EECS 489
Computer Networks

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Agenda

- TCP congestion control wrap-up
- TCP throughput equation
- Problems with congestion control

Recap

- Flow Control
  - Restrict window to RWND to make sure that the receiver isn't overwhelmed
- Congestion Control
  - Restrict window to CWND to make sure that the network isn't overwhelmed
- Together
  - Restrict window to min{RWND, CWND} to make sure that neither the receiver nor the network are overwhelmed

CC Implementation

- States at sender
  - CWND (initialized to a small constant)
  - ssthresh (initialized to a large constant)
  - Timer
- Events
  - ACK (new data)
  - Timeout

Event: ACK (new data)

- If CWND < ssthresh
  - CWND += 1

- *CWND packets per RTT*
- *Hence, after one RTT with no drops:*
  CWND = 2xCWND

Event: ACK (new data)

- If CWND < ssthresh
  - CWND += 1

Slow start phase

- Else
  - CWND = CWND + 1/CWND

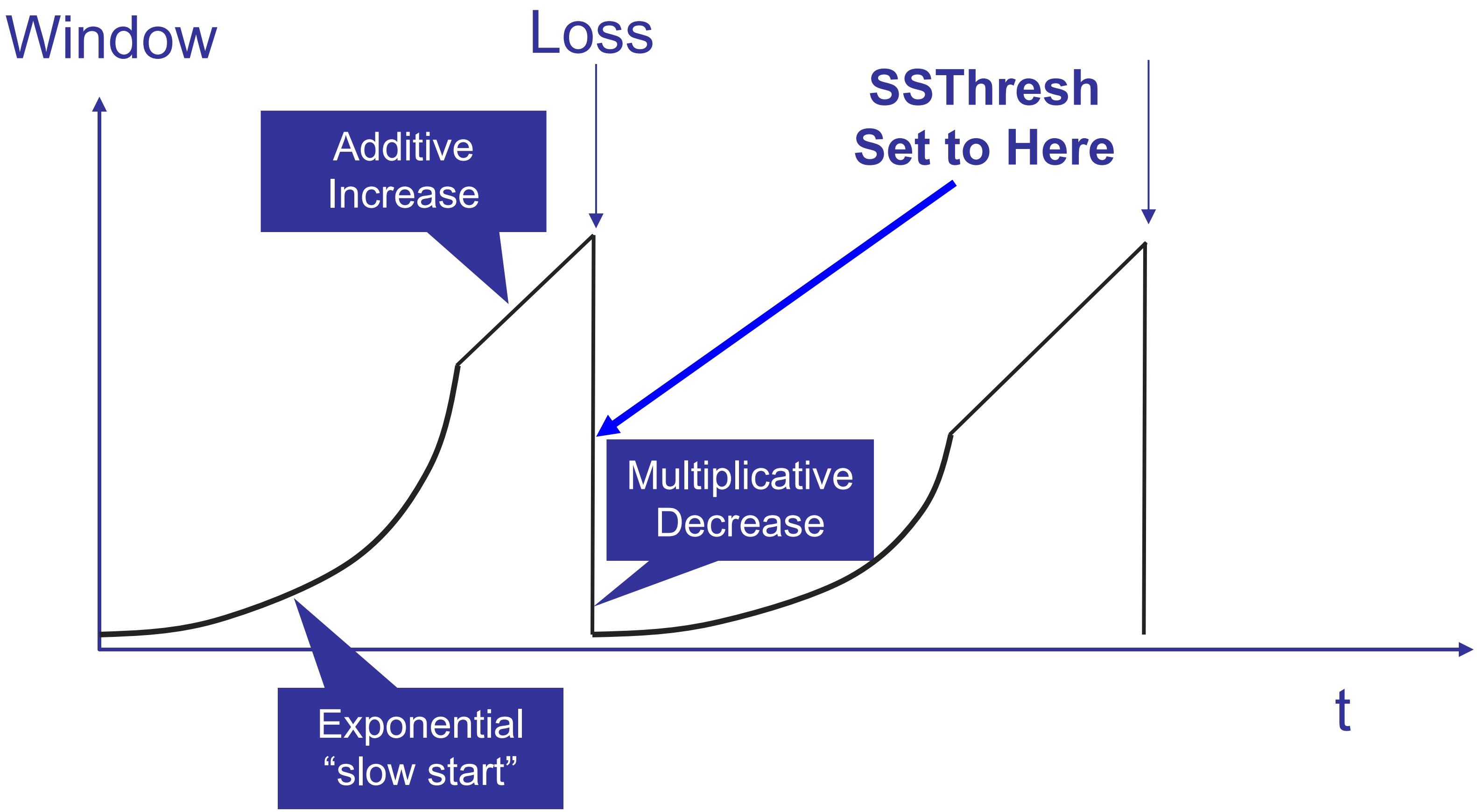
Congestion avoidance phase

- *CWND packets per RTT*
- *Hence, after one RTT with no drops:*
  CWND = CWND + 1

Event: TimeOut

- On Timeout
  - ssthresh ← CWND/2
  - CWND ← 1

AIMD leads to TCP sawtooth



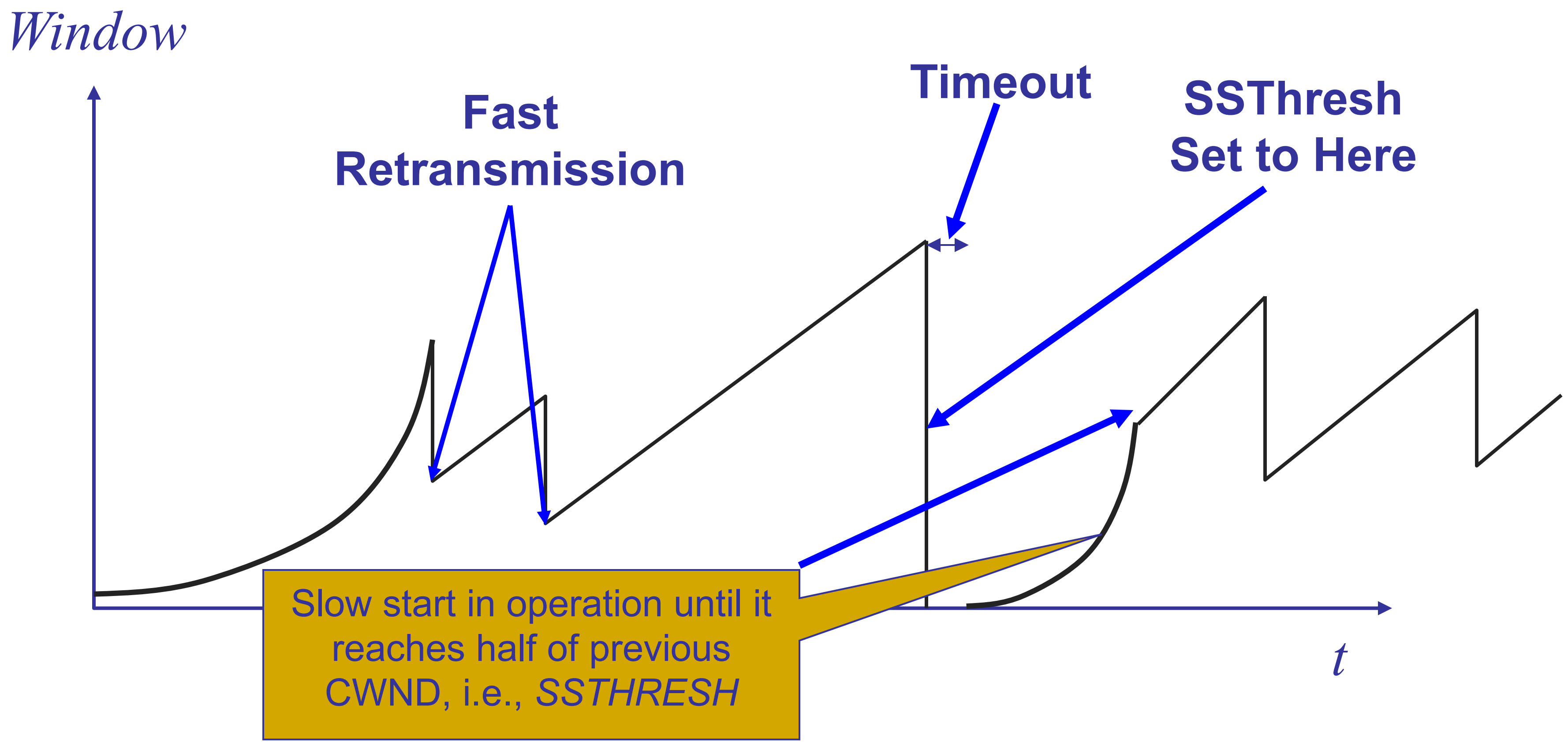
CC Implementation (cont.)

- States at sender
  - CWND (initialized to a small constant)
  - ssthresh (initialized to a large constant)
  - Timer
  - dupACKcount
- Events
  - ACK (new data)
  - Timeout
  - dupACK (duplicate ACK for old data)

Event: dupACK

- dupACKcount ++
- If dupACKcount = 3 /* fast retransmit */
  - ssthresh = CWND/2
  - CWND = CWND/2

Example



Slow-start restart: Go back to CWND = 1 MSS, but take advantage of knowing the previous value of CWND

Why AIMD?

