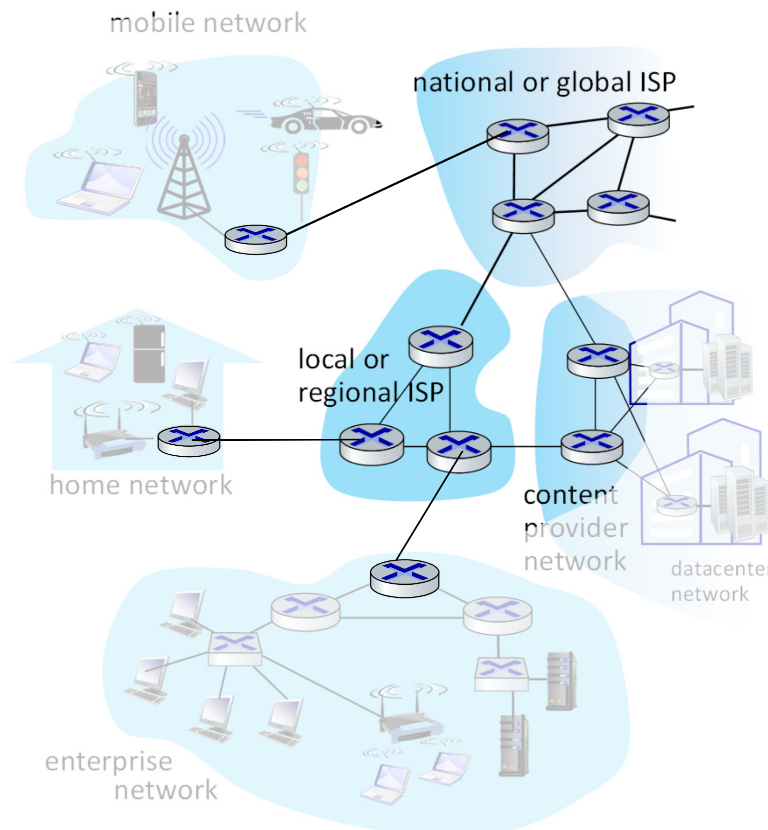
Chapter 1: roadmap

- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Security
- Protocol layers, service models
- History

The network core

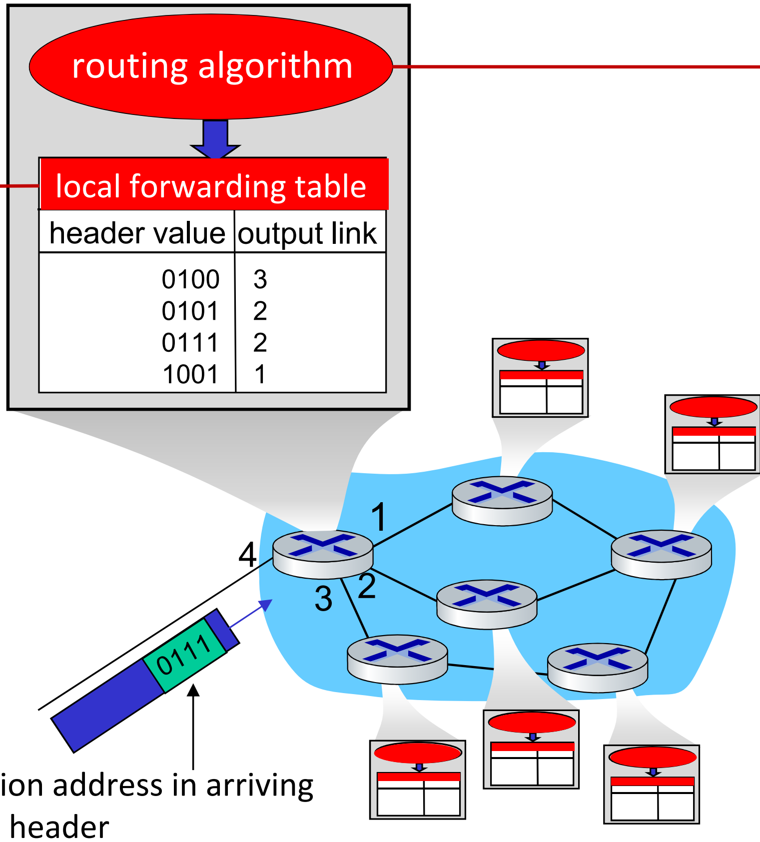
- composed of mesh of interconnected routers
- main goal: transfer data (for multiple sources-destination pairs) through network
  - circuit switching: dedicated circuit per call
  - packet switching: network forwards packets from one router to the next router, across *shared links* on path from source to destination



Two key network-core functions

Forwarding:

- aka "switching"
- *local* action: move arriving packets from router's input link to appropriate router output link



Routing:

