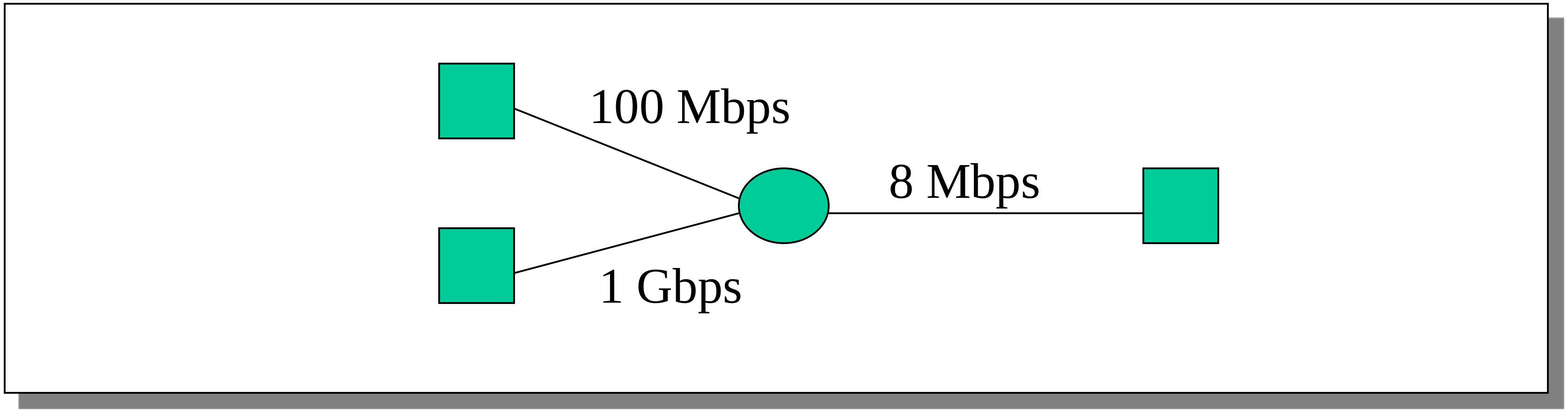
Principles of congestion control

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)
- A top-10 problem!

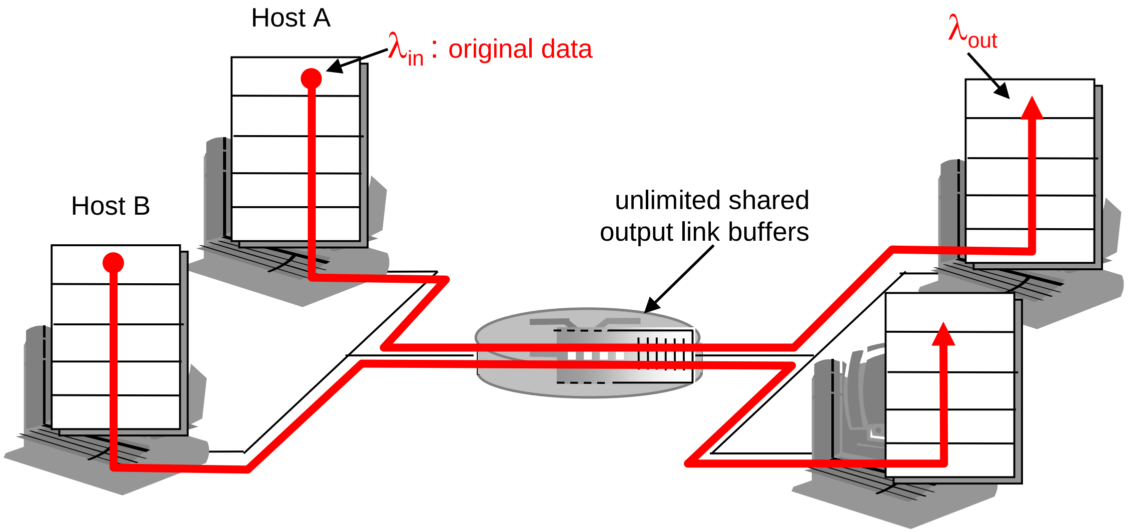
Congestion

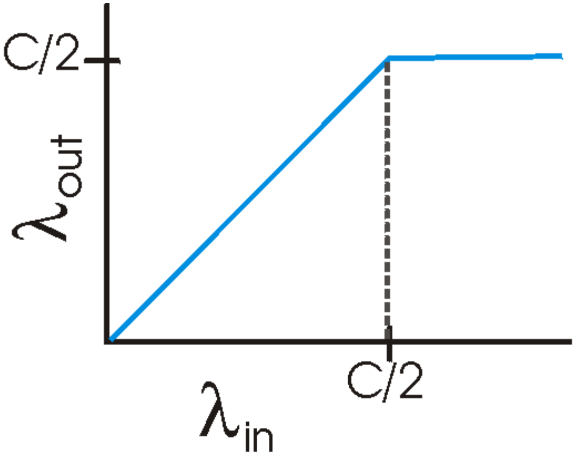


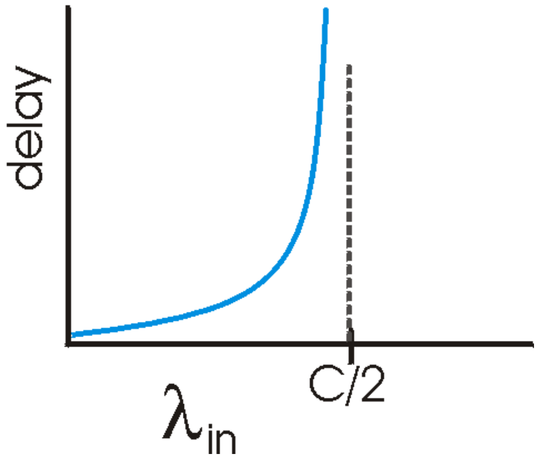
- Different sources compete for resources inside network
- Why is it a problem?
  - Sources are unaware of current state of resource
  - Sources are unaware of each other
  - In many situations will result in < 8 Mbps of throughput (congestion collapse)