- Recall the three issues
  - Finding available bottleneck bandwidth
  - Adjusting to bandwidth variations
  - Sharing bandwidth

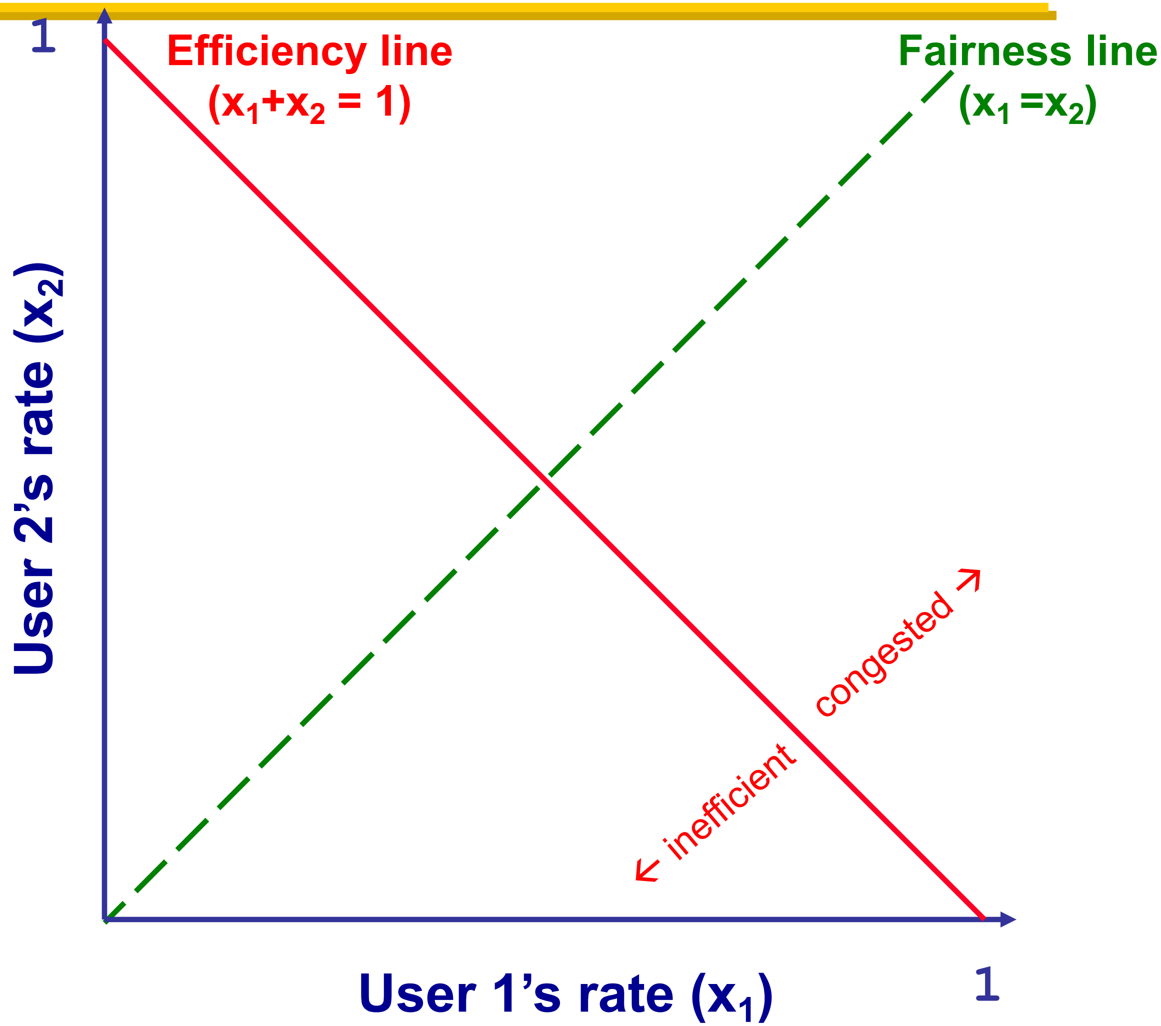
- Two goals for bandwidth sharing
  - Efficiency: High utilization of link bandwidth
  - Fairness: Each flow gets equal share

Why AIMD?

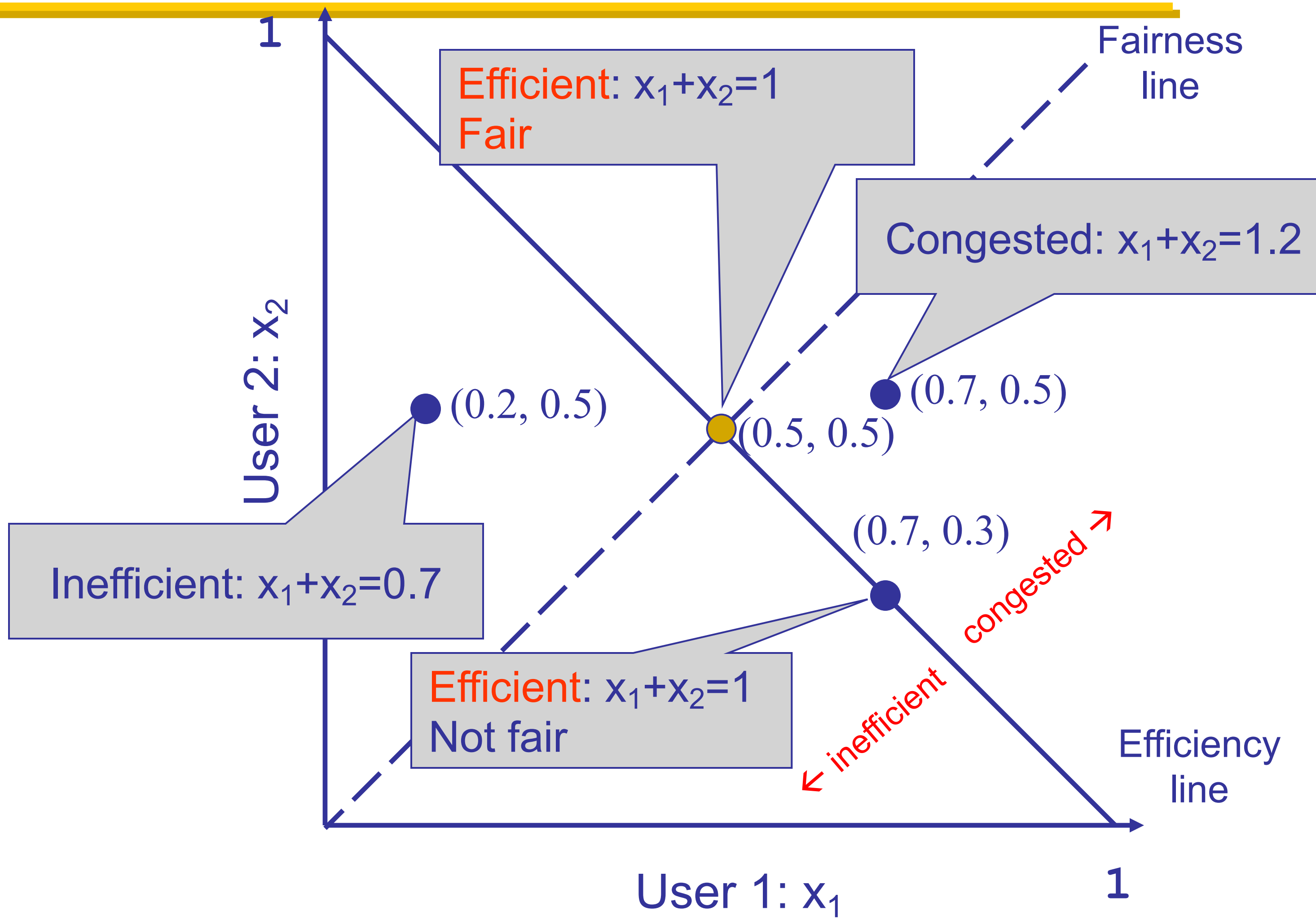
- Every RTT, we can do
  - Multiplicative increase or decrease: CWND$\rightarrow$ a*CWND
  - Additive increase or decrease: CWND$\rightarrow$ CWND + b
- Four alternatives:
  - AIAD: gentle increase, gentle decrease
  - AIMD: gentle increase, drastic decrease
  - MIAD: drastic increase, gentle decrease
  - MIMD: drastic increase and decrease

Simple model of congestion control

- Two users
  - rates x1 and x2
- Congestion when x1+x2 > 1
- Unused capacity when x1+x2 < 1
- Fair when x1 =x2



