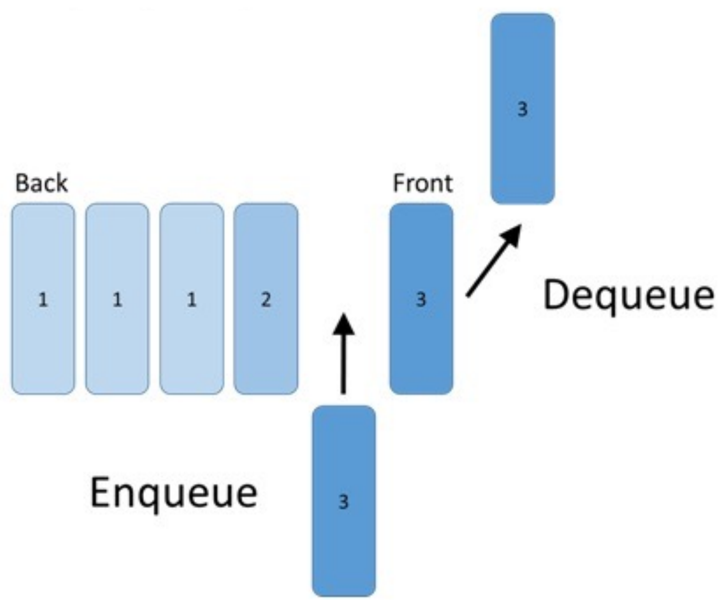
Loss and Delay

- Packets *queue* in router buffers
  - Packet arrival rate to link (temporarily) exceeds output link capacity
  - Packets queue, wait for turn
  - Packets are dropped in the tail part (drop-tail queue)

