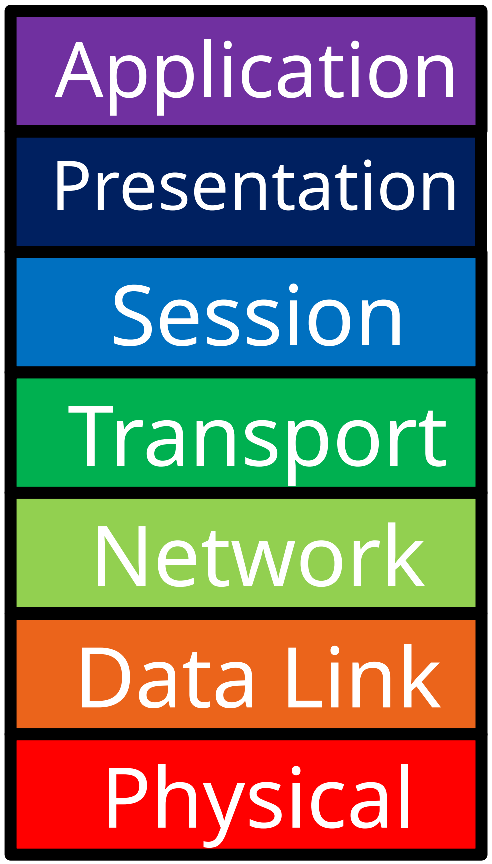
Computer Networks

Lecture 10: Transport layer Part II

Based on slides from D. Choffnes Northeastern U. and P. Gill from StonyBrook University
Revised Autumn 2015 by S. Laki

Transport Layer



- Function:
  - Demultiplexing of data streams
- Optional functions:
  - Creating long lived connections
  - Reliable, in-order packet delivery
  - Error detection
  - Flow and congestion control
- Key challenges:
  - Detecting and responding to congestion
  - Balancing fairness against high utilization

TCP Congestion Control

- **The network is congested if the load in the network is higher than its capacity.**
- Each TCP connection has a window
  - Controls the number of unACKed packets
- Sending rate is ~ window/RTT
- Idea: vary the window size to control the send rate
- Introduce a congestion window at the sender
  - Congestion control is sender-side problem

Two Basic Components

1. Detect congestion
   - Packet dropping is most reliably signal
     - Delay-based methods are hard and risky
   - How do you detect packet drops? ACKs
     - Timeout after not receiving an ACK
     - Several duplicate ACKs in a row (ignore for now)
2. Rate adjustment algorithm
   - Modify *cwnd*
   - Probe for bandwidth
   - Responding to congestion

Rate Adjustment

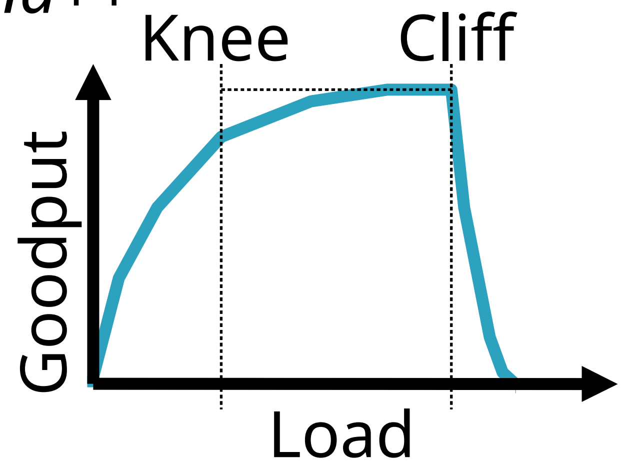
- Recall: TCP is ACK clocked
  - Congestion = delay = long wait between ACKs
  - No congestion = low delay = ACKs arrive quickly
- Basic algorithm
  - Upon receipt of ACK: increase cwnd
    - Data was delivered, perhaps we can send faster
    - *cwnd* growth is proportional to RTT
  - On loss: decrease cwnd
    - Data is being lost, there must be congestion
- Question: increase/decrease functions to use? !!!!

Implementing Congestion Control

- Maintains three variables:
  - *cwnd*: congestion window
  - *adv_wnd*: receiver advertised window
  - *ssthresh*: threshold size (used to update *cwnd*)
- For sending, use: *wnd = min(cwnd, adv_wnd*)
- Two phases of congestion control
  1. Slow start (*cwnd* < *ssthresh*)
     - Probe for bottleneck bandwidth
  2. Congestion avoidance (*cwnd* >= *ssthresh*)
     - AIMD

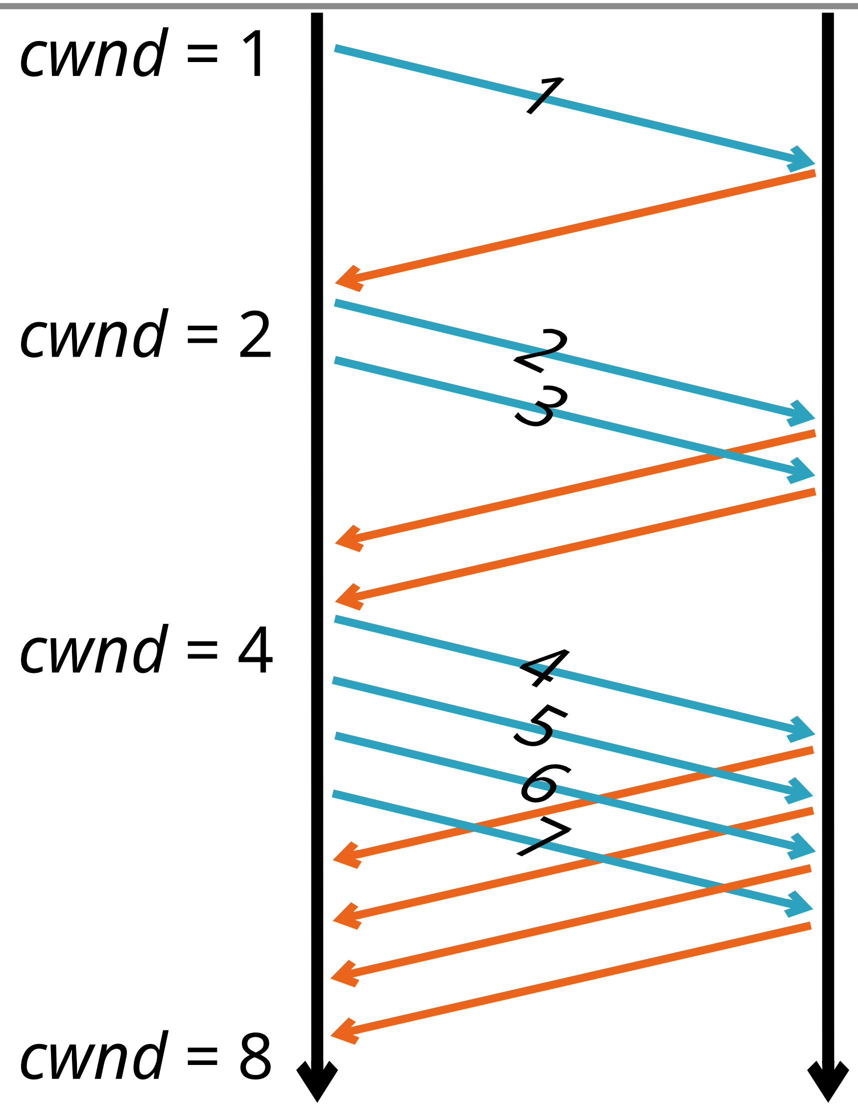
Slow Start

- Goal: reach knee quickly
- Upon starting (or restarting) a connection
  - *cwnd* =1
  - *ssthresh* = *adv_wnd*
  - Each time a segment is ACKed, *cwnd*++
- Continues until…
  - *ssthresh* is reached
  - Or a packet is lost
- Slow Start is not actually slow
  - *cwnd* increases exponentially