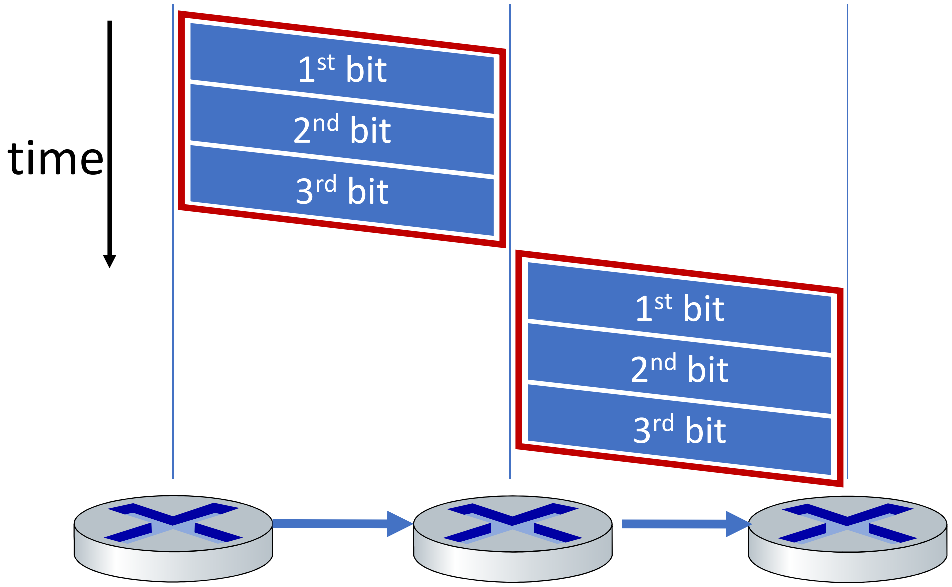
- *global* action: determine source-destination paths taken by packets
- routing algorithms


routing
45 h
3,053 miles
48 h
3,309 miles
United States
Victoria
Seattle
WASHINGTON
Portland
OREGON
IDAHO
MONTANA
WYOMING
NORTH DAKOTA
SOUTH DAKOTA
MINNESOTA
Minneapolis
WISCONSIN
MICHIGAN
IOWA
Chicago
Detroit
Toronto
Ottawa
Montreal
Quebec City
VERMONT
NEW HAMPSHIRE
MAINE
Northampton
CT
RI
New York
PENNSYLVANIA
Philadelphia
NJ
MARYLAND
DE
OHIO
INDIANA
Indianapolis
ILLINOIS
Kansas City
MISSOURI
NEVADA
UTAH
COLORADO
Sacramento
San Francisco
San Jose
CALIFORNIA
Las Vegas
Los Angeles
San Diego
ARIZONA
Phoenix
Tucson
NEW MEXICO
El Paso
OKLAHOMA
ARKANSAS
TEXAS
Dallas
Austin
Houston
San Antonio
LOUISIANA
New Orleans
MISSISSIPPI
ALABAMA
GEORGIA
Atlanta
TENNESSEE
Nashville
KENTUCKY
WEST VIRGINIA
VIRGINIA
NORTH CAROLINA
Charlotte
SOUTH CAROLINA
Jacksonville
Orlando
Tampa
FLORIDA
BAJA CALIFORNIA
SONORA
CHIHUAHUA
COAHUILA

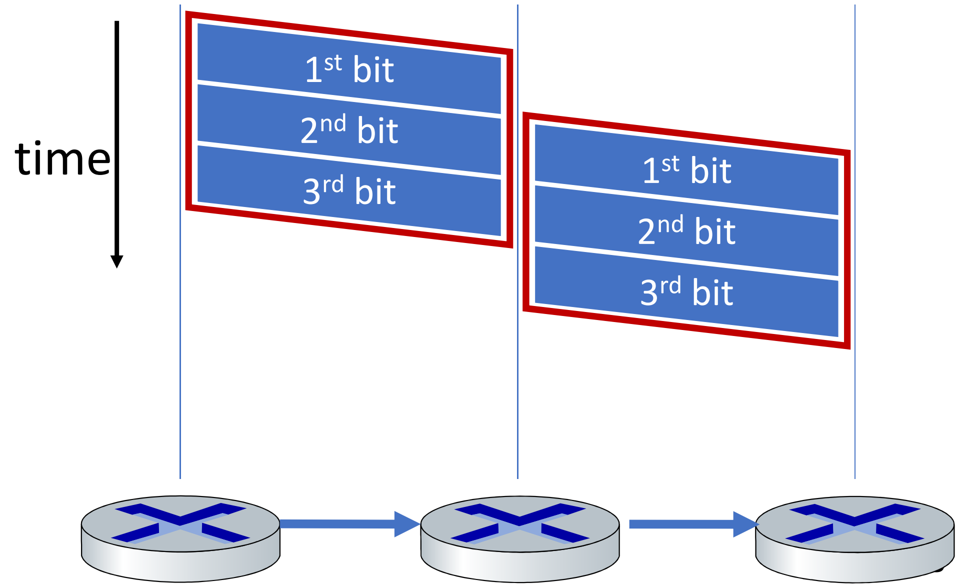

forwarding
forwarding
45 h
3,053 miles
48 h
3,309 miles
San Jose
Northampton
United States
Cleveland
Sacramento

Packet switching: store-and-forward (mostly)

- store-and-forward
  - *entire* packet must arrive at router (and integrity is verified) before it can be transmitted on next link.

