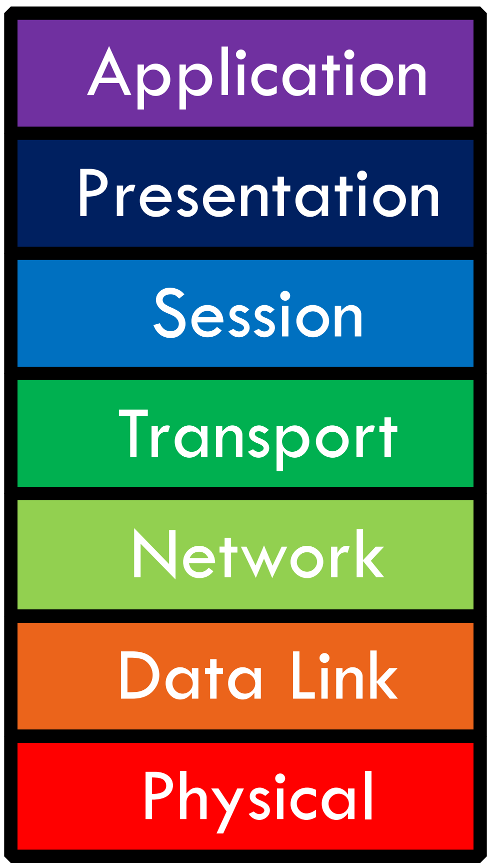
CS 3700

Networks and Distributed Systems

Lecture 10: Congestion Control

Revised 2/9/2014

Transport Layer



- Function:
  - Demultiplexing of data streams
- Optional functions:
  - Creating long lived connections
  - Reliable, in-order packet delivery
  - Error detection
  - Flow and congestion control
- Key challenges:
  - Detecting and responding to congestion
  - Balancing fairness against high utilization

Outline

- Congestion Control
- Evolution of TCP
- Problems with TCP

What is Congestion?

- Load on the network is higher than capacity

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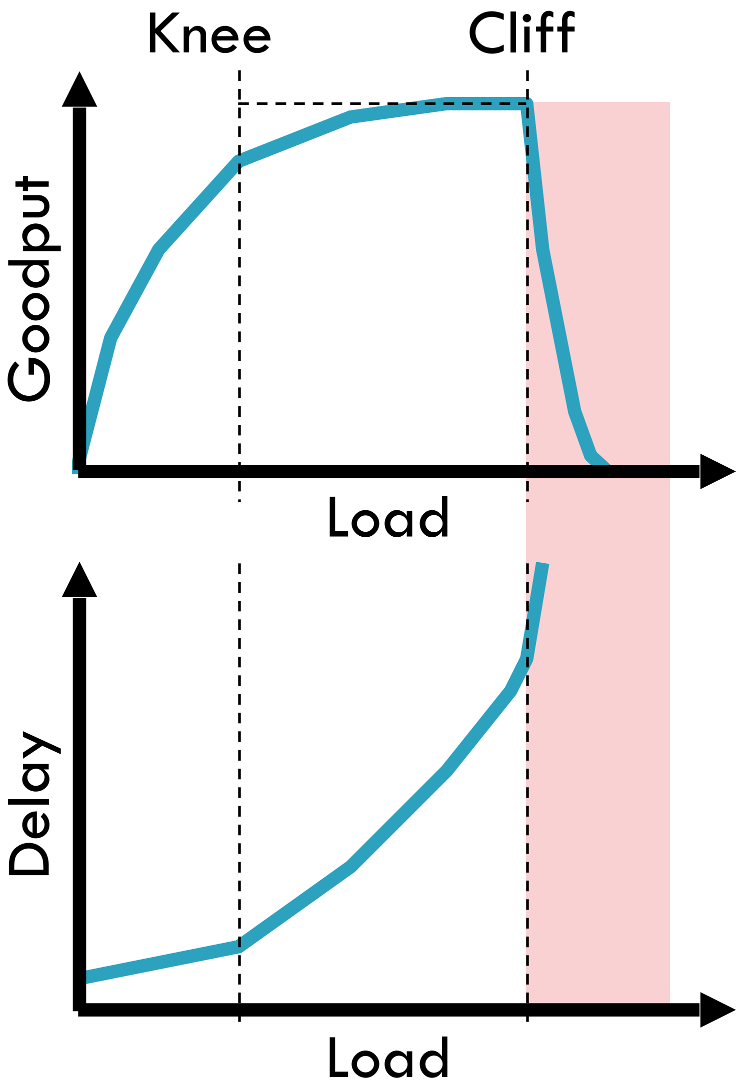
- Load on the network is higher than capacity
  - Capacity is not uniform across networks
    - Modem vs. Cellular vs. Cable vs. Fiber Optics
  - There are multiple flows competing for bandwidth
    - Residential cable modem vs. corporate datacenter
  - Load is not uniform over time
    - 10pm, Sunday night = Bittorrent Game of Thrones

Why is Congestion Bad?

- Results in packet loss
  - Routers have finite buffers
  - Internet traffic is self similar, no buffer can prevent all drops
  - When routers get overloaded, packets will be dropped
- Practical consequences
  - Router queues build up, delay increases
  - Wasted bandwidth from retransmissions
  - Low network goodput

The Danger of Increasing Load

- Knee – point after which
  - Throughput increases very slow
  - Delay increases fast
- In an M/M/1 queue
  - Delay = 1/(1 – utilization)
- Cliff – point after which
  - Throughput → 0
  - Delay → ∞



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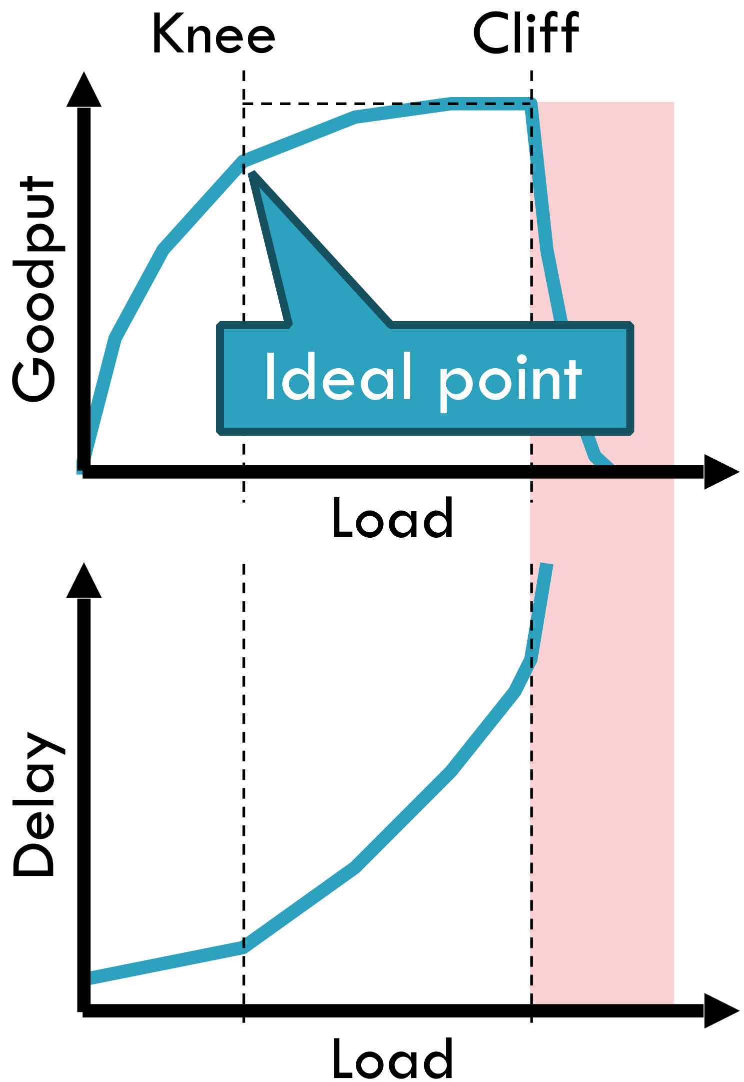

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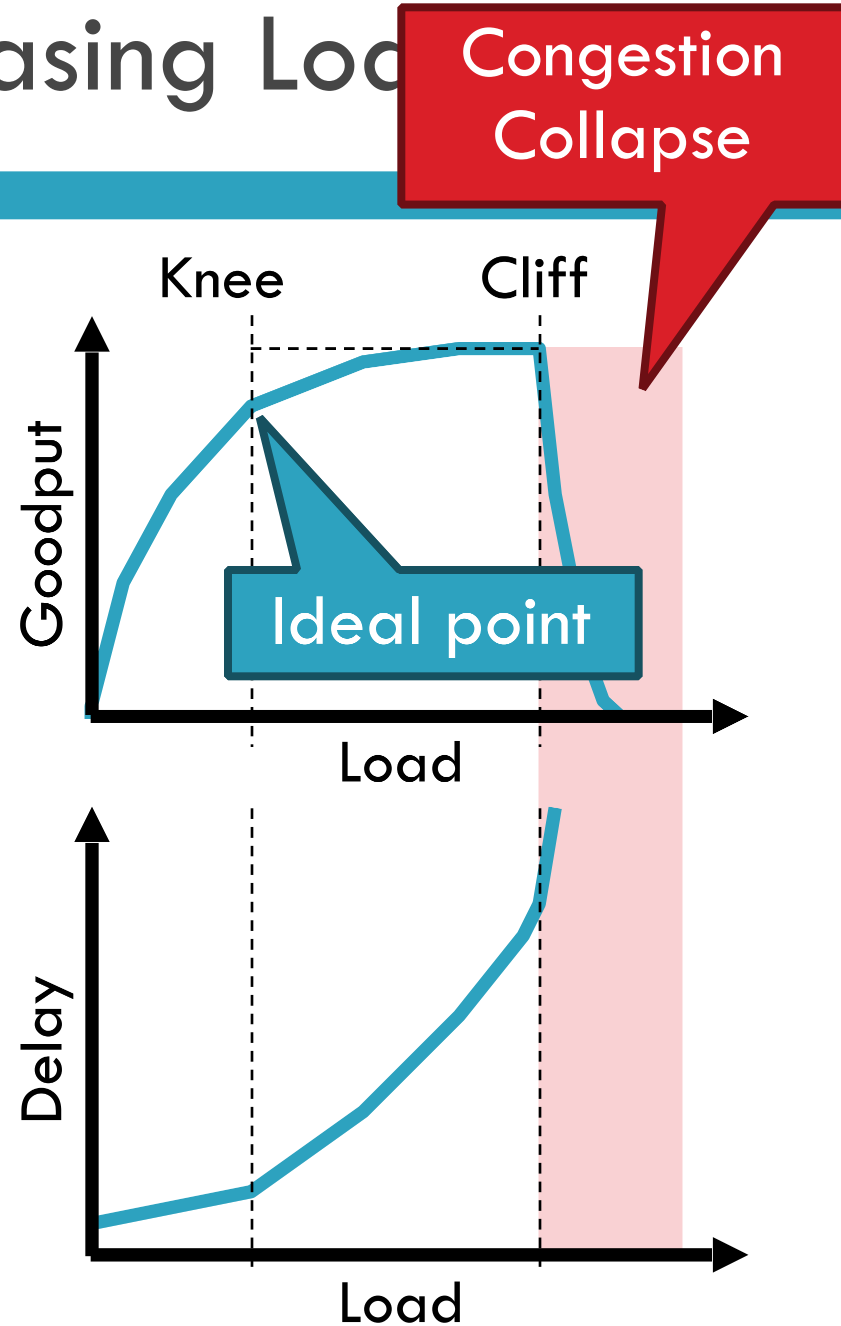
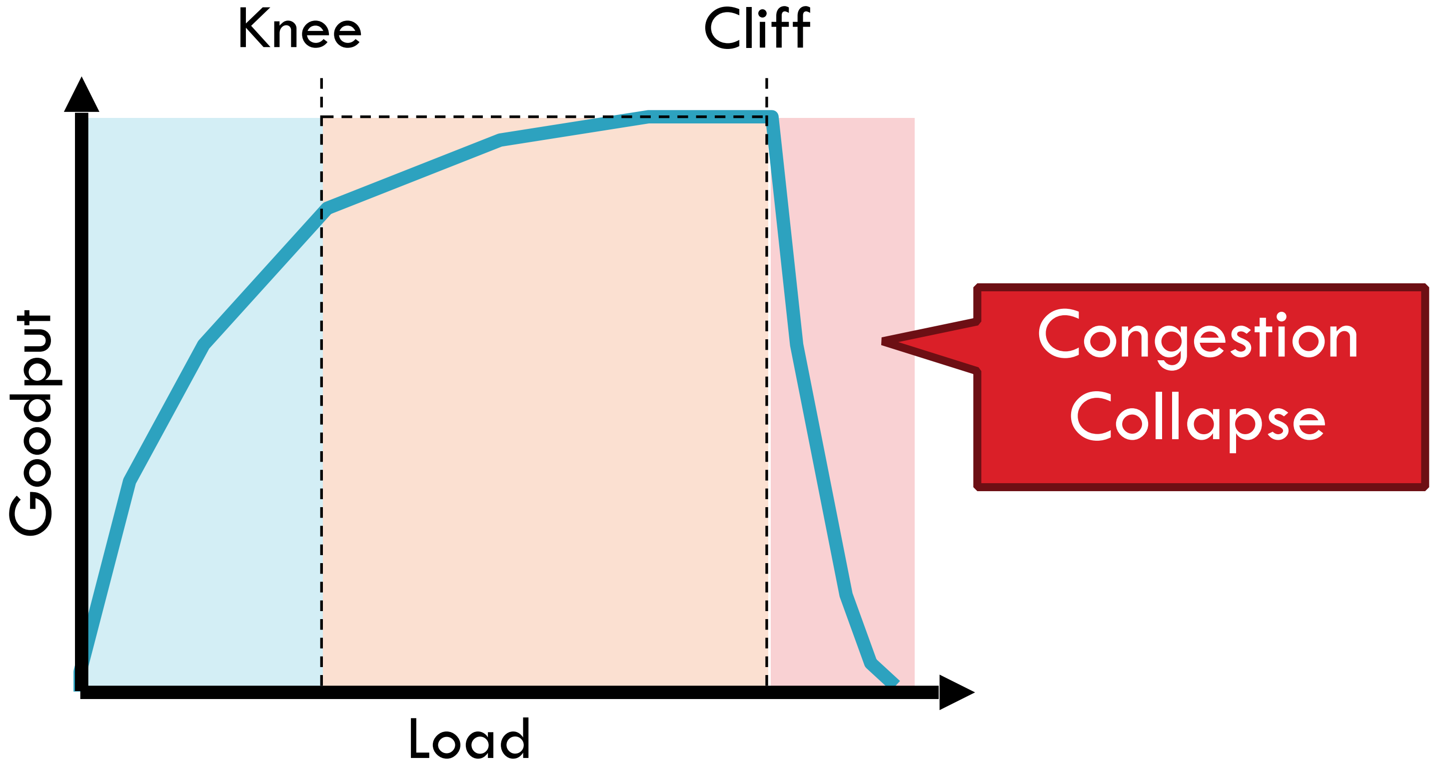


Cong. Control vs. Cong. Avoidance



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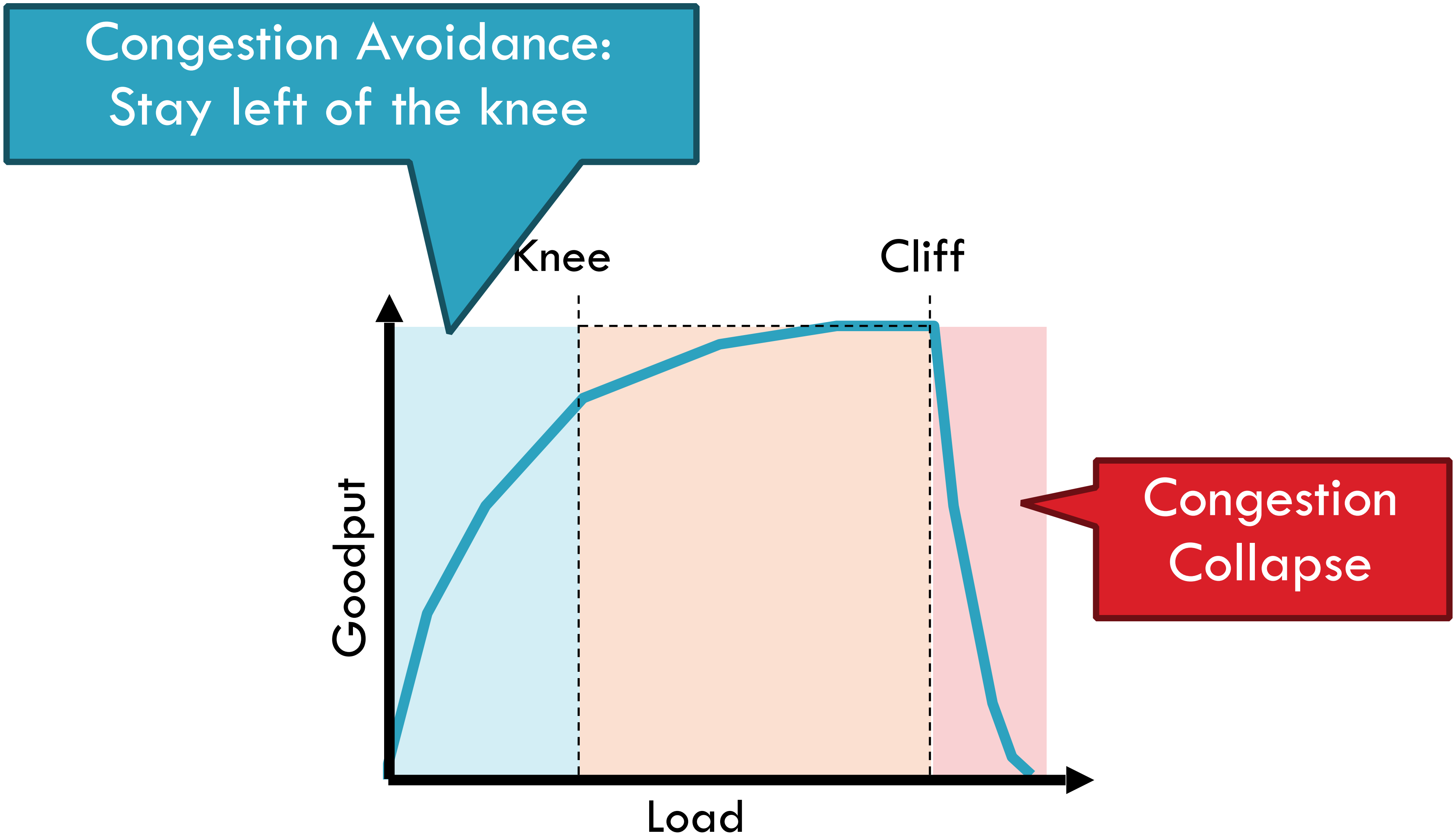

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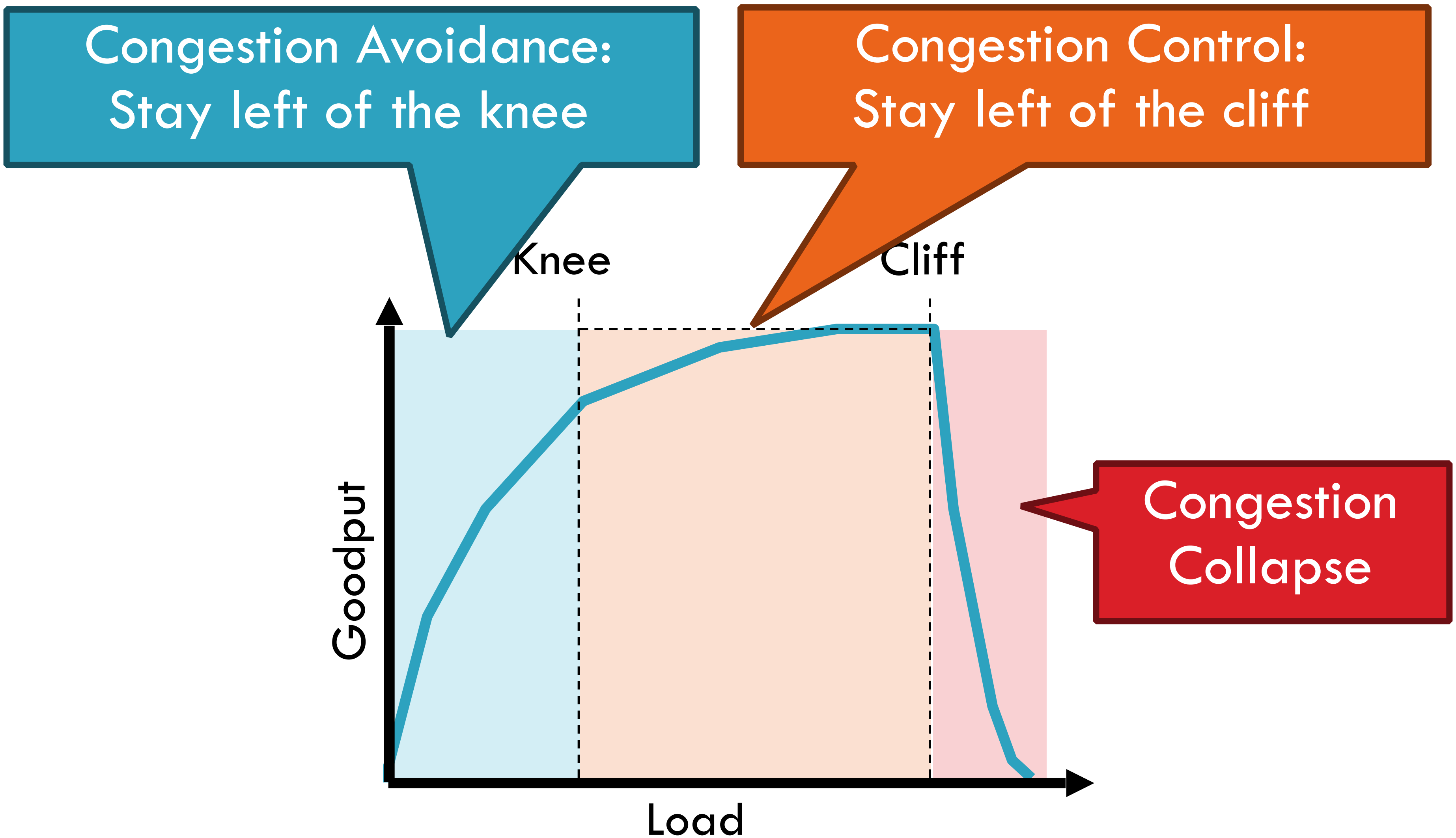

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- Key points
  - Window size determines send rate
  - Window must be adjusted to prevent congestion collapse

Goals of Congestion Control

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1. Adjusting to the bottleneck bandwidth
2. Adjusting to variations in bandwidth
3. Sharing bandwidth between flows
4. Maximizing throughput

General Approaches

- Do nothing, send packets indiscriminately
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- Idea: vary the window size to control the send rate
- Introduce a congestion window at the sender
  - Congestion control is sender-side problem

Congestion Window (*cwnd*)

