Principles of congestion control

Congestion:

- Informally: "too many sources sending too much data too fast for *network* to handle"
- Different from flow control!
- Manifestations:
  - Lost packets (buffer overflow at routers)
  - Long delays (queueing in router buffers)
- Another top-10 problem!

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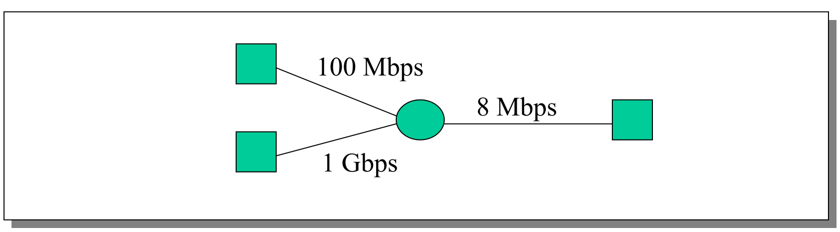
Congestion



- Different sources compete for resources inside network
- Why is it a problem?
  - Sources are unaware of current state of resource
  - Sources are unaware of each other
  - In many situations will result in < 8 Mbps of throughput (congestion collapse)

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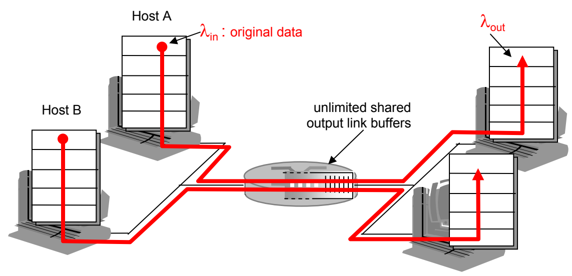
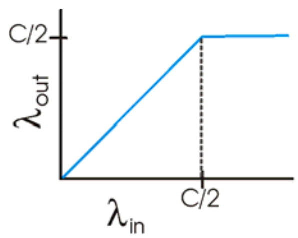
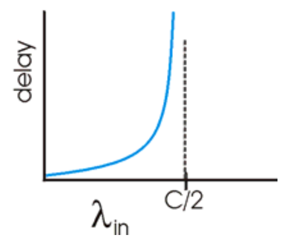
Causes/costs of congestion: Scenario 1

- Two senders, two receivers
- One router, infinite buffers
- No retransmission



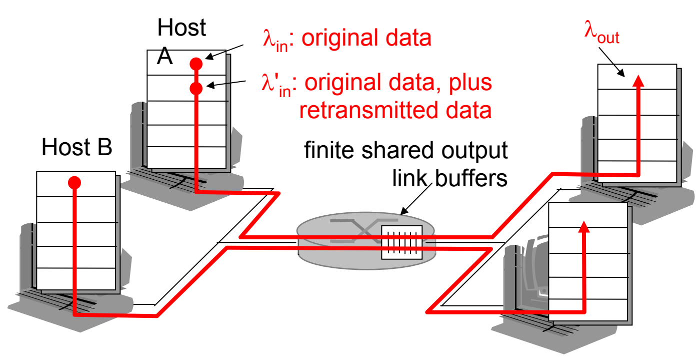




- Maximum achievable throughput
- Large delays when congested

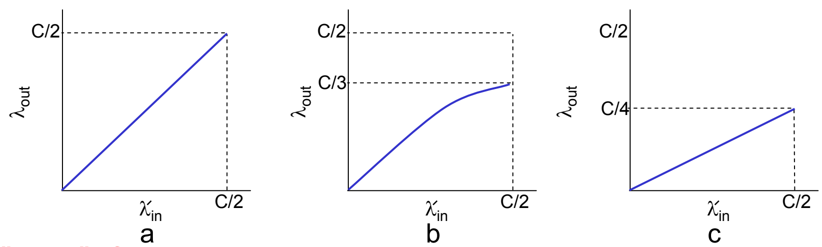
Causes/costs of congestion: Scenario 2

- One router, *finite* buffers
- Sender retransmission of lost packet



Causes/costs of congestion: Scenario 2

- Always: $\lambda_{in} = \lambda_{out}$ (goodput)
- "Perfect" retransmission only when loss: $\lambda'_{in} > \lambda_{out}$
- Retransmission of delayed (not lost) packet makes λ'_{in} larger (than perfect case) for same λ_{out}