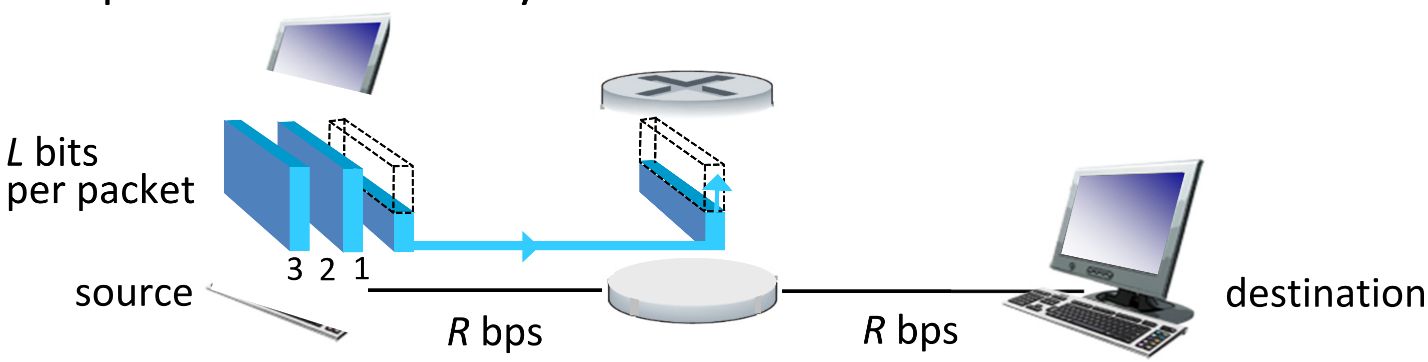


- cut-through
  - starts forwarding a packet before the whole packet has been received

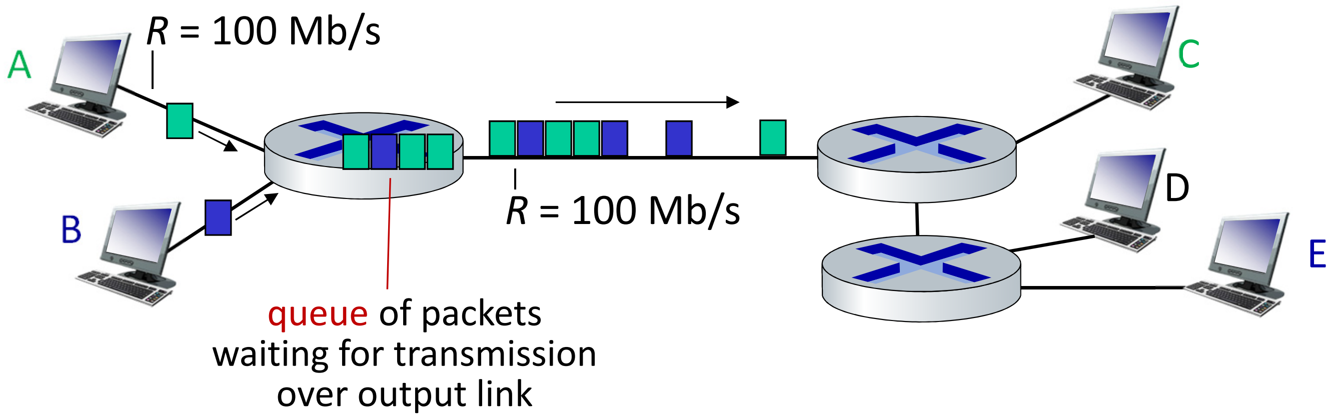


Packet switching: transmission delay

- transmission delay of a *L*-bit packet over a *R*-bps link
  - It takes *L*/*R* seconds
- transmission delay **caused by store-and-forward**
  - example: *L* = 10 Kbits and *R* = 100 Mbps
    - 1-hop transmission delay = 0.1 msec
    - 2-hop transmission delay = 0.2 msec

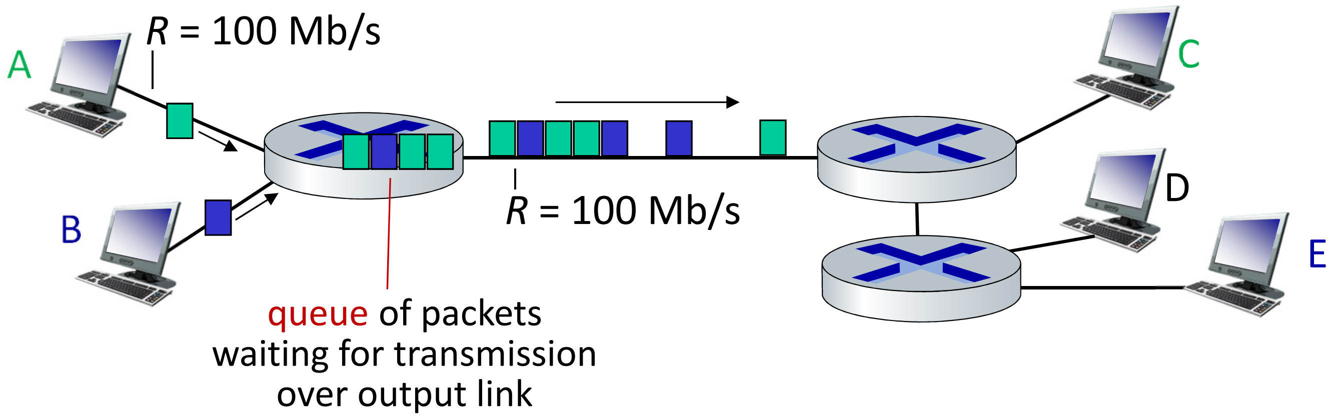


Packet switching: queueing



Queueing occurs when work arrives faster than it can be serviced:

Packet switching: queueing



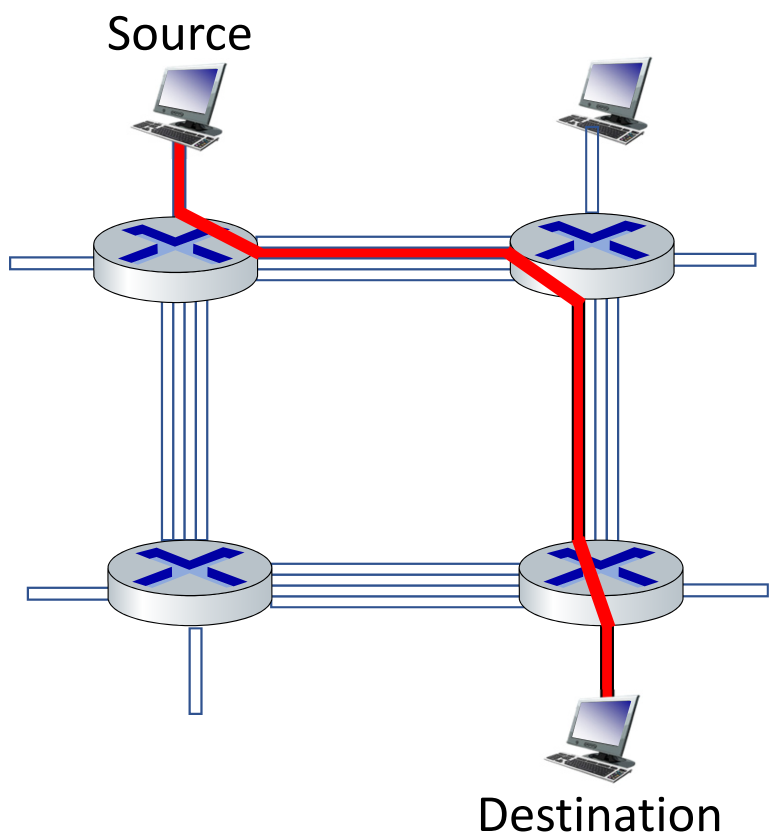
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up

Alternative to packet switching: circuit switching

end-to-end resources allocated to and reserved for a "call" between source and destination

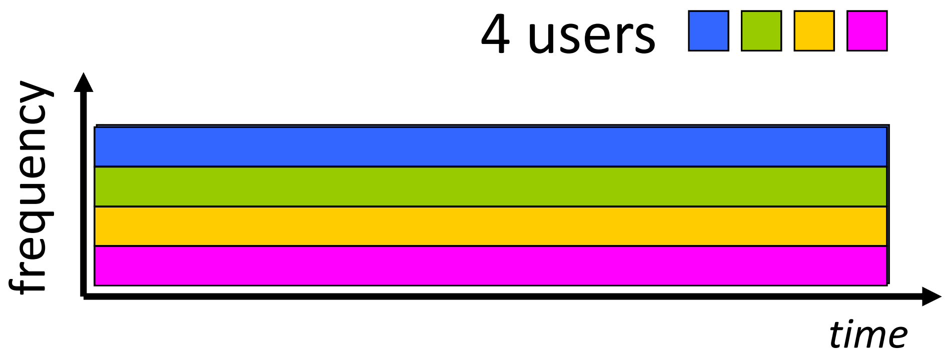
- in diagram, each link has four circuits.
  - The call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idles if not used by call
- commonly used in traditional telephone networks



Circuit switching: FDM and TDM

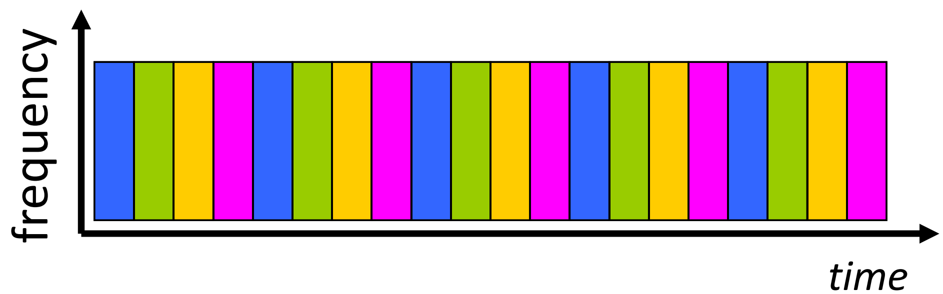
Frequency Division Multiplexing (FDM)

