Lecture 02:
Packets, Routing, and Performance

CS 326E Computer Networks

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Please, interrupt and ask questions AT ANY TIME !

Help session for Env Setup/Linux/Python3 Basics

- 9/4 Wed 5 PM via Zoom (Find the meeting link at Canvas -> Zoom)
- 9/5 Thurs 4:30 PM – 5:30 PM @ GDC 5.304
- Will be going over
  - VPN+ssh to CS machine
  - Project env setup
  - Basic linux/unix command
  - Brush up on Python3
- Pre-req to all hands-on and projects
- Recordings will be provided in-case you cannot come miss

UTCS Account Canvas Quiz is up!

Pair Activity

Pick 2 from below and tell your neighbor about it

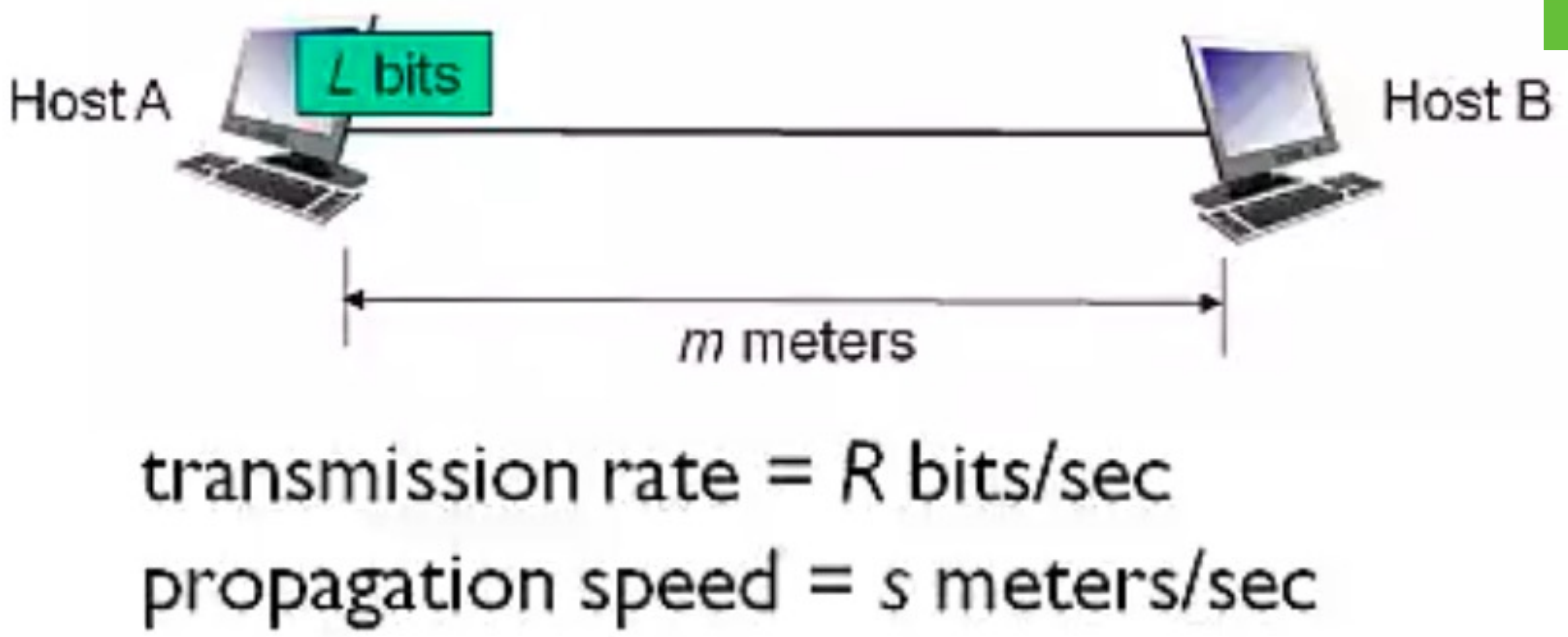
- 1 MAC address and IP address:
  At each hop which src/dst addresses get changed?
  Which src/dst addresses remain the same end-to-end?

- 2 What is transmission delay?
- 3 What is propagation delay?

- 4 What is the difference between routing vs forwarding?

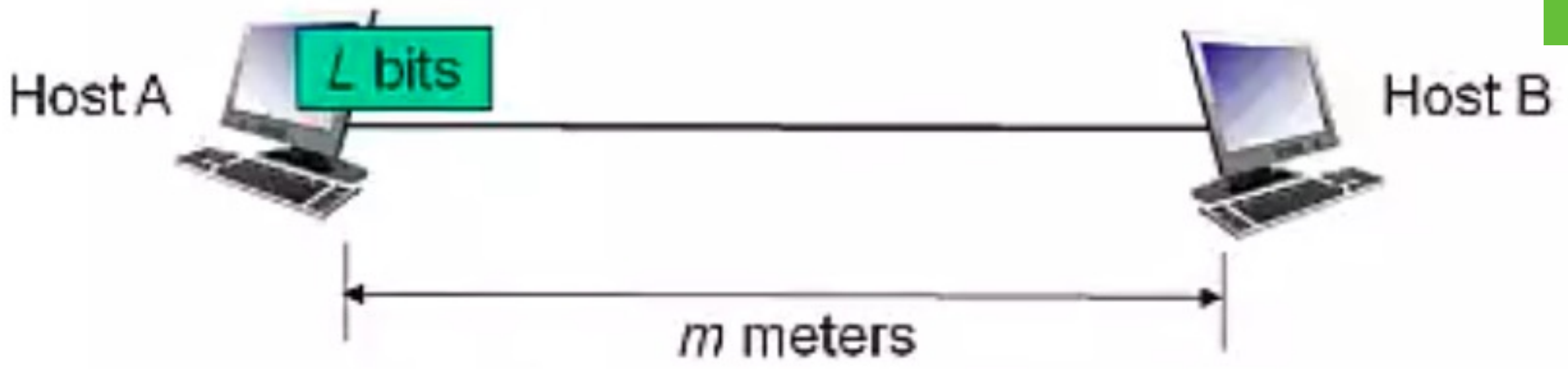

forwarding
routing
45 h
3,053 miles
48 h
3,309 miles
San Jose
Northampton
Sacramento

