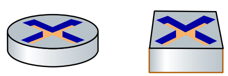
The Internet: a "Nuts And Bolts" View

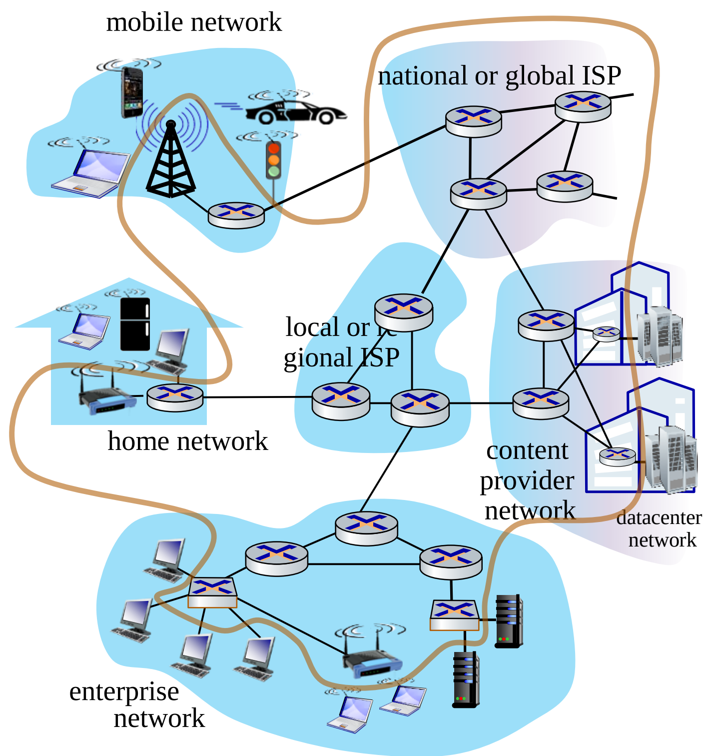
Billions of connected computing *devices*:
- *hosts = end systems*
- running *network apps* at Internet's "edge"



Packet switches: forward packets (chunks of data)
- *routers, switches*

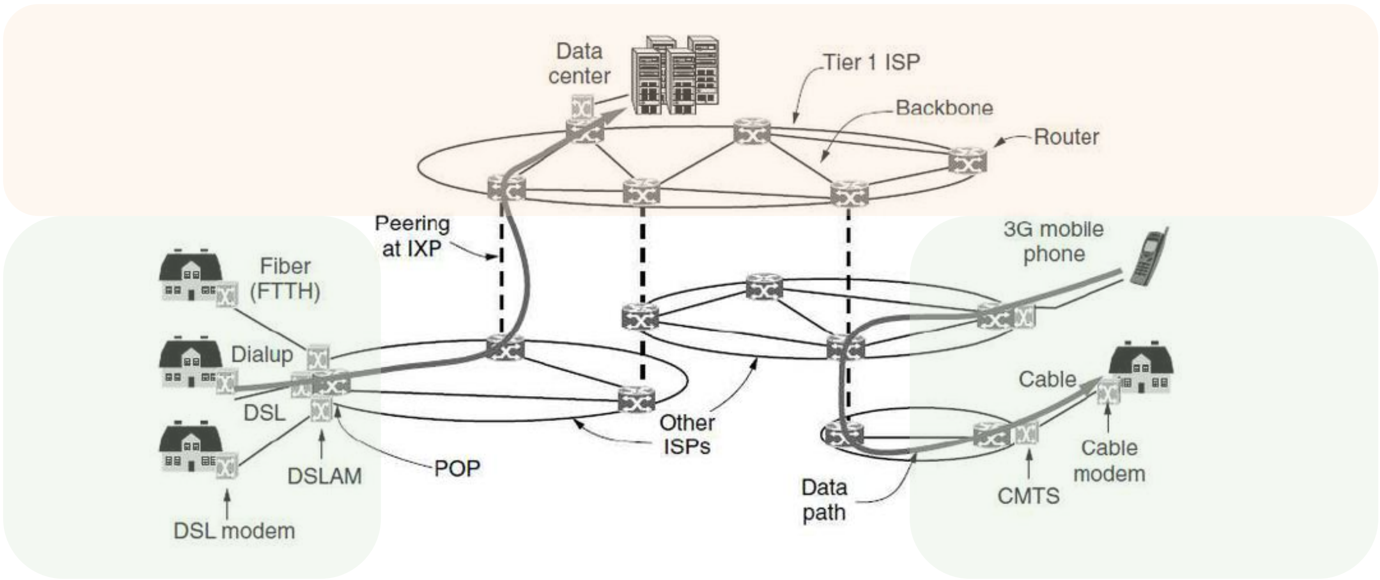
Communication links
- fiber, copper, radio, satellite
- transmission rate: *bandwidth*