- Limits how much data is in transit
- Denominated in bytes

1. *wnd* = min(*cwnd*, *adv_wnd*);
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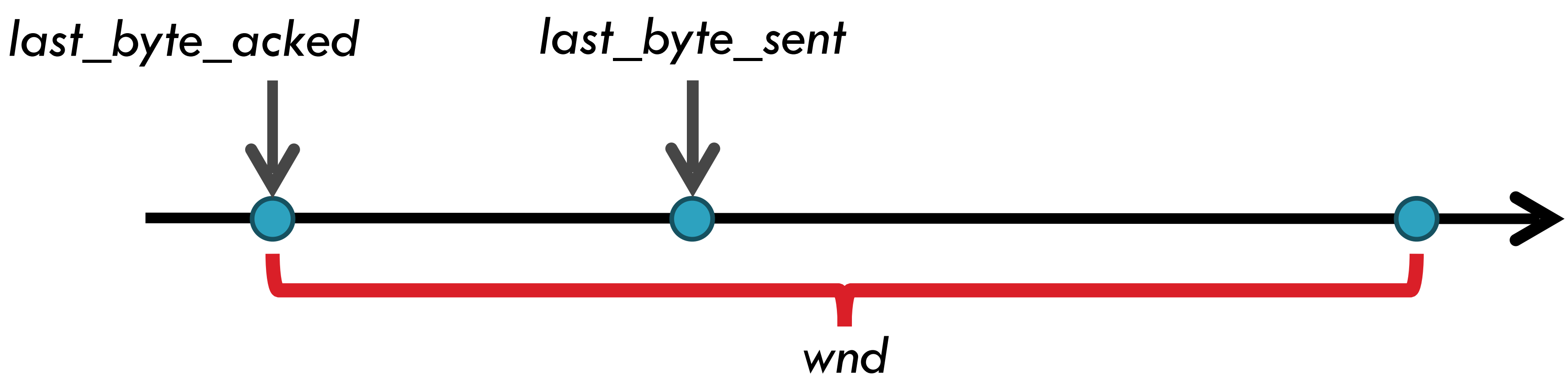

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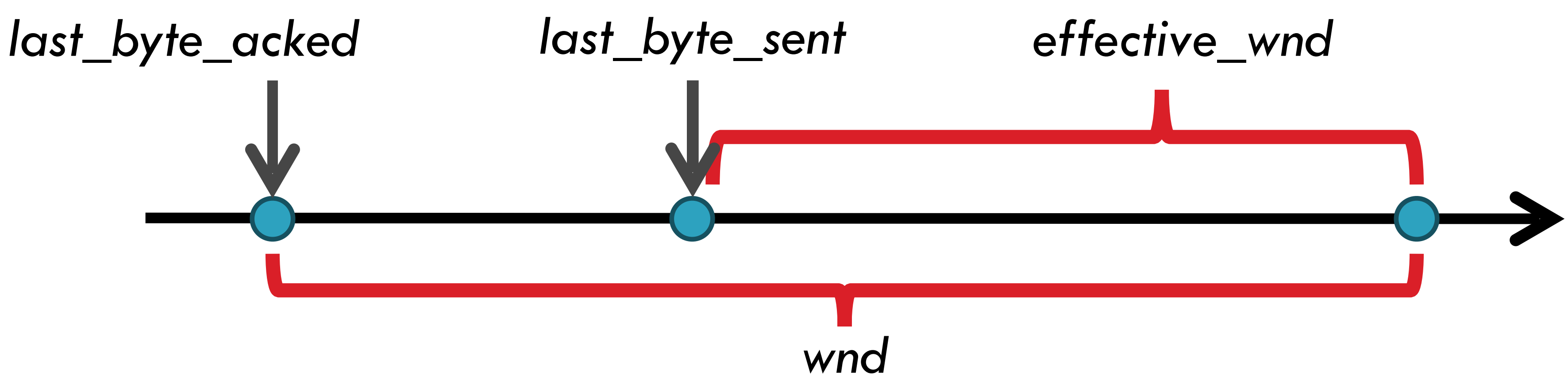

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   - Packet dropping is most reliably signal
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2. Rate adjustment algorithm
   - Modify *cwnd*
   - Probe for bandwidth
   - Responding to congestion

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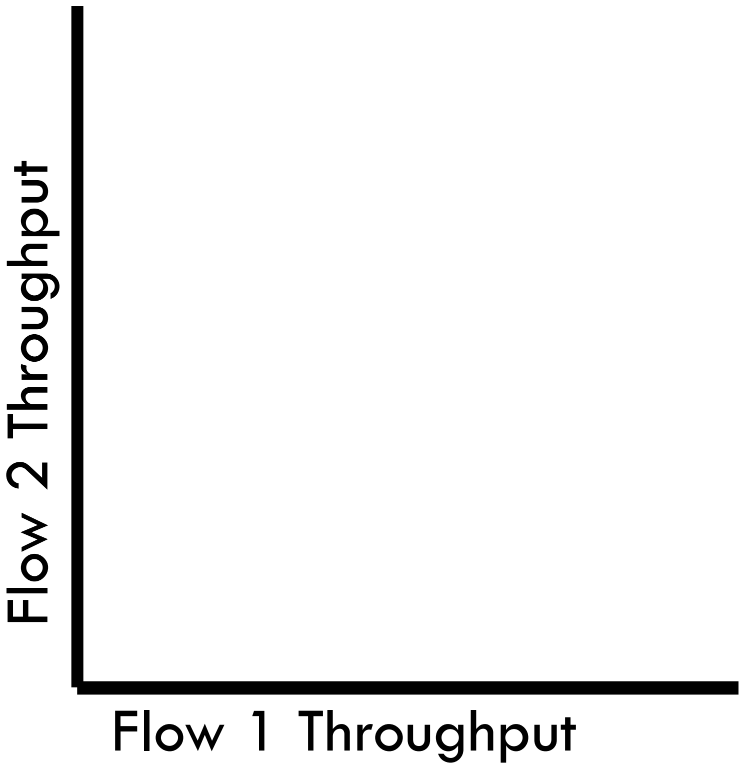
- Question: increase/decrease functions to use?

Utilization and Fairness



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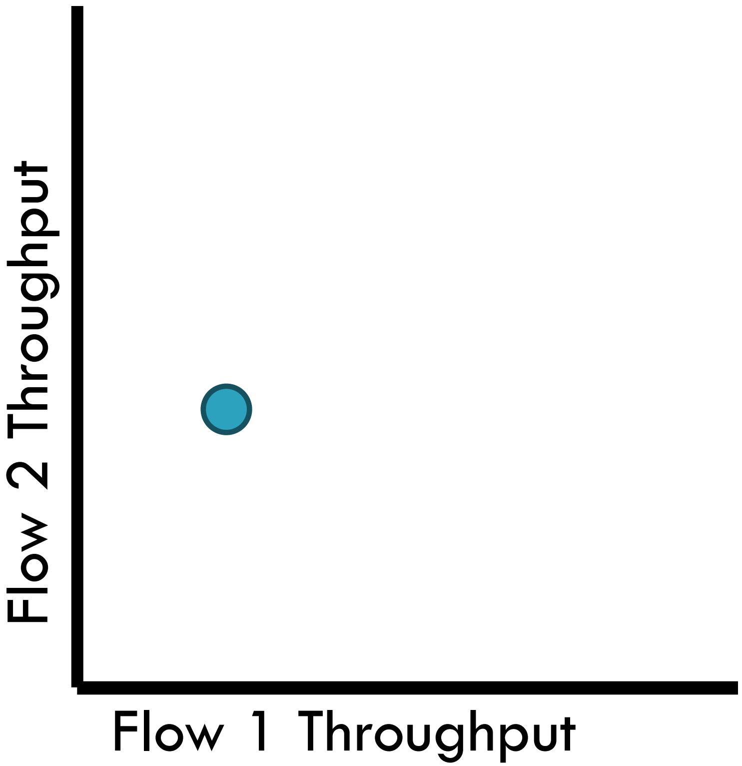

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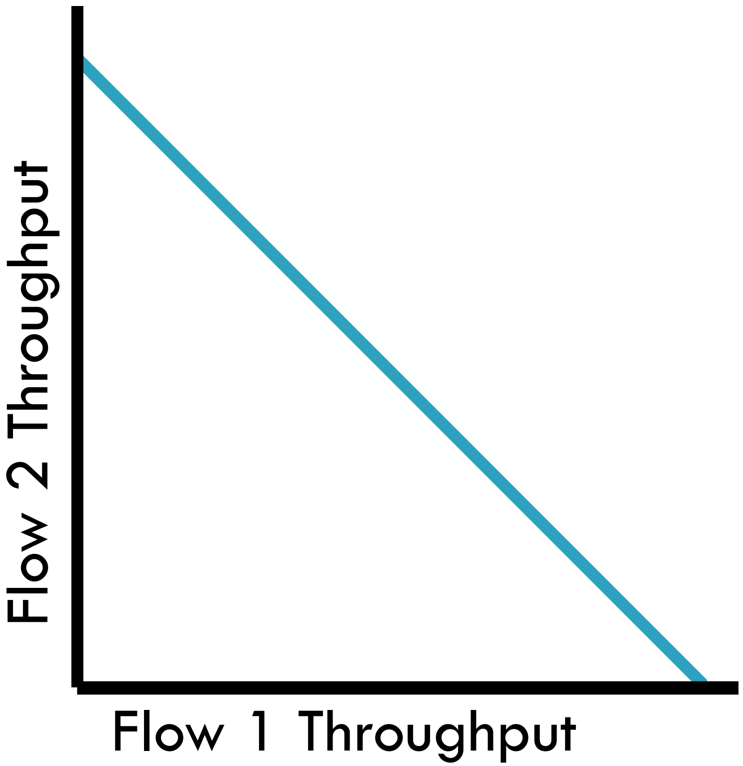

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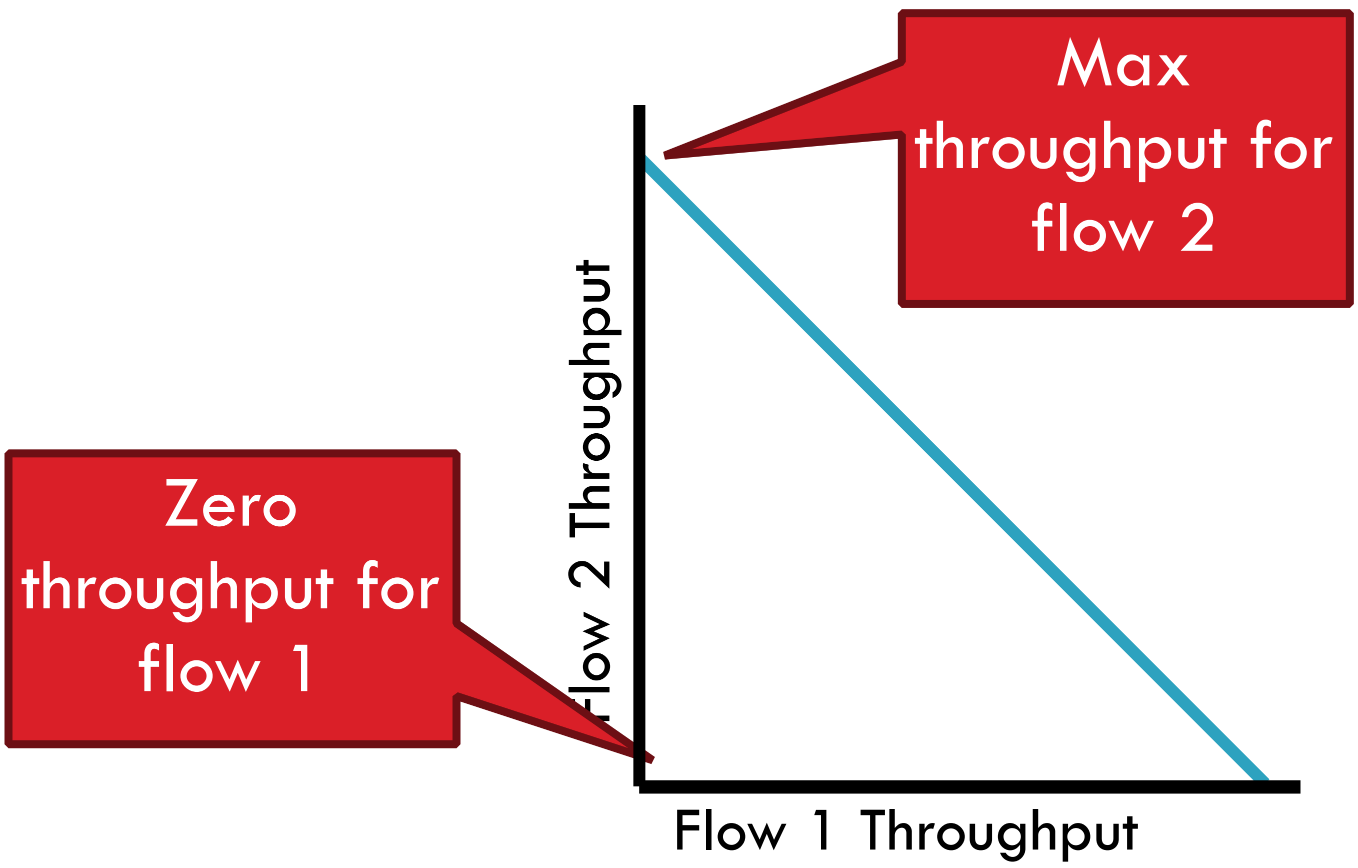

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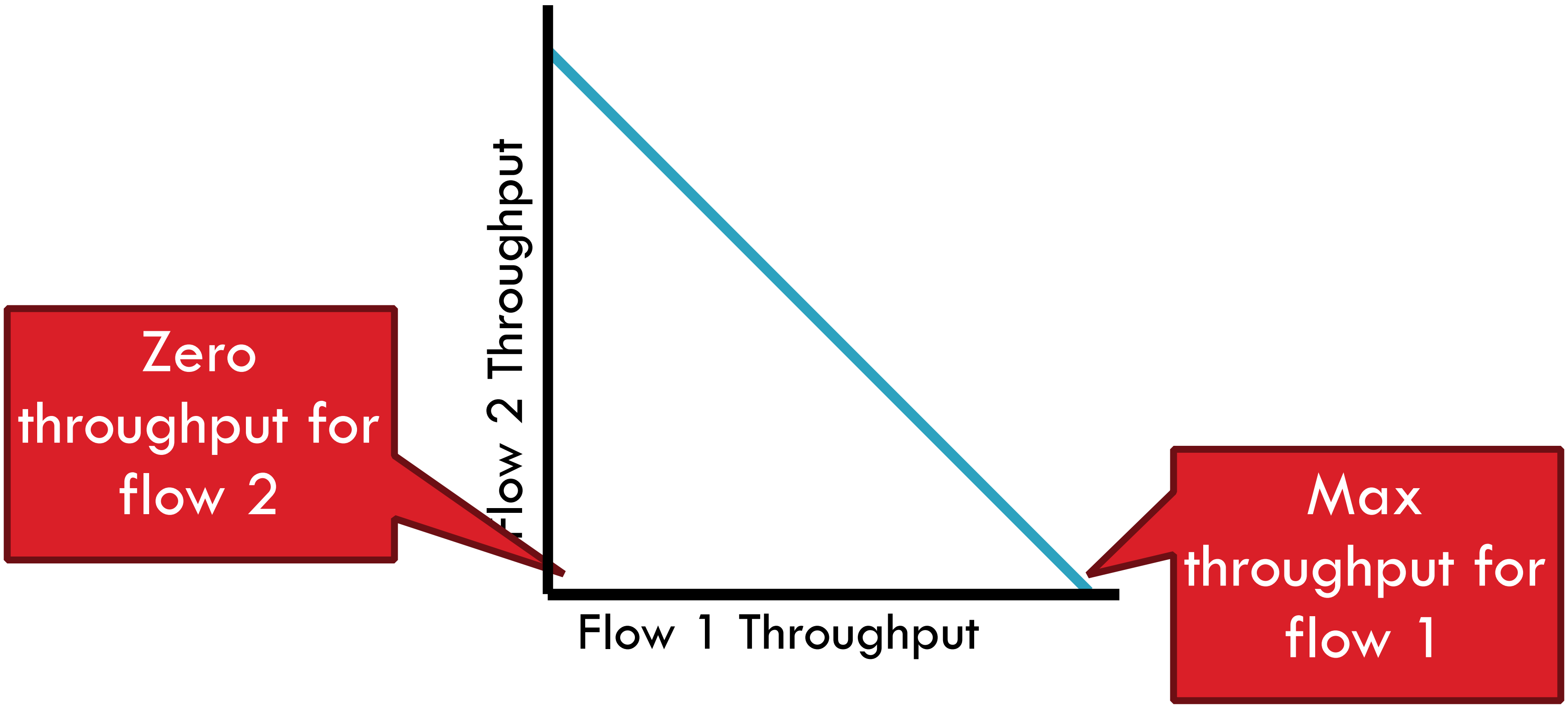

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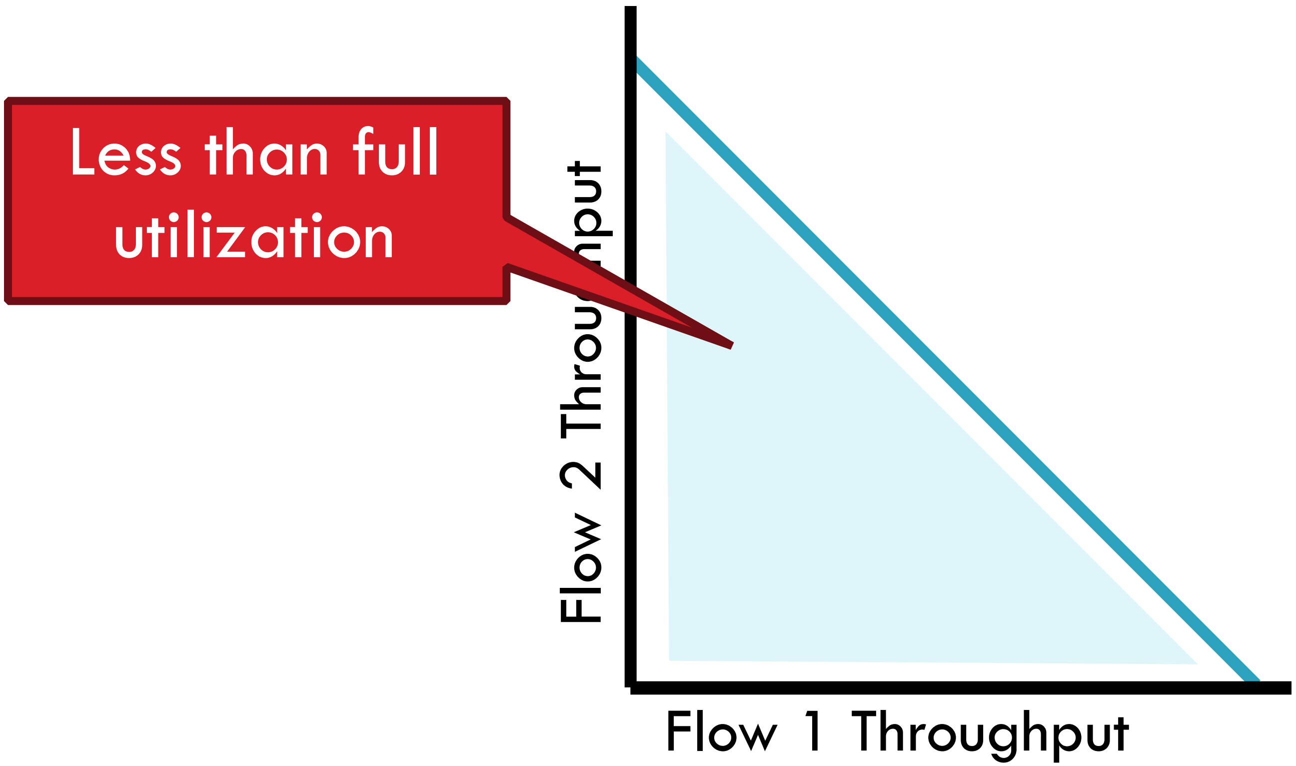

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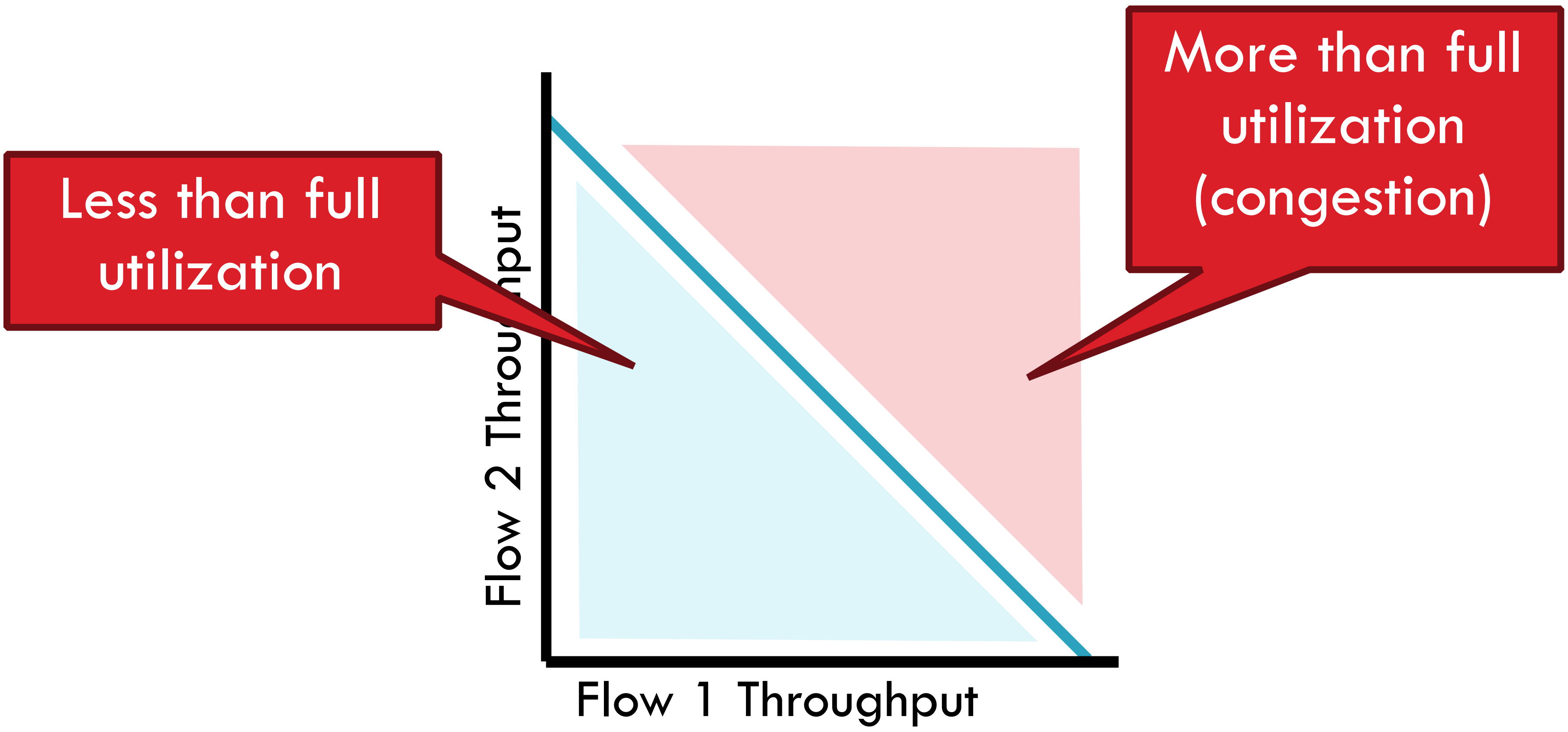