"Costs" of congestion:

- More work (retransmissions) for given "goodput"
- Unneeded retransmissions: Link carries multiple copies of pkt

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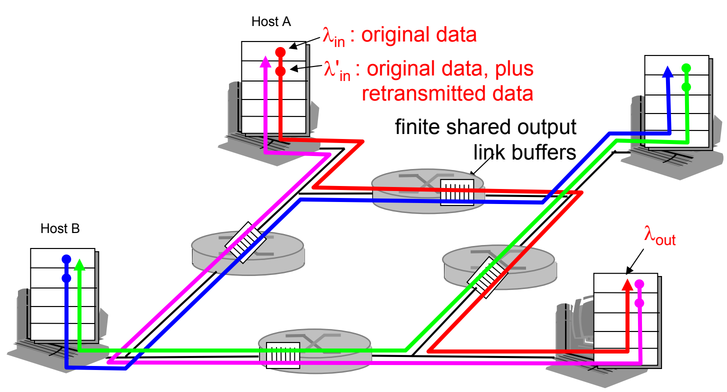
Causes/costs of congestion: Scenario 3

- Four senders
- Multihop paths
- Timeout/retransmit

Q: What happens as λ_{in} and λ'_{in} increase ?



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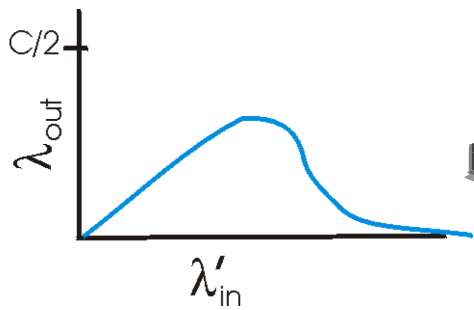
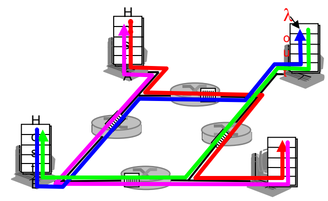
Causes/costs of congestion: Scenario 3





Another "cost" of congestion:

- When packet dropped, any "upstream" transmission capacity used for that packet was wasted!

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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
    - How can this happen with packet conservation
    - Solution: Better timers and TCP congestion control
  - Undelivered packets
    - Packets consume resources and are dropped elsewhere in network
    - Solution: Congestion control for ALL traffic

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Other congestion collapse causes

- ❒ Fragments
  - ❍ Mismatch of transmission and retransmission units
  - ❍ Solutions
    - Make network drop all fragments of a packet
    - Do path MTU discovery
- ❒ Control traffic
  - ❍ Large percentage of traffic is for control
    - Headers, routing messages, DNS, etc.
- ❒ Stale or unwanted packets
  - ❍ Packets that are delayed on long queues
  - ❍ "Push" data that is never used

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Where to prevent collapse?

- ❒ Can end hosts prevent problem?
  - ❍ Yes, but must trust end hosts to do right thing
  - ❍ E.g., sending host must adjust amount of data it puts in the network based on detected congestion
- ❒ Can routers prevent collapse?
  - ❍ No, not all forms of collapse
  - ❍ Doesn't mean they can't help
  - ❍ Sending accurate congestion signals
  - ❍ Isolating well-behaved from ill-behaved sources

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Congestion control and avoidance

- A mechanism which …
  - uses network resources efficiently
  - preserves fair network resource allocation
  - prevents or avoids collapse

- Congestion collapse is not just a theory
  - Has been frequently observed in many networks

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Congestion collapse

- Congestion collapse was first observed on the early Internet in October 1986, when the NSFnet phase-I backbone dropped three orders of magnitude from its capacity of 32 kbit/s to 40 bit/s, and continued to occur until end nodes started implementing Van Jacobson's congestion control between 1987 and 1988.

