Congestion Control

Overview

Queueing Disciplines

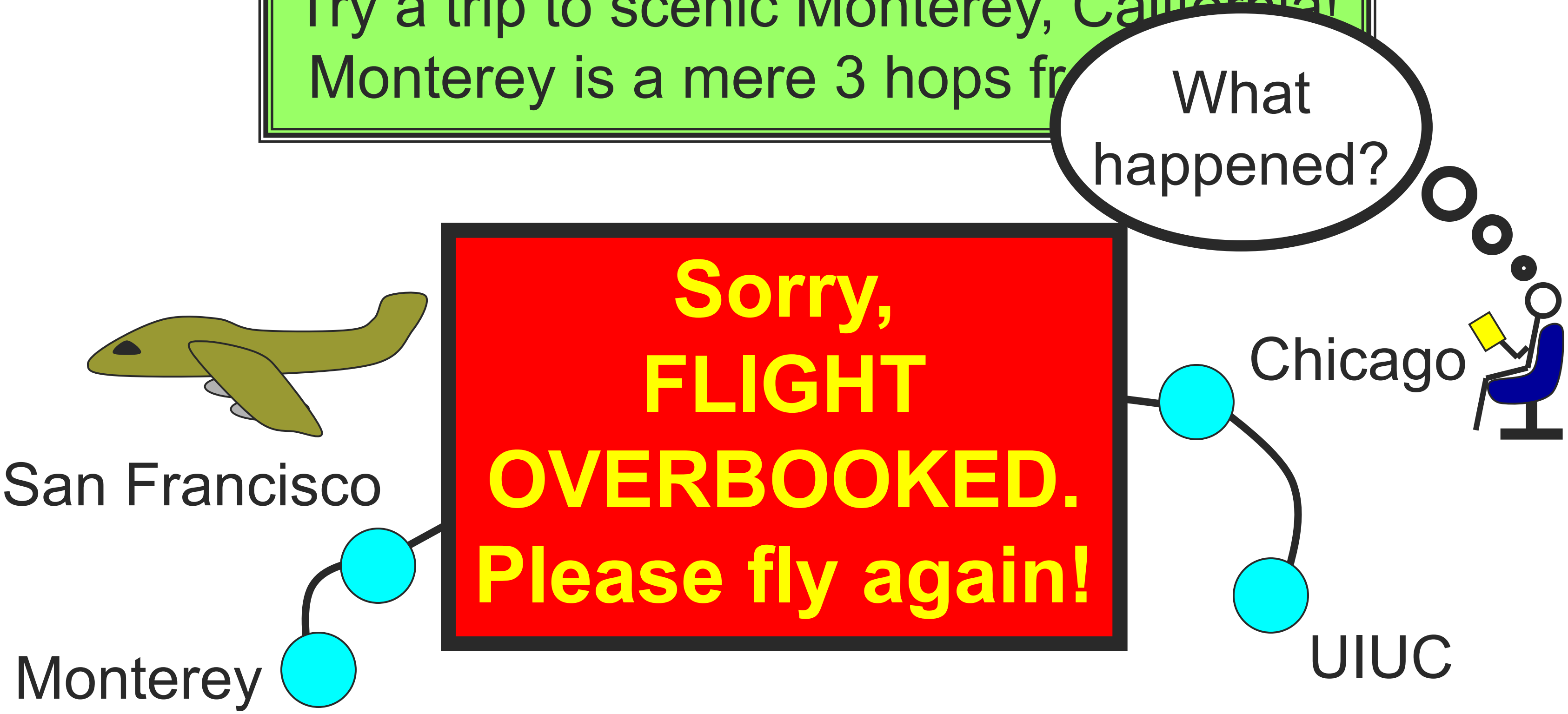
TCP Congestion Control

Congestion Avoidance Mechanisms

Quality of Service

Today’s Topic: Vacations

Planning a vacation?
Try a trip to scenic Monterey, California!
Monterey is a mere 3 hops fr



Congestion Control

reading: Peterson and Davie, Ch. 6

- Basics:
  - Problem, terminology, approaches, metrics
- Solutions
  - Router-based: queueing disciplines
  - Host-based: TCP congestion control
- Congestion avoidance
  - DECbit
  - RED gateways
- Quality of service

Congestion Control Basics

- Problem
  - Demand for network resources can grow beyond the resources available
  - Want to provide "fair" amount to each user
- Examples
  - Bandwidth between Chicago and San Francisco
  - Bandwidth in a network link
  - Buffers in a queue

Congestion Collapse

- Definition
  - Increase in network load results in decrease of useful work done
- Many possible causes
  - Spurious retransmissions of packets still in flight
    - Classical congestion collapse
    - Solution: better timers and TCP congestion control
  - Undelivered packets
    - Packets consume resources and are dropped elsewhere in network
    - Solution: congestion control for ALL traffic

Dealing with Congestion

- Range of solutions
  - Congestion control
    - Cure congestion when it happens
  - Congestion avoidance
    - Predict when congestion might occur and avoid causing it
  - Resource allocation
    - Prevent congestion from occurring
- Model of network
  - Packet-switched internetwork (or network)
  - Connectionless flows (logical channels/connections) between hosts

Congestion Control

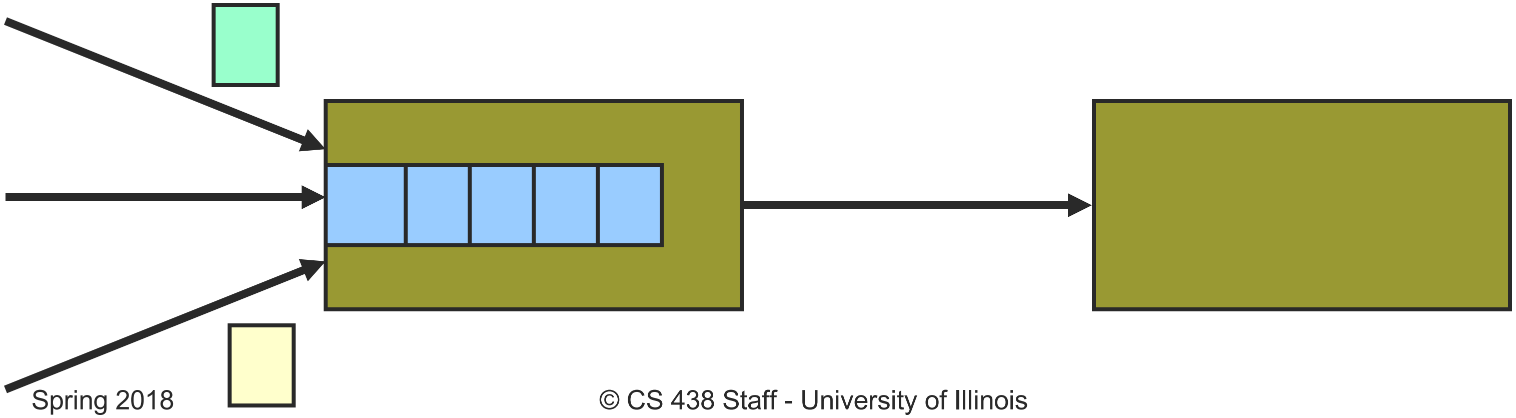
- Goal
  - Effective and fair allocation of resources among a collection of competing users
  - Learning when to say no and to whom
- Resources
  - Bandwidth
  - Buffers
- Problem
  - Contention at routers causes packet loss

Flow Control vs. Congestion Control

- Flow control
  - Preventing *one sender* from overrunning the capacity of a *slow receiver*
- Congestion control
  - Preventing a *set of senders* from overloading the *network*!

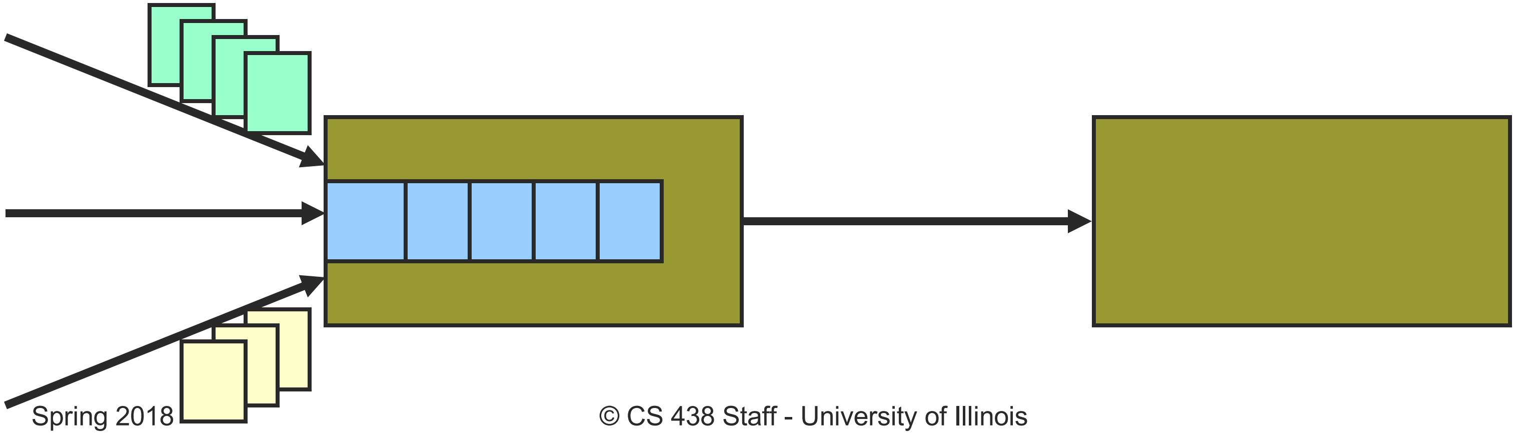
Congestion is Natural

- Because Internet traffic is bursty!
- If two packets arrive at the same time
  - The node can only transmit one
  - … and either buffers or drops the other



Congestion is Natural

- Because Internet traffic is bursty!
- If two packets arrive at the same time
  - The node can only transmit one
  - … and either buffers or drops the other
- If many packets arrive in a short period of time
  - The node cannot keep up with the arriving traffic
  - Causes delays, and the buffer may eventually overflow