Networks
- collection of devices, routers, links: managed by an organization



Network Core/Edge

- *Network core:*
  - interconnected routers
  - network of networks

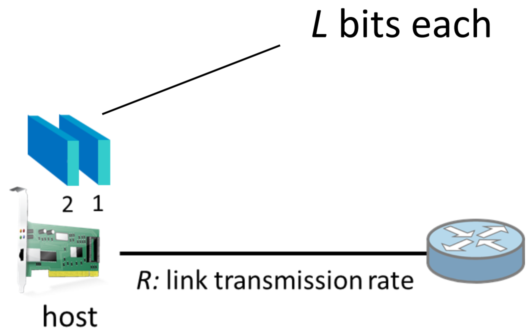


- *Network edge:*
  - hosts: clients and servers
  - servers often in data centers
- *Access network (last-mile network)*

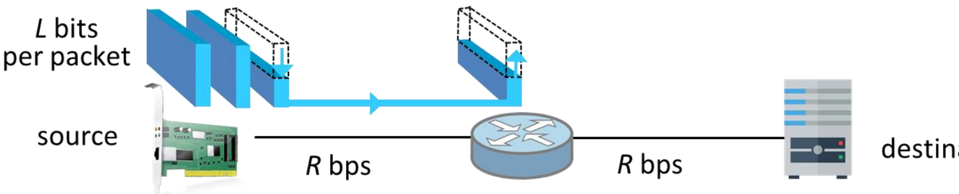
Network Core

Transmission delay:

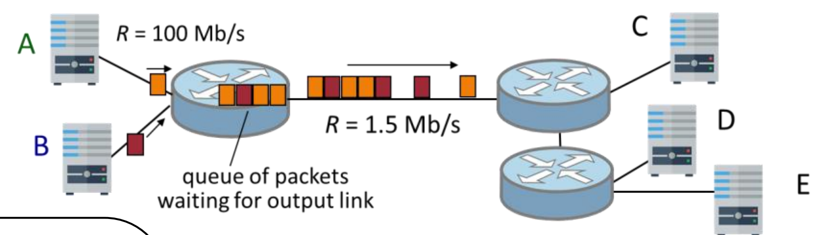
packet transmission delay = time needed to transmit *L*-bit packet into link = $\frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$



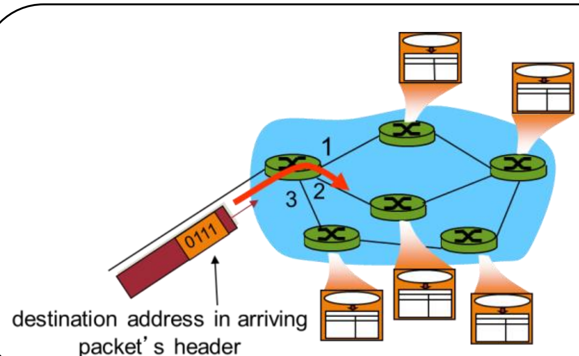
store and forward: entire packet must arrive at router before it can be transmitted on next link



queuing and loss: if arrival rate (in bits) to link exceeds transmission rate of link for a period of time



