Congestion Control

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Based in part on slides by Ion Stoica

Announcements

A starting point:
the sliding window protocol

TCP flow control

Make sure receiving end can handle data

Negotiated end-to-end, with no regard to network

Ends must ensure that no more than W packets are in flight if buffer has size W

- Receiver ACKs packets
- When sender gets an ACK, it knows packet has arrived

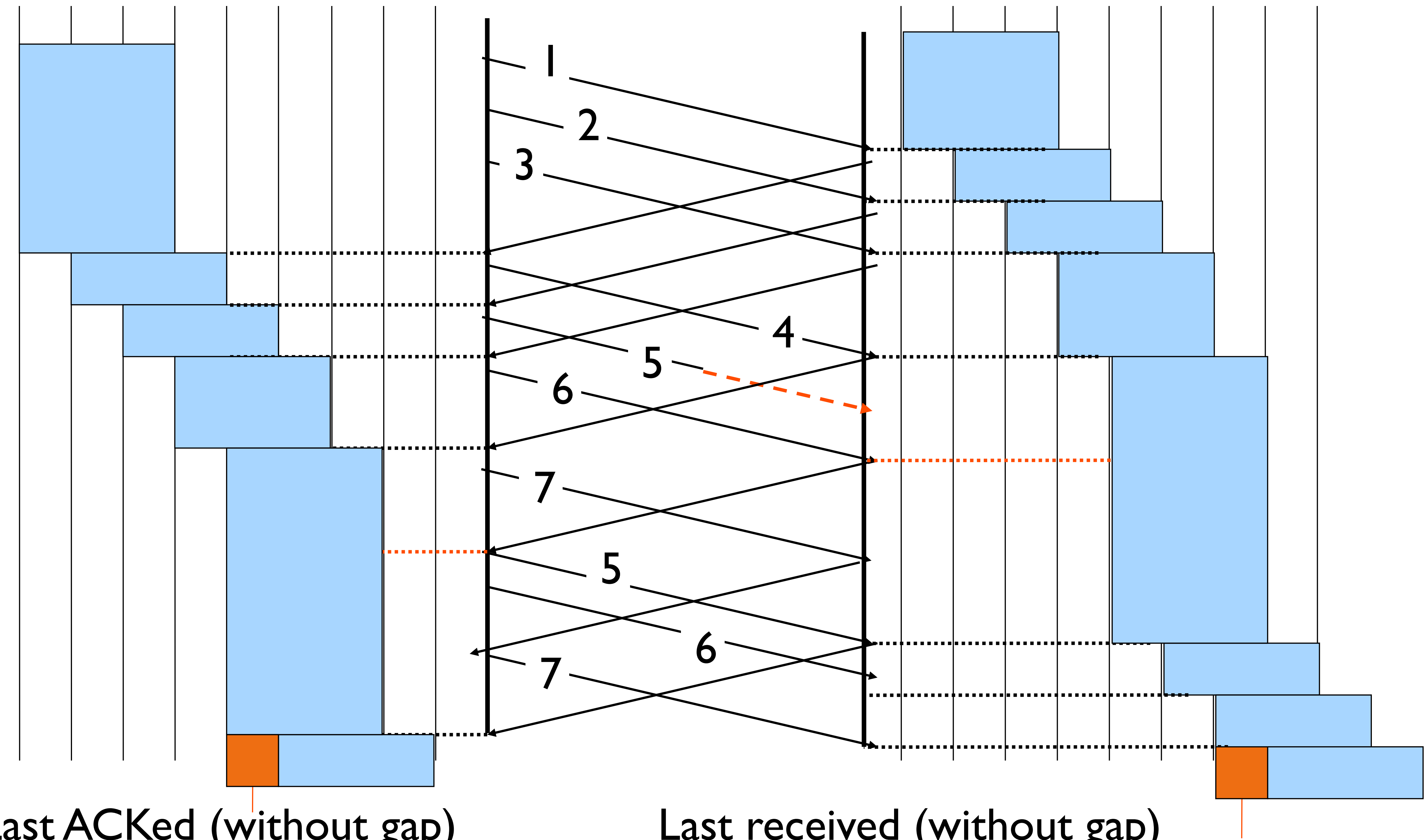
Sliding window-based flow control

At the sender...

Sliding window-based flow control

At the receiver...

Sliding window



Last ACKed (without gap)

Last received (without gap)

Observations

What is the throughput in terms of RTT and window size, in theory?

- Throughput is ~ (w/RTT)

On to Jacobson'88

Getting to equilibrium: Slow Start

- Initial **rate** is slow: very conservative starting point
- But **acceleration** is high
- …or is it? Maybe too conservative now
  - http://research.google.com/pubs/pub36640.html

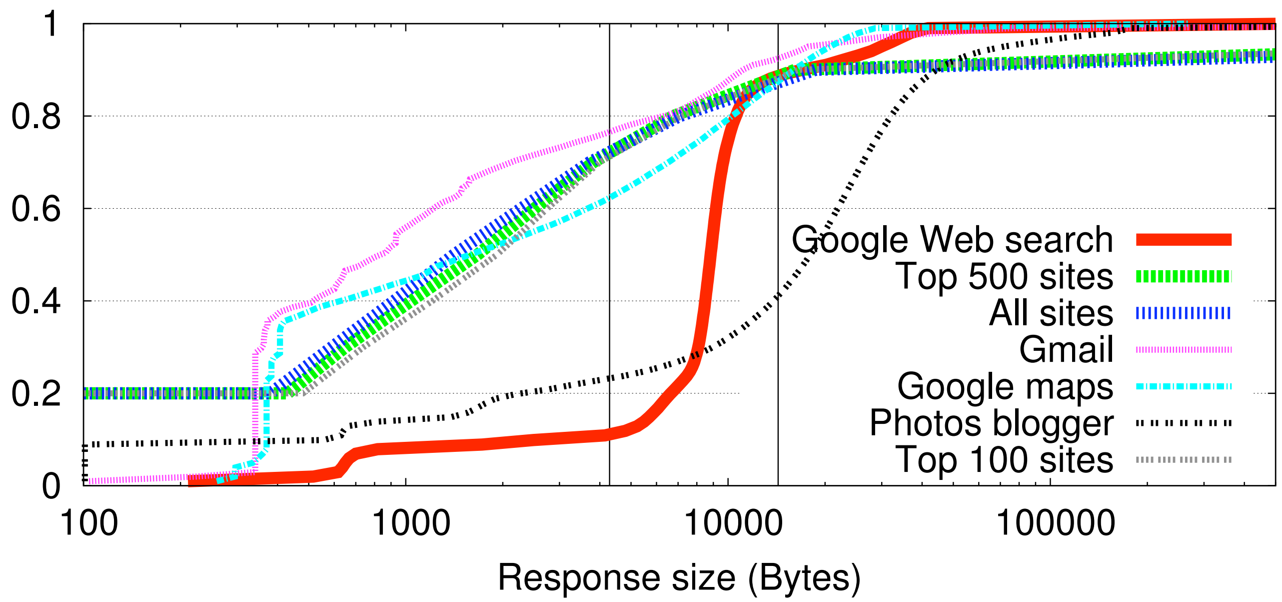


Figure 1: CDF of HTTP response sizes for top 100 sites, top 500 sites, all the Web, and for a few popular Google services. Vertical lines highlight response sizes of 3 and 10 segments.