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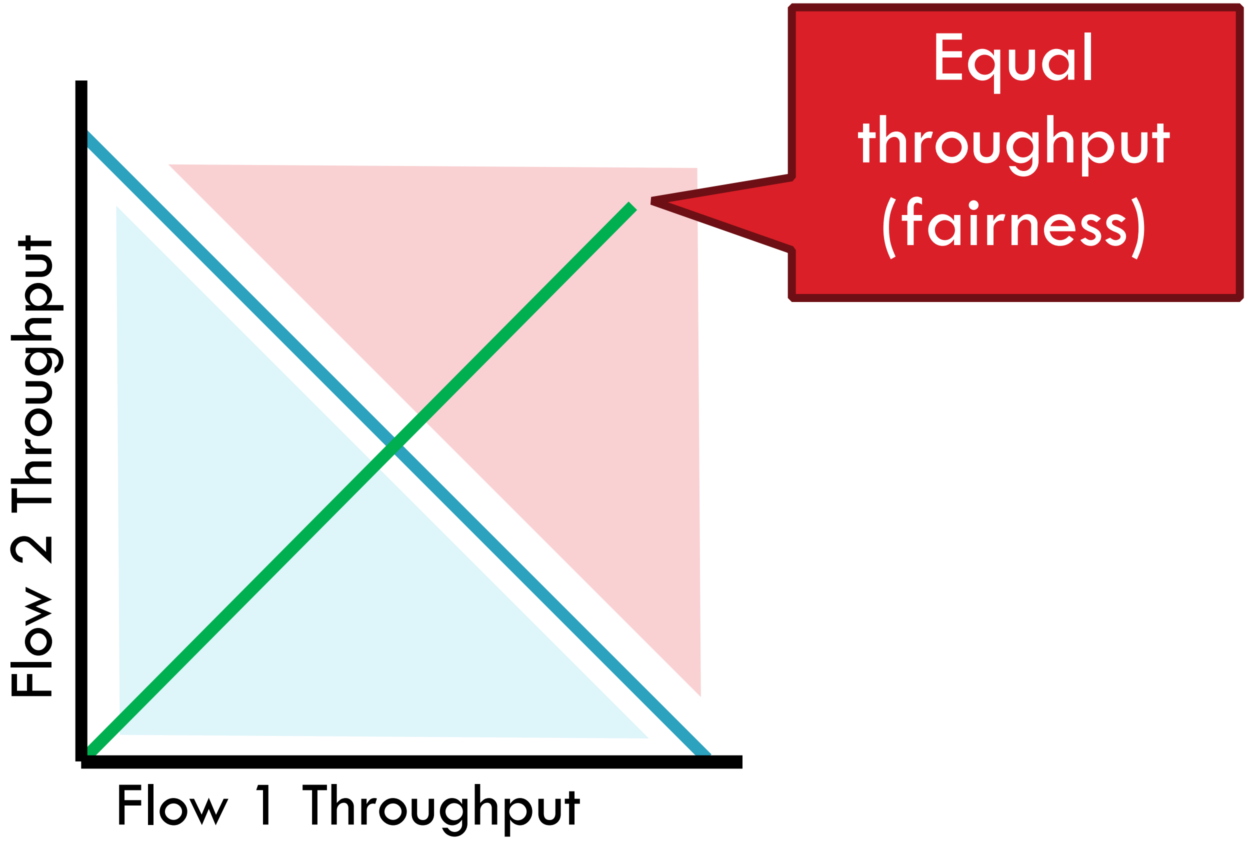

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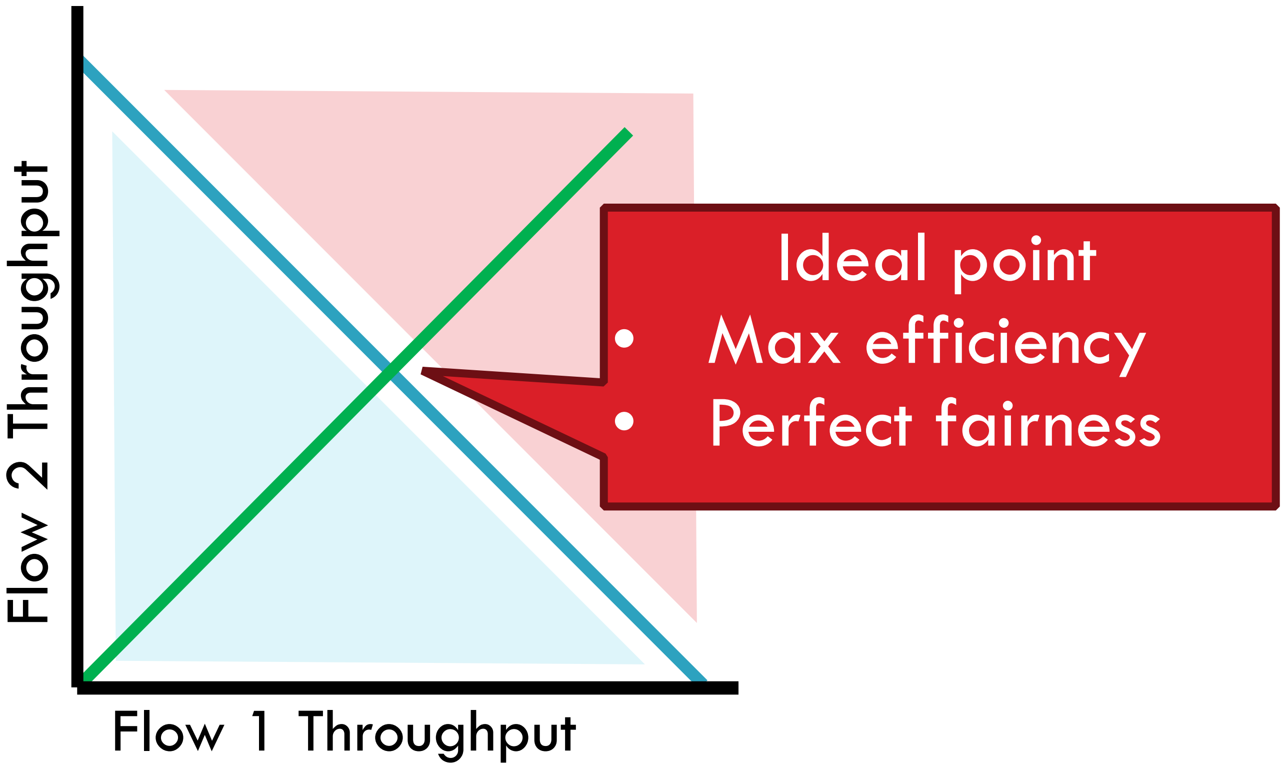
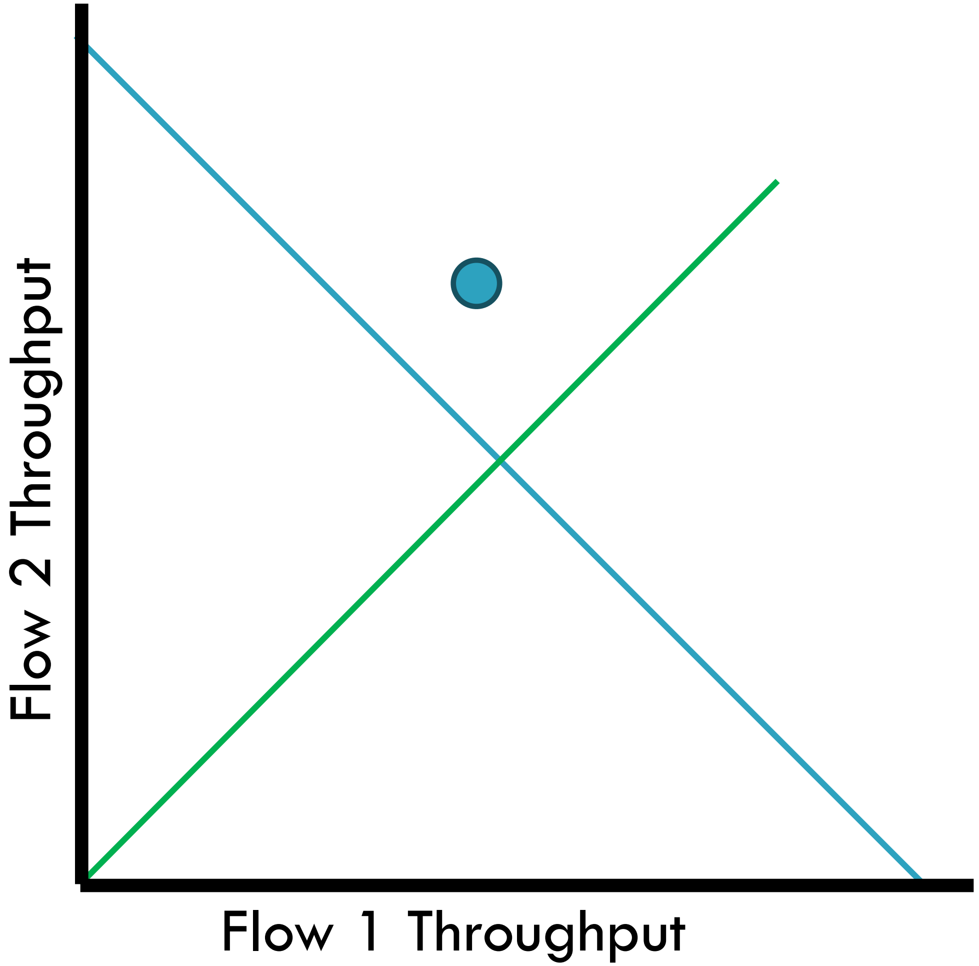


Multiplicative Increase, Additive Decrease



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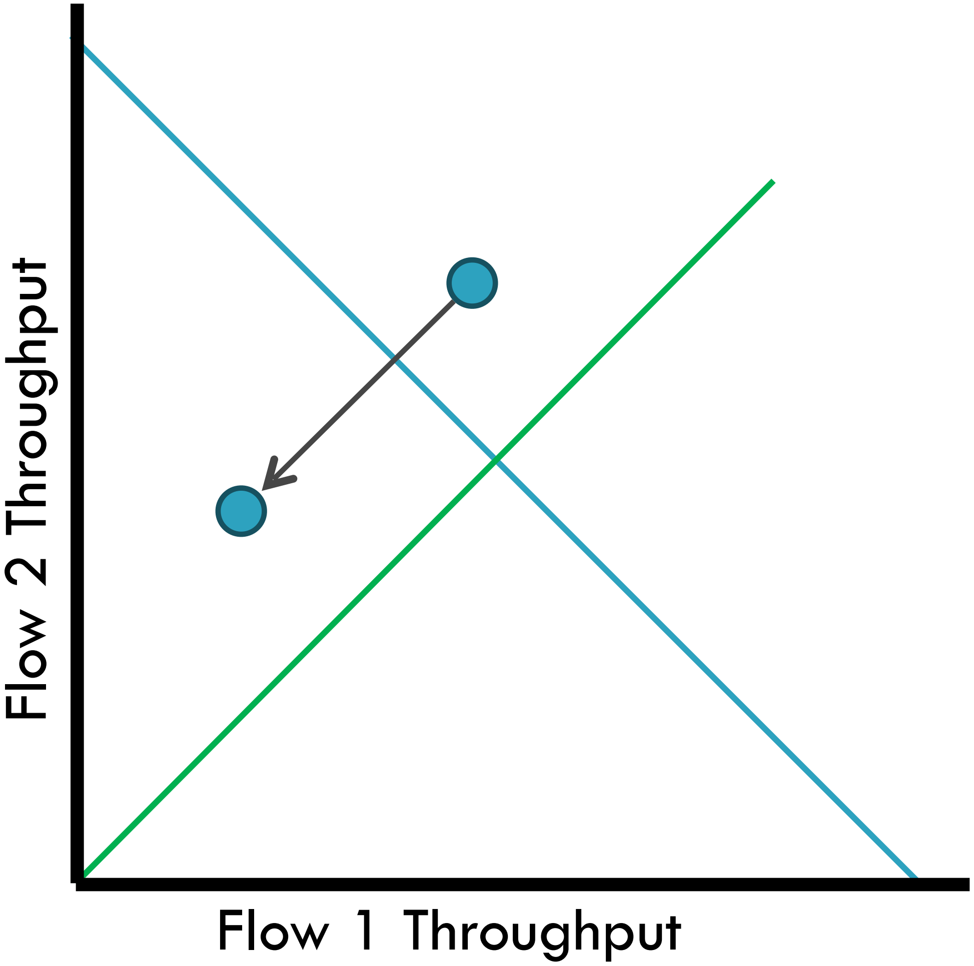

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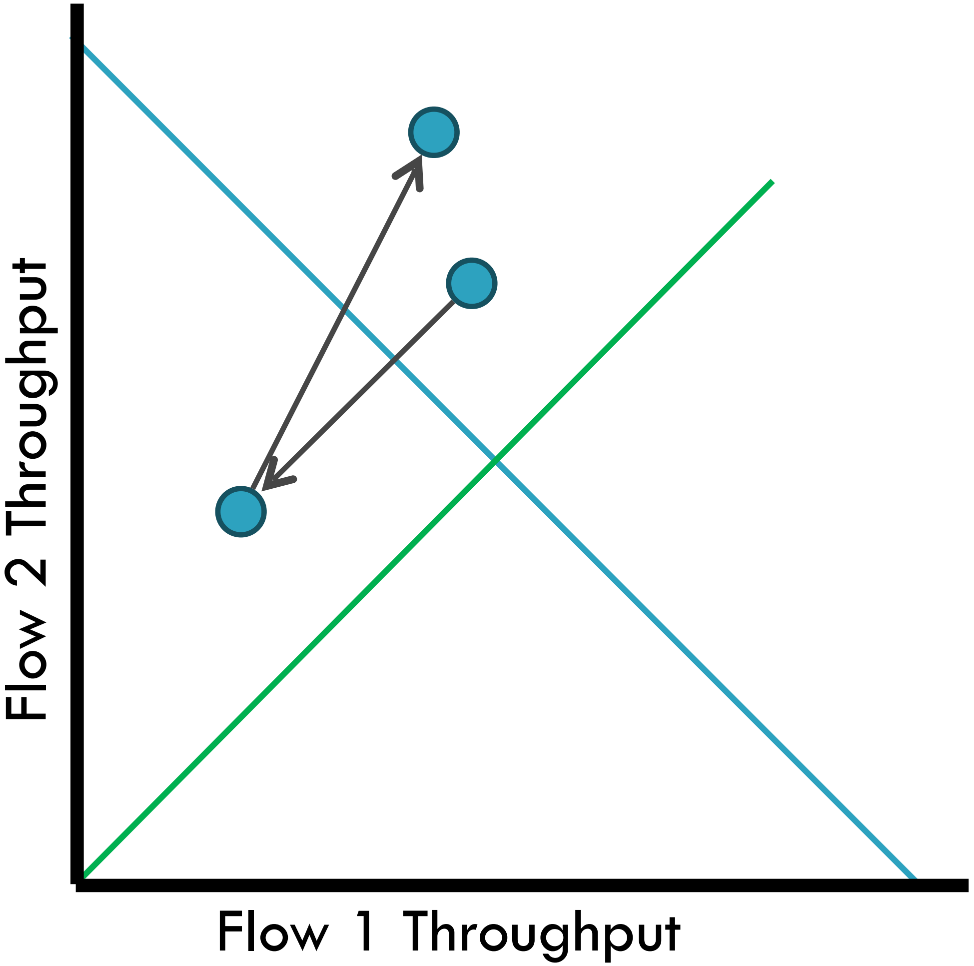

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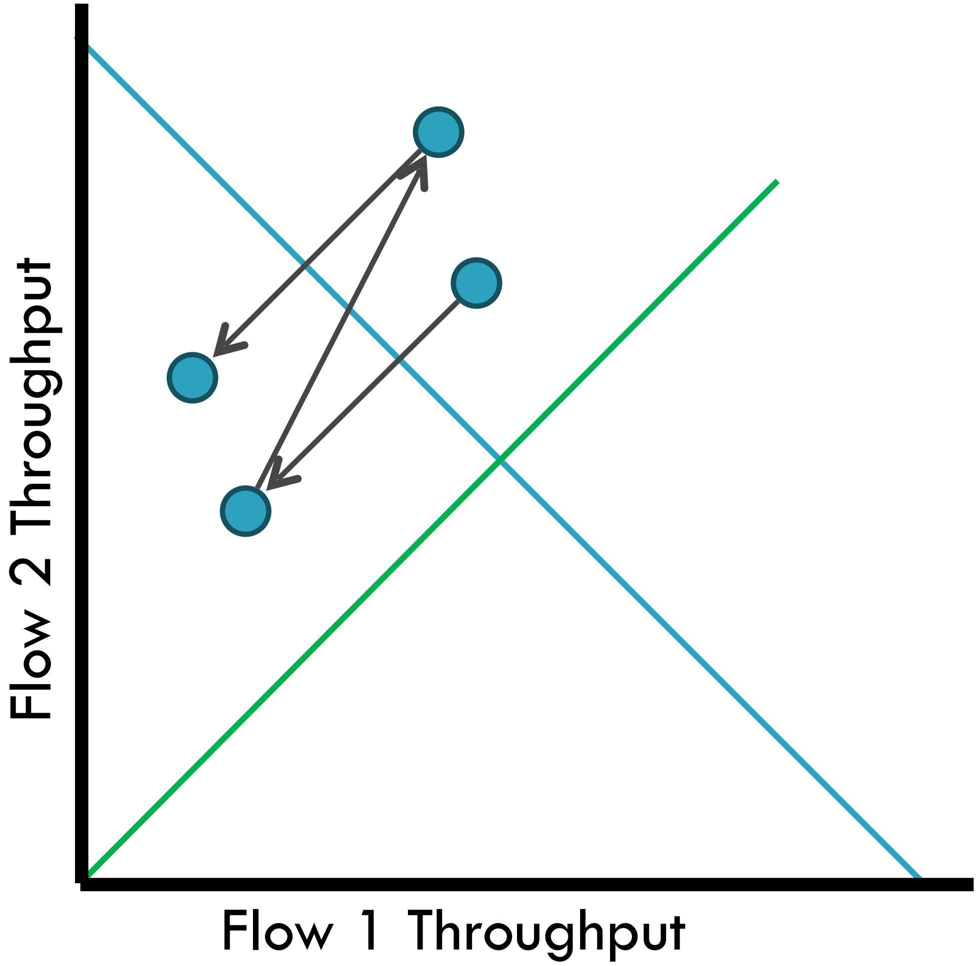

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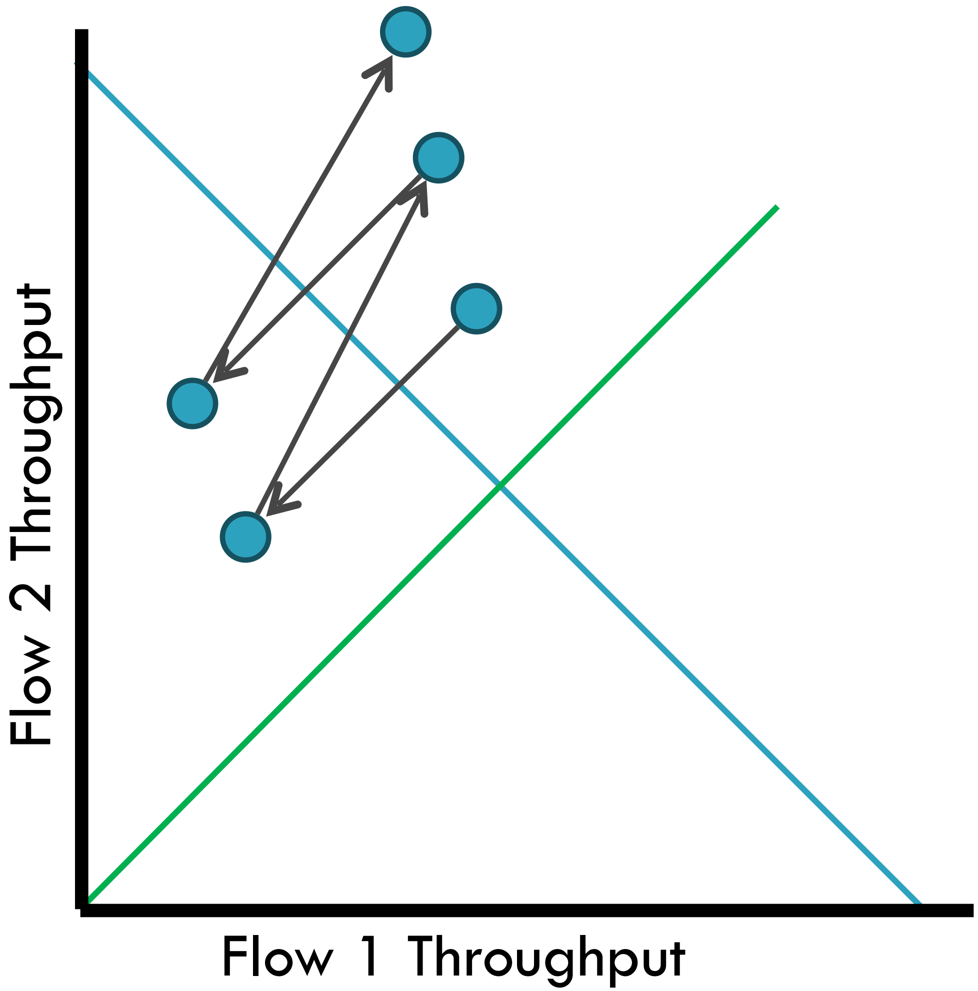

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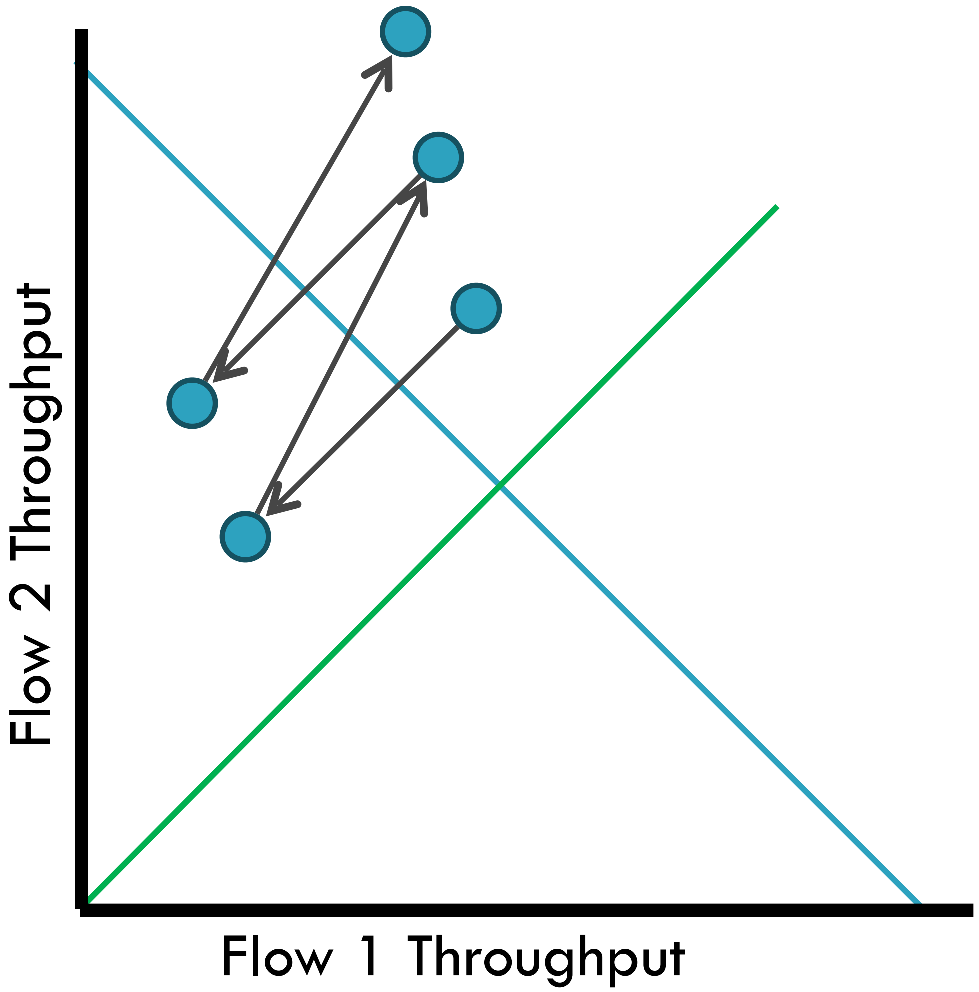
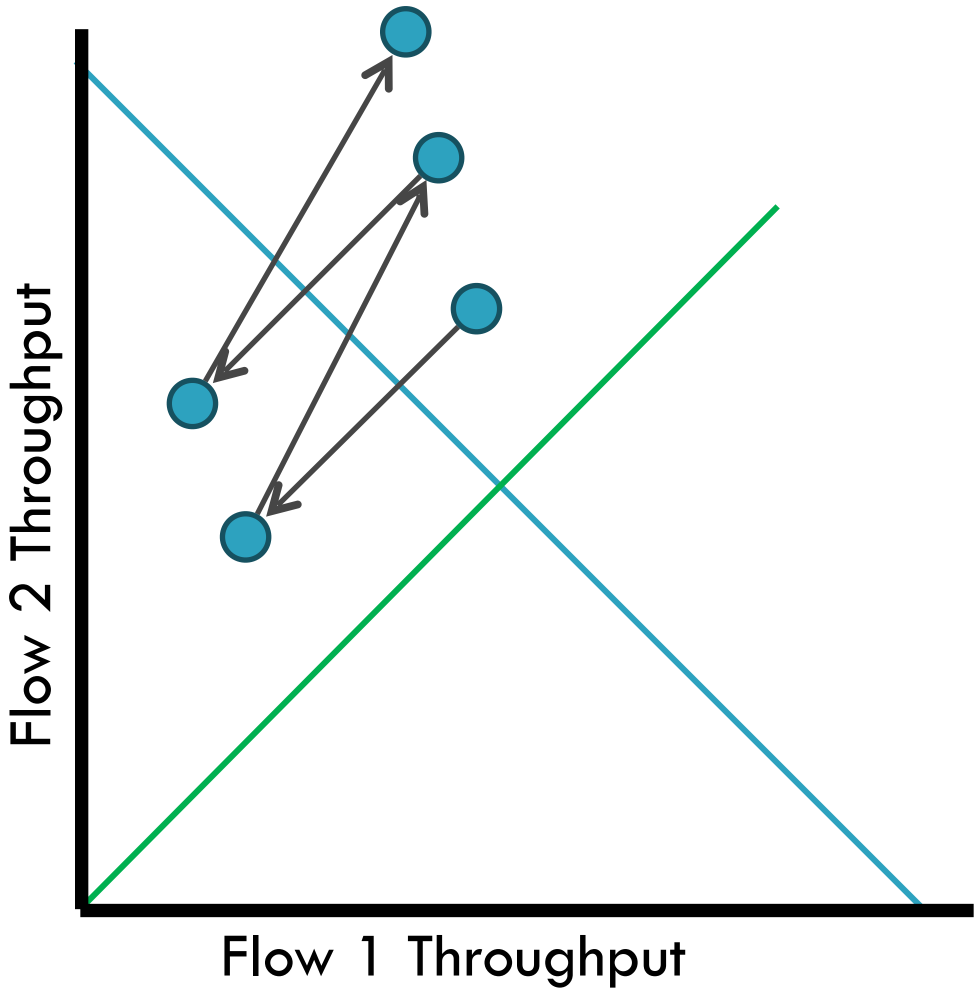