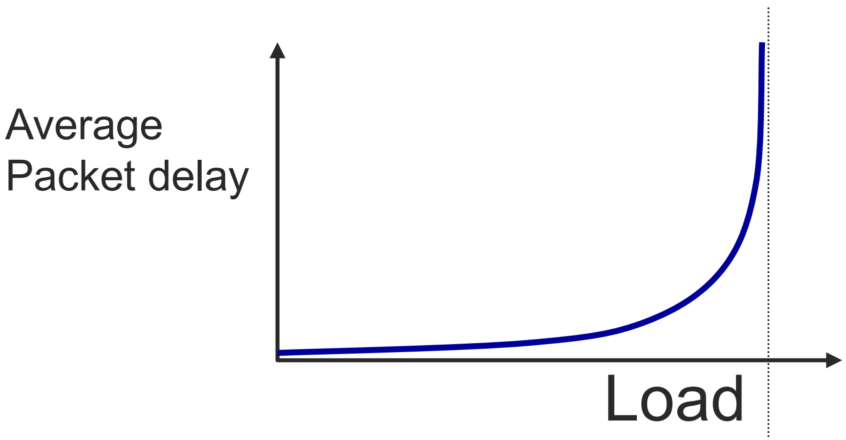
Load and Delay

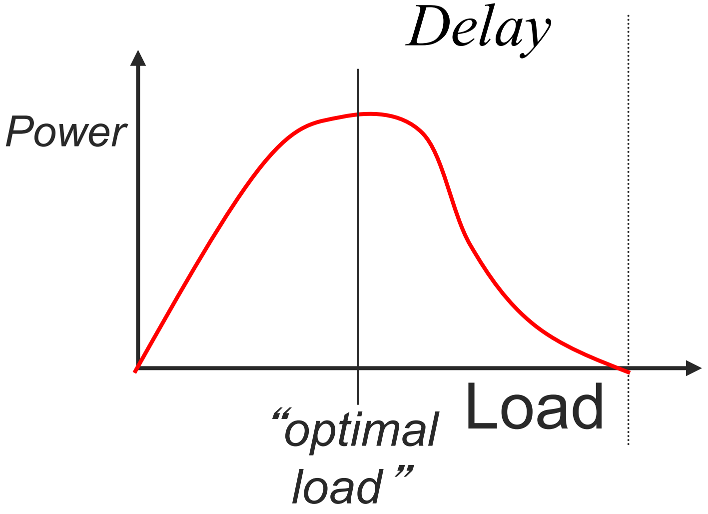
Typical behavior of queueing systems with bursty arrivals:

Ideal: low delays and high utilization
Reality: must balance the two

Maximizing "power" is an example

$$Power = \frac{Load}{Delay}$$



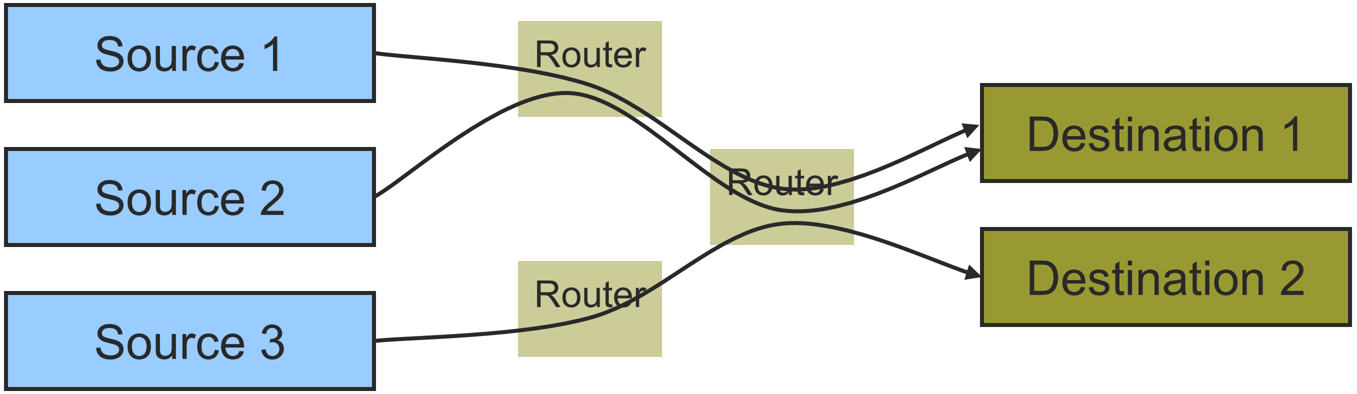


Basic Design Choices

- Prevention or Cure?
  - Pre-allocate resources to avoid congestion
  - Send data and control congestion if and when it occurs
- Possible implementation points
  - Hosts at the edge of the network
    - Transport protocol
  - Routers inside the network
    - Queueing disciplines
- Underlying service model
  - Best effort vs. quality of service (QoS)

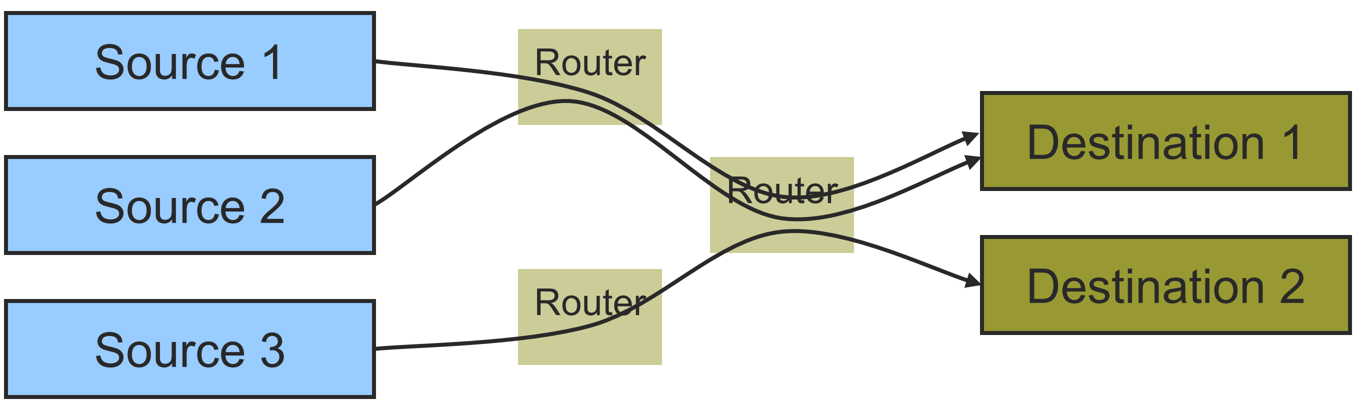
Flows

- Sequence of packets sent between source/destination pair
  - Similar to end-to-end abstraction of channel, but seen at routers
- Maintain per-flow soft state at the routers



Router State

- Soft state:
  - Information about flows
  - Helps control congestion
  - Not necessary for correct routing
- Hard state:
  - state used to support routing



Congestion Control

- Router role
  - Controls forwarding and dropping policies
  - Can send feedback to source
- Host role
  - Monitors network conditions
  - Adjusts accordingly
- Routing vs. congestion
  - Effective adaptive routing schemes can sometimes help congestion
  - But not always

Congestion Control Taxonomy

congestion control

feedback-based

reservation-based,
implemented by routers,
controlled by rate,
a.k.a. quality of service/QoS

implicit feedback,
implemented by hosts,
controlled by window
abstraction,
a.k.a. best effort

explicit feedback,
implemented by routers,
but not per flow…why?

Router-Centric vs. Host-Centric Flow Control

- Router-centric
  - Each router takes responsibility for deciding
    - When packets are forwarded
    - Which packets are to be dropped
    - Informing hosts of sending limitations
- Host-centric
  - Hosts observe network conditions and adjust their behavior accordingly

Reservation-Based vs. Feedback-Based Flow Control

- Reservation-based
  - End host asks network for capacity at flow establishment time
  - Routers along flow's route allocate appropriate resources
  - If resources are not available, flow is rejected
  - Implies the use of router-centric mechanisms
- Feedback-based
  - End host begins sending without asking for capacity
  - End host adjusts sending rate according to feedback
    - Explicit vs. implicit feedback mechanisms
  - May use router-centric (explicit) or host-centric (implicit) mechanisms

Per-flow Congestion Feedback

- Question
  - Why is explicit per-flow congestion feedback from routers rarely used in practice?

Per-flow Congestion Feedback

- Problem
  - Too many sources to track
    - Millions of flows may fan in to one router
    - Can't send feedback to all of them
  - Adds complexity to router
    - Need to track more state
    - Certainly can't track state for all sources
  - Wastes bandwidth: network already congested, not the time to generate more traffic
  - Can't force the sources (hosts) to use feedback

Window-based vs. Rate-based Flow Control

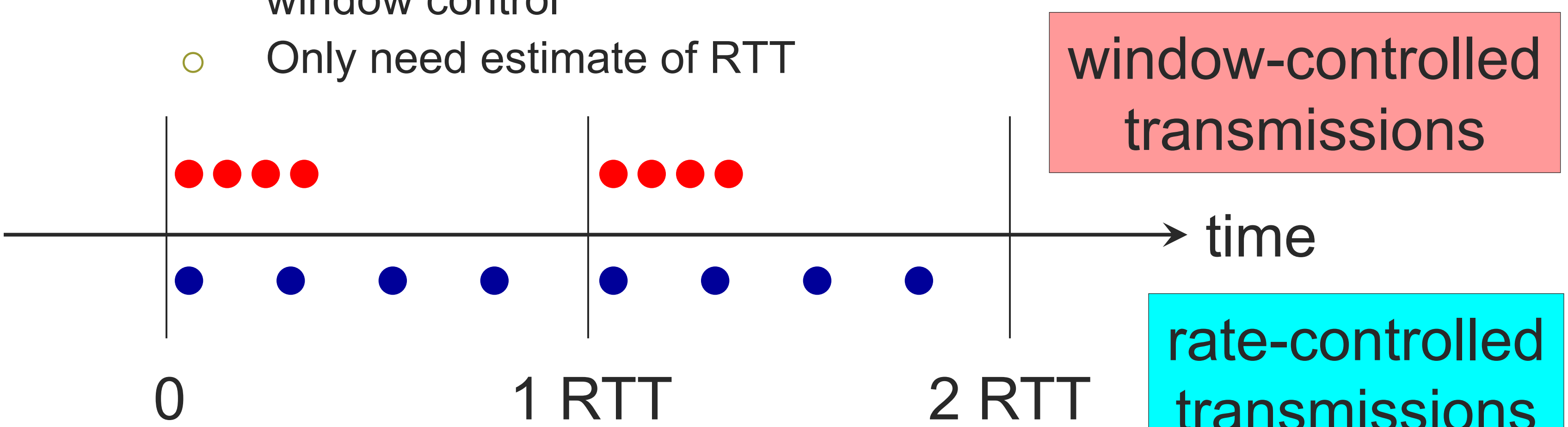
- Remember
  - Given a RTT and window size W, long term throughput rate is
    - Rate = min(link speed, W/RTT)
- Since rate can be controlled by the window size, is there really any difference between controlling the window size and controlling the rate?