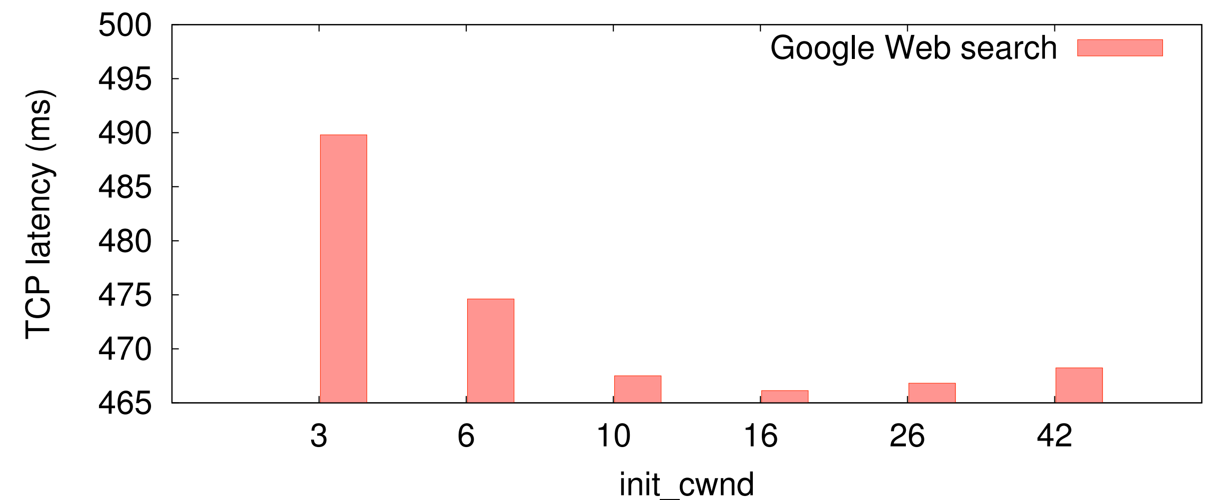


Figure 2: TCP latency for Google search with different *init_cwnd* values.

[Figures from Dukkipati et al, CCR July 2010]

On to Jacobson'88

Getting to equilibrium: Slow Start

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Conservation: Round-Trip Timing

Congestion Avoidance

Round-trip timing

Error recovery

Must retransmit packets that were dropped

To do this efficiently

- Keep transmitting whenever possible
- Detect dropped packets and retransmit quickly

Requires:

- Timeouts (with good timers)
- Other hints that packet were dropped

A bad timer algorithm

T(n) = measured RTT of this packet

mean:

```
A(n) = b*A(n-1) + (1 – b)*T(n)

Timeout(n) = 2*A(n)
```

Is twice the mean what we really want?

- No: want outliers
- 2A(n) a poor estimate of outliers
- Idea: measure deviation from mean

Better timer [Jacobson]

T(n) = measured RTT of this packet

mean:
deviation:

```
A(n) = b*A(n-1) + (1 – b)*T(n)
D(n) = b*D(n-1) + (1 – b)*(T(n) – A(n))
Timeout(n) = A(n) + 4D(n)
```

Questions:

- Measure T(n) only for original transmissions. Why?
- Double Timeout after a timeout happens. Why?
- Is deviation what we really want? Really?

Better timer [Jacobson]

Is deviation what we REALLY want? Really?

[SNL]

Better still…

What do we REALLY want?

- Estimate whether Pr[packet lost] is high
- Is timing the only way?

Another way: Duplicate ACKs

- Receiver sends an ACK whenever a packet arrives
- ACK has seq. # of last consecutively received packet
- Duplicate ACKs suggest missing packet (assumptions?)
- Modern TCPs: Fast Retransmit after 3 dup-ACKs

Does this eliminate need for timers?

- No: What if we get no packets from receiver?
- But, makes them less important

What should the receiver ACK?

ACK every packet, giving its sequence number

Use negative ACKs (NACKs), indicating which packet did not arrive

Use cumulative ACK, where an ACK for number n implies ACKS for all $k < n$

Use selective ACKs (SACKs), indicating those that did and did not arrive, even if not in order

Congestion

TCP congestion control

Can the network handle the rate of data?

Determined end-to-end, but TCP is making guesses about the state of the network

Two papers:

- Good science vs great engineering

Dangers of increasing load

Knee – point after which

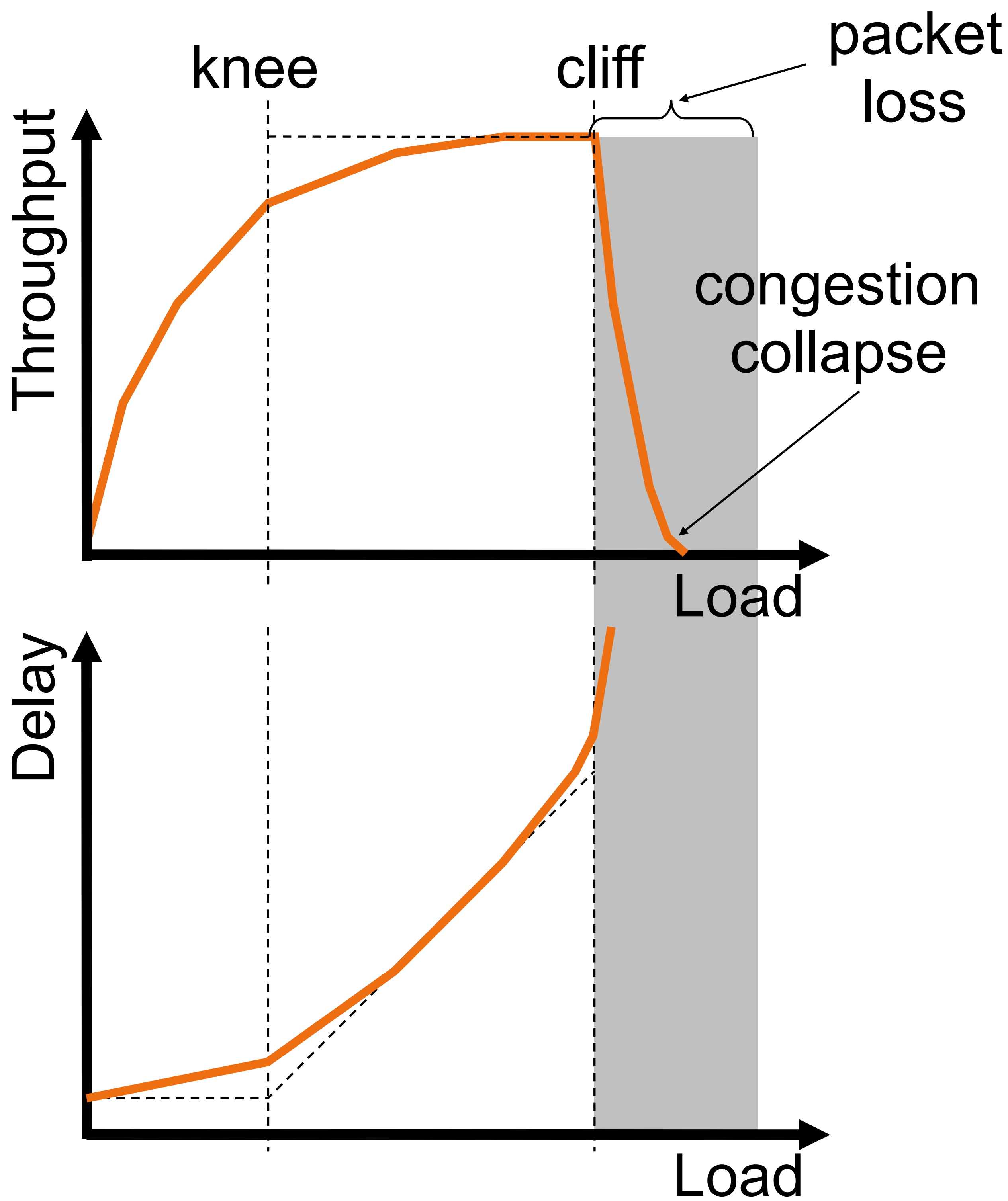
- Throughput increases very slowly
- Delay increases quickly

Cliff – point after which

- Throughput starts to decrease very fast to zero (congestion collapse)
- Delay approaches infinity

In an M/M/1 queue

- Delay = 1/(1 – utilization)