Multiplicative Increase, Additive Decrease

- Not stable!
- Veers away from fairness



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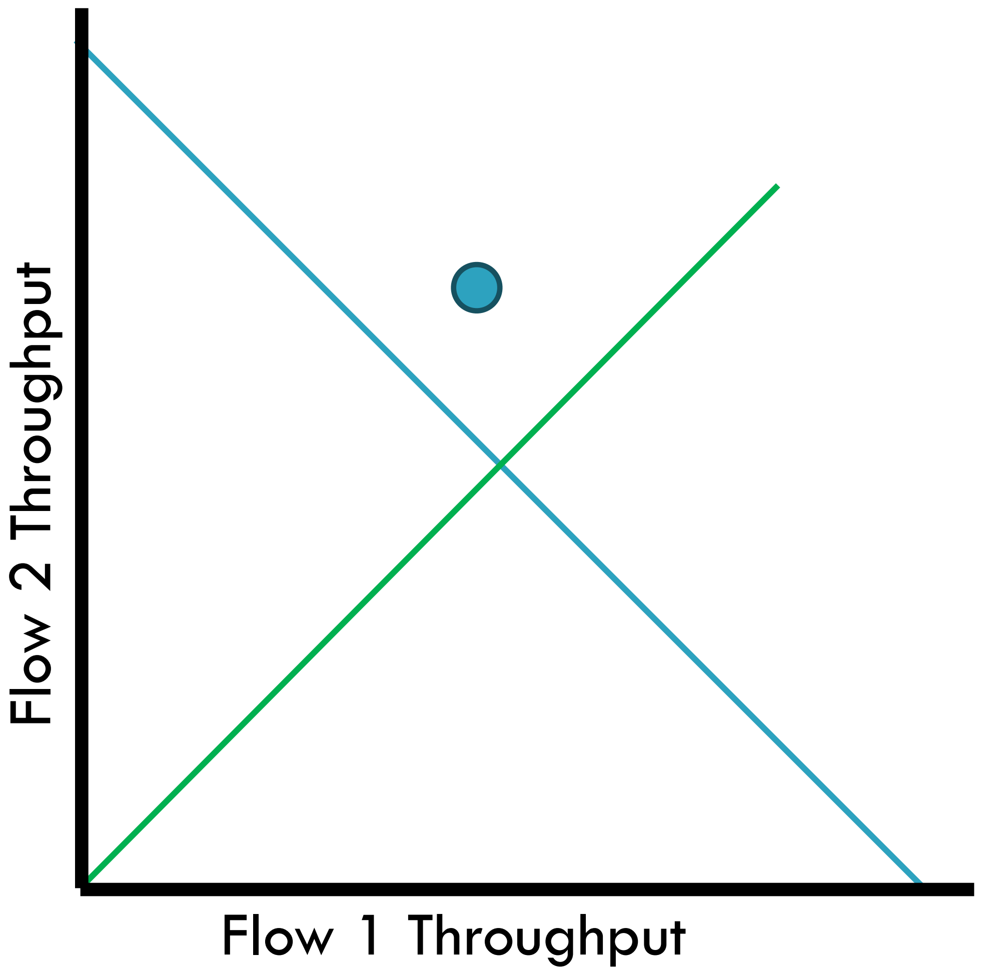

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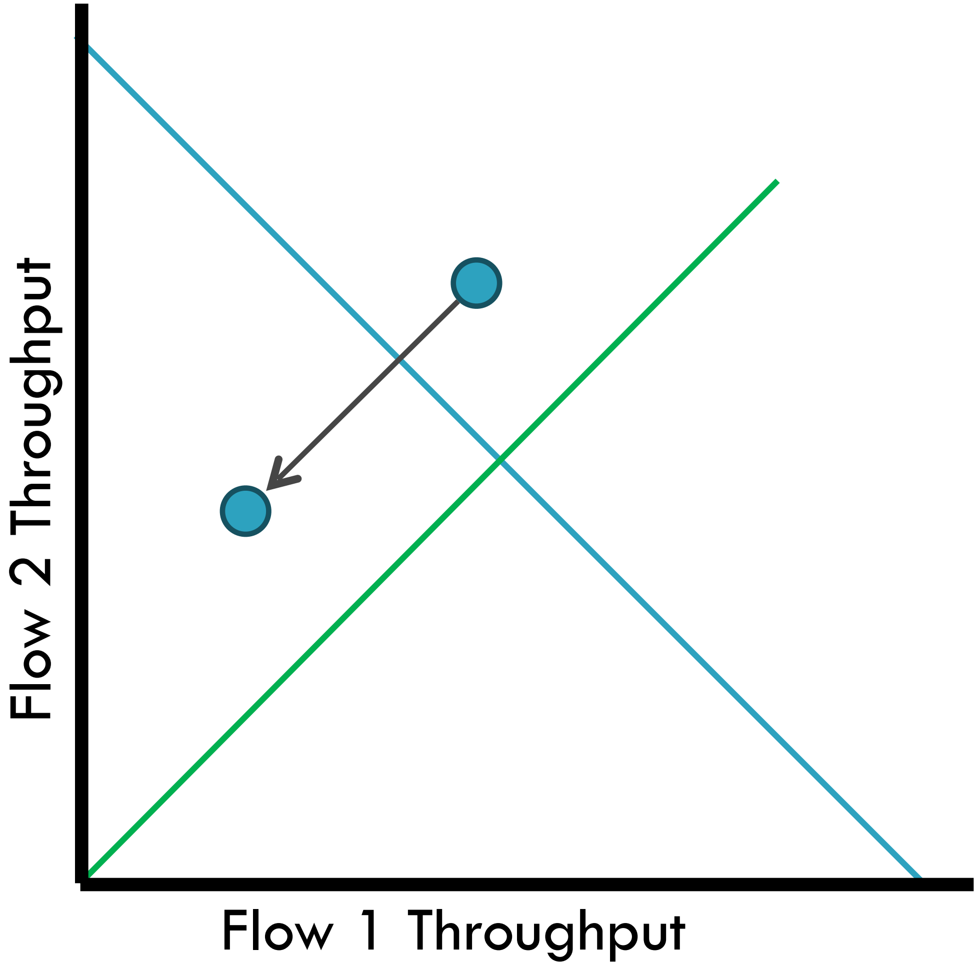

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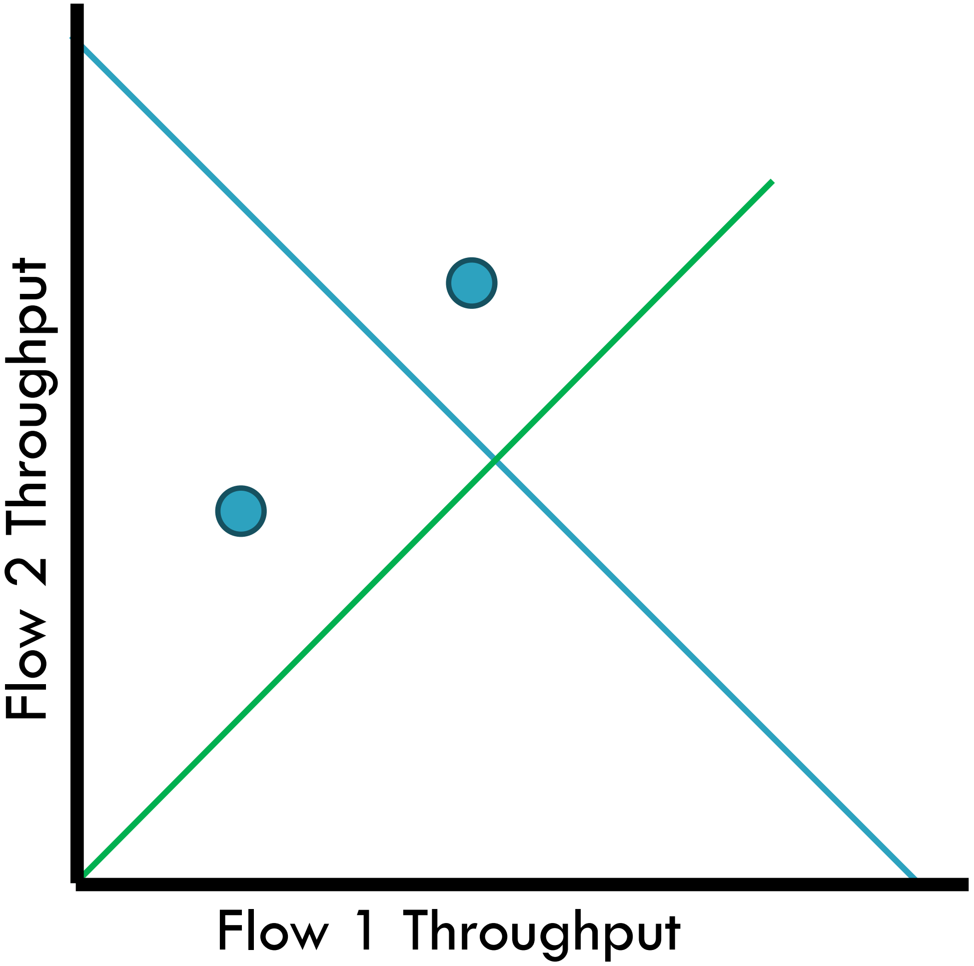

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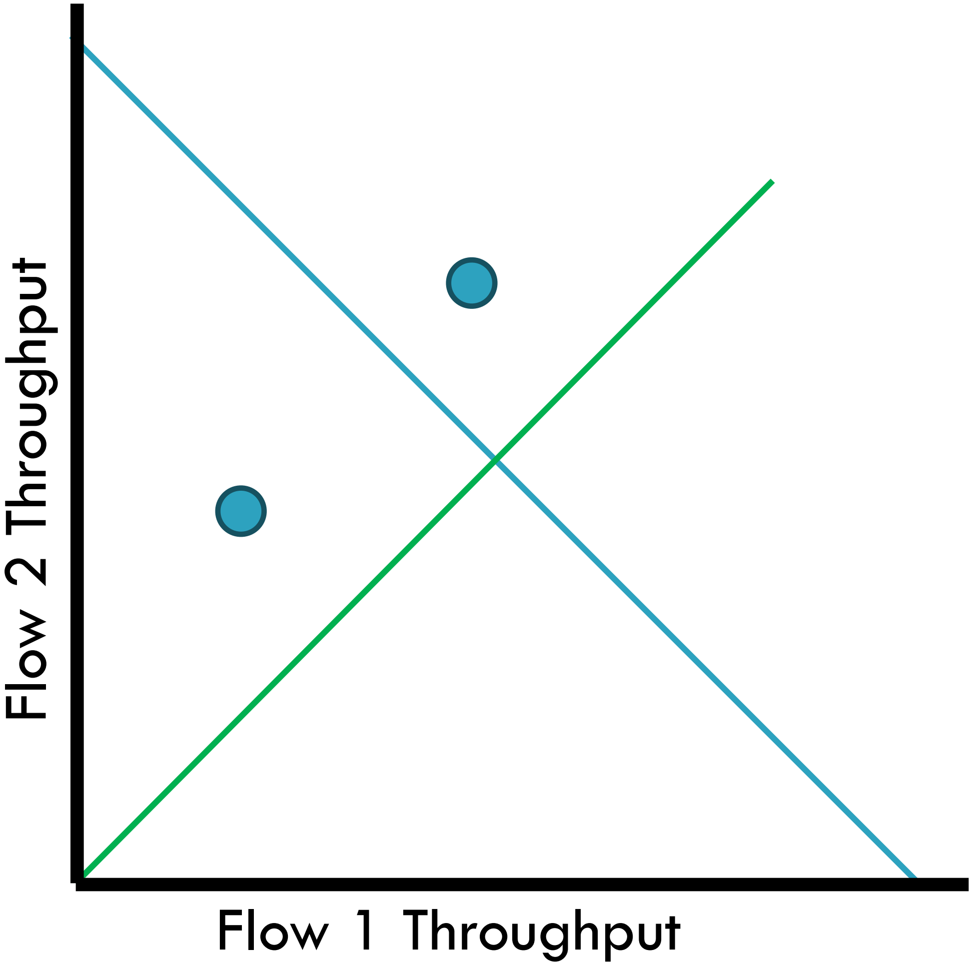

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- Stable
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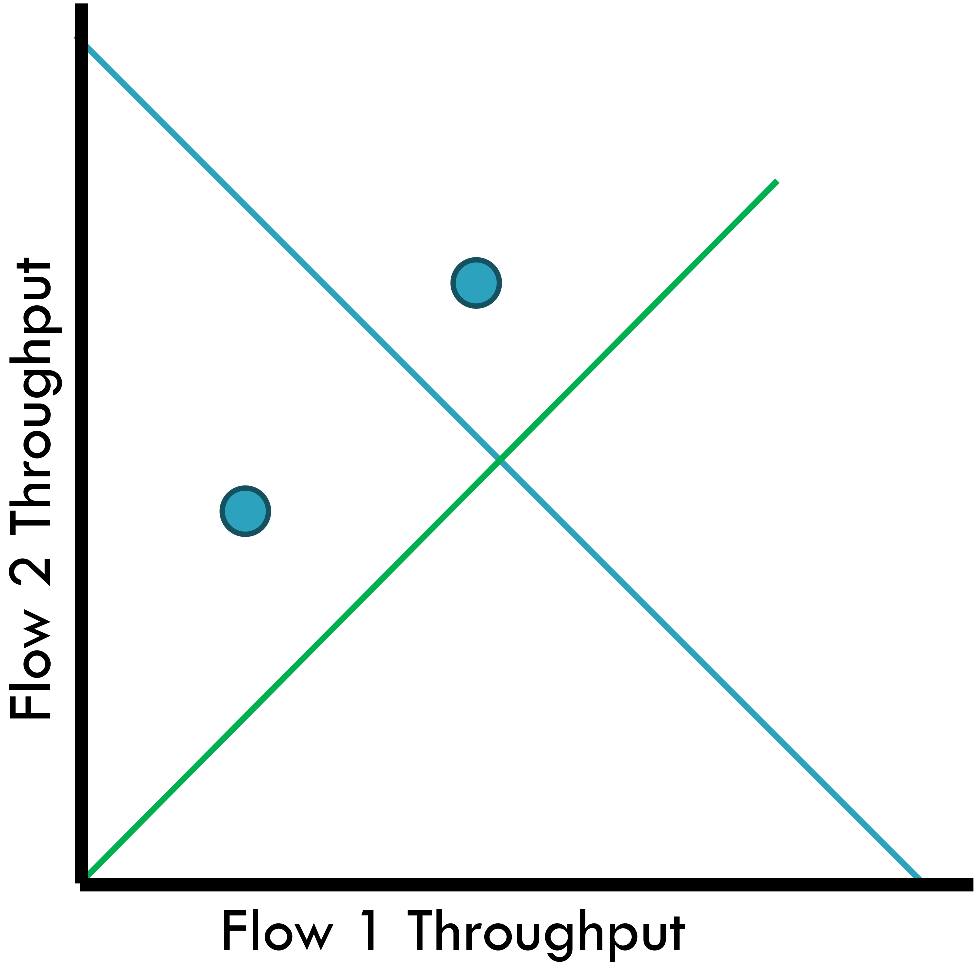

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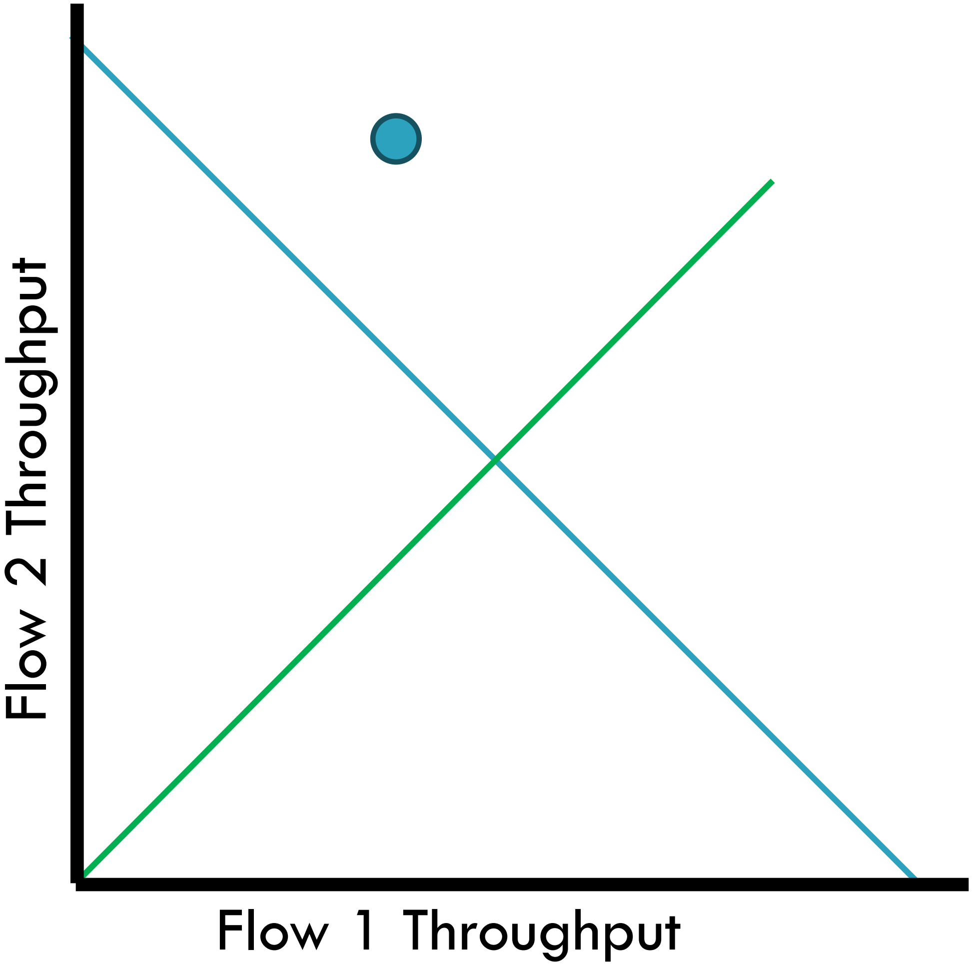

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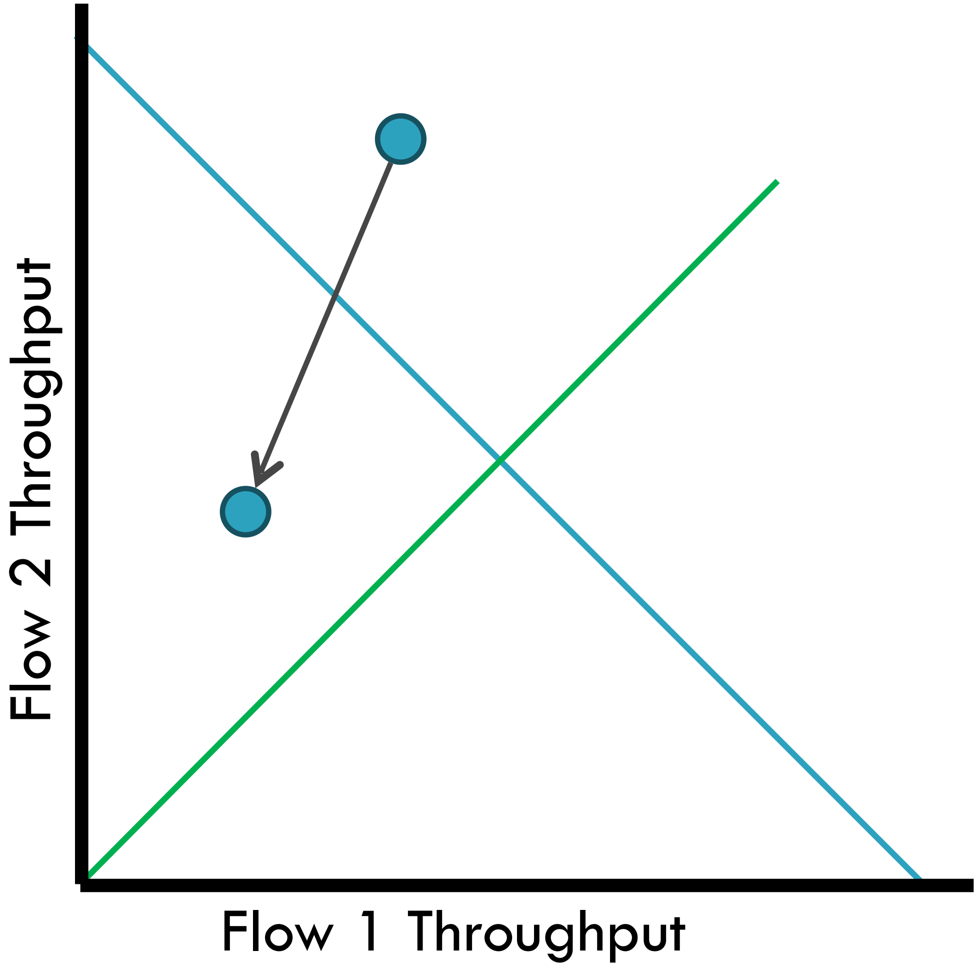