Packet Switching & Routing



Introduction

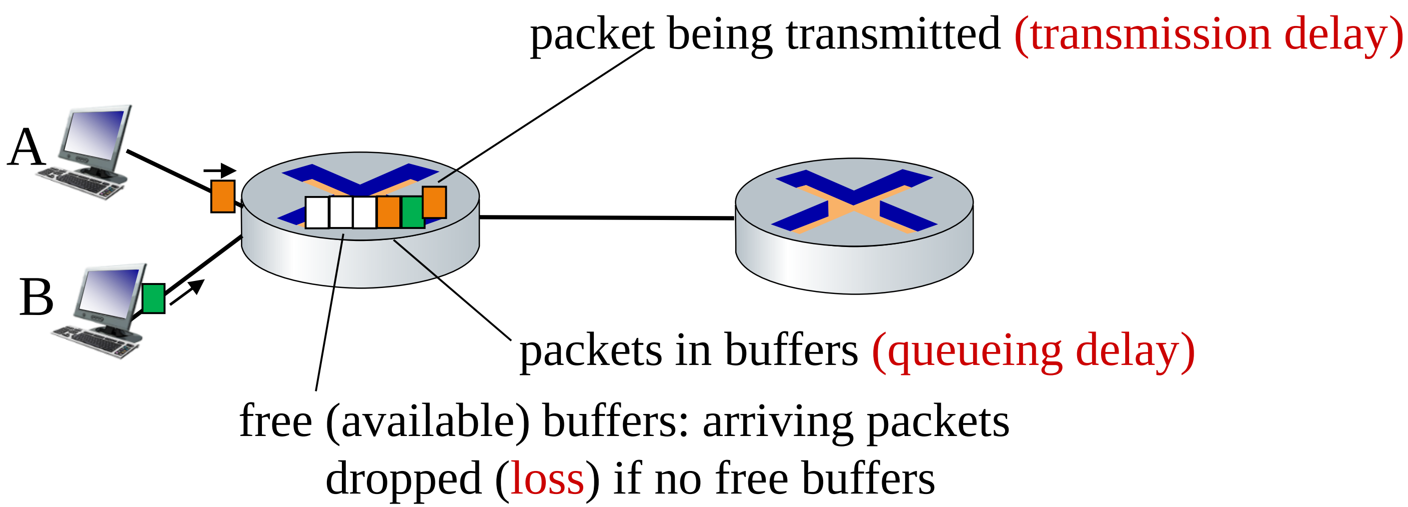
CSE351

Computer Networks

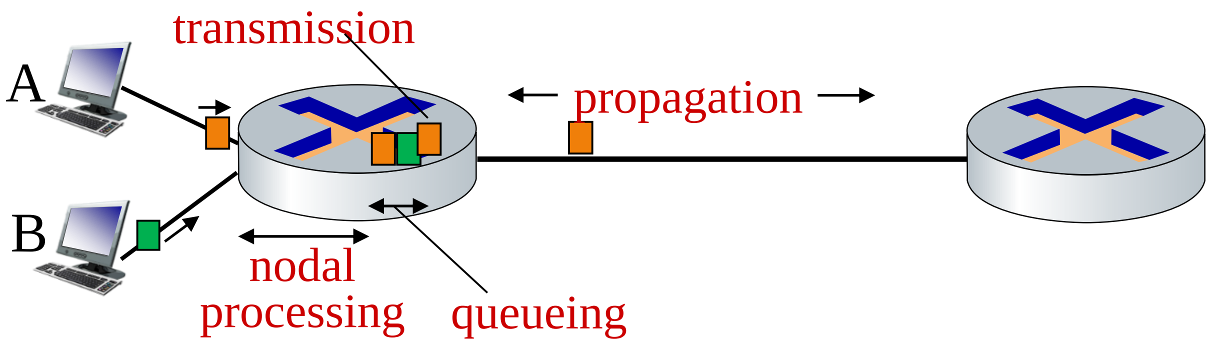
How do loss and delay occur?

packets *queue* in router buffers

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



Packet Delay: four sources



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

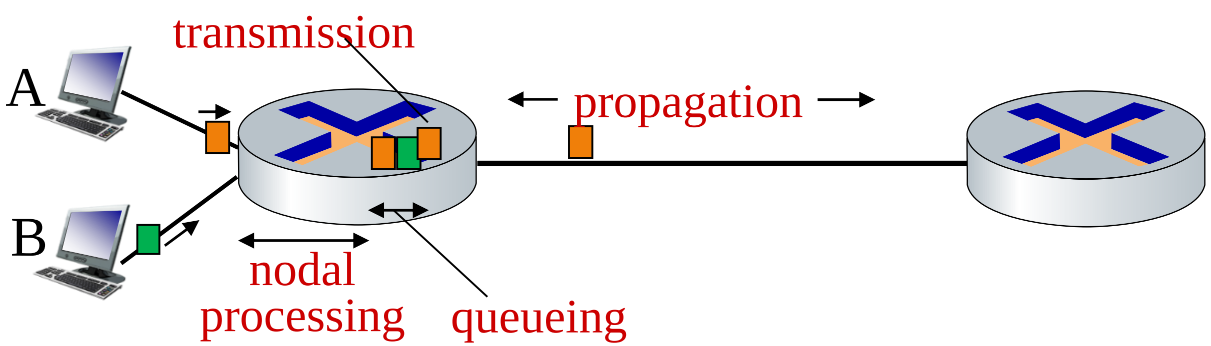
d_{proc}: nodal processing

- 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

Packet Delay: four sources



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

d_{trans}: transmission delay:

- L: packet length (bits)
- R: link *transmission rate (bps)*
- $d_{\text{trans}} = L/R$

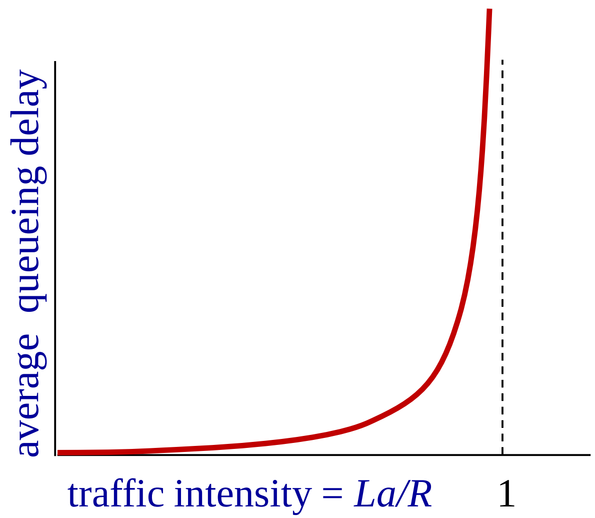
d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed (~2×10^8 m/sec)
- $d_{\text{prop}} = d/s$

d_{trans} and d_{prop} *very* different

* Check out the online interactive exercises: http://gaia.cs.umass.edu/kurose_ross

Queueing Delay (revisited)



- *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 servi ced - average delay infinite!