Recap: Kahoot Exercise



At time t=d_trans, where is the last bit of the packet?
(d_trans is the trasmission delay)

Recap: Kahoot Exercise

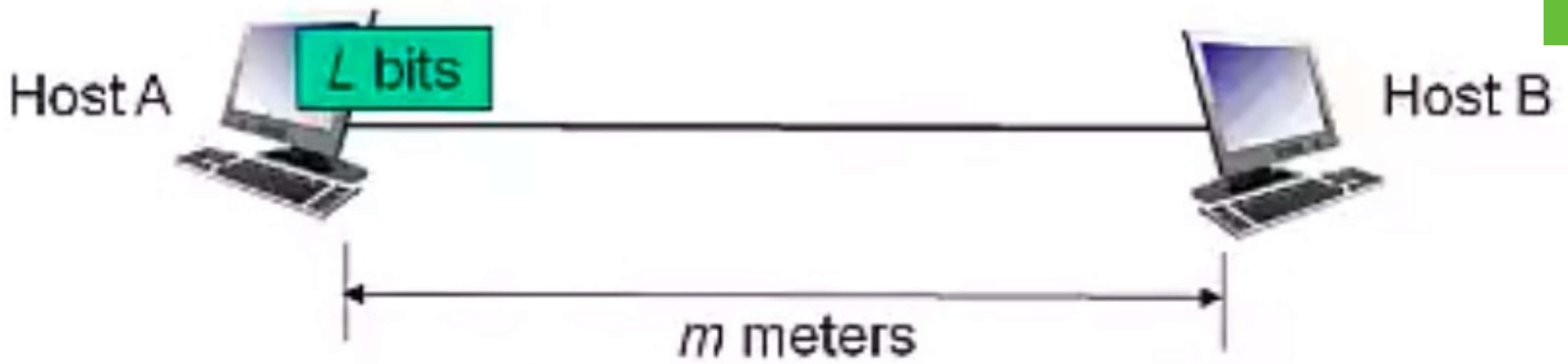


transmission rate = R bits/sec

propagation speed = s meters/sec

Suppose d_prop > d_trans, at t=d_trans where is the first bit?

Recap: Kahoot Exercise



transmission rate = R bits/sec

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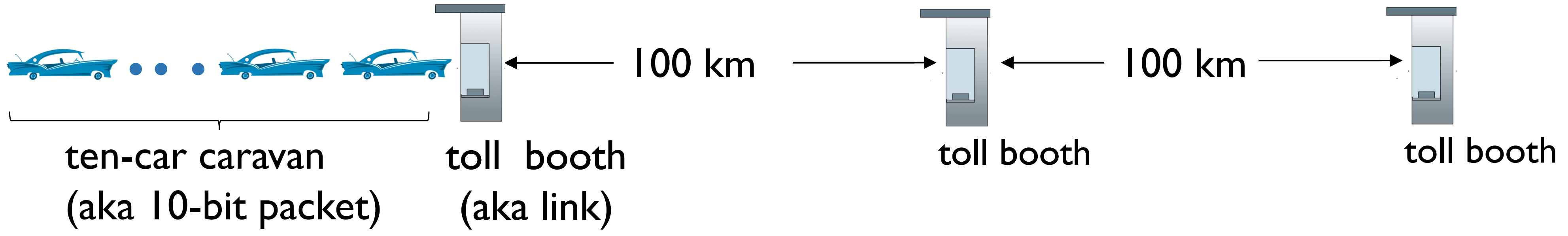
Suppose d_prop < d_trans, at t=d_trans where is the first bit?

Caravan analogy

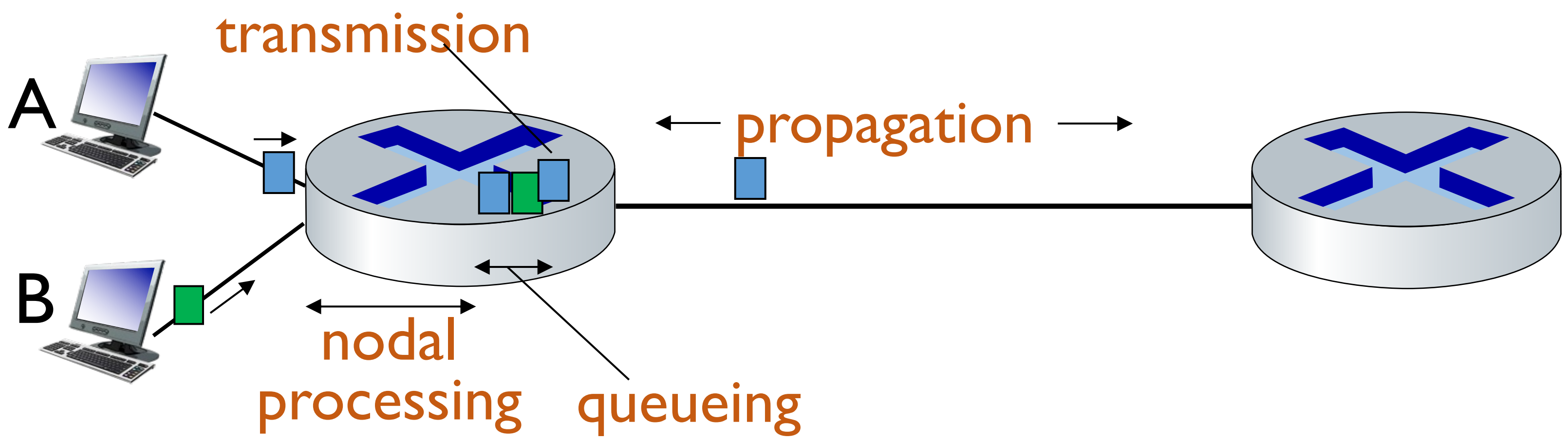


- car ~ bit; caravan ~ packet; toll service ~ link transmission
- toll booth takes 12 sec to service a car (bit transmission time)
- "propagate" at 100 km/hr
- Q: How long until caravan is lined up before 2nd toll booth?
- time to "push" entire caravan through toll booth onto highway = 12*10 = 120 sec
- time for last car to propagate from 1st to 2nd toll both: 100km/(100km/hr) = 1 hr
- A: 62 minutes