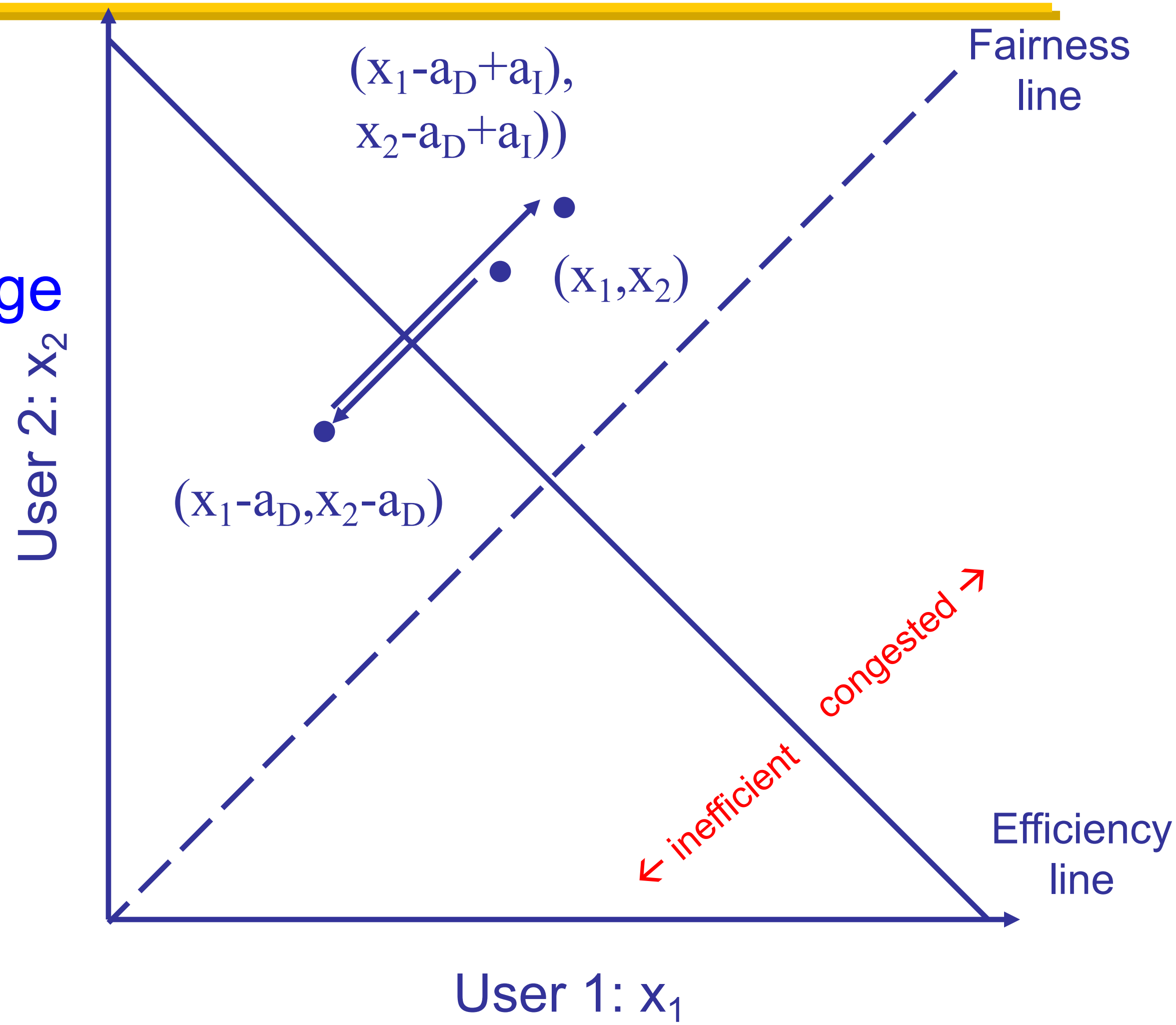
Example



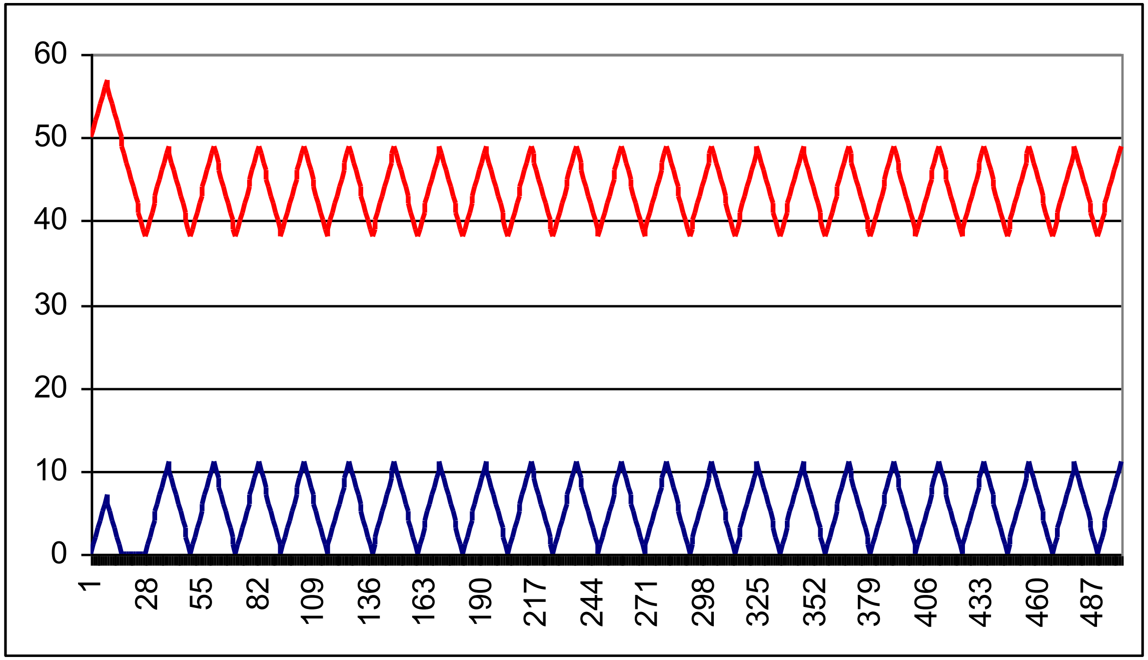
1
Fairness line
Efficient: $x_1+x_2=1$
Fair
Congested: $x_1+x_2=1.2$
User 2: x_2
(0.2, 0.5)
(0.5, 0.5)
(0.7, 0.5)
(0.7, 0.3)
Inefficient: $x_1+x_2=0.7$
congested →
Efficient: $x_1+x_2=1$
Not fair
← inefficient
Efficiency line
User 1: x_1
1