Causes/costs of congestion: Scenario 1

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



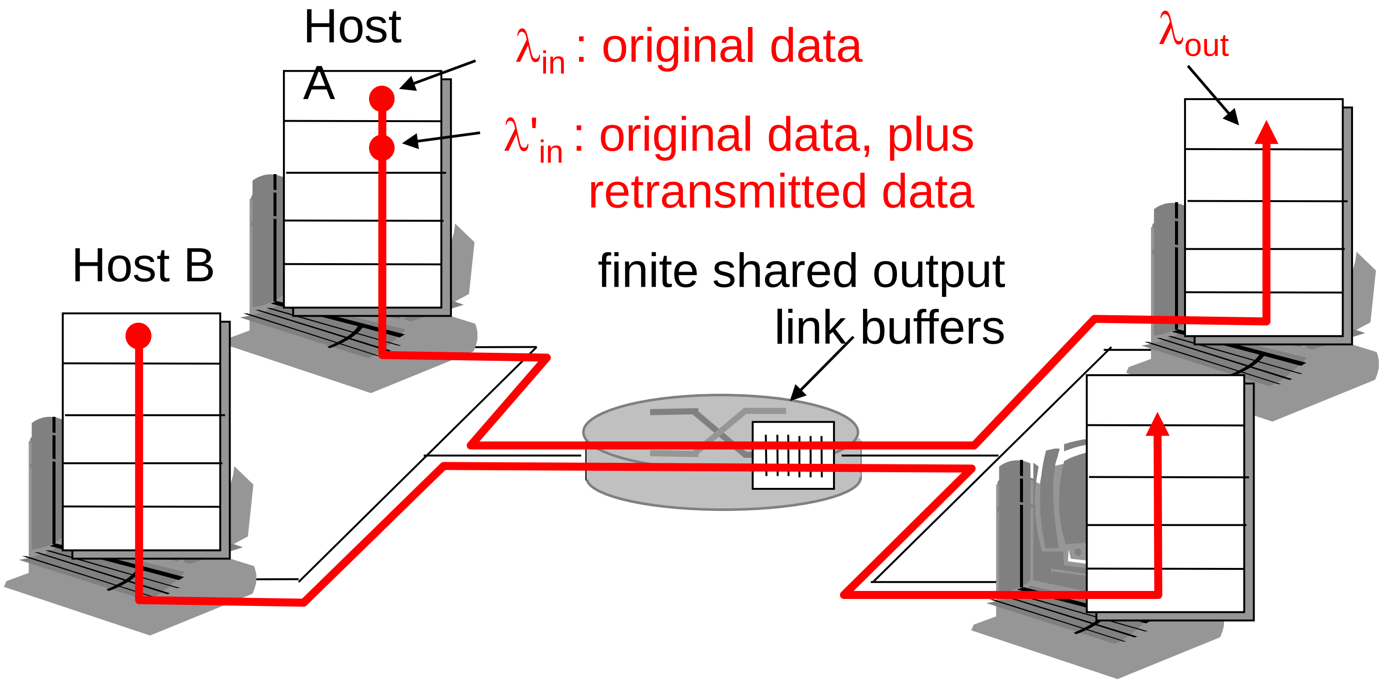




- Maximum achievable throughput
- Large delays when congested

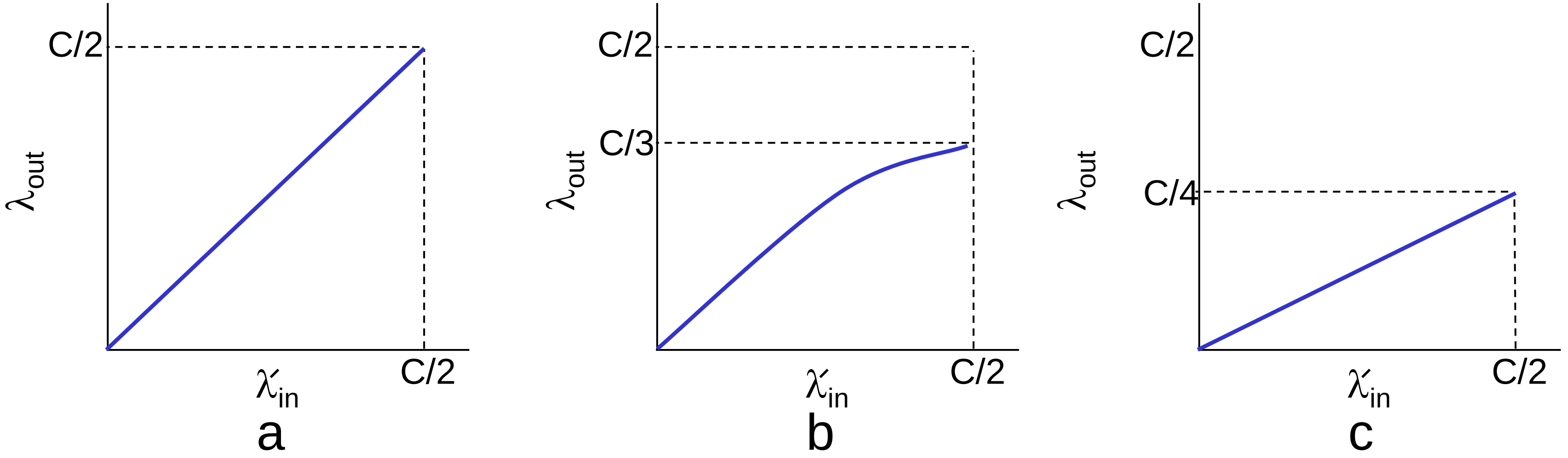
Causes/costs of congestion: Scenario 2

- 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}



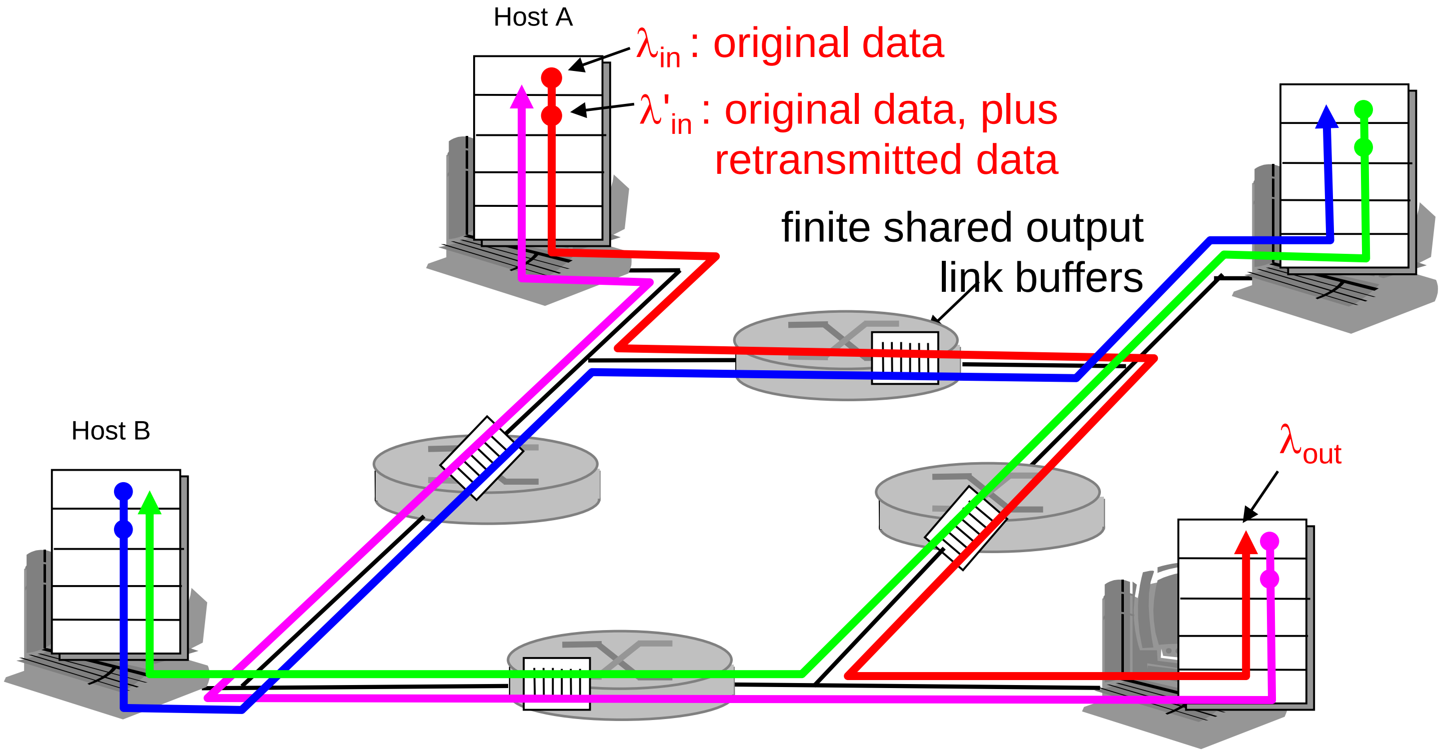
"Costs" of congestion:

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

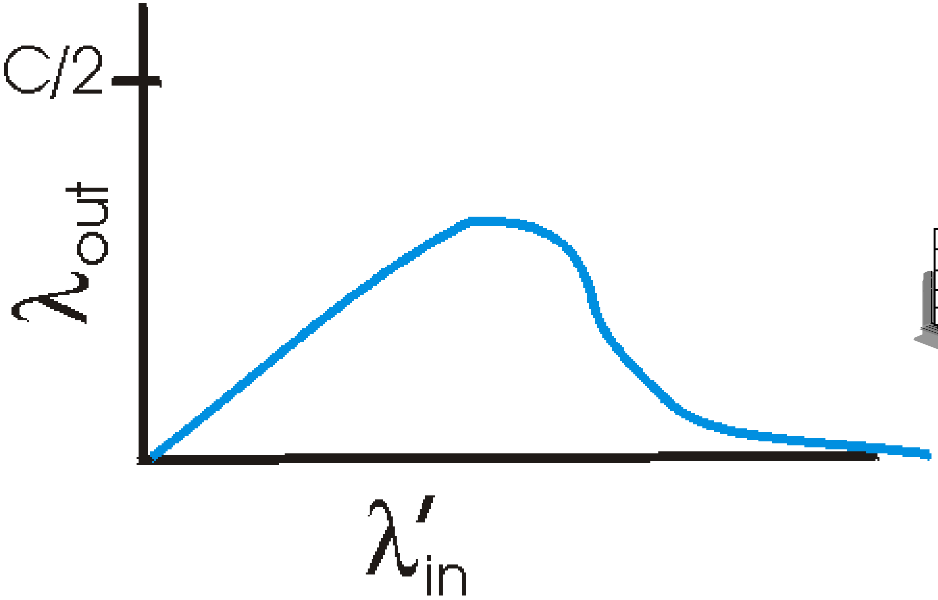
Causes/costs of congestion: Scenario 3

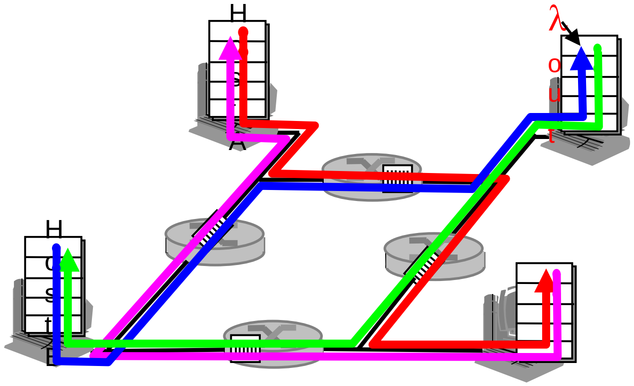
- Four senders
- Multihop paths
- Timeout/retransmit

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



Causes/costs of congestion: Scenario 3





Another "cost" of congestion:

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

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

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

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

Congestion control and avoidance

- A mechanism which
  - Uses network resources efficiently
  - Preserves fair network resource allocation
  - Prevents or avoids collapse

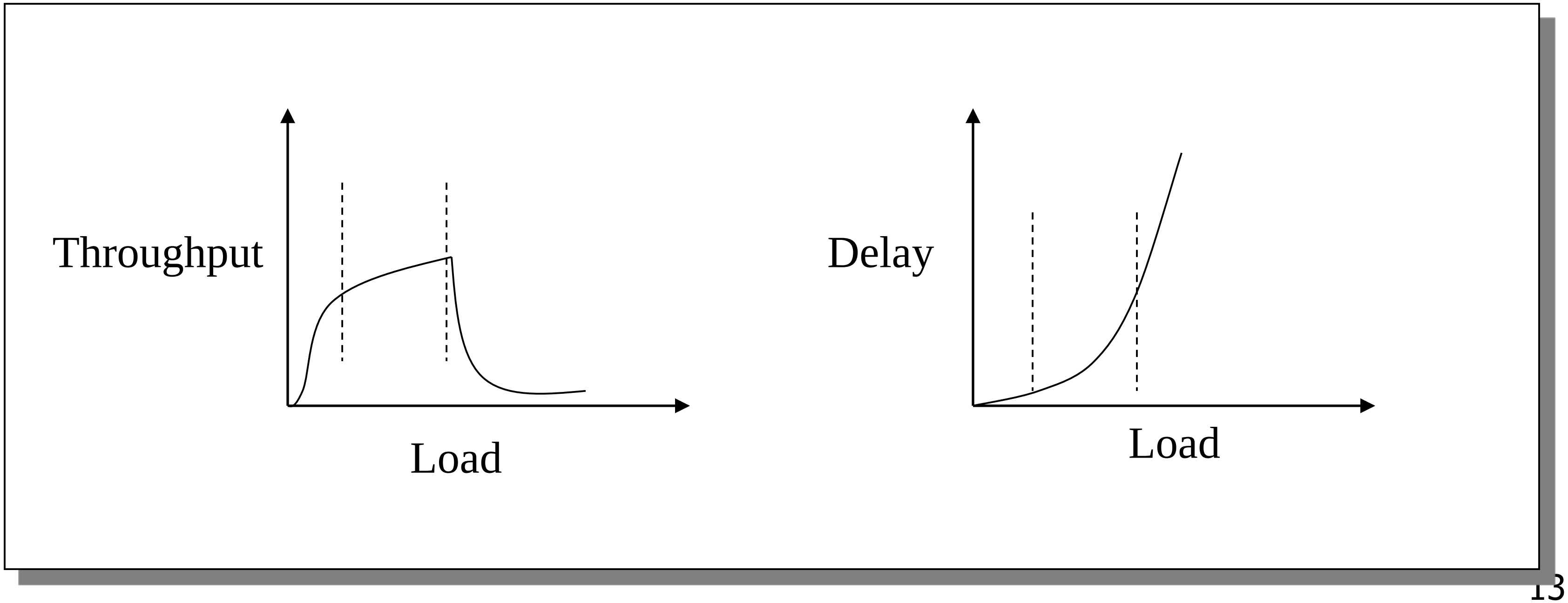
- Congestion collapse is not just a theory
  - Has been frequently observed in many networks

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.

