Project 2: Traceroute

- Project 2 (Traceroute) is out
- Due Friday, March 22nd at 11:59 PM PST
- Project 2 is hard(er)
  - **Start Early**
  - Don’t expect a perfect score
- Ethan Jackson is the lead TA.
- See the website for his office hours.

TCP Congestion Control (contd.)

CS 168

http://cs168.io

Sylvia Ratnasamy

TCP Congestion Control (contd.)

CS 168

http://cs168.io

Sylvia Ratnasamy

Today

- The TCP state machine
- Modeling TCP throughput
- Critiquing TCP
- Router-assisted CC (briefly)

TCP Implementation

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- **State at sender**
  - CWND (initialized to a 1 MSS)
  - SSTHRESH (initialized to a large constant)
  - dupACKcount (initialized to zero, as before)
  - Timer (as before)

TCP Implementation

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- **Events at sender**
  - ACK (for new data)
  - dupACK (duplicate ACK for old data)
  - Timeout

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  - CWND (initialized to a 1 MSS)
  - SSTHRESH (initialized to a large constant)
  - dupACKcount (initialized to zero, as before)
  - Timer (as before)
- **Events at sender**
  - ACK (for new data)
  - dupACK (duplicate ACK for old data)
  - Timeout
- What about receiver?
  - Just send ACKs like before

Event: ACK (new data)

- If in slow start
  - CWND += 1 (MSS)

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>   *CWND = 2xCWND*

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"Congestion Avoidance" phase (additive increase)

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- If in slow start
  - CWND += 1 (MSS)

Slow start phase

- Else
  - CWND = CWND + 1/CWND

"Congestion Avoidance" phase (additive increase)

- Plus the usual ...
  - Reset timer, dupACKcount
  - Send new data packets (if CWND allows)

Event: TimeOut

- On Timeout
  - SSTHRESH ← CWND/2
  - CWND ← 1
  - And retransmit packet (as always)

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Remain in AIMD
after fast retransmission…

Any Questions?

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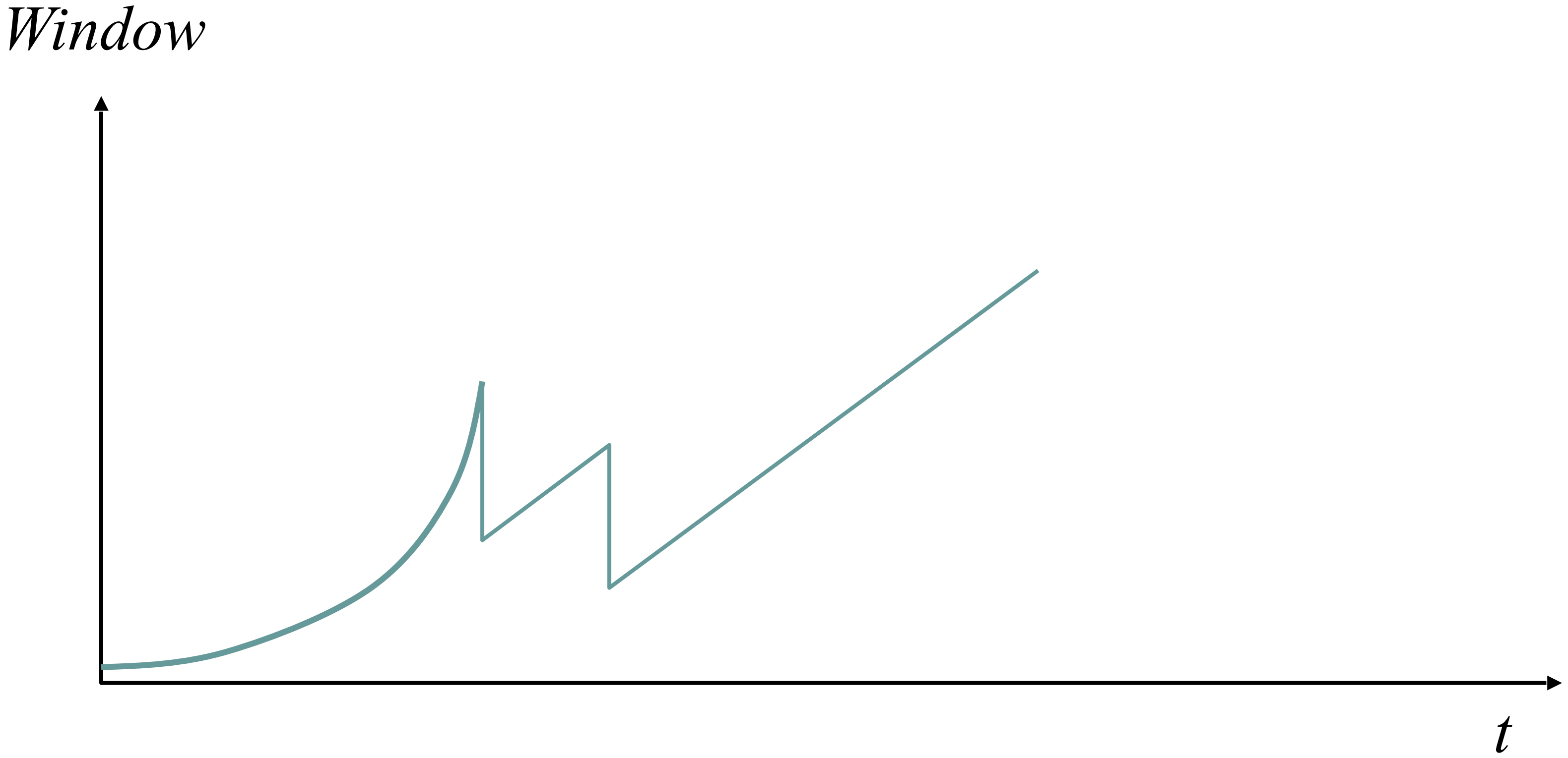
Time Diagram



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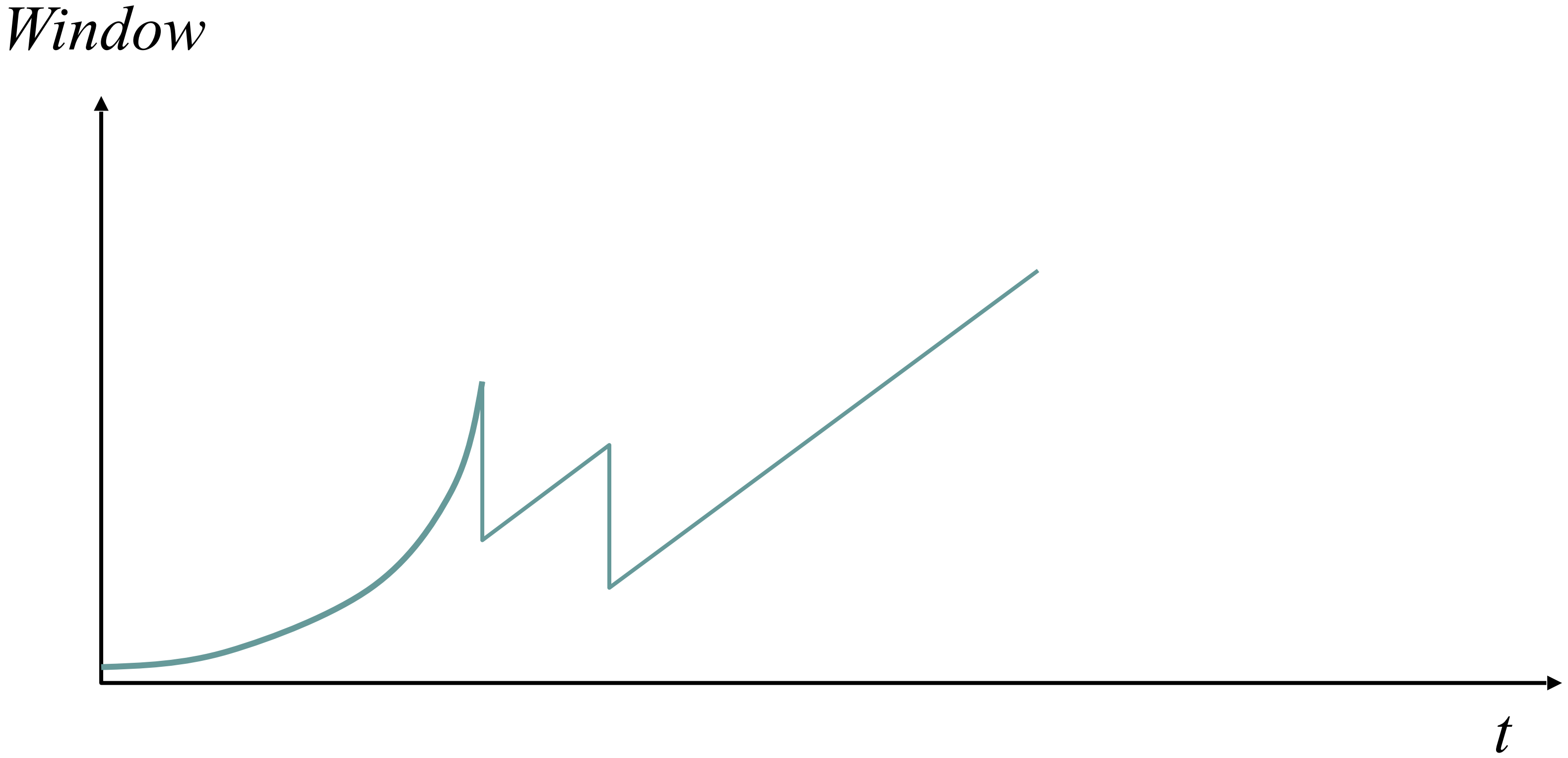

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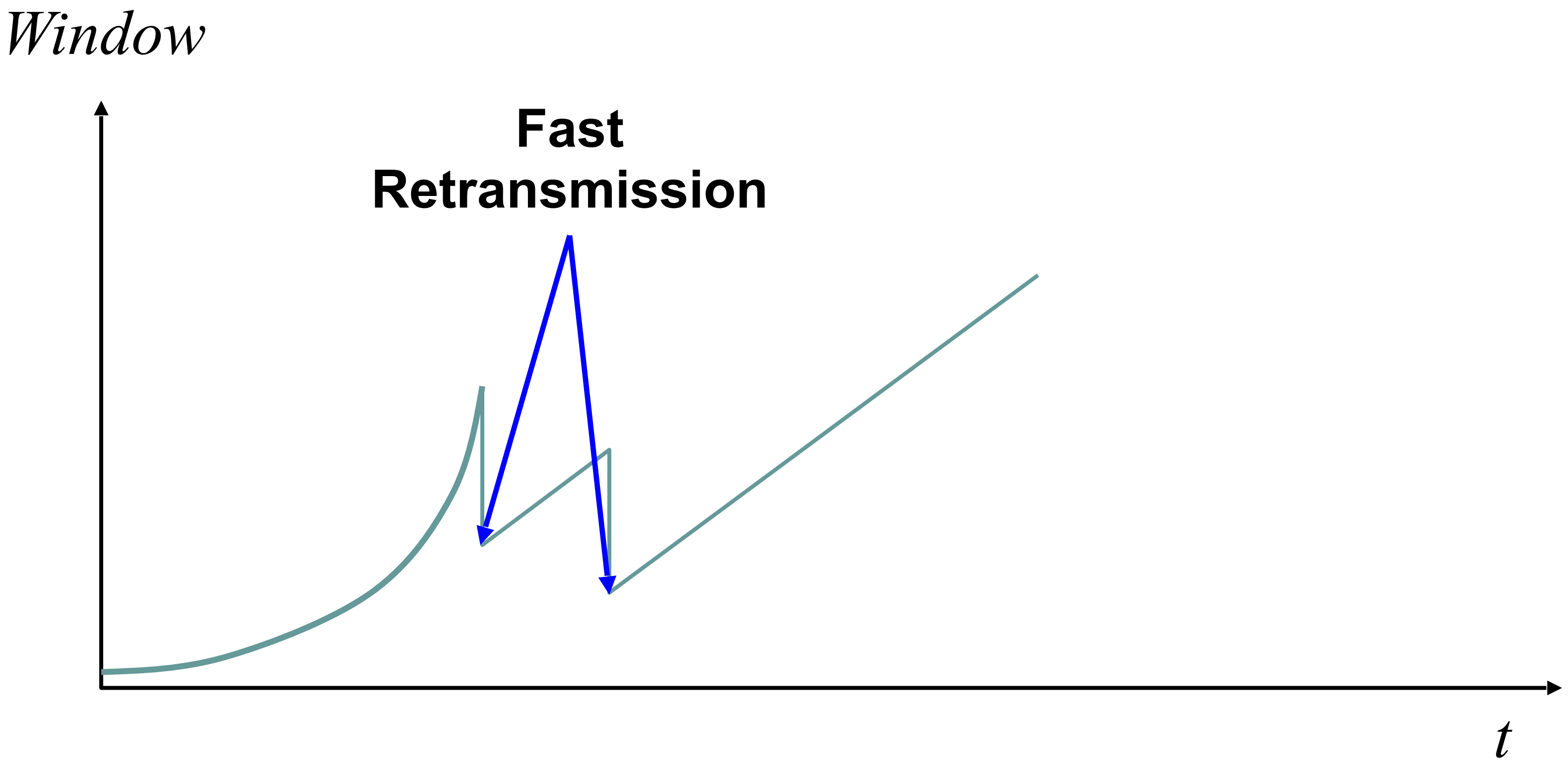

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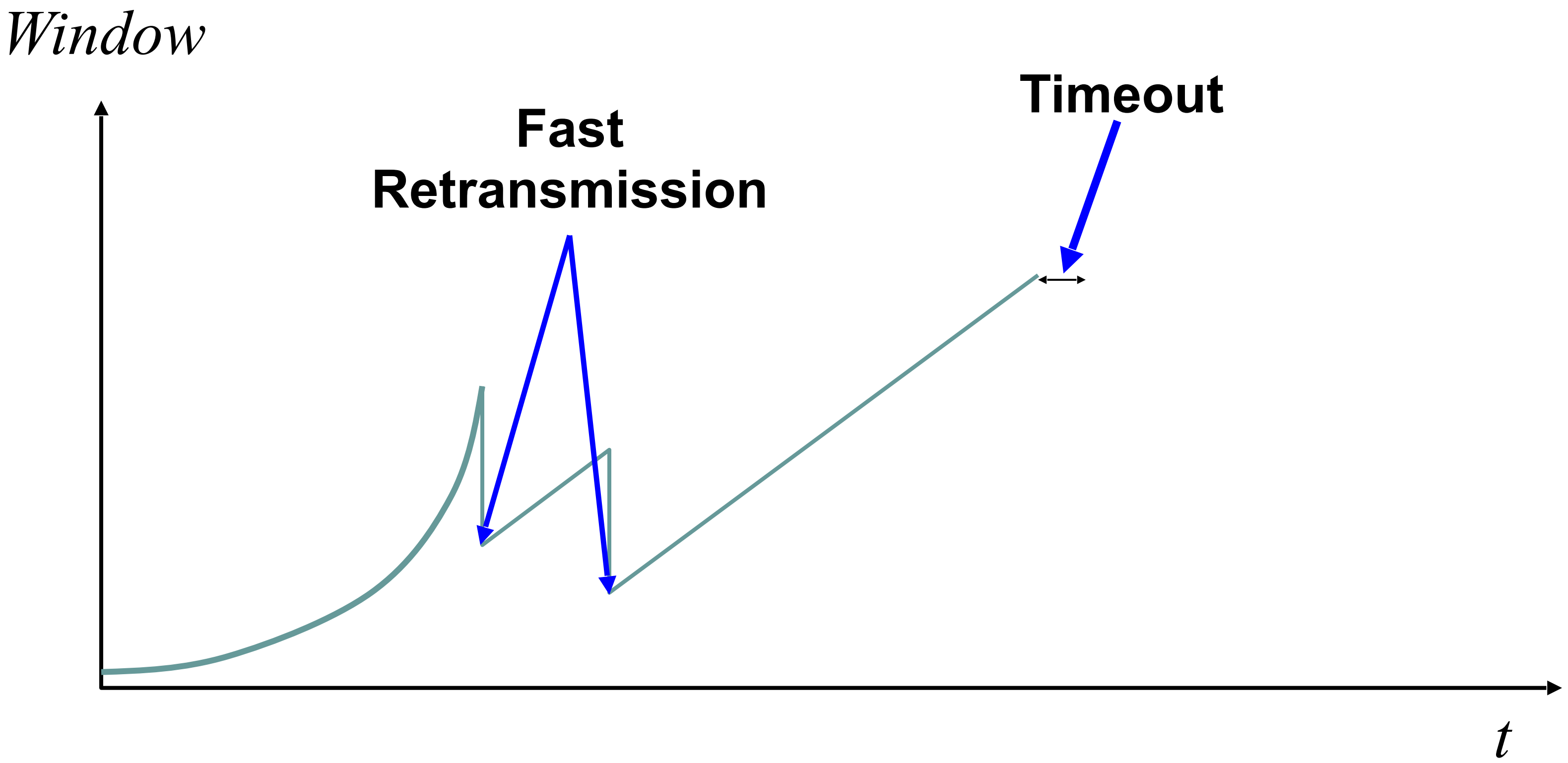

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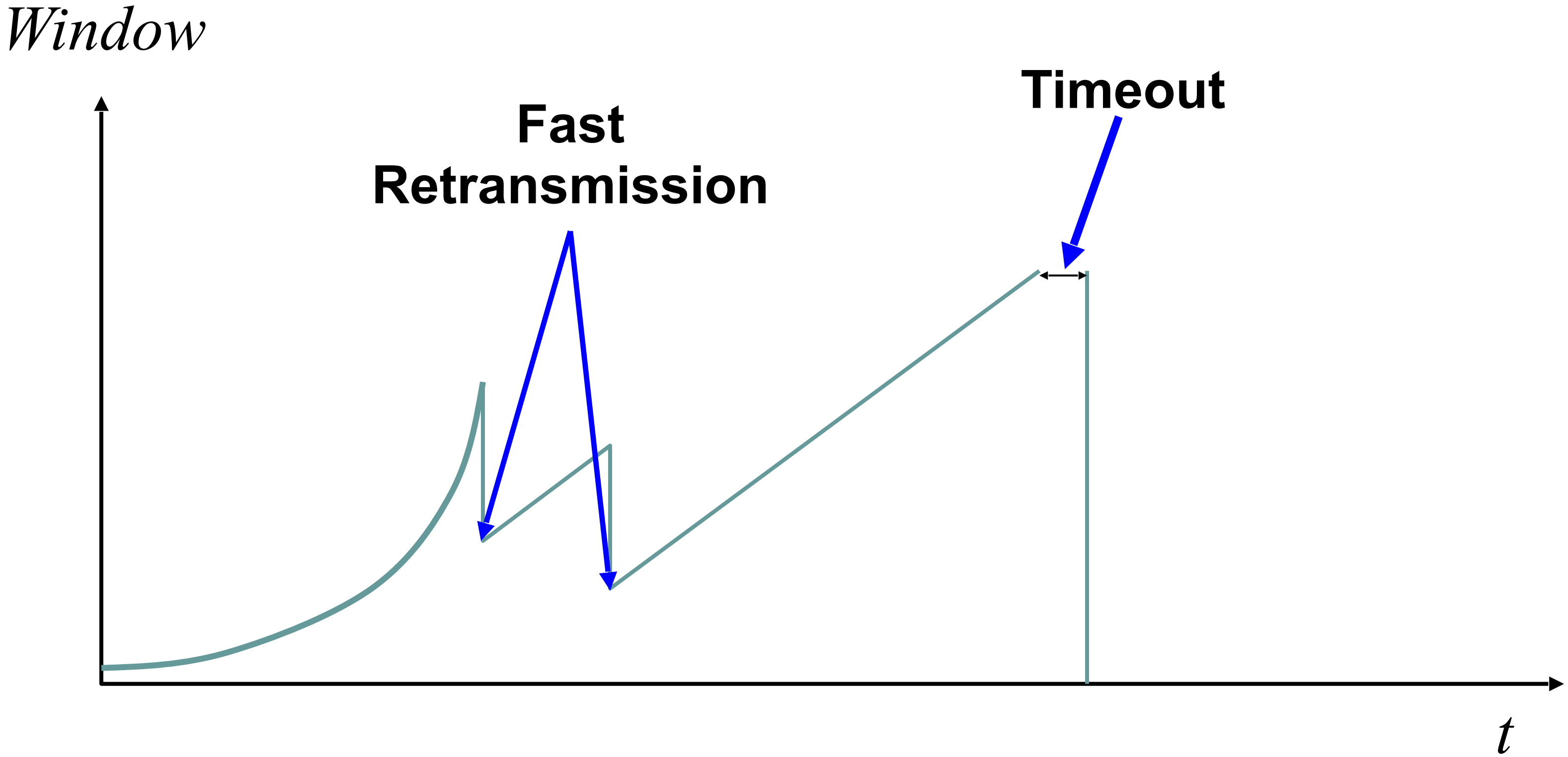