AIAD

- Increase: $x + a_I$
- Decrease: $x - a_D$
- Does not converge to fairness

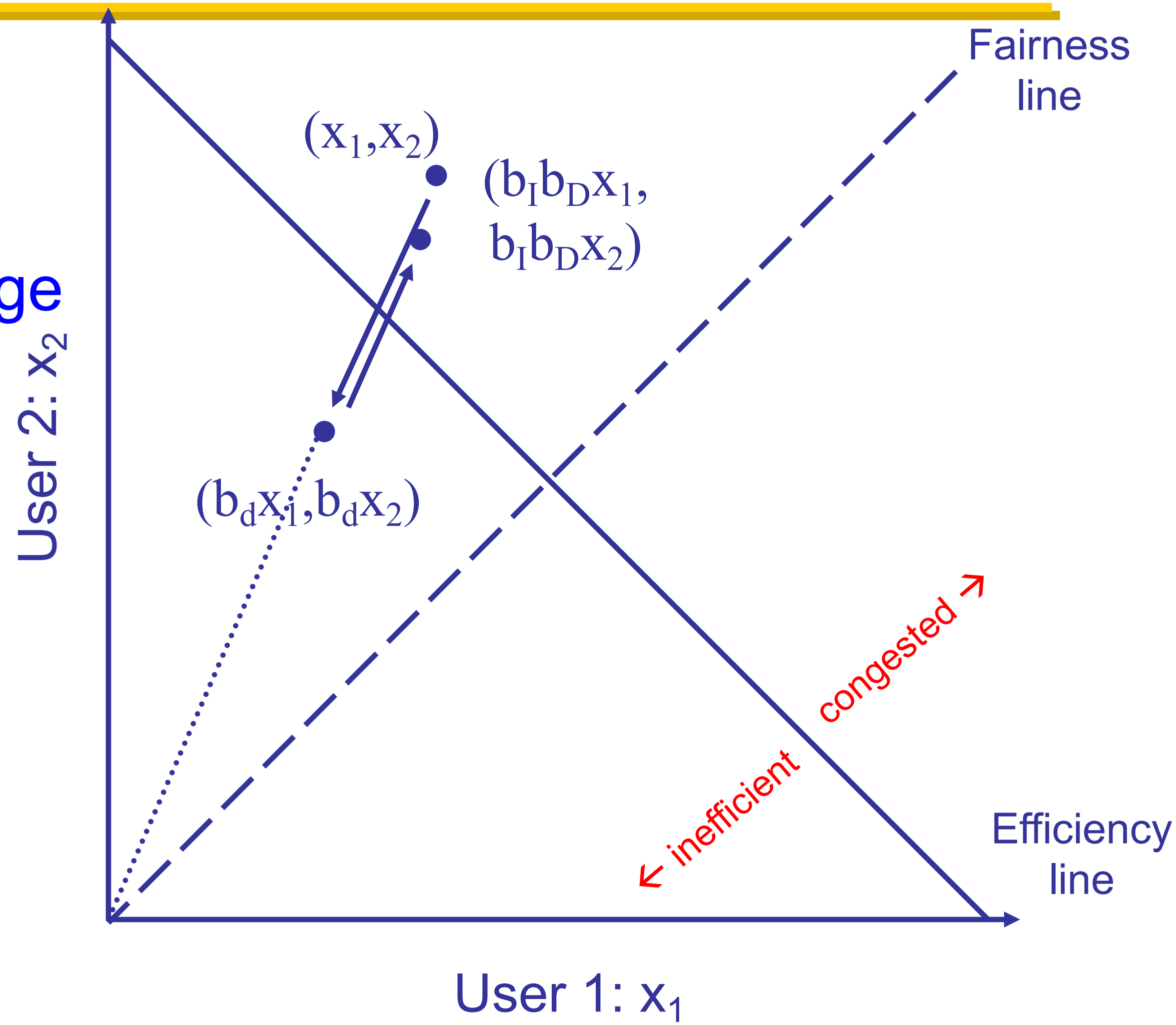


AIAD Sharing Dynamics



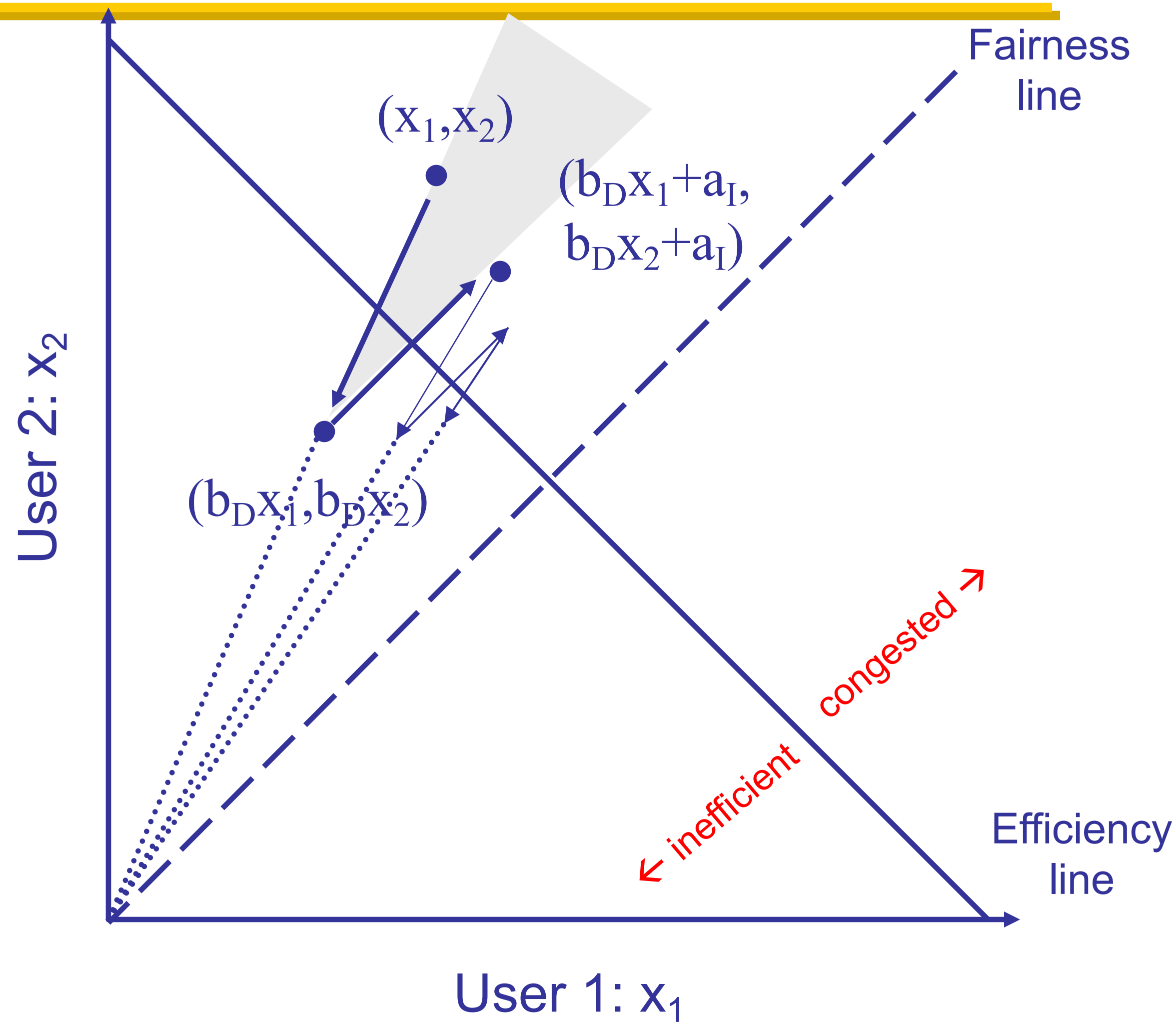
MIMD

- Increase: x^*b_I
- Decrease: x^*b_D
- Does not converge to fairness

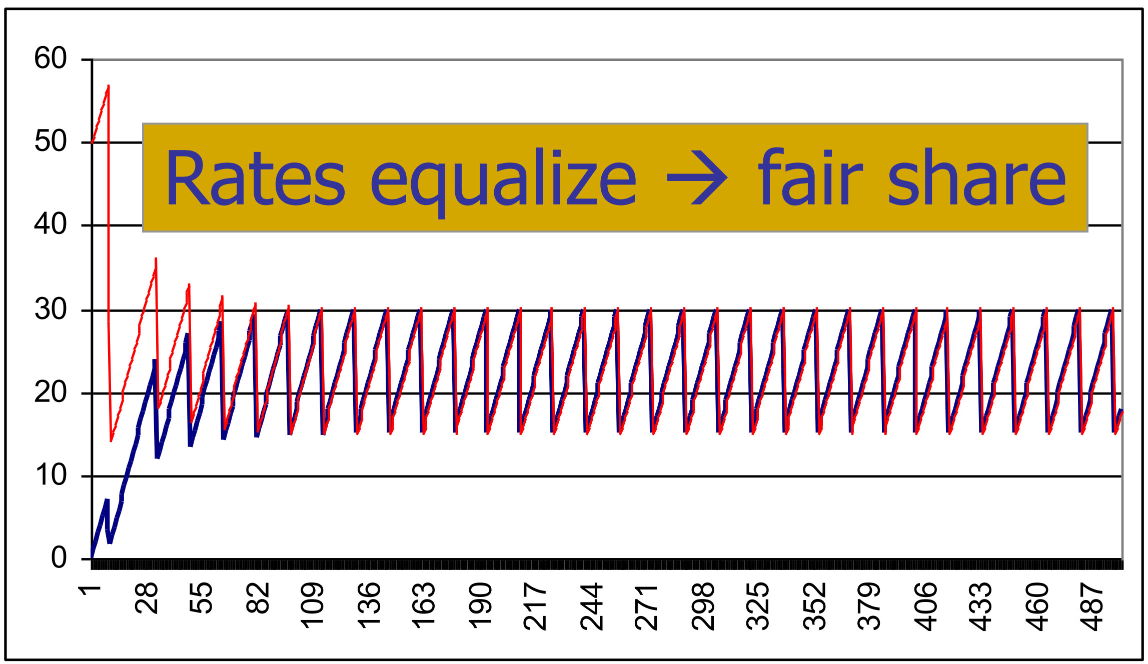


AIMD

- Increase: $x+a_I$
- Decrease: $x*b_D$
- Converges to fairness



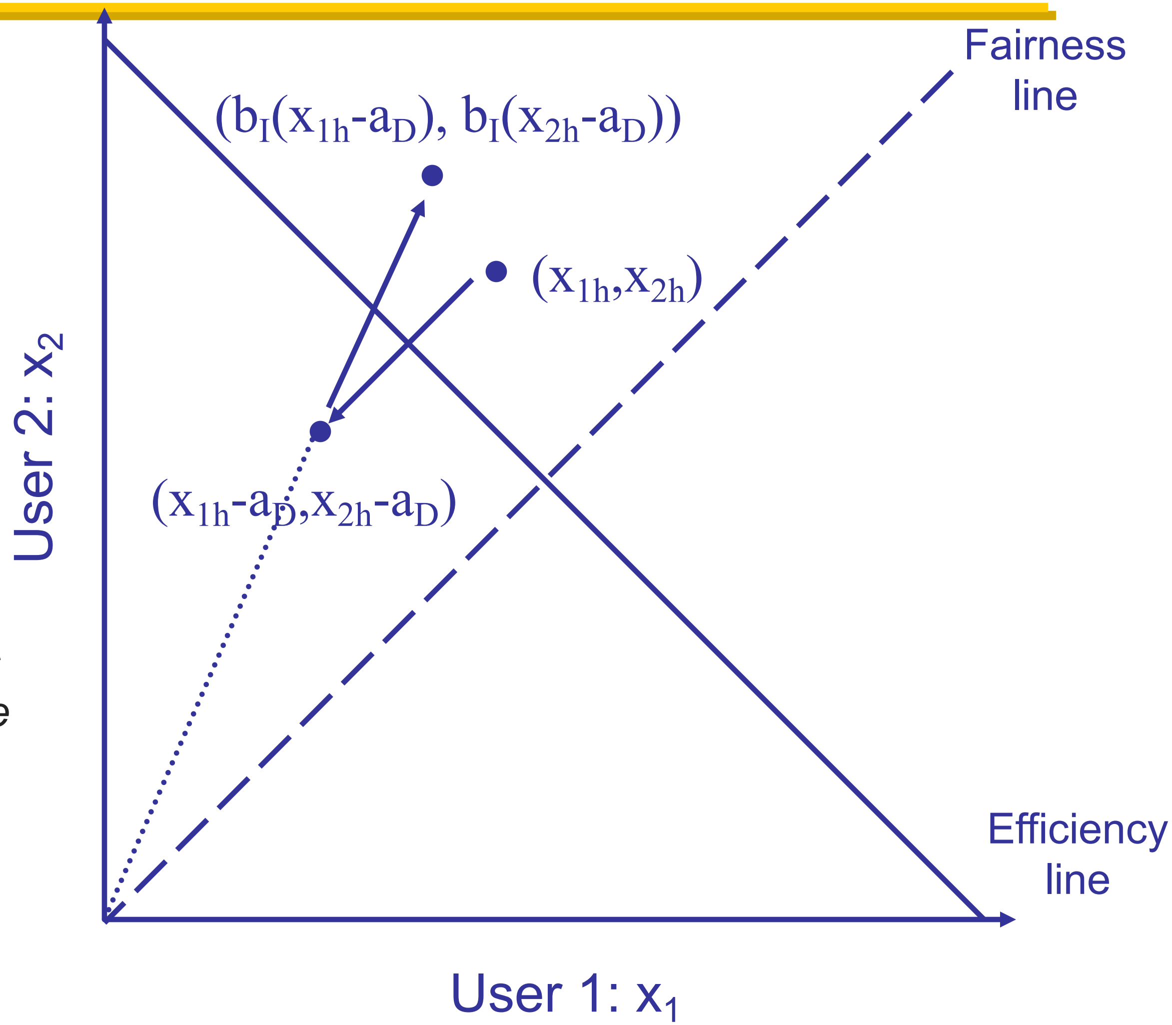
AIMD Sharing Dynamics



MIAD

- Increase: x^*b_I
- Decrease: $x - a_D$
- Does not converge to fairness
- Does not converge to efficiency