Outline

1. Recap
2. Performance: delay and loss

Packet delay: four sources



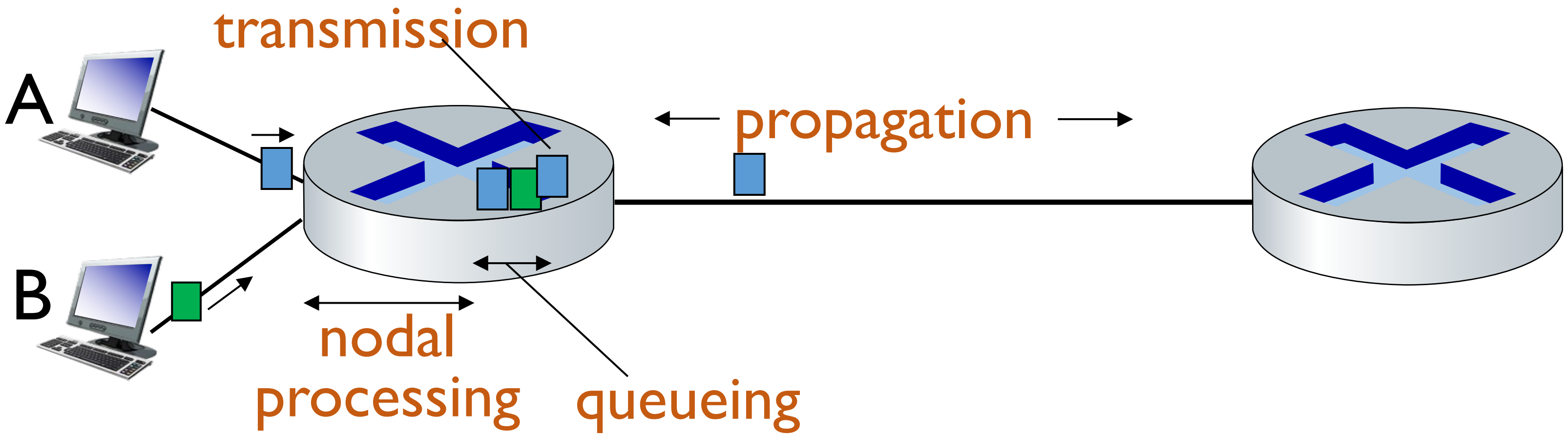
$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

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 (~$2\text{x}10^8$ m/sec)
- d_{prop} = d/s

d_{trans} and d_{prop}
very different

Packet delay: four sources

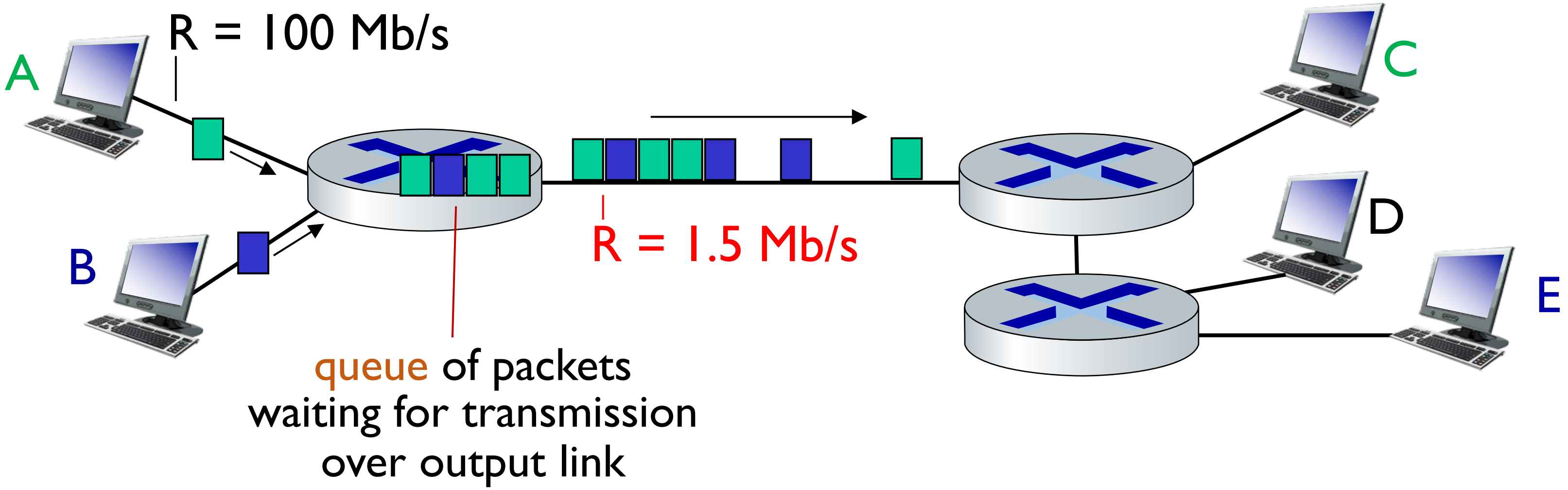


$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

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

Queueing delays



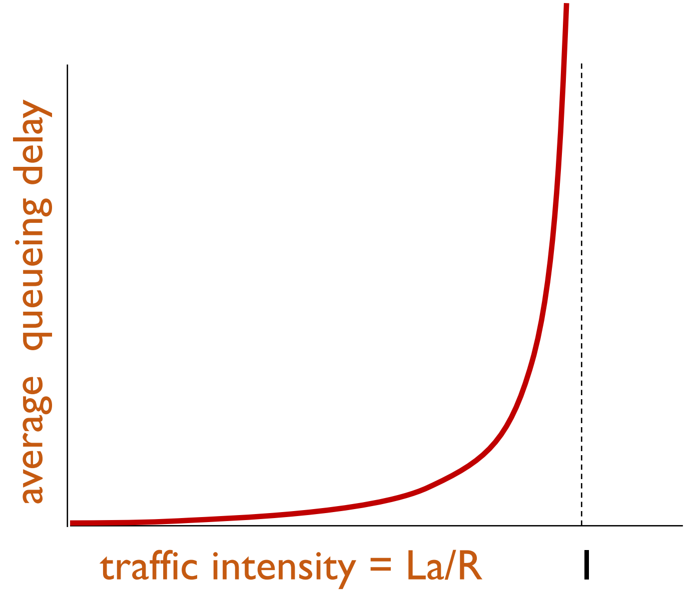
Queueing occurs when work arrives faster than it can be serviced:

Queueing delay analysis

- a: average packet arrival rate
- L: packet length (bits)
- R: transmission rate

$$\frac{L \cdot a}{R} : \frac{\text{arrival rate of bits}}{\text{service rate of bits}}$$

“traffic intensity”



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

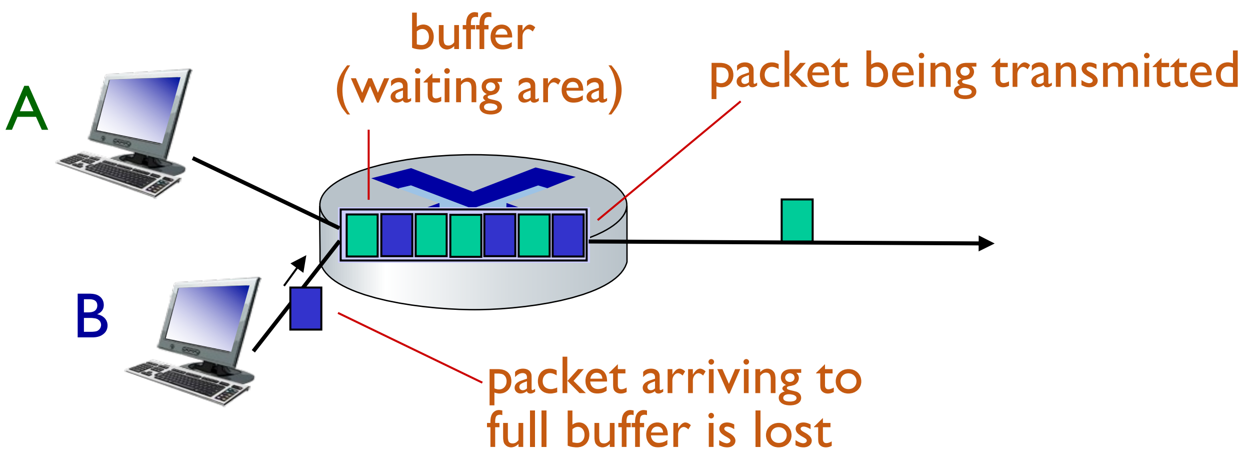
La/R ~ 0

La/R => 1

How about packet loss? Why/where does it happen?

Packet loss happens

- queue (buffer) has finite capacity
- packets arriving to full queue dropped (lost)
- Lost packets may be retransmitted by src, previous hop, or not at all!



Where else can packet loss happen?

Outline

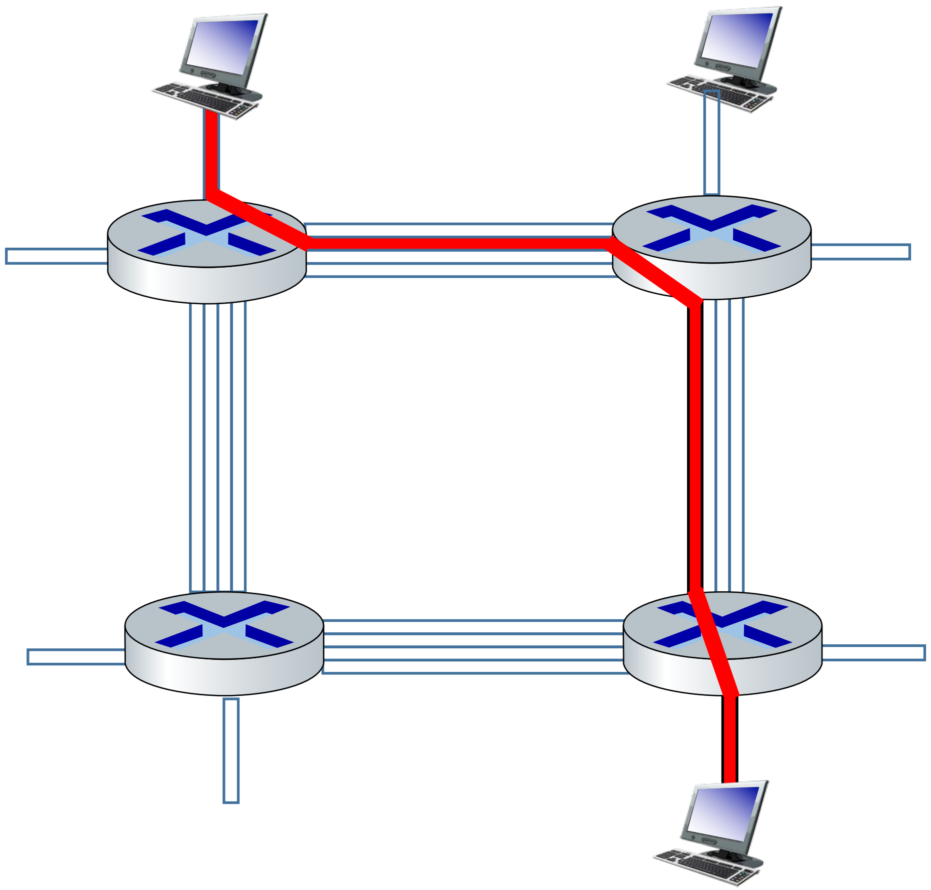
1. Recap
2. Performance: delay and loss
3. Sharing is caring: Packet switching vs circuit switching

How to share a link between multiple users?