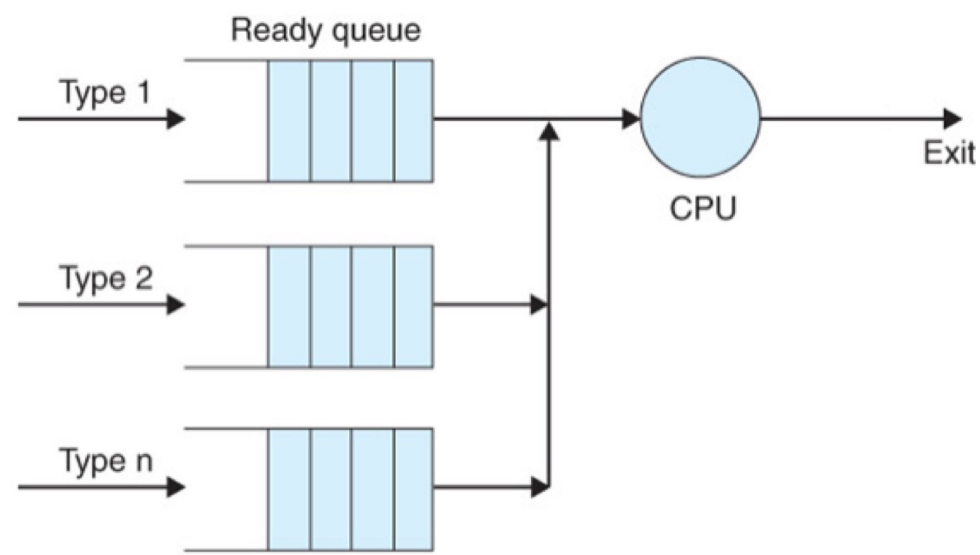


Priority Queue

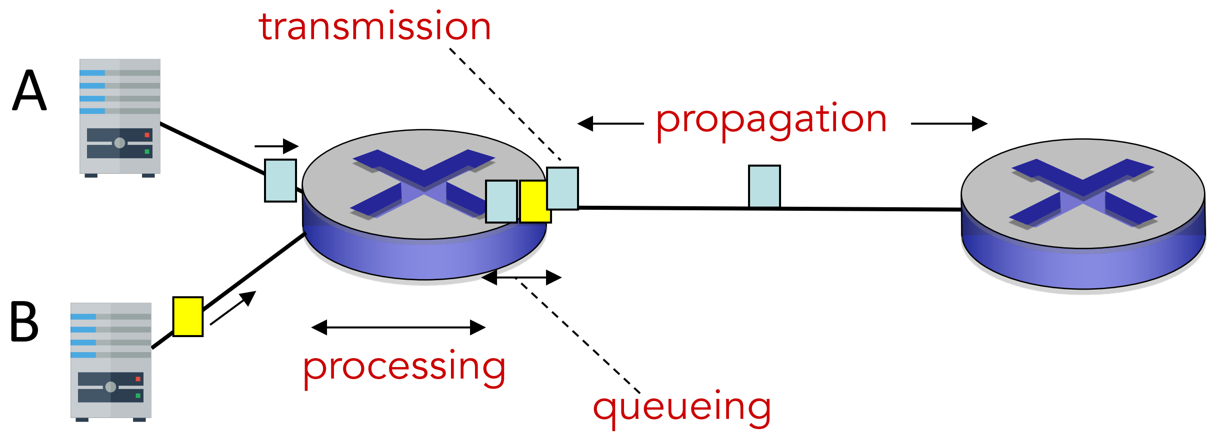
Priority Queue



Multi Queue with Preemption



Queueing and Delay (and Throughput)



$$d_{e2e} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

Nearly deterministic in L2/L3/L4 switches

Variable in L7 switch

Largely unpredictable

Increases in multi-hop (store-and-forward)

2×10^8 m/s
in copper cable & optical fiber

Real Internet Delay

ping www.google.com

```
PING www.google.com (172.217.160.68): 56 data bytes
64 bytes from 172.217.160.68: icmp_seq=0 ttl=44 time=71.642 ms
64 bytes from 172.217.160.68: icmp_seq=1 ttl=44 time=82.027 ms
64 bytes from 172.217.160.68: icmp_seq=2 ttl=44 time=67.633 ms
64 bytes from 172.217.160.68: icmp_seq=3 ttl=44 time=67.492 ms
64 bytes from 172.217.160.68: icmp_seq=4 ttl=44 time=80.396 ms
64 bytes from 172.217.160.68: icmp_seq=5 ttl=44 time=83.657 ms
```

traceroute www.google.com