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
```

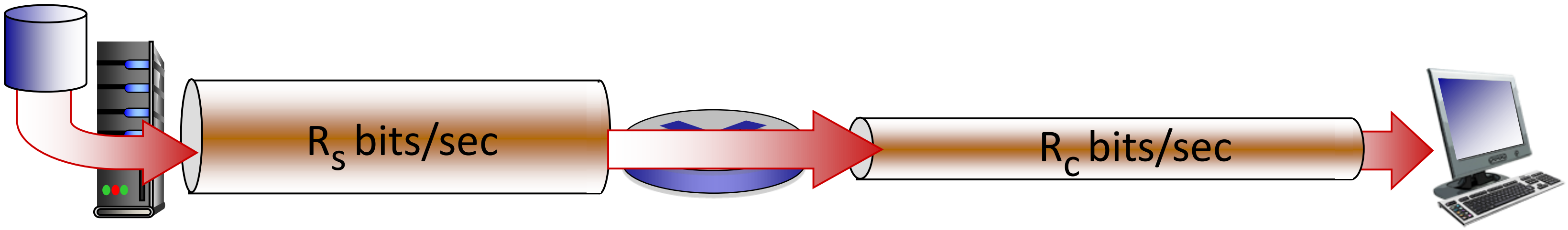
traceroute www.google.com

```
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?