Circuit switching is an alternative approach

end-end resources are allocated to, reserved for "call" btw src and dst

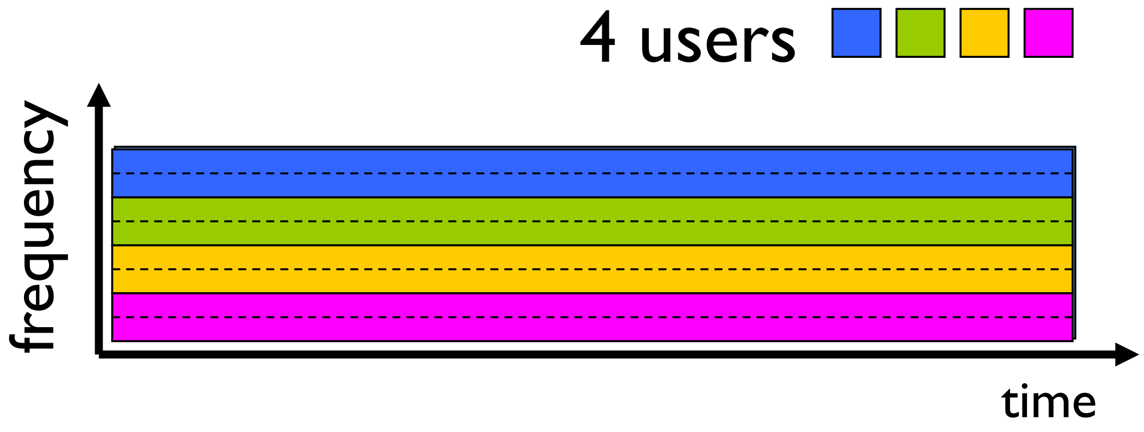
- in diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used
- commonly used in traditional telephone networks



Circuit switching: FDM and TDM

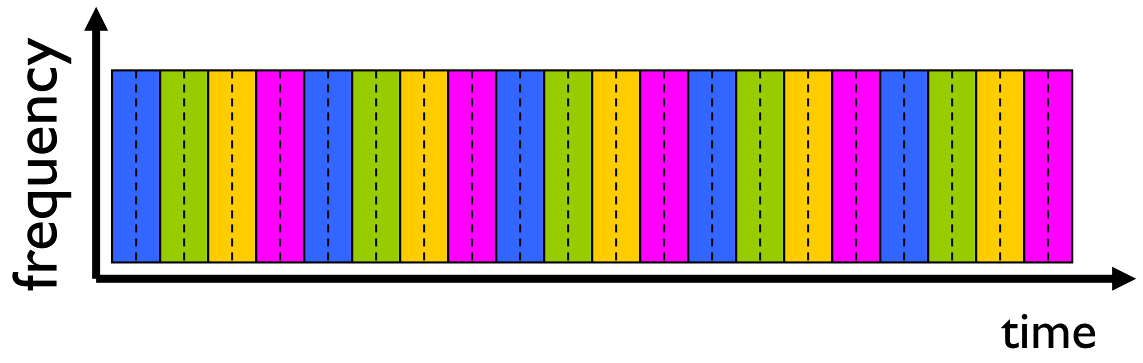
Frequency Division Multiplexing (FDM)

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



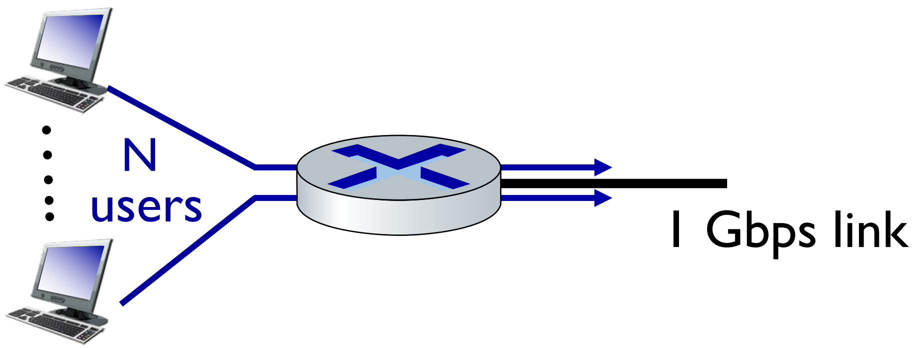
Time Division Multiplexing (TDM)

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



Circuit switching reserves 100Mbps per user

example:
- 1 Gb/s link
- each user:
  - 100 Mb/s when "active"
  - active 10% of time (happens randomly)



Q: What is the max number of users that can share this network?

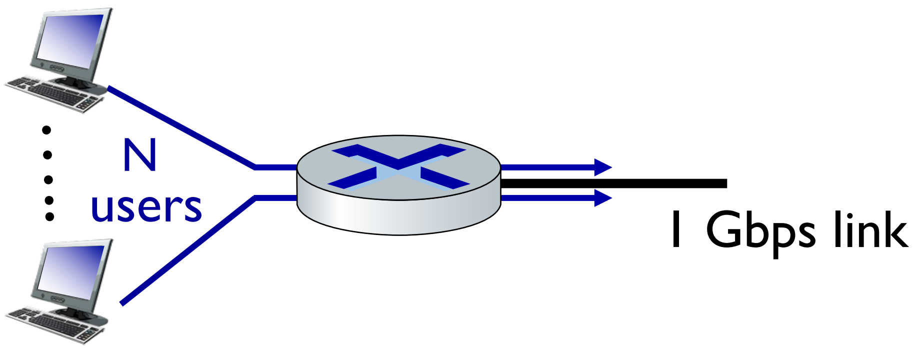
- circuit-switching:

  Only 10 users (=1 Gbps/100 Mbps)

Given each users are active only 10% of the time
Can we allow more number of users?

Packet switching allows more users to share with some probability of failure

example:
- 1 Gb/s link
- each user:
  - 100 Mb/s when "active"
  - active 10% of time (happens randomly)



Q: What is the max number of users that can share this network?