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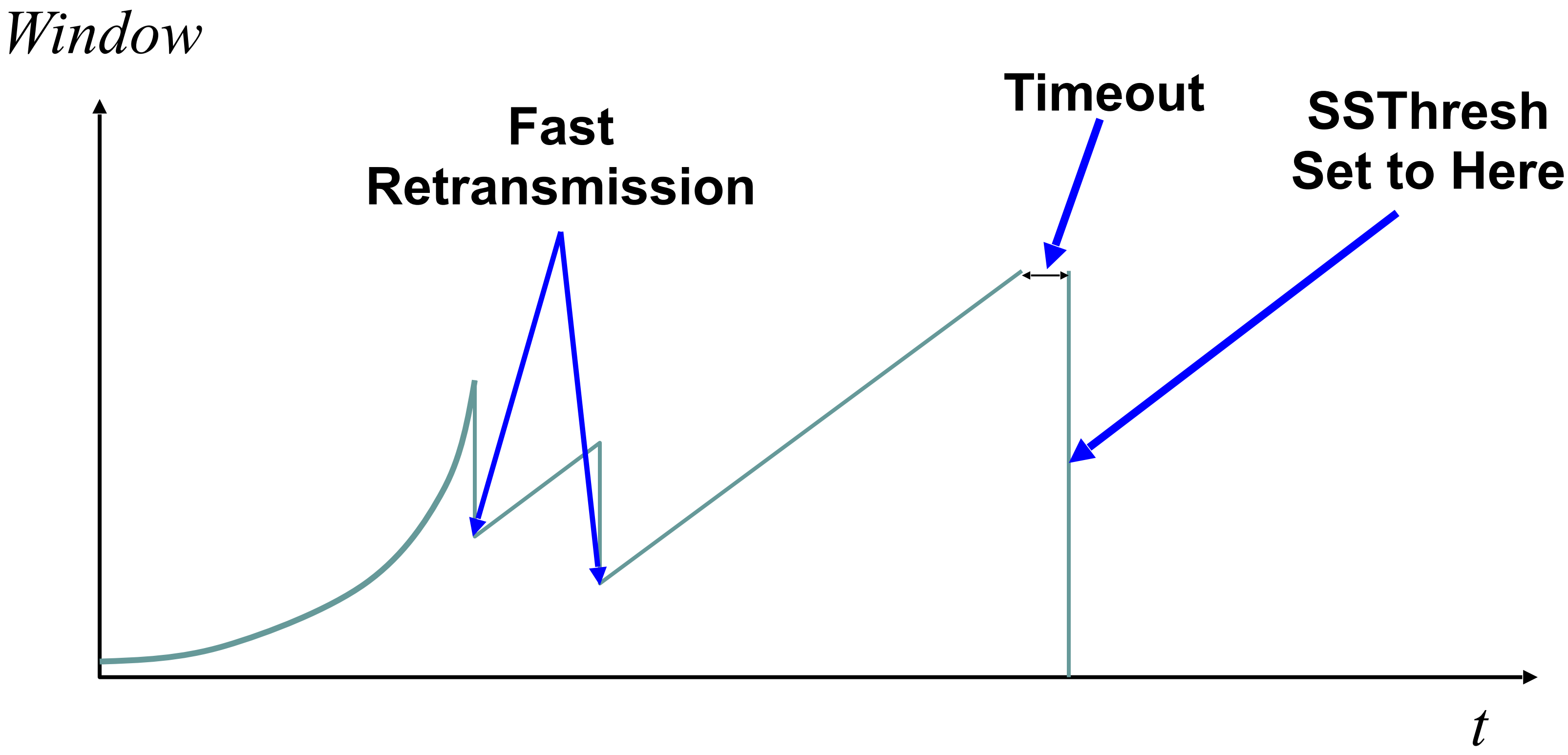

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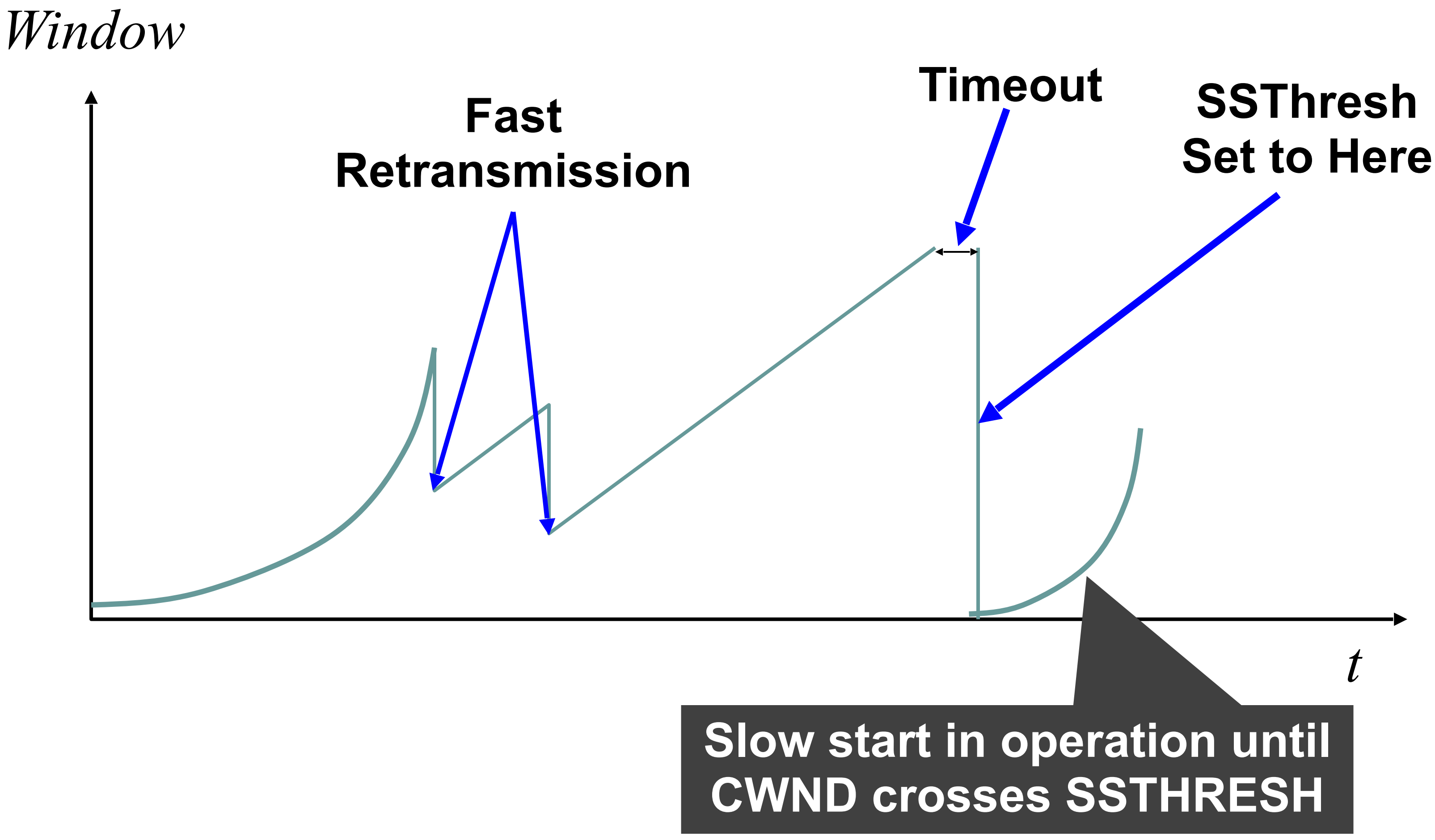

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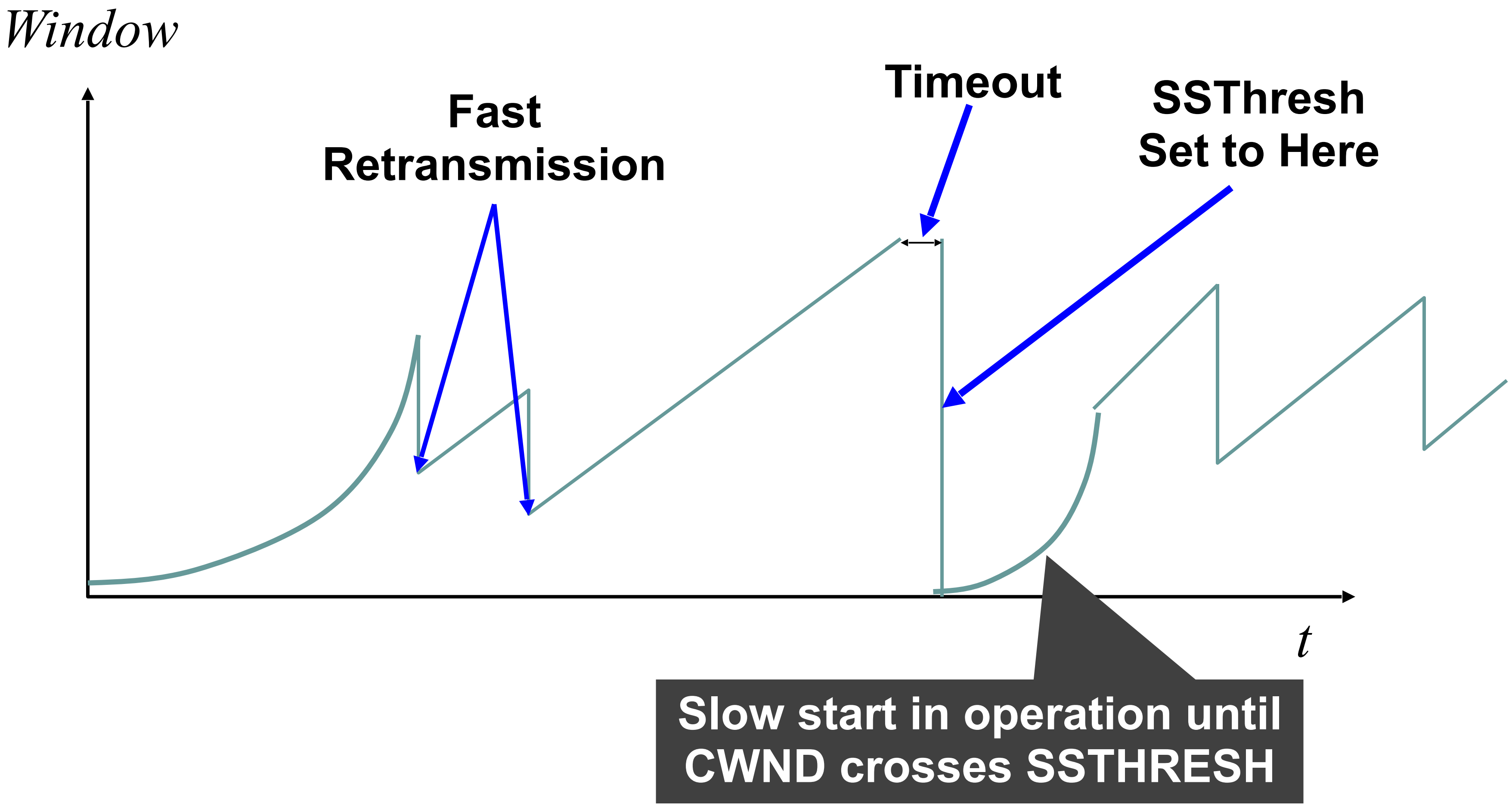

One Final Phase: Fast Recovery

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

One Final Phase: Fast Recovery

- The problem: congestion avoidance too slow in recovering from an isolated loss
- This last feature is an optimization to improve performance
  - Bit of a hack, but effective

Example

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- Again: counting packets, not bytes
  - If you want example in bytes, assume MSS=1000 and add three zeros to all sequence numbers

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  - If you want example in bytes, assume MSS=1000 and add three zeros to all sequence numbers
- 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
  - What ACKs do they generate and how does the sender respond?

Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

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Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)

Timeline (at sender)

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- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)
- ACK 101 (due to 103) cwnd=10 dupACK#2 (no xmit)

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- RETRANSMIT 101 ssthresh=5 cwnd= 5

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Note that you do not restart dupACK counter on same packet!

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- ACK 101 (due to 110) cwnd=5 (no xmit)
- ACK 111 (due to 101) ← only now can we transmit new packets

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- ACK 101 (due to 105) cwnd=5 (no xmit)
- ACK 101 (due to 106) cwnd=5 (no xmit)
- ACK 101 (due to 107) cwnd=5 (no xmit)
- ACK 101 (due to 108) cwnd=5 (no xmit)
- ACK 101 (due to 109) cwnd=5 (no xmit)
- ACK 101 (due to 110) cwnd=5 (no xmit)
- ACK 111 (due to 101) ← only now can we transmit new packets
- Plus no packets in flight so no additional ACKs for another RTT

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  - Have to wait a long time before sending again
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- How would you fix it?

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  - SSTHRESH = CWND/2
  - CWND = SSTHRESH + 3

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- While in fast recovery
  - CWND = CWND + 1 (MSS) for each additional duplicate ACK
  - This allows source to send an additional packet…
  - …to compensate for the packet that arrived (generating dupACK)

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  - SSTHRESH = CWND/2
  - CWND = SSTHRESH + 3
- While in fast recovery
  - CWND = CWND + 1 (MSS) for each additional duplicate ACK
  - This allows source to send an additional packet…
  - …to compensate for the packet that arrived (generating dupACK)
- Exit fast recovery after receiving new ACK
  - set CWND = SSTHRESH

Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1

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- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd= 8 (5+3)

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In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110 ✗ **101**

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd= 8 (5+3)
- ACK 101 (due to 105) cwnd= 9 (no xmit)

Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110 **101**

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 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)

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In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110 **101 111,**

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- REXMIT 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**)

Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110 **101 111, 112,**

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 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**)

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- 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**)

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In flight: 101✗, 102, 103, 104, 105, 106, 107, 108, 109, 110 **101 111, 112, ...**

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- 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**)

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In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110 **101 111, 112, …**

- ACK 101 (due to 102) cwnd=10 dupACK#1
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- 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

Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110 ✗ **101 111, 112, ...**

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 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 (and now sending 115)

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- ACK 101 (due to 105) cwnd= 9 (no xmit)
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- 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 (and now sending 115)
- ACK 112 (due to 111) cwnd = 5 + 1/5 ← back in congestion avoidance

Updated Event-Actions

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Event: ACK (new data)

- If in slow start
  - CWND += 1 (MSS)

Slow start phase

- If in fast recovery
  - CWND = SSTHRESH

Leaving Fast Recovery

- Else
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"Congestion Avoidance" phase (additive increase)

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Event: dupACK

- dupACKcount ++
- If dupACKcount = 3 /* fast retransmit */
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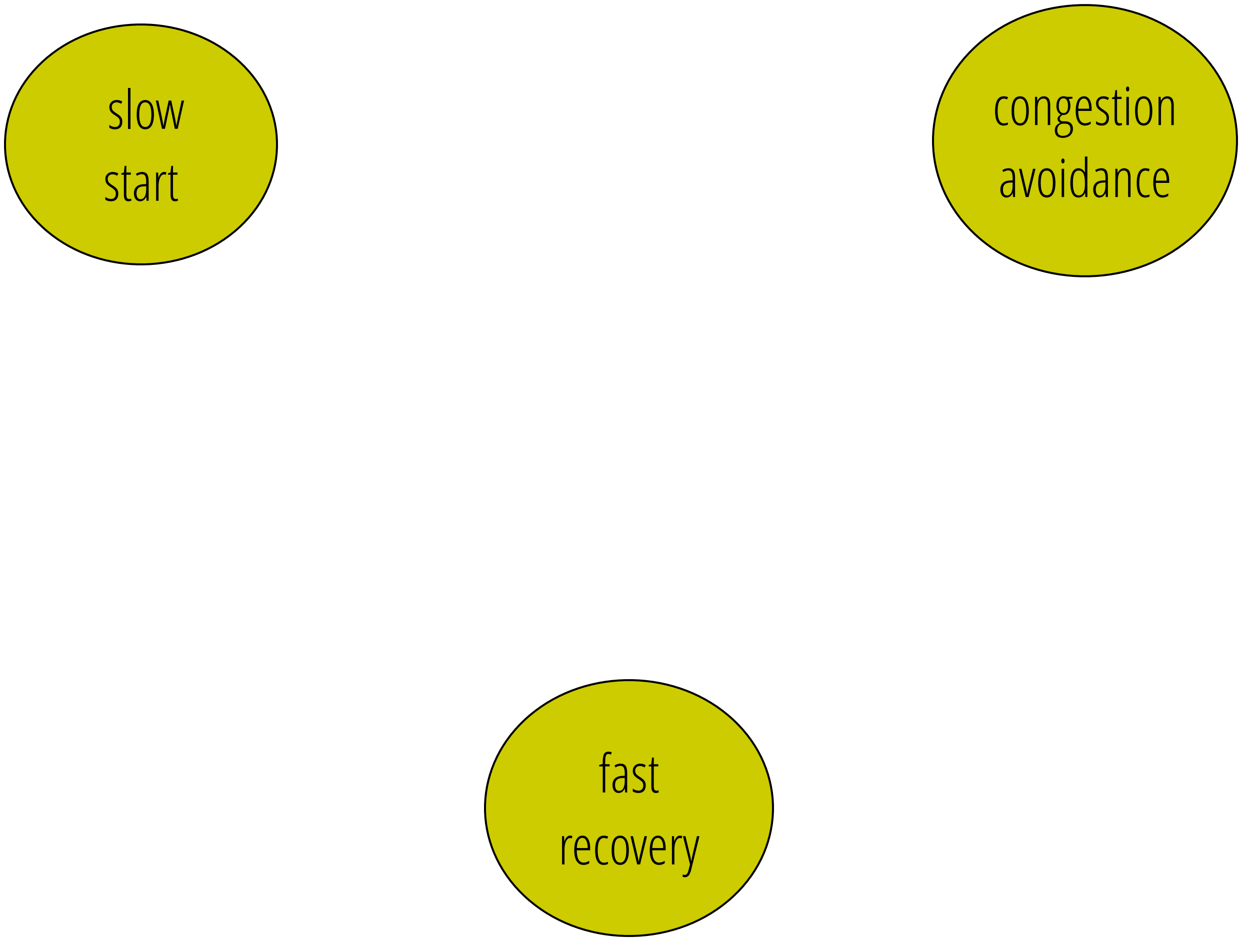