Slow Start Example

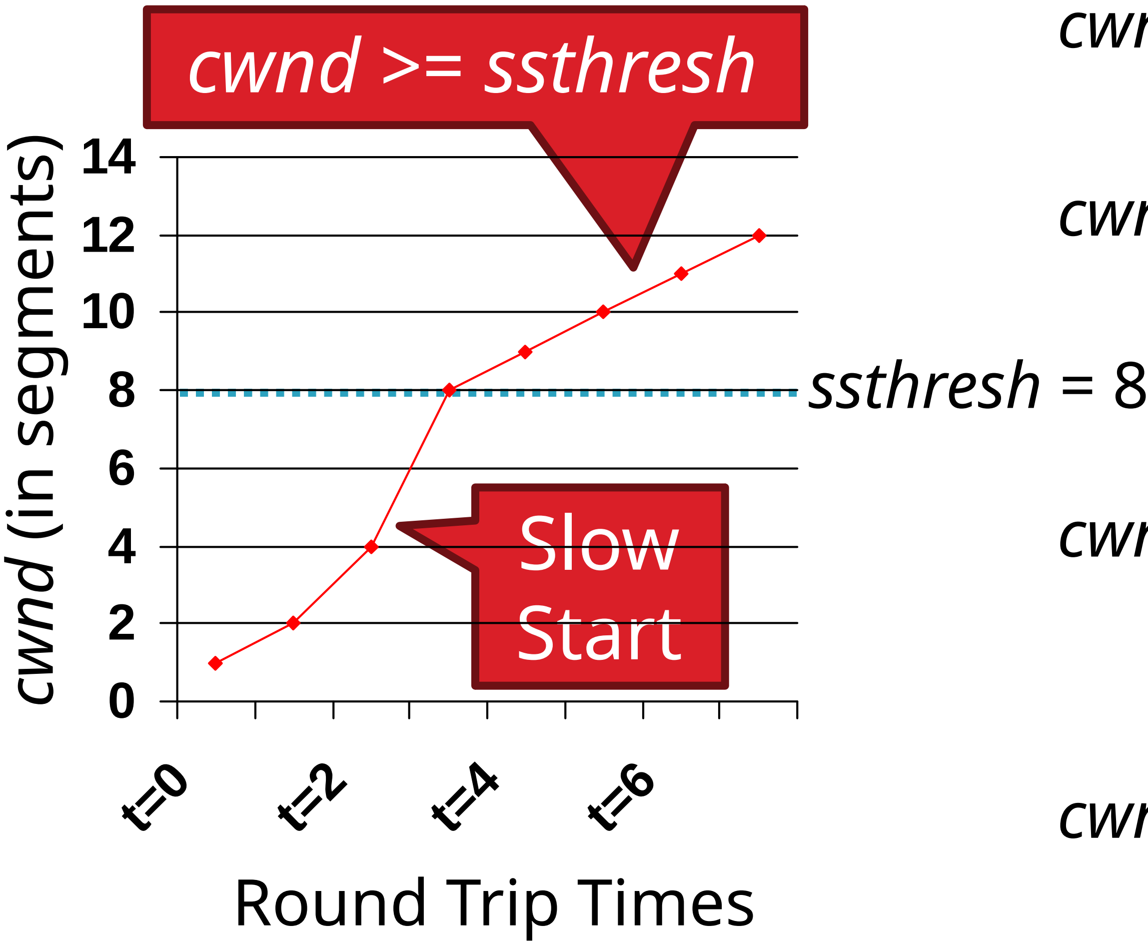
- *cwnd* grows rapidly
- Slows down when…
  - *cwnd >= ssthresh*
  - Or a packet drops