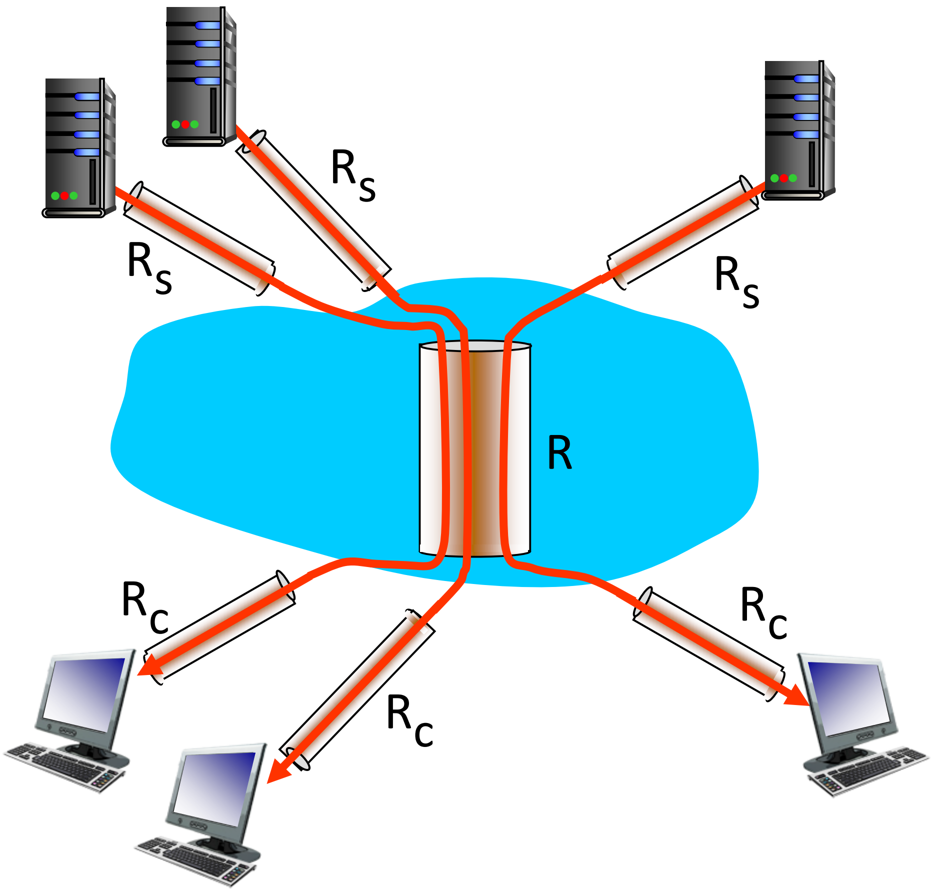


- *Bottleneck link*
  - link on e2e path that constrains e2e throughput

Throughput and Bottleneck

- Per-connection end-end throughput: $min(R_c,R_s,R/10)$

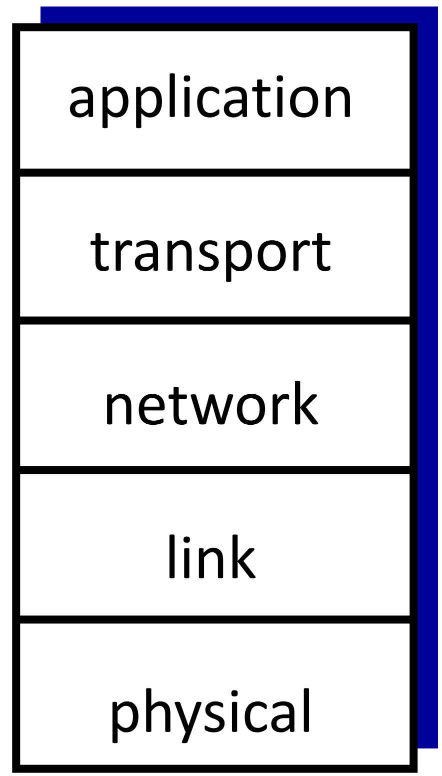
- In practice: R_c or R_s is often bottleneck

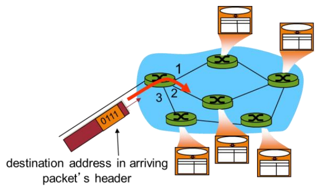


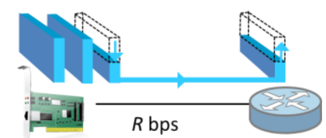
10 connections (fairly) share backbone link of *R* bits/sec

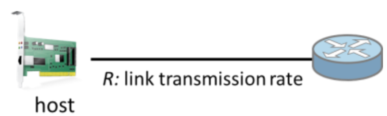
Internet Protocol Stacks (Layering)

- *application:* supporting network applications
  - FTP, SMTP, HTTP
- *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, 802.11 (WiFi), Bluetooth
- *physical:* bits "on the wire"