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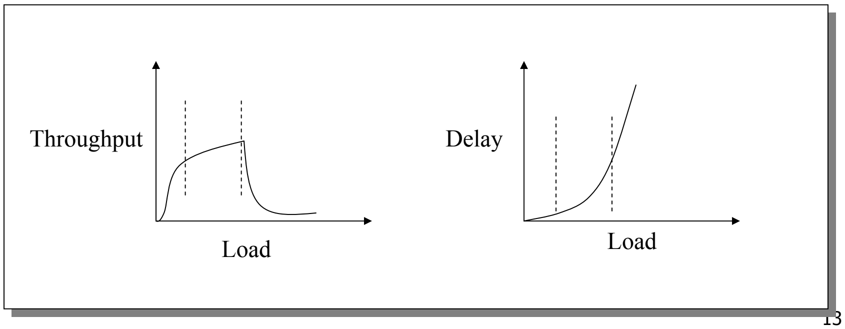
Congestion control vs. avoidance

- Avoidance keeps the system performing at the knee
- Control kicks in once the system has reached a congested state



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Approaches towards congestion control

Two broad approaches towards congestion control:

End-end congestion control:

- No explicit feedback from network
- Congestion inferred from end-system observed loss, delay
- Approach taken by TCP

Network-assisted congestion control:

- Routers provide feedback to end systems
  - Choke packet from router to sender
  - Single bit indicating congestion (SNA, DECbit, TCP/IP ECN, ATM)
  - Explicit rate sender should send at

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End-to-end congestion control – objectives

- Simple router behavior
- Distributedness
- Efficiency: $X_{knee} = \Sigma x_i(t)$
- Fairness: $(\Sigma x_i)^2 / n(\Sigma x_i^2)$
- Power: $(\text{throughput}^{\alpha}/\text{delay})$
- Convergence: control system must be stable

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Basic control model

- Let's assume window-based control
- Reduce window when congestion is perceived
  - How is congestion signaled?
    - Either mark or drop packets
  - When is a router congested?
    - Drop tail queues – when queue is full
    - Average queue length – at some threshold
- Increase window otherwise
  - Probe for available bandwidth – how?

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Linear control mechanism

- Many different possibilities for reaction to congestion and probing
  - Examine simple linear controls
  - Window(t + 1) = a + b Window(t)
  - Different a_i/b_i for increase and a_d/b_d for decrease
- Supports various reaction to signals
  - Increase/decrease additively
  - Increased/decrease multiplicatively
  - Which of the four combinations is optimal?

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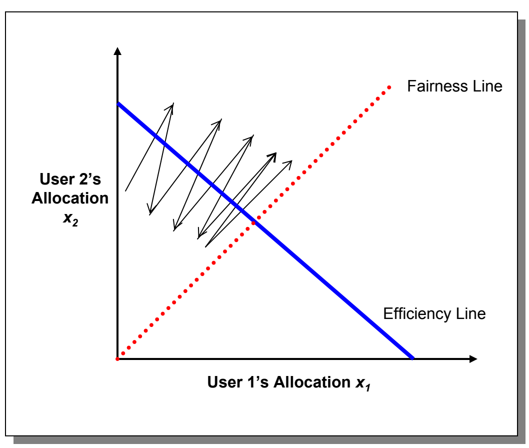
Phase plots