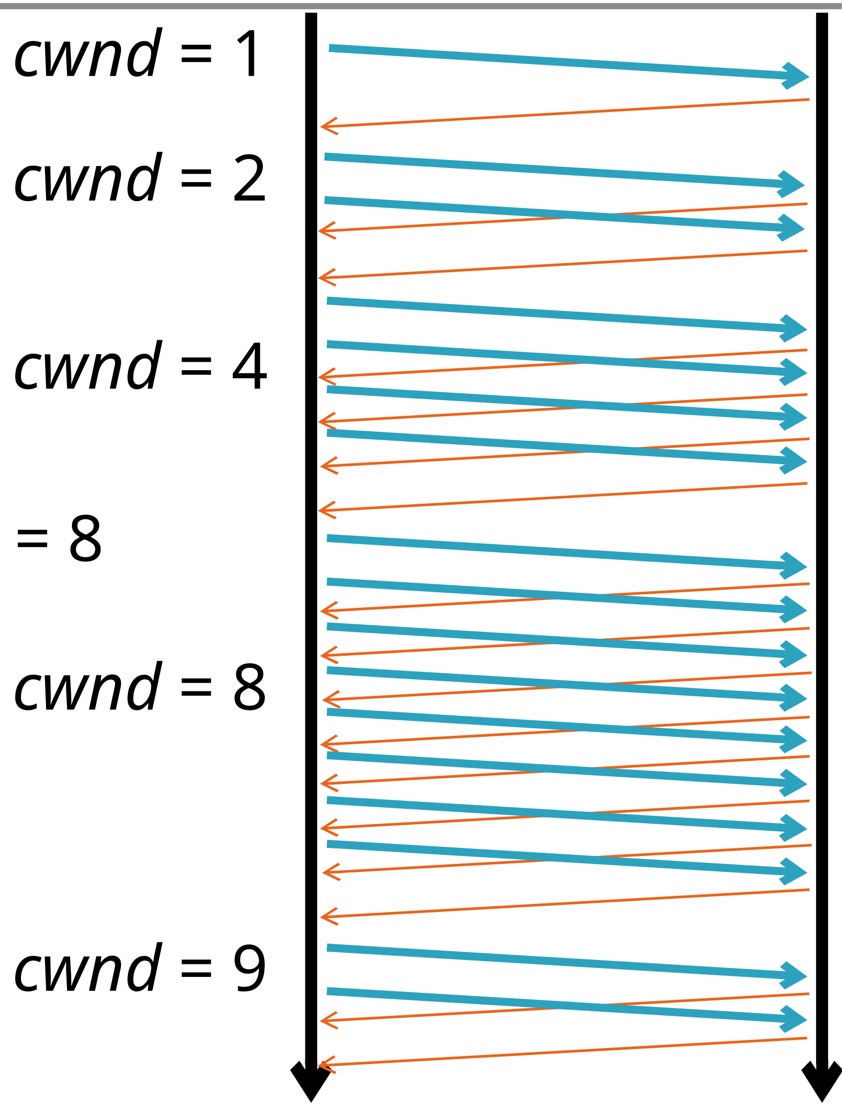


Congestion Avoidance

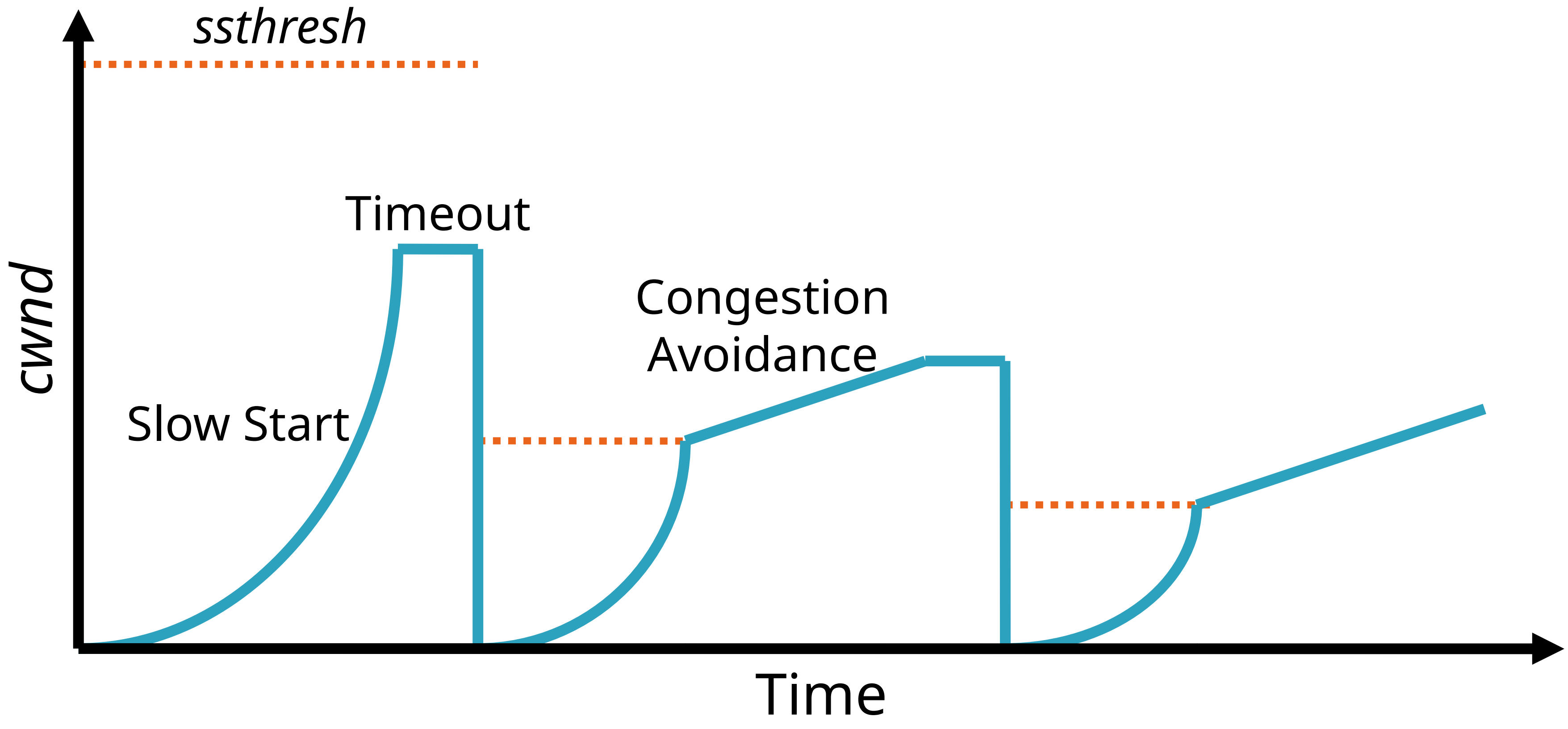
- Additive Increase Multiplicative Decrease (AIMD) mode
- *ssthresh* is lower-bound guess about location of the knee
- **If** *cwnd* >= *ssthresh* **then**
  each time a segment is ACKed
  increment *cwnd by 1/cwnd (cwnd += 1/cwnd).*
- So *cwnd* is increased by one only if all segments have been acknowledged

Congestion Avoidance Example





The Big Picture – TCP Tahoe (the original TCP)



Outline

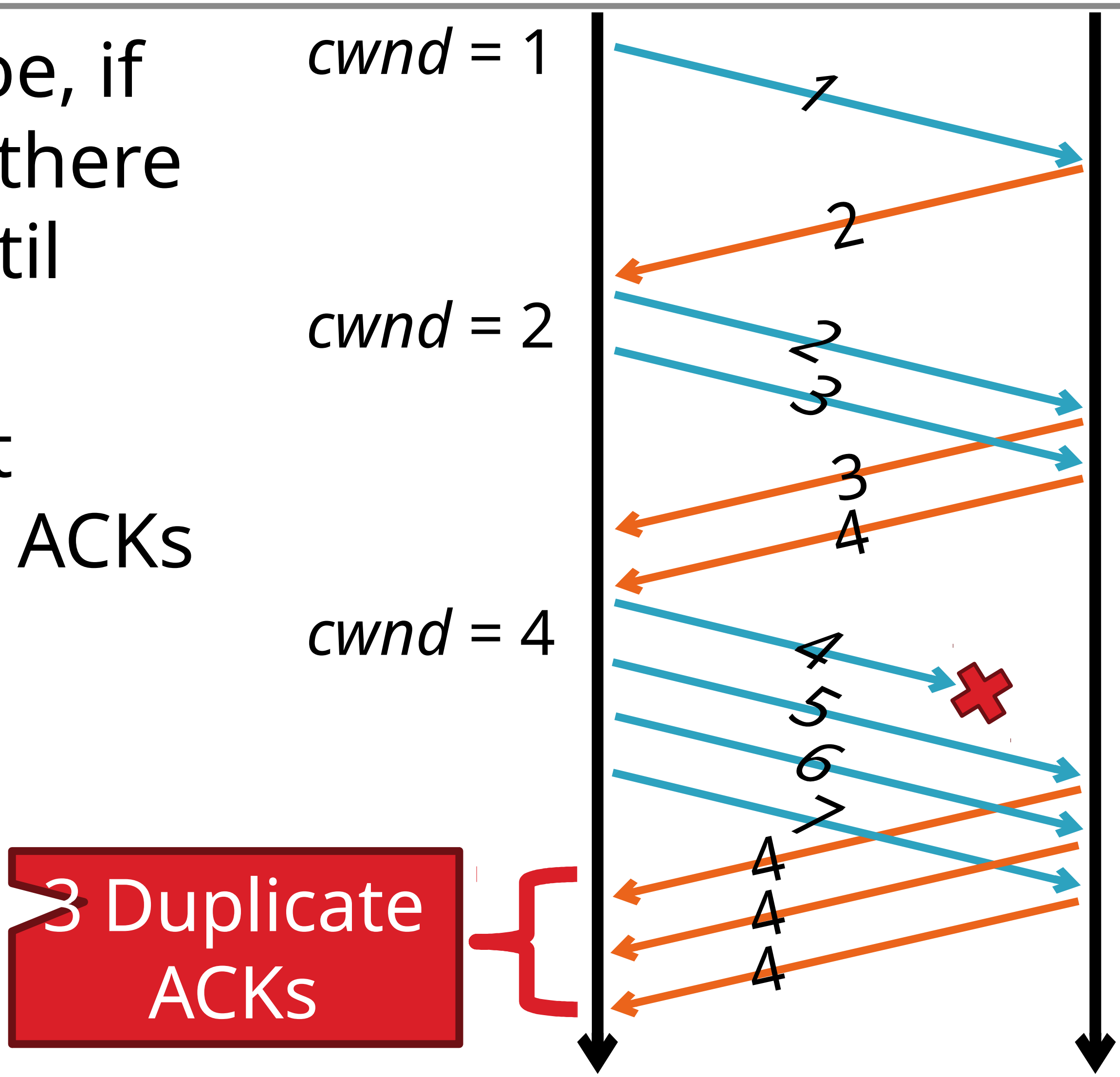
- UDP
- TCP
- Congestion Control
- **Evolution of TCP**
- Problems with TCP

The Evolution of TCP

- Thus far, we have discussed TCP Tahoe
  - Original version of TCP
- However, TCP was invented in 1974!
  - Today, there are many variants of TCP
- Early, popular variant: TCP Reno
  - Tahoe features, plus…
  - Fast retransmit
    - 3 duplicate ACKs? -> retransmit (don't wait for RTO)
  - Fast recovery
    - On loss: set cwnd = cwnd/2 (ssthresh = new cwnd value)