Congestion control vs. avoidance

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



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

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

Basic control model

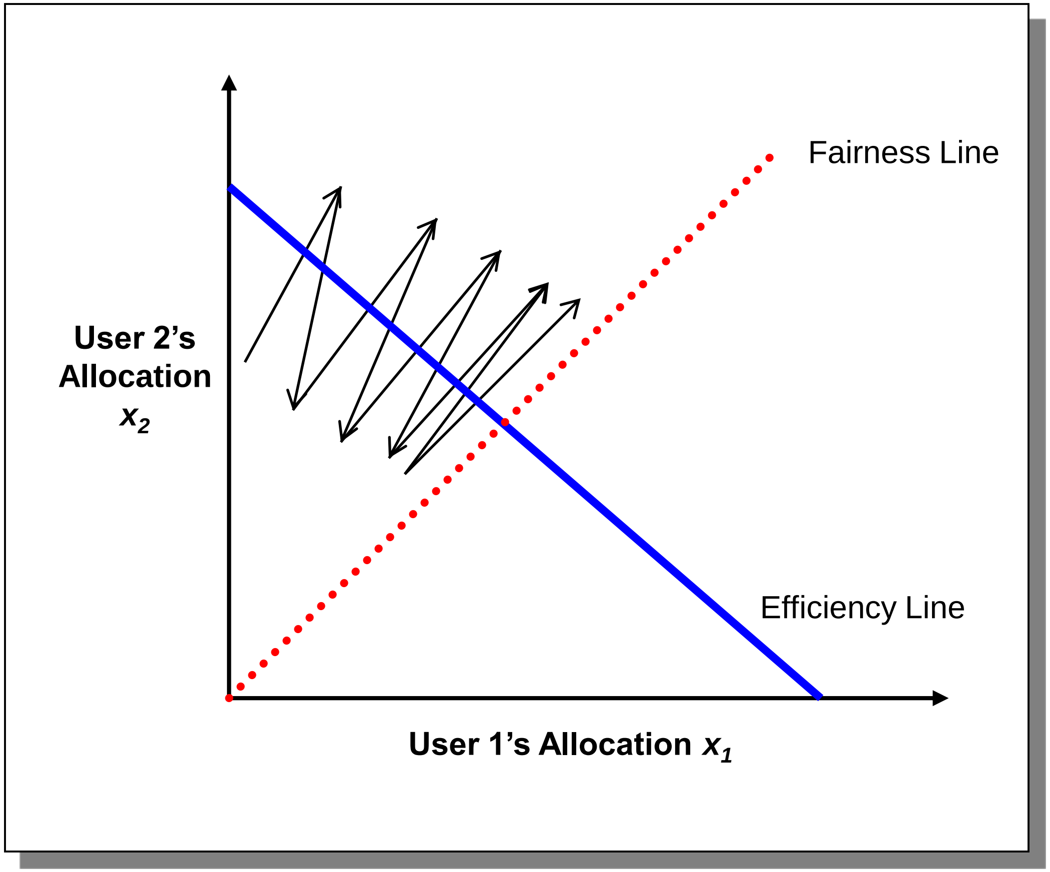
- Let’s assume window-based control
- Reduce window when congestion is perceived
  - How is congestion signaled?
    - Either mark or drop packets
  - When is a router congested?
    - Drop tail queues – when queue is full
    - Average queue length – at some threshold
- Increase window otherwise
  -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

Linear control

- 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?