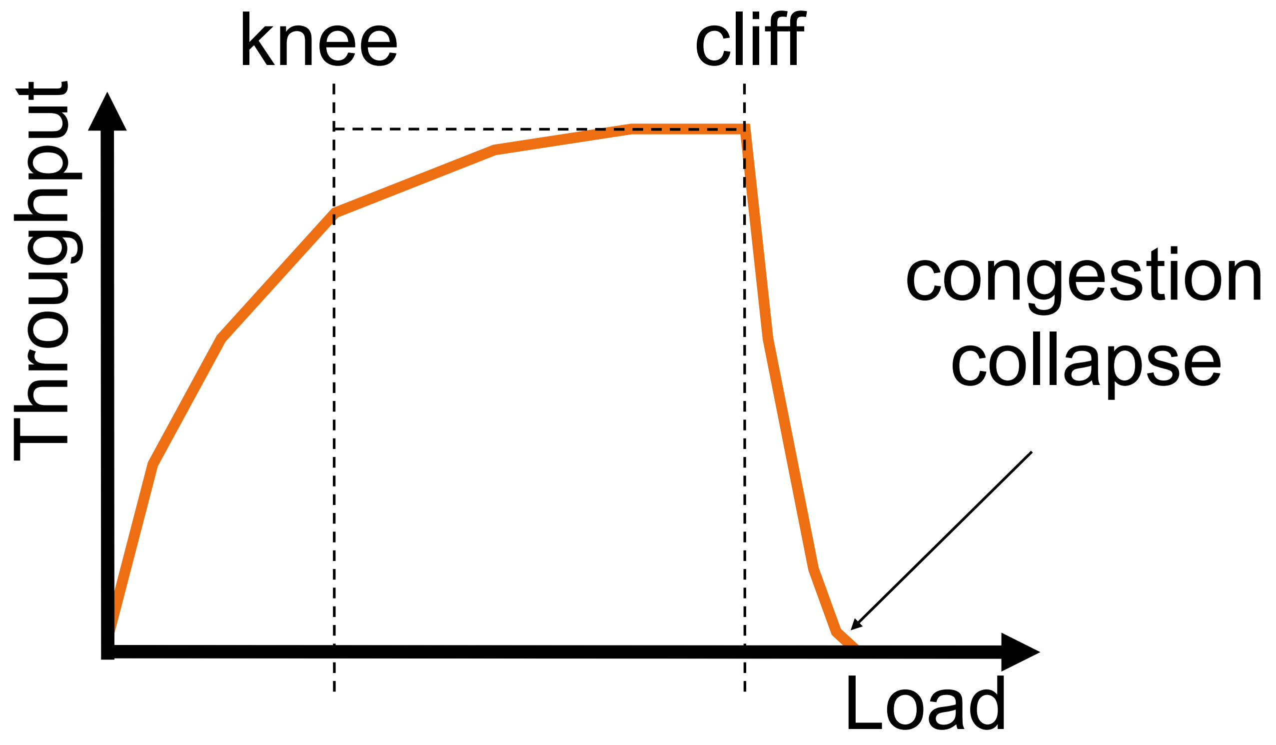
Cong. control vs. cong. avoidance

Congestion control goal

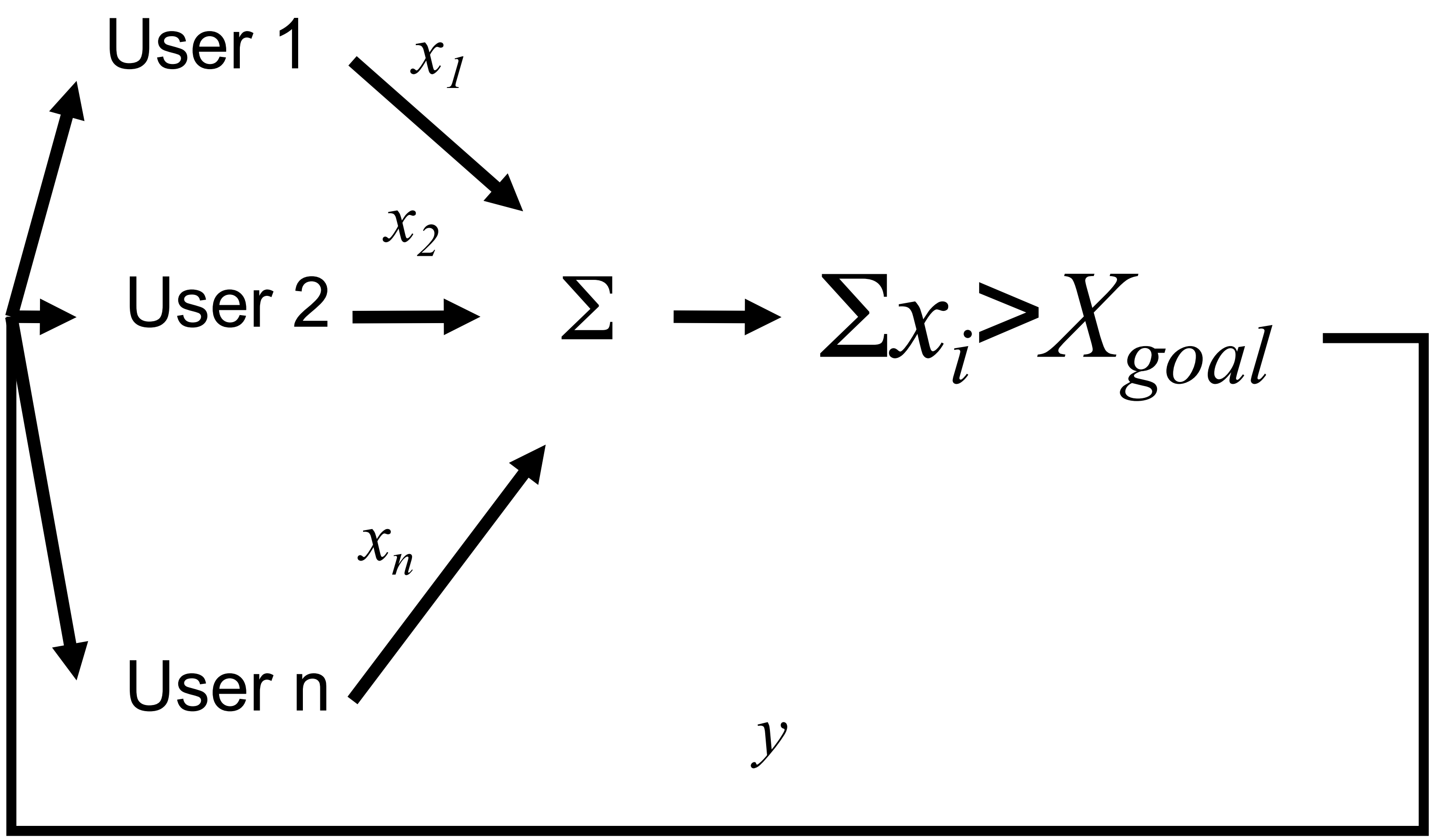
- Stay left of cliff

Congestion avoidance goal

- Stay left of knee



Control system model [CJ89]