TCP Reno: Fast Retransmit

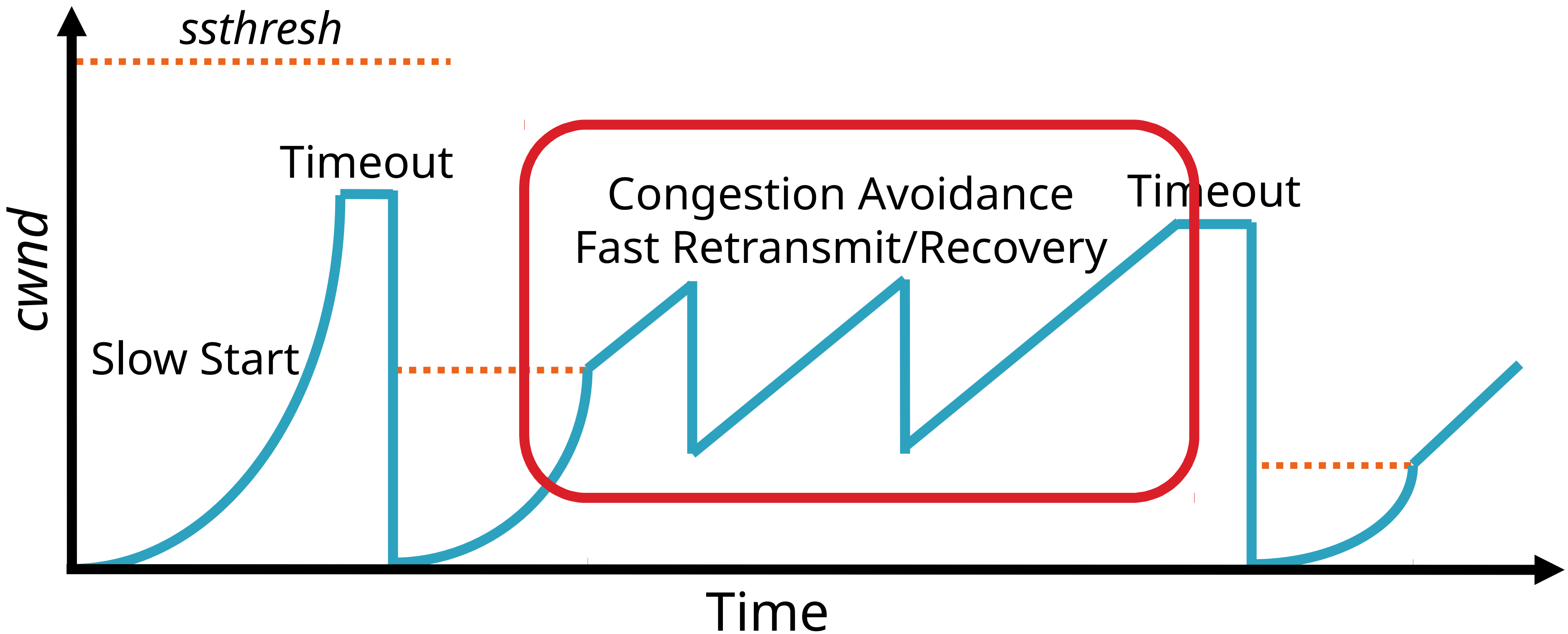
- Problem: in Tahoe, if segment is lost, there is a long wait until the RTO
- Reno: retransmit after 3 duplicate ACKs



TCP Reno: Fast Recovery

- After a fast-retransmit set *cwnd* to *cwnd/2*
  - Also reset ssthresh to the new halved cwnd value
  - i.e. don't reset *cwnd* to 1
  - Avoid unnecessary return to slow start
  - Prevents expensive timeouts
- But when RTO expires still do *cwnd* = 1
  - Return to slow start, same as Tahoe
  - Indicates packets aren't being delivered at all
  - i.e. congestion must be really bad

Fast Retransmit and Fast Recovery



- At steady state, *cwnd* oscillates around the optimal window size
- TCP always forces packet drops

Many TCP Variants…

- Tahoe: the original
  - Slow start with AIMD
  - Dynamic RTO based on RTT estimate
- Reno:
  - fast retransmit (3 dupACKs)
  - fast recovery (cwnd = cwnd/2 on loss)
- NewReno: improved fast retransmit
  - Each duplicate ACK triggers a retransmission
  - Problem: >3 out-of-order packets causes pathological retransmissions
- Vegas: delay-based congestion avoidance
- And many, many, many more…

TCP in the Real World

- What are the most popular variants today?
  - Key problem: TCP performs poorly on high bandwidth-delay product networks (like the modern Internet)
  - Compound TCP (Windows)
    - Based on Reno
    - Uses two congestion windows: delay based and loss based
    - Thus, it uses a *compound* congestion controller
  - TCP CUBIC (Linux)
    - Enhancement of BIC (Binary Increase Congestion Control)
    - Window size controlled by cubic function

High Bandwidth-Delay Product

- Key Problem: TCP performs poorly when
  - The capacity of the network (bandwidth) is large
  - The delay (RTT) of the network is large
  - Or, when bandwidth * delay is large
    - b * d = maximum amount of in-flight data in the network
    - a.k.a. the bandwidth-delay product
- Why does TCP perform poorly?
  - Slow start and additive increase are slow to converge
  - TCP is ACK clocked
    - i.e. TCP can only react as quickly as ACKs are received

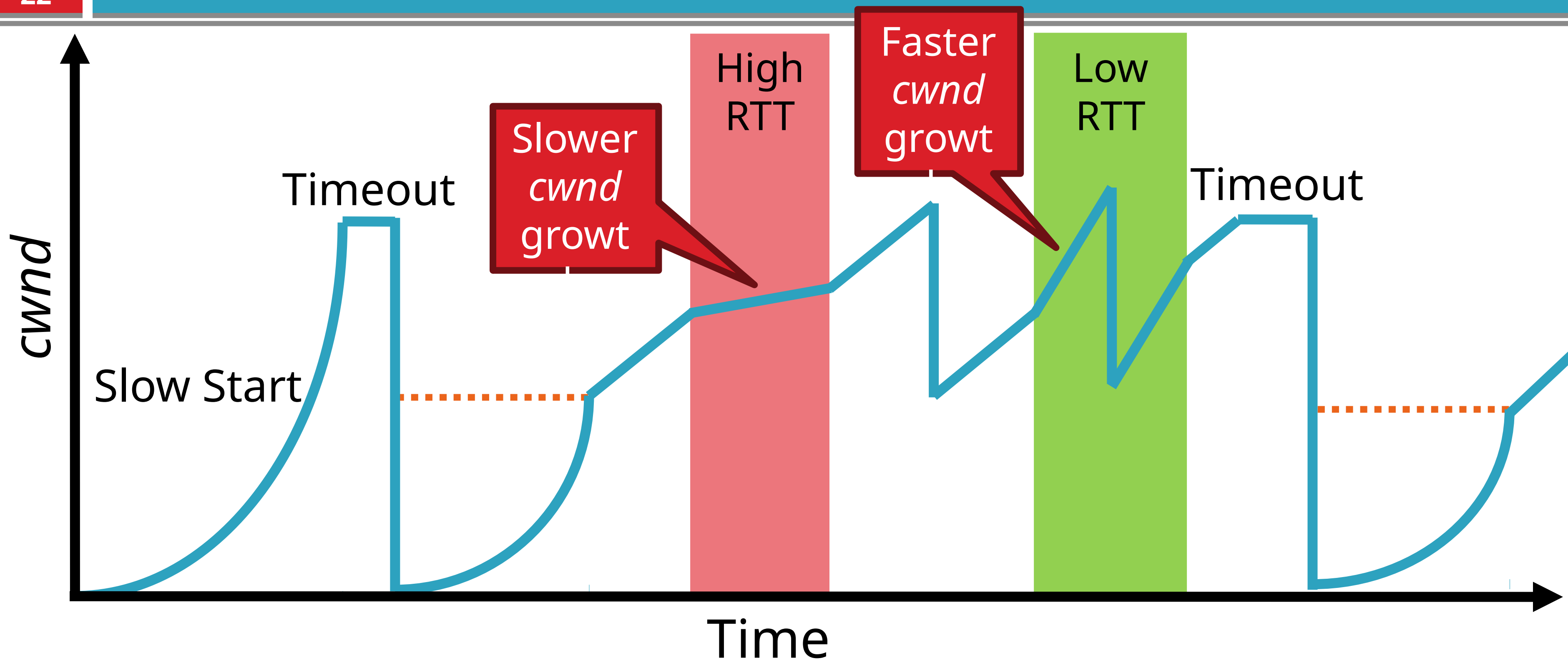
Goals

- Fast window growth
  - Slow start and additive increase are too slow when bandwidth is large
  - Want to converge more quickly
- Maintain fairness with other TCP varients
  - Window growth cannot be too aggressive
- Improve RTT fairness
  - TCP Tahoe/Reno flows are not fair when RTTs vary widely
- Simple implementation