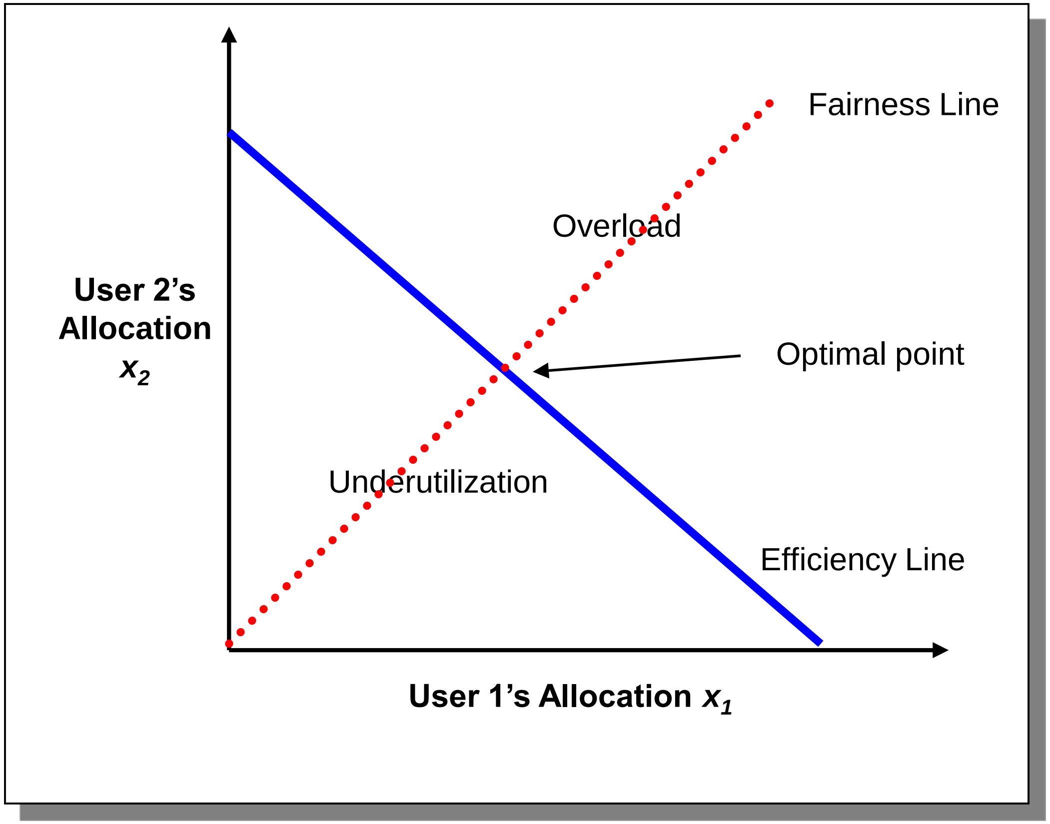
Phase plots

- Simple way to visualize behavior of competing connections over time



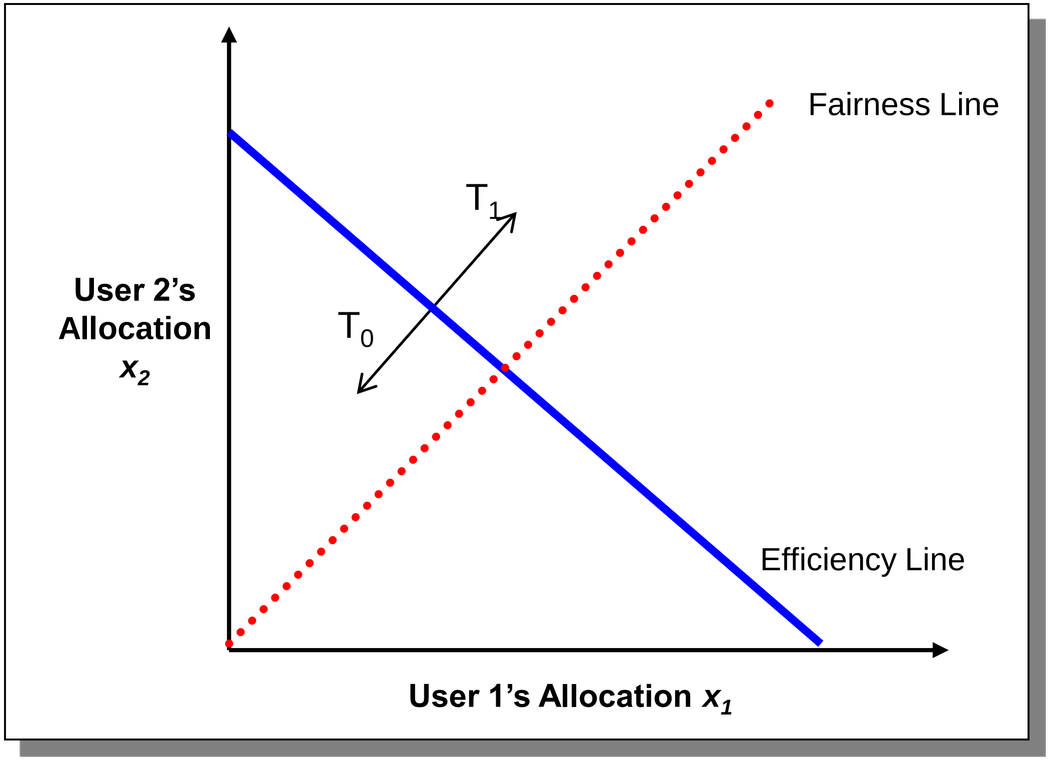
Phase plots

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



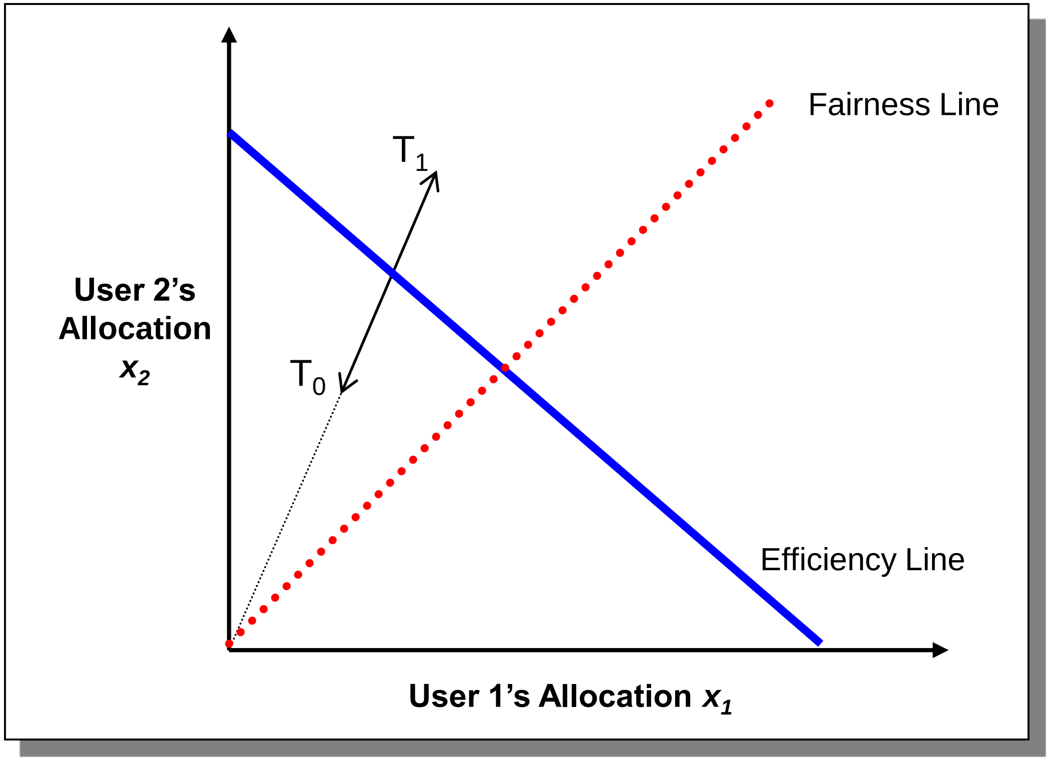
Additive increase/decrease

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