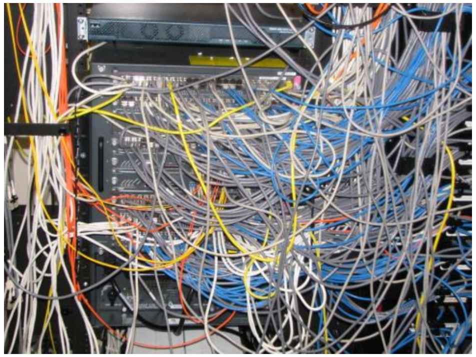


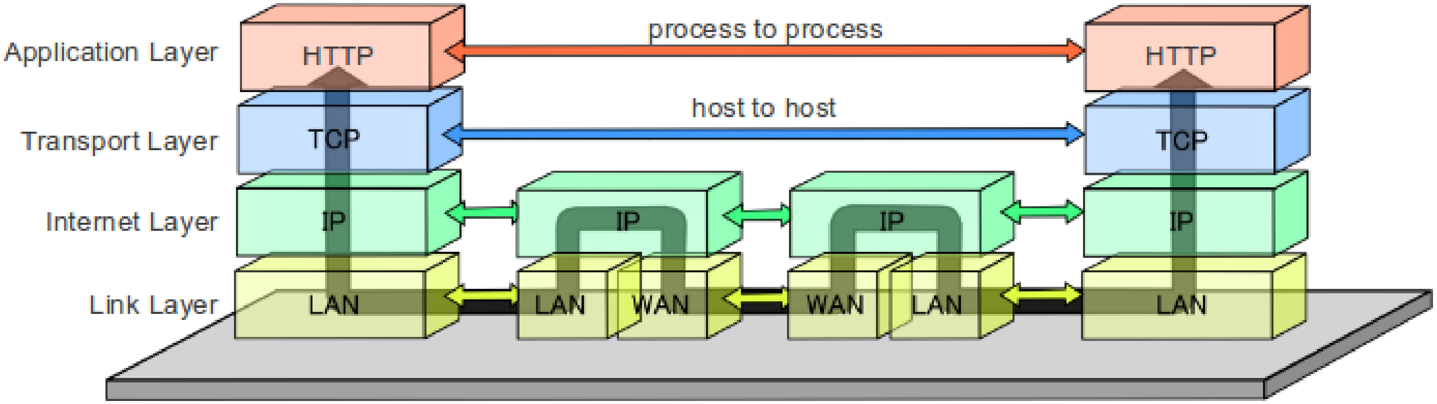




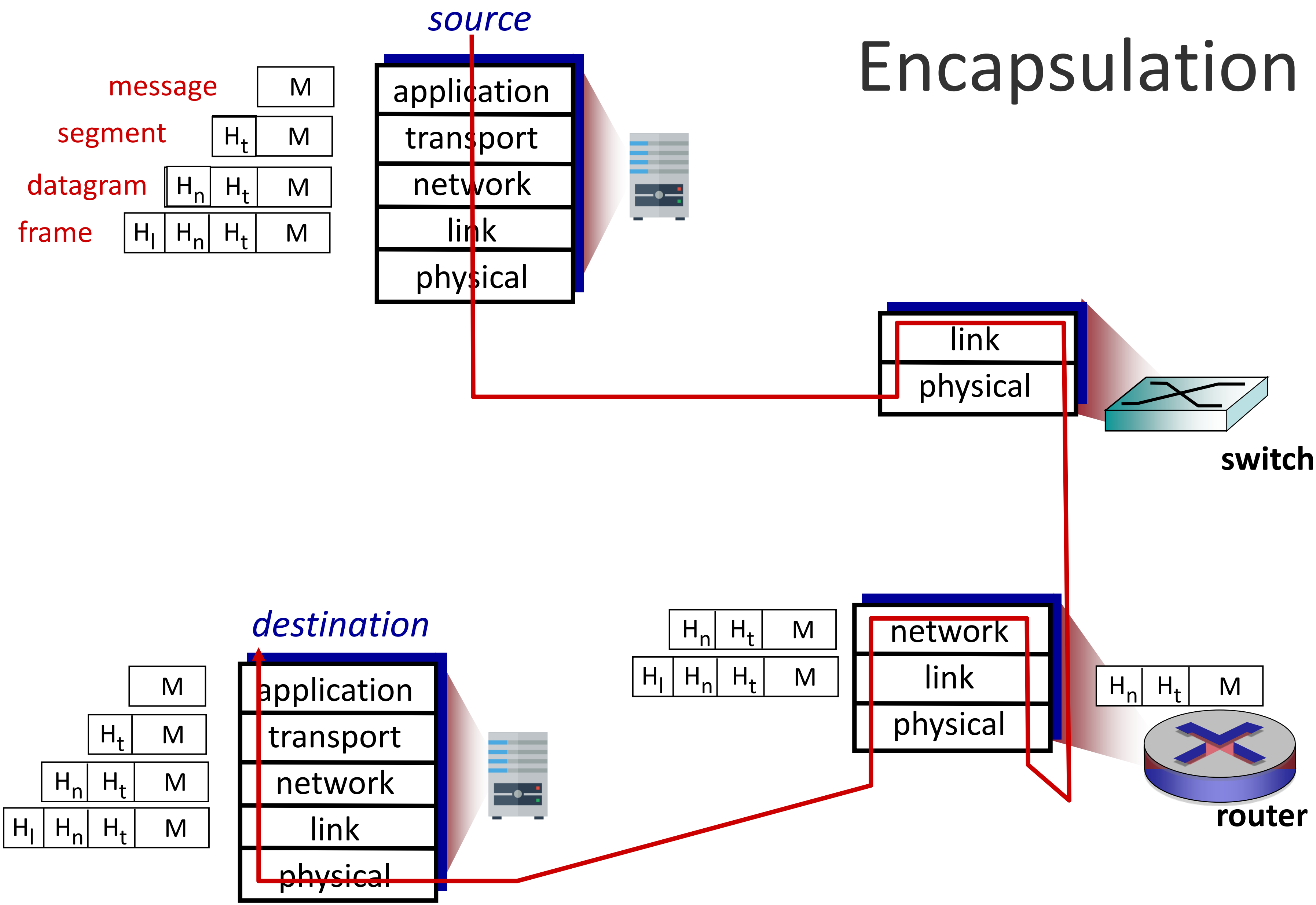


Communication over the Internet

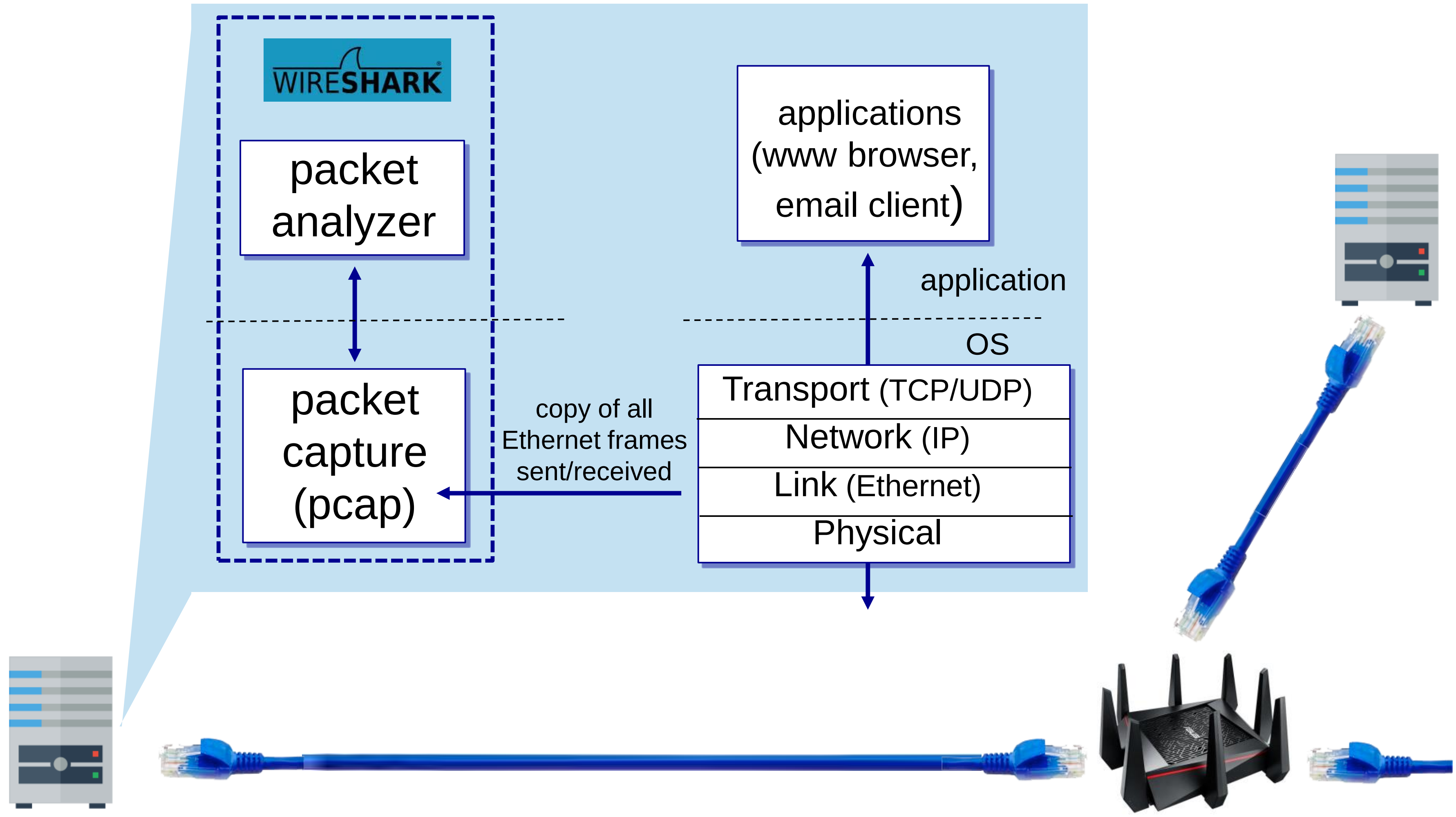




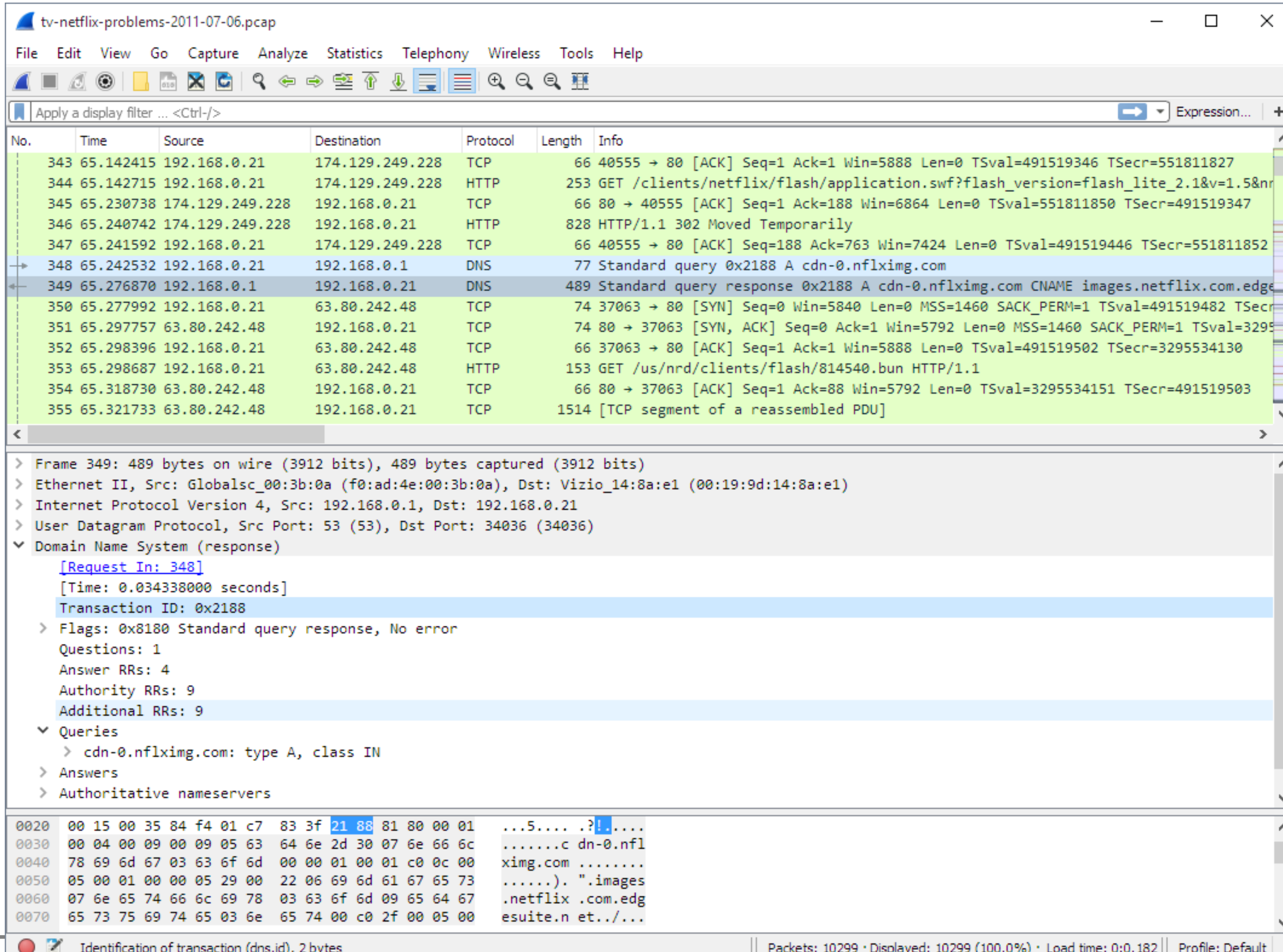
Encapsulation



Packet Capturing



Packet Capturing

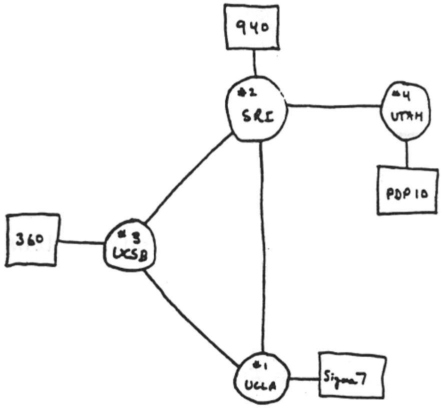


Internet History