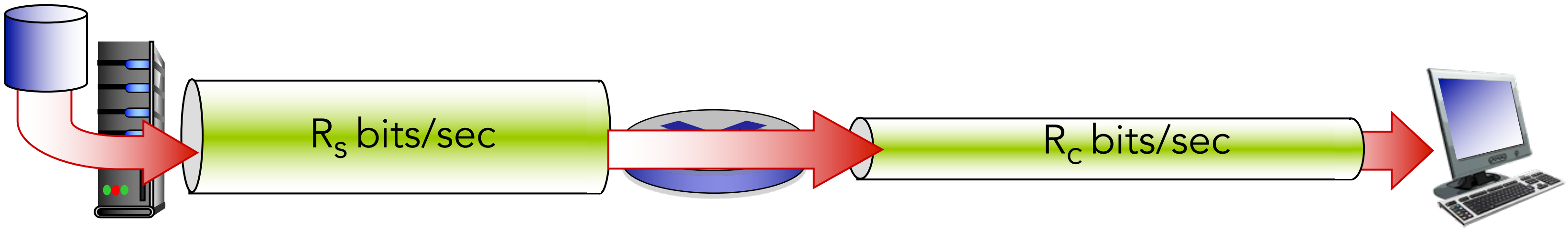
```
traceroute to www.google.com (172.217.160.68), 64 hops max, 52 byte packets
 1  router.asus.com (192.168.2.1)  2.360 ms  1.030 ms  1.131 ms
 2  router.asus.com (192.168.1.1)  1.624 ms  4.172 ms  1.429 ms
 3  * * *
 4  10.240.88.237 (10.240.88.237)  4.098 ms  3.047 ms *
 5  10.204.92.105 (10.204.92.105)  2.368 ms  4.382 ms  3.328 ms
 6  1.213.64.165 (1.213.64.165)  2.583 ms
    1.208.64.161 (1.208.64.161)  2.580 ms
    1.213.64.165 (1.213.64.165)  2.552 ms
 7  1.214.58.177 (1.214.58.177)  9.980 ms
    1.209.58.181 (1.209.58.181)  9.874 ms
    1.214.58.205 (1.214.58.205)  9.172 ms
 8  1.208.104.61 (1.208.104.61)  10.285 ms
    1.213.104.61 (1.213.104.61)  9.528 ms  10.819 ms
 9  1.208.148.141 (1.208.148.141)  12.972 ms  10.580 ms  8.417 ms
10  203.233.117.81 (203.233.117.81)  10.343 ms
    203.248.208.229 (203.248.208.229)  18.325 ms
    210.120.117.113 (210.120.117.113)  9.409 ms
```