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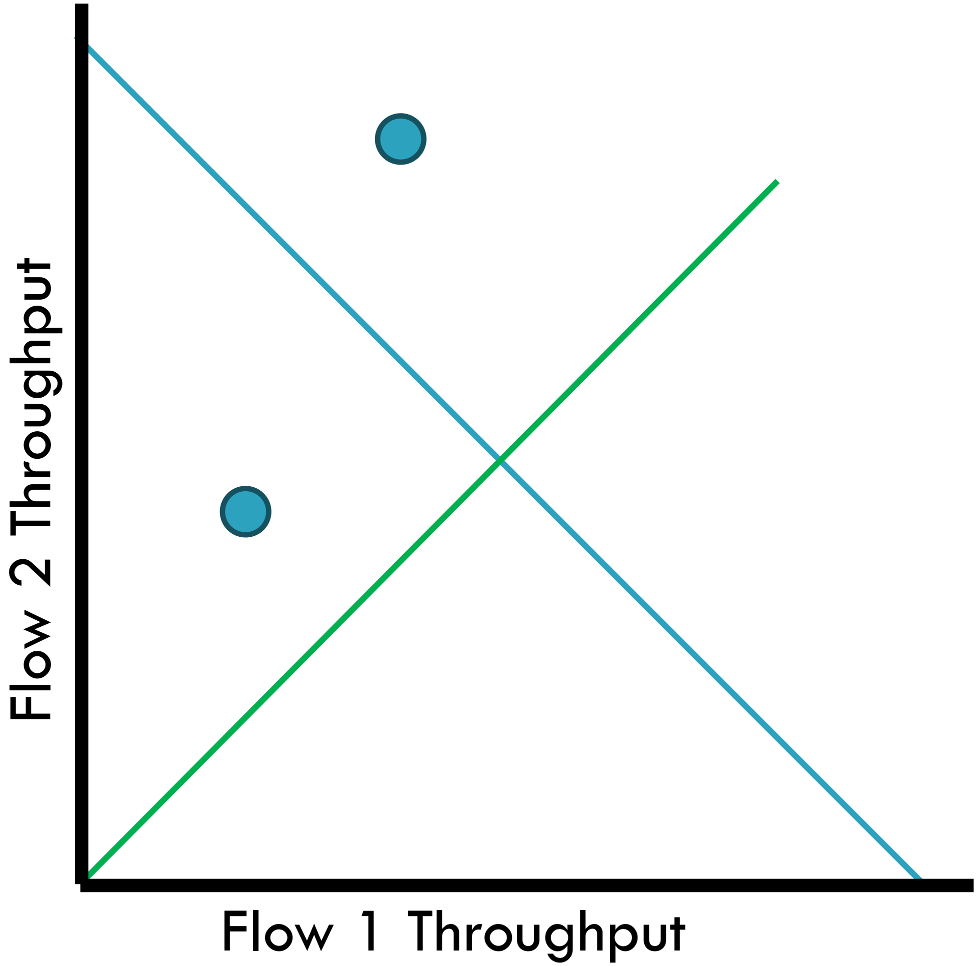

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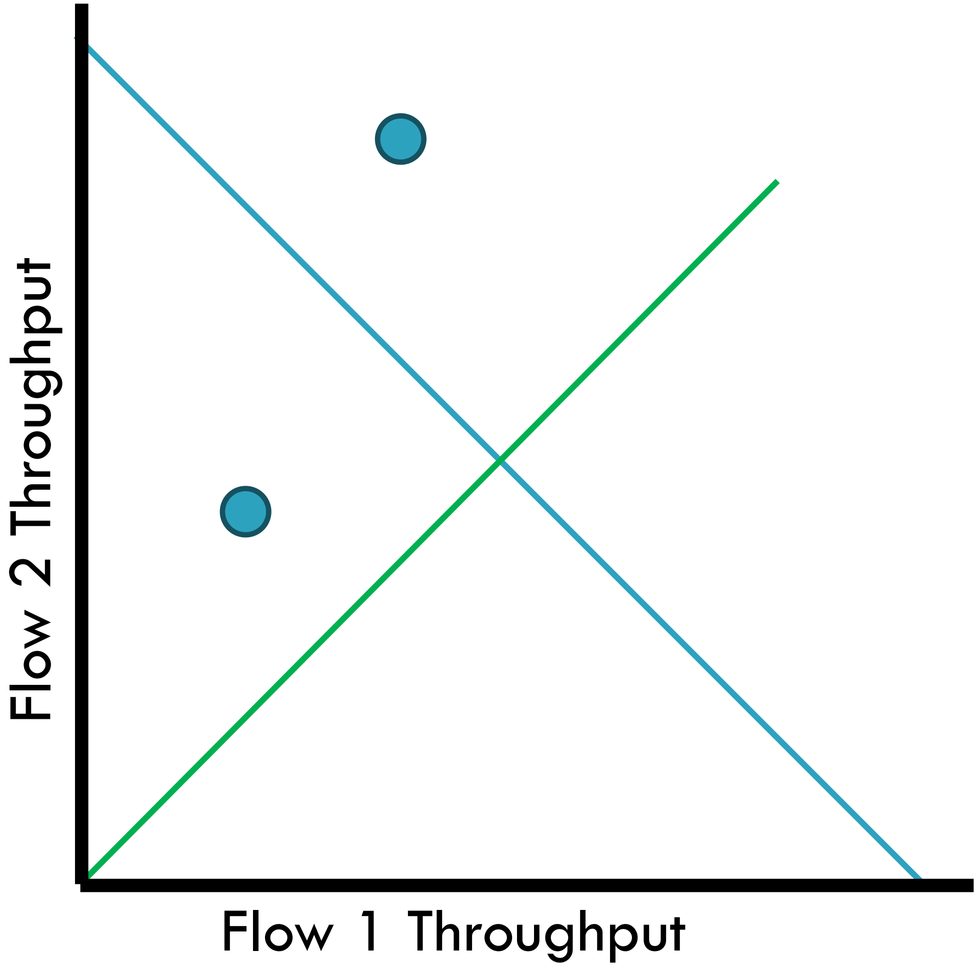

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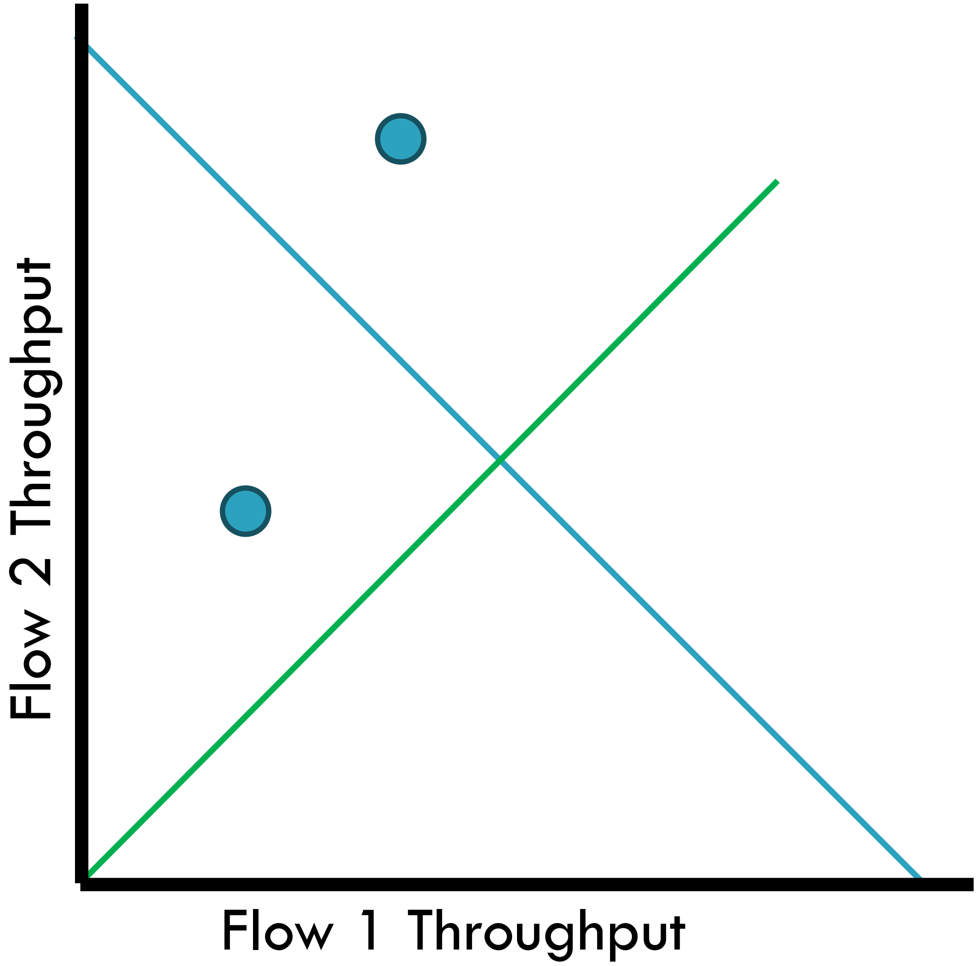

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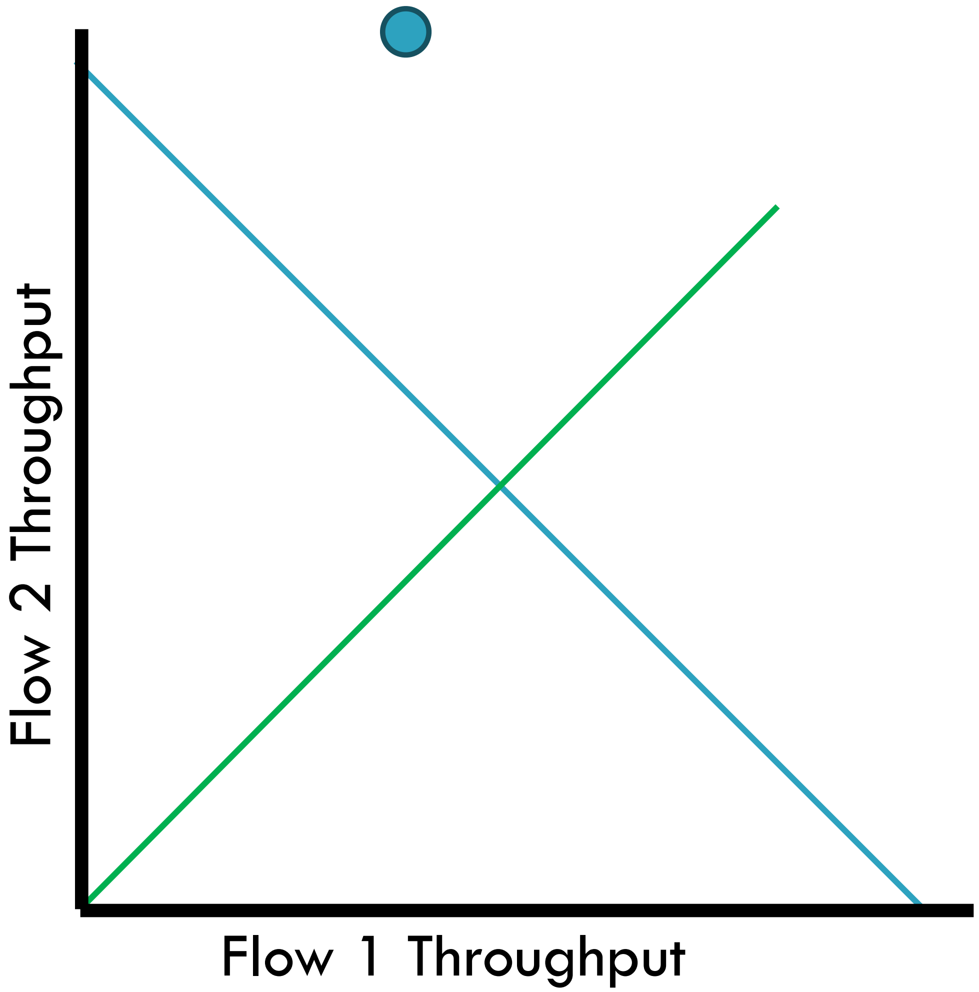

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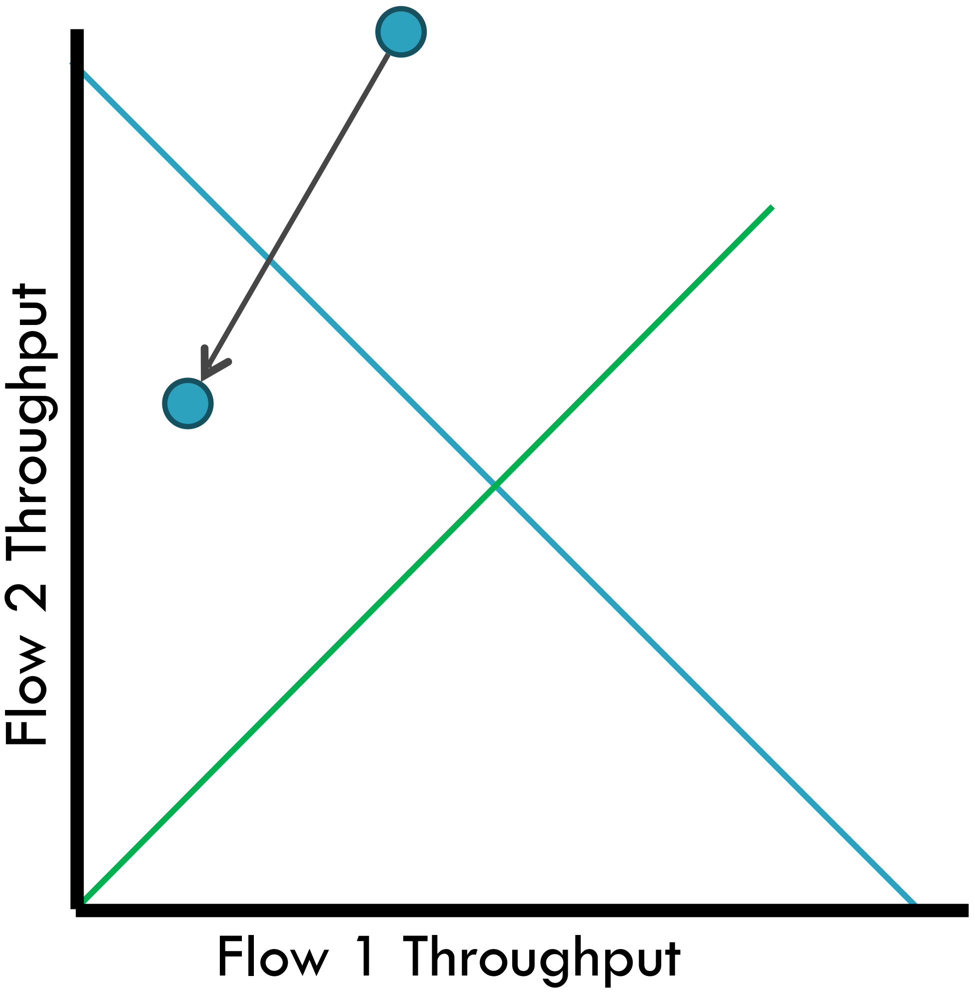

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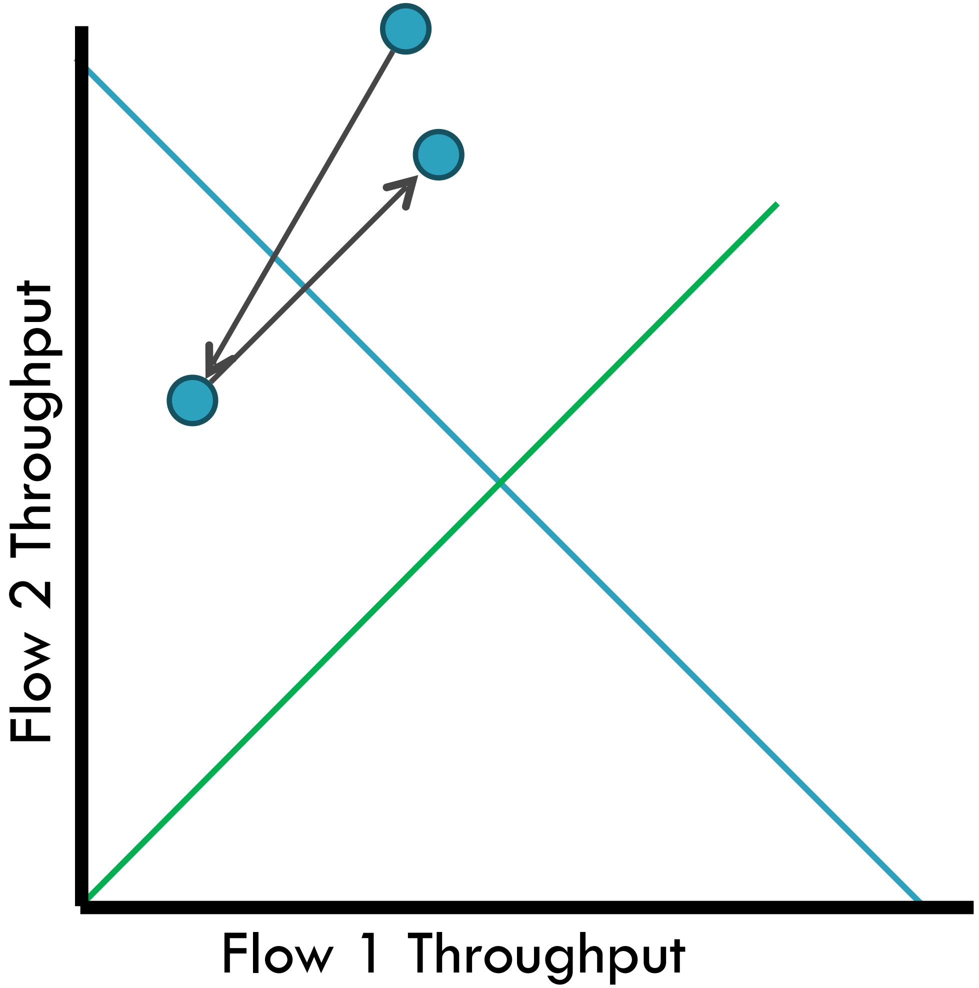

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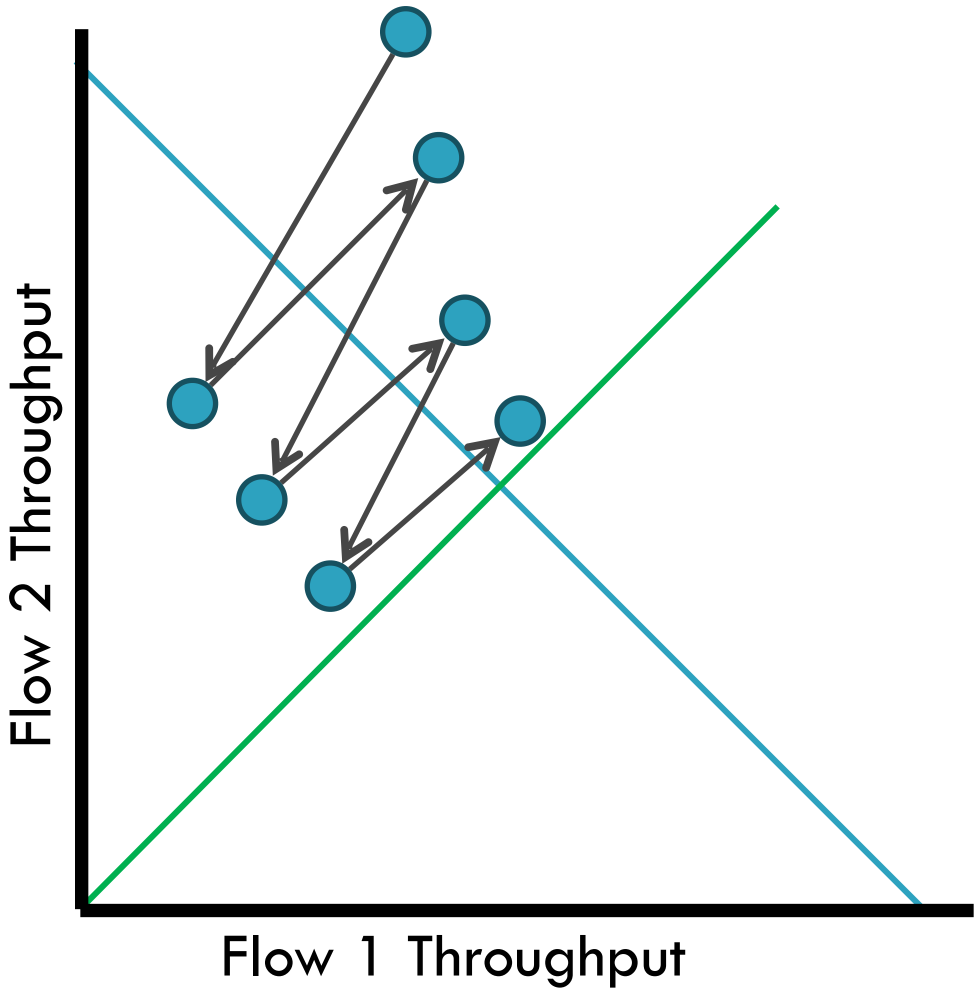
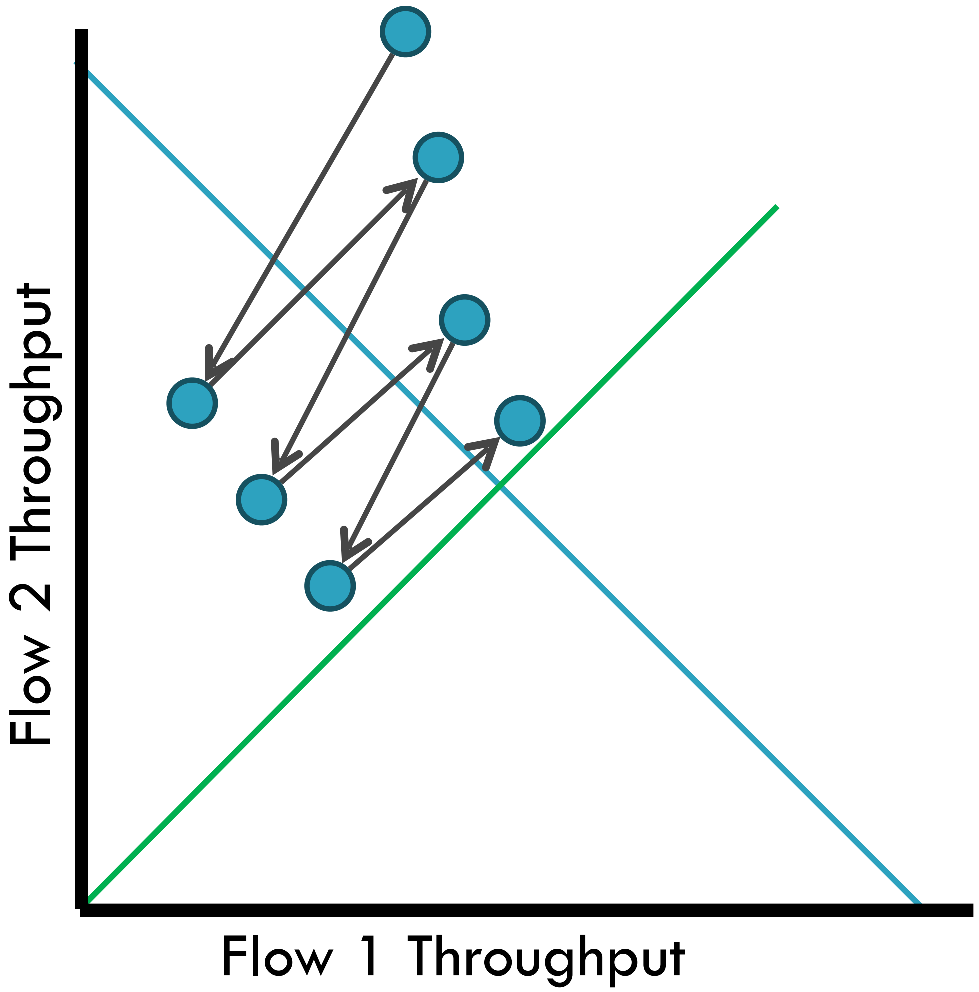