- optical, electromagnetic frequencies divided into (narrow) frequency bands
- each call is allocated its own band and thus can transmit at max rate of that narrow band



Time Division Multiplexing (TDM)

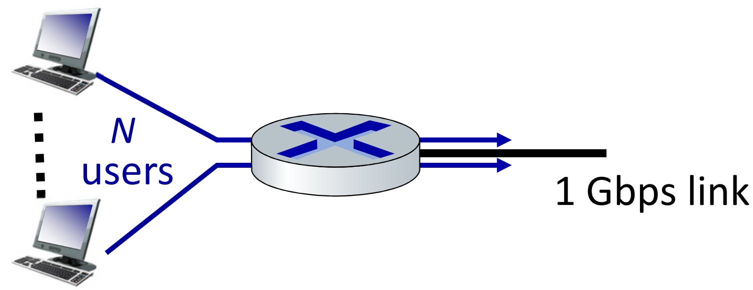
- time divided into slots
- each call is allocated periodic slot(s) and can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



Packet switching versus circuit switching

example:

- 1 Gb/s link
- each user:
  - 100 Mb/s when “active”
  - active 10% of time



Q: how many users can use this network under circuit-switching and packet switching?

- *circuit switching:*
  - at most ___ users
- *packet switching:*
  - at most ___ users

- *packet switching:*
  - with 35 users, the probability of >10 active users at same time is roughly 0.0004

Packet switching versus circuit switching

Is packet switching a "slam dunk winner"?

- great for "bursty" data – sometimes has data to send, but at other times not
  - allow more concurrent users
  - better resource sharing
  - simpler, no call setup
- excessive congestion is possible: packet delay and loss due to buffer overflow
  - protocols needed for reliable data transfer and congestion control
- *Q:* How to provide circuit-like behavior with packet switching?
  - "It's complicated." We'll study various techniques that try to make packet switching as "circuit-like" as possible.

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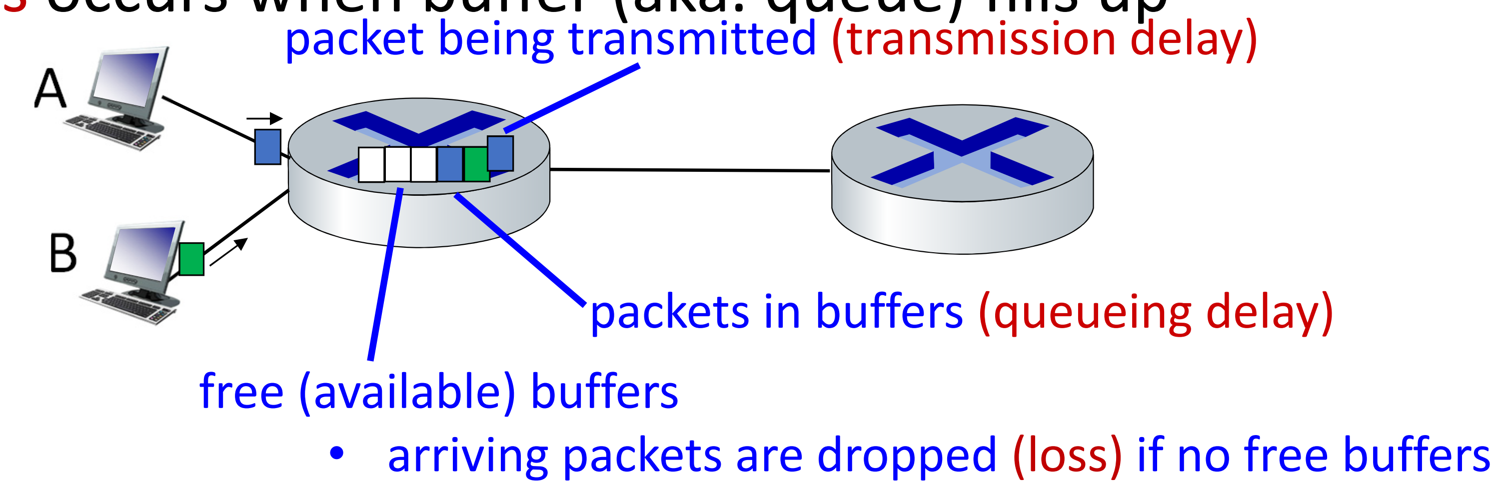
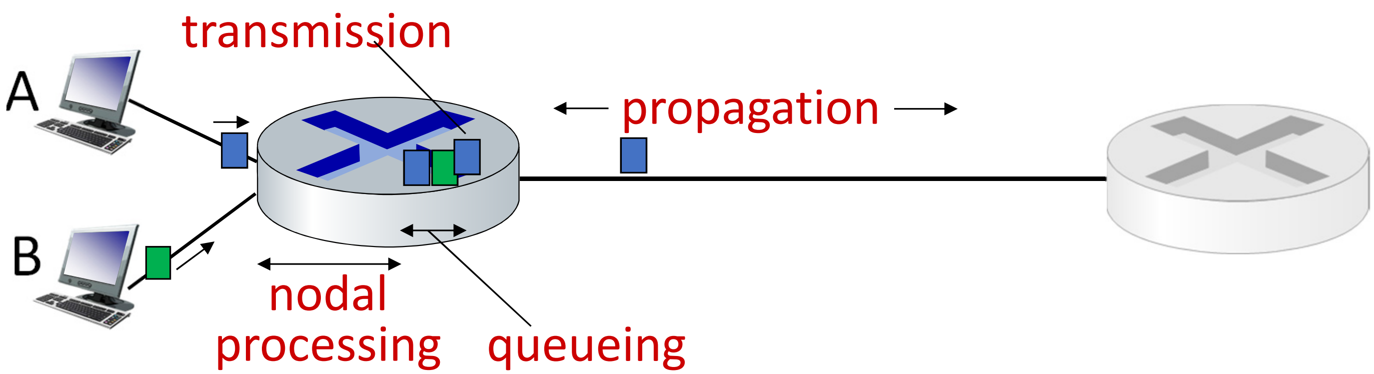
How do packet delay and loss occur?