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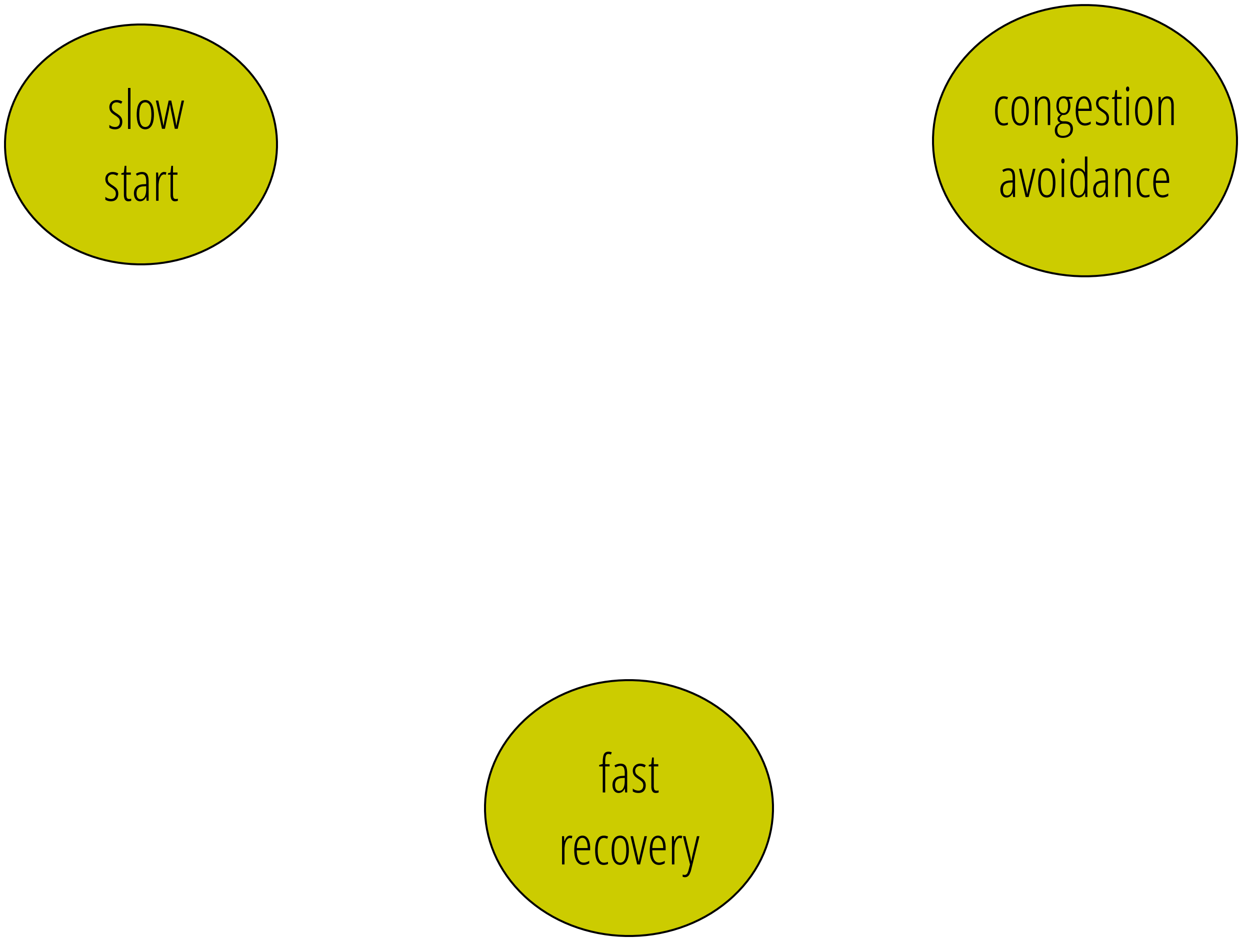

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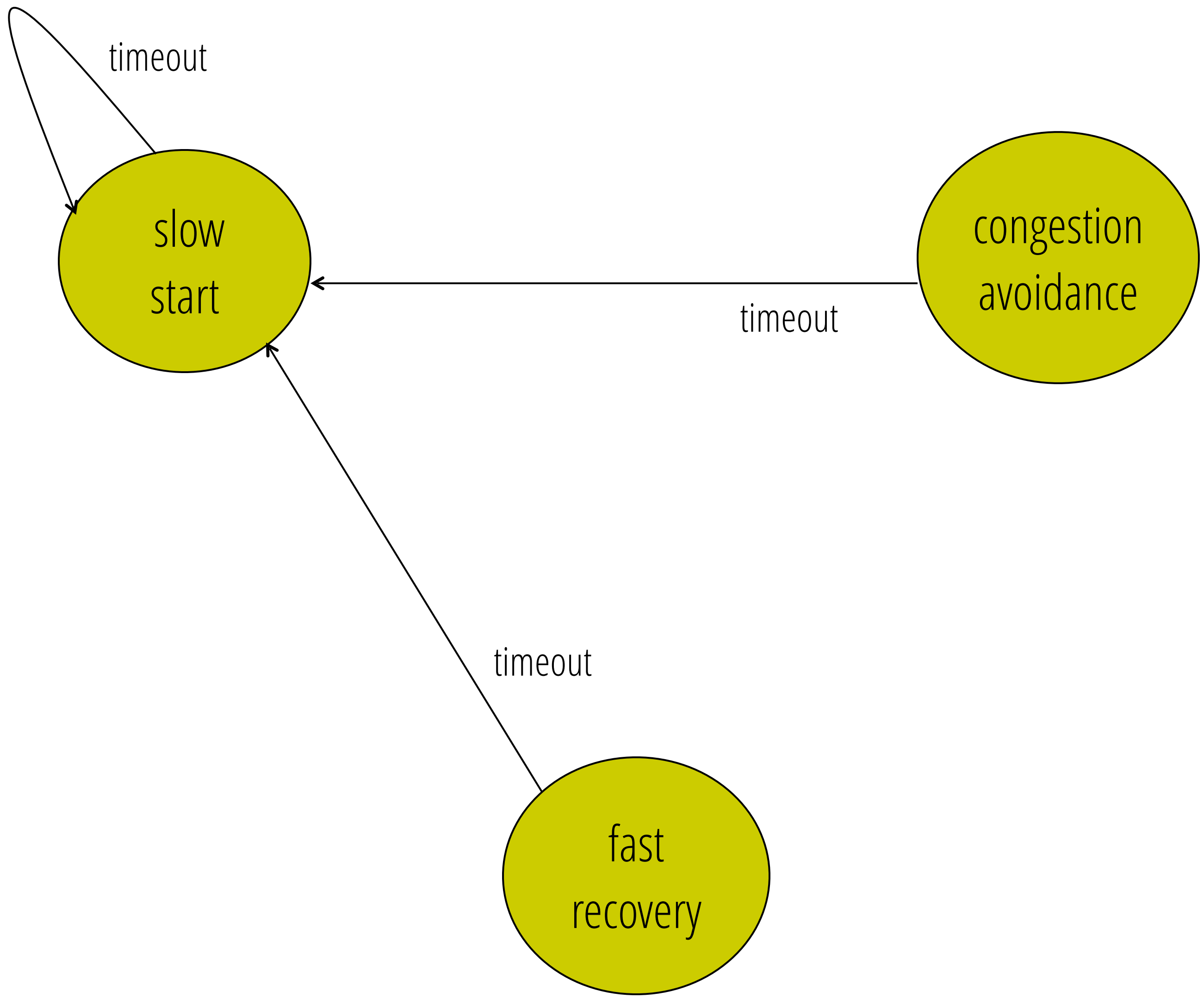

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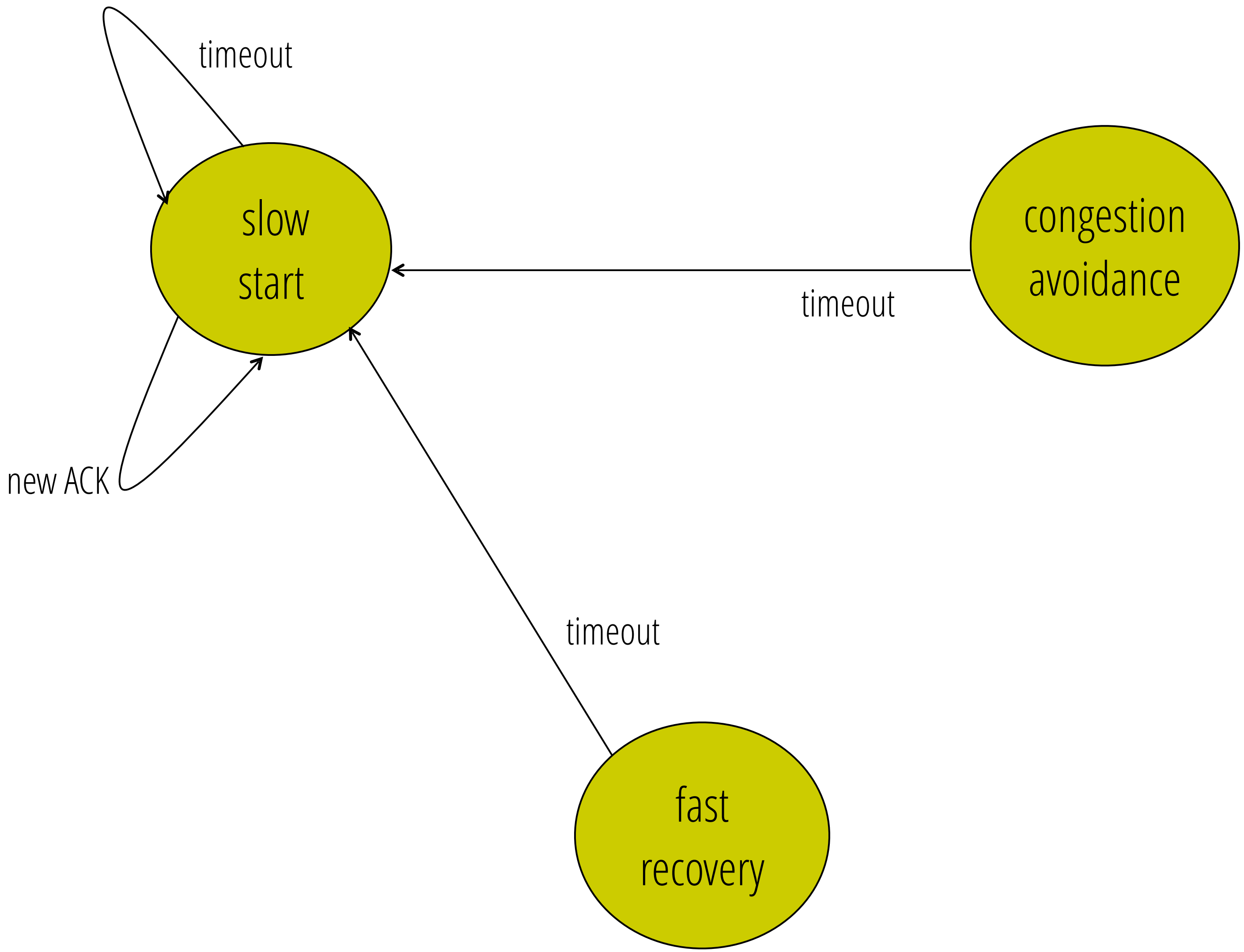

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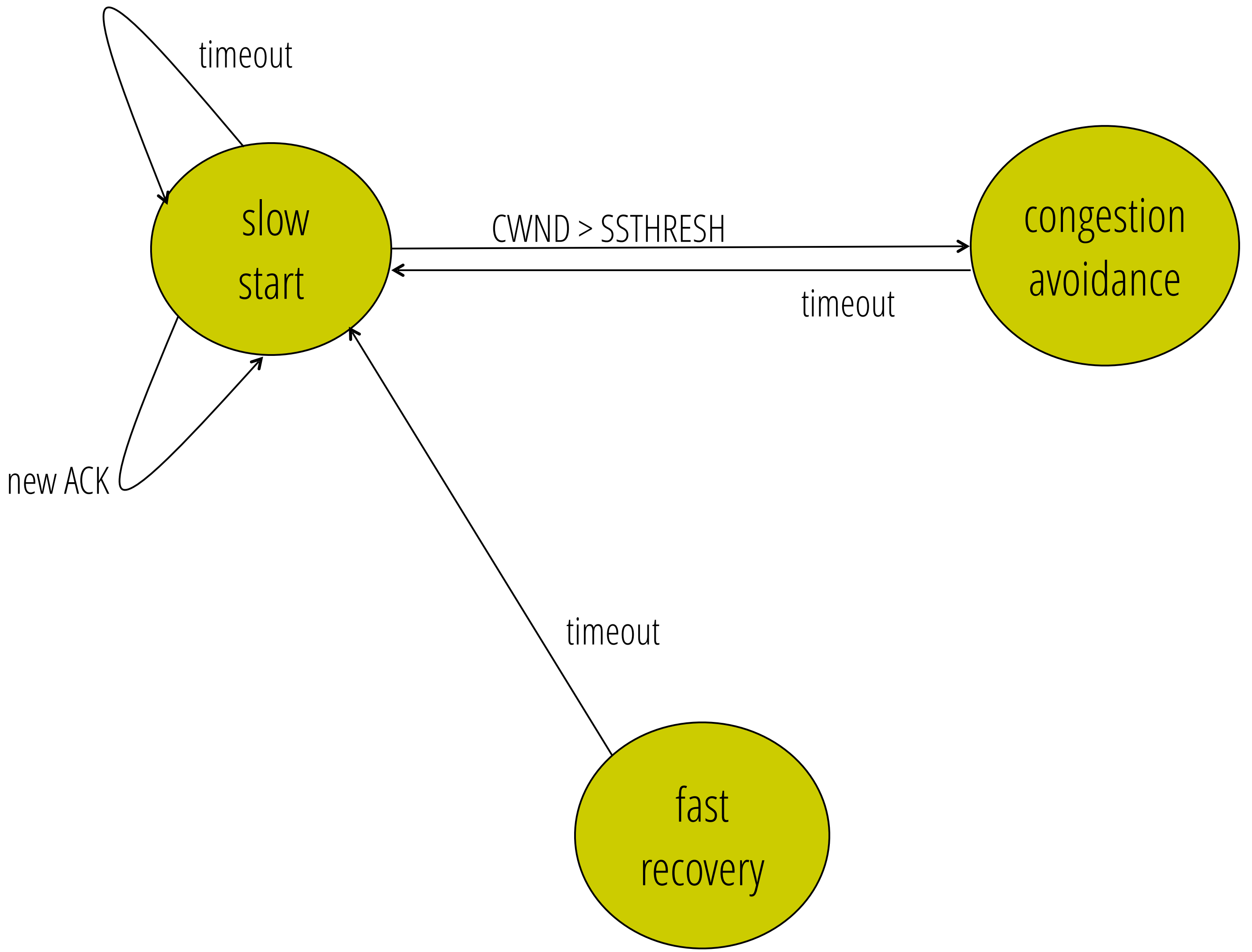

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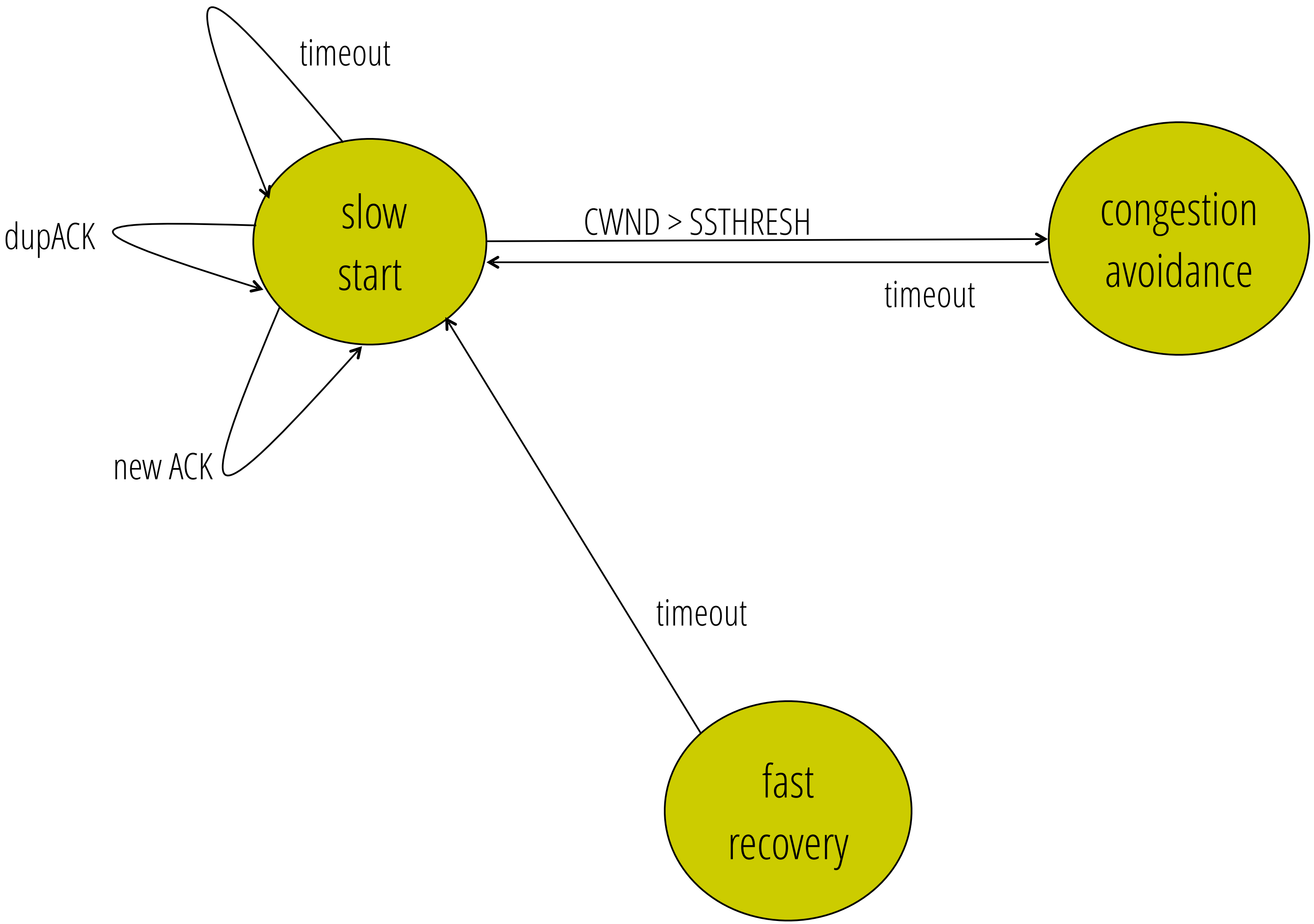