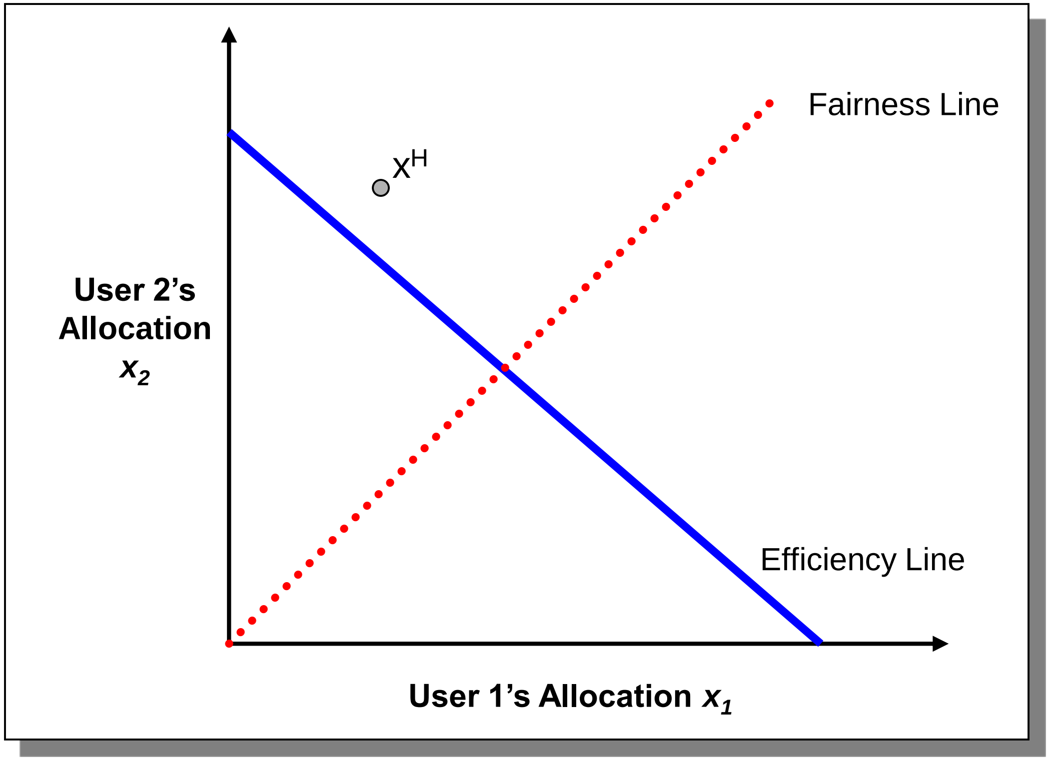
Multiplicative increase/decrease

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

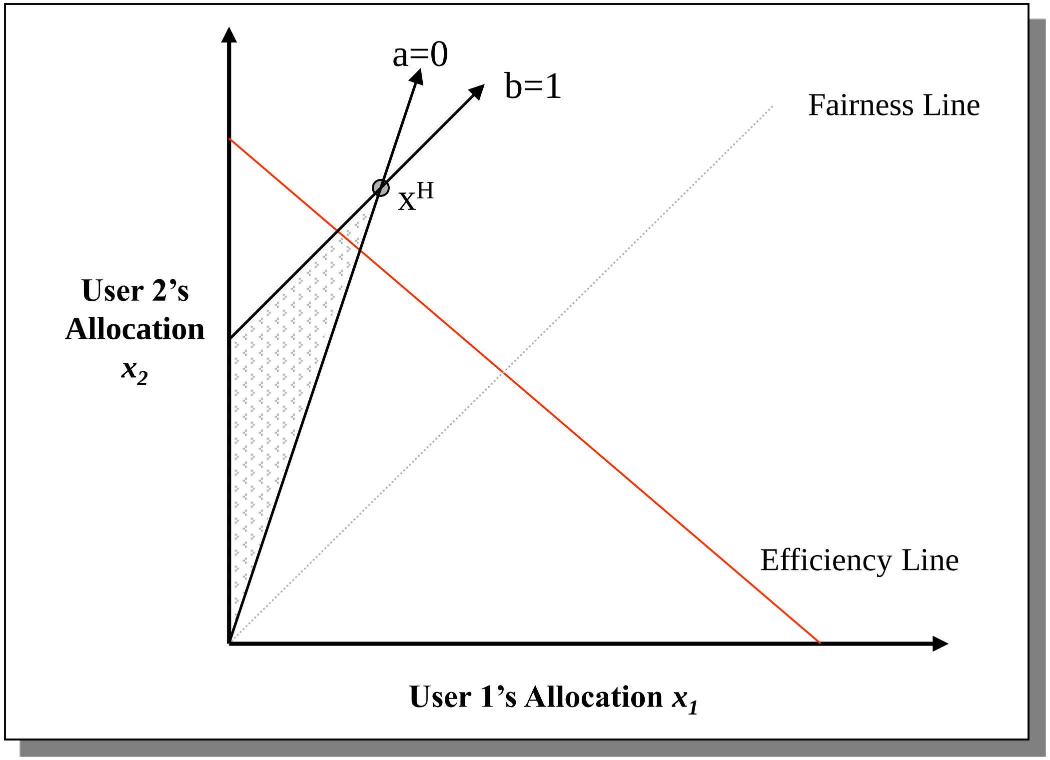


Convergence to efficiency

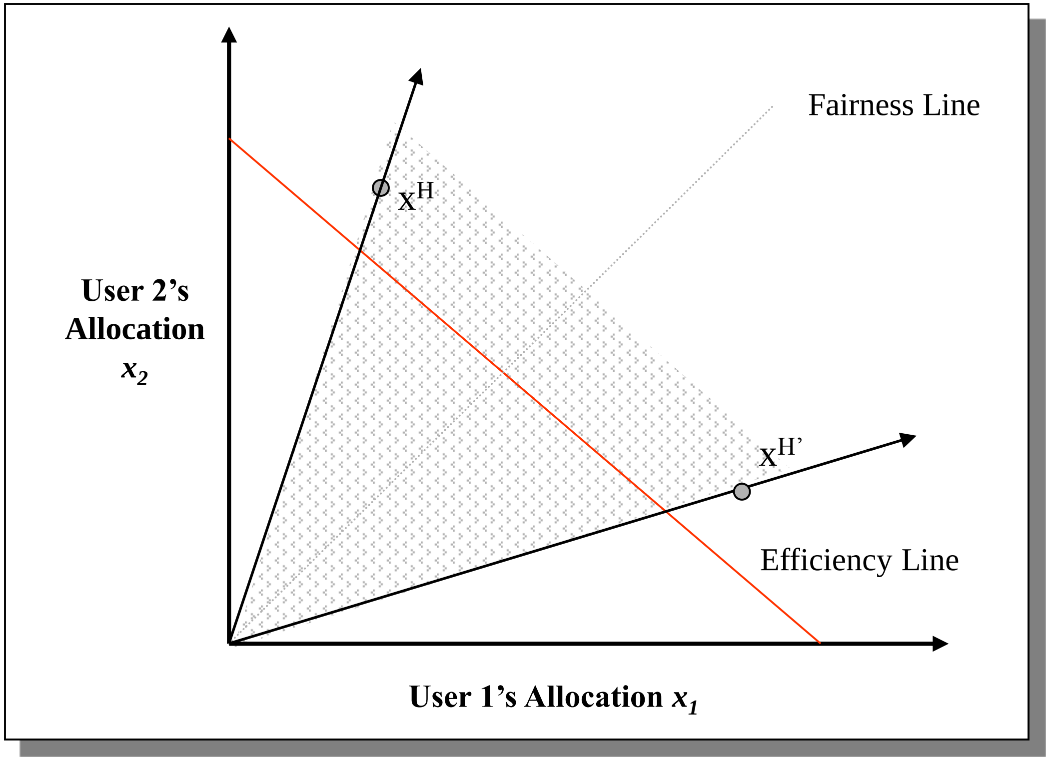
- Want to converge quickly to intersection of fairness and efficiency lines