Simple, yet powerful model

Explicit binary signal of congestion

Possible choices

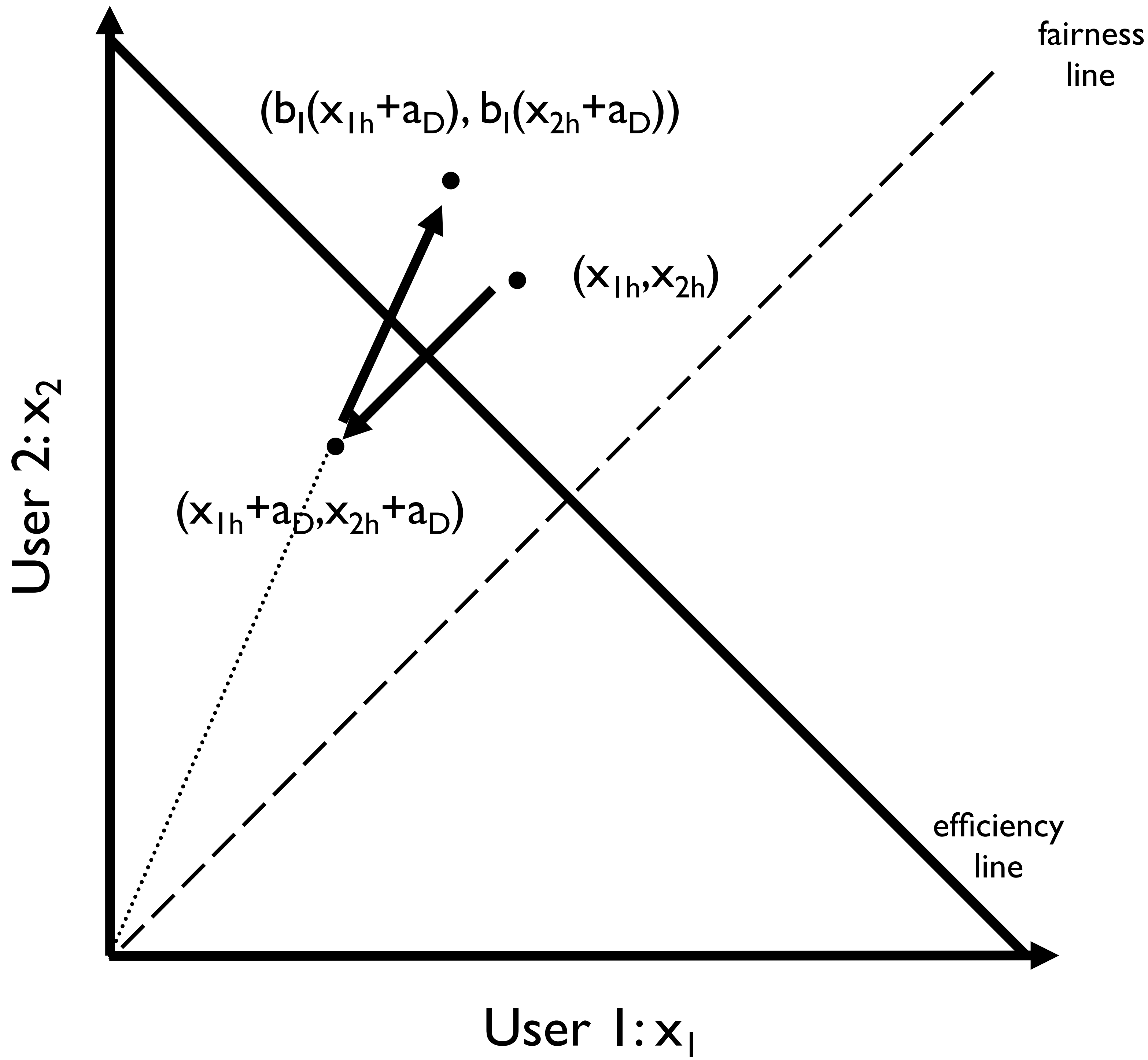
$$x_i(t+1) = \begin{cases} a_I + b_I x_i(t) & increase \\ a_D + b_D x_i(t) & decrease \end{cases}$$

- Multiplicative increase, additive decrease
  - $a_I=0,\ b_I>1,\ a_D<0,\ b_D=1$
- Additive increase, additive decrease
  - $a_I>0,\ b_I=1,\ a_D<0,\ b_D=1$
- Multiplicative increase, multiplicative decrease
  - $a_I=0,\ b_I>1,\ a_D=0,\ 0<b_D<1$
- Additive increase, multiplicative decrease
  - $a_I>0,\ b_I=1,\ a_D=0,\ 0<b_D<1$

Which should we pick?

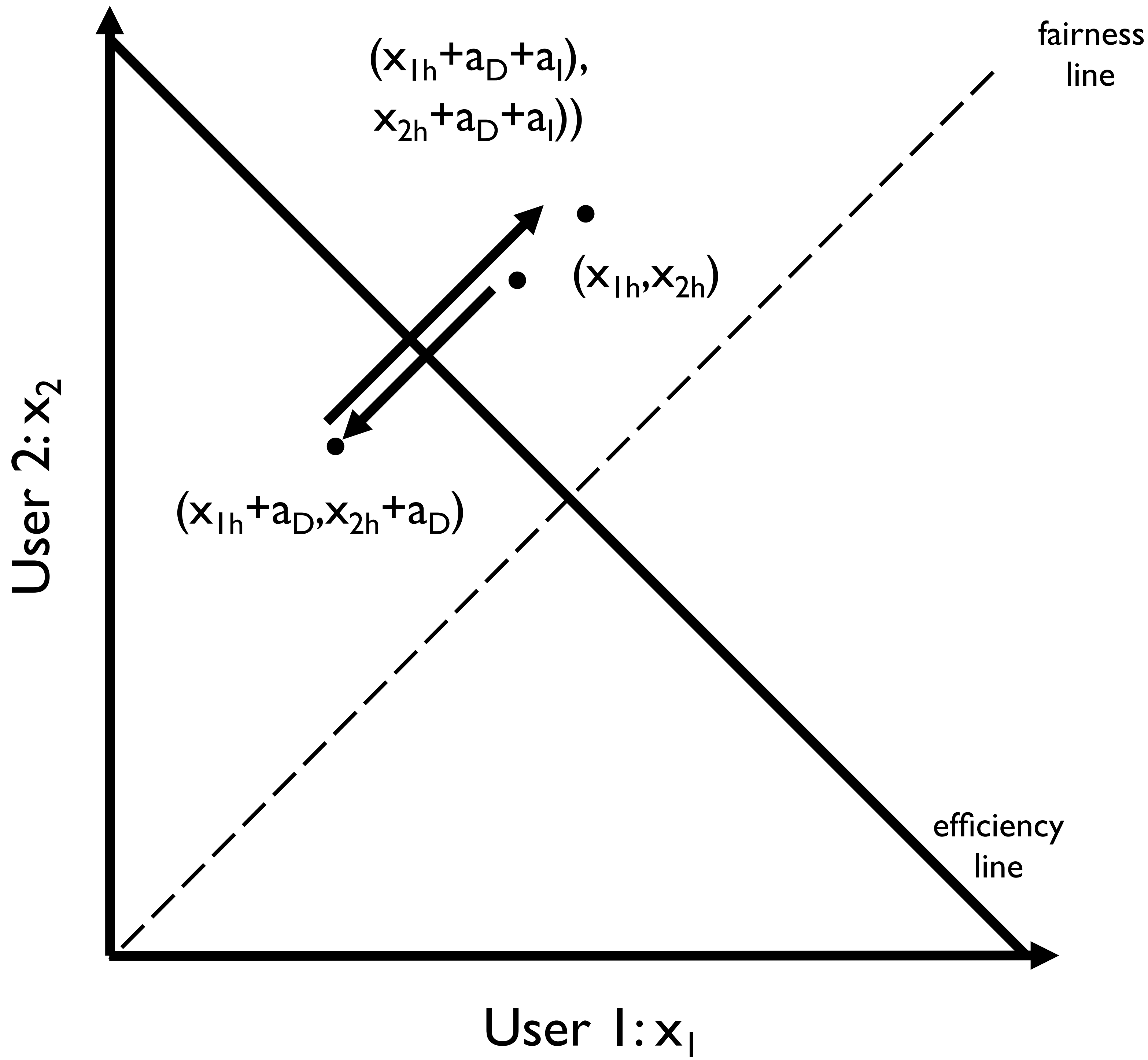
Mult. increase, additive decrease

- Does not converge to fairness
- (Additive decrease worsens fairness)