- packet switching:

A: Need some assumption on link availability guarantee.

Say we guarantee 99.99% link availability for each user.

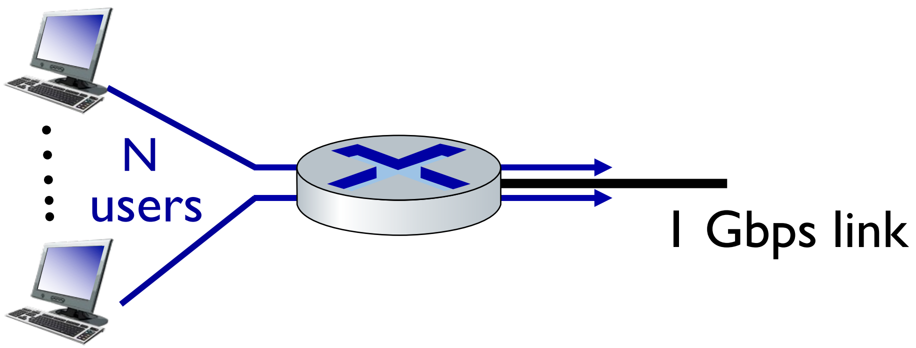
That is failure rate < 0.01% == 0.0001

When does "failure" happen?

When does failure happen?

example:

- 1 Gb/s link
- each user:
  - 100 Mb/s when "active"
  - active 10% of time (happens randomly)

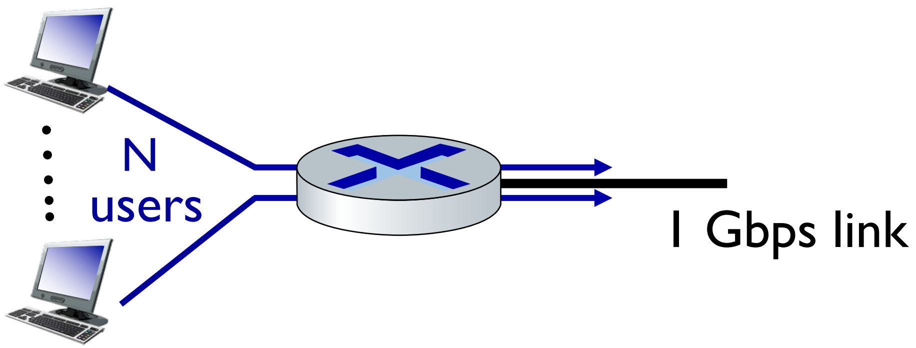


Whenever more than 10 users happen to be active simultaneously!

What is the total number of users in the system we can allow such that the probability of more than 10 users being active simultaneously < 0.0001?

Say total number of users is 15 (N=15)

example:
- 1 Gb/s link
- each user:
  - 100 Mb/s when "active"
  - active 10% of time (happens randomly)



What is the probability of failure?

- Case 1: When 11 out of 15 users are happen to be active simultaneously
- Case 2: When 12 out of 15 users are happen to be active simultaneously
- Case 3:When 13 out of 15 users ...
- Case 4 :When 14 out of 15 users …
- Case 5:When 15 out of 15 users are happen to be active simultaneously

$$Probabiilty\ of\ failure = Prob(Case\ 1) + \cdots + Prob(Case\ 5)$$

What is the probability of k users out of N users are active simultaneously?

- Let's scope it down
- Say, N = 5
- 2 users out of 5 users are active simultaneously

The probability of exactly 2 users are active among 5 users

- This means all other users must be silent (non-active)
- One possible outcome: AANNN
- What's the probability to get above?

  $P(A) \times P(A) \times P(N) \times P(N) \times P(N) = P(A)^2 \times P(N)^3 = 0.1^2 \times (1\text{-}0.1)^3$
- Another possible outcome: NNNAA

  $P(N) \times P(N) \times P(N) \times P(A) \times P(A) = P(A)^2 \times P(N)^3 = 0.1^2 \times (1\text{-}0.1)^3$
- All outcomes have the same prob of $P(A)^2 \times P(N)^3$
- How many possible outcome?

  $${}_5C_2 = \frac{5!}{(5-2)!2!} = 10$$
- Putting it together

  ${}_5C_2 \times P(A)^2 \times P(N)^3 = 10 \times 0.1^2 \times (1\text{-}0.1)^3 = 0.0729$

This is an example of binomial distribution

Group activity

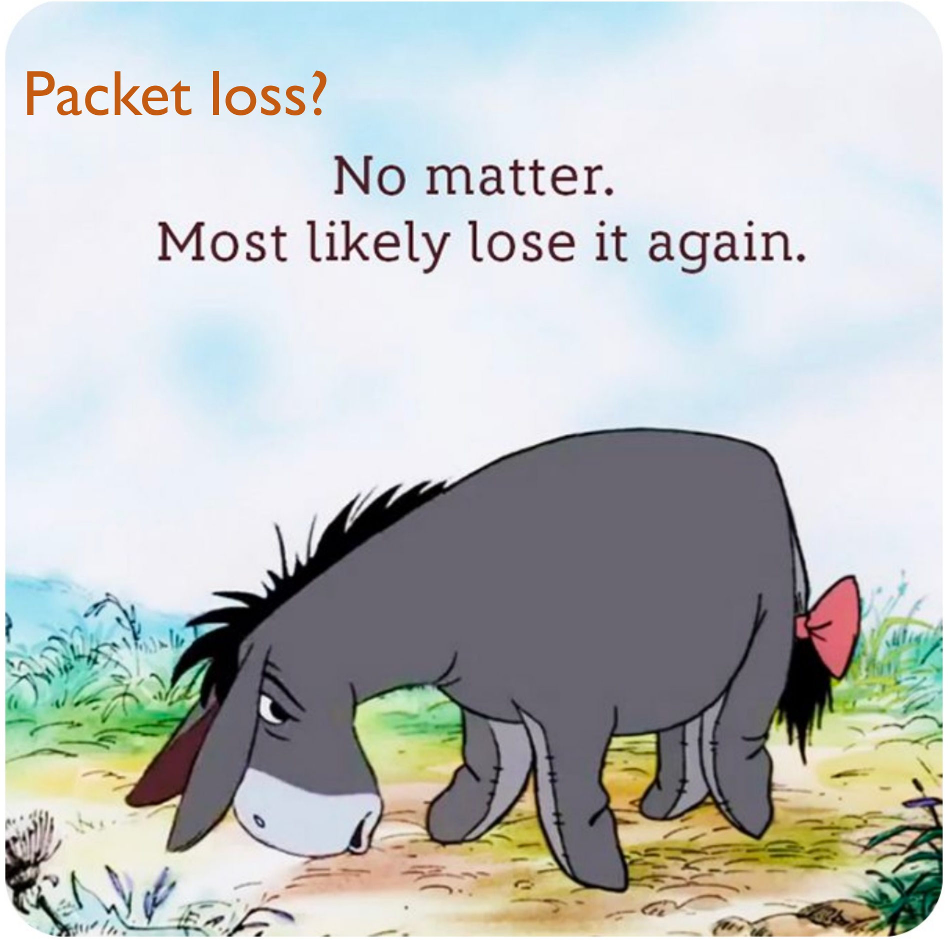
- Make sure to submit to Canvas as well!