Rate Control

- Question
  - Why consider rate control?
- Problems
  - Buffer space (window size) is an intrinsic physical quantity
  - Can provide rate control with window control
  - Only need estimate of RTT

Answer

Want rate control when granularity of averaging must be smaller than RTT



Criticisms of Resource Allocation

- Example
  - Divide 10 Gbps bandwidth out of UIUC
- Case 1: reserve whatever you want
  - Users' line of thought
    - On average, I don't need much bandwidth, but when my personal Web crawler goes to work, I need at least 100 Mbps, so I'll reserve that much.
  - Result
    - 100 users consume all bandwidth, all others get 0

Criticisms of Resource Allocation

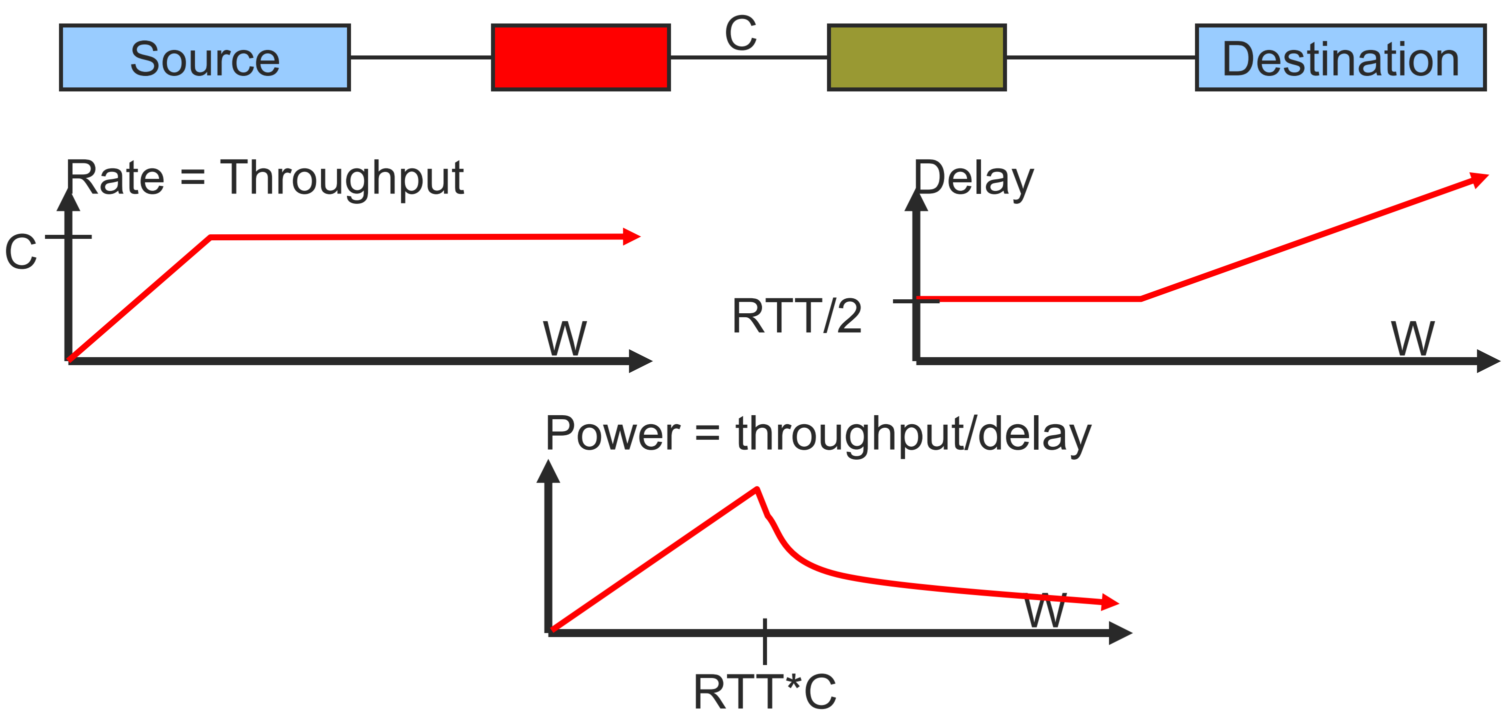
- Example
  - Divide 10 Gbps bandwidth out of UIUC
- Case 2: fair/equitable reservations
  - 35,000 students + 5,000 faculty and staff
  - Each user gets 250 kbps, almost 5x a modem!

Resource Allocation

- Back to the air travel analogy
  - Daily Chicago to San Francisco flight, 198 seats
  - Case 1: reserve whatever you want
    - 198 of us get seats. I' m Gold...are you?
  - Case 2: fair/equitable reservations
    - 2,000,000 possible customers
    - 0.000099 seats per customer per flight
    - Disclaimer:
      the passenger assumes all risks and damages
      related to unsuccessful reassembly in Chicago

Window Size

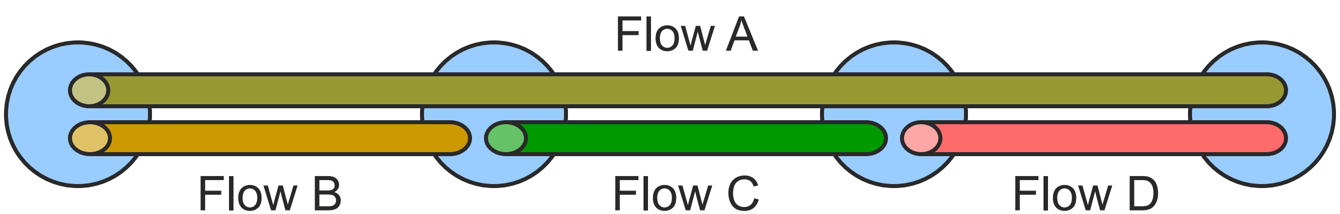
For non-random network with bottleneck capacity C:



Fairness

- Goals
  - Allocate resources "fairly"
  - Isolate ill-behaved users
  - Still achieve statistical multiplexing
    - One flow can fill entire pipe if no contenders
    - Work conserving → scheduler never idles link if it has a packet
- At what granularity?
  - Flows, connections, domains?

What’s Fair?



Which is more fair:

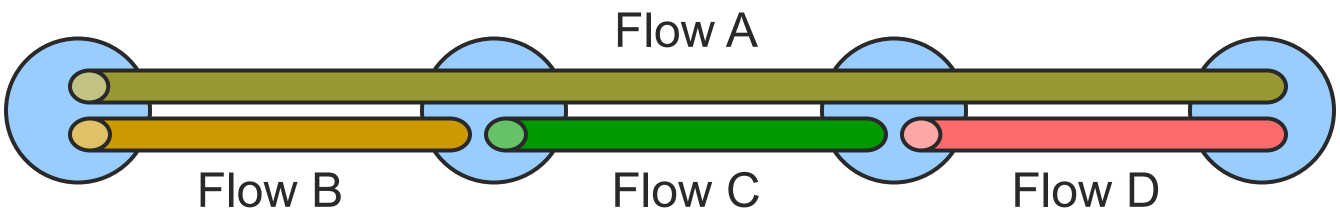
Globally Fair: Fa = Capacity/4, Fb = Fc = Fd = 3Capacity/4

or

Locally Fair: Fa = Fb = Fc = Fd = Capacity/2

This is the so-called “max-min fair” rate allocation. The minimum rate is maximized.

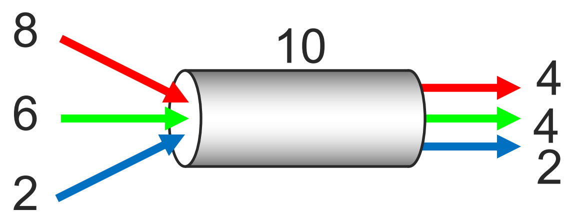
Max-Min Fairness



1. No user receives more than requested bandwidth
2. No other scheme with 1 has higher min bandwidth
3. 2 remains true recursively on removing minimal user $\mu_l = \mathrm{MIN}(\mu_{fair}, \rho_i)$

Max-Min Fairness: Example

- Capacity(C) = 10
  - 3 Flows: r1 = 8, r2 = 6, r3 = 2
- C/3 = 3.33 →
  - Can service all of r3
  - Remove r3 from the accounting: C = C – r3 = 8; N = 2
- C/2 = 4 →
  - Can't service all of r1 or r2
  - So hold them to the remaining fair share: f = 4



Queueing Disciplines

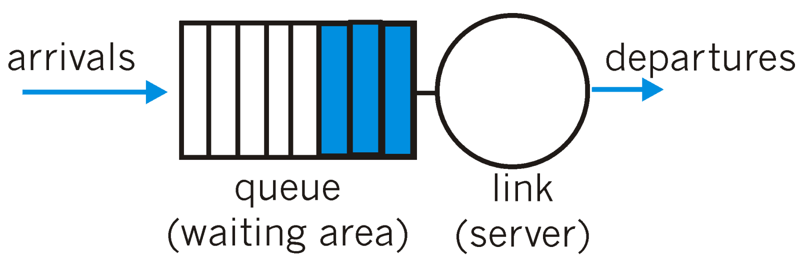
- Goal
  - Decide how packets are buffered while waiting to be transmitted
  - Provide protection from ill-behaved flows
  - Each router MUST implement some queuing discipline regardless of what the resource allocation mechanism is
- Impact
  - Directly impacts buffer space usage
  - Indirectly impacts flow control

Queueing Disciplines

- Allocate bandwidth
  - Which packets get transmitted
- Allocate buffer space
  - Which packets get discarded
- Affect packet latency
  - When packets get transmitted

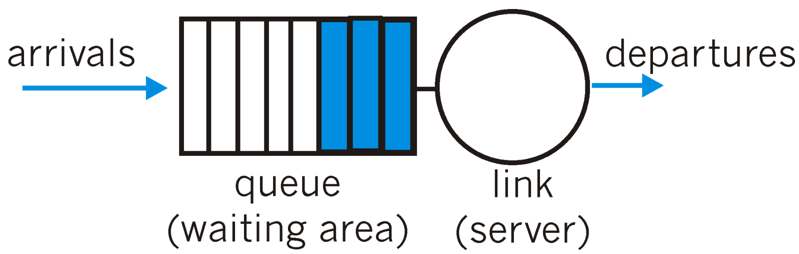
Scheduling Policies

- FIFO (First In First Out) a.k.a. FCFS (First Come First Serve)
  - Service
    - In order of arrival to the queue
  - Management
    - Packets that arrive to a full buffer are discarded
    - Another option: discard policy determines which packet to discard (new arrival or something already queued)



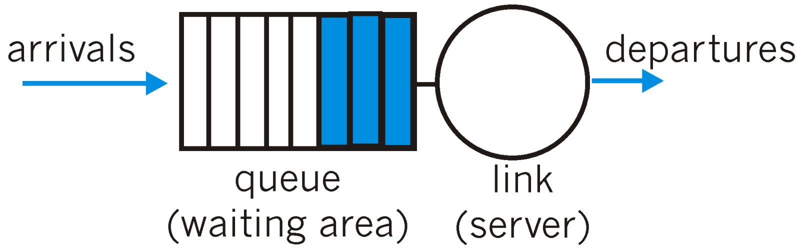
Scheduling Policies

- FIFO (First In First Out)
  - Problem 1: send more packets, get more service
    - Selfish senders trying to grab as much as they can
    - Malicious senders trying to deny service to others
  - Problem 2: not all packets should be equal