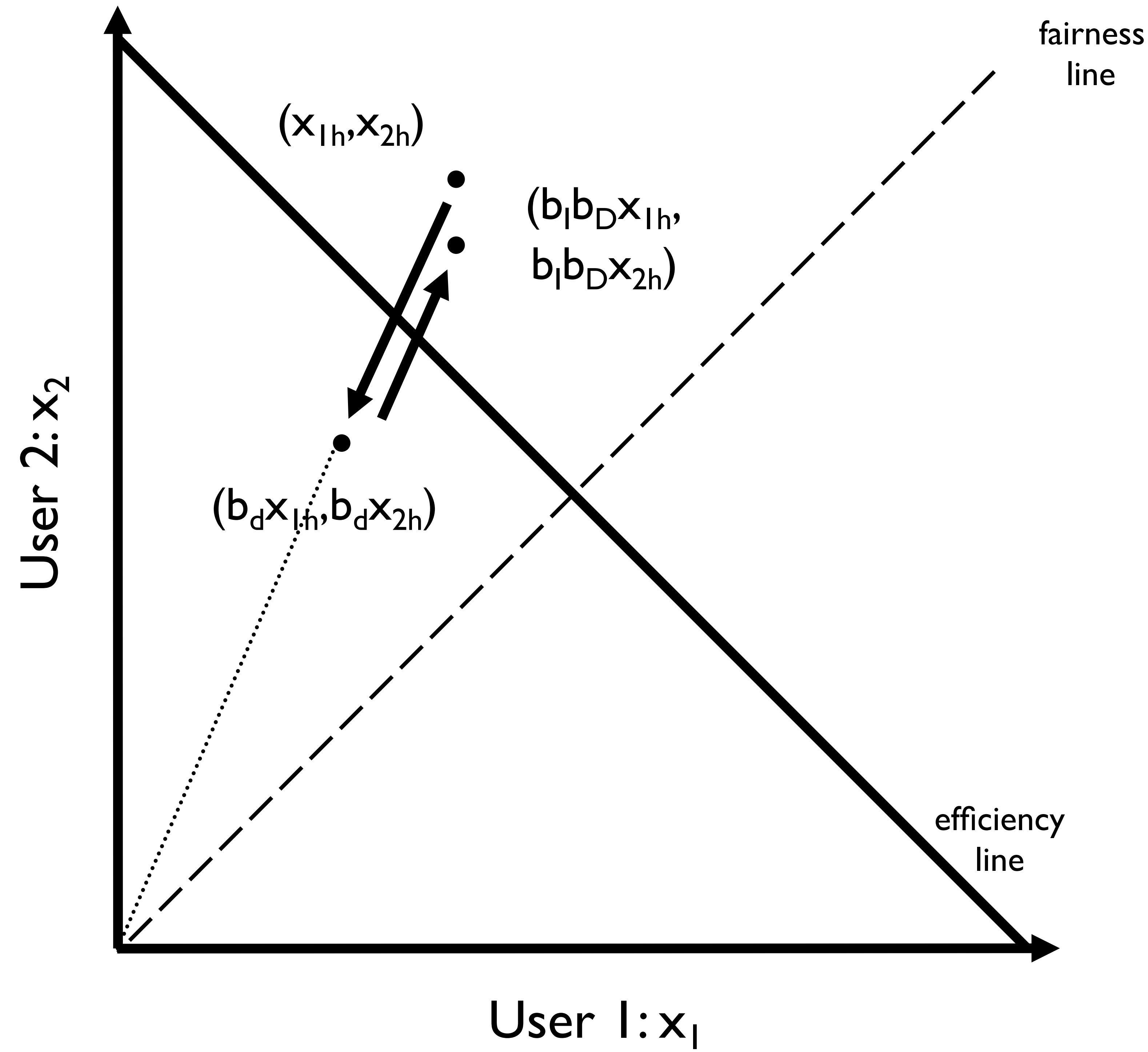
Additive increase, add. decrease

- Reaches stable cycle, but does not converge to fairness



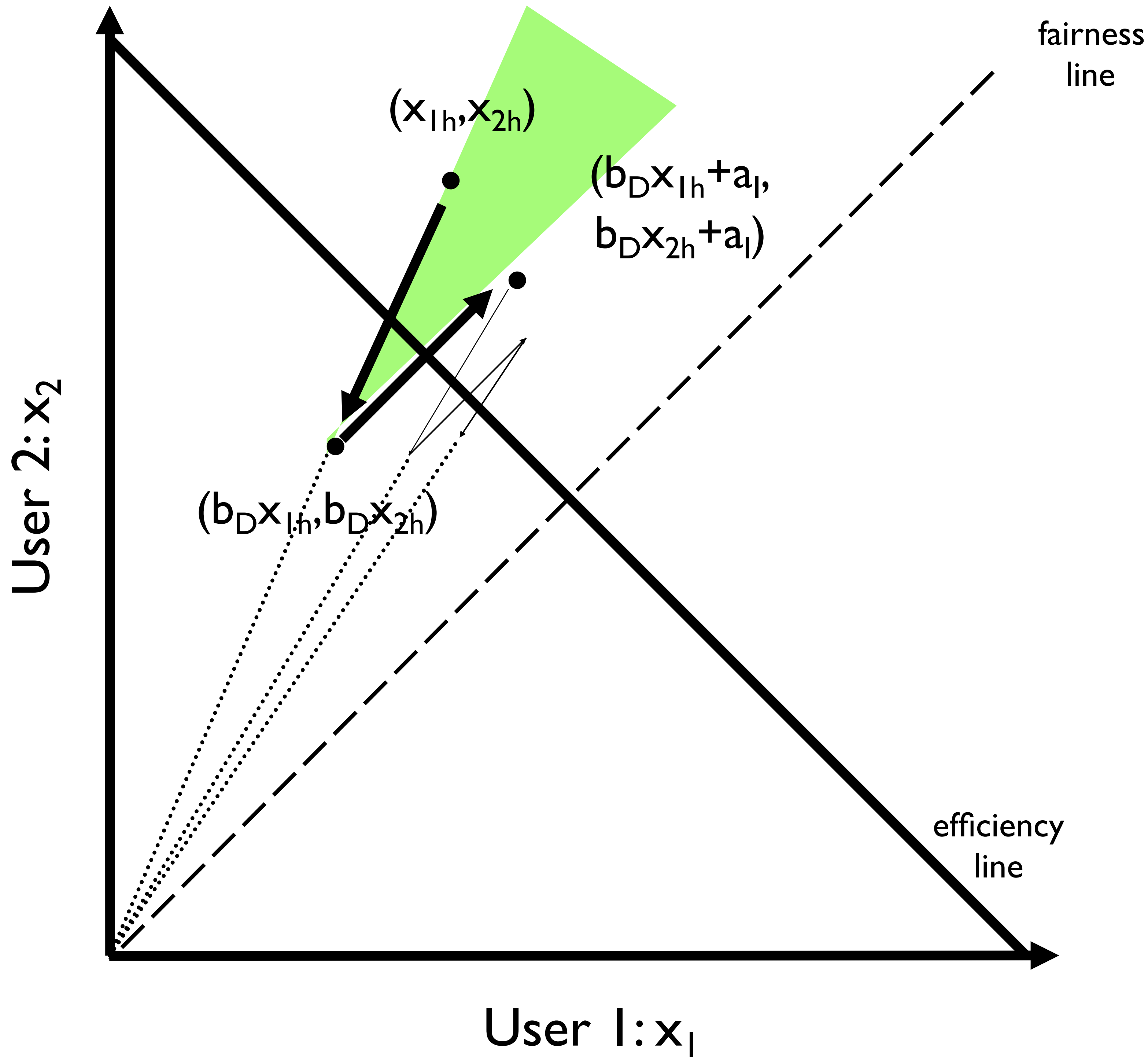
Mult. increase, mult. decrease

- Converges to stable cycle, but is not fair



Additive increase, mult. decrease

- Converges to stable and fair cycle



Modeling

Critical to understanding complex systems

- [CJ89] model relevant after nearly 30 years, 10^6 increase in bandwidth, 1000x increase in number of users

Criteria for good models

- Two conflicting goals: reality and simplicity
- Realistic, complex model → too hard to understand, too limited in applicability
- Unrealistic, simple model → can be misleading

- Where does this model fit?

Putting the pieces together

TCP congestion control

[CJ89] provides theoretical basis for basic congestion avoidance mechanism

Must turn this into real protocol

TCP congestion control

Maintains three variables:

- cwnd: congestion window
- flow_win: flow window; receiver advertised window
- ssthresh: threshold size (used to update cwnd)

For sending, use: win = min(flow_win, cwnd)

TCP: slow start

Goal: reach knee quickly

Upon starting (or restarting):

- Set cwnd = 1
- Each time a segment is acknowledged, increment cwnd by one (cwnd++).