- *"Analysis of the Increase and Decrease Algorithms for Congestion Avoidance in Computer Networks"*
  -- Chiu and Jain



Not done yet!

- Problem: congestion avoidance too slow in recovering from an isolated loss

Example

- Consider a TCP connection with:
  - CWND=10 packets
  - Last ACK was for packet # 101
    - i.e., receiver expecting next packet to have seq. no. 101
- 10 packets [101, 102, 103,…, 110] are in flight
  - Packet 101 is dropped

Timeline: [~~101~~, 102, ..., 110]

- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)
- ACK 101 (due to 103) cwnd=10 dupACK#2 (no xmit)
- ACK 101 (due to 104) cwnd=10 dupACK#3 (no xmit)
- RETRANSMIT 101 ssthresh=5 cwnd= 5
- ACK 101 (due to 105) cwnd=5 + 1/5 (no xmit)
- ACK 101 (due to 106) cwnd=5 + 2/5 (no xmit)
- ACK 101 (due to 107) cwnd=5 + 3/5 (no xmit)
- ACK 101 (due to 108) cwnd=5 + 4/5 (no xmit)
- ACK 101 (due to 109) cwnd=5 + 5/5 (no xmit)
- ACK 101 (due to 110) cwnd=6 + 1/6 (no xmit)
- ACK 111 (due to 101) ← only now can we transmit new packets
- Plus no packets in flight so ACK “clocking” (to increase CWND) stalls for another RTT

Solution: Fast recovery

- Idea: Grant the sender temporary “credit” for each dupACK so as to keep packets in flight
- If dupACKcount = 3
  - ssthresh = CWND/2
  - CWND = ssthresh + 3
- While in fast recovery
  - CWND = CWND + 1 for each additional dupACK
- Exit fast recovery after receiving new ACK
  - set CWND = ssthresh

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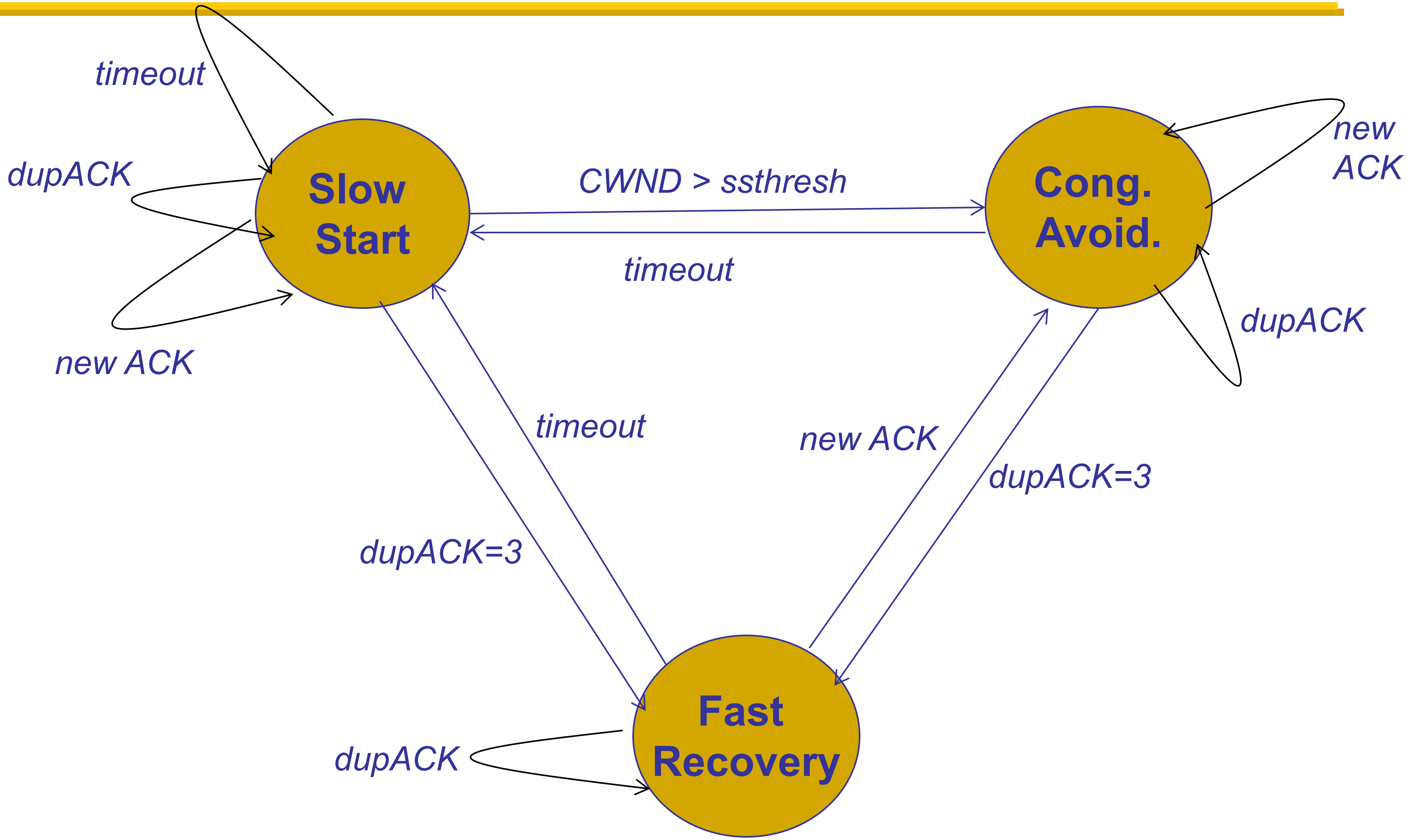
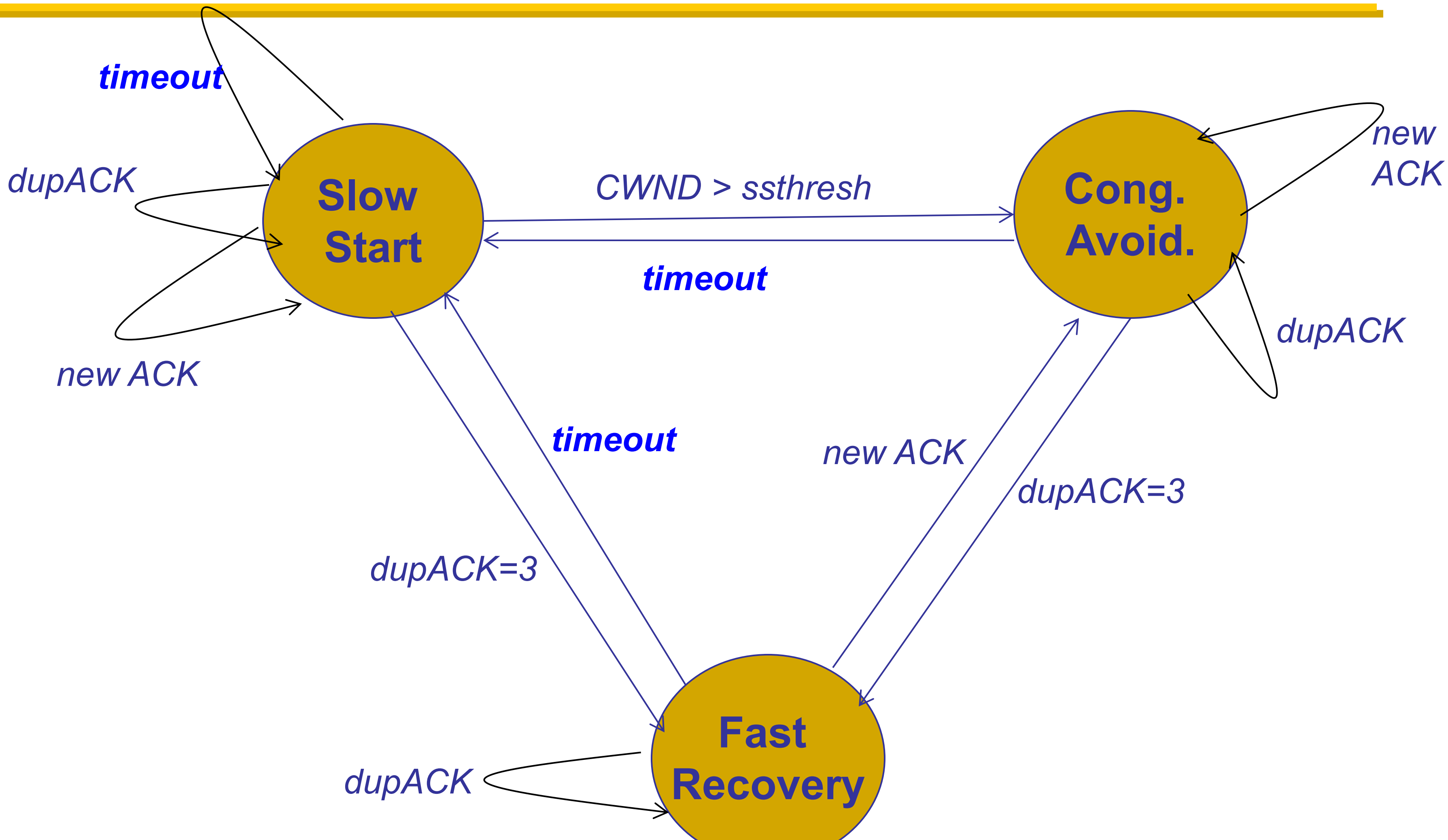
- ACK 101 (due to 104) cwnd=10 dup#3
- RETRANSMIT 101 ssthresh=5 cwnd= 8 (5+3)
- ACK 101 (due to 105) cwnd= 9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
- ACK 101 (due to 108) cwnd=12 (xmit 112)
- ACK 101 (due to 109) cwnd=13 (xmit 113)
- ACK 101 (due to 110) cwnd=14 (xmit 114)
- ACK 111 (due to 101) cwnd = 5 (xmit 115) ← exiting fast recovery
- Packets 111-114 already in flight
- ACK 112 (due to 111) cwnd = 5 + 1/5 ← back in cong. avoidance