Compound TCP Implementation

- Default TCP implementation in Windows
- Key idea: split *cwnd* into two separate windows
  - Traditional, loss-based window
  - New, delay-based window
- *wnd* = min(*cwnd* + *dwnd*, *adv_wnd*)
  - *cwnd* is controlled by AIMD
  - *dwnd* is the delay window
- Rules for adjusting *dwnd:*
  - If RTT is increasing, decrease *dwnd* (*dwnd* >= 0)
  - If RTT is decreasing, increase *dwnd*
  - Increase/decrease are proportional to the rate of change

Compound TCP Example



- Aggressiveness corresponds to changes in RTT
- Advantages: fast ramp up, more fair to flows with different RTTs
- Disadvantage: must estimate RTT, which is very challenging

TCP CUBIC Implementation

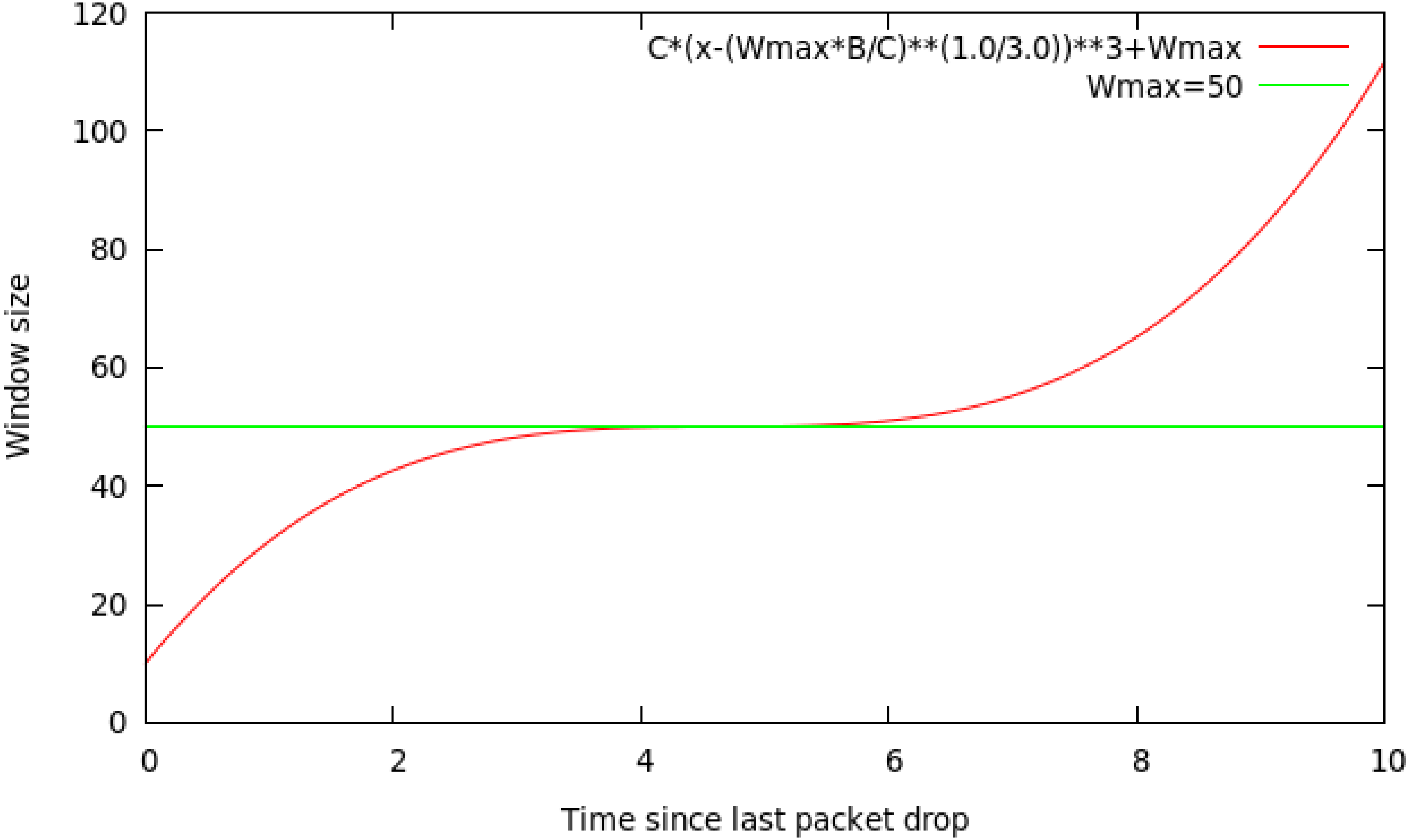
- Default TCP implementation in Linux
- Replace AIMD with cubic function

$$W_{cubic} = C(T - K)^3 + W_{max} \tag{1}$$

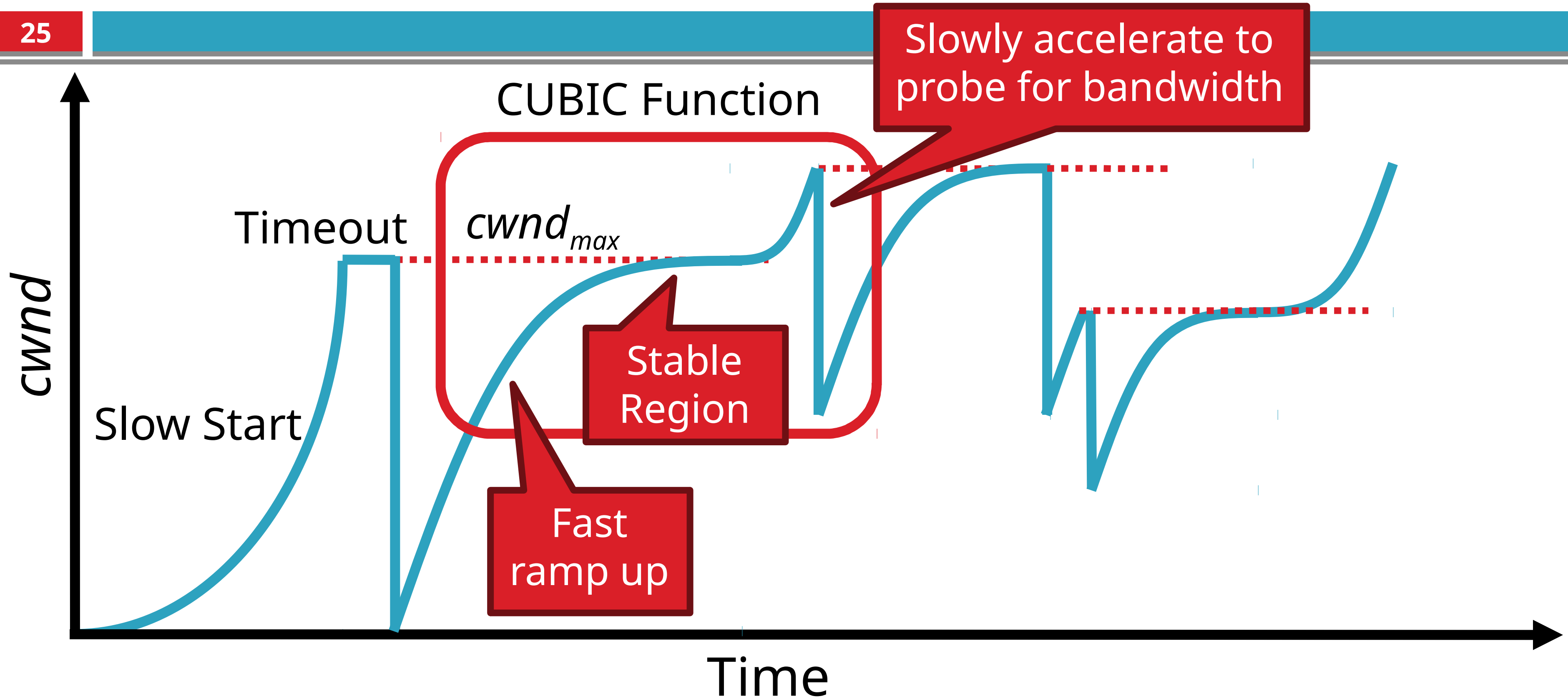
C is a scaling constant, and $K = \sqrt[3]{\frac{W_{max}\beta}{C}}$

