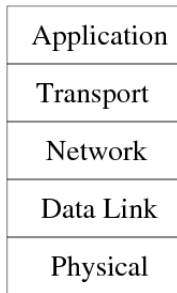


# Layered Architecture



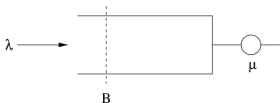
# TCP: Transmission Control Protocol

- Application Multiplexing/Demultiplexing
- Error Detection
- Reliable Data Transfer
- Congestion Control

# Congestion Control

- Why is congestion “bad”?
  - How does congestion affect performance of applications?
  - How to avoid (react to) congestion?
- > One of the most important problems in networking

# Congestion: Example 1



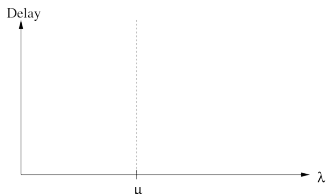
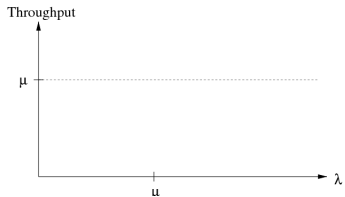
$$p_n = \frac{1 - \rho}{1 - \rho^{B+1}} \rho^n, \quad n = 0, \dots, B$$

Throughput is equal to  $(1 - p_0)\mu = \mu\rho \frac{(1 - \rho^B)}{(1 - \rho^{B+1})}$

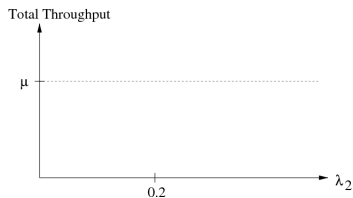
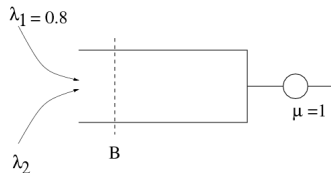
Average delay is equal to  $\frac{1}{\mu} + \sum_{n=1}^{B-1} n \frac{1}{\mu} p'_n$

# Congestion: Example 1

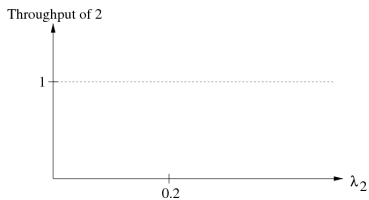
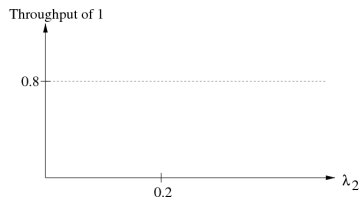
For large  $B$ :



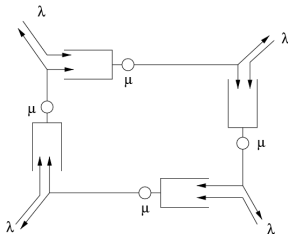
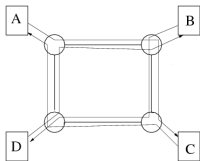
# Congestion: Example 2



# Congestion: Example 2

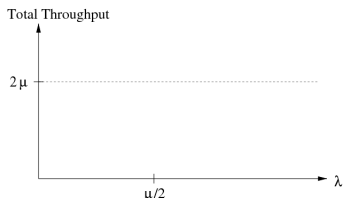
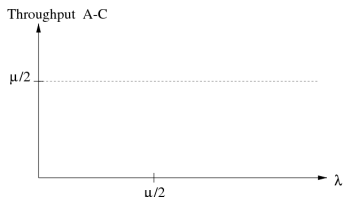


# Congestion: Example 3





# Congestion: Example 2



# How to Deal with Congestion

- Packet discarding
- Packet blocking
- Call (Session) blocking

# Congestion Control: Classification

**Open-Loop Control:** During connection setup, the transmission rate of a connection is determined.

- Call Admission Control
- Policing: Leaky Bucket

**Closed-Loop Control / Feed Back Control:** Connections are informed dynamically about the congestion state of the network, and asked to adapted their rate accordingly.

- TCP Congestion Control

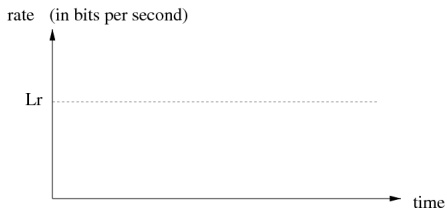
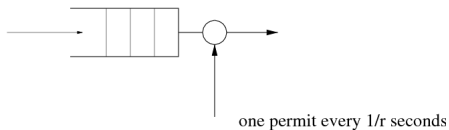
# Transmission Rate Policing: Leaky Bucket

Issue:

- During call admission control, a connection was assigned a rate of  $r$  packets per second.
  - How do we make sure that the connection does not transmit packets at a higher rate?
- > Leaky Bucket

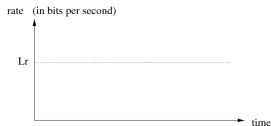
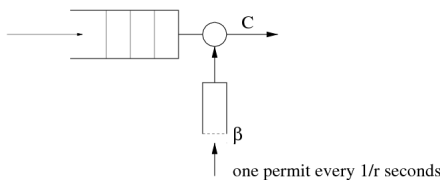
# Leaky Bucket

## First Approach



$L$ : length of one packet

# Leaky Bucket



Average rate:  $Lr$  bits per second

Peak rate:  $C$  bits per second for at most  $\frac{\beta L}{C}$  seconds

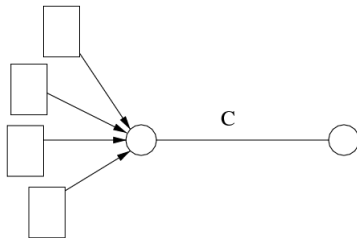
# TCP Congestion Control

- Closed-Loop Control
- Dynamically changes sender window size (TCP window size)

## Issue

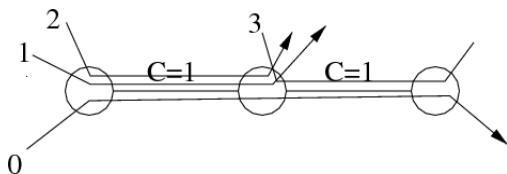
- Fairness

# Fairness





# Max-Min Fairness



(for exact definition see additional handout)