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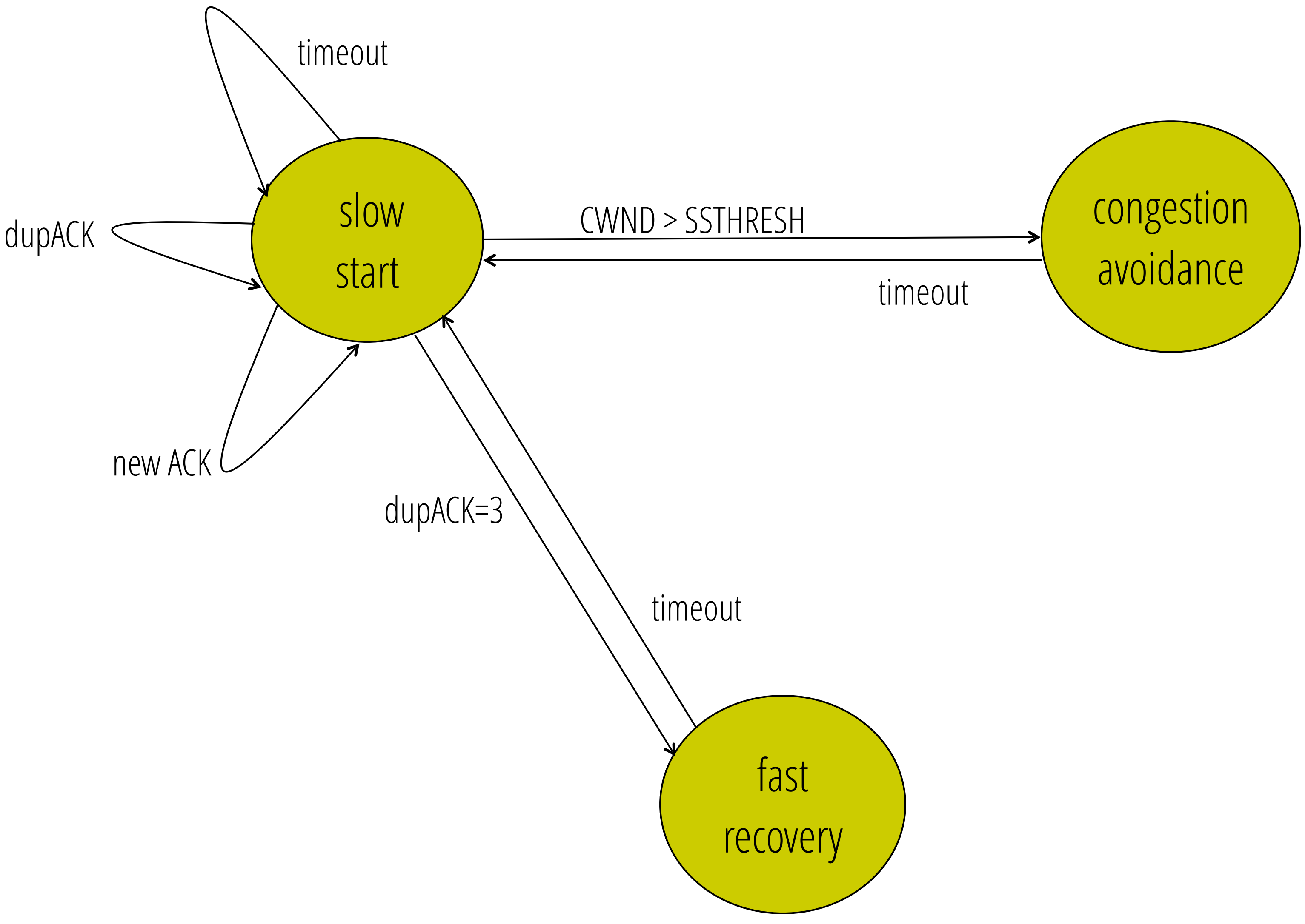

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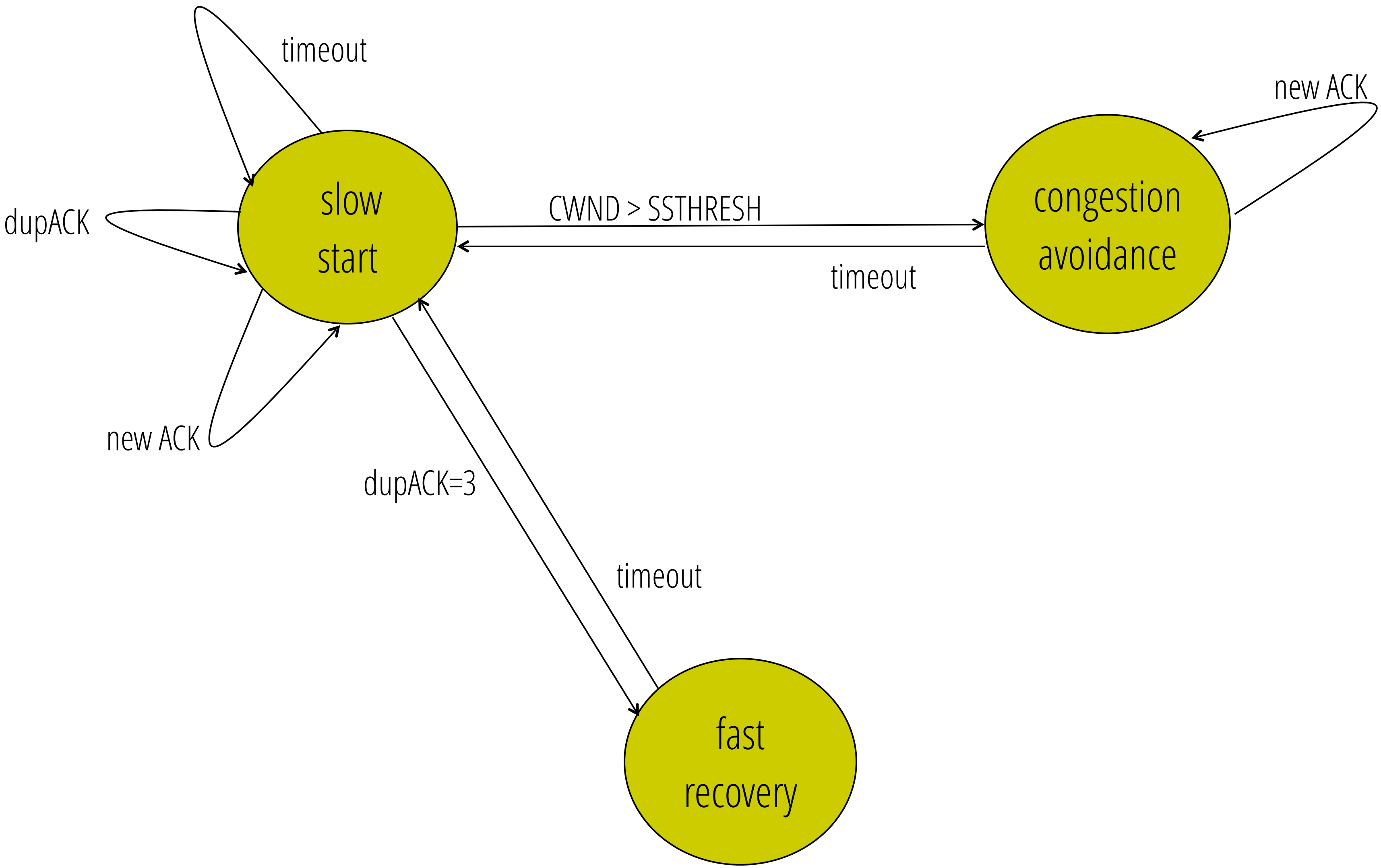

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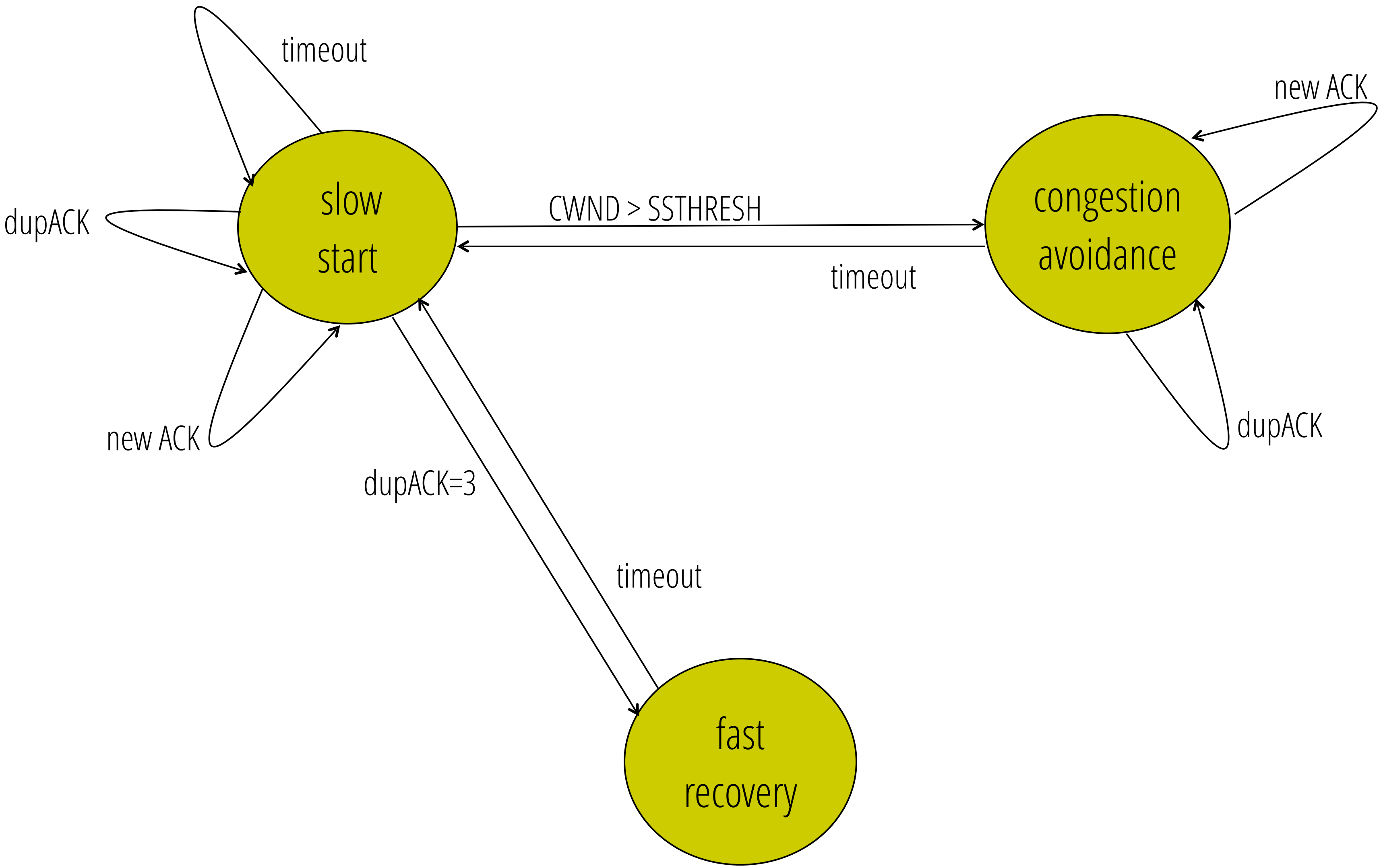

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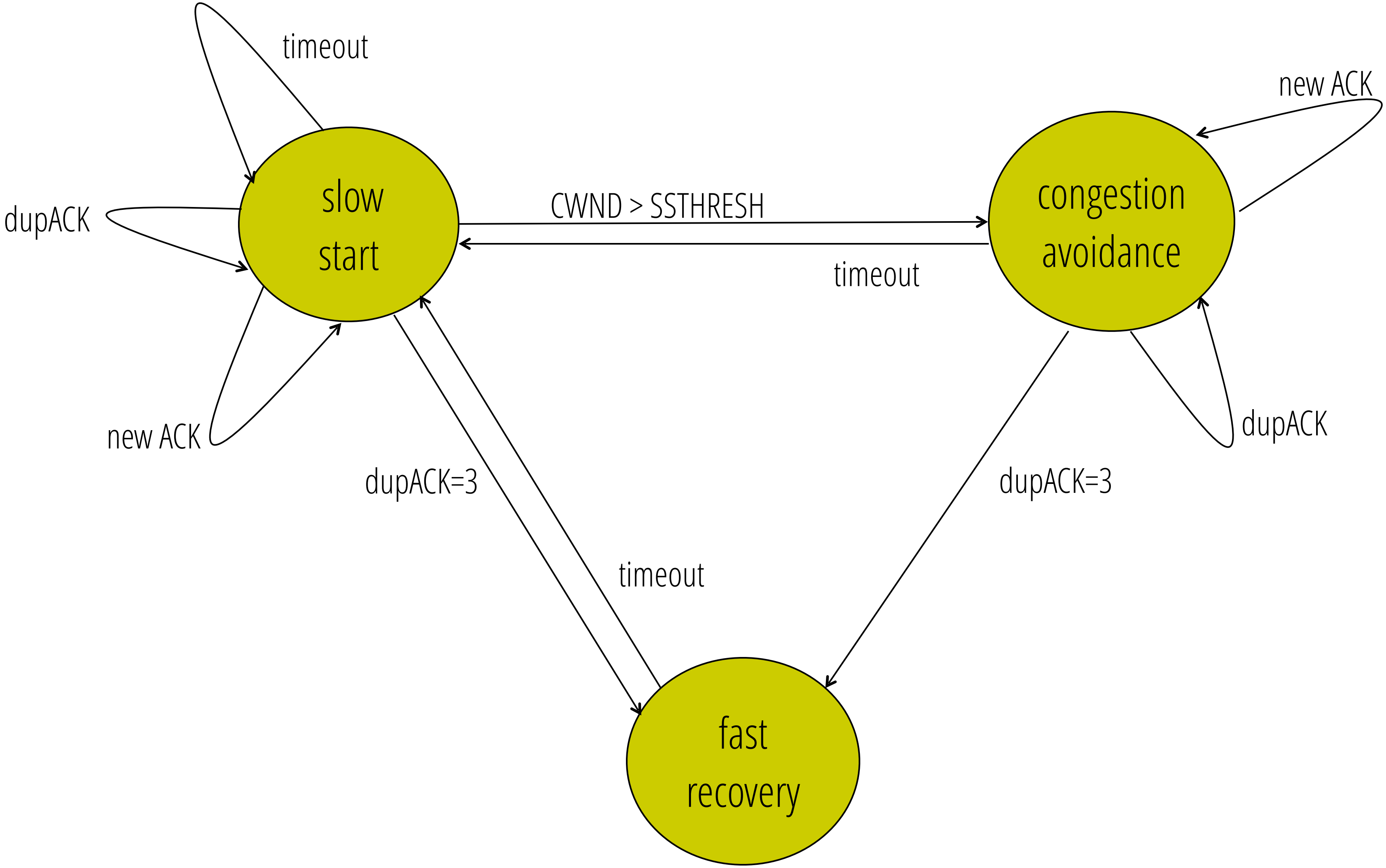

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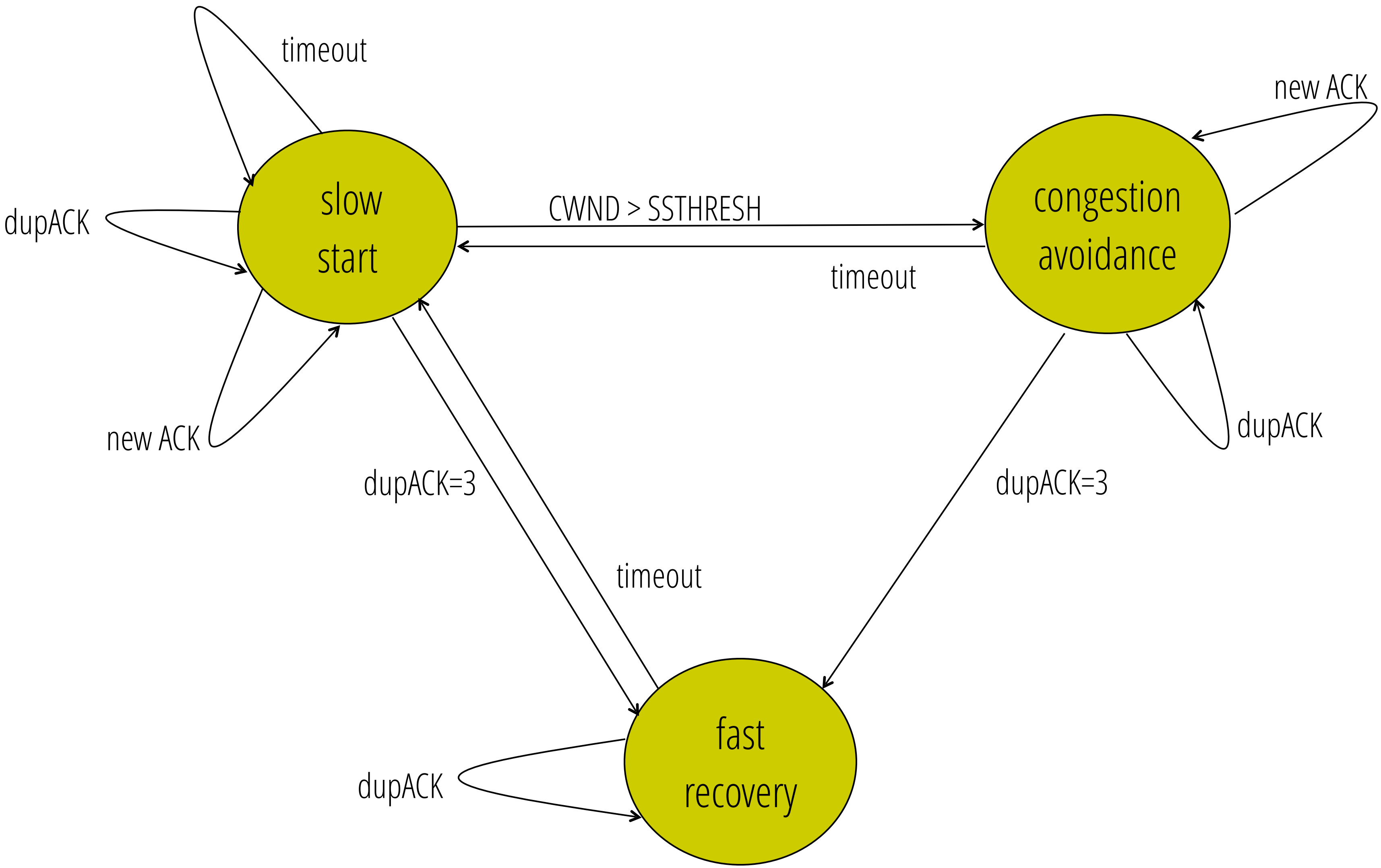

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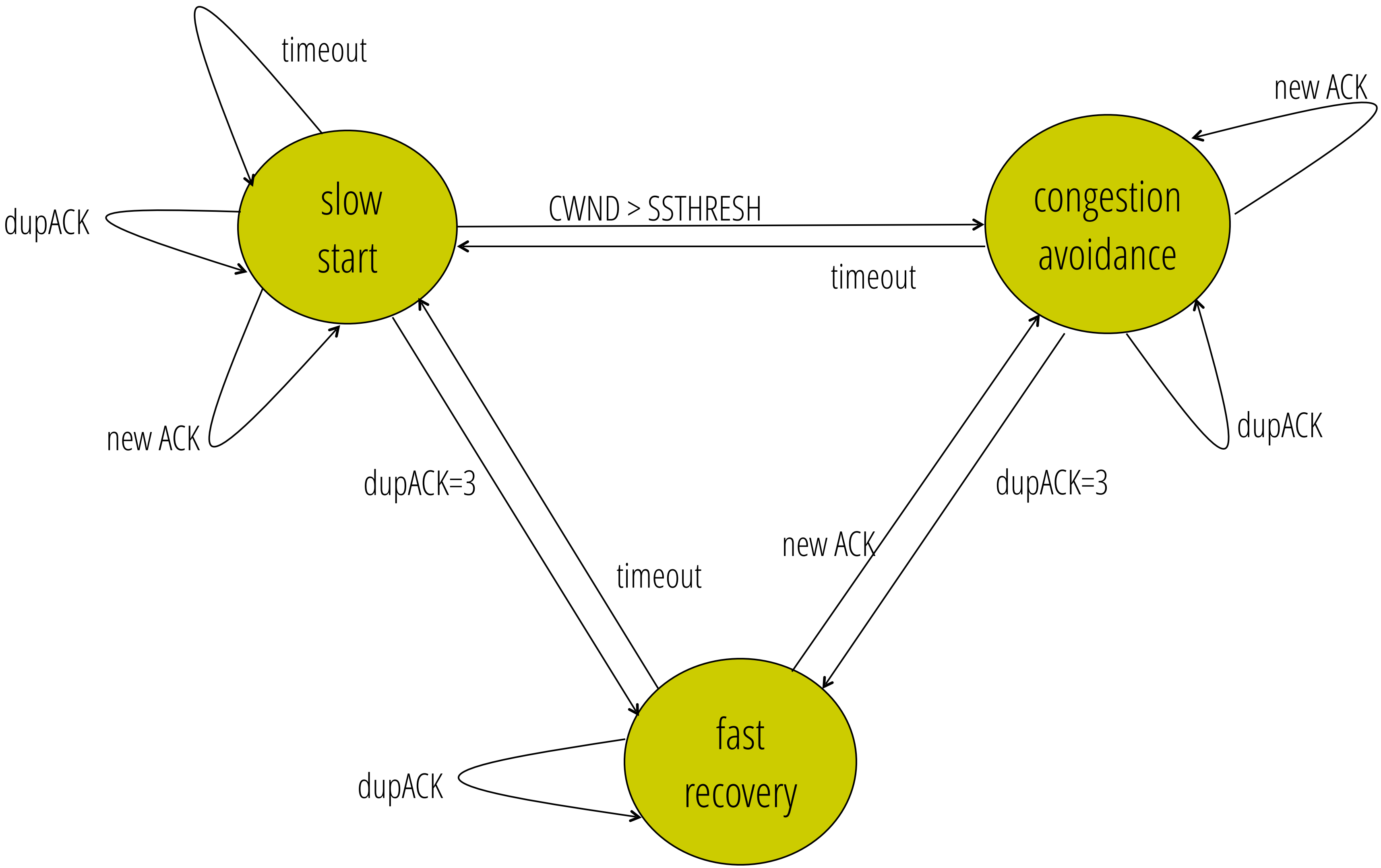