5-MINUTE BREAK!

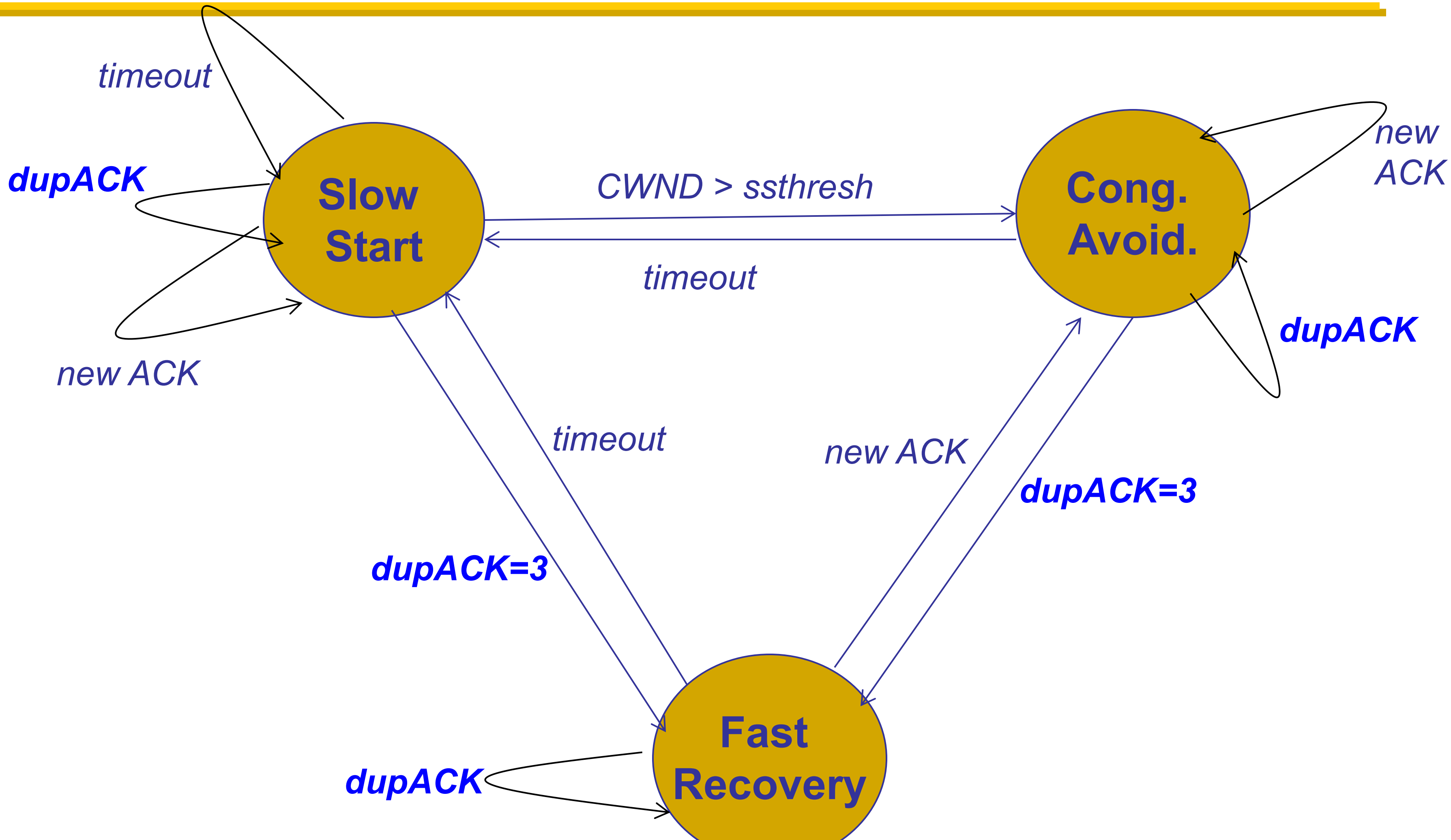
TCP state machine



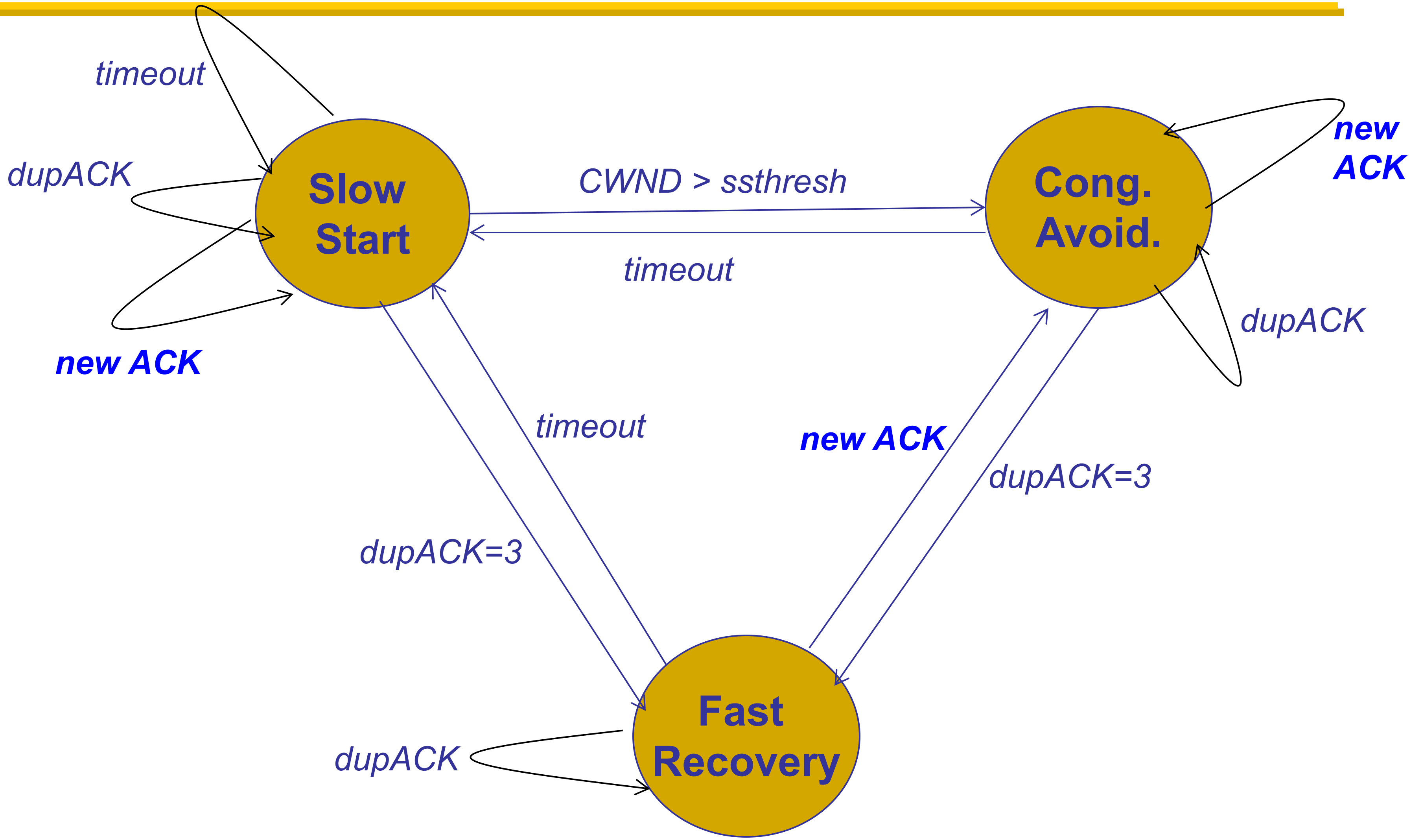
Timeouts → Slow Start



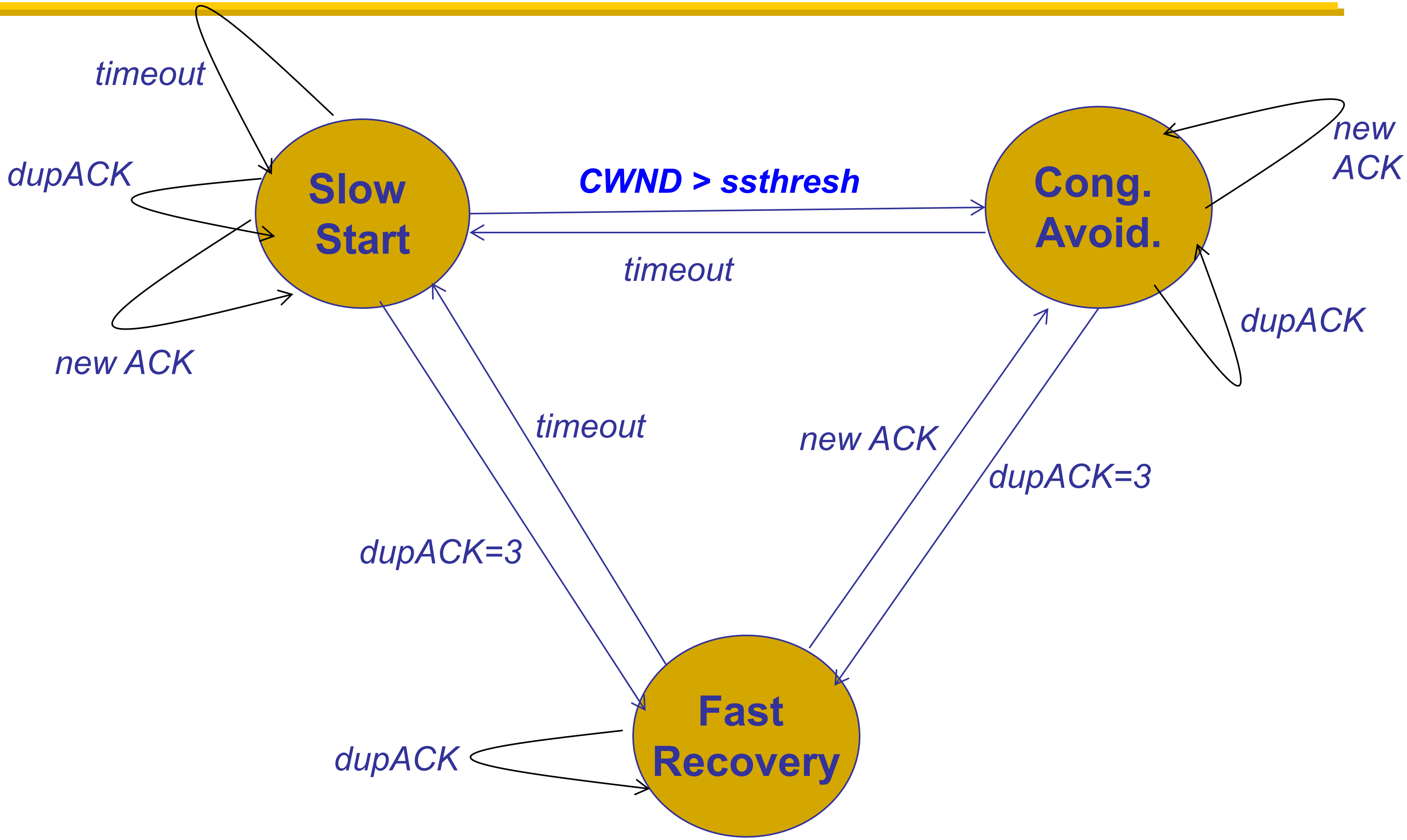
dupACKs → Fast Recovery



New ACK changes state ONLY from Fast Recovery



TCP state machine



TCP flavors