- Simple way to visualize behavior of competing connections over time



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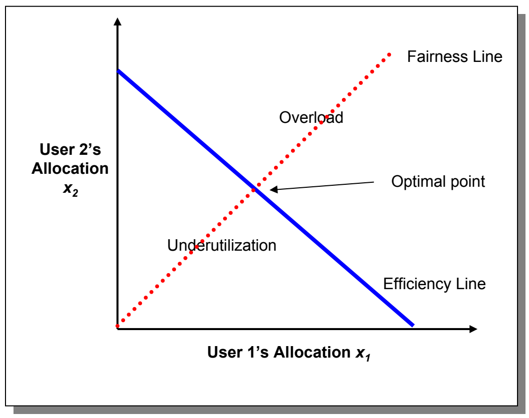
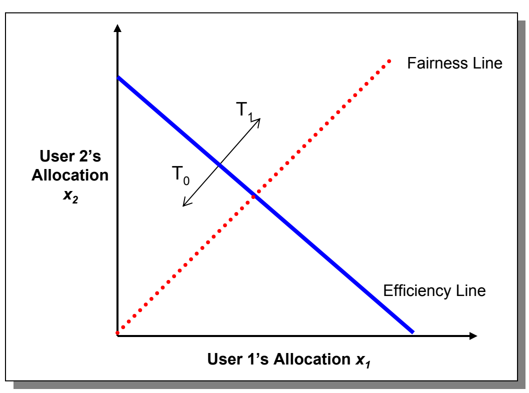
Phase plots

- What are desirable properties?
- What if flows are not equal?



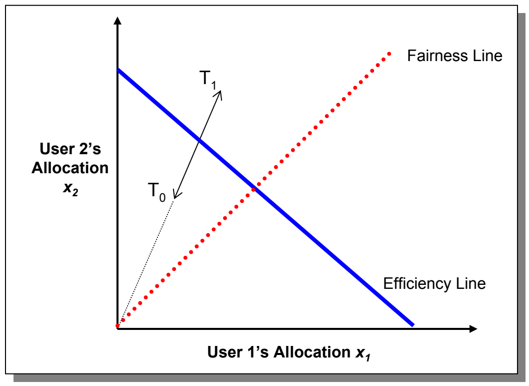
Additive increase/decrease

- X_1 and X_2 in-/decrease by same amount over time



Multiplicative increase/decrease

- X_1 and X_2 in-/decrease by the same factor
  - Extension from origin



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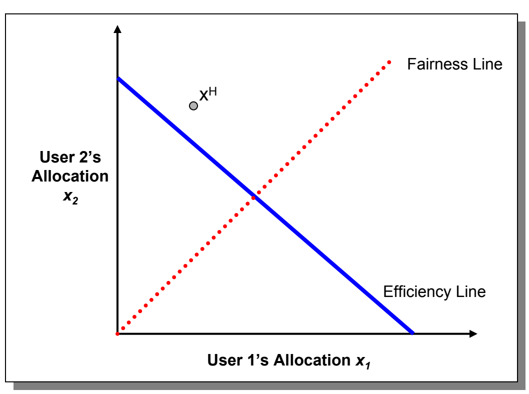
Convergence to efficiency

- Want to converge quickly to intersection of fairness and efficiency lines



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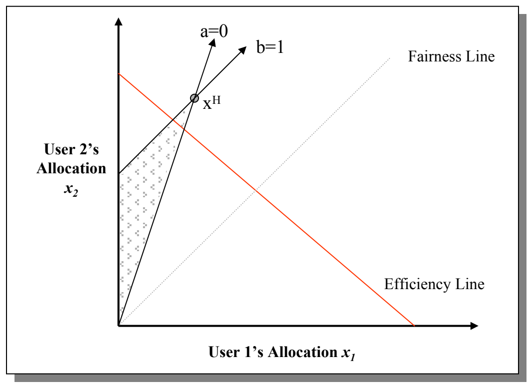
Distributed convergence to efficiency