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Our default assumption

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TCP Throughput Equation

TCP Throughput

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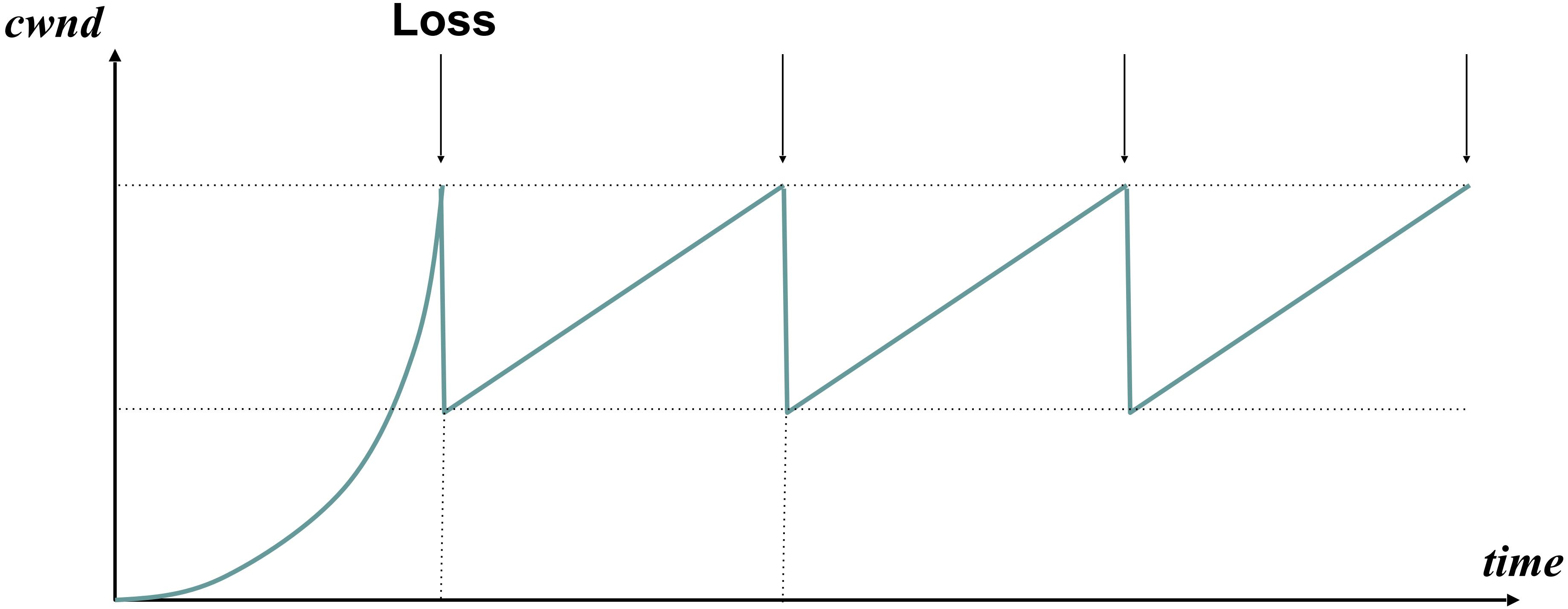
- We'll derive a simple model that expresses TCP throughput in terms of path properties:
  - RTT
  - Loss rate, p

A Simple Model for TCP Throughput



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  - $\frac{1}{2}W_{max}$ +2 (two RTTs later)
  - $\frac{1}{2}W_{max}$ +3 (three RTTs later)
  - ...
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$\frac{1}{2}W_{max}$ RTTs

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- And is detected by duplicate ACKs (i.e., no timeouts)

- Hence, evolution of window size:
  - Increase by 1 for $\frac{1}{2}W_{max}$ RTTs, then drop, then repeat

- Average window size per RTT = $\frac{3}{4}W_{max}$

- Average throughput = $\frac{3}{4}W_{max}$ x $\frac{MSS}{RTT}$

- Remaining step: express W_{max} in terms of loss rate p

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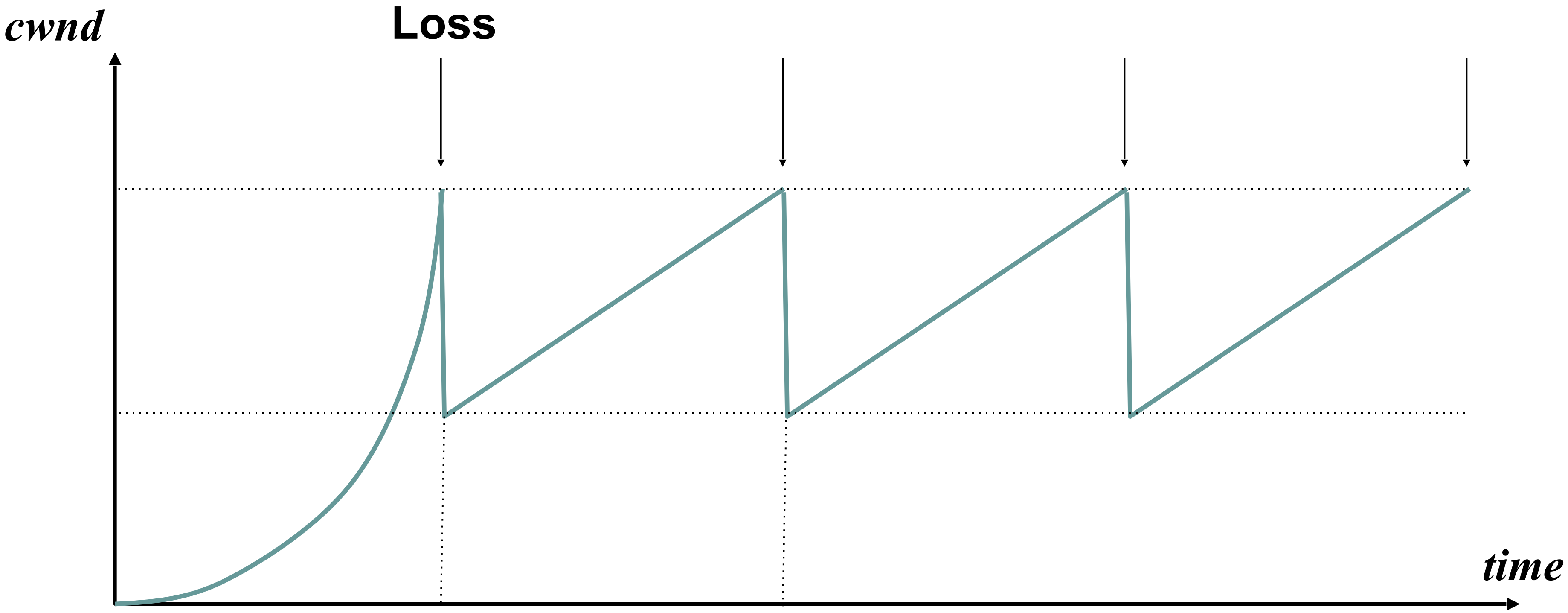

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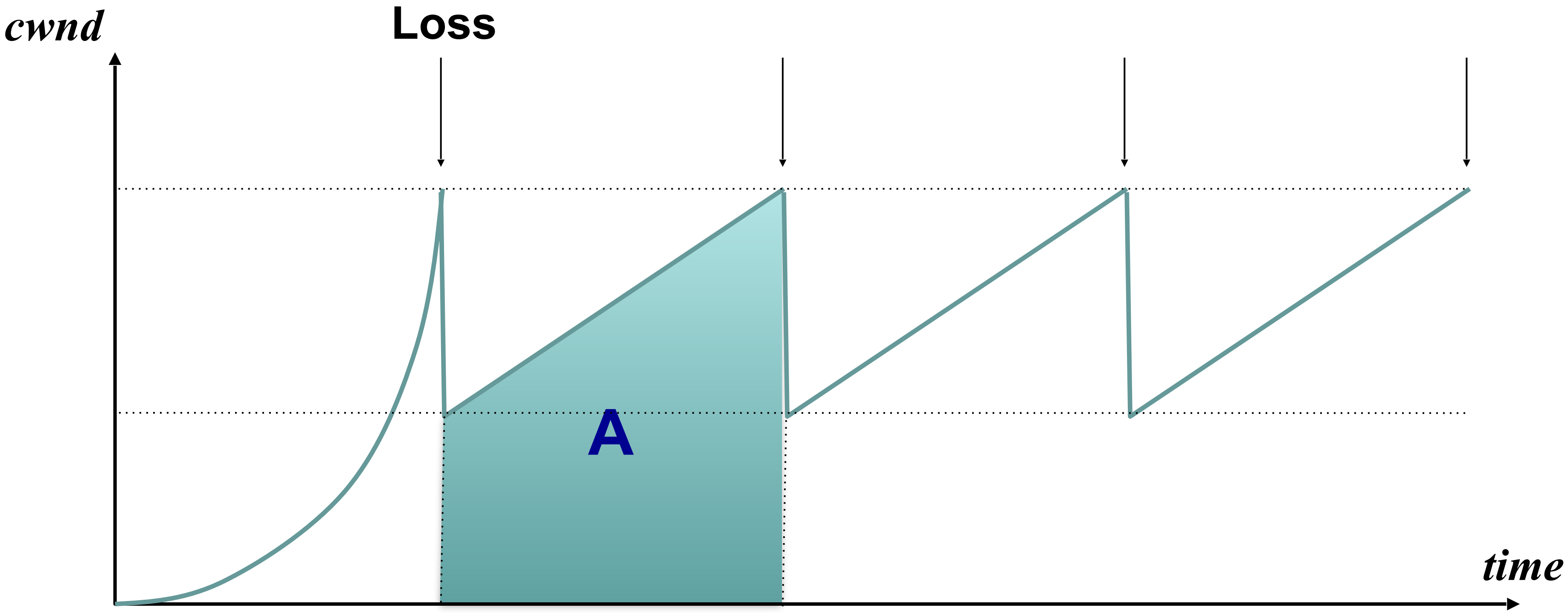

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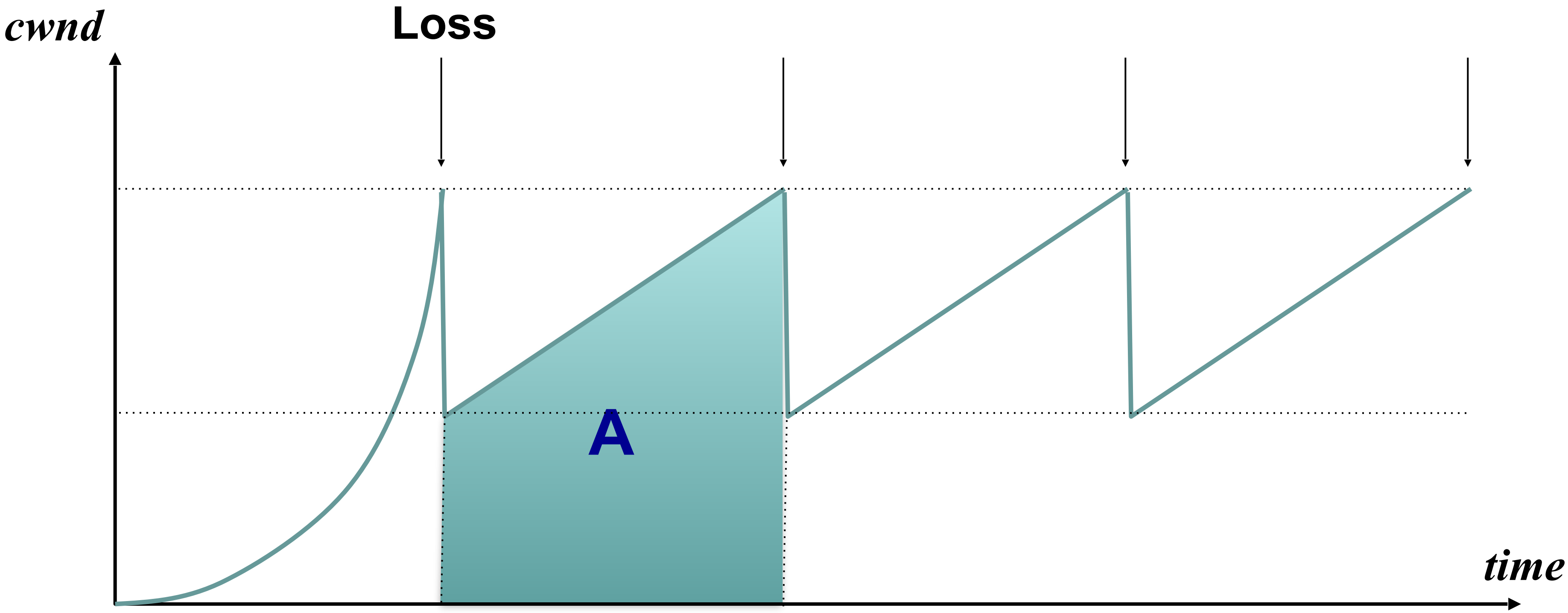

On average, one of all packets in shaded region is lost
(i.e., loss rate is 1/A, where A is #packets in shaded region)

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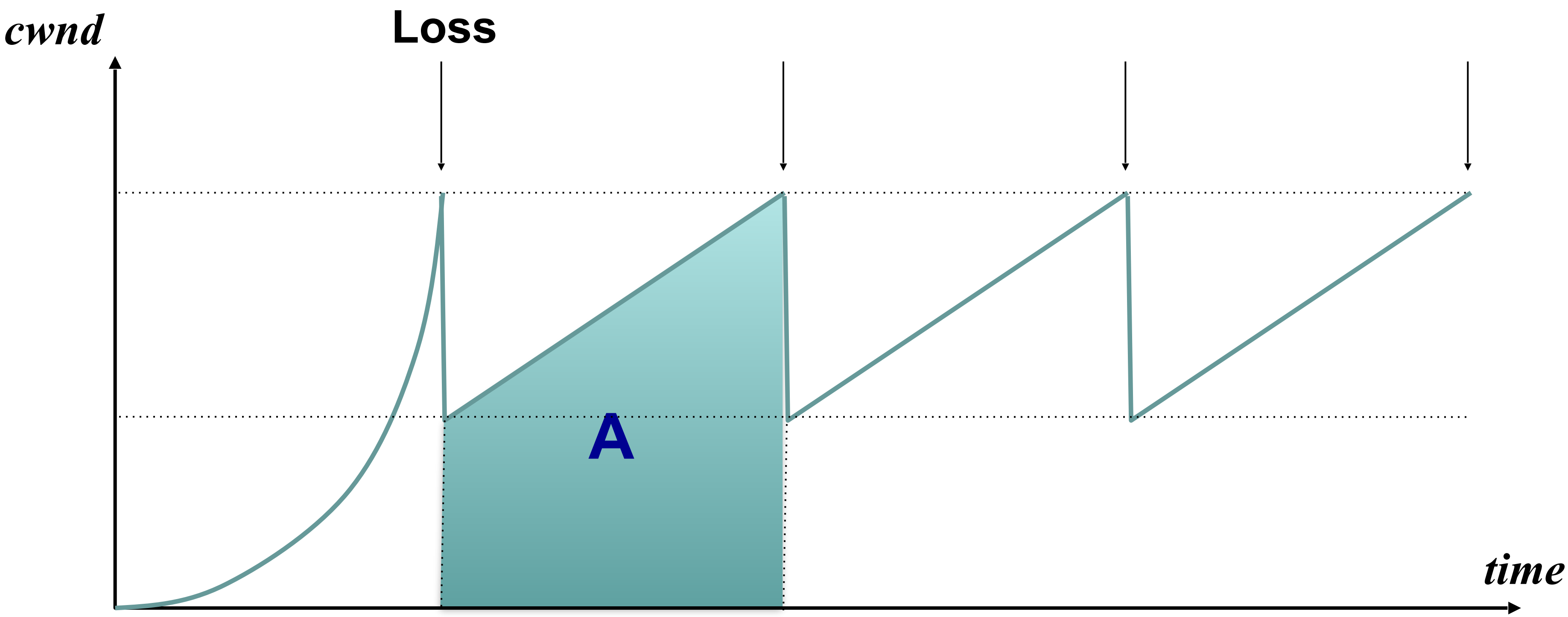

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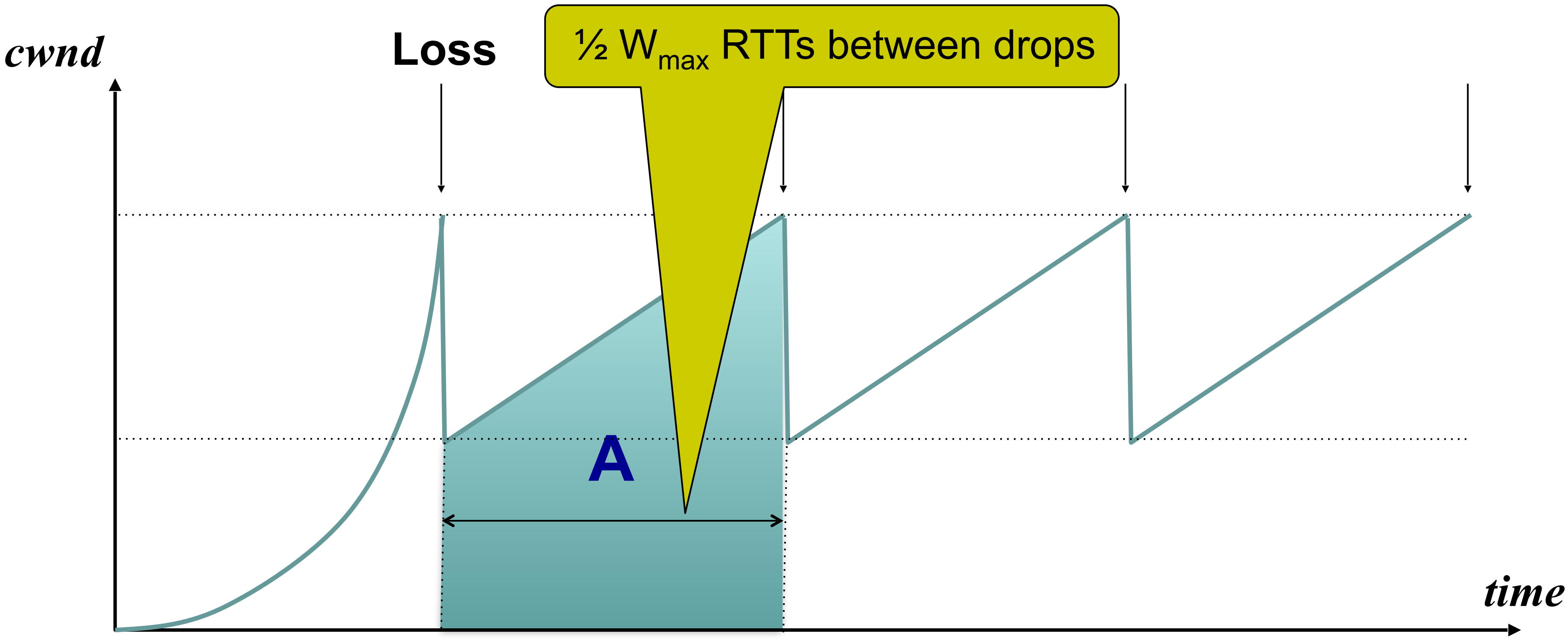