  - B a constant fraction for multiplicative increase
  - T time since last packet drop
  - W_max cwnd when last packet dropped

TCP CUBIC Implementation



TCP CUBIC Example



- Less wasted bandwidth due to fast ramp up
- Stable region and slow acceleration help maintain fairness
  - Fast ramp up is more aggressive than additive increase
  - To be fair to Tahoe/Reno, CUBIC needs to be less aggressive

Outline

- UDP
- TCP
- Congestion Control
- Evolution of TCP
- Problems with TCP

Issues with TCP

- The vast majority of Internet traffic is TCP
- However, many issues with the protocol
  - Poor performance with small flows
  - Really poor performance on wireless networks
  - Susceptibility to denial of service

Small Flows

- Problem: TCP is biased against short flows
  - 1 RTT wasted for connection setup (SYN, SYN/ACK)
  - *cwnd* always starts at 1
- Vast majority of Internet traffic is short flows
  - Mostly HTTP transfers, <100KB
  - Most TCP flows never leave slow start!
- Proposed solutions (driven by Google):
  - Increase initial *cwnd* to 10
  - TCP Fast Open: use cryptographic hashes to identify receivers, eliminate the need for three-way handshake

Wireless Networks

- Problem: Tahoe and Reno assume loss = congestion
  - True on the WAN, bit errors are very rare
  - False on wireless, interference is very common
- TCP throughput ~ 1/sqrt(drop rate)
  - Even a few interference drops can kill performance
- Possible solutions:
  - Break layering, push data link info up to TCP
  - Use delay-based congestion detection (TCP Vegas)
  - Explicit congestion notification (ECN)

Denial of Service

- Problem: TCP connections require state
  - Initial SYN allocates resources on the server
  - State must persist for several minutes (RTO)
- SYN flood: send enough SYNs to a server to allocate all memory/meltdown the kernel
- Solution: SYN cookies
  - Idea: don’t store initial state on the server
  - Securely insert state into the SYN/ACK packet (sequence number field)
  - Client will reflect the state back to the server

Further topics

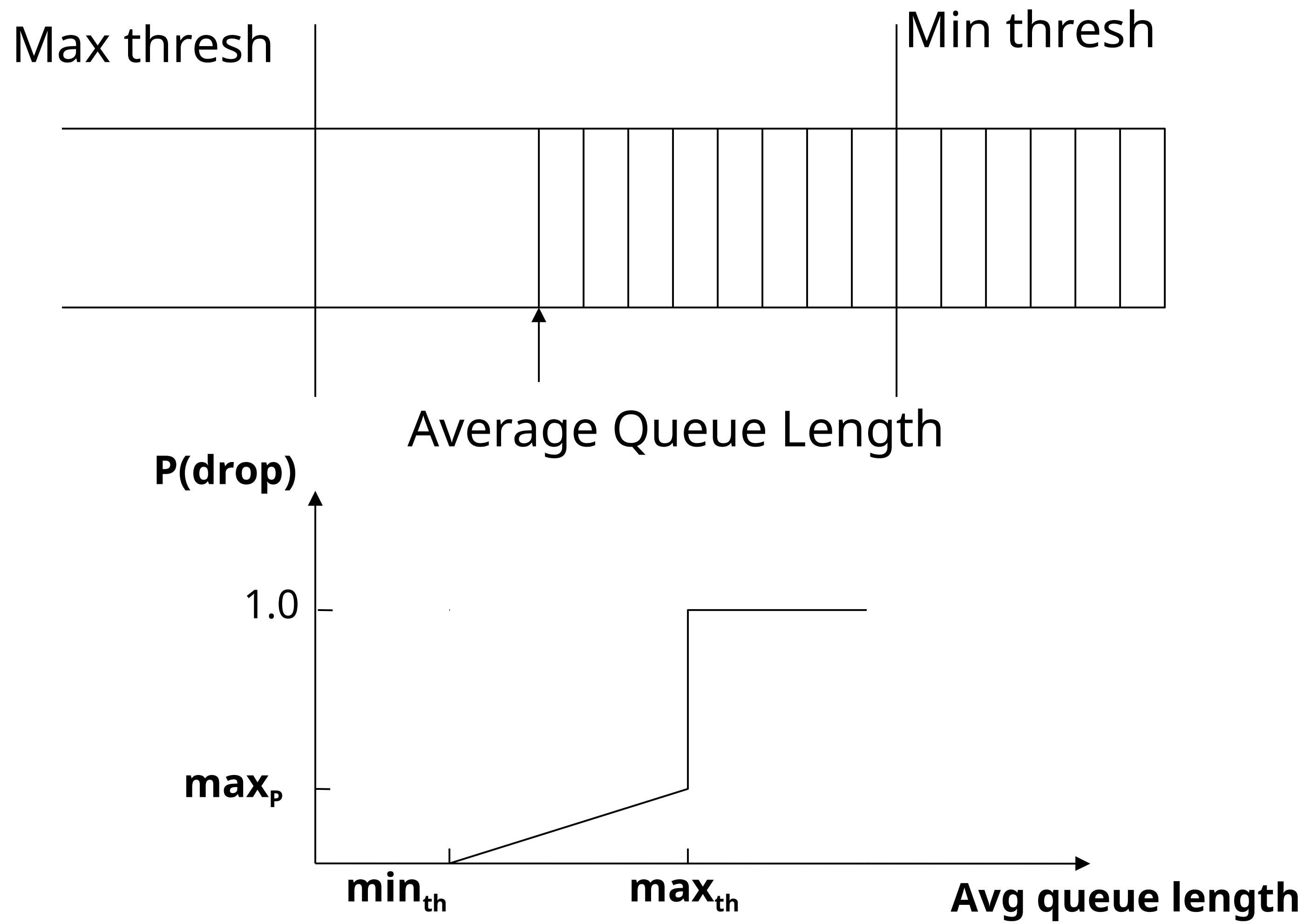
Typical Internet Queuing

- FIFO + drop-tail
  - Simplest choice
  - Used widely in the Internet
- FIFO (first-in-first-out)
  - Implies single class of traffic
- Drop-tail
  - Arriving packets get dropped when queue is full regardless of flow or importance
- Important distinction:
  - FIFO: scheduling discipline
  - Drop-tail: drop policy

RED Algorithm

- Maintain running average of queue length
- If avgq < min_{th} do nothing
  - Low queuing, send packets through
- If avgq > max_{th}, drop packet
  - Protection from misbehaving sources
- Else mark packet in a manner proportional to queue length
  - Notify sources of incipient congestion
  - E.g. by ECN IP field or dropping packets with a given probability

RED Operation



RED Algorithm

- Maintain running average of queue length
- For each packet arrival
  - Calculate average queue size (avg)
  - If $min_{th} \leq avgq < max_{th}$
    - Calculate probability P_a
    - With probability P_a
      - Mark the arriving packet: drop or set-up ECN
    - Else if $max_{th} \leq avg$
      - Mark the arriving packet: drop, ECN