- TCP-Tahoe
  - CWND =1 on 3 dupACKs
- TCP-Reno
  - CWND =1 on timeout
  - CWND = CWND/2 on 3 dupACKs
- TCP-newReno
  - TCP-Reno + improved fast recovery
- TCP-SACK
  - Incorporates selective acknowledgements

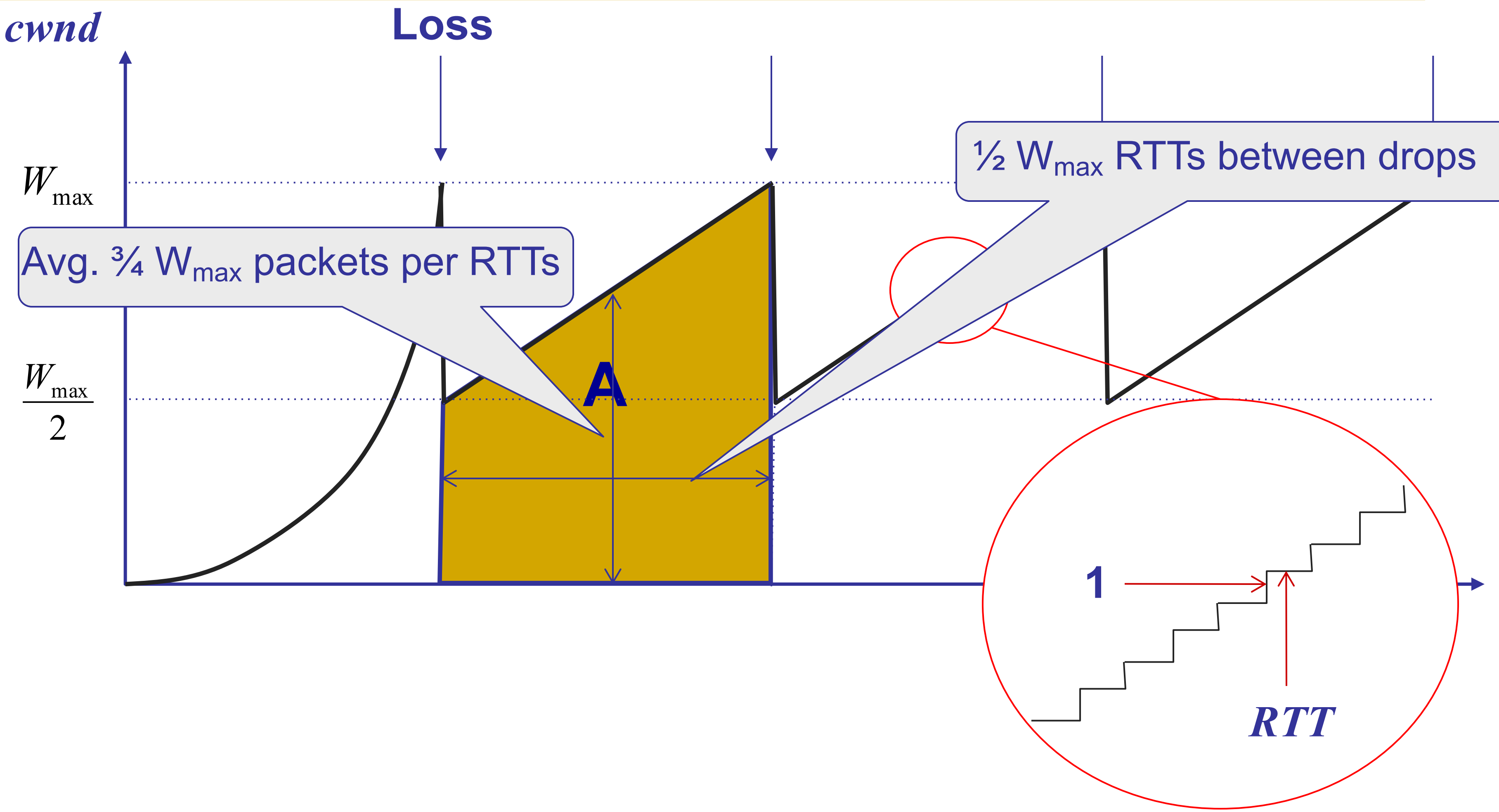
Our default assumption

How can they coexist?