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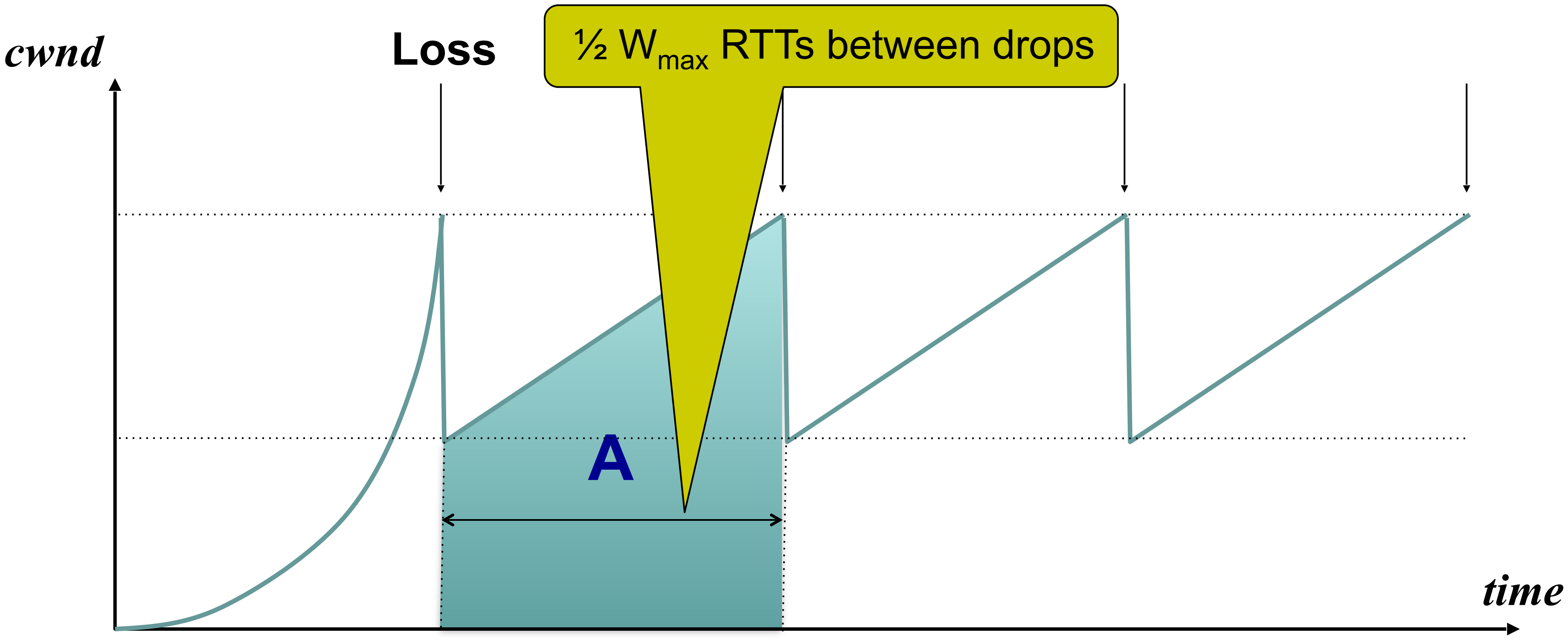

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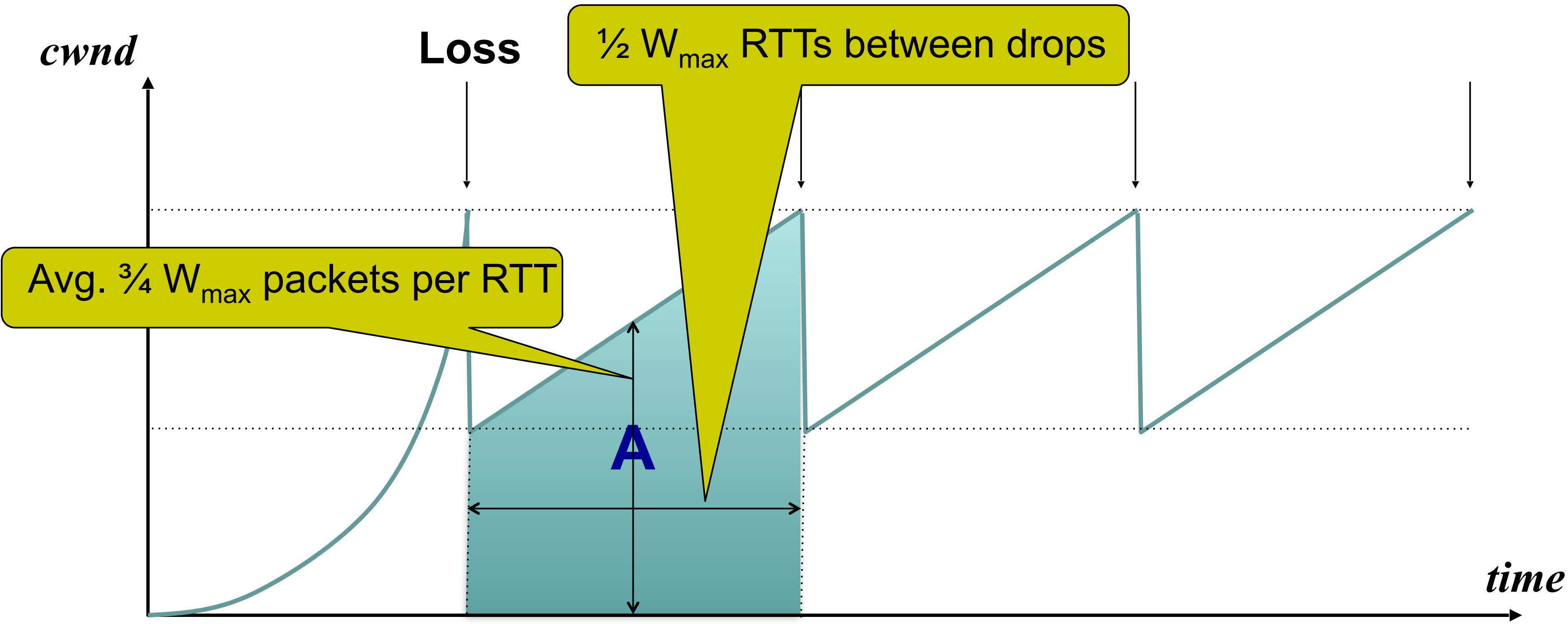

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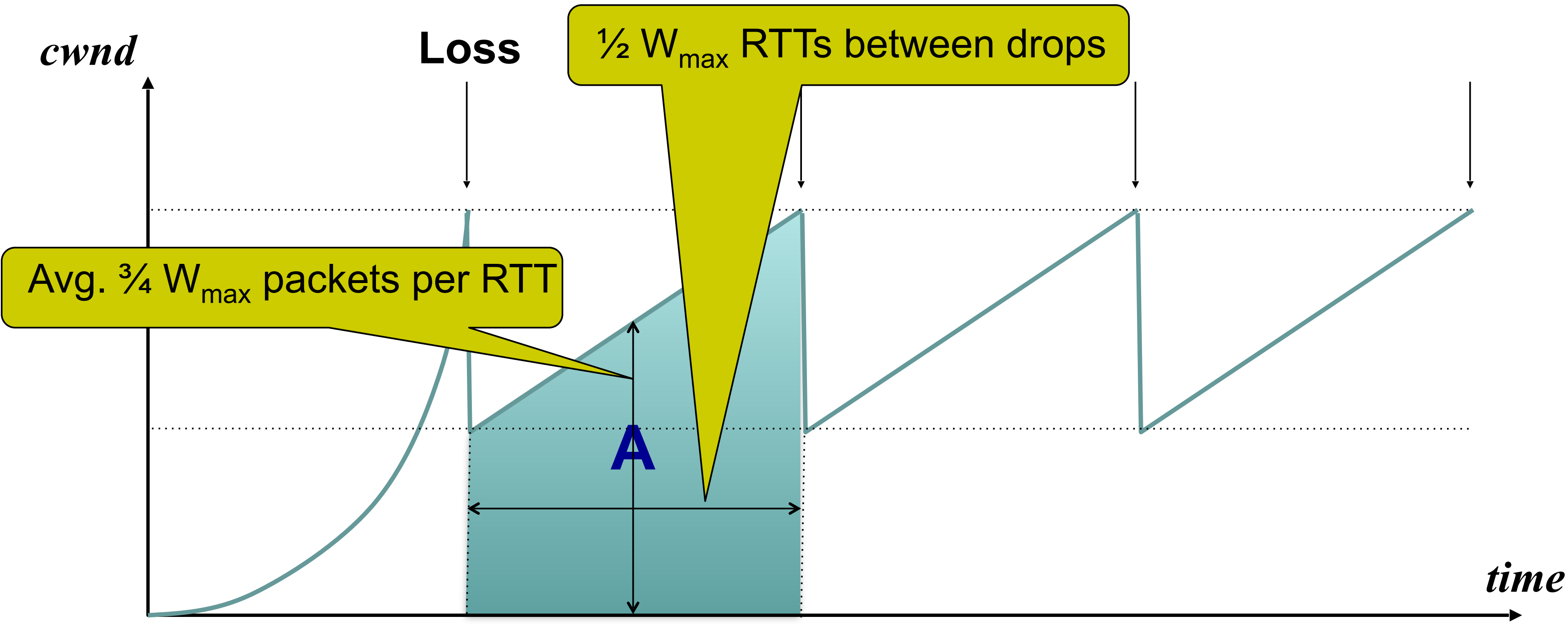

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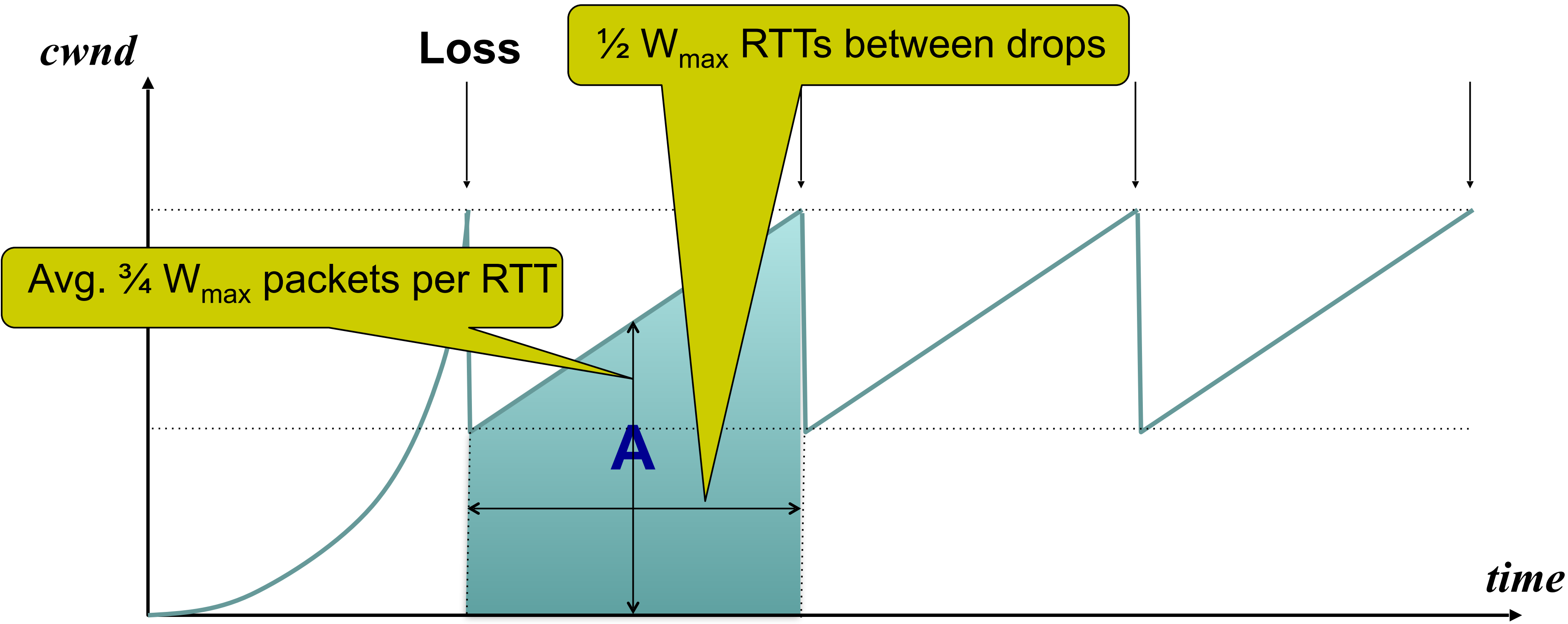

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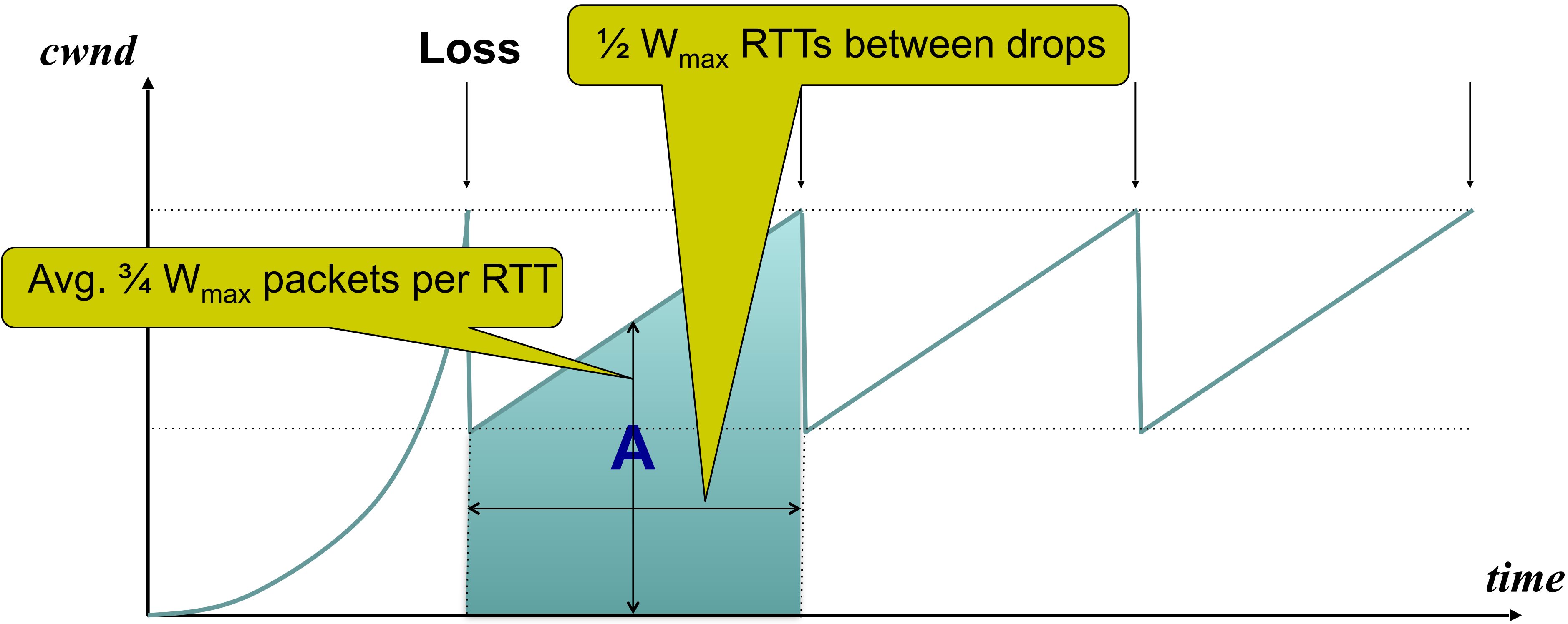

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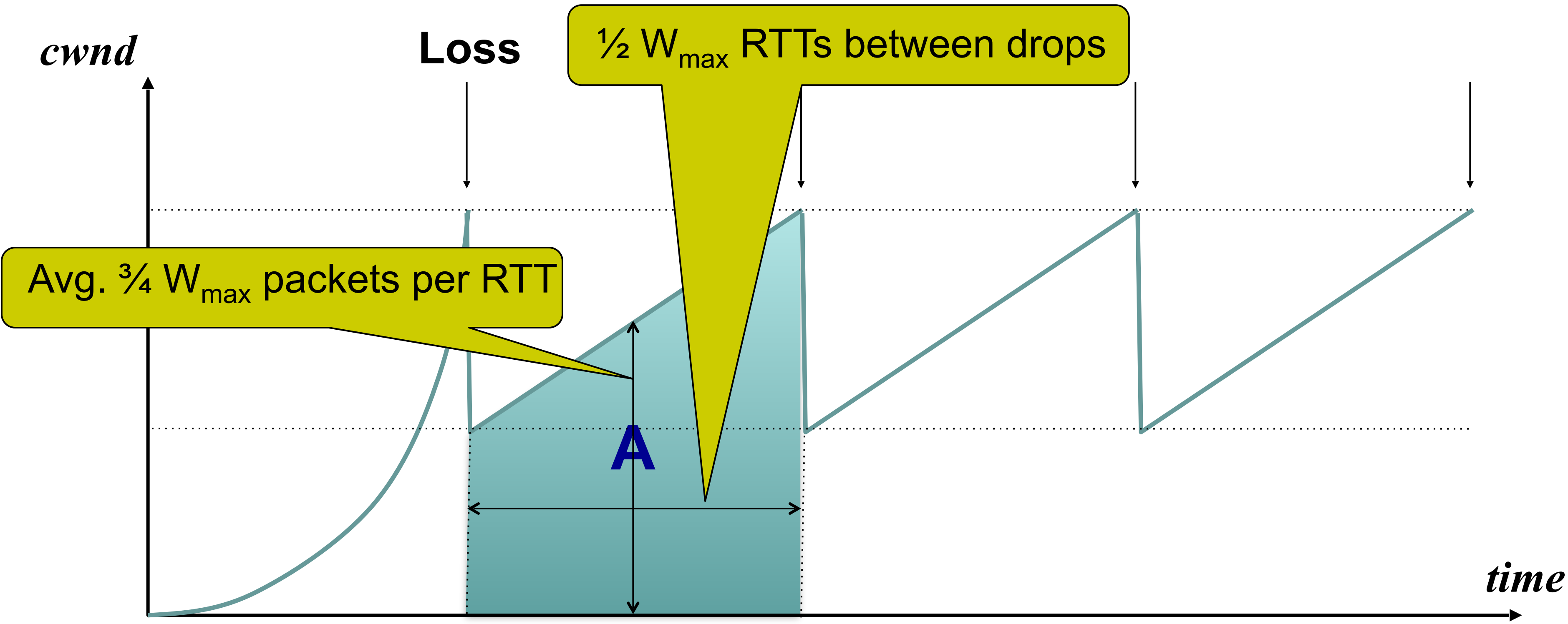