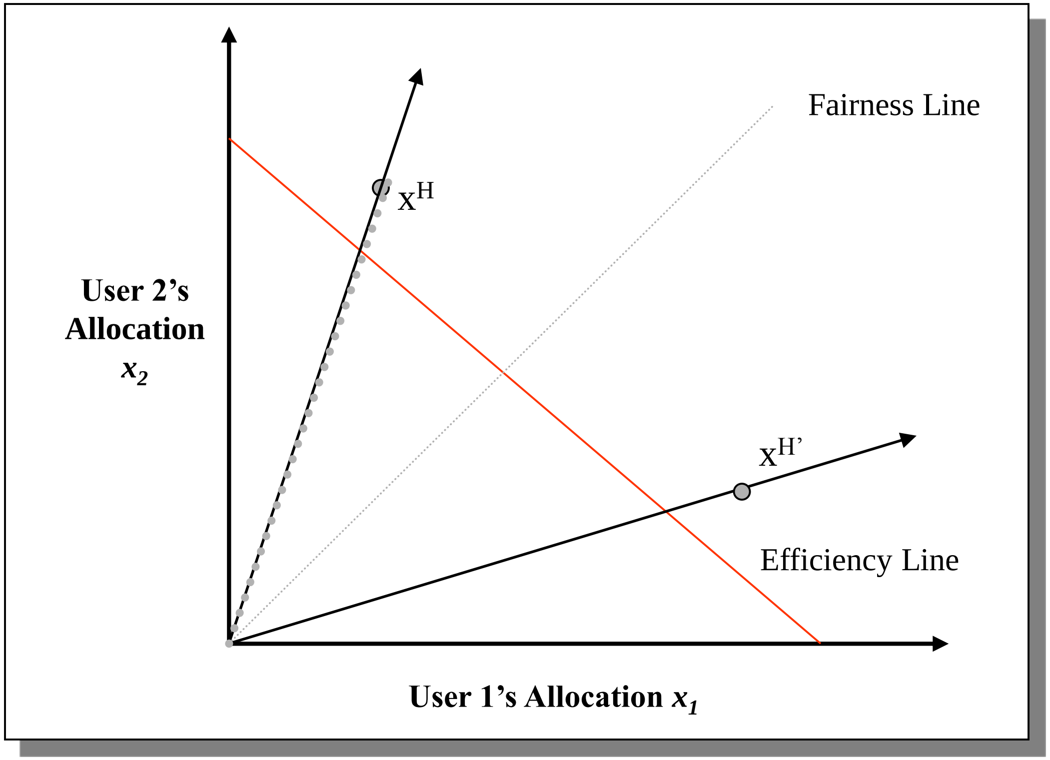
Distributed convergence to efficiency



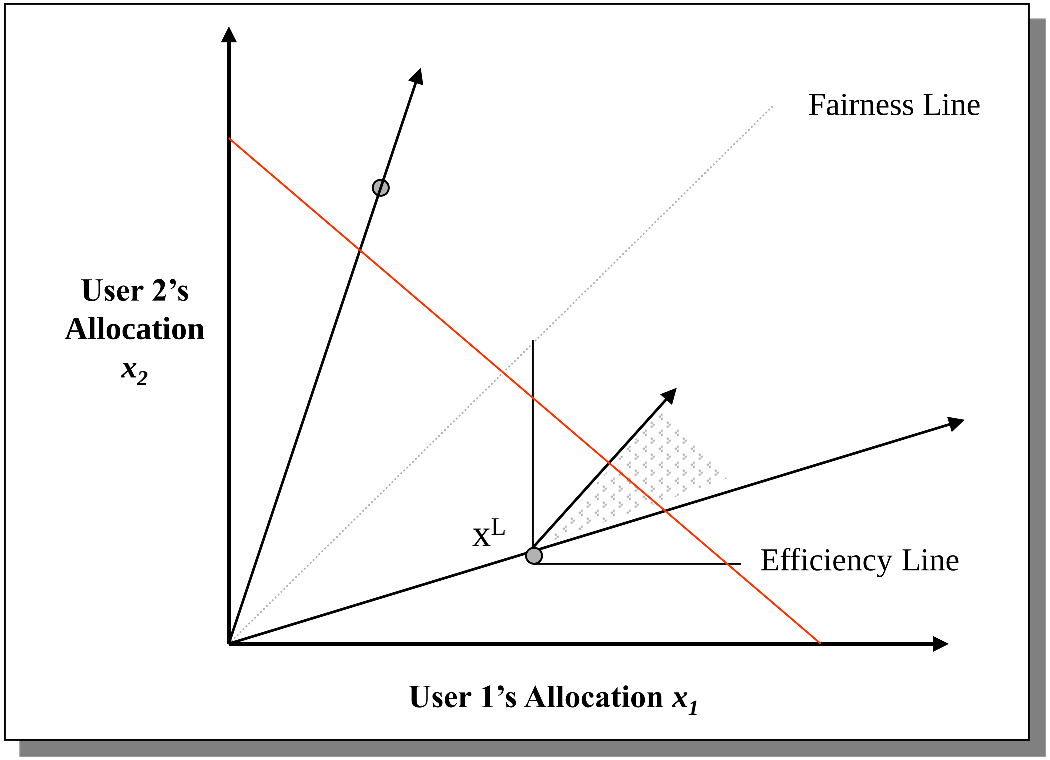
Convergence to fairness



Convergence to efficiency & fairness

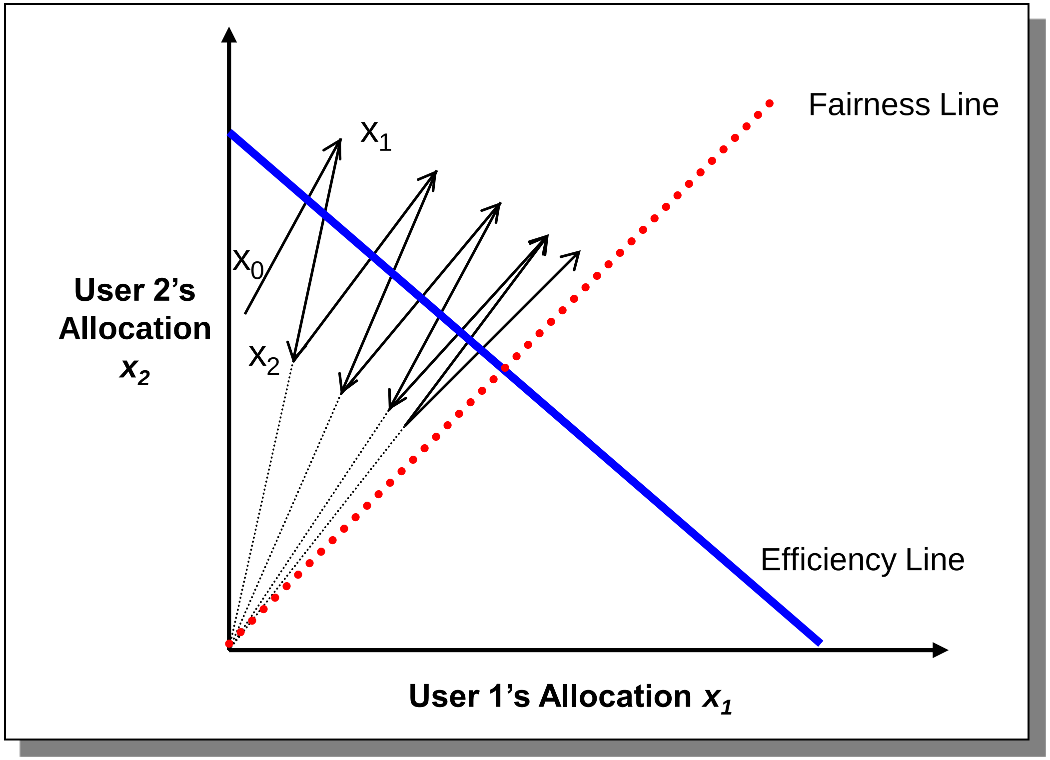


Increase


Fairness Line
User 2's Allocation x_2
x^L
Efficiency Line
User 1's Allocation x_1

What is the right choice?