Additive Increase, Multiplicative Decrease

- Converges to stable and fair cycle



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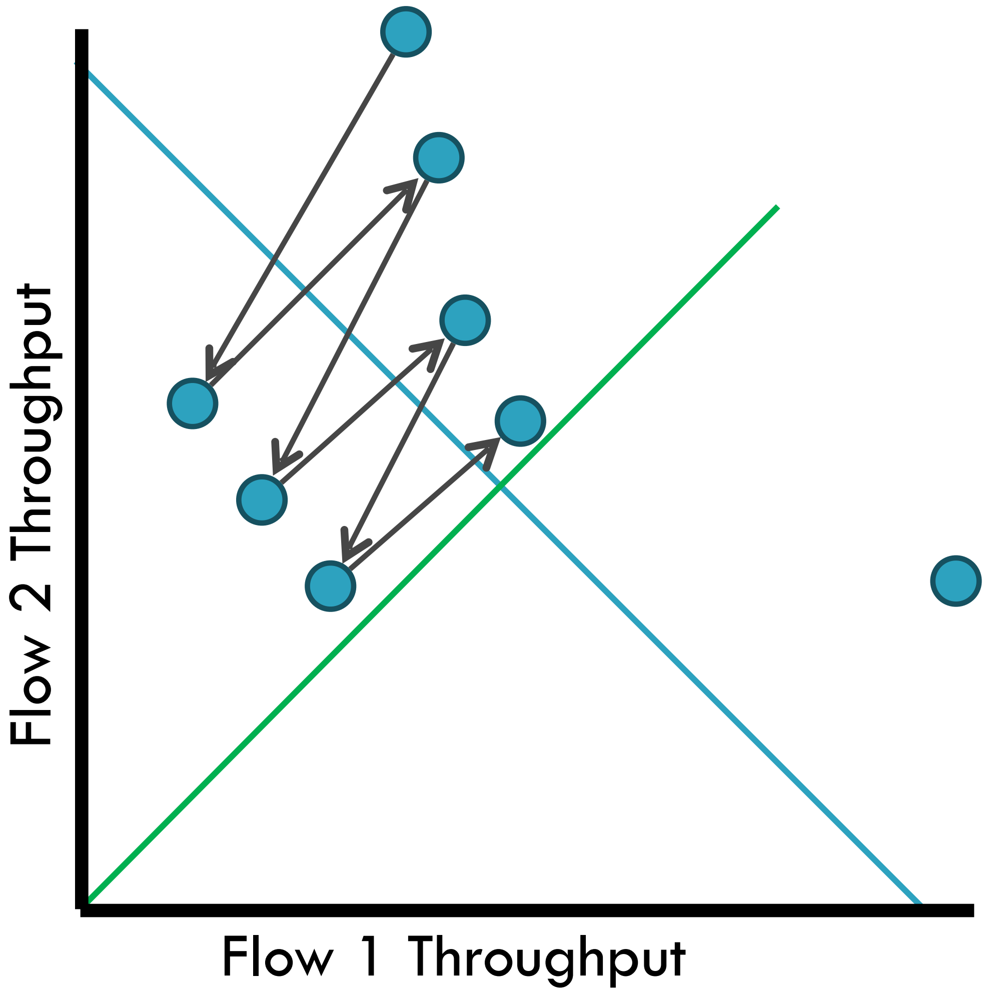

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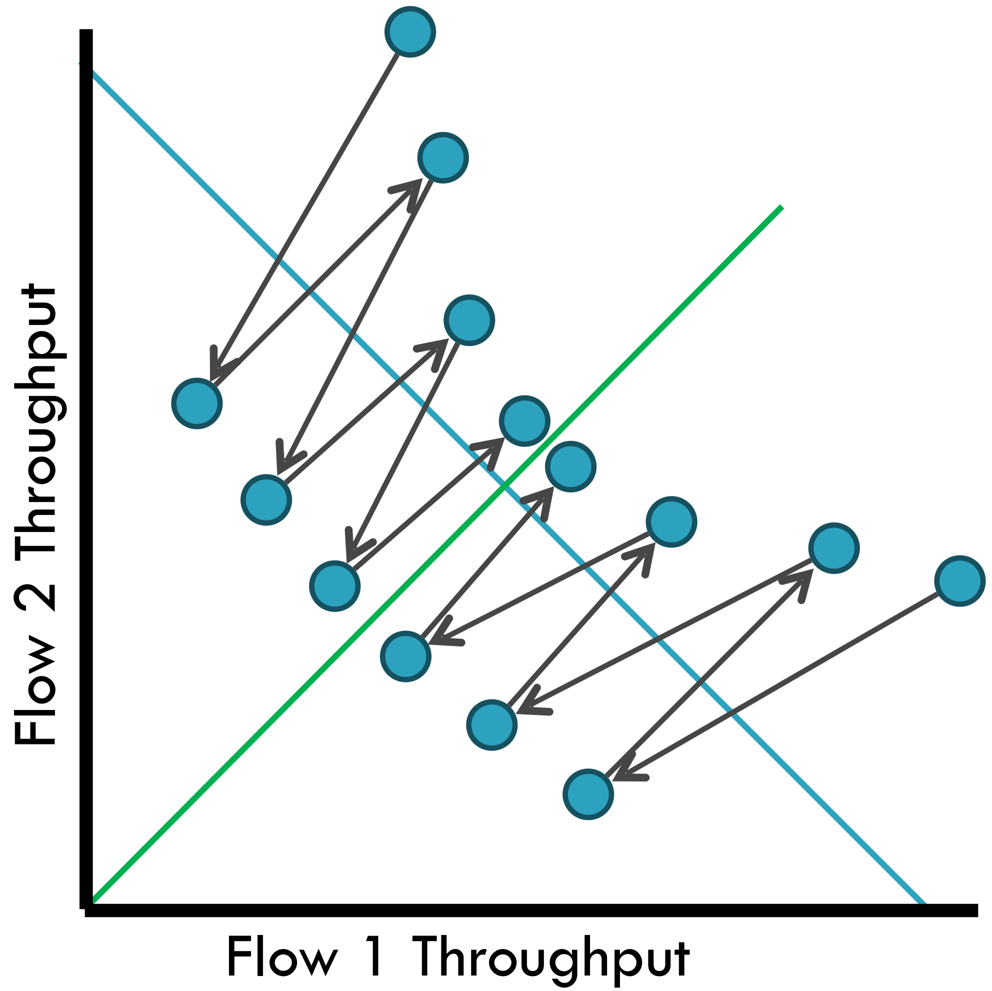
- Symmetric around $y=x$



Implementing Congestion Control

- Maintains three variables:
  - *cwnd*: congestion window
  - *adv_wnd*: receiver advertised window
  - *ssthresh*: threshold size (used to update *cwnd*)
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- Two phases of congestion control
  1. Slow start (*cwnd* < *ssthresh*)
     - Probe for bottleneck bandwidth
  2. Congestion avoidance (*cwnd* >= *ssthresh*)
     - AIMD

Slow Start

- Goal: reach knee quickly
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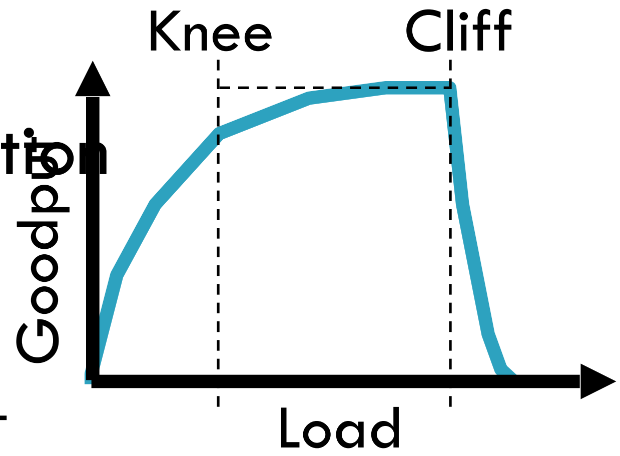

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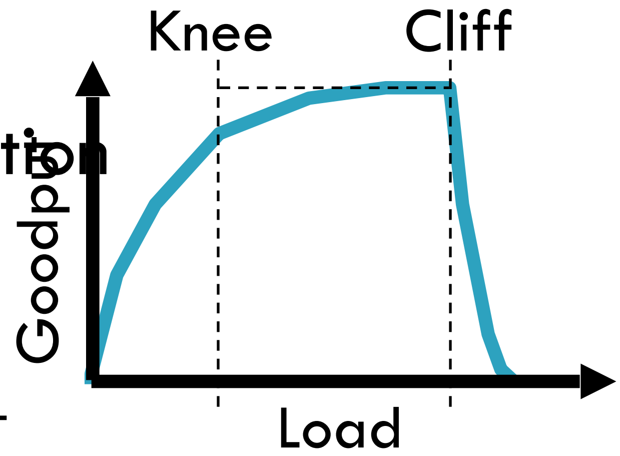

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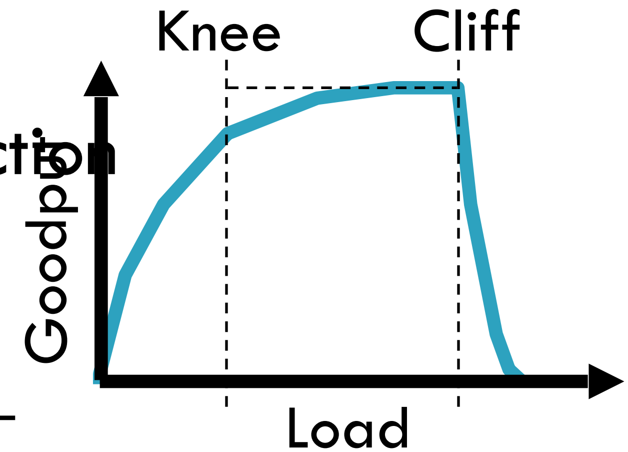
- Slow Start is not actually slow
  - *cwnd* increases exponentially



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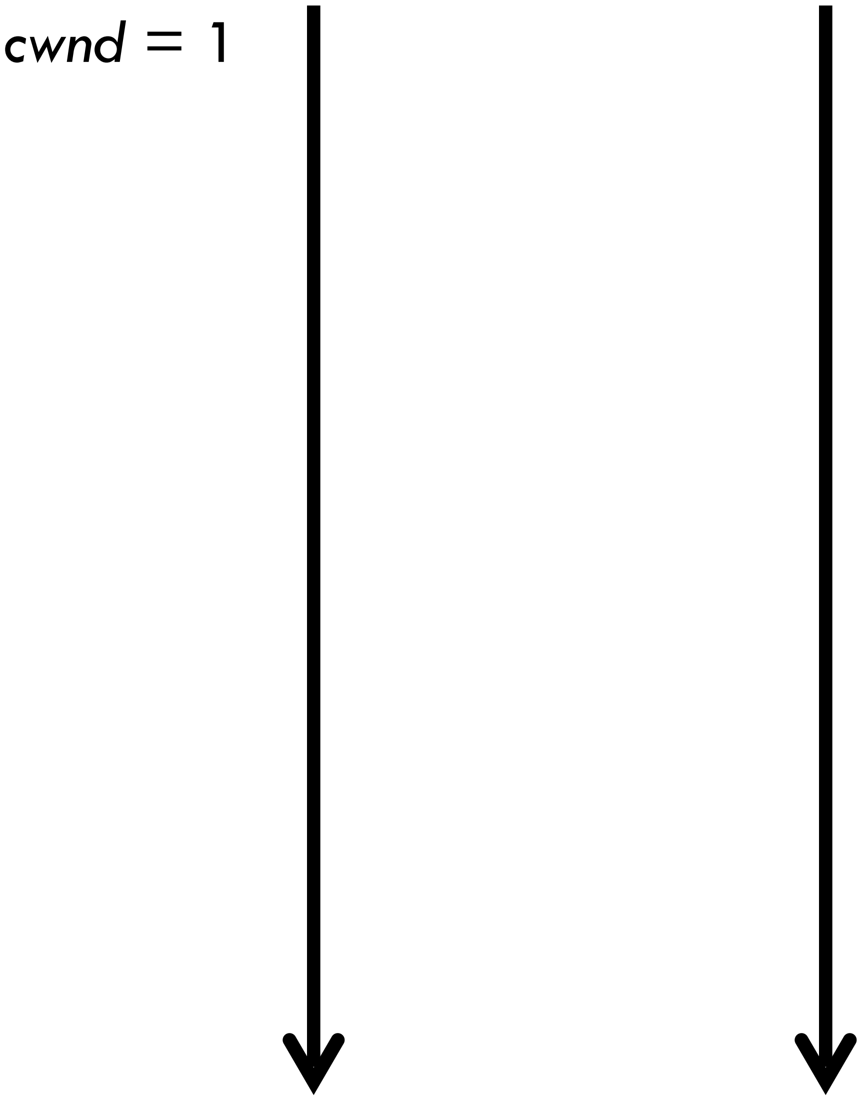

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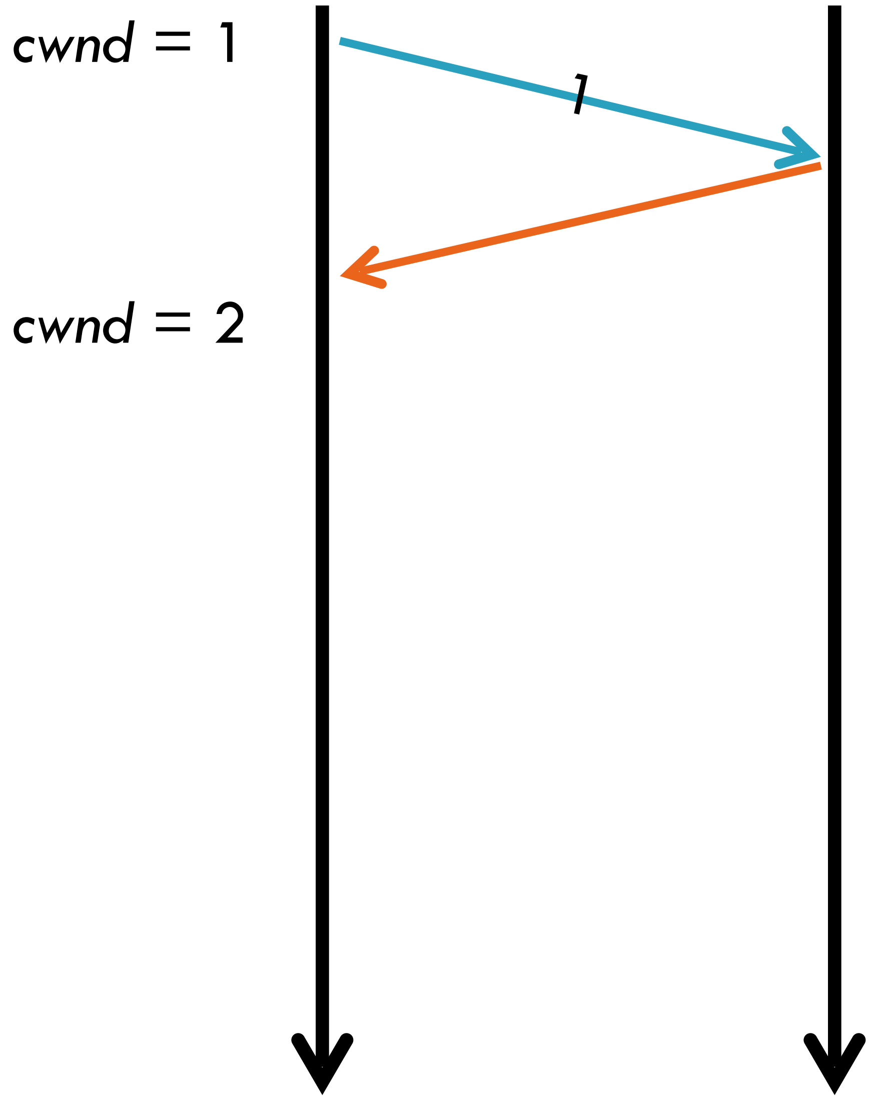

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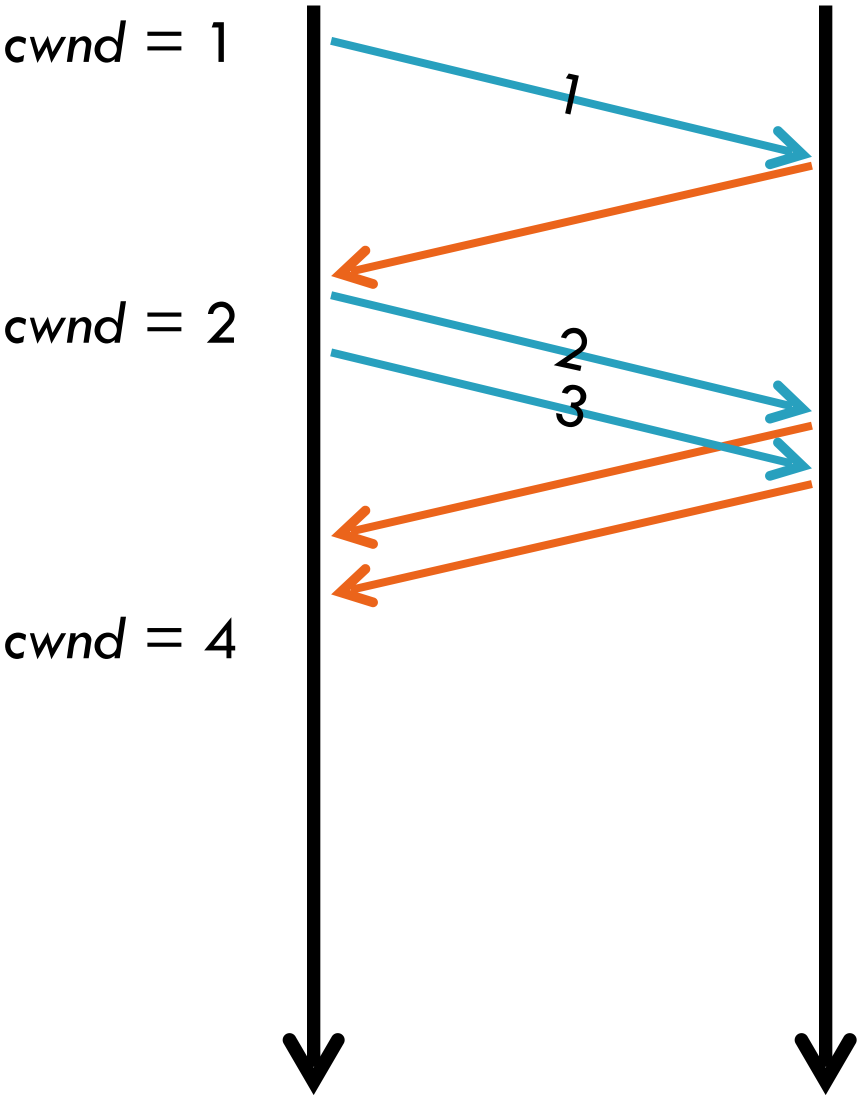

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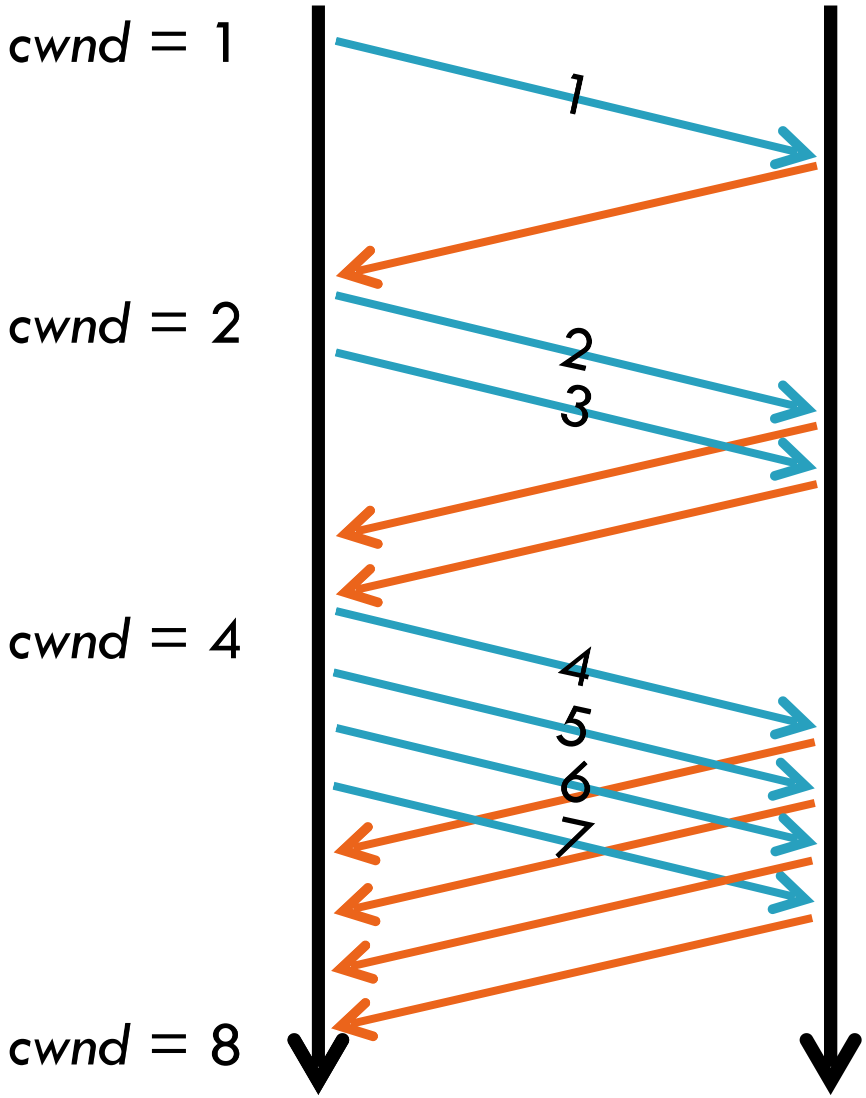
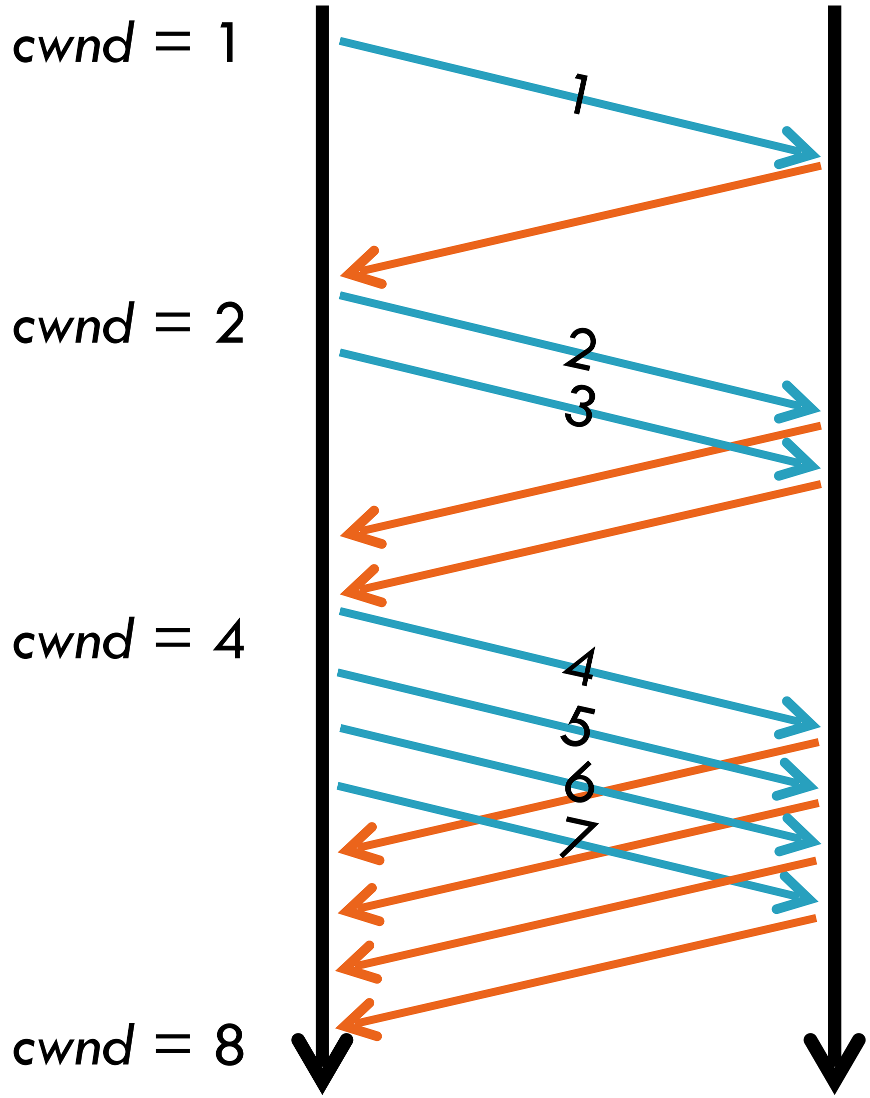