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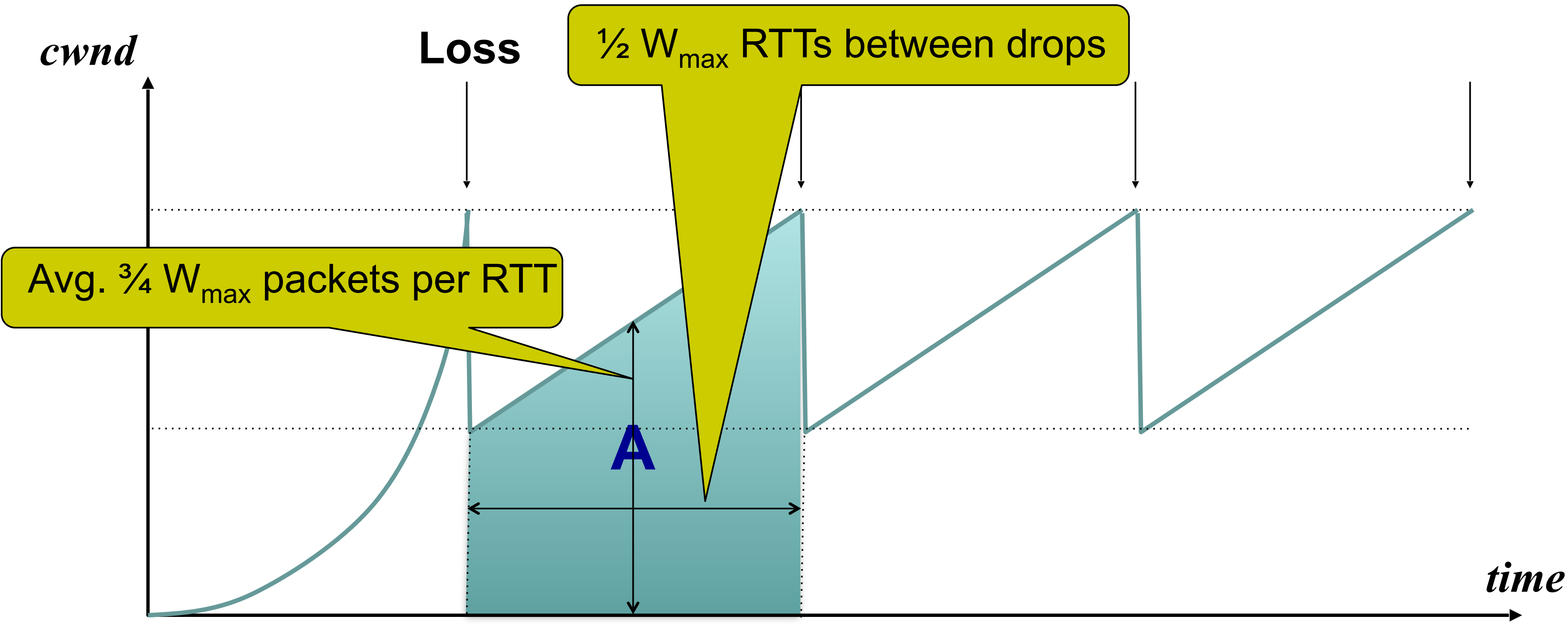

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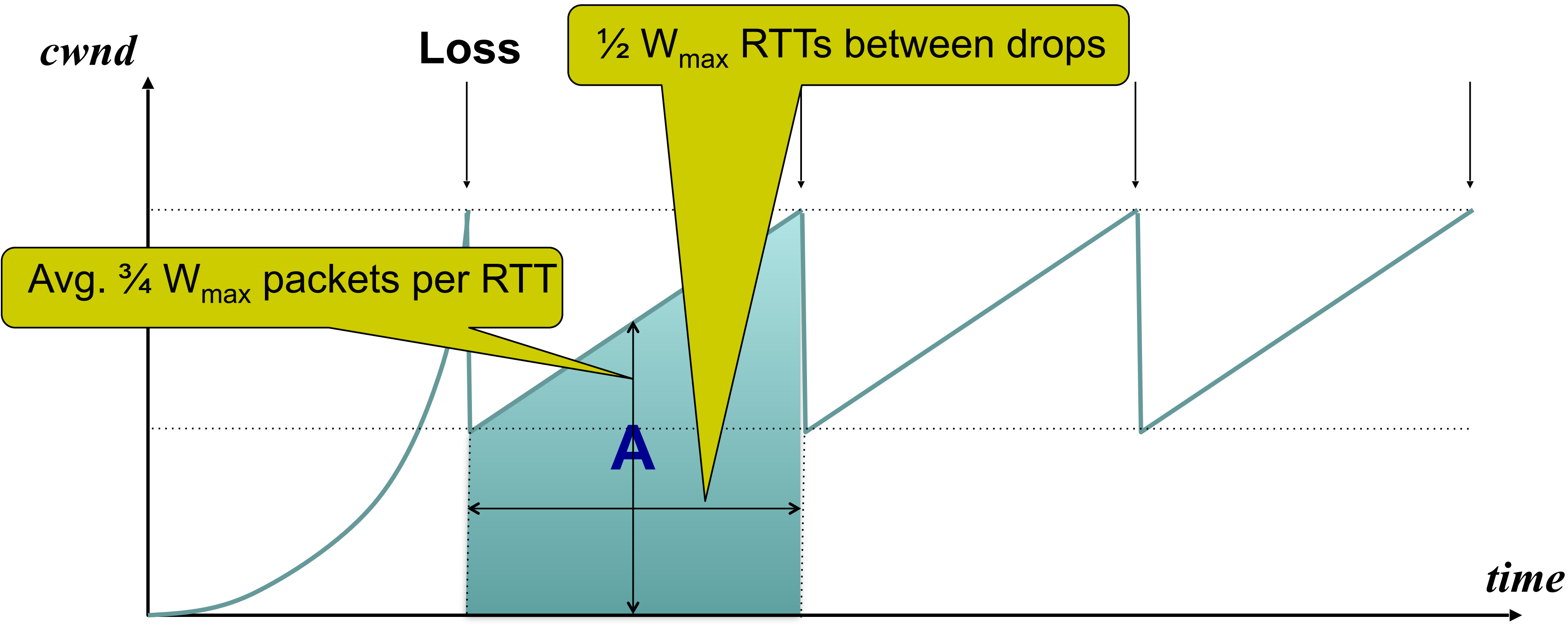

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- But leads to some insights (coming up)

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- TCP throughput depends on path RTT and loss rate

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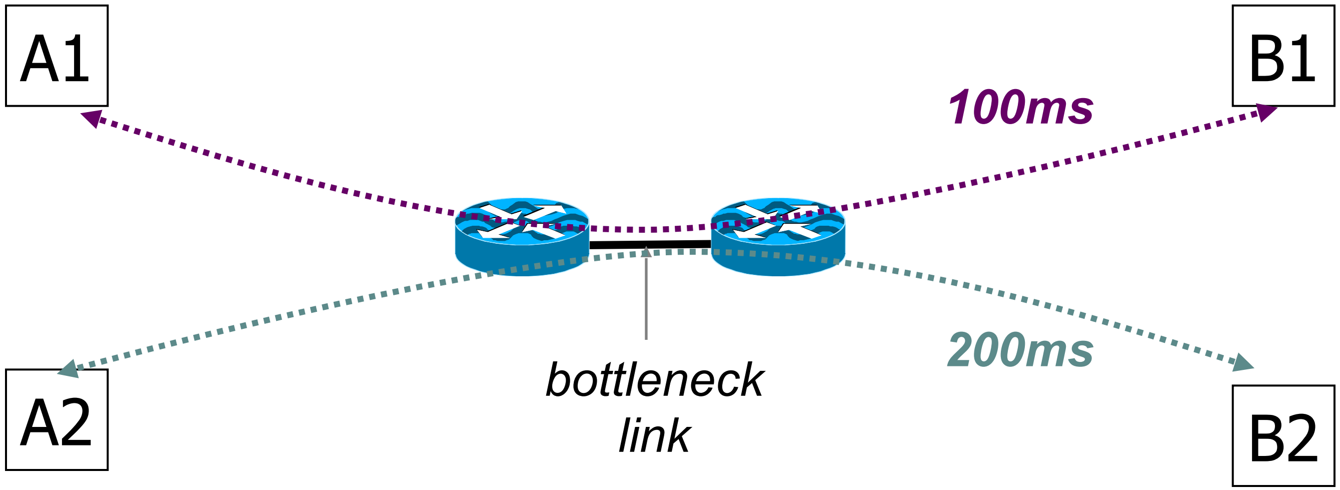

Implications (1): Different RTTs

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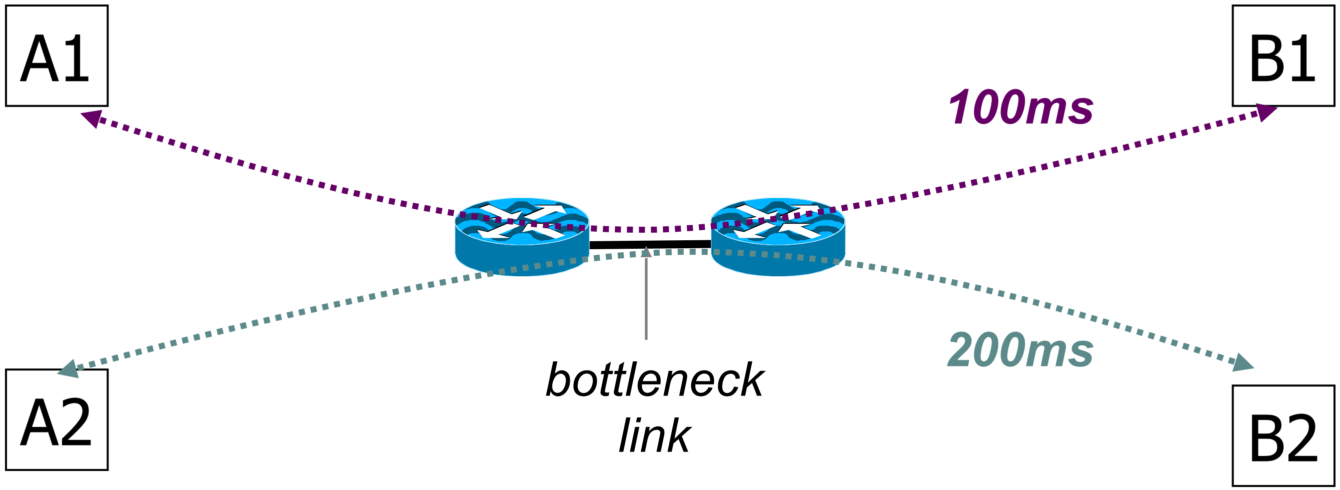
- Flows get throughput inversely proportional to RTT
- TCP unfair in the face of heterogeneous RTTs!



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  - measure RTT and drop percentage *p*, and set rate accordingly
- Following the TCP equation ensures we're "TCP friendly"
  - i.e., use no more than TCP does in similar setting

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- Flow will cut its rate
  - Throughput ~ $\frac{1}{\sqrt{p}}$ even for non-congestion losses!

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- A partial fix: use a higher initial CWND [RFC IW10]

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  - Consider a flow transferring a 10GB file sharing a bottleneck link with 10 flows transferring 100B
- Problem exacerbated by the trend towards adding large amounts of memory on routers (a.k.a. “bufferbloat”)

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- Focus of Google's BBR algorithm[1]

[1] *BBR: Congestion-Based Congestion Control; Cardwell et al, ACM Queue 2016*

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- Basic idea (simplified):
  - Sender learns its minimum RTT (~ propagation RTT)
  - Decreases its rate when the observed RTT exceeds the minimum RTT

[1] *BBR: Congestion-Based Congestion Control; Cardwell et al, ACM Queue 2016*

(6) Cheating

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- Three easy ways to cheat
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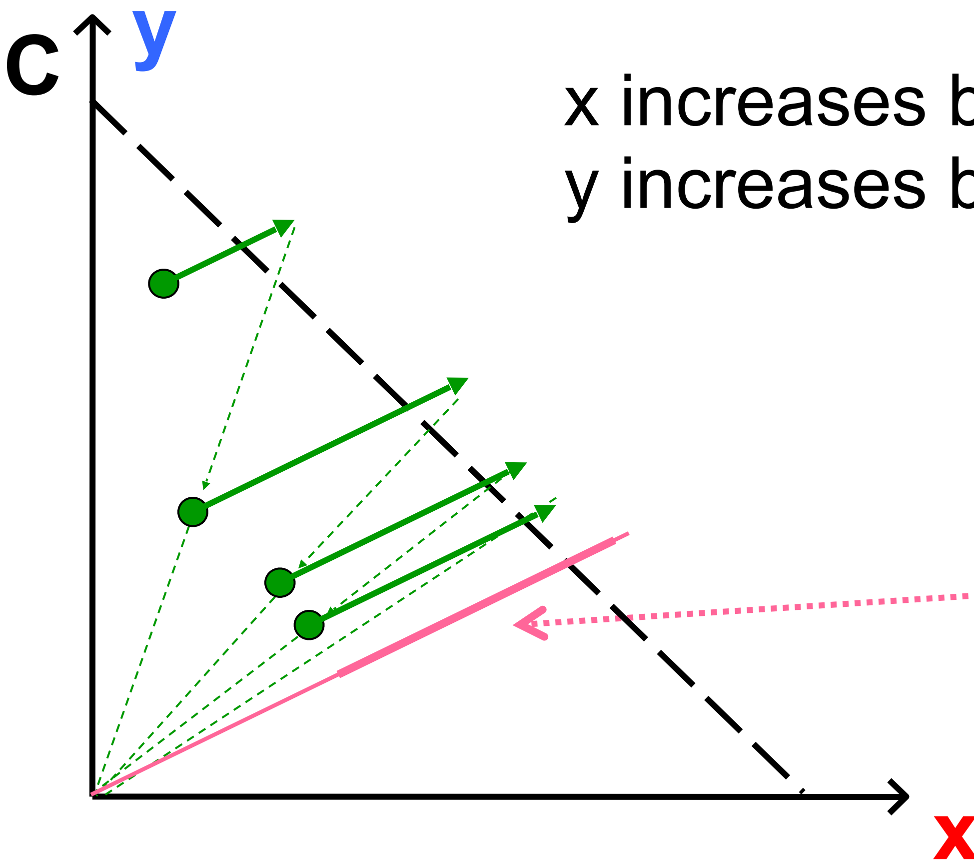
Increasing CWND Faster



x increases by 2 per RTT
y increases by 1 per RTT

Limit rates:
x = 2y

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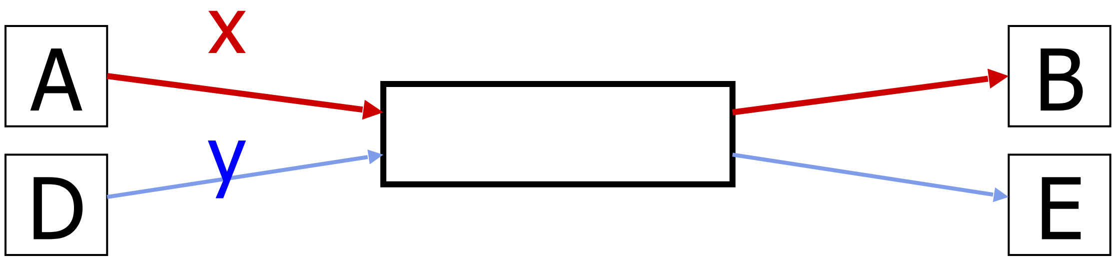
Open Many Connections



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

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  - Increasing CWND faster than +1 MSS per RTT
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  - Using large initial CWND

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MOTHERBOARD
TECH BY VICE

Google’s Network Congestion Algorithm Isn’t Fair, Researchers Say

Why hasn't the Internet suffered another congestion collapse?

- Even "cheaters" do back off!
  - Leads to unfairness, not necessarily collapse

- Hard to say whether unfair behavior is common

MOTHERBOARD
TECH BY VICE

Google's Network Congestion Algorithm Isn't Fair, Researchers Say

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Routers enforce fair sharing

Could fix many of these with some help from routers!

Router-Assisted Congestion Control

- Three ways routers can help
  - Enforce fairness
  - More precise rate adaptation
  - Detecting congestion

How can routers ensure each flow gets its “fair share”?

Fairness: General Approach

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- What does "fair" mean exactly?

Max-Min Fairness

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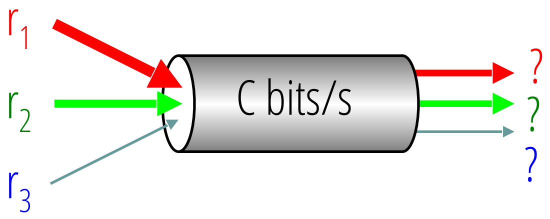
Max-Min Fairness



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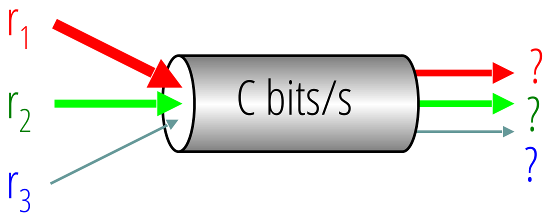

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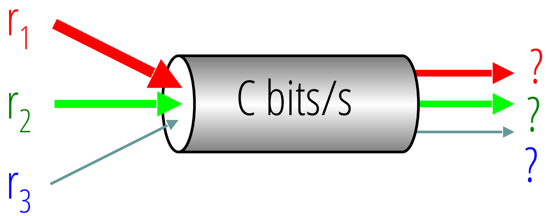

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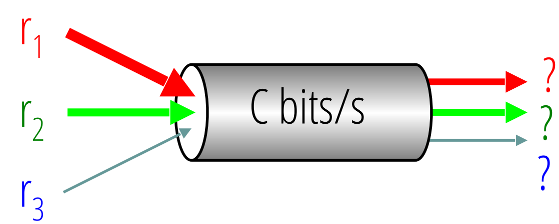

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where f is the unique value such that $\mathrm{Sum}(a_i) = C$

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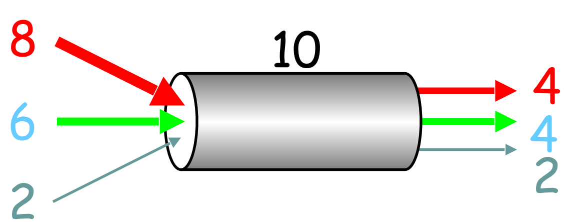

$f = 4$:
min(8, 4) = 4
min(6, 4) = 4
min(2, 4) = 2

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  - If you don't get full demand, no one gets more than you

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- But we can approximate it
  - This is what **"fair queuing"** routers do

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Analysis and Simulation of a Fair Queueing Algorithm