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



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

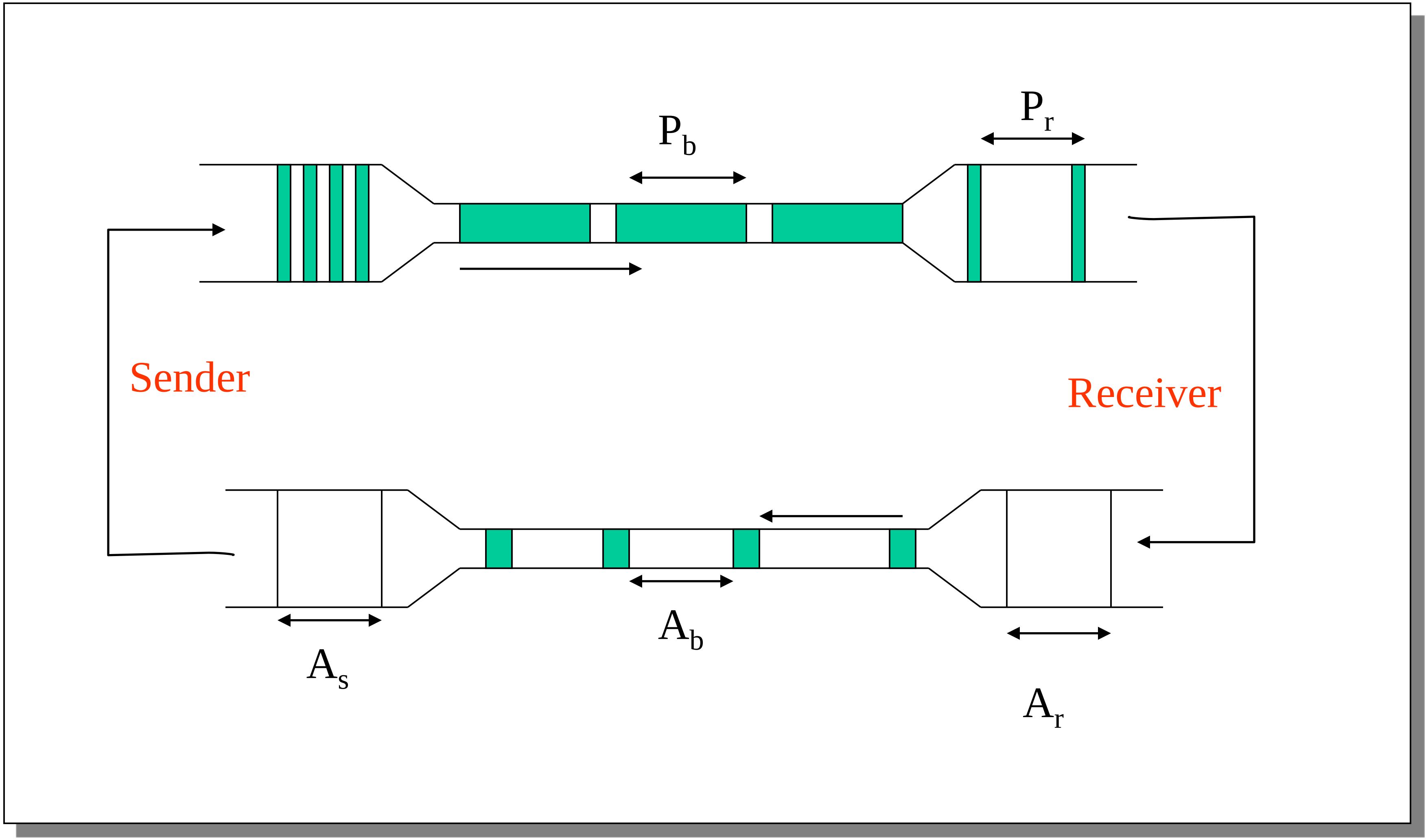
TCP congestion control - solutions

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

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

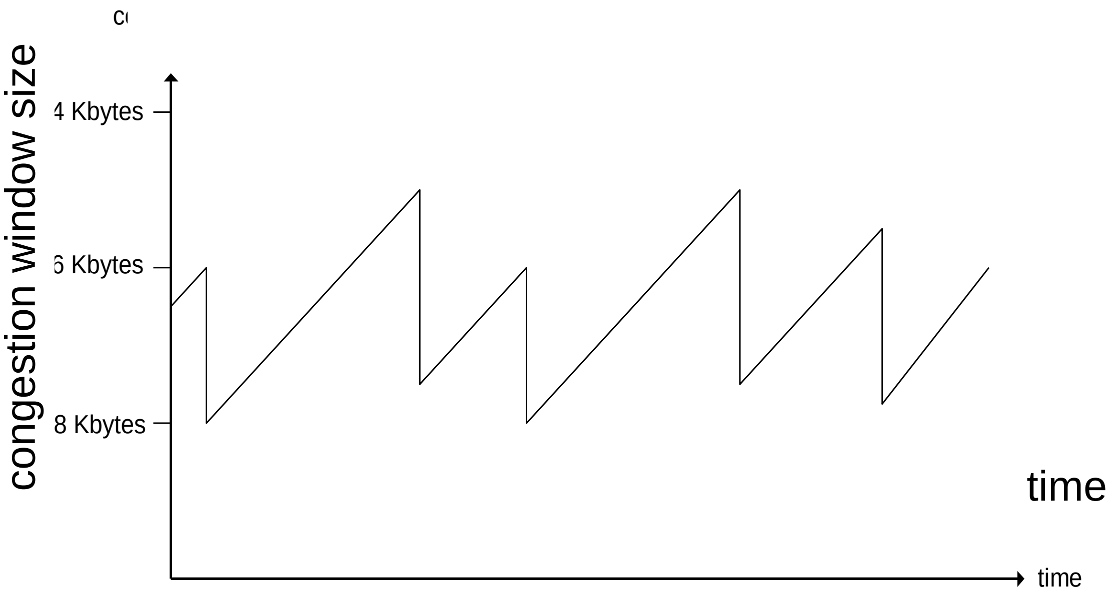
Self-clocking



TCP congestion control: Additive increase, multiplicative decrease (AIMD)

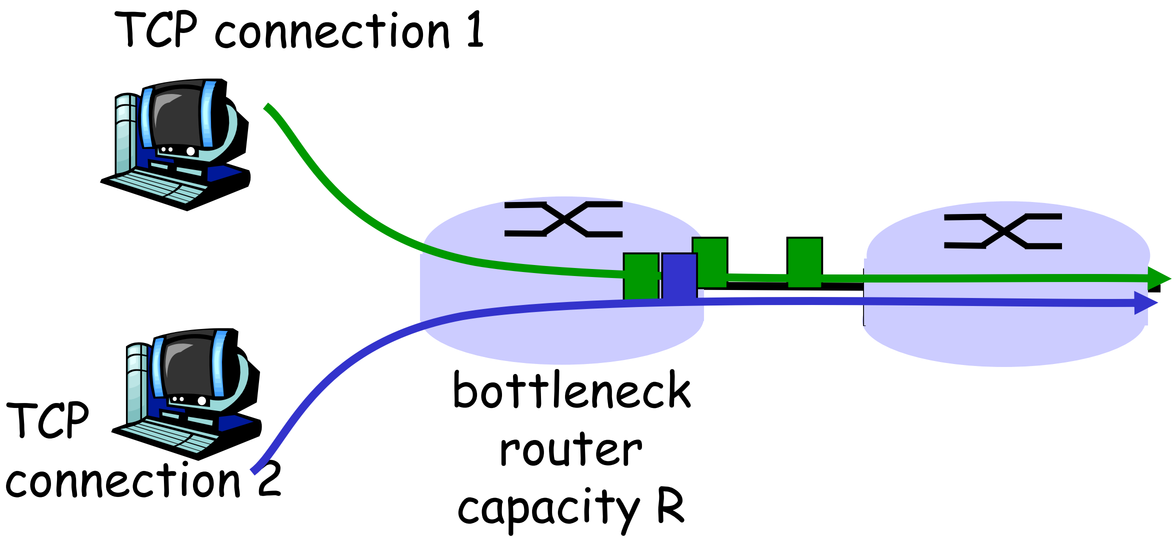
- *Approach:* Increase transmission rate (window size), probing for usable bandwidth, until loss occurs
  - *Additive increase:* Increase **cwnd** by 1 MSS every RTT until loss detected
  - *Multiplicative decrease*: Cut **cwnd** in half after loss

Saw tooth behavior: probing for bandwidth



TCP Fairness

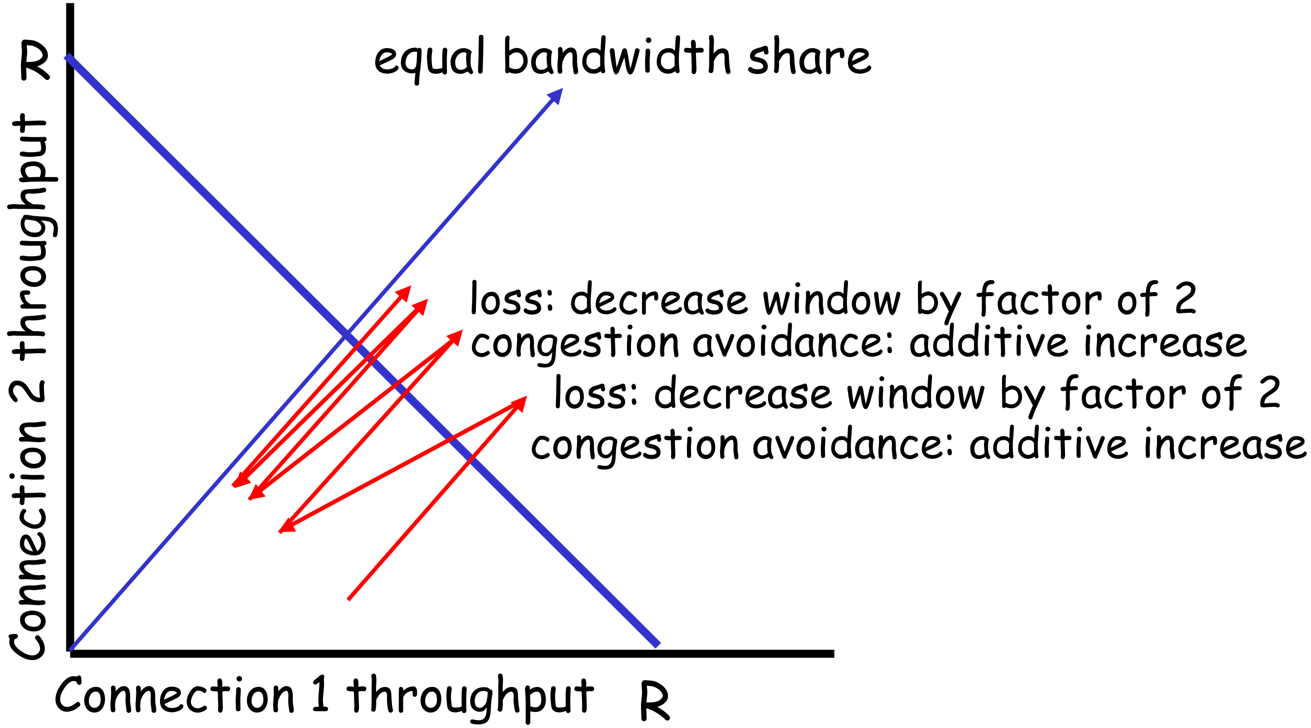
Fairness goal: if N TCP sessions share same bottleneck link, each should get 1/N of link capacity



Why is TCP fair? (Ideal case!)

Two competing sessions:

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



Assumption for TCPs fairness

- Window under consideration is large enough
- Same RTT
- Similar TCP parameters
- Enough data to send
- ....