Is packet switching a "slam dunk winner"?

- great for "bursty" data – sometimes has data to send, but at other times not
  - resource sharing
  - simpler, no call setup
- excessive congestion possible: packet delay and loss due to buffer overflow
  - protocols needed for reliable data transfer, congestion control

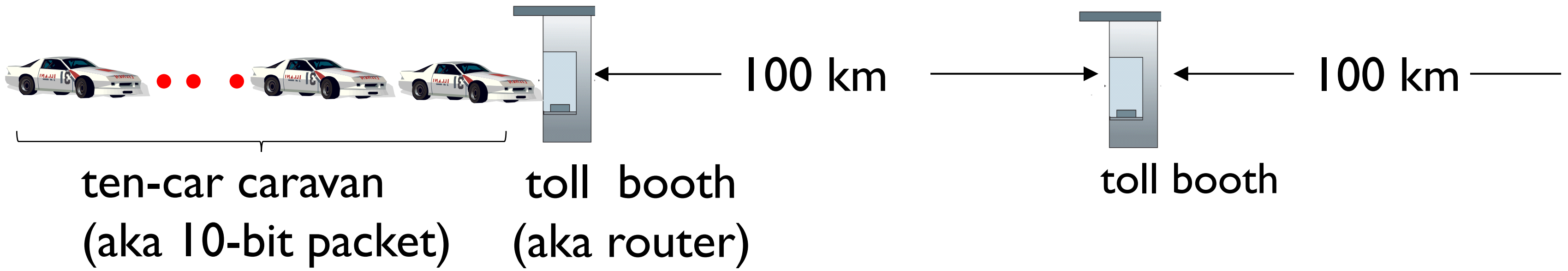
Best of both worlds:
How to provide "circuit-like" behavior with packet-switching?

Questions?



Backup Slides

Caravan analogy



- suppose each car now "propagates" 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, first car arrives at second booth; three cars still at first booth

Why La = 1 results in infinitely long queue?

- See this example
- Read this paper

We now compute the mean number in queue from (4). The most convenient way to do this is using generating functions. We have

$$G_N(z) = E[z^N] = \sum_{n=0}^{\infty}(1-\rho)\rho^n z^n = \frac{1-\rho}{1-\rho z},$$

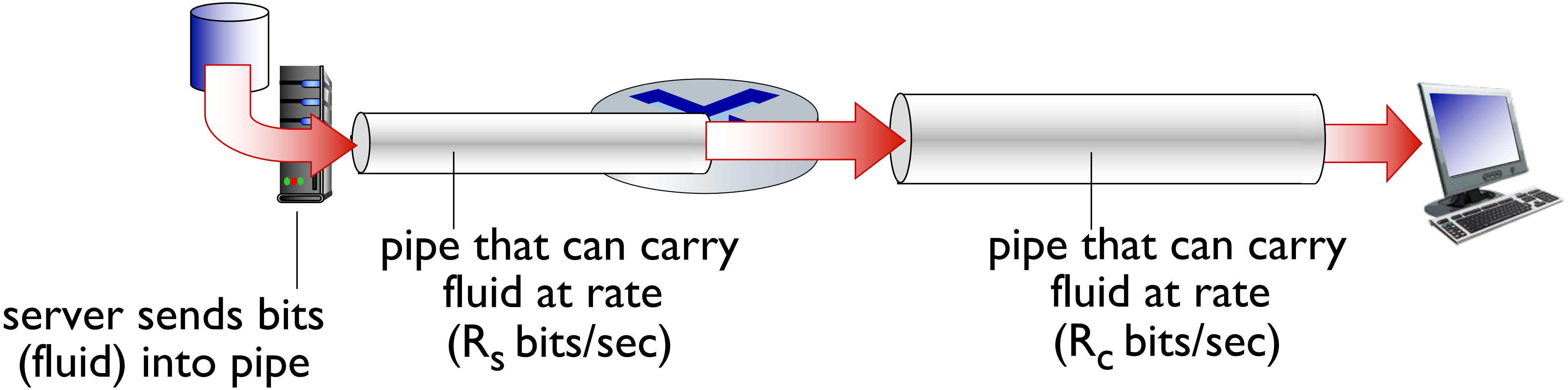
provided $|z| < 1/\rho$. From this, we obtain

$$E[N] = G'_N(1) = \frac{\rho(1-\rho)}{(1-\rho z)^2} \mid |_{z=1} = \frac{\rho}{1-\rho}. \tag{5}$$

Observe that the mean queue length increases to infinity as ρ increases to 1,

Throughput is the rate at which bits are being sent from original sender to final receiver

- instantaneous: rate at given point in time
- average: rate over longer period of time



The probability to flip exactly 2 HEADs among 5 coin tosses

- This means all other coin toss must be TAIL
- One possible outcome: HHTTT
- What's the probability to get above?