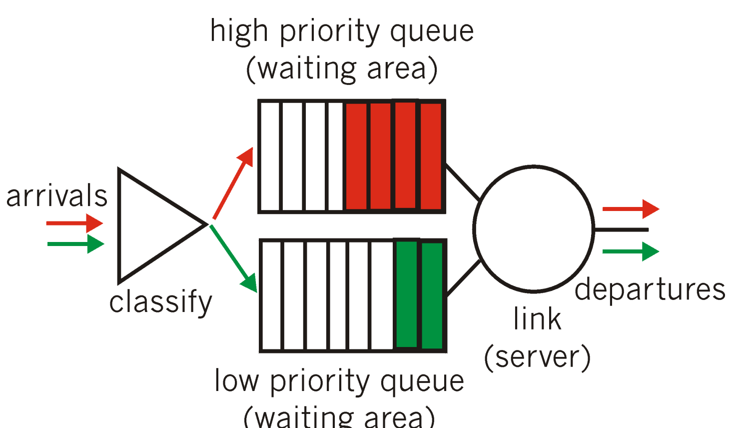
Scheduling Policies

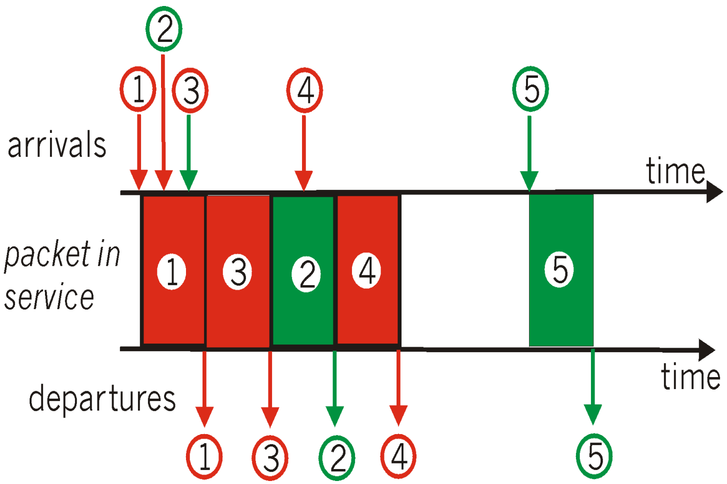
- FIFO
  - Does not discriminate between traffic sources
  - Congestion control left to the sources
  - Tail drop dropping policy
  - Fairness for latency
  - Minimizes per-packet delay
  - Bandwidth not considered (not good for congestion)



Scheduling Policies

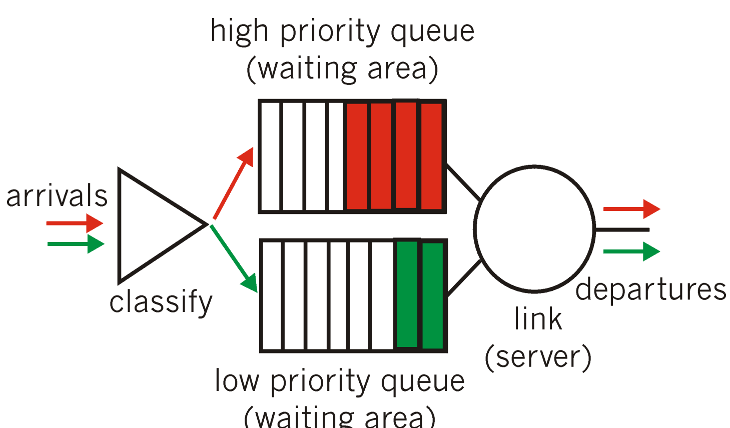
- Priority Queuing
  - Classes have different priorities
    - May depend on explicit marking or other header info
      - e.g., IP source or destination, TCP Port numbers, etc.
  - Service
    - Transmit packet from highest priority class with a non-empty queue

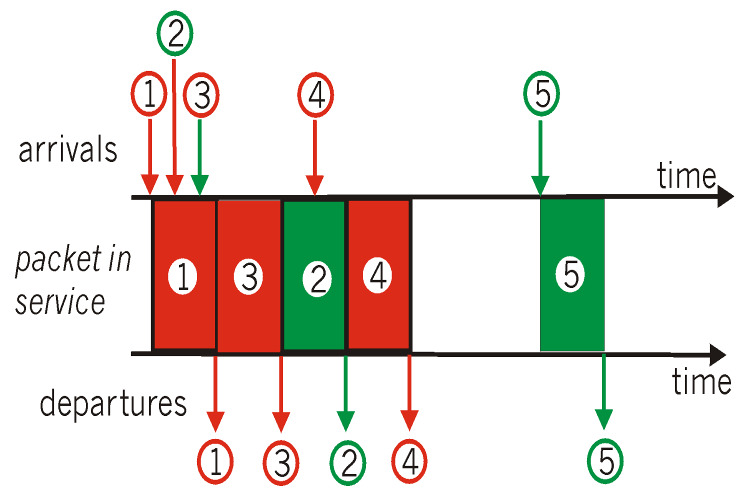




Scheduling Policies

- Priority Queuing
  - Isolation for the high-priority traffic
    - Almost like it has a dedicated link
    - Except for the (small) delay for packet transmission
      - High-priority packet arrives during transmission of low-priority
      - Router completes sending the low-priority traffic first



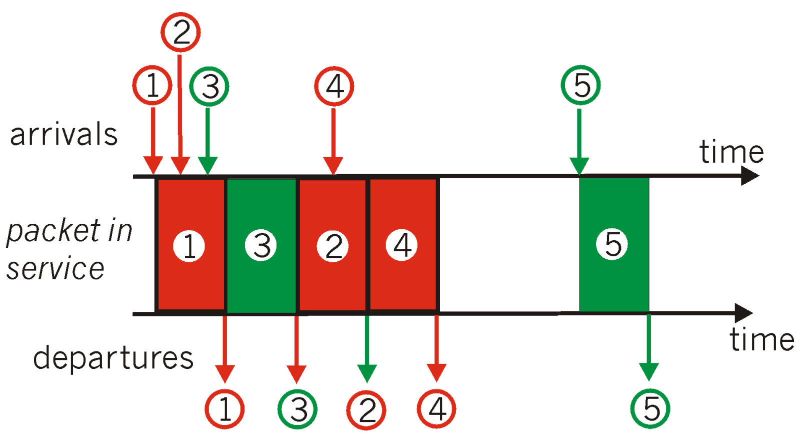


Scheduling Policies

- Priority Queueing Versions
  - Preemptive
    - Postpone low-priority processing if high-priority packet arrives
  - Non-preemptive
    - Any packet that starts getting processed finishes before moving on
- Limitation
  - May starve lower priority flows

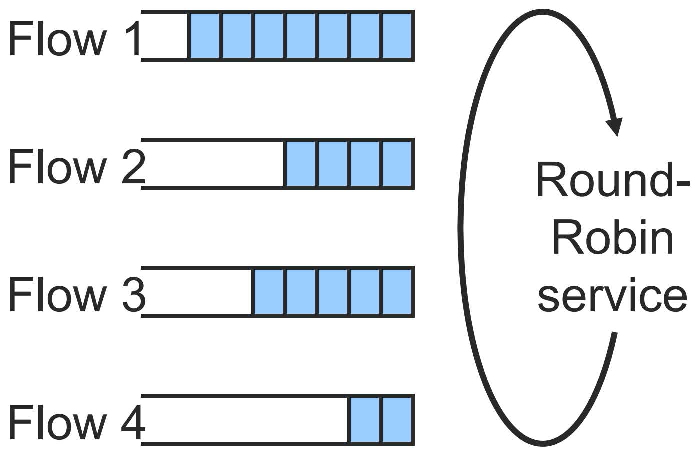
Scheduling Policies

- Round Robin
  - Each flow gets its own queue
  - Circulate through queues, process one packet (if queue non-empty), then move to next queue



Scheduling Policies

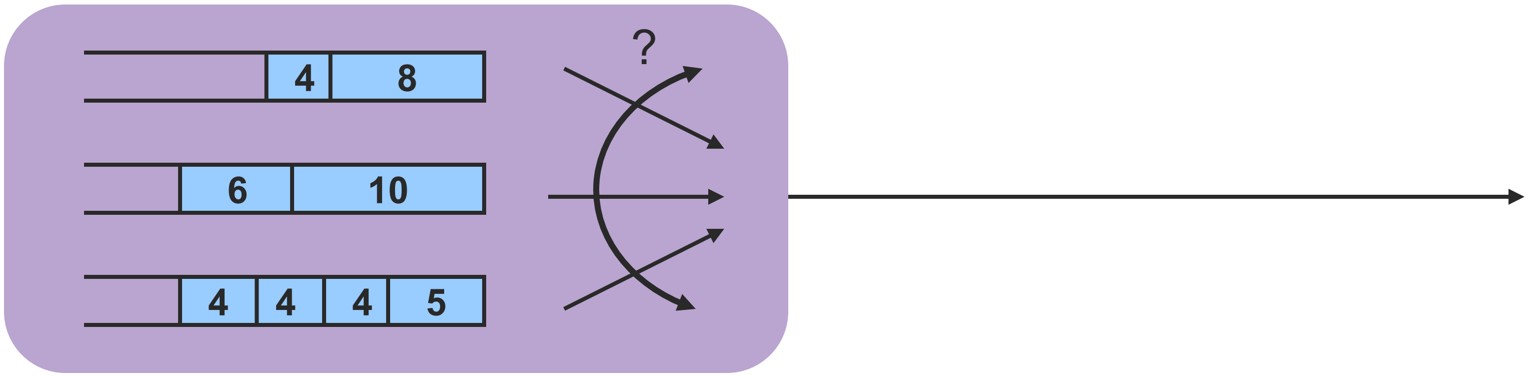
- Fair Queueing (FQ)
  - Explicitly segregates traffic based on flows
  - Ensures no flow captures more than its share of the capacity
  - Fairness for bandwidth
  - Delay not considered



Each flow is guaranteed ¼ of capacity

Fair Queueing with Variable Packet Length

- How should we implement FQ if packets are not all the same length?
  - Bit-by-bit round-robin
    - Not feasible to implement, must use packet scheduling
    - Solution: approximate



Fair Queueing with Variable Packet Length

- Idea
  - Let S_i = amount of service flow i has received so far
  - Always serve a flow with minimum value of S_i
    - Can also use minimum (S_i + next packet length)
  - Upon serving a packet of length P from flow i, update:
    - $S_i = S_i + P$
- Never leave the link idle if there is a packet to send
  - Work conserving
    - A source will gets its fair share of the bandwidth
    - Unused bandwidth will be evenly divided between other sources

Fair Queueing with Variable Packet Length

- Problem
  - A flow resumes sending packets after being quiet for a long time
- Effect
  - Such a flow could be considered to have “saved up credit”
  - Can lock out all other flows until credits are level again
- Solution
  - Enforce “use it or lose it policy”
    - Compute S_{min} = min(S_i such that queue i is not empty)
    - If queue j is empty, set $S_j = S_{min}$

Fair Queueing with Variable Packet Length

- Problem
  - A flow resumes se
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- Effect
  - Such a flow could
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- Solution
  - Enforce “use it or
    - Compute S_{min} =
    - If queue j is emp

Note:

The text book computes

$F = MAX(F_{i-1}, A_i) = P_i$

And then for multiple flows

- Calculate F_i for each packet that arrives on each flow
- Treat all F_i as timestamps
- Next packet to transmit is one with lowest timestamp

Extension: Weighted Fair Queueing

- Extend fair queueing
  - Notion of importance for each flow
- Suppose flow i has weight w_i
  - Example: w_i could be the fraction of total service that flow i is targeted for
- Need only change basic update to
  - $S_i = S_i + P/w_i$