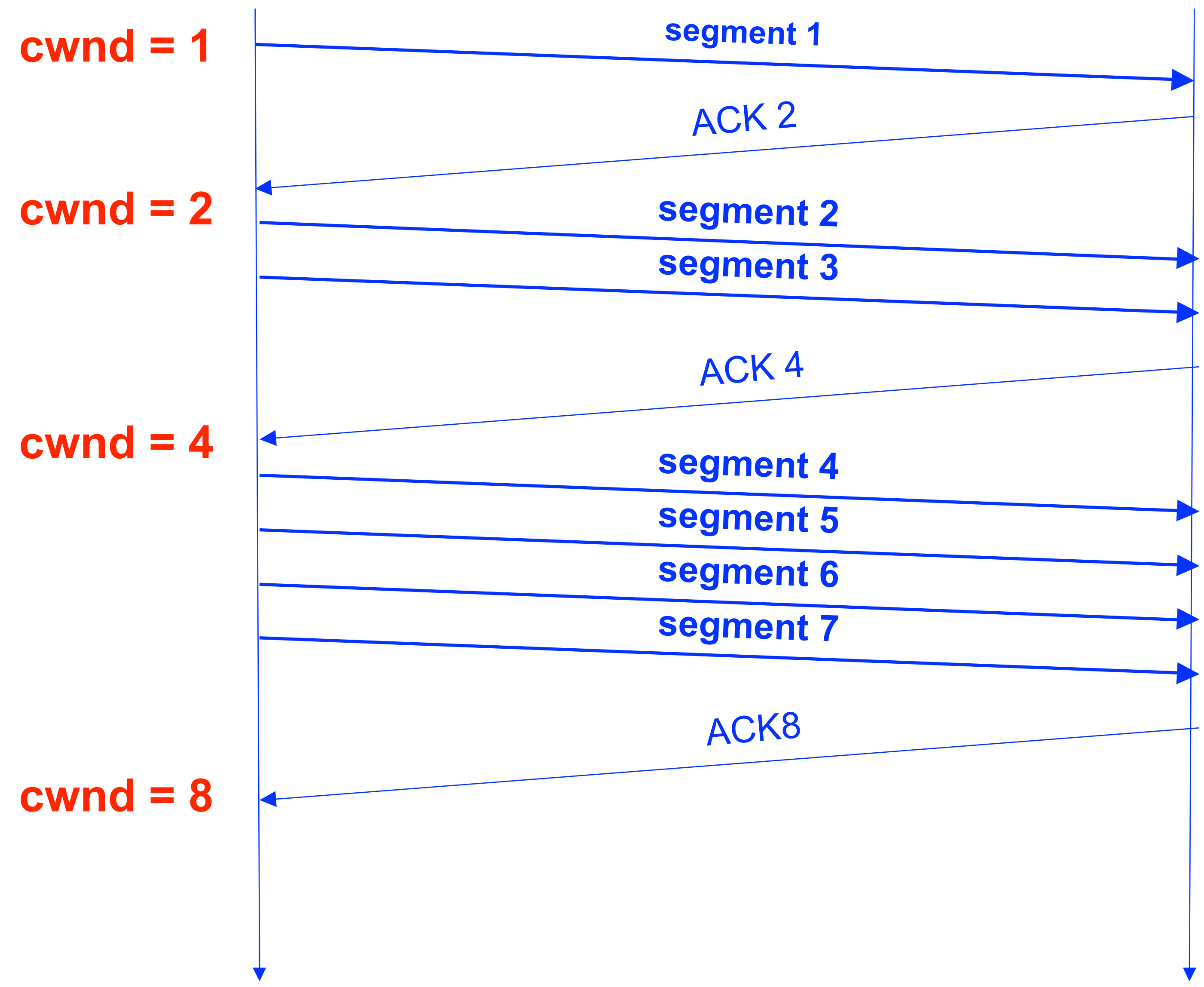
Starts slow but accelerates quickly

- cwnd increases exponentially

Slow start example

The congestion window size grows very rapidly

TCP slows down the increase of cwnd when cwnd ≥ ssthresh



Congestion avoidance

Slow down "Slow Start"

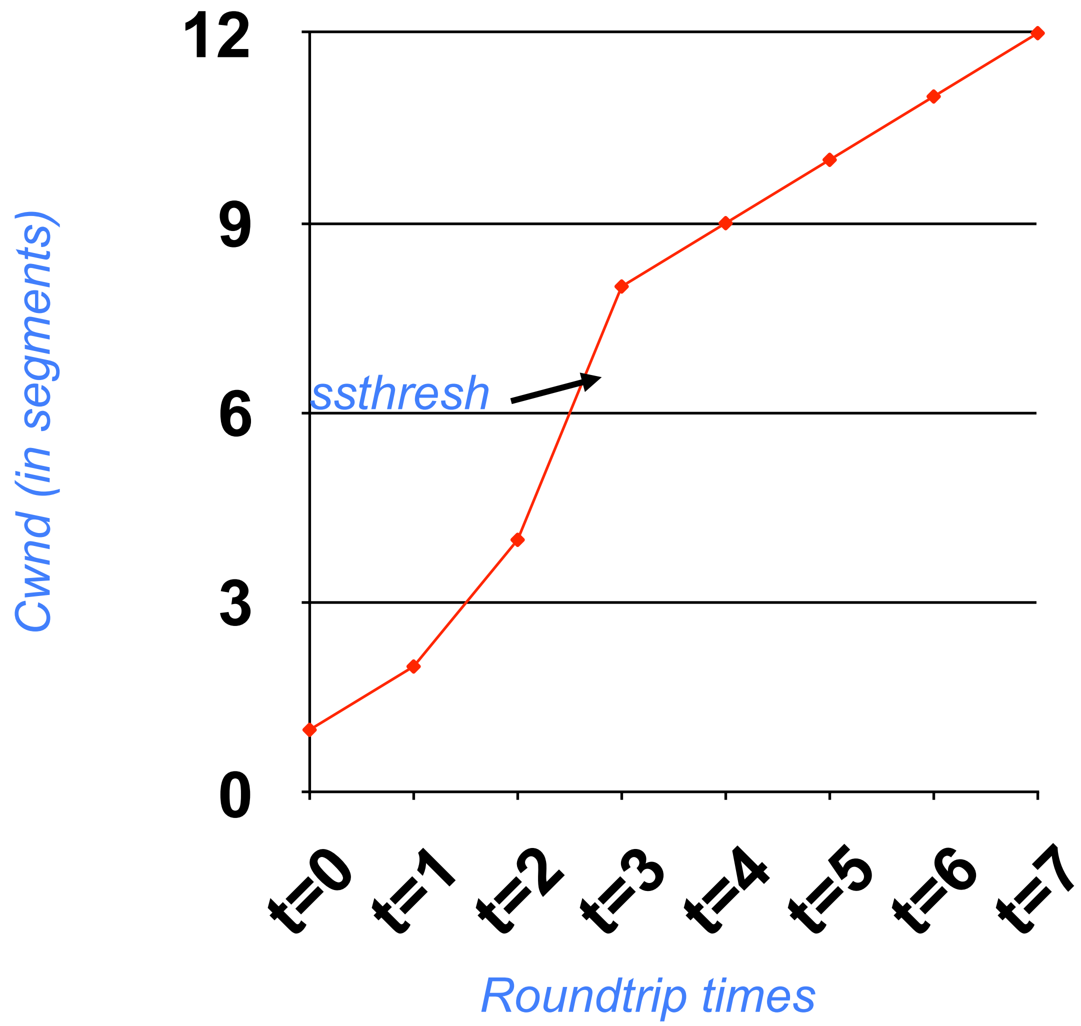
ssthresh variable is lower-bound guess about location of knee