Slow Start Example

- *cwnd* grows rapidly
- Slows down when…
  - *cwnd* >= *ssthresh*
  - Or a packet drops



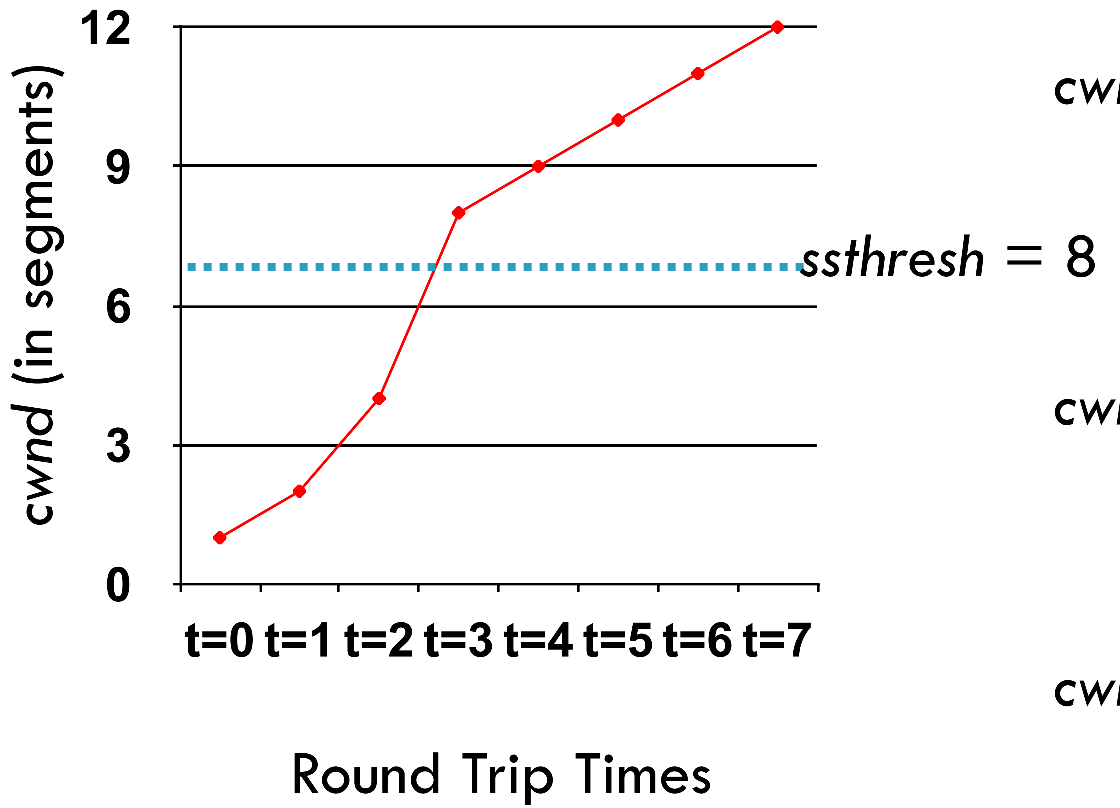
Congestion Avoidance

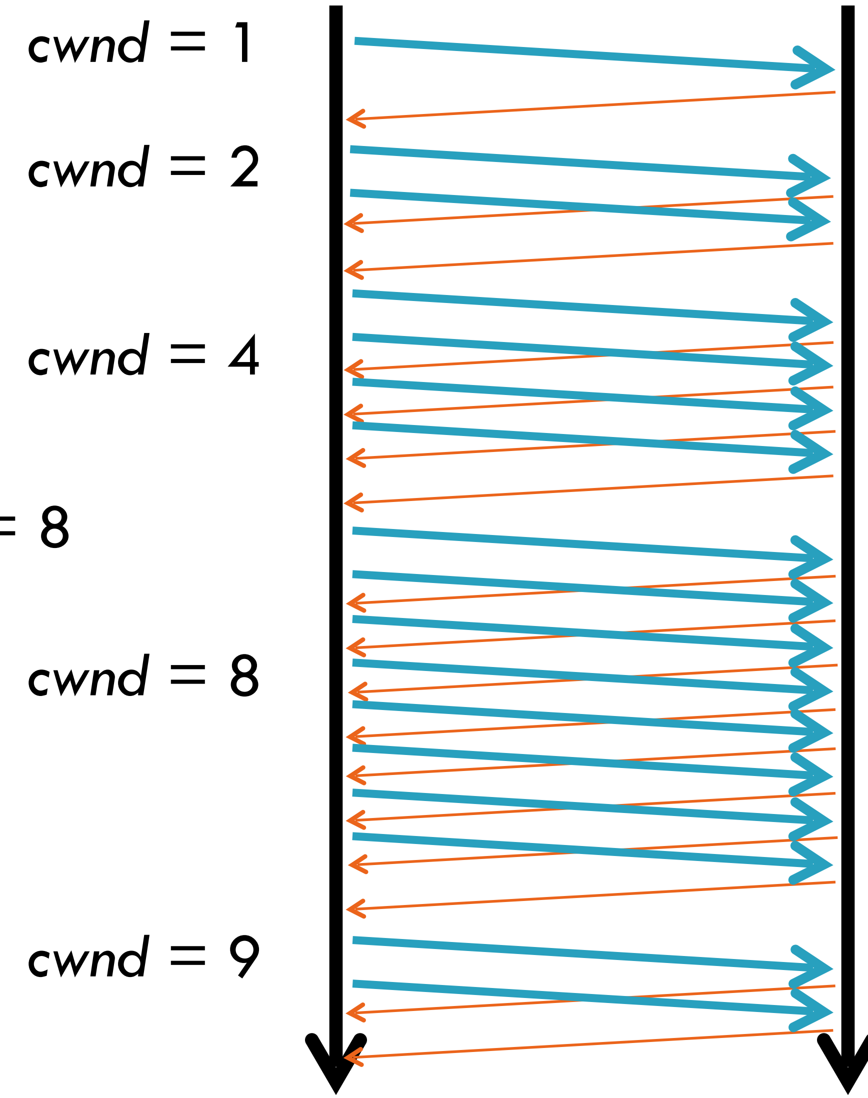
- AIMD mode
- *ssthresh* is lower-bound guess about location of the knee
- **If** *cwnd* >= *ssthresh* **then**

  each time a segment is ACKed

  increment *cwnd by 1/cwnd* (*cwnd* += *1/cwnd*).
- So *cwnd* is increased by one only if all segments have been acknowledged

Congestion Avoidance Example





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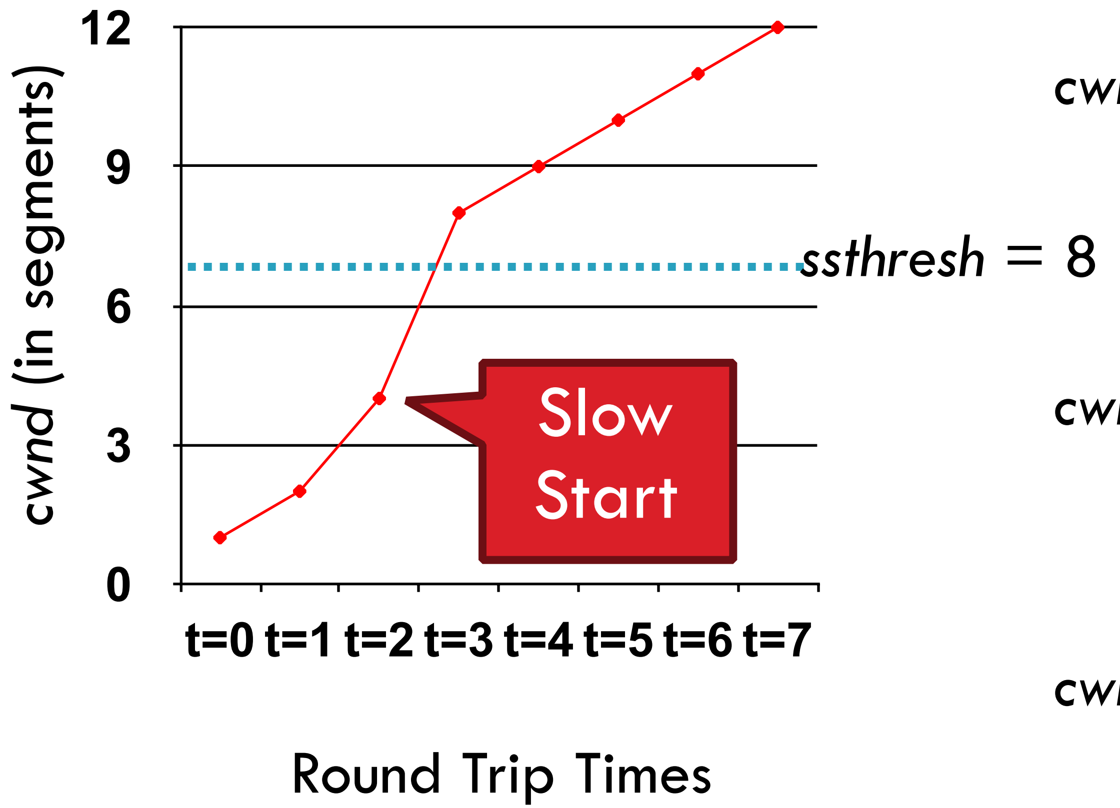

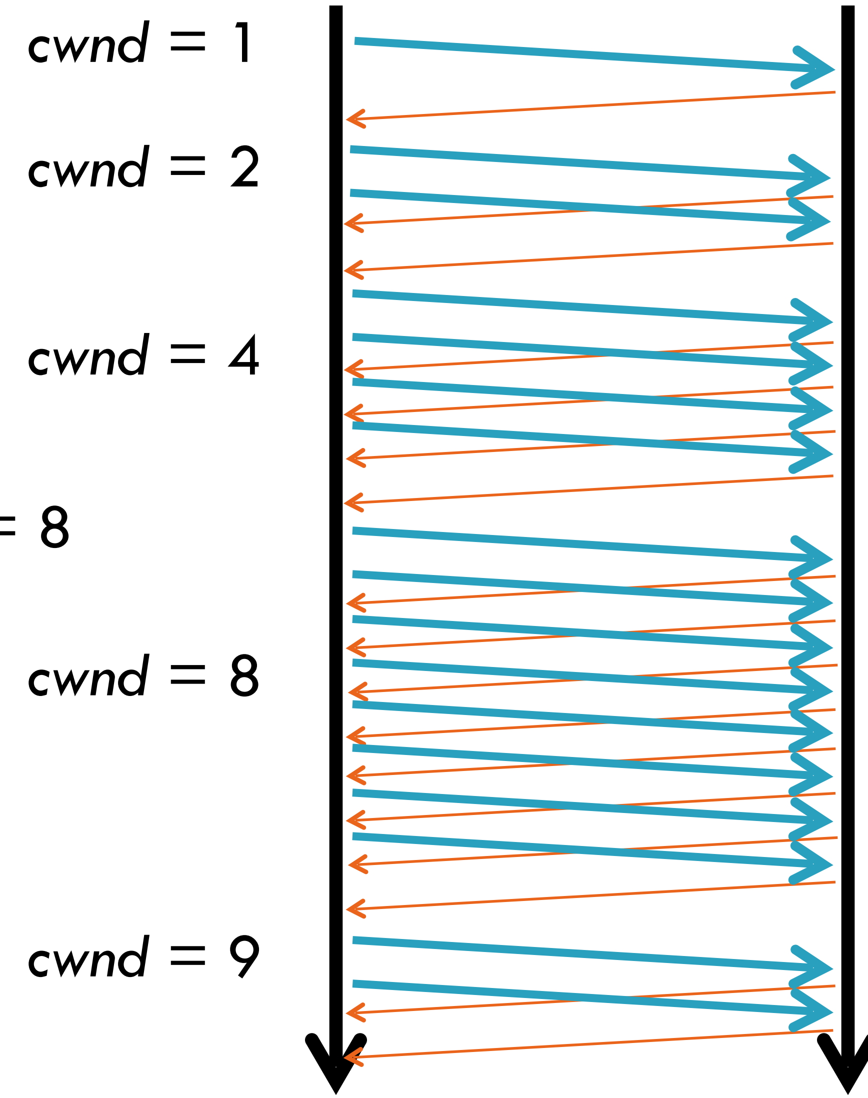

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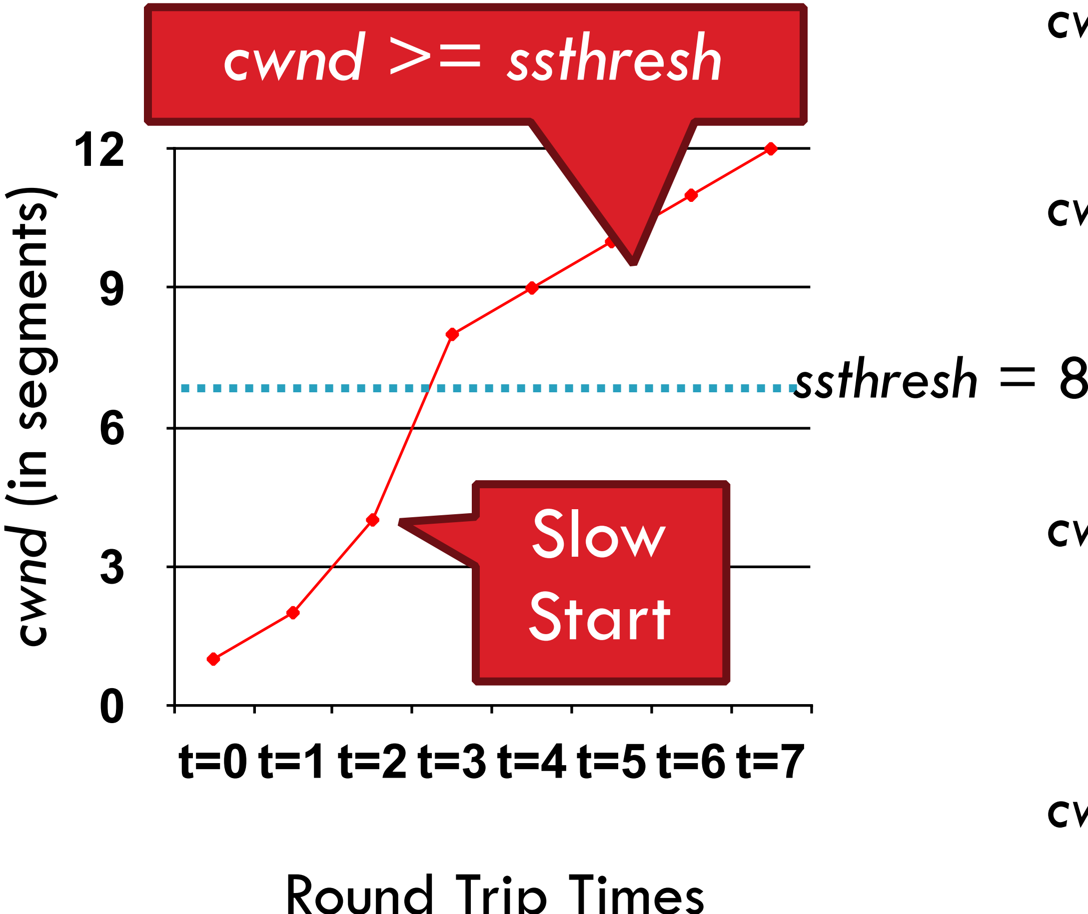
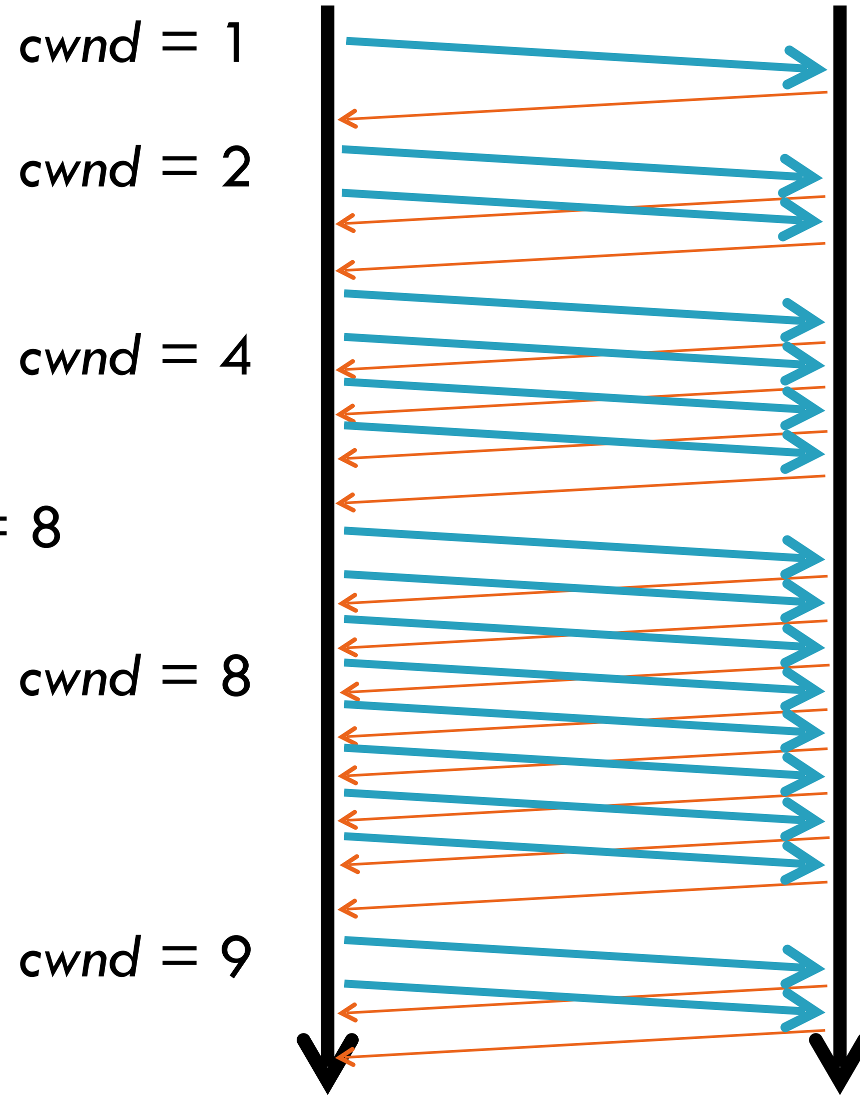
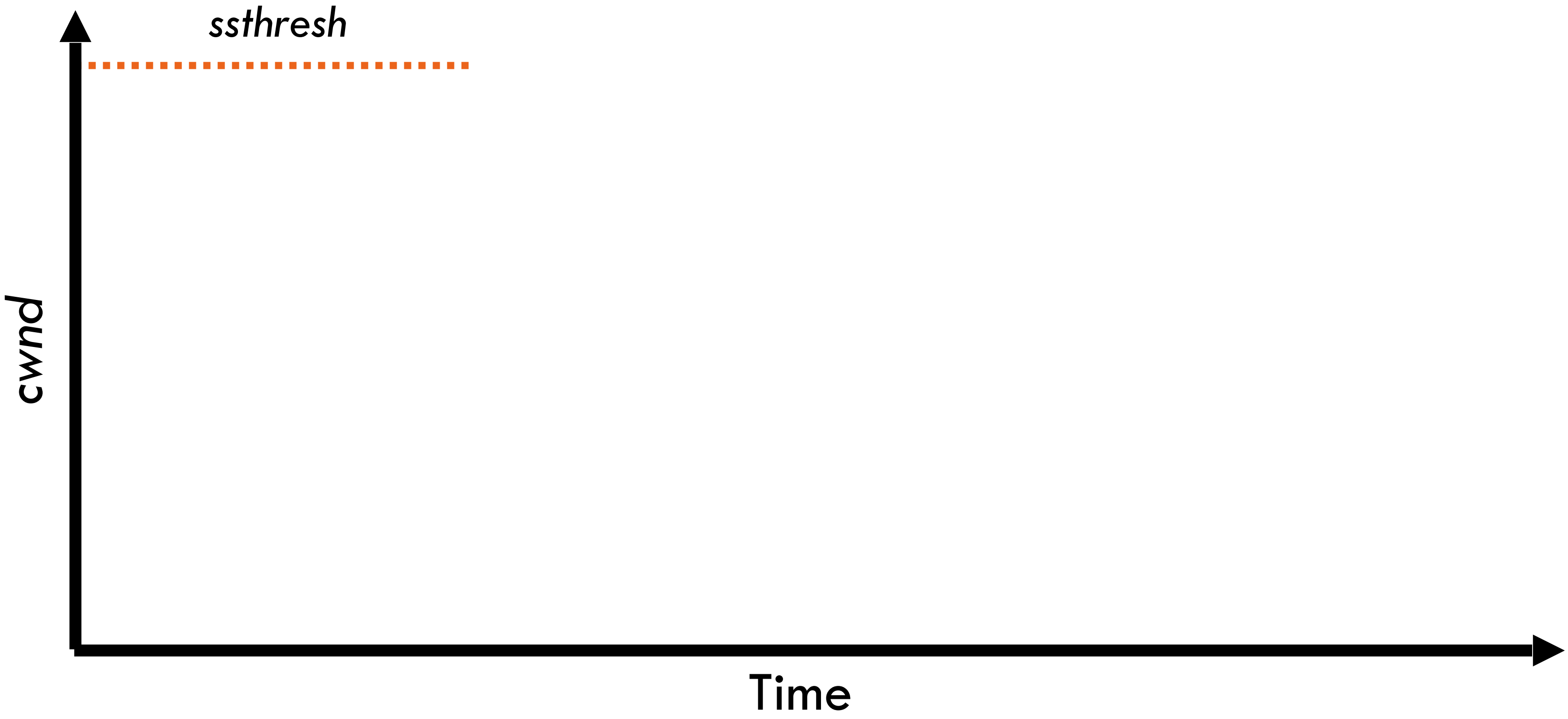




TCP Pseudocode


```
Initially:
        cwnd = 1;
        ssthresh = adv_wnd;
New ack received:
        if (cwnd < ssthresh)
            /* Slow Start*/
            cwnd = cwnd + 1;
        else
            /* Congestion Avoidance */
            cwnd = cwnd + 1/cwnd;
Timeout:
        /* Multiplicative decrease */
        ssthresh = cwnd/2;
        cwnd = 1;
```