- packets *queue* in router buffers, waiting for turn for transmission
  - queue length grows when arrival rate to link (temporarily) exceeds output link capacity
- packet loss occurs when buffer (aka. queue) fills up



Packet delay: four sources



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

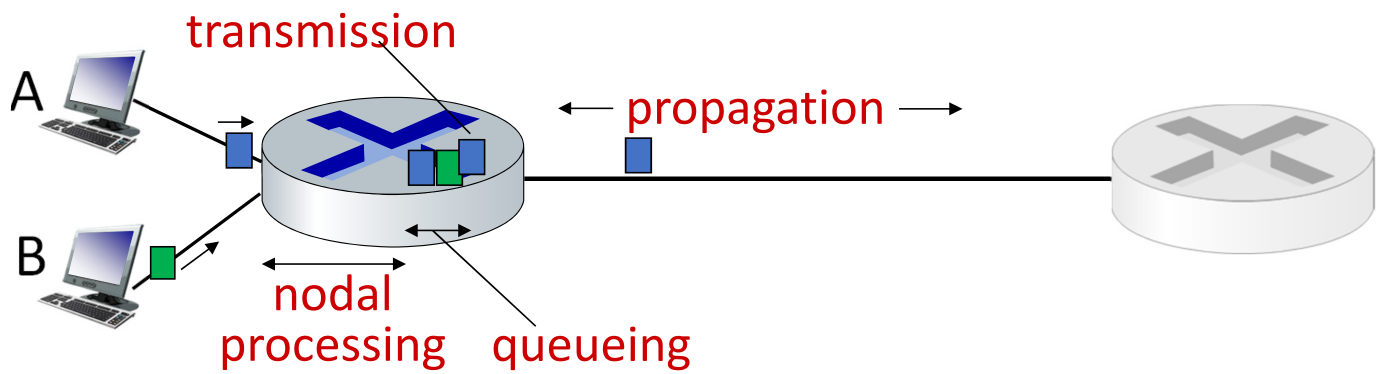
d_{proc}: nodal processing

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

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)*
- $d_{trans} = L/R$

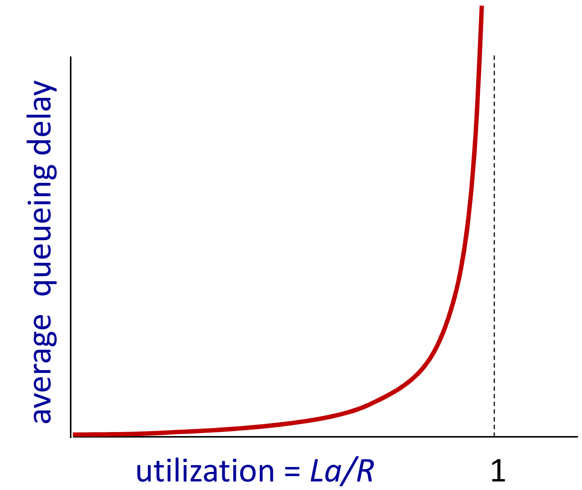
d_{prop}: propagation delay

- d: length of physical link
- s: propagation speed (~2x10^8 m/sec)
- $d_{\text{prop}} = d/s$

Queueing delay (revisited)

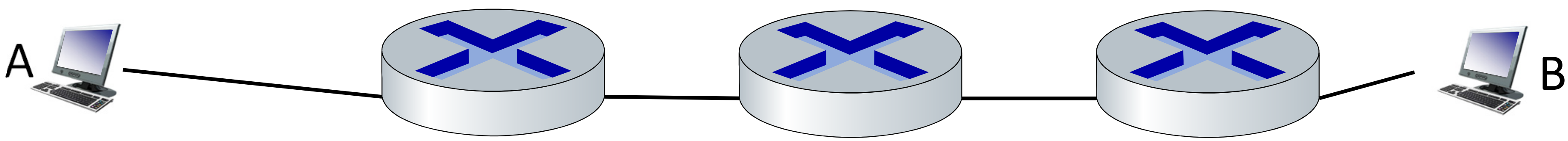
- *a:* average packet arrival rate (packets/s)
- *L:* packet length (bits/packet)
- *R:* link bandwidth [aka. transmission rate] (bits/s)

$$\frac{L \cdot a}{R} : \frac{\text{arrival rate in bits/s}}{\text{service rate in bits/s}}$$ *"utilization"*