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



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
- late70's: proprietary architectures: DECnet, SNA, XNA
- late 70's: 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

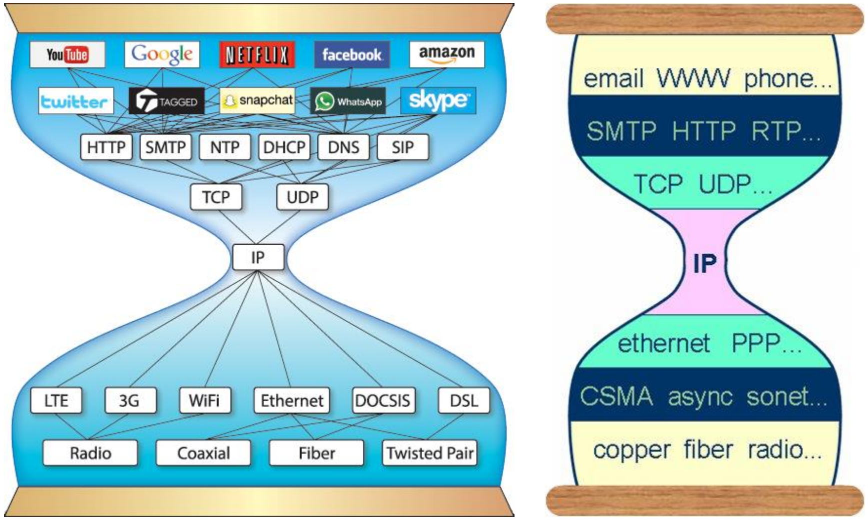
define today's Internet architecture

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

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

- Early 1990's: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned, 1995)
- Early 1990's : Web
  - hypertext [Bush 1945, Nelson 1960's]
  - HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990's: commercialization of the Web

- Late 1990's – 2000's:
  - 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)