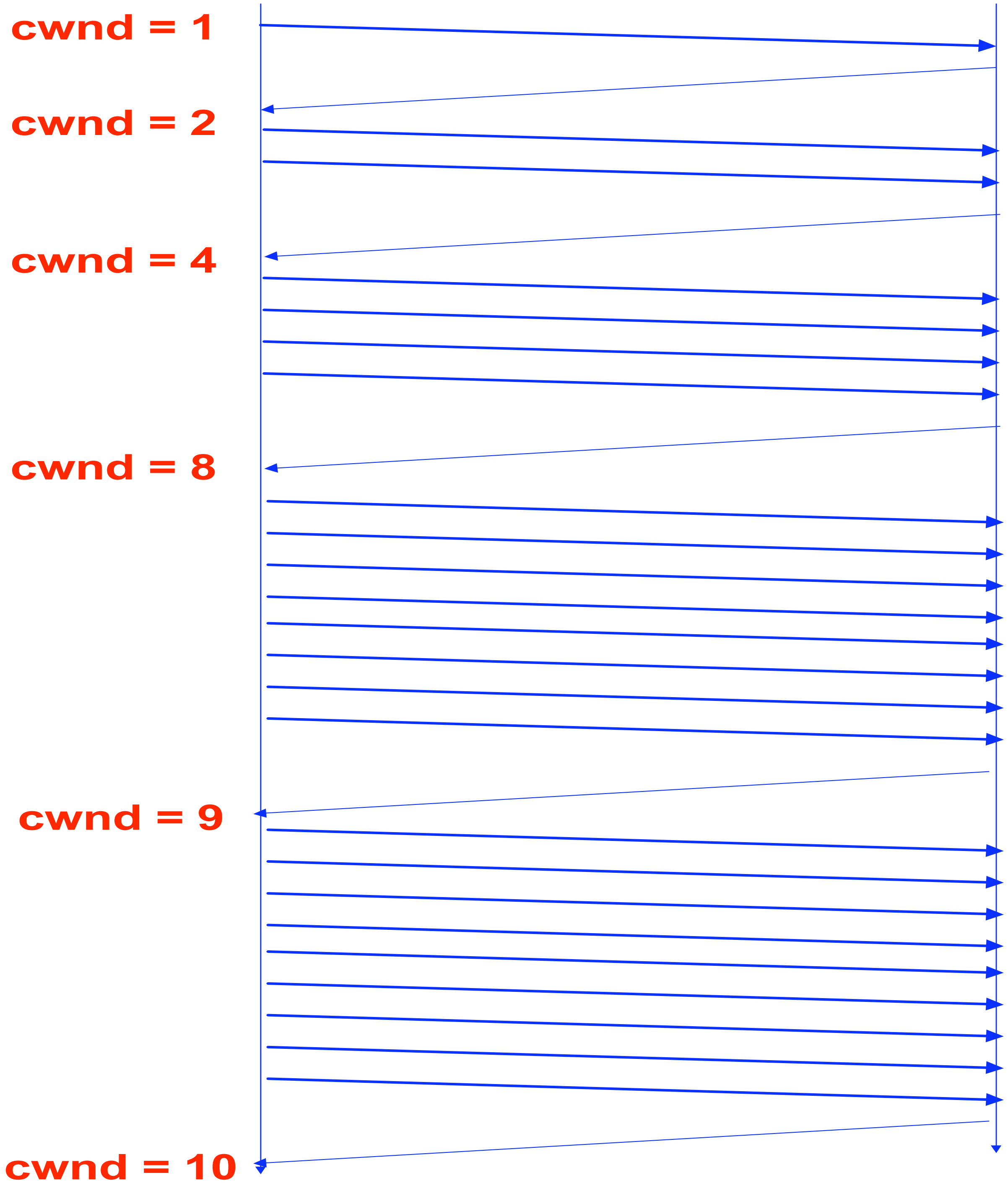
If cwnd > ssthresh then
    each time a segment is acknowledged,
    increment cwnd by 1/cwnd (cwnd += 1/cwnd).

Result: cwnd is increased by one after a full window of segments have been acknowledged

Slow start/cong. avoidance example

- Assume that *ssthresh = 8*





All together: TCP pseudocode

Initially:

```
cwnd = 1;
ssthresh = infinite;
```

New ack received:

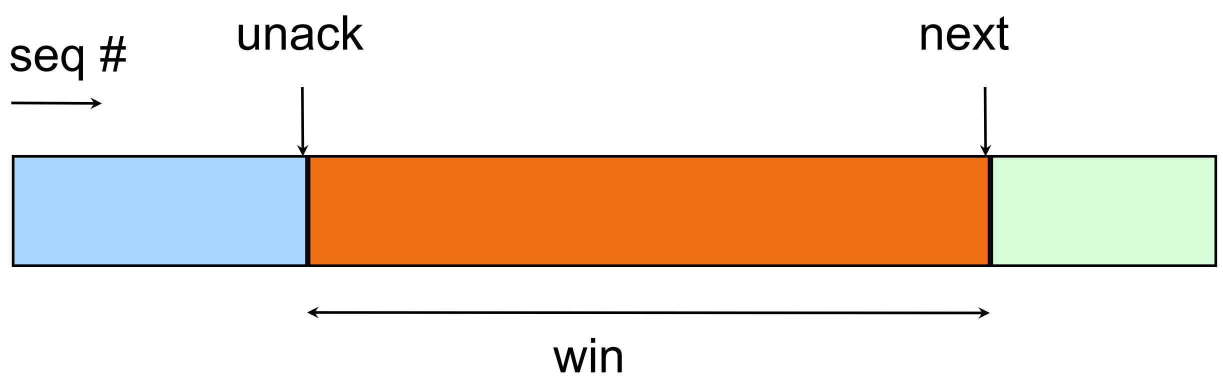
```
if (cwnd < ssthresh)
    /* Slow Start*/
    cwnd = cwnd + 1;
else
    /* Additive increase */
    cwnd = cwnd + 1/cwnd;
```

Timeout:

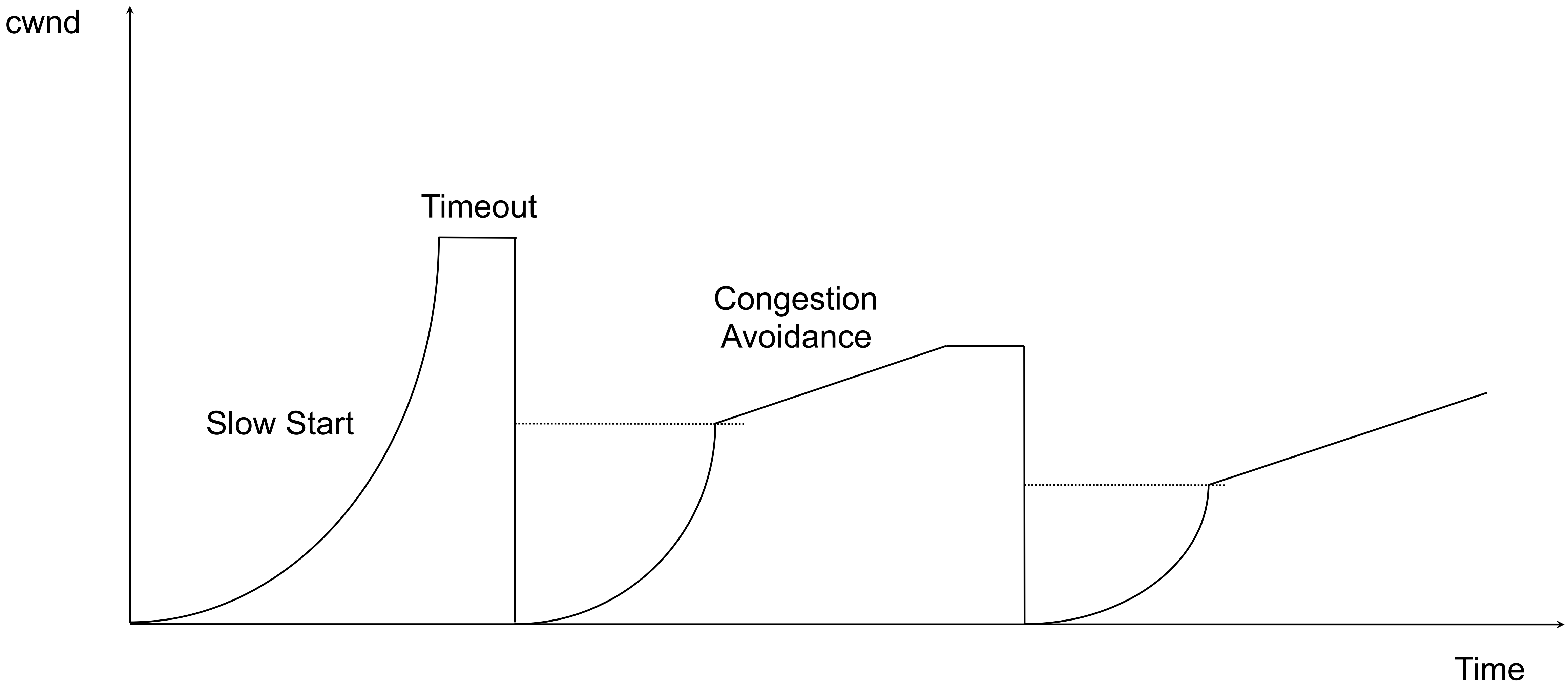
```
/* Multiplicative decrease */
ssthresh = cwnd/2;
cwnd = 1;
```

```
while (next < unack + win)
    transmit next packet;

where   win = min(cwnd, flow_win);
```