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

End-to-end delay

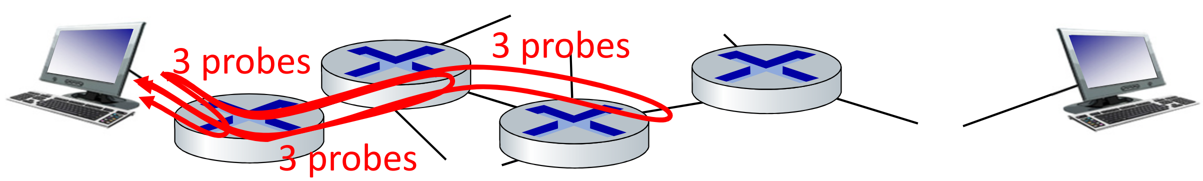


$$\underbrace{\qquad}_{d_{N_1}} \quad \underbrace{\qquad}_{d_{N_2}} \quad \underbrace{\qquad}_{d_{N_3}} \quad \underbrace{\qquad}_{d_{N_4}}$$

End-to-end delay from A to B $= \; d_{N_1} + d_{N_2} + d_{N_3} + d_{N_4}$

“Real” Internet delays and routes

- what do “real” Internet delay & loss look like?
- **traceroute** (or tracert) program: provides delay measurement from source to each router along the path towards destination. For each router *i:*
  - sends three packets that will reach router *i* on path towards destination (with time-to-live field value of *i*)
  - router *i* will return packets to sender
  - sender measures time interval between transmission and reply



Real Internet delays and routes

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

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

3 delay measurements
to border1-rt-fa5-1-0.gw.umass.edu

trans-oceanic link

looks like delays
decrease! Why?

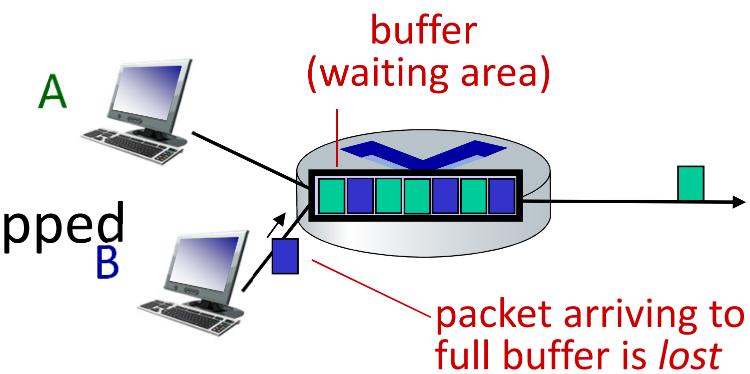
```
1  cs-gw (128.119.240.254)  1 ms  1 ms  2 ms
2  border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)  1 ms  1 ms  2 ms
3  cht-vbns.gw.umass.edu (128.119.3.130)  6 ms 5 ms 5 ms
4  jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)  16 ms 11 ms 13 ms
5  jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)  21 ms 18 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
```

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

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

Packet loss

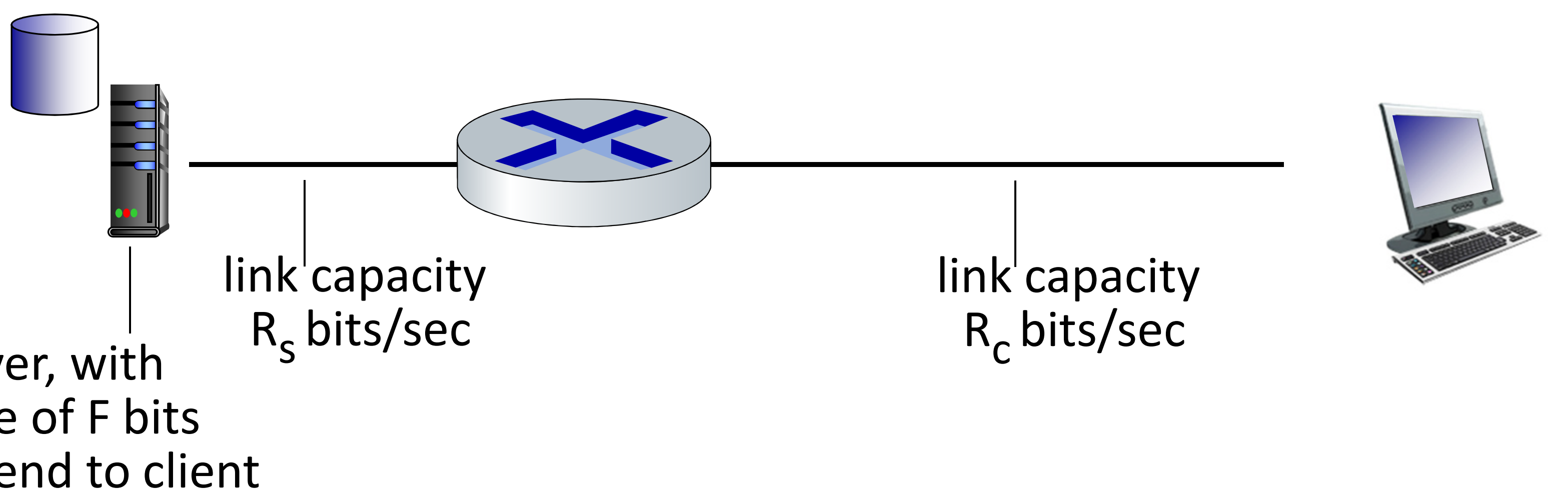
- As aforementioned,
  - queue (aka buffer) has finite capacity
  - packet that arrives to a full buffer is dropped