Fair Queuing Tradeoffs

- FQ can control congestion by monitoring flows
  - Non-adaptive flows can still be a problem – why?
- Complex state
  - Must keep queue per flow
    - Hard in routers with many flows (e.g., backbone routers)
    - Flow aggregation is a possibility (e.g. do fairness per domain)
- Complex computation
  - Classification into flows may be hard
  - Must keep queues sorted by finish times
  - Changes whenever the flow count changes

Fair Queueing

- Question
  - What makes up a flow for fair queueing in the Internet?
- Considerations
  - Too many resources to have separate queues/variables for host-to-host flows
  - Scale down number of flows
  - Typically just based on inputs
    - e.g., share outgoing STS-12 between incoming ISP's

TCP Congestion Control

Host Solutions

- Host has very little information
  - Assumes best-effort network
  - Acts independently of other hosts
- Host actions
  - Reduce transmission rate below congestion threshold
  - Continuously monitor network for signs of congestion

Detecting Congestion

- How can a TCP sender determine that the network is under stress?
- Network could tell it (ICMP Source Quench)
  - Risky, because during times of overload the signal itself could be dropped (and add to congestion)!
- Packet delays go up (knee of load-delay curve)
  - Tricky: noisy signal (delay often varies considerably)
- Packet loss
  - Fail-safe signal that TCP already has to detect
  - Complication: non-congestive loss (checksum errors)

TCP Congestion Control

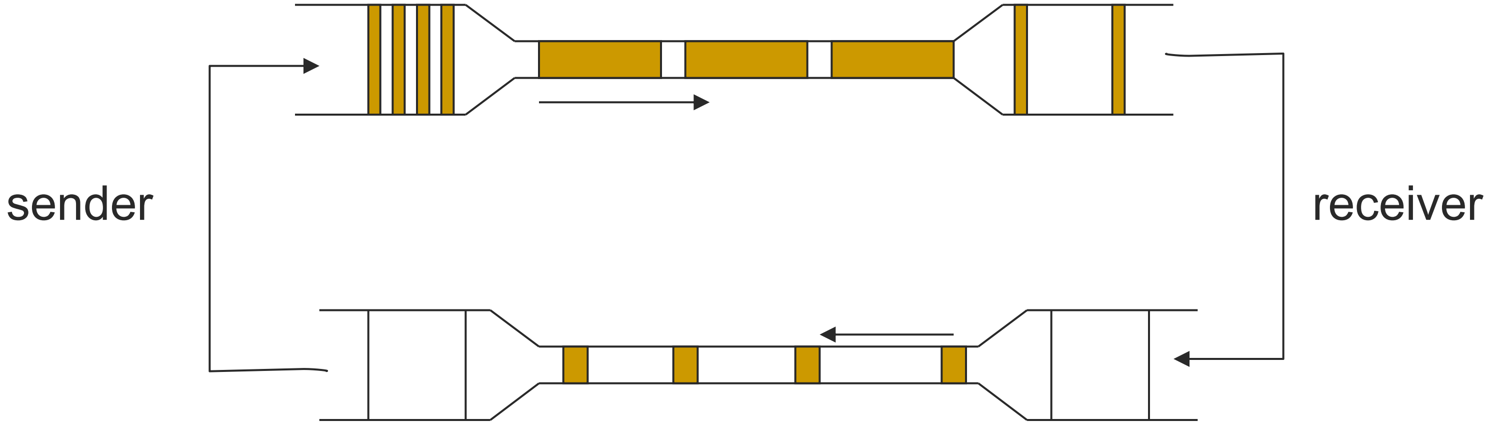
- Idea
  - Assumes best-effort network
    - FIFO or FQ
  - Each source determines network capacity for itself
  - Implicit feedback
  - ACKs pace transmission (self-clocking)
- Challenge
  - Determining initial available capacity
  - Adjusting to changes in capacity in a timely manner

TCP Congestion Control

- Basic idea
  - Add notion of congestion window
  - Effective window is smaller of
    - Advertised window (flow control)
    - Congestion window (congestion control)
  - Changes in congestion window size
    - Slow increases to absorb new bandwidth
    - Quick decreases to eliminate congestion

TCP Congestion Control

- Specific strategy
  - Self-clocking
    - Send data only when outstanding data ACK’d
    - Equivalent to send window limitation mentioned



TCP Congestion Control

- Specific strategy
  - Self-clocking
    - Send data only when outstanding data ACK’d
    - Equivalent to send window limitation mentioned
  - Growth
    - Add one maximum segment size (MSS) per congestion window of data ACK’d
    - It’s really done this way, at least in Linux:
      - see tcp_cong_avoid in tcp_input.c.
      - Actually, every ack for new data is treated as an MSS ACK’d
    - Known as additive increase

TCP Congestion Control

- Specific strategy (continued)
  - Decrease
    - Cut window in half when timeout occurs
    - In practice, set window = window /2
    - Known as multiplicative decrease
  - Additive increase, multiplicative decrease (AIMD)

Additive Increase/ Multiplicative Decrease

- Objective
  - Adjust to changes in available capacity
- Basic idea
  - Consequences of over-sized window much worse than having an under-sized window
    - Over-sized window: packets dropped and retransmitted
    - Under-sized window: somewhat lower throughput

Additive Increase/ Multiplicative Decrease

- Tools
  - React to observance of congestion
  - Probe channel to detect more resources
- Observation
  - On notice of congestion
    - Decreasing too slowly will not be reactive enough
  - On probe of network
    - Increasing too quickly will overshoot limits

Additive Increase/ Multiplicative Decrease

- New TCP state variable
  - **`CongestionWindow`**
    - Similar to **`AdvertisedWindow`** for flow control
  - Limits how much data source can have in transit
    - **`MaxWin = MIN(CongestionWindow, AdvertisedWindow)`**
    - **`EffWin = MaxWin - (LastByteSent - LastByteAcked)`**
    - TCP can send no faster then the slowest component, network or destination
- Idea
  - Increase **`CongestionWindow`** when congestion goes down
  - Decrease **`CongestionWindow`** when congestion goes up

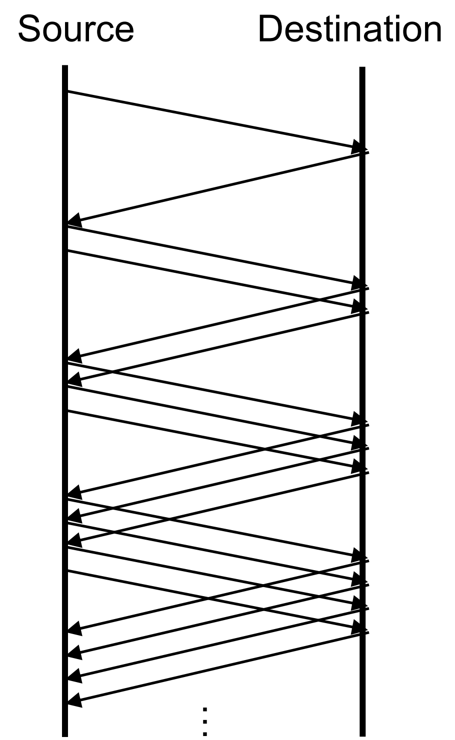
Additive Increase/ Multiplicative Decrease

- Question
  - How does the source determine whether or not the network is congested?
- Answer
  - Timeout signals packet loss
  - Packet loss is rarely due to transmission error (on wired lines)
  - Lost packet implies congestion!

Additive Increase/ Multiplicative Decrease

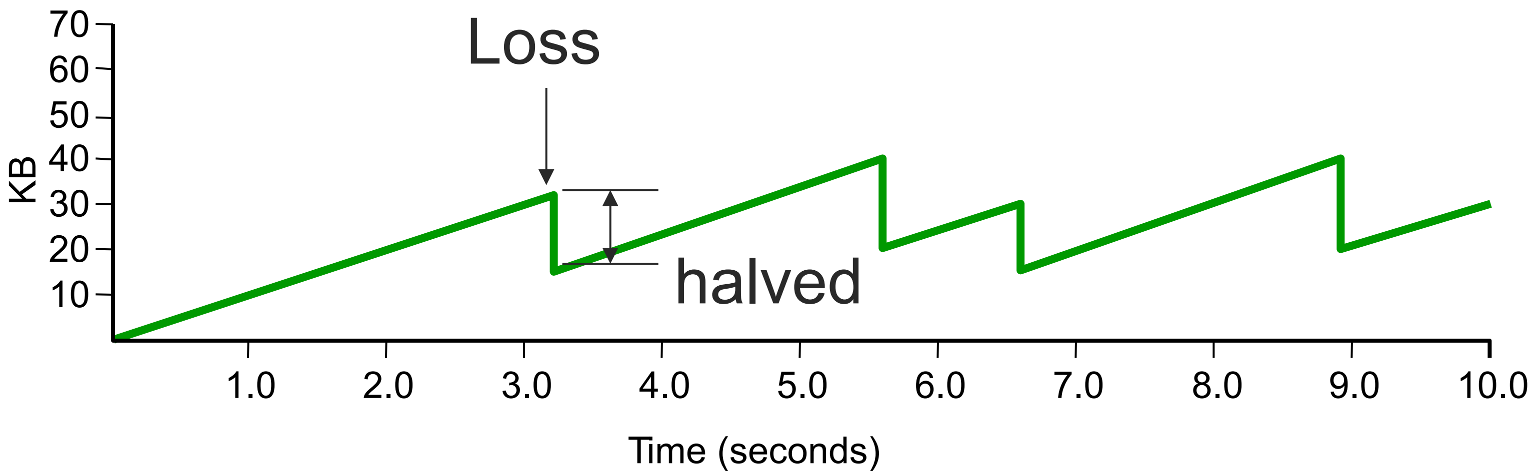
- Algorithm
  - Increment CongestionWindow by one packet per RTT
    - Linear increase
  - Divide CongestionWindow by two whenever a timeout occurs
    - Multiplicative decrease
- In practice
  - increment a little for each ACK

```
Inc = MSS * MSS/CongestionWindow
CongestionWindow += Inc
```