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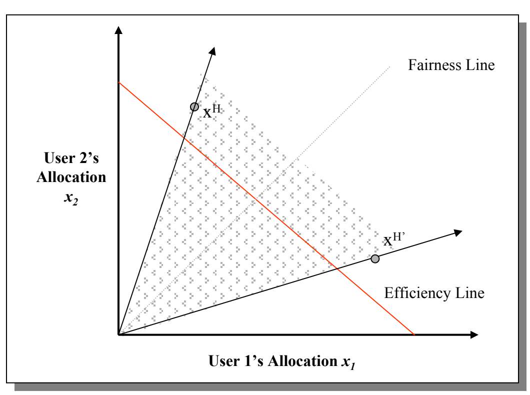
Convergence to fairness



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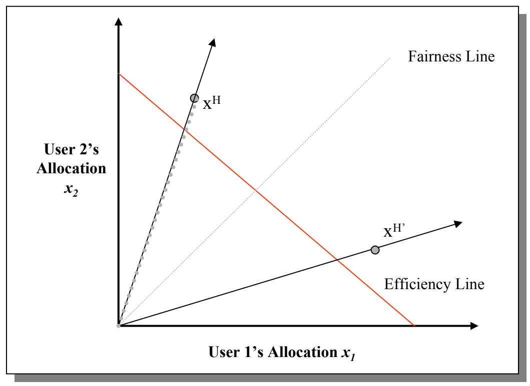
Convergence to efficiency & fairness



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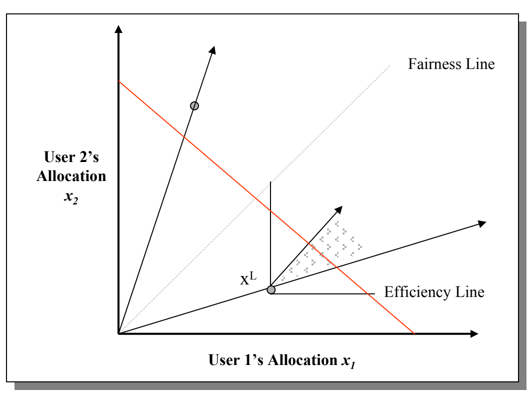
Increase



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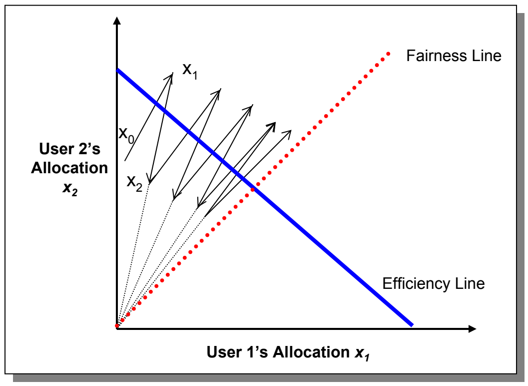
What is the right choice?

- Constraints limit us to AIMD
  - Can have multiplicative term in increase
  - AIMD moves towards optimal point



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TCP congestion control

- Motivated by ARPANET congestion collapse
- Underlying design principle: Packet conservation
  - At equilibrium, inject packet into network only when one is removed
  - Basis for stability of physical systems
- Why was this not working?
  - Connection doesn't reach equilibrium
  - Spurious retransmissions
  - Resource limitations prevent equilibrium

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TCP congestion control – solutions

- Reaching equilibrium
  - Slow start
- Eliminates spurious retransmissions
  - Accurate RTO estimation
  - Fast retransmit
- Adapting to resource availability
  - Congestion avoidance

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TCP congestion control basics

- Keep a congestion window, cwnd
  - Denotes how much network is able to absorb
- Sender's maximum window:
  - Min (advertised receiver window, cwnd)
- Sender's actual window:
  - Max window – unacknowledged segments
- If we have large actual window, should we send data in one shot?
  - No, use acks to clock sending new data