  $P(H) \times P(H) \times P(T) \times P(T) \times P(T) = P(H)^2 \times P(T)^3 = 0.5^2 \times (1\text{-}0.5)^3$
- Another possible outcome: TTTHH

  $P(T) \times P(T) \times P(T) \times P(H) \times P(H) = P(H)^2 \times P(T)^3 = 0.5^2 \times (1\text{-}0.5)^3$
- All outcomes have the same prob of $P(H)^2 \times P(T)^3$
- How many possible outcome?

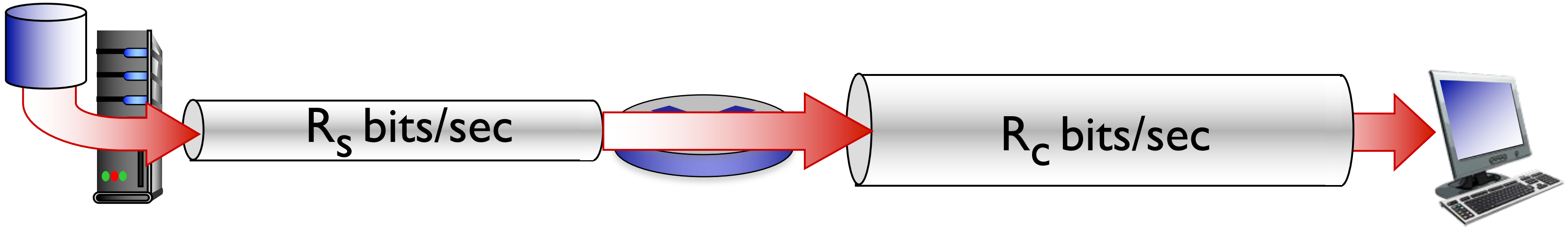
  $${}_5C_2 = \frac{5!}{(5-2)!2!} = 10$$
- Putting it together

  ${}_5C_2 \times P(T)^2 \times P(H)^3 = 10 \times 0.5^2 \times (1\text{-}0.5)^3 = 0.3125$

This is an example of binomial distribution

Throughput

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



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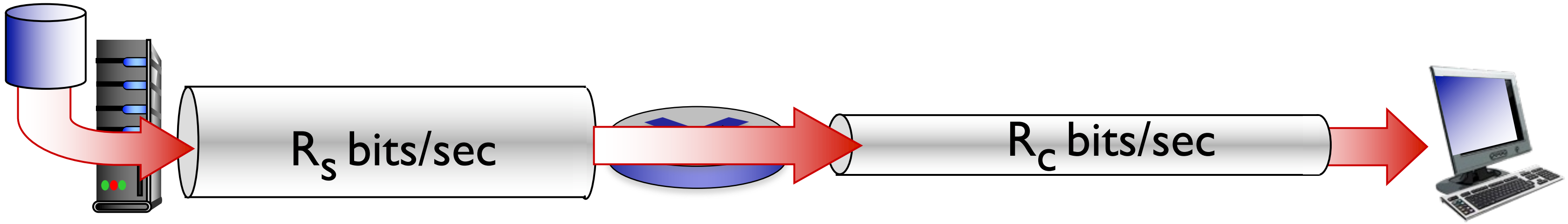
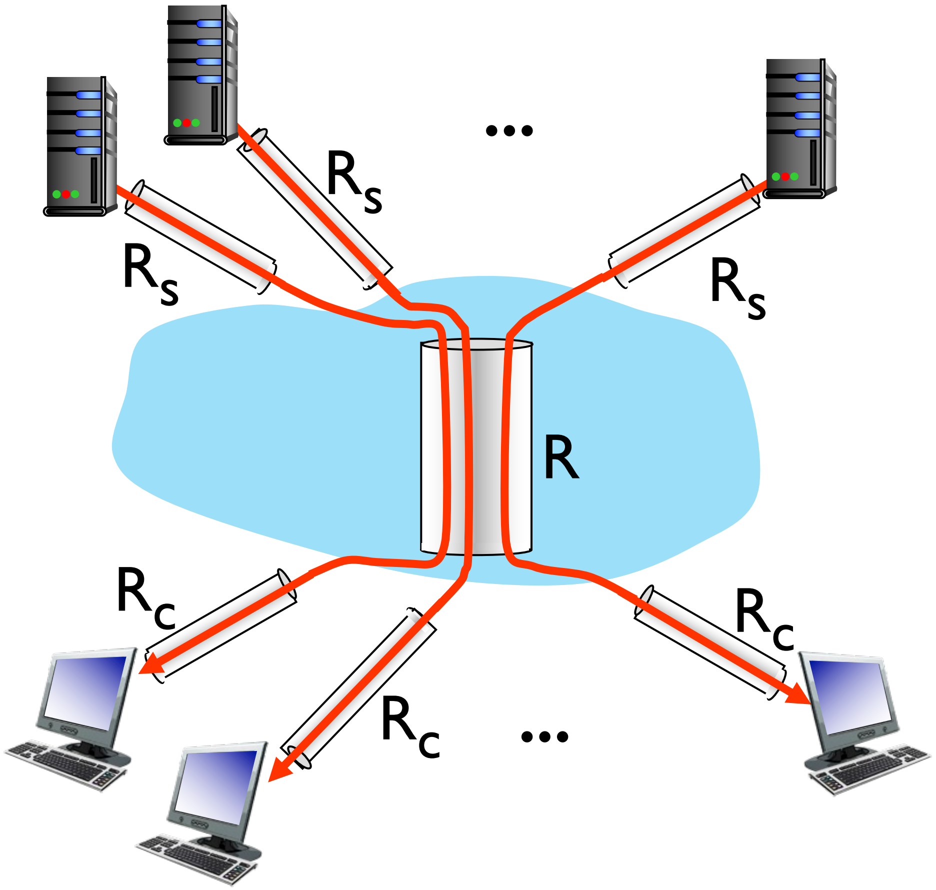


bottleneck link

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

Throughput: network scenario



Say10 connections fairly share backbone bottleneck link R bits/sec

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

Acknowledgements

Slides are adopted from Kurose' Computer Networking