Alan Demers
Srinivasan Keshav†
Scott Shenker

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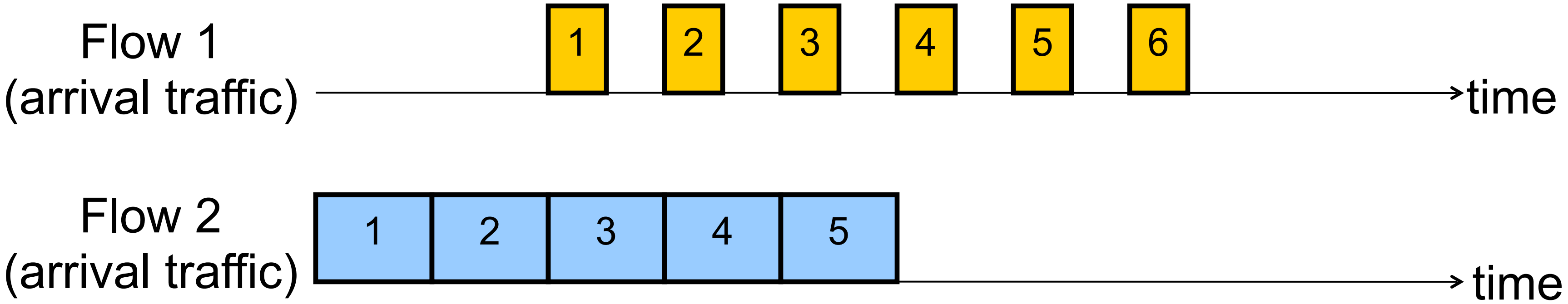
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1
2
3
4
5
6
time
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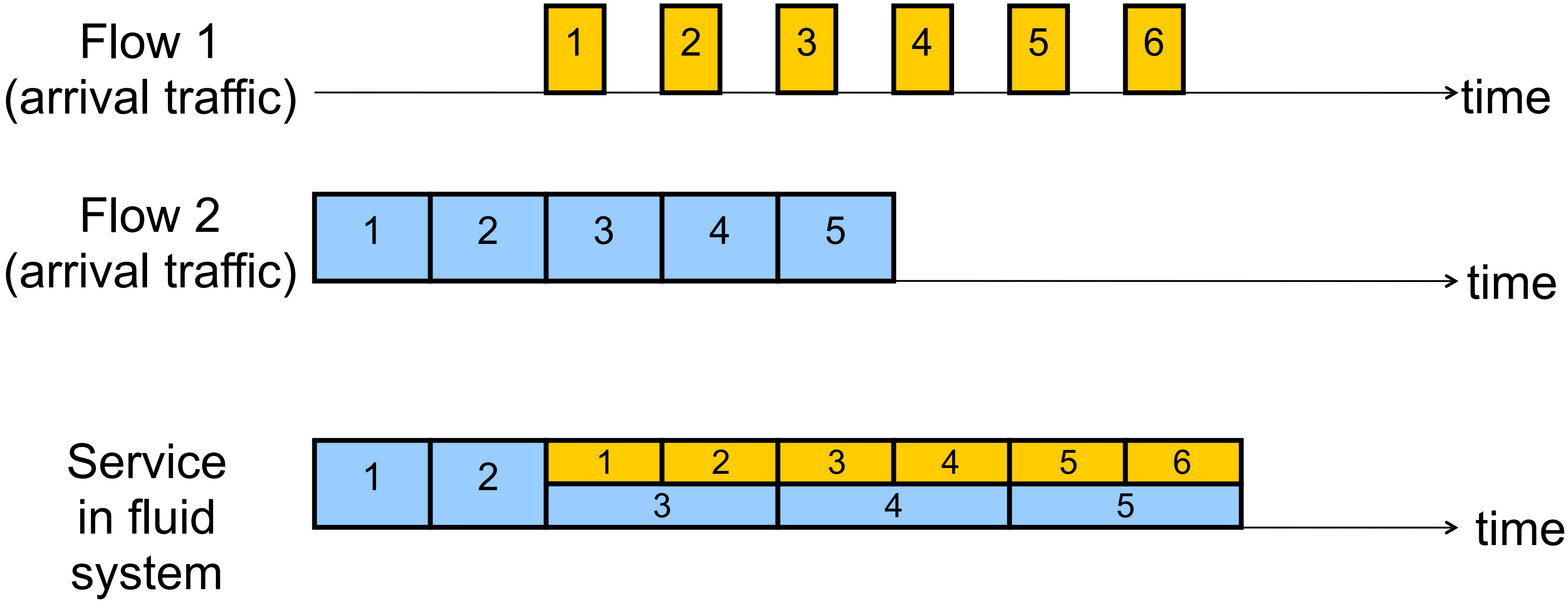

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in fluid
system
1
2
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4
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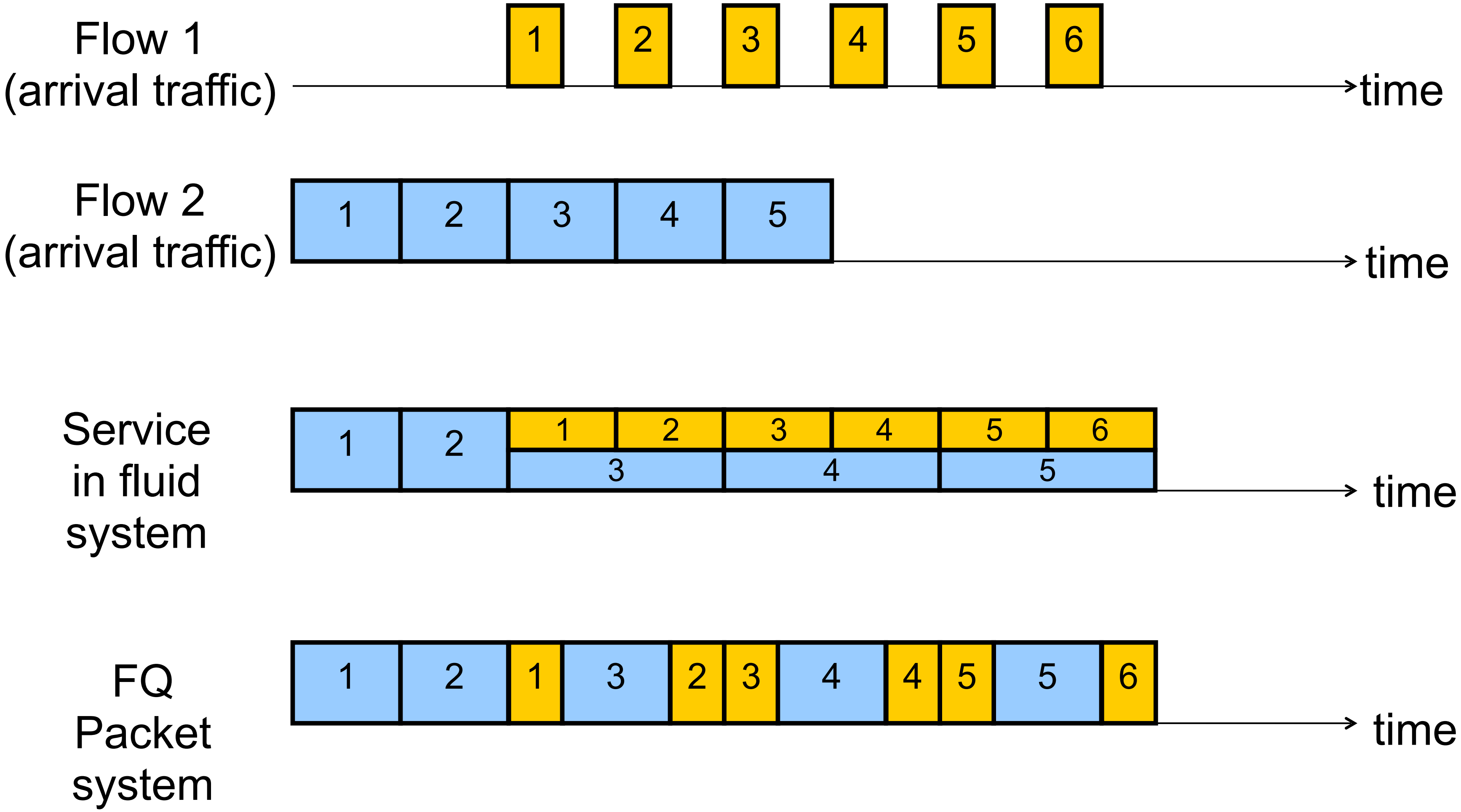
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FQ
Packet
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- Disadvantages:
  - More complex than FIFO: per flow queue/state, additional per-packet book-keeping
  - Still only a partial solution (coming up)

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- "Pure" FQ too complex to implement at high speeds
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  - E.g., Deficit Round Robin (DRR)
- Today:
  - Routers typically implement approximate FQ (e.g., DRR)
  - For a small number of queues
  - Commonly used for coarser-grained isolation (e.g., for select customer prefixes) rather than per-flow isolation

FQ in the big picture

- FQ does not eliminate congestion → it just manages the congestion

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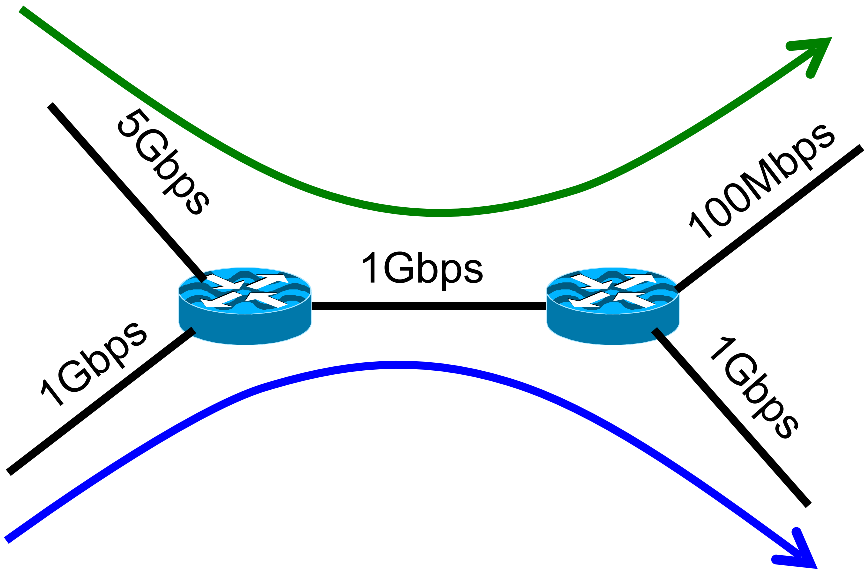

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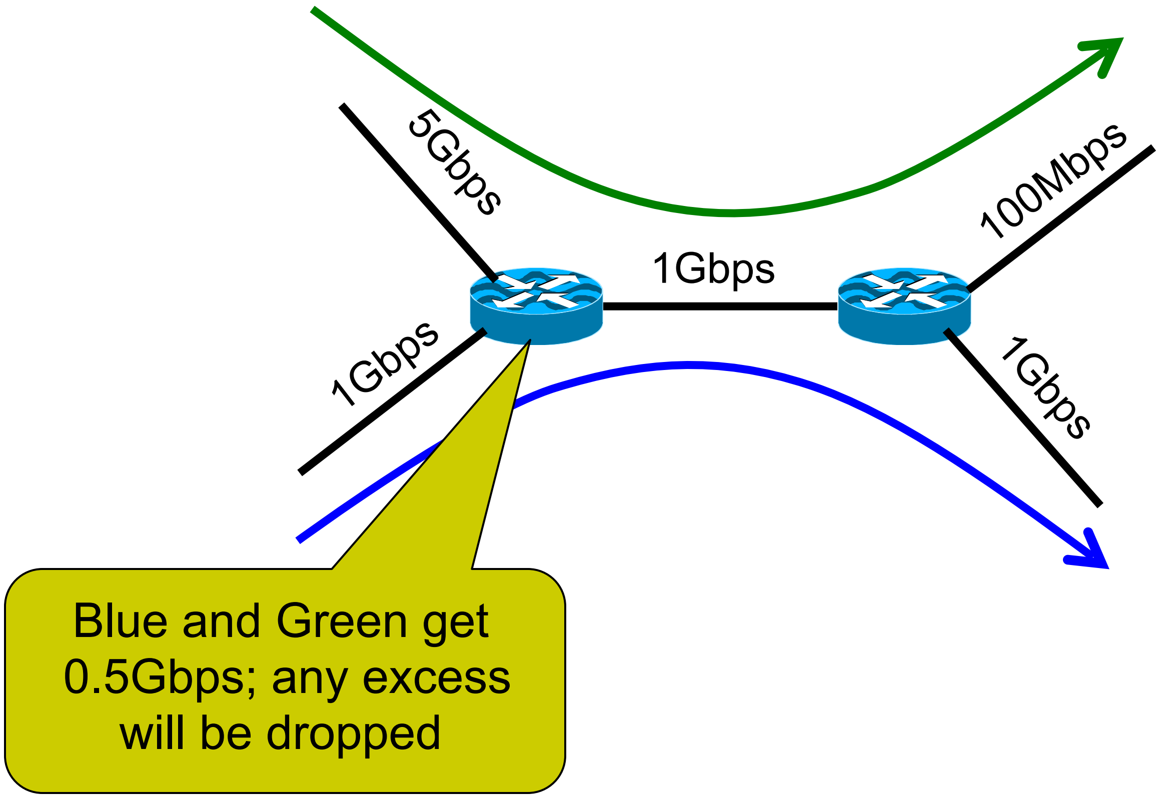

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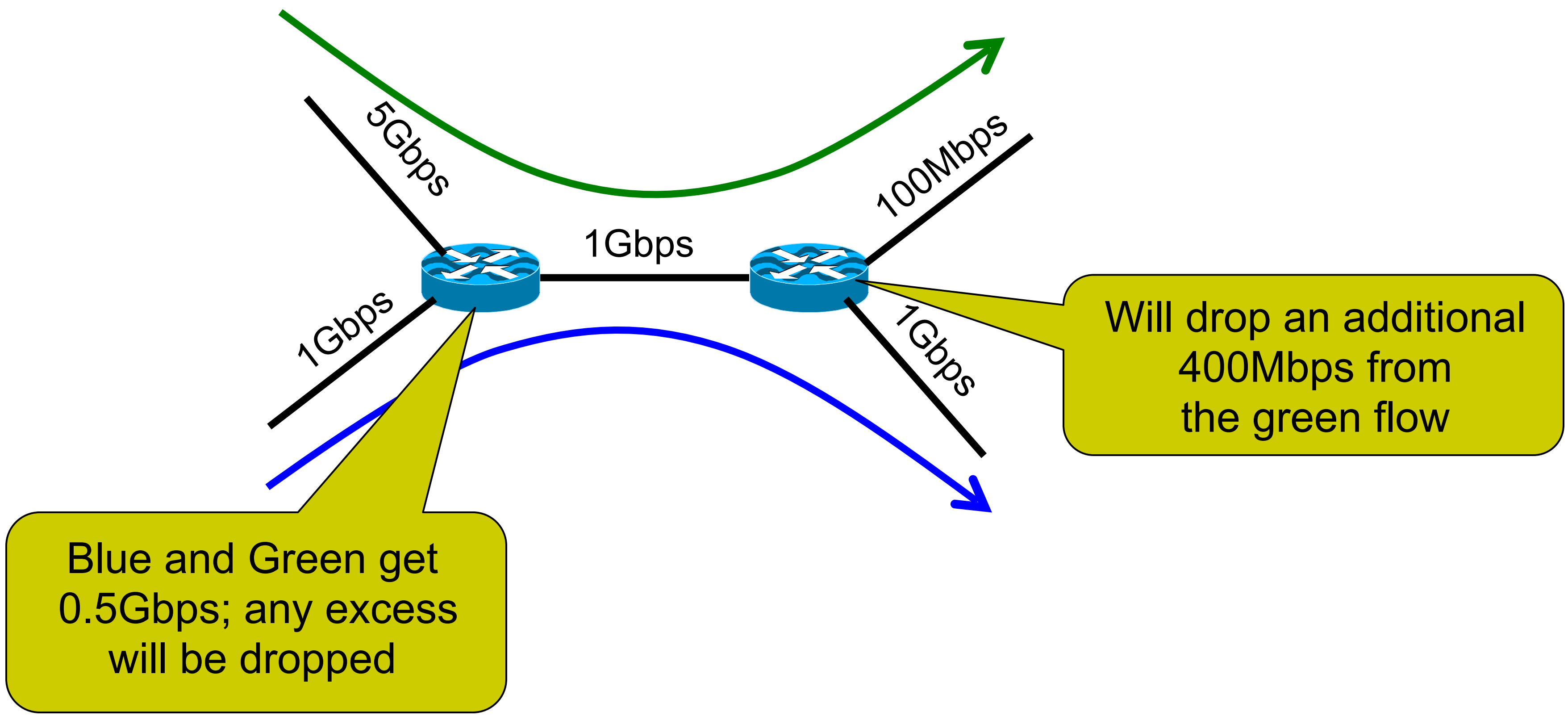

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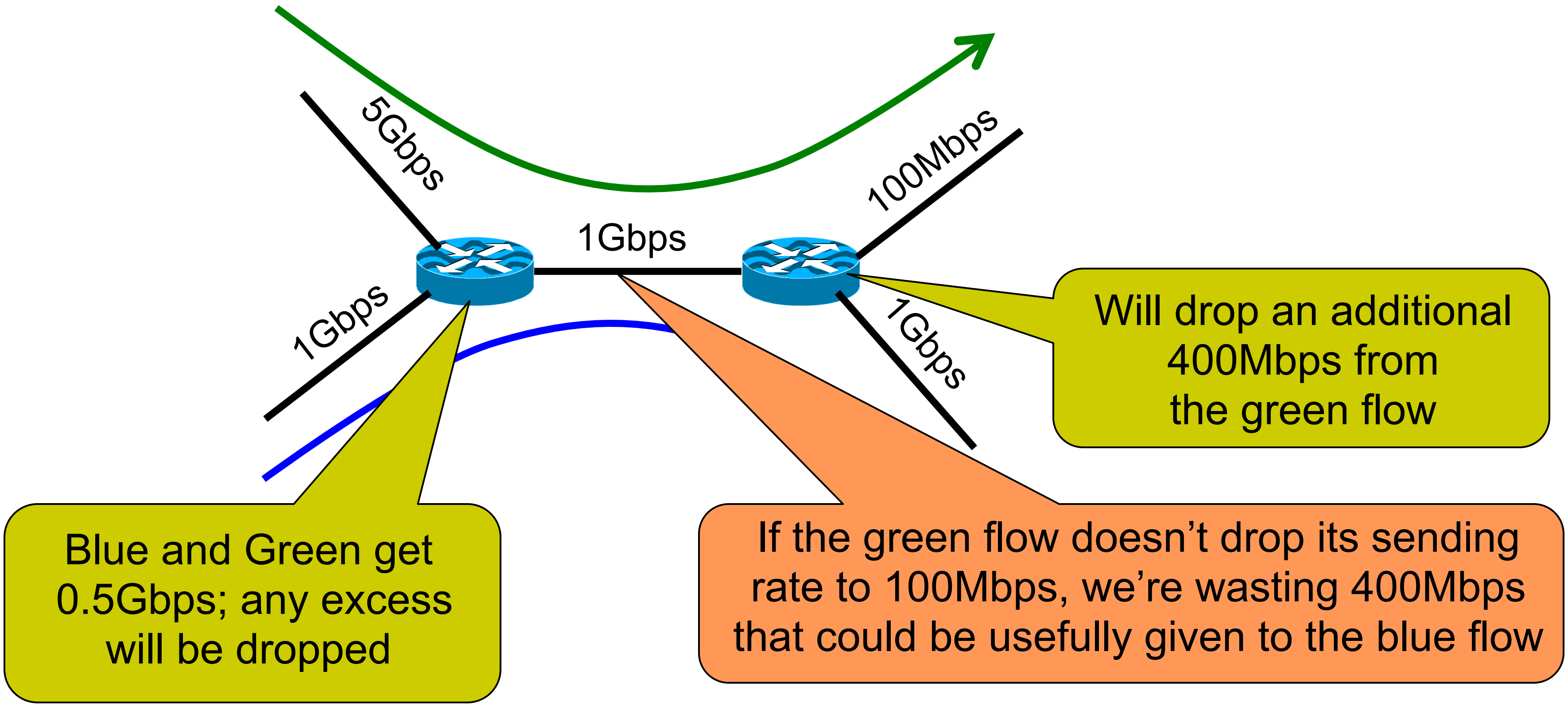

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- But congestion and packet drops still occur
- And we still want end-hosts to discover/adapt to their fair share!

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- Nonetheless, FQ/DRR is a great way to ensure **isolation**
  - Avoiding starvation even in the worst cases

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- Three ways routers can help
  - Enforce fairness
  - More precise rate adaptation
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- End-hosts set sending rate (or window size) to *f*

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- Today:
  - Widely implemented in routers
  - Commonly used in datacenters (e.g., Azure)

Recap: Router-Assisted CC

- FQ: routers *enforce* per-flow fairness
- RCP: routers *inform* endhosts of their fair share
- ECN: routers set “I’m congested” bit in packets

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  - Some require deployment at *every* router
- Though worth revisiting in datacenter contexts

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- Though datacenters are the CC agenda
  - different needs and constraints (future lecture)