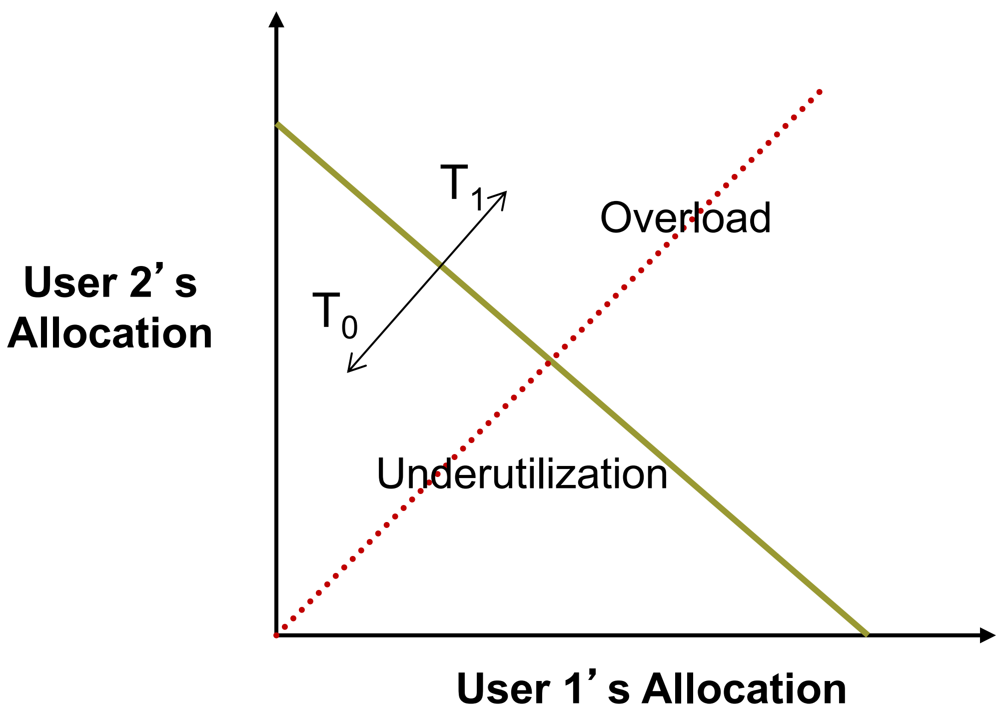
AIMD – Sawtooth Trace

- Packet loss is seen as sign of congestion and results in a multiplicative rate decrease
  - Factor of 2
- TCP periodically probes for available bandwidth by increasing its rate



Additive Increase/Decrease

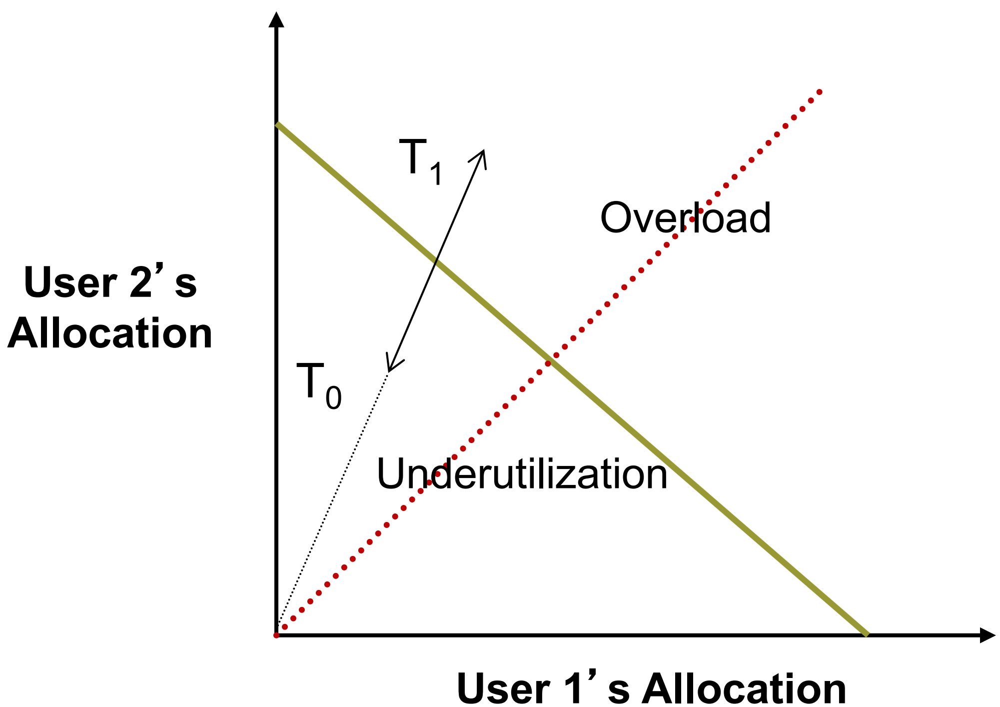
- Both increase/ decrease by the same amount



- Additive increase improves fairness
- Additive decrease reduces fairness

Muliplicative Increase/Decrease

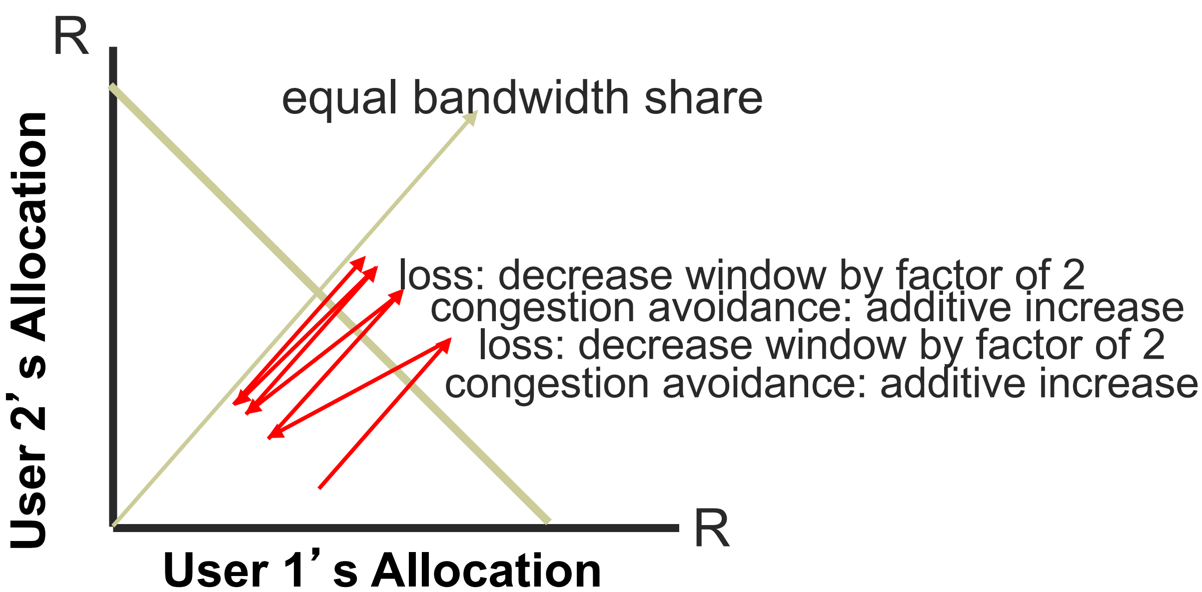
- Both increase/ decrease by the same amount



- Additive increase improves fairness
- Additive decrease reduces fairness

Why is AIMD Fair?

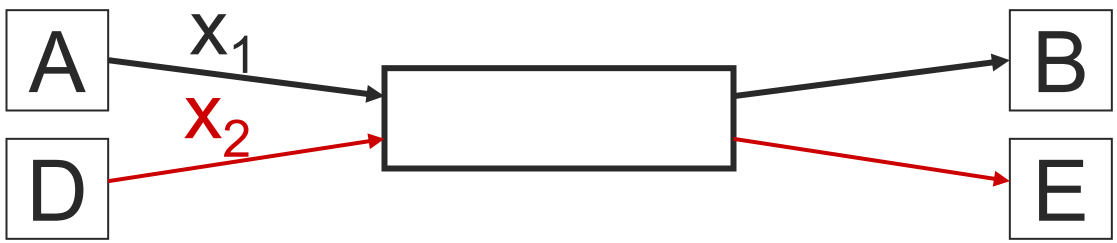
- Additive increase gives slope of 1, as throughout increases
- Multiplicative decrease decreases throughput proportionally

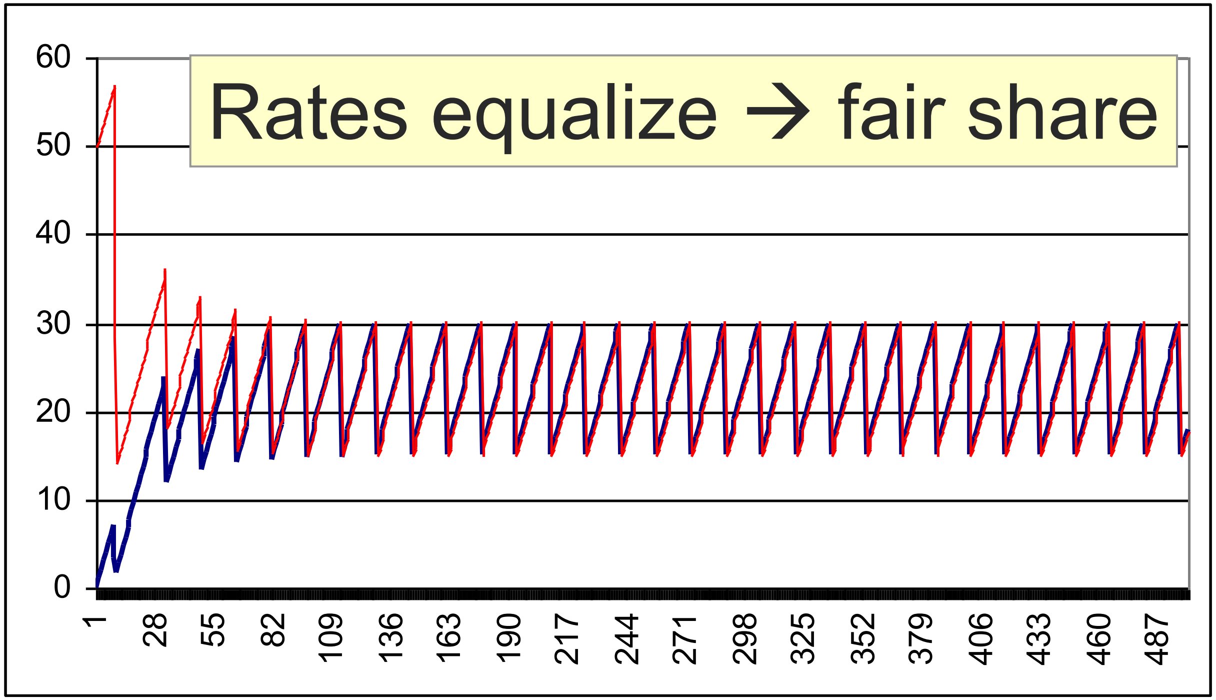


AIMD Sharing Dynamics

- No congestion → rate increases by one packet/RTT every RTT
- Congestion → decrease rate by factor 2