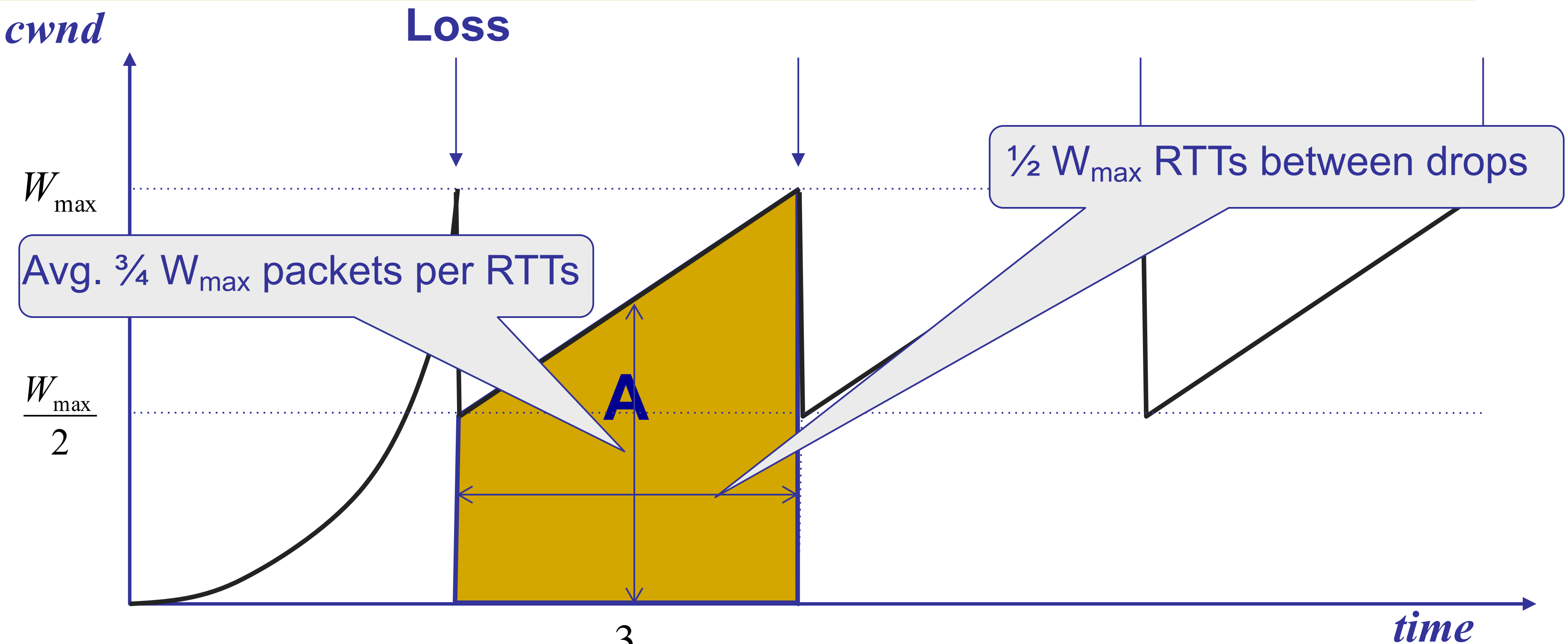
- All follow the same principle
  - Increase CWND on good news
  - Decrease CWND on bad news

TCP THROUGHPUT EQUATION

A simple model for TCP throughput



A simple model for TCP throughput

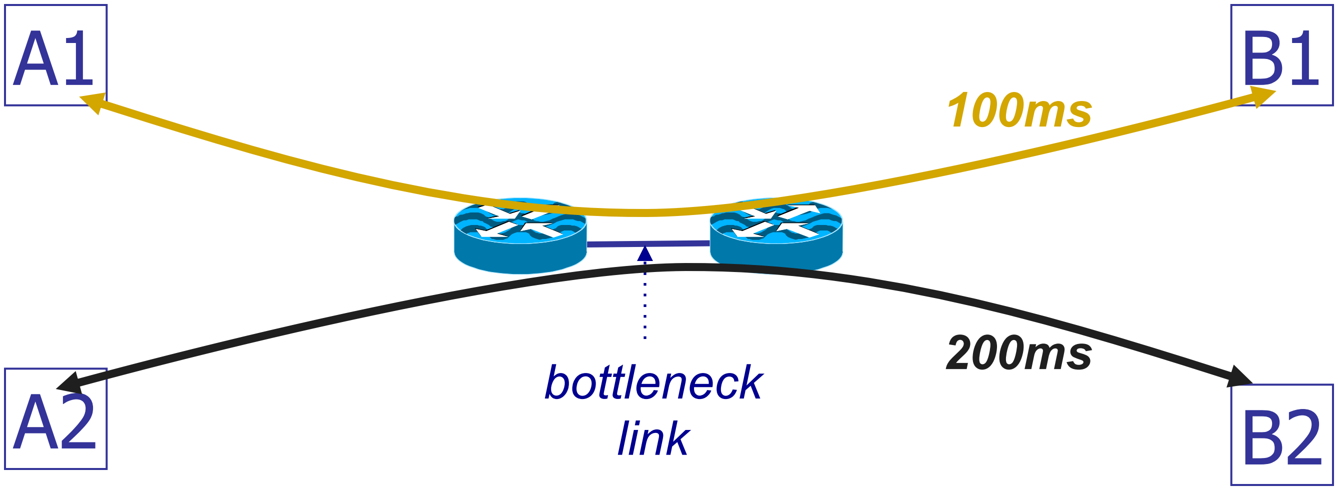


$$A = \frac{3}{8} W_{max}^2$$

Implications (1): Different RTTs

$$\text{Throughput} = \sqrt{\frac{3}{2}} \frac{1}{RTT\sqrt{p}}$$

- Flows get throughput inversely proportional to RTT
- TCP unfair in the face of heterogeneous RTTs!



Implications (2): High-speed TCP

$$\text{Throughput} = \sqrt{\frac{3}{2}}\frac{1}{RTT\sqrt{p}}$$

- Assume RTT = 100ms, MSS=1500bytes, BW=100Gbps
- What value of p is required to reach 100Gbps throughput?
  - ~ 2 x 10^{-12}
- How long between drops?
  - ~ 16.6 hours
- How much data has been sent in this time?
  - ~ 6 petabits

Implications (3): Rate-based CC

$$\text{Throughput} = \sqrt{\frac{3}{2}}\frac{1}{RTT\sqrt{p}}$$

- TCP throughput is swings between W/2 to W
- Apps may prefer steady rates (e.g., streaming)
- "Equation-Based Congestion Control"
  - Ignore TCP's increase/decrease rules and just follow the equation
  - Measure drop percentage p, and set rate accordingly
- Following the TCP equation ensures "TCP friendliness"
  - i.e., use no more than TCP does in similar setting

Implications (4): Loss not due to congestion?

- TCP will confuse corruption with congestion
- Flow will cut its rate
  - Throughput ~ 1/sqrt(p) where p is loss prob.
  - Applies even for non-congestion losses!

Implications (5): Short flows cannot ramp up

- 50% of flows have < 1500B to send; 80% < 100KB
- Implications
  - Short flows never leave slow start!
    - They never attain their fair share
  - Too few packets to trigger dupACKs
    - Isolated loss may lead to timeouts
    - At typical timeout values of ~500ms, might severely impact flow completion time

Implications (6): Short flows share long delays

- A flow deliberately overshoots capacity, until it experiences a drop
- Means that delays are large, and are large for everyone
  - Consider a flow transferring a 10GB file sharing a bottleneck link with 10 flows transferring 100B
  - Larger flows dominate smaller ones

Implications (7): Cheating

- Three easy ways to cheat
  - Increasing CWND faster than +1 MSS per RTT

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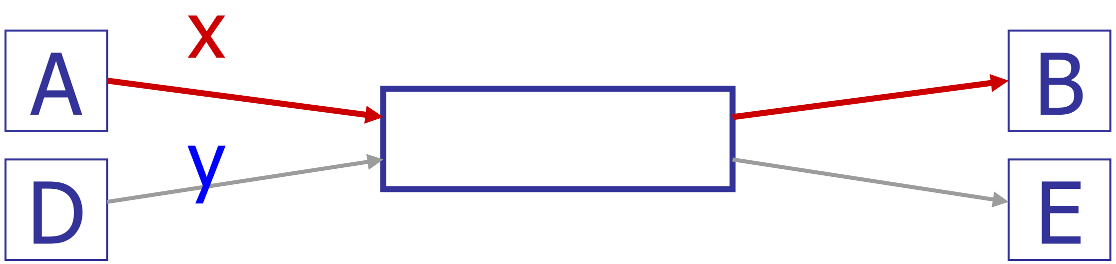
- Three easy ways to cheat
  - Increasing CWND faster than +1 MSS per RTT
  - Using large initial CWND
    - Common practice by many companies
  - Opening many connections

Open many connections



- Assume
  - A starts 10 connections to B
  - D starts 1 connection to E
  - Each connection gets about the same throughput

- Then A gets 10 times more throughput than D

Implications (8): CC intertwined with reliability

- CWND adjusted based on ACKs and timeouts
- Cumulative ACKs and fast retransmit/recovery rules
- Complicates evolution
  - Changing from cumulative to selective ACKs is hard
- Sometimes we want CC but not reliability
  - e.g., real-time applications
- We may also want reliability without CC

Recap: TCP problems

- Misled by non-congestion losses
- Fills up queues leading to high delays
- Short flows complete before discovering available capacity
- AIMD impractical for high speed links
- Saw tooth discovery too choppy for some apps
- Unfair under heterogeneous RTTs
- Tight coupling with reliability mechanisms
- End hosts can cheat

Routers tell endpoints if they're congested

Routers tell endpoints what rate to send at

Routers enforce fair sharing

Could fix many of these with some help from routers!

Summary

- TCP works even though it has many flaws
- Many of them can be fixed via assistance from the network

- Next: The Network Layer

Adapting TCP to high speed

- Once past a threshold speed, increase CWND faster
  - A proposed standard [Floyd'03]: once speed is past some threshold, change equation to $p^{-.8}$ rather than $p^{-.5}$
  - Let the additive constant in AIMD depend on CWND
- Other approaches?
  - Multiple simultaneous connections (hack but works today)
  - Router-assisted approaches