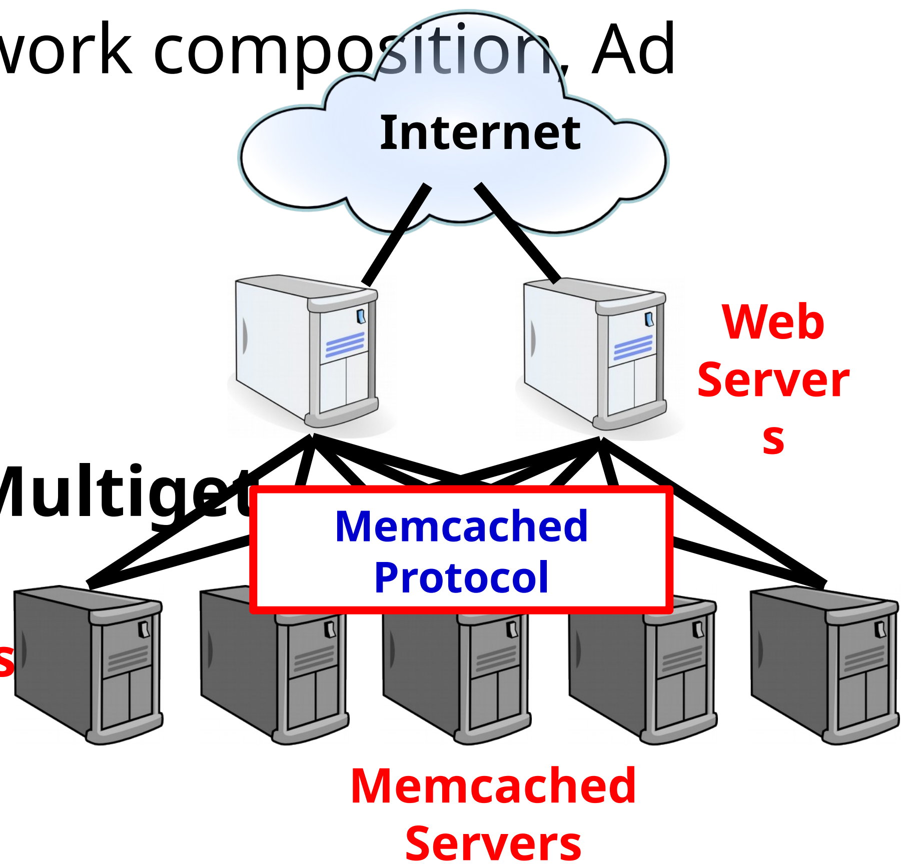
Data Center TCP: DCTCP

Generality of Partition/Aggregate

- The foundation for many large-scale web applications.
  - Web search, Social network composition, Ad selection, etc.
- Example: **Facebook**

Partition/Aggregate ~ Multiget

- Aggregators: **Web Servers**
- Workers: **Memcached Servers**



Workloads

- Partition/Aggregate
  (Query)

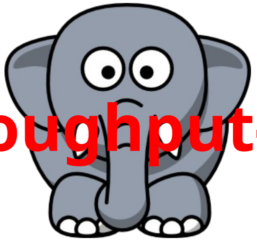
→ **Delay-sensitive**

- Short messages [50KB-1MB]
  (Coordination, Control state)

→ **Delay-sensitive**

- Large flows [1MB-50MB]
  (Data update)

→ **Throughput-sensitive**

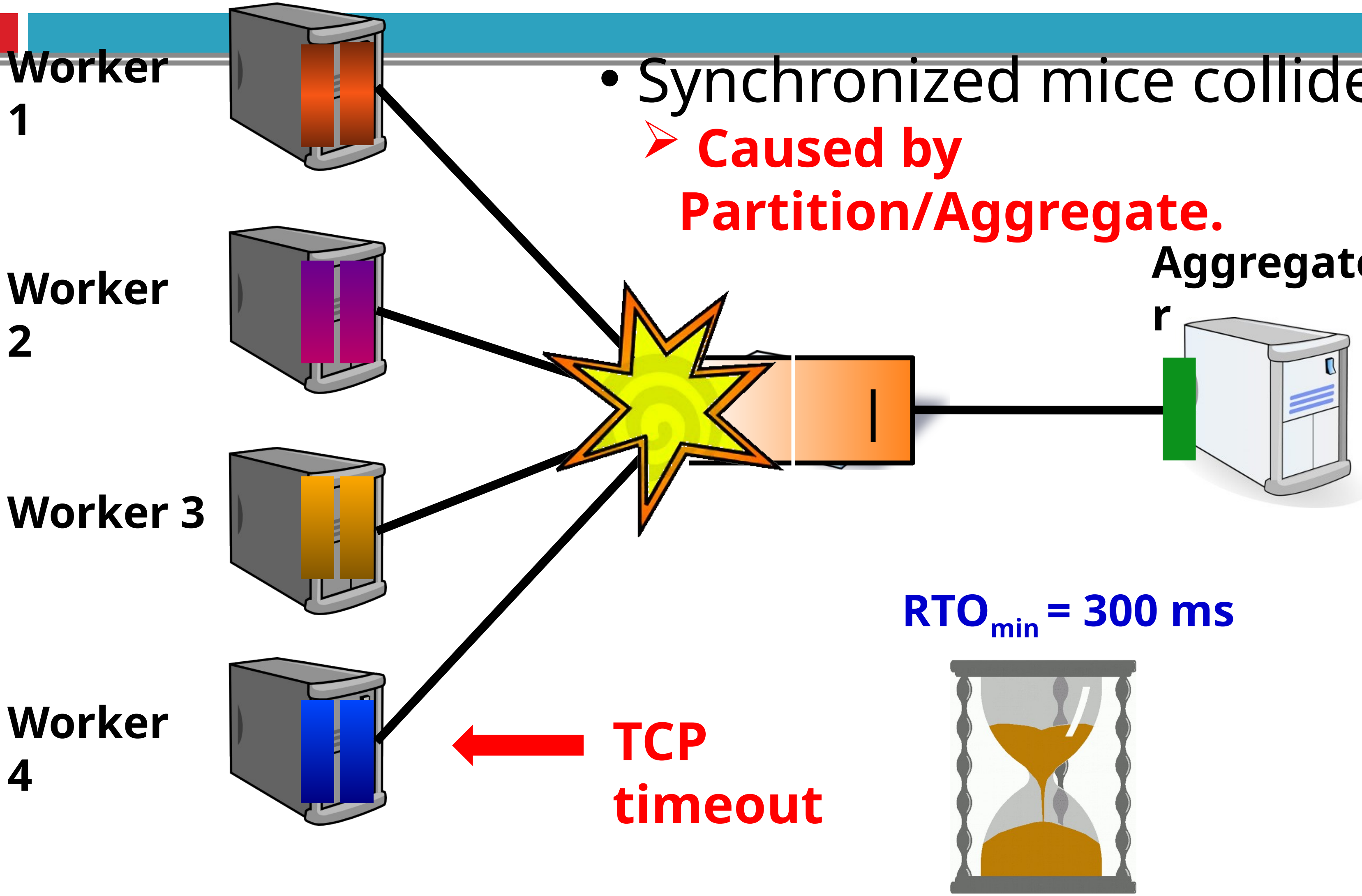


Impairments

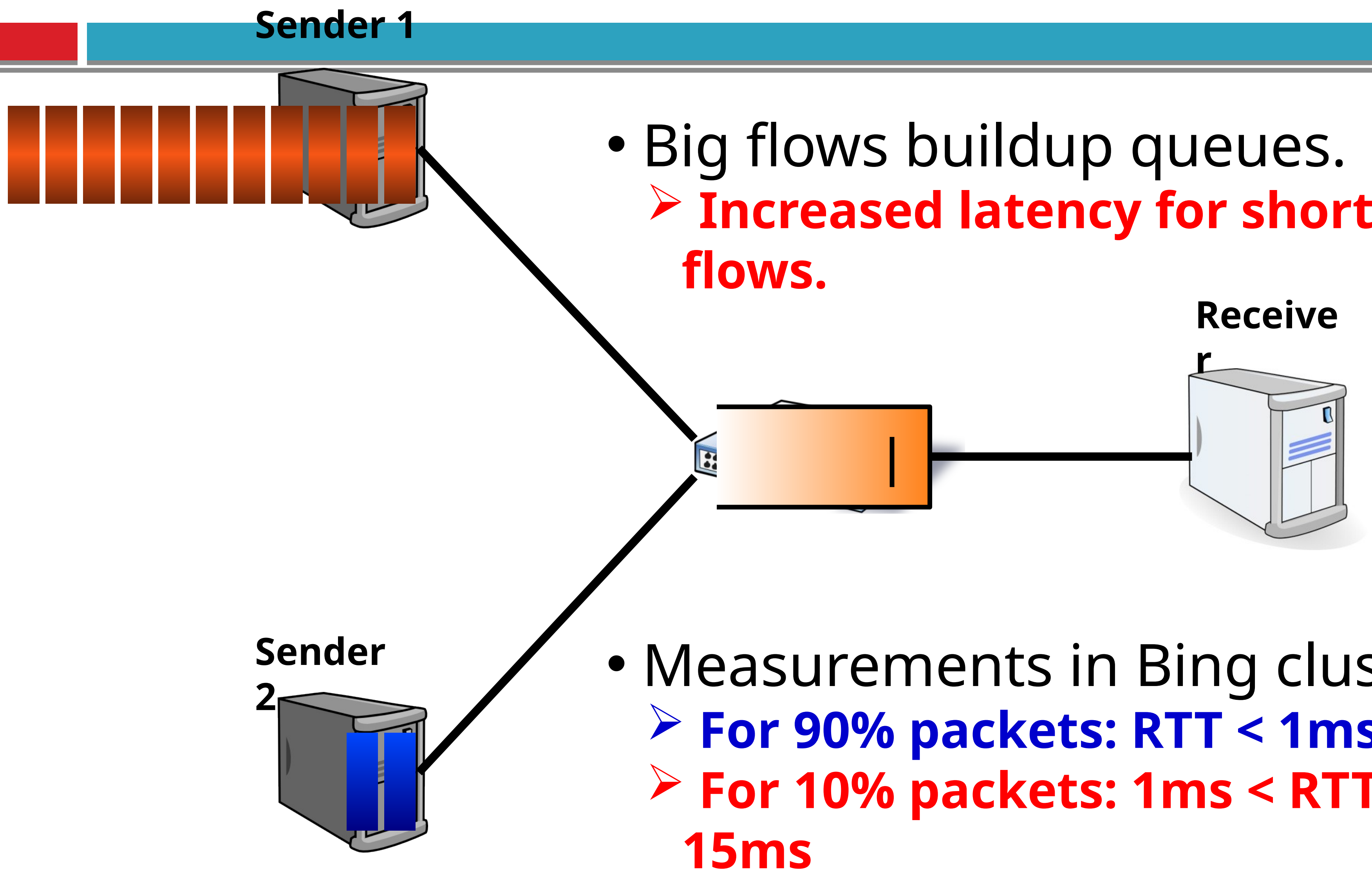
- Incast
- Queue Buildup
- Buffer Pressure