Hop-by-hop ping

Throughput and Bottleneck

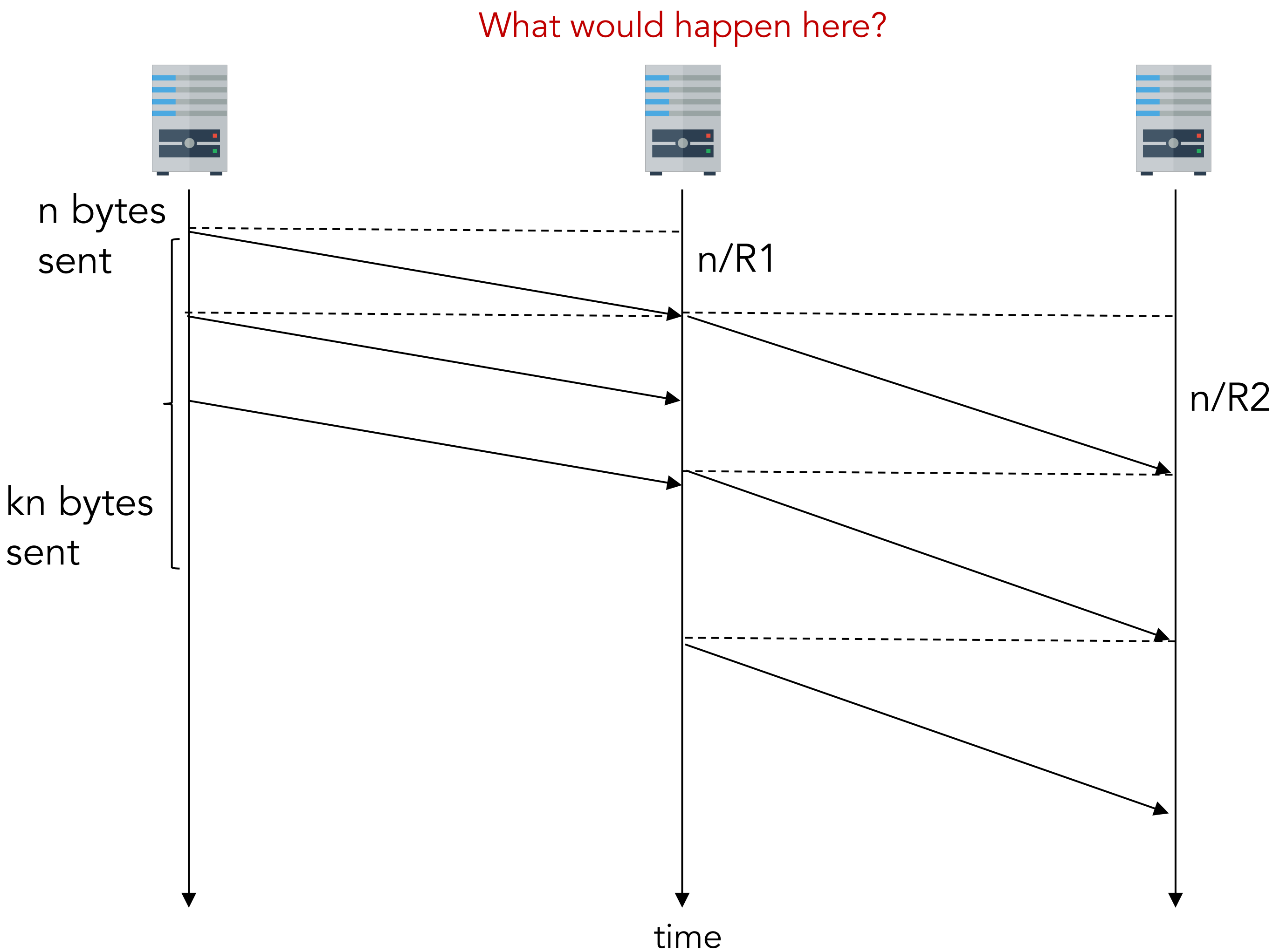
- *Throughput:* rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time