- lost packet may be retransmitted
  - by previous node,
  - by source end system,
  - or not at all

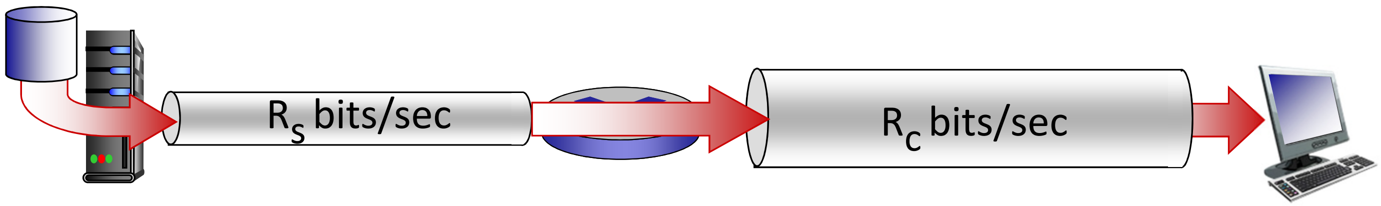
Throughput

- *throughput:* rate (bits/s) at which bits are being received at the destination
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time



Throughput

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



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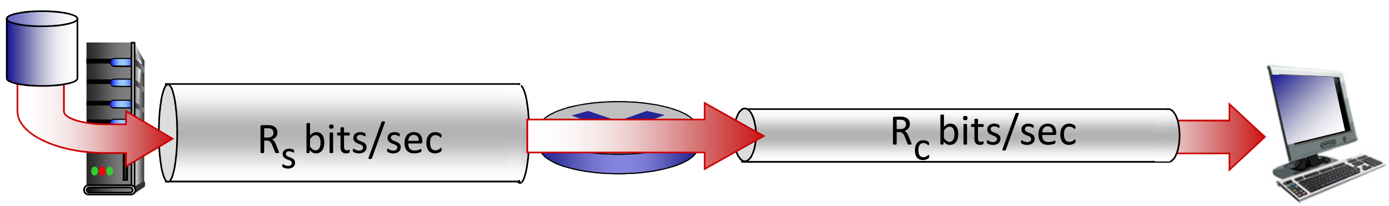
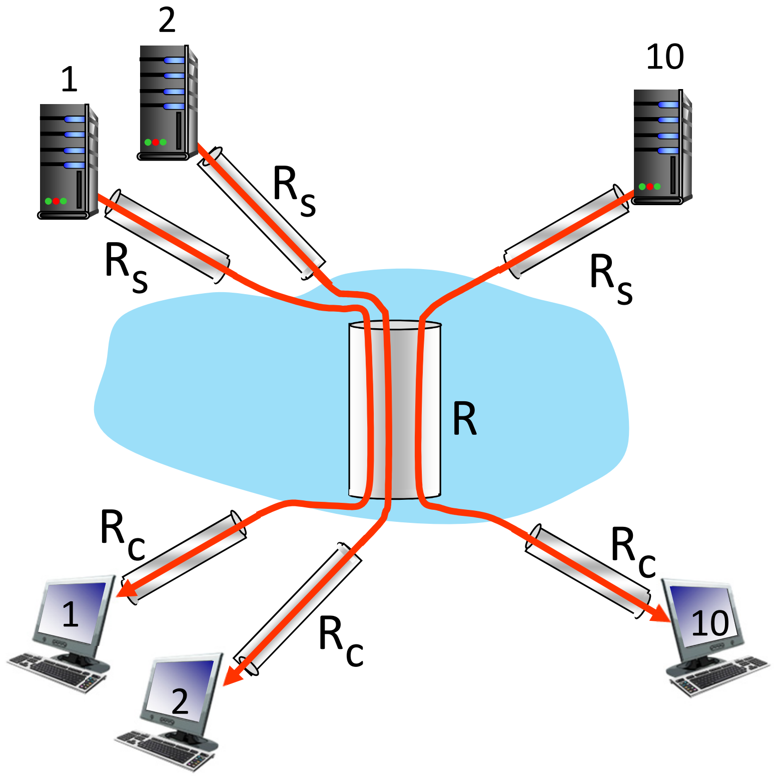


bottleneck link

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

Throughput: network scenario



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

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