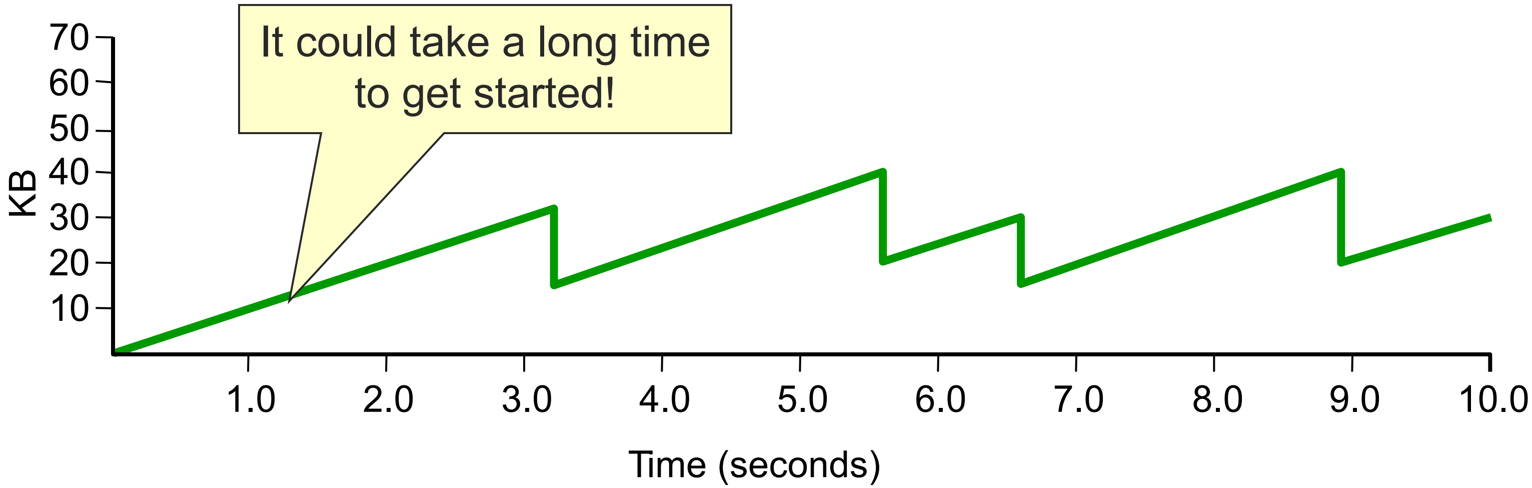
AIMD Sharing Dynamics





TCP Start Up Behavior

- How should TCP start sending data?
  - AIMD is good for channels operating at capacity
  - AIMD can take a long time to ramp up to full capacity from scratch



TCP Start Up Behavior

- How should TCP start sending data?
  - AIMD is good for channels operating at capacity
  - AIMD can take a long time to ramp up to full capacity from scratch
  - Use Slow Start to increase window rapidly from a cold start

TCP Start Up Behavior: Slow Start

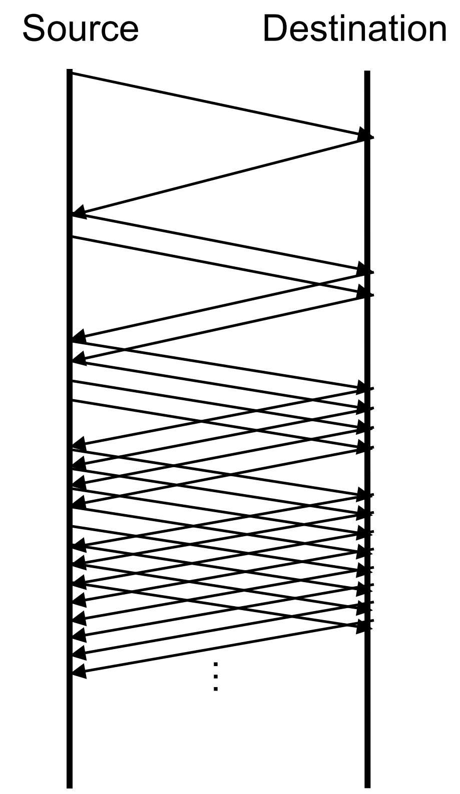
- Initialization of the congestion window
  - Congestion window should start small
    - Avoid congestion due to new connections
  - Start at 1 MSS,
    - Initially, CWND is 1 MSS
    - Initial sending rate is MSS/RTT
  - Reset to 1 MSS with each timeout
    - timeouts are coarse-grained, ~1/2 sec

TCP Start Up Behavior: Slow Start

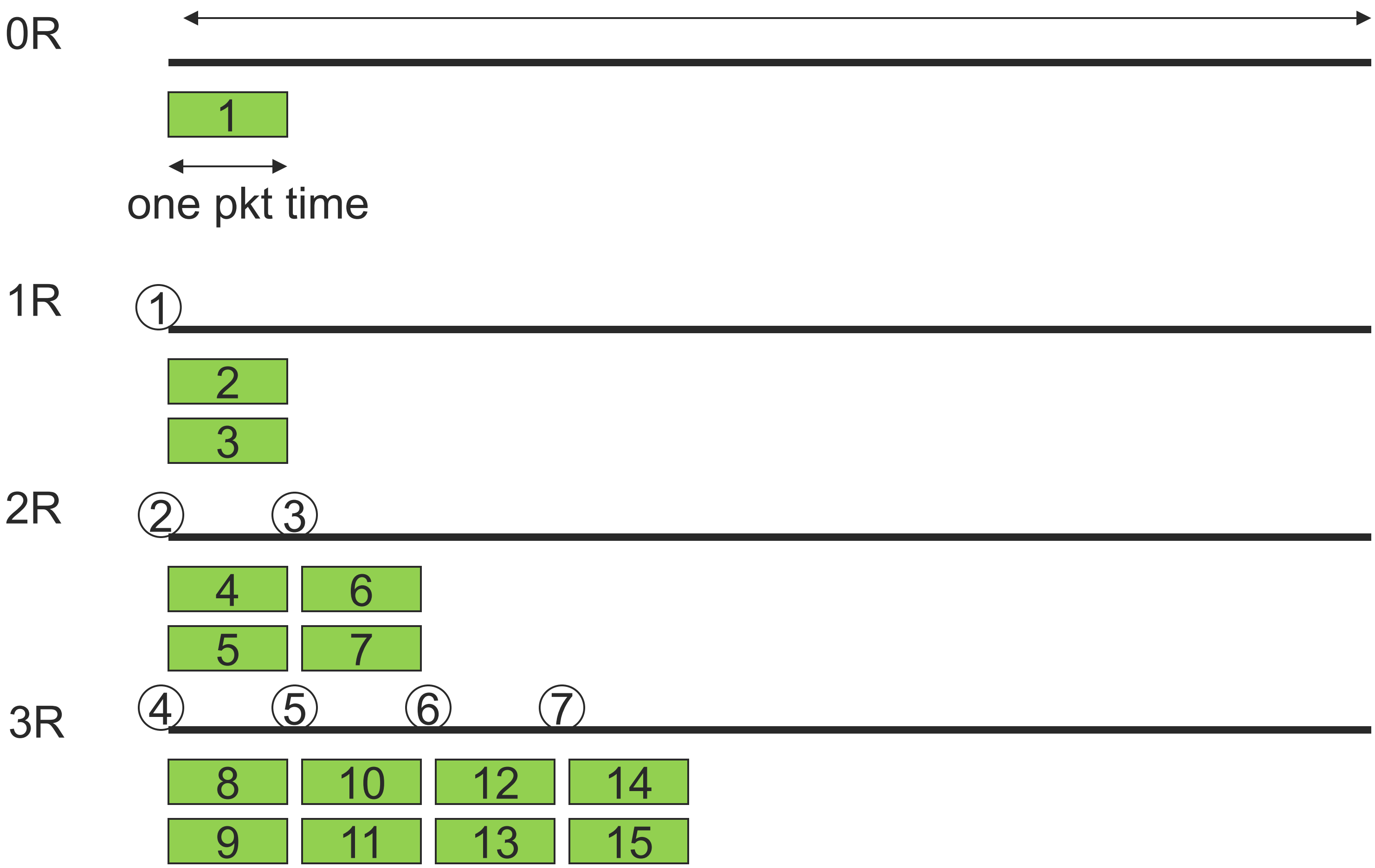
- Growth of the congestion window
- Linear growth could be pretty wasteful
  - Might be much less than the actual bandwidth
  - Linear increase takes a long time to accelerate
- Start slow but then grow fast
  - Sender starts at a slow rate
  - Increase the rate exponentially
  - Until the first loss event

Slow Start

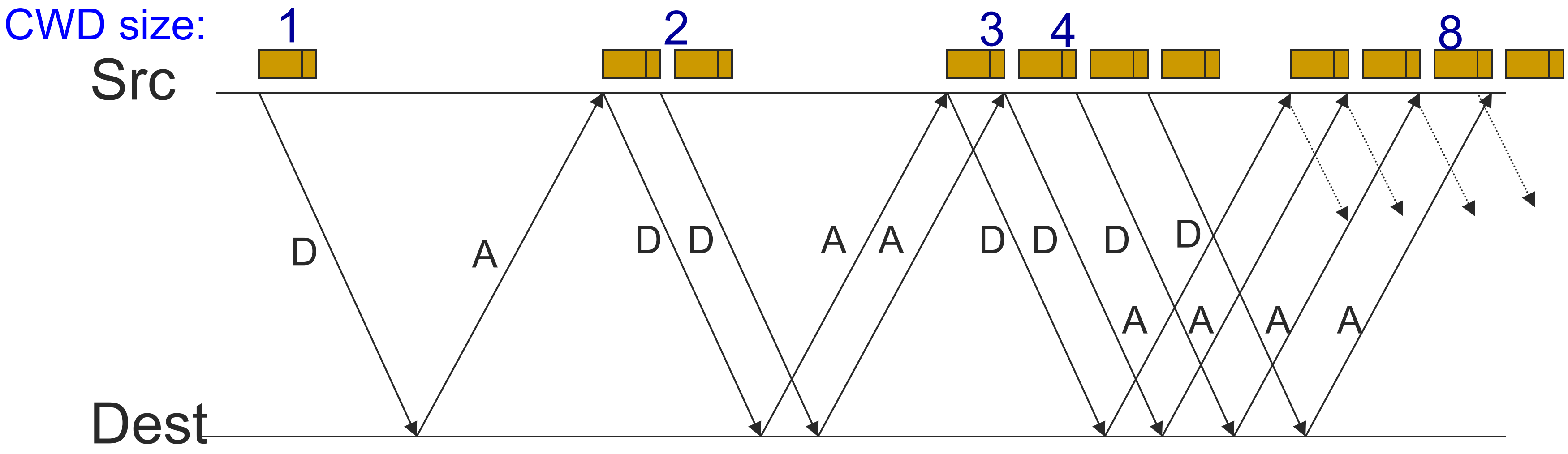
- Objective
  - Determine initial available capacity
- Idea
  - Begin with **`CongestionWindow`** = 1 packet
  - Double **`CongestionWindow`** each RTT
    - Increment by 1 packet for each ACK
  - Continue increasing until loss