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



- *Bottleneck link*
  - link on e2e path that constrains e2e throughput

Throughput (Illustrated)

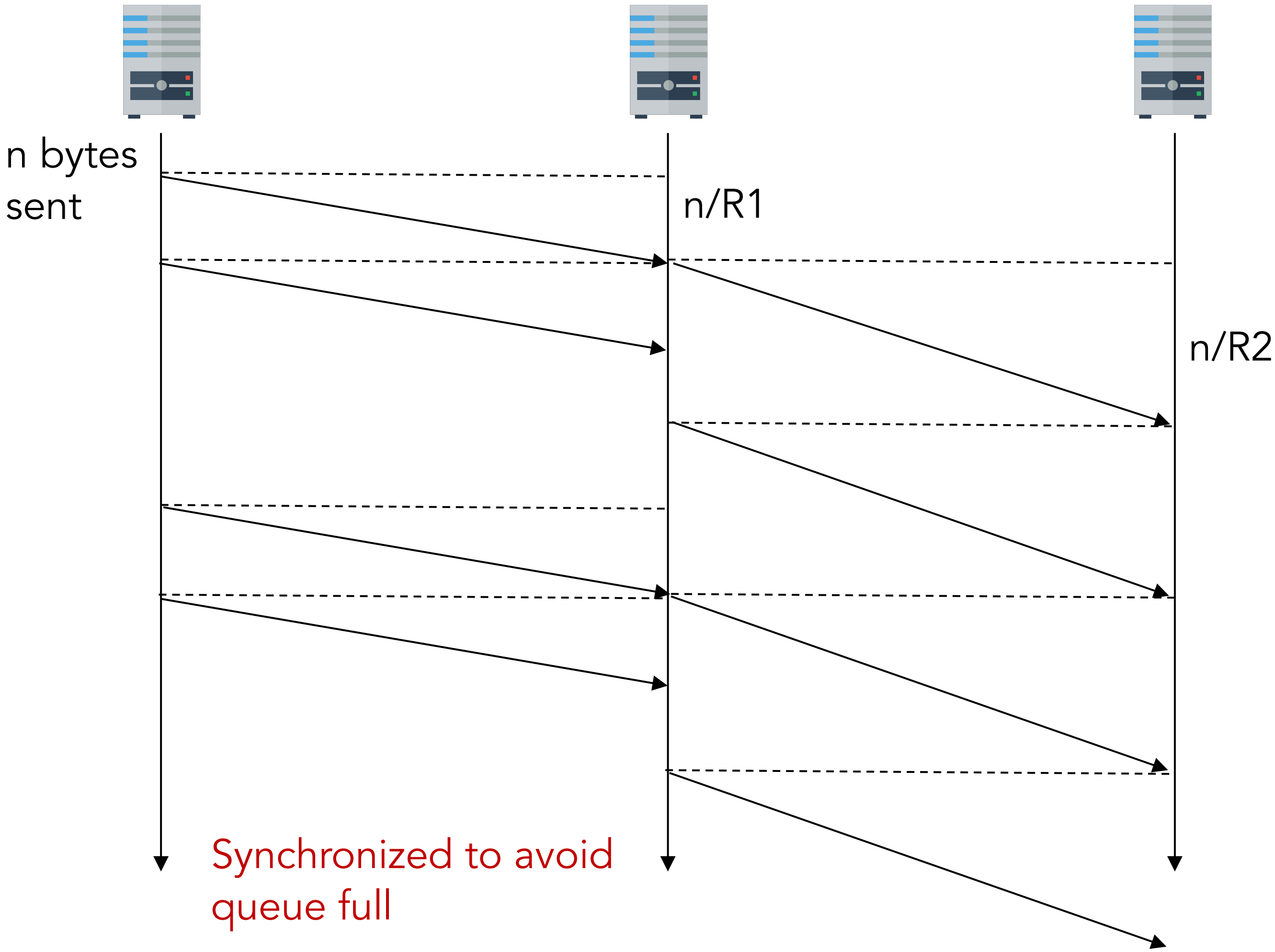


When R1 > R2

Throughput
= n/ (n/R1+n/R2)
= R1R2/(R1+R2)
??

Throughput
= kn/ (n/R1+kn/R2)
= kR1R2/(kR1+R2)
??

Throughput (Illustrated again)

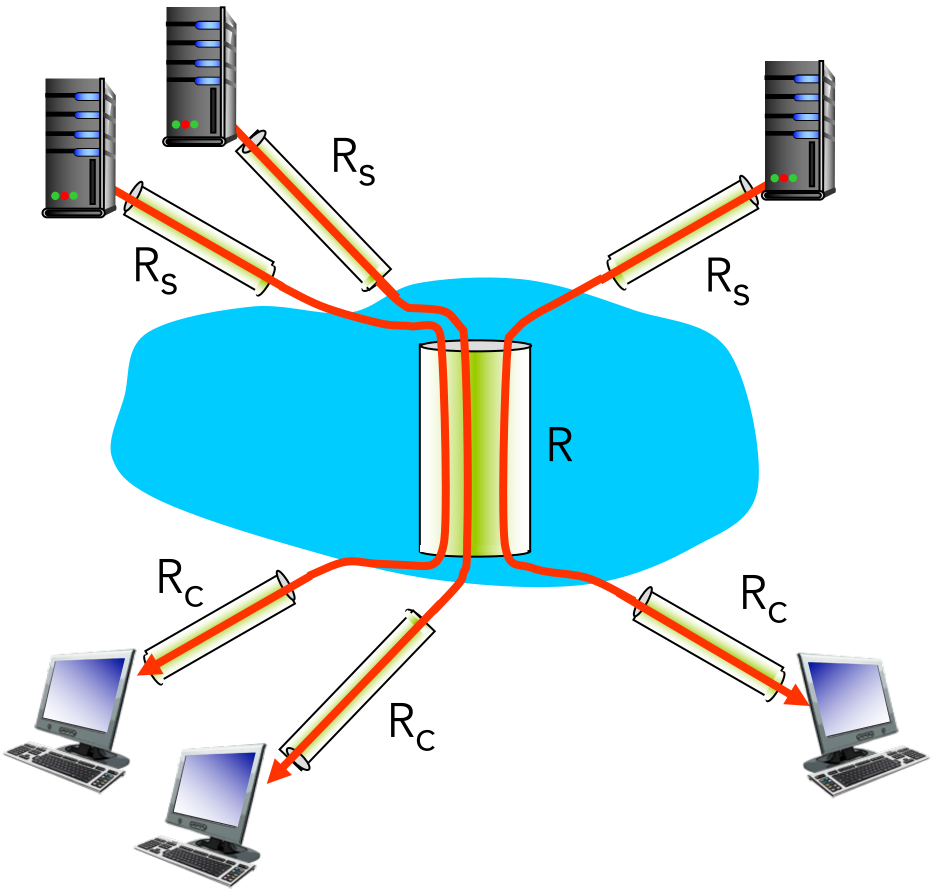


Throughput
= kn/ (n/R1+kn/R2)
= kR1R2/(kR1+R2)
??