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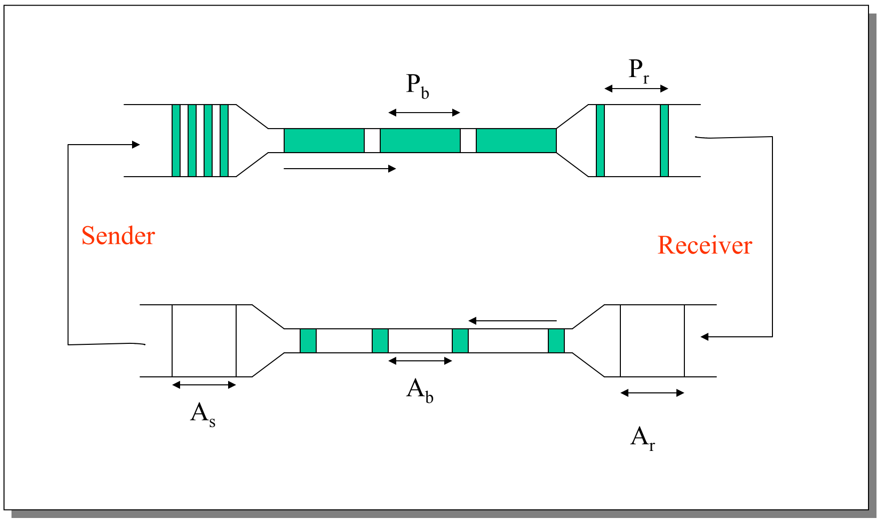
Self-clocking



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TCP congestion control

- End-end control (no network assistance)
- TCP throughput limited by rcvr window (flow control)
- Transmission rate limited by congestion window size, **`cwnd`**, over segments:

- w segments, each with MSS bytes sent in one RTT:

$$\text{throughput} = \frac{w * MSS}{RTT} \text{ Bytes/sec}$$

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TCP congestion control:

- "Probing" for usable bandwidth:
  - Ideally: transmit as fast as possible (**cwnd** as large as possible) without loss
  - *Increase* **cwnd** until loss (congestion)
  - Loss: *decrease* **cwnd**, then begin probing (increasing) again
- Two "phases"
  - Slow start
  - Congestion avoidance
- Important variables:
  - **Cwnd (congwin)**
  - **Threshold:** defines threshold between slow start phase, congestion avoidance phase

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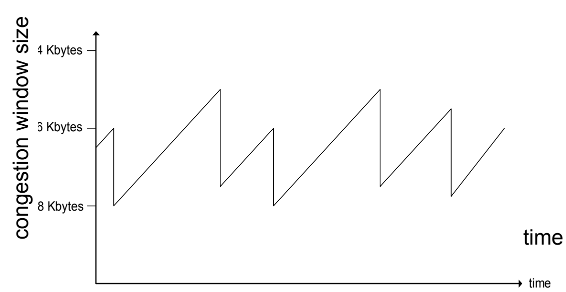
TCP congestion control: additive increase, multiplicative decrease

- *Approach:* Increase transmission rate (window size), probing for usable bandwidth, until loss occurs
  - *Additive increase:* Increase **cwnd** by 1 MSS every RTT until loss detected
  - *Multiplicative decrease*: Cut **cwnd** in half after loss

Saw tooth behavior: probing for bandwidth



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TCP congestion control: Details

- Sender limits transmission:
  `LastByteSent-LastByteAcked`
  $\leq$ `cwnd`
- Roughly,

$$\text{rate} = \frac{\text{cwnd}}{\text{RTT}} \text{ Bytes/sec}$$

- **Cwnd** is dynamic, function of perceived network congestion

How does sender perceive congestion?

- Loss event = timeout *or* 3 duplicate acks
- TCP sender reduces rate (**cwnd**) after loss event

Three mechanisms:

- AIMD
- Slow start
- Conservative after timeout events

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