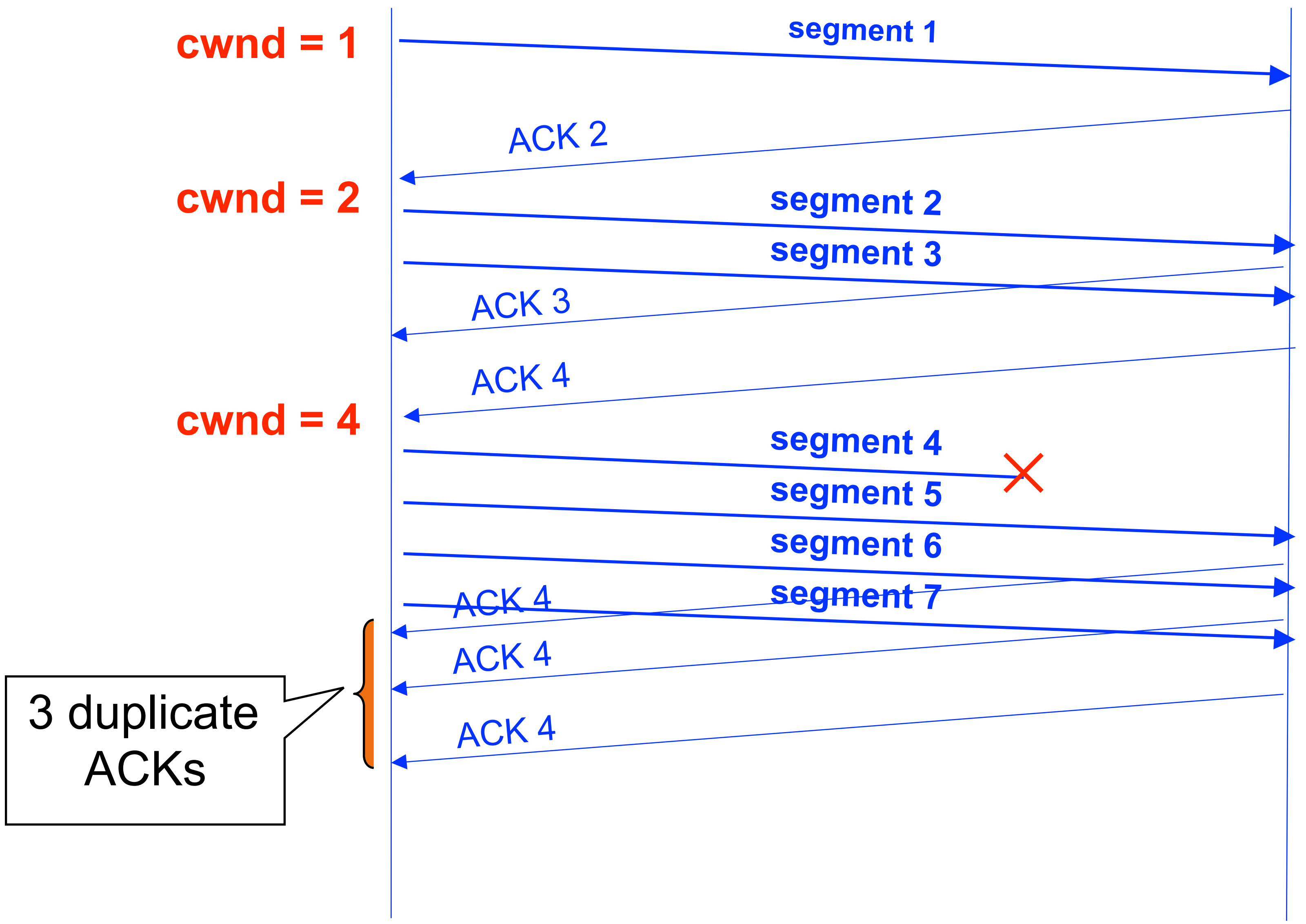
The big picture (so far)



Fast retransmit

Resend a segment after 3 duplicate ACKs

Avoids waiting for timeout to discover loss



Fast recovery

After a fast-retransmit set *cwnd* to *ssthresh*/2

- i.e., don't reset *cwnd* to 1

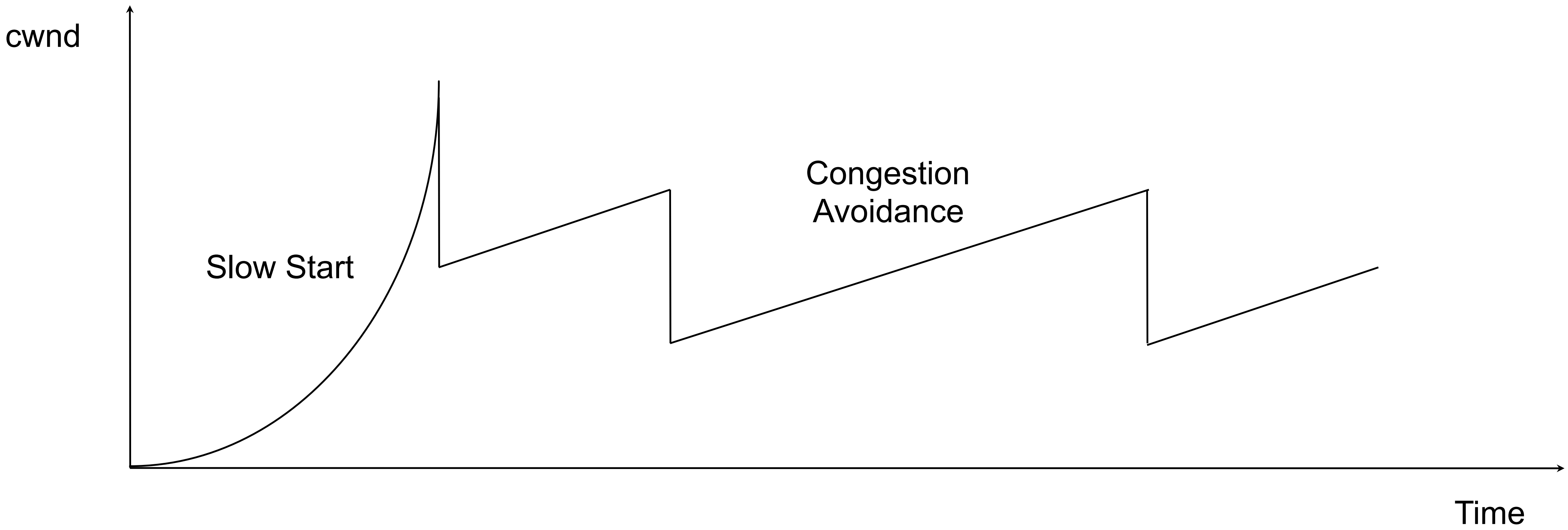
But when RTO expires still do *cwnd* = 1

Fast Retransmit and Fast Recovery

- Implemented by TCP Reno & other variants

Lesson: avoid RTOs at all costs!

Picture with fast retransmit & recov.



Retransmit after 3 duplicated acks

- prevent expensive timeouts

No need to slow start again

At steady state, cwnd oscillates around the optimal window size

Discussion

Engineering vs. Science in CC

Great engineering by Jacobson and others built useful protocol

- TCP Reno, etc.

Good science by Chiu, Jain and others

- Basis for understanding why it works so well

Limitations of TCP CC

In what ways is TCP congestion control broken or suboptimal?

A partial list...

Efficiency

Tends to fill queues

- creates latency and loss

Slow to converge

- for short flows or links with high bandwidth•delay product

Loss ≠ congestion

Often does not fully utilize bandwidth

A partial list...

Fairness

Unfair to large-RTT flows (less throughput)

Unfair to short flows if *ssthresh* starts small

Equal rates isn't necessarily "fair" or best

Vulnerable to selfish & malicious behavior

- TCP assumes everyone is running TCP!

Announcements

Assignment 1 was due today

Mon: Congestion control in the network (2 papers)

Wed: Project proposals due