What if R1 < R2?

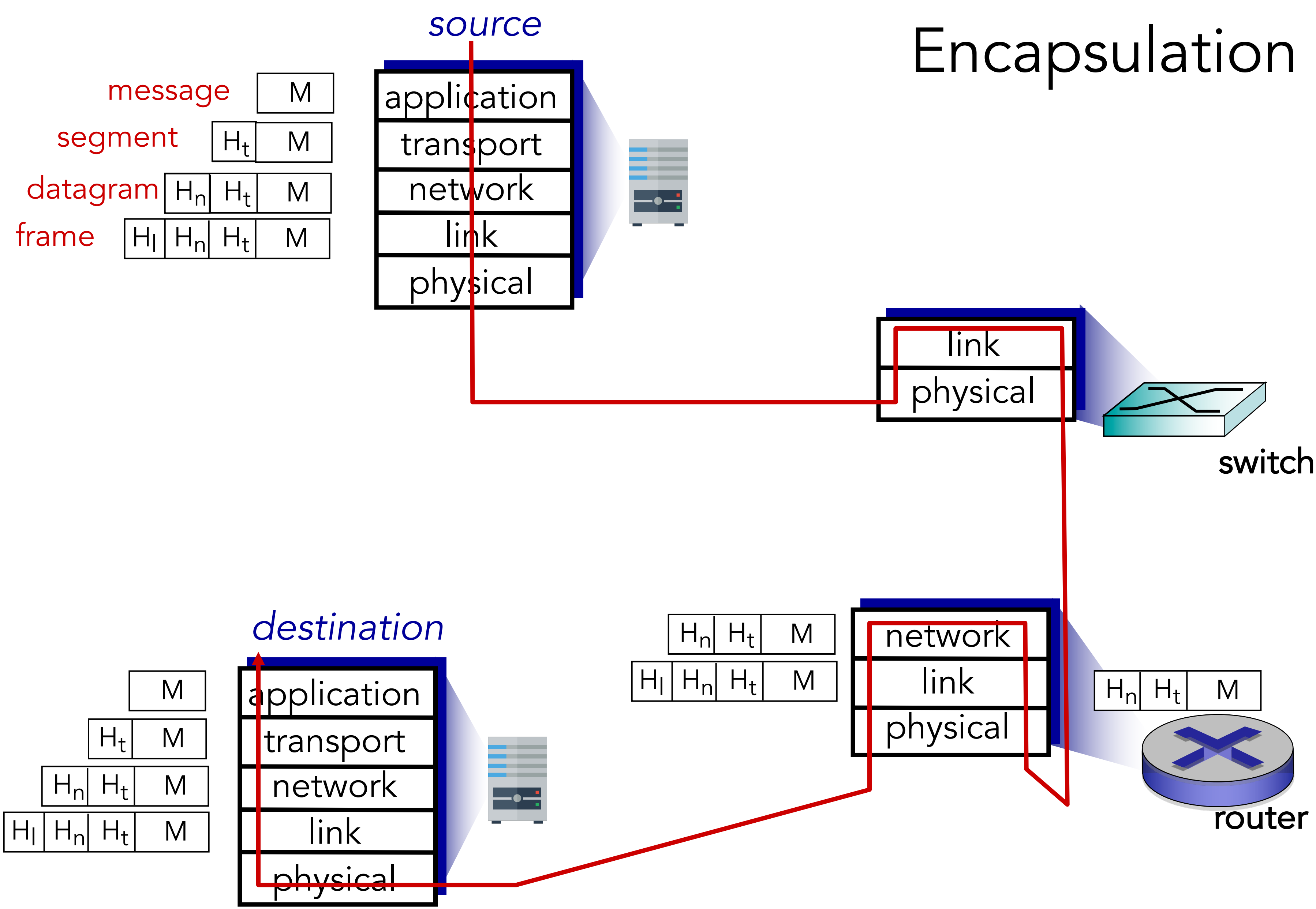
Throughput and Bottleneck

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

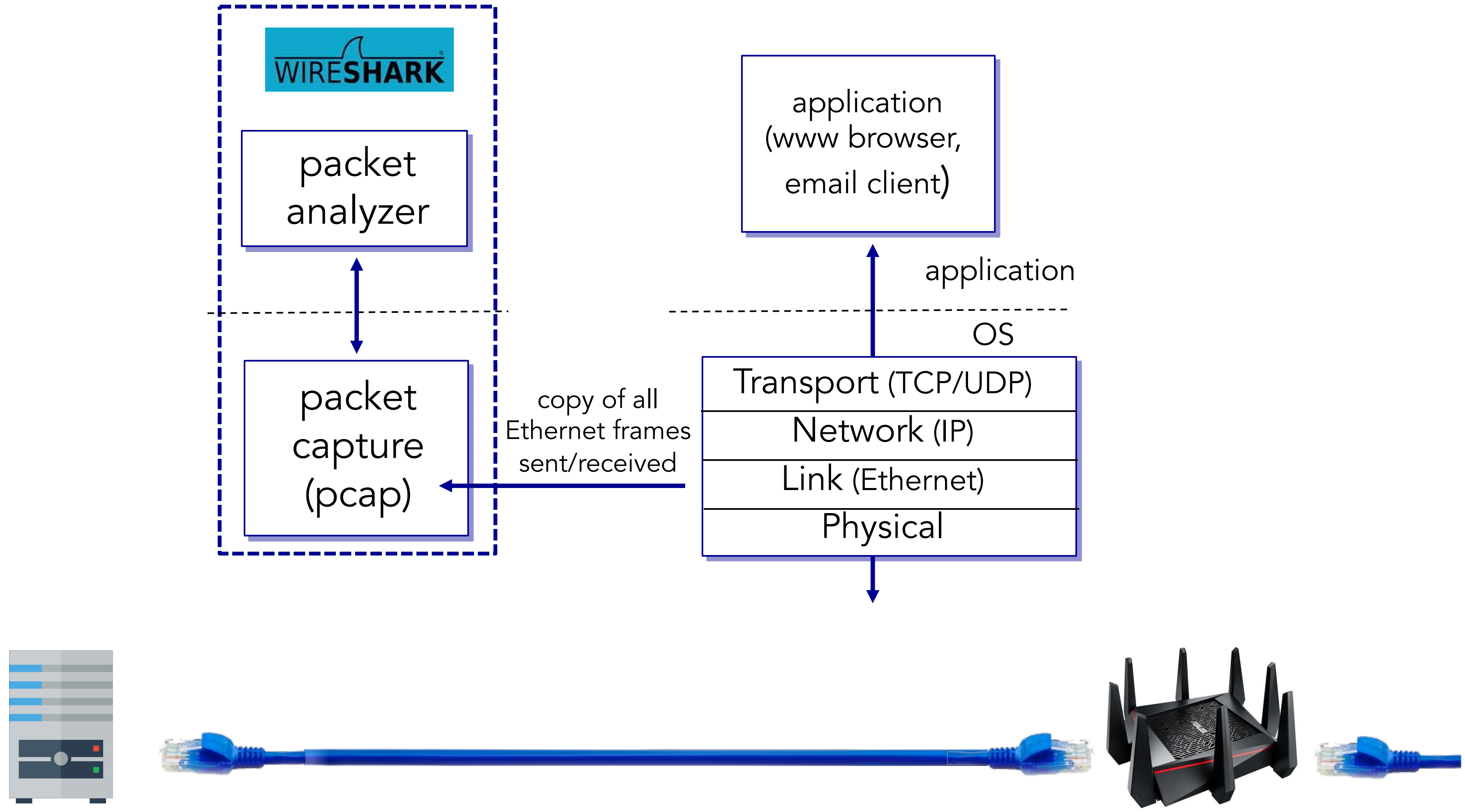


10 connections (fairly) share backbone bottleneck link *R* bits/sec

Encapsulation



Packet Capturing



Internet History (1962-1972: Early Packet-Switching Principles)

- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching

- 1964: Baran - packet-switching in military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational (with 4 nodes)

- 1972:
  - ARPAnet public demo
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes

The ARPANET in December 1969

Internet History
(1972-1980: Internetworking, new and proprietary nets)

- 1970: ALOHAnet satellite network in Hawaii
- 1974: Cerf and Kahn - architecture for interconnecting networks
- 1976: Ethernet at Xerox PARC
- late70s: proprietary architectures: DECnet, SNA, XNA
- late 70s: switching fixed length packets (ATM precursor)
- 1979: ARPAnet has 200 nodes

Cerf and Kahn's internetworking principles:
- minimalism, autonomy - no internal changes required to interconnect networks
- best effort service model
- stateless routers
- decentralized control

define today's Internet architecture

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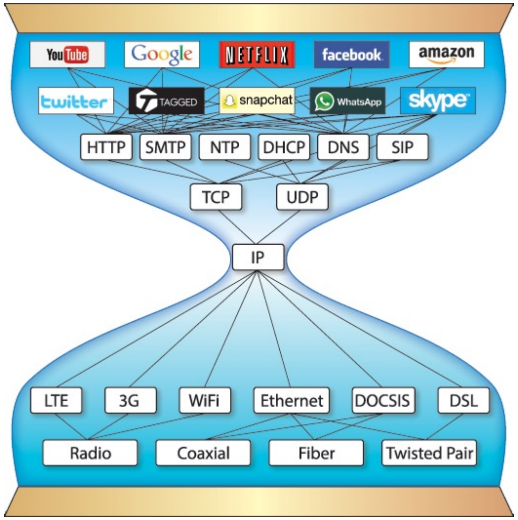
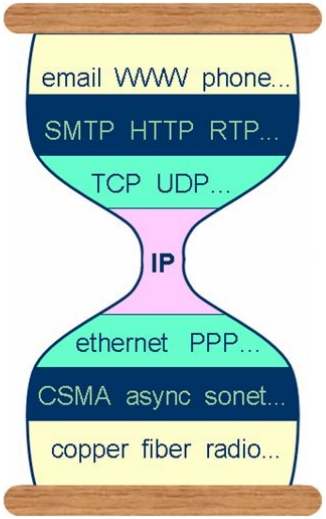
Internet History
(1980-1990: new protocols, a proliferation of networks)

- 1983: deployment of TCP/IP
- 1982: smtp e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: FTP protocol defined
- 1988: TCP congestion control

- new national networks: CSnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks





Drawing from Johann Schleier-Smith

Internet History
(1990s, 2000s: commercialization, the Web, new apps)

- Early 1990s: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned, 1995)
- Early 1990s : Web
  - hypertext [Bush 1945, Nelson 1960s]
  - 1990: HTML, HTTP by Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990s: commercialization of the Web
- Late 1990s – 2000s:
  - more killer apps: instant messaging, P2P file sharing
  - network security to forefront
  - est. 50 million host, 100 million+ users
  - backbone links running at Gbps

Internet History (2005-present)

- ~5B devices attached to Internet (2016)
  - smartphones and tablets
- Aggressive deployment of broadband access
- Increasing ubiquity of high-speed wireless access
- Emergence of online social networks:
  - Facebook: ~ one billion users
- Service providers (Google, Microsoft) create their own networks
  - bypass Internet, providing "instantaneous" access to search, video content, email, etc.
- e-commerce, universities, enterprises running their services in "cloud" (e.g., Amazon EC2)

Reading Assignment #2 – Chapter 2

Quiz #1: 9/30 (covering chapters 1 and 2, 4-5 questions, 40 mins, Lecture will follow)

Sample question: What are the advantages and the disadvantages of packet-switched networks over circuit-switched networks?