Incast

- Synchronized mice collide.
  - ➢ **Caused by Partition/Aggregate.**



Queue Buildup



- Big flows buildup queues.
  - **Increased latency for short flows.**
- Measurements in Bing cluster
  - **For 90% packets: RTT < 1ms**
  - **For 10% packets: 1ms < RTT < 15ms**

Data Center Transport Requirements

1. **High Burst Tolerance**
   – Incast due to Partition/Aggregate is common.

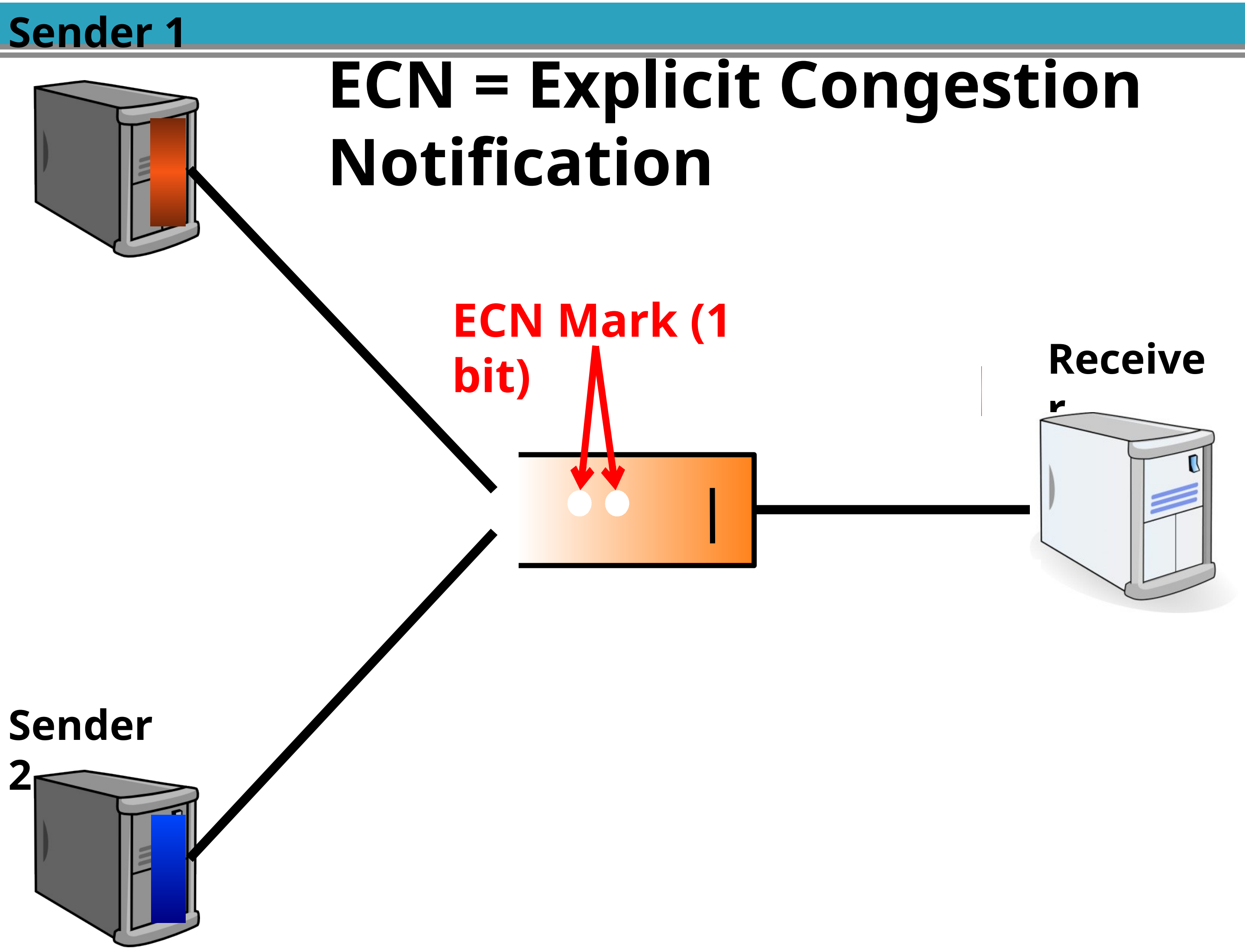
2. **Low Latency**
   – Short flows, queries

3. **High Throughput**
   – Continuous data updates, large file transfers

The challenge is to achieve these three together.

DCTCP: The TCP/ECN Control Loop

ECN = Explicit Congestion Notification



DCTCP: Two Key Ideas

1. React in proportion to the **extent** of congestion, not its **presence**.
   - ✓ Reduces **variance** in sending rates, lowering queuing

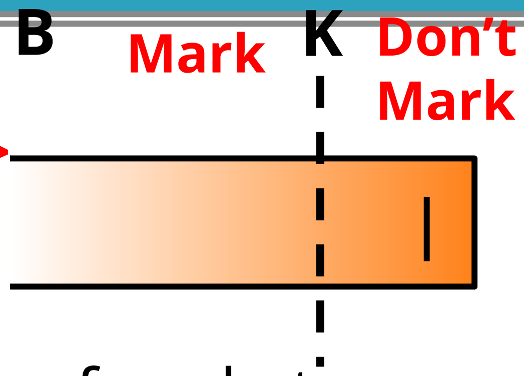
ECN Marks	TCP	DCTCP
1 0 1 1 1 1 0 1 1 1	Cut window by 50%	Cut window by 40%
0 0 0 0 0 0 0 0 0 1	Cut window by 50%	Cut window by 5%

2. Mark based on **instantaneous** queue length.
   - ✓ Fast feedback to better deal with bursts.

Data Center TCP Algorithm

Switch side:

- Mark packets when **Queue Length > K.**



Sender side:

– Maintain running average of ***fraction*** of packets marked **(*α*)**.

In each RTT:

$$F = \frac{\#\ of\ marked\ ACKs}{Total\ \#\ of\ ACKs} \qquad \alpha \leftarrow (1-g)\alpha + gF$$

$$Cwnd \leftarrow \left(1 - \frac{\alpha}{2}\right)Cwnd$$

➢ **Adaptive window decreases:**

– Note: decrease factor between 1 and 2.