Slow Start Example



Another Slow Start Example



Slow Start

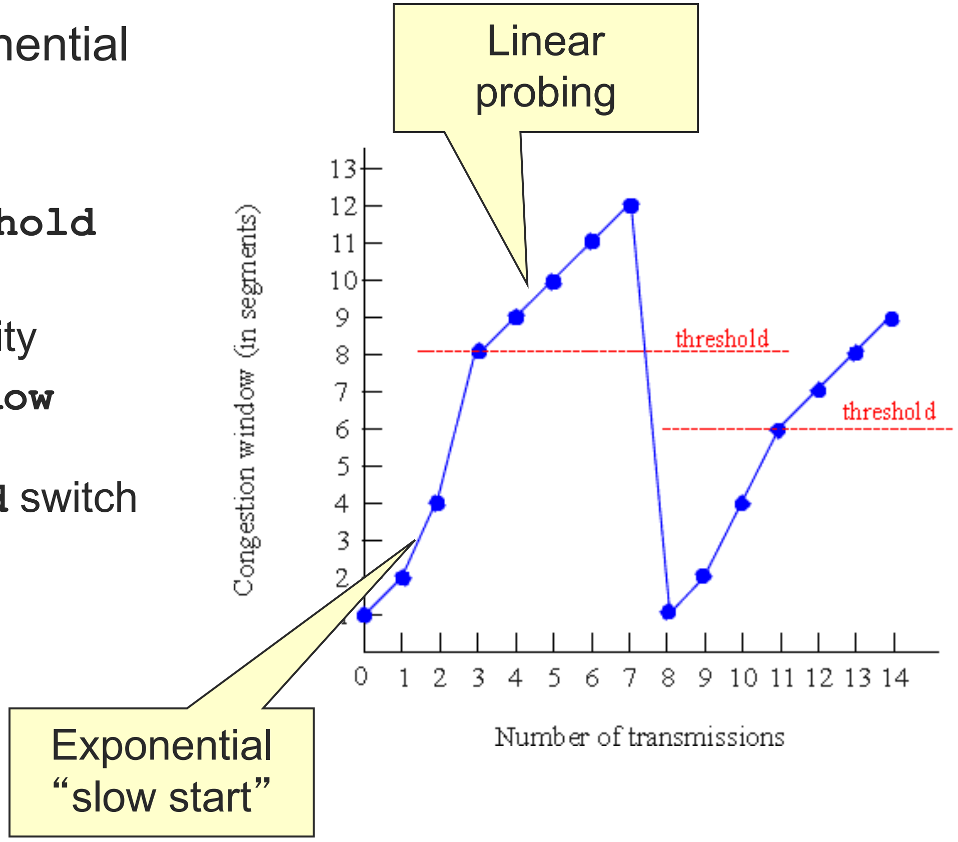
- Used
  - When first starting connection
  - When connection times out
- Why is it called slow-start?
  - Because TCP originally had no congestion control mechanism
  - The source would just start by sending a whole window’s worth of data

TCP Congestion Control

- Maintain threshold window size
  - Threshold value
    - Initially set to maximum window size
    - Set to 1/2 of current window on timeout
  - Use multiplicative increase
    - When congestion window smaller than threshold
    - Double window for each window ACK'd
- In practice
  - Increase congestion window by one MSS for each ACK of new data (or N bytes for N bytes)

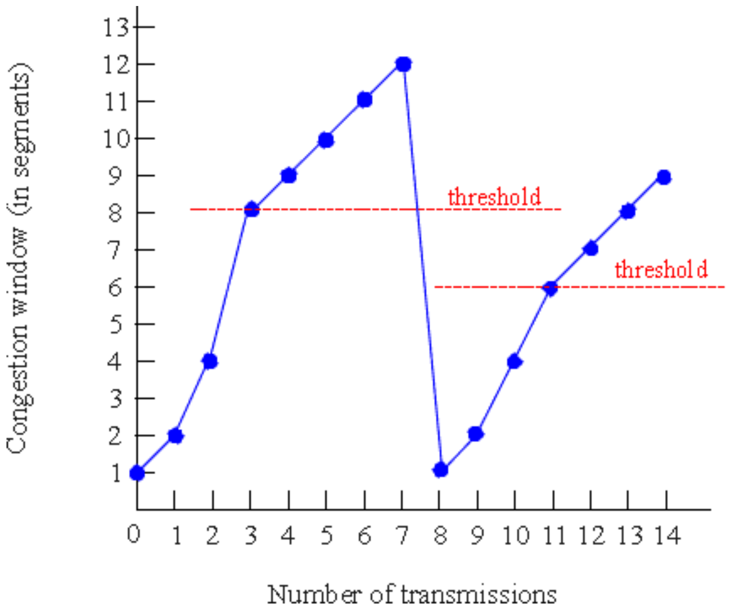
Slow Start

- How long should the exponential increase from slow start continue?
  - Use `CongestionThreshold` as target window size
  - Estimates network capacity
  - When `CongestionWindow` reaches `CongestionThreshold` switch to additive increase



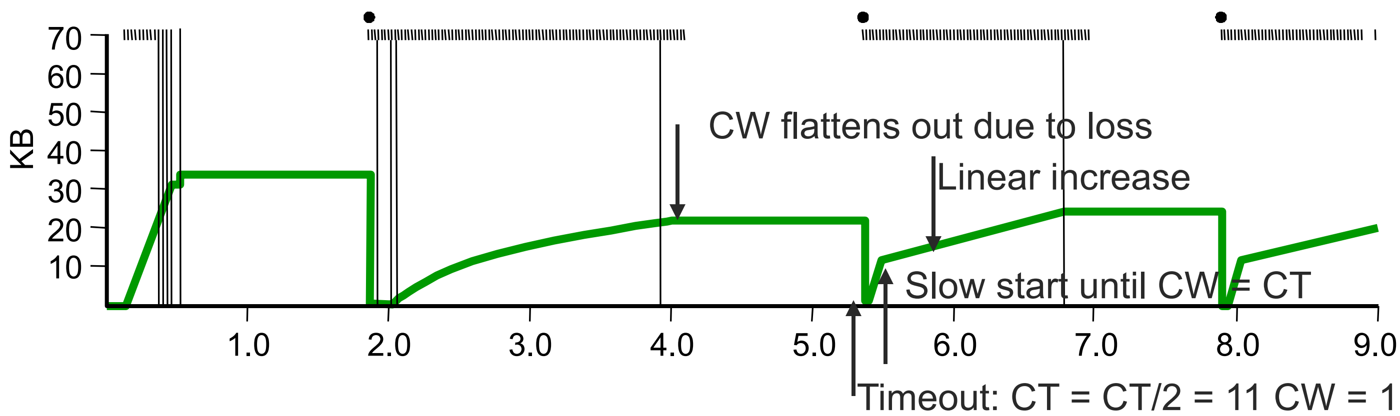
Slow Start

- Initial values
  - `CongestionThreshold = 8`
  - `CongestionWindow = 1`
- Loss after transmission 7
  - `CongestionWindow` currently 12
  - Set `Congestionthreshold = CongestionWindow/2`
  - Set `CongestionWindow = 1`



Slow Start

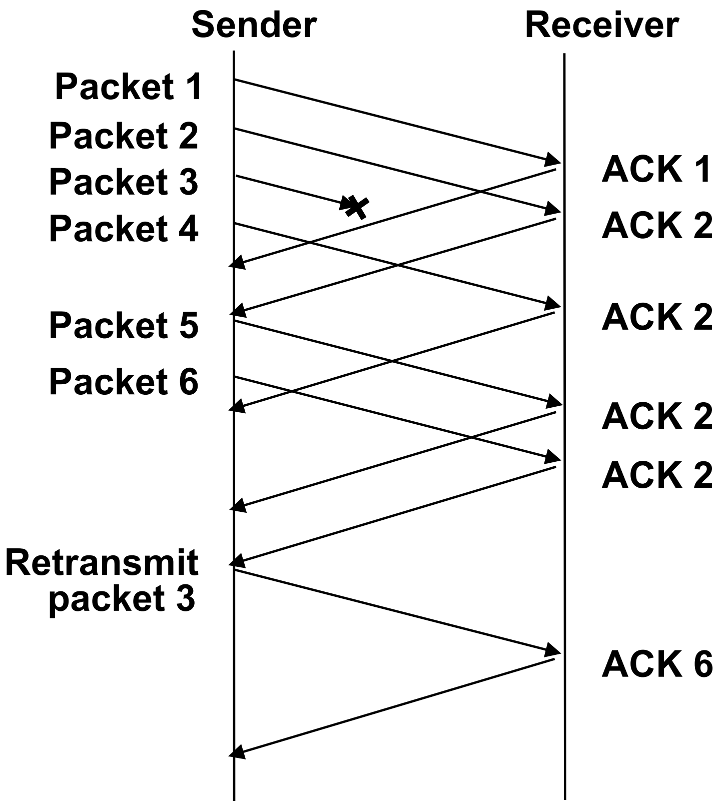
- Example trace of **`CongestionWindow`**



- Problem
  - Have to wait for timeout
  - Can lose half **`CongestionWindow`** of data

Fast Retransmit and Fast Recovery

- Problem
  - Coarse-grain TCP timeouts lead to idle periods
- Solution
  - Fast retransmit: use duplicate ACKs to trigger retransmission

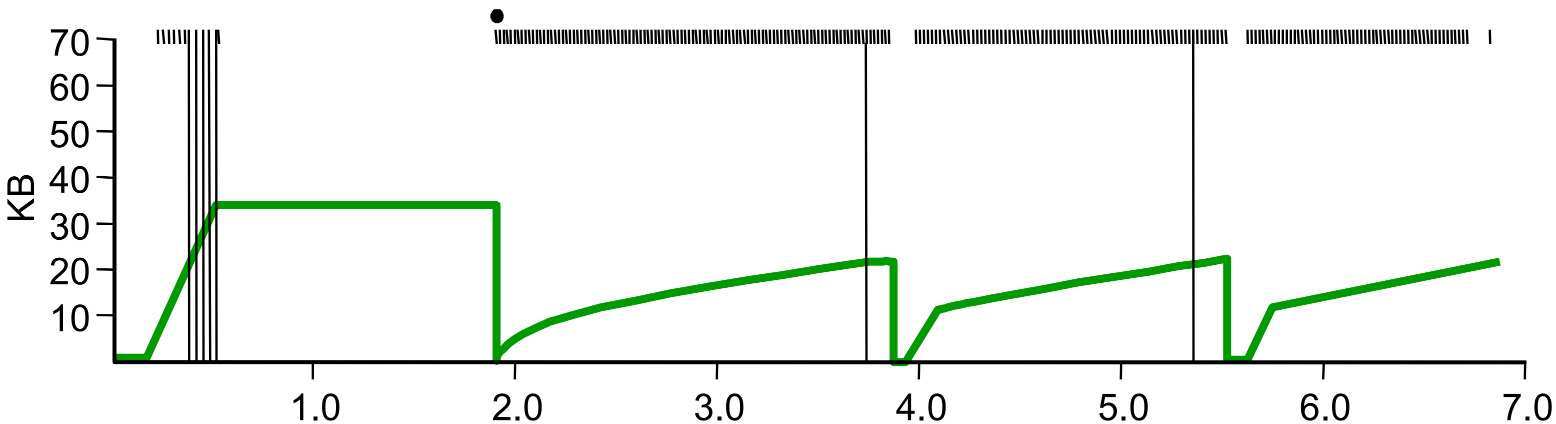


Fast Retransmit and Fast Recovery

- Send ACK for each segment received
- When duplicate ACK's received
  - Resend lost segment immediately
  - Do not wait for timeout
  - In practice, retransmit on 3rd duplicate
- Fast recovery
  - When fast retransmission occurs, skip slow start
  - Congestion window becomes 1/2 previous
  - Start additive increase immediately

Fast Retransmit and Fast Recovery

- Results



- Fast Recovery
  - Bypass slow start phase
  - Increase immediately to one half last successful **`CongestionWindow`** **(`ssthresh`)**

TCP Congestion Window Trace