The Big Picture



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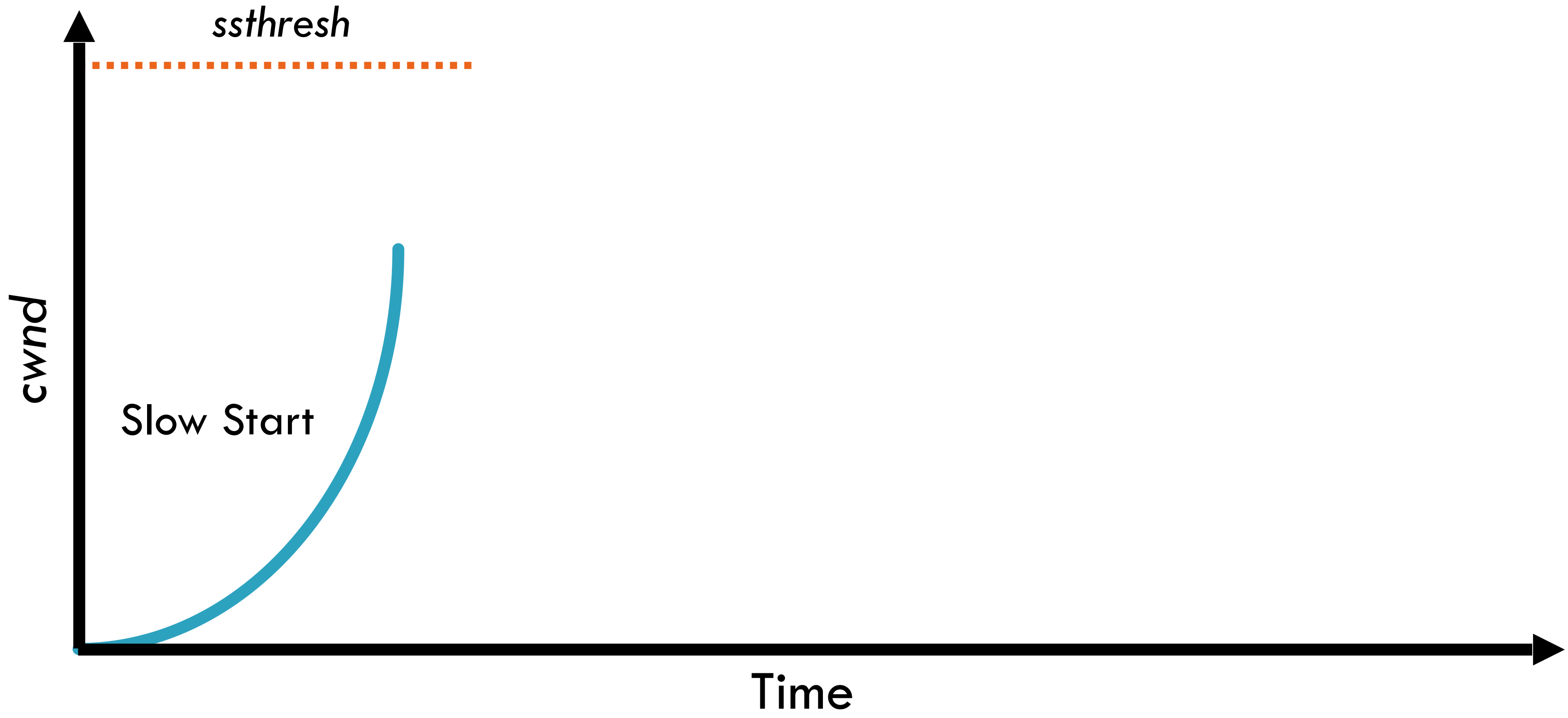

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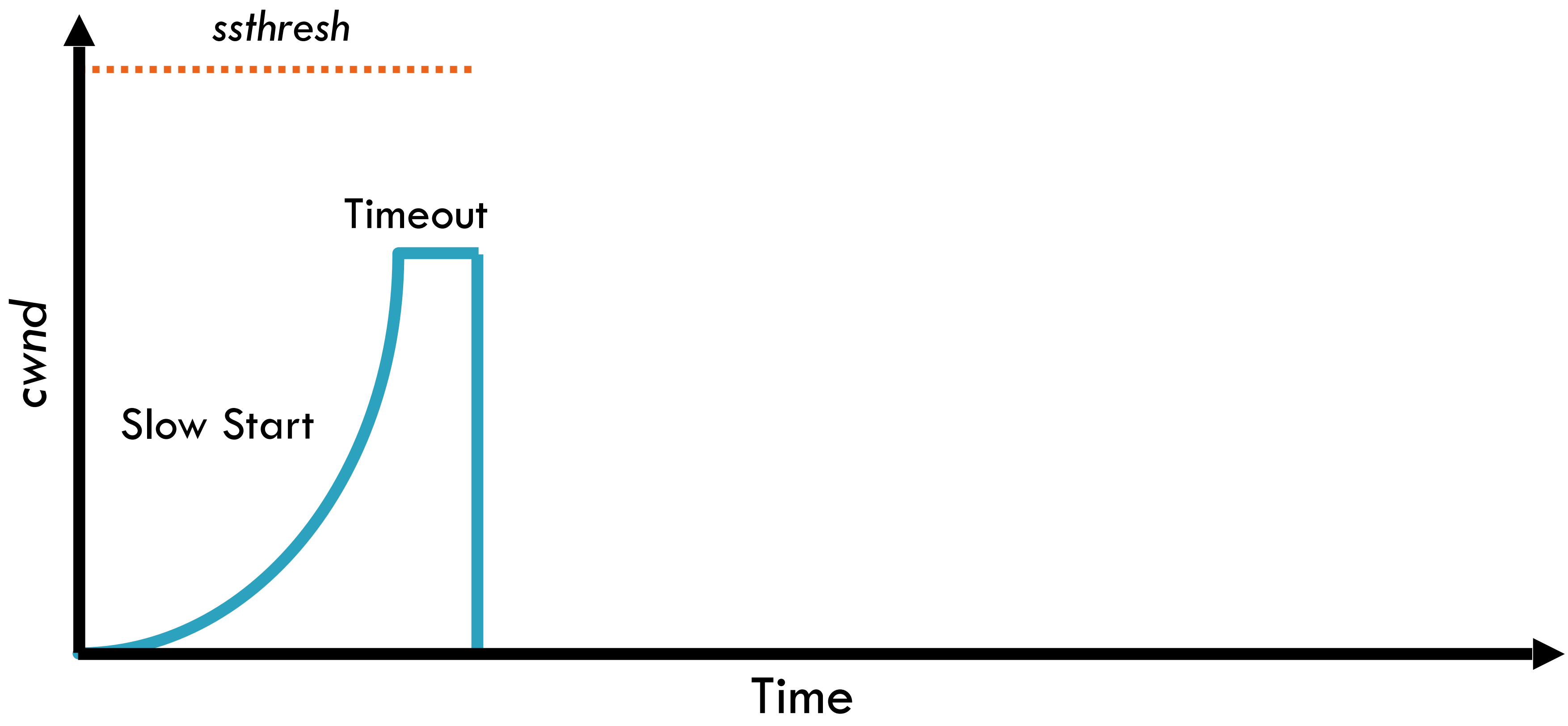

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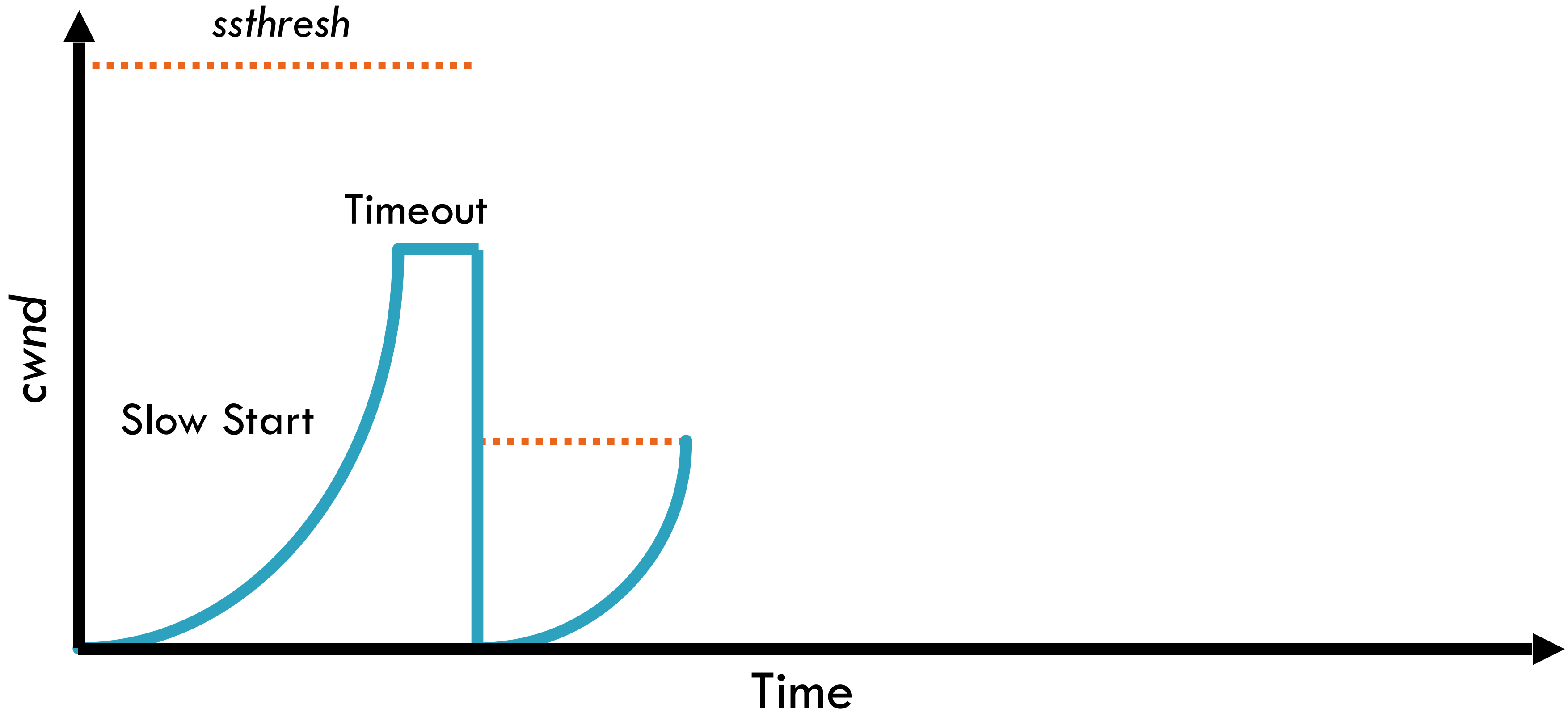

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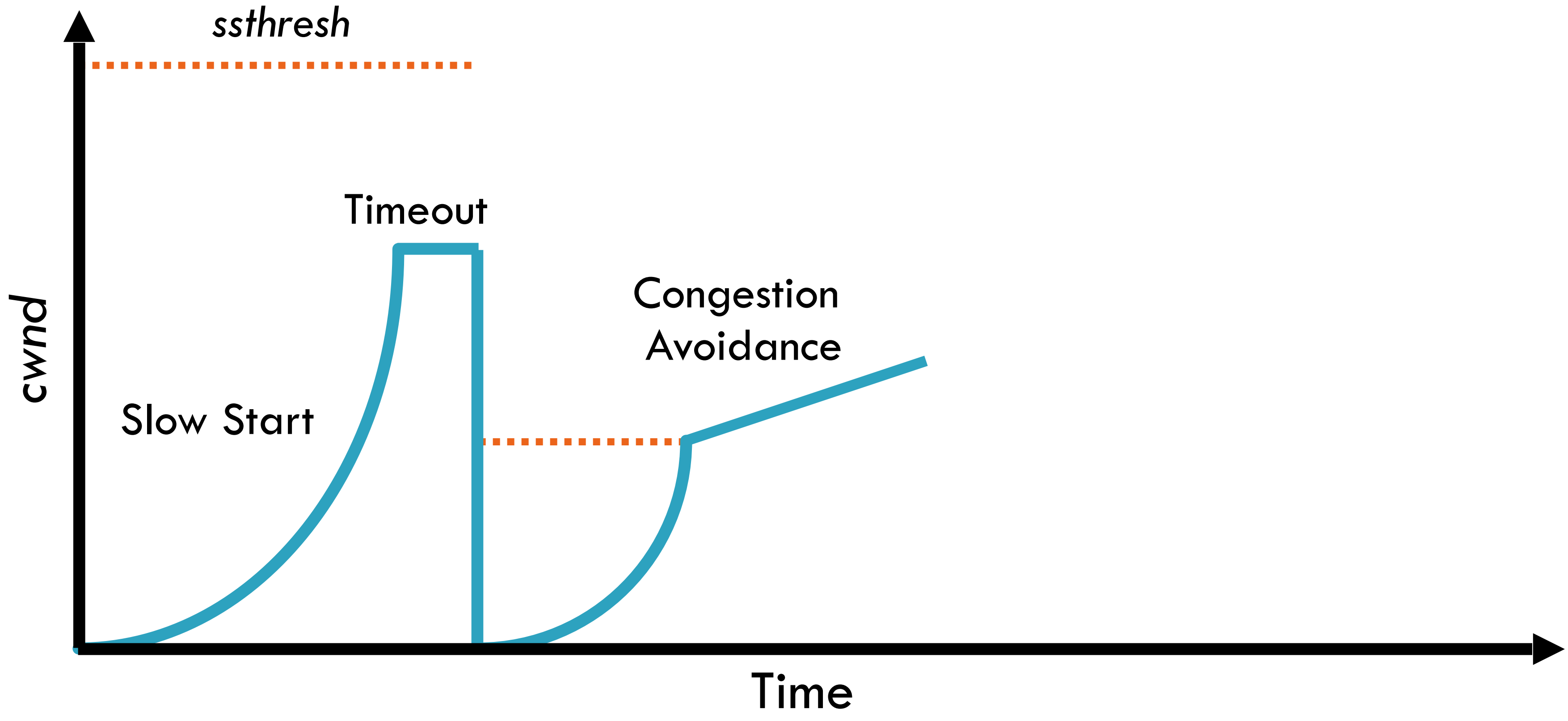

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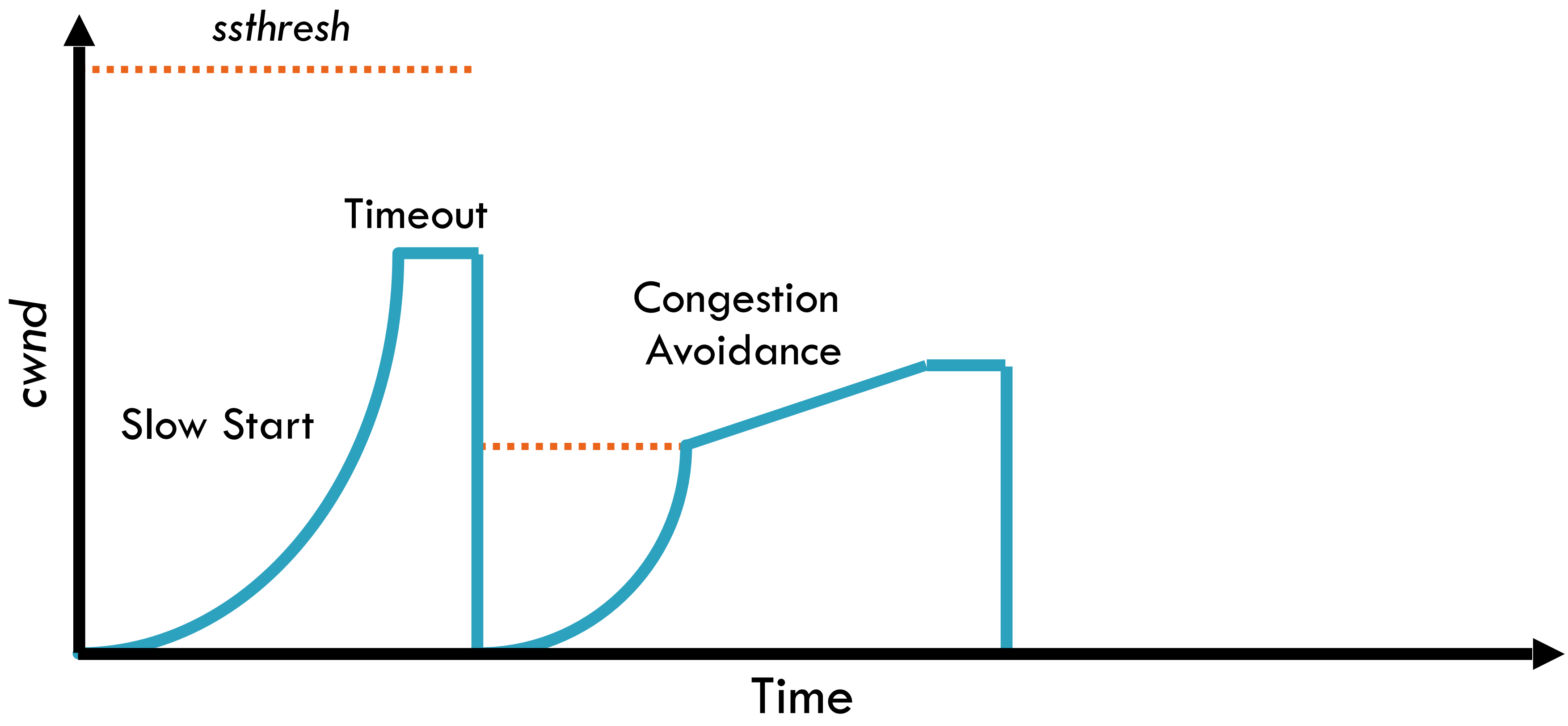

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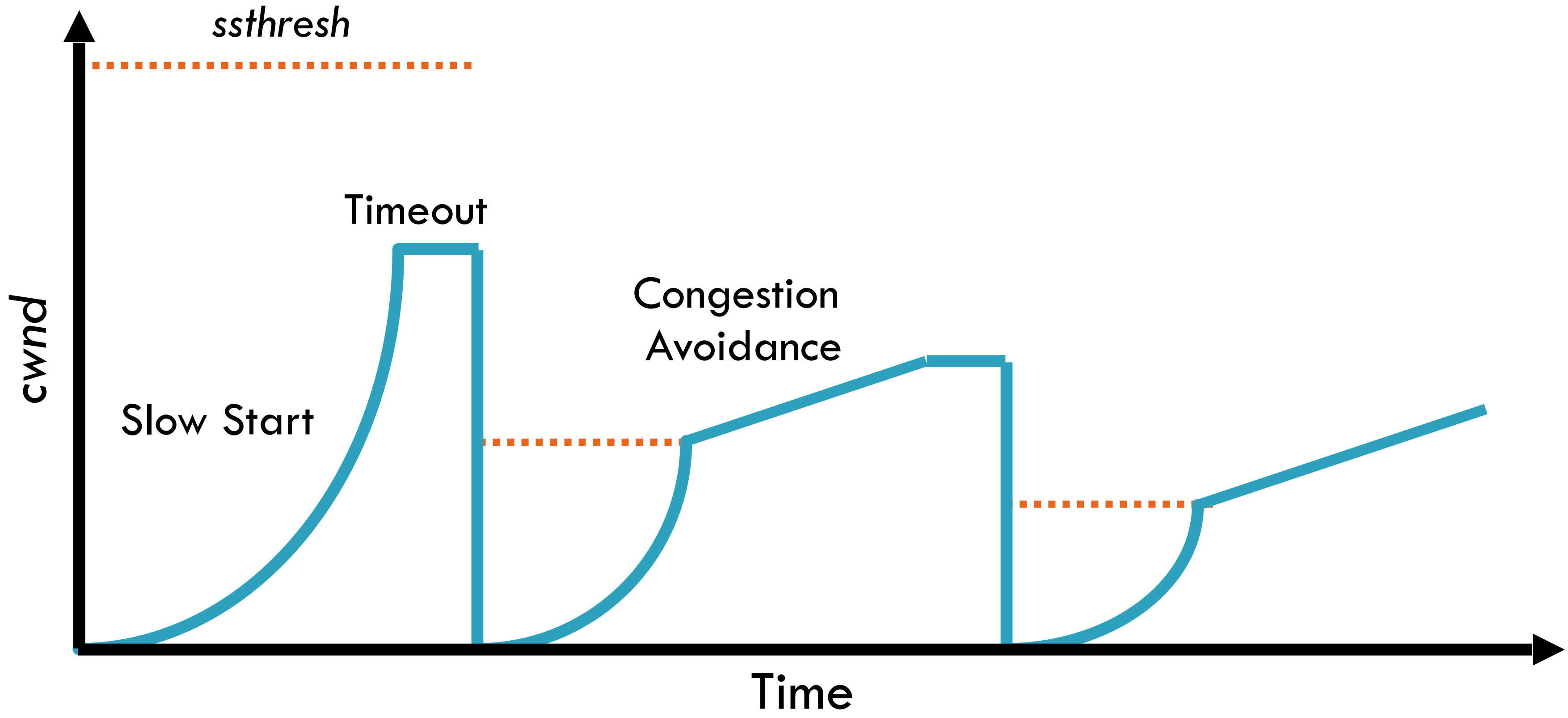

Outline

- Congestion Control
- Evolution of TCP
- Problems with TCP

The Evolution of TCP

- Thus far, we have discussed TCP Tahoe
  - Original version of TCP
- However, TCP was invented in 1974!
  - Today, there are many variants of TCP

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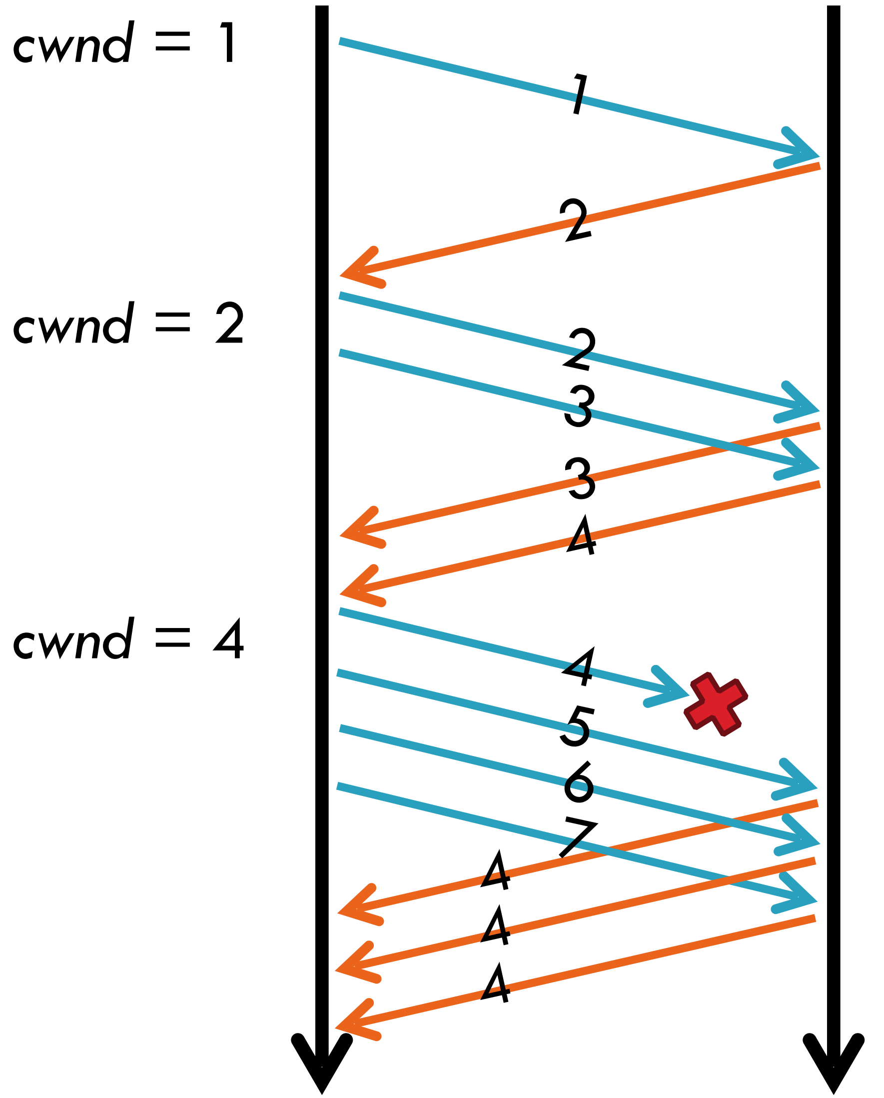
- However, TCP was invented in 1974!
  - Today, there are many variants of TCP
- Early, popular variant: TCP Reno
  - Tahoe features, plus…
  - Fast retransmit
  - Fast recovery

TCP Reno: Fast Retransmit

- Problem: in Tahoe, if segment is lost, there is a long wait until the RTO
- Reno: retransmit after 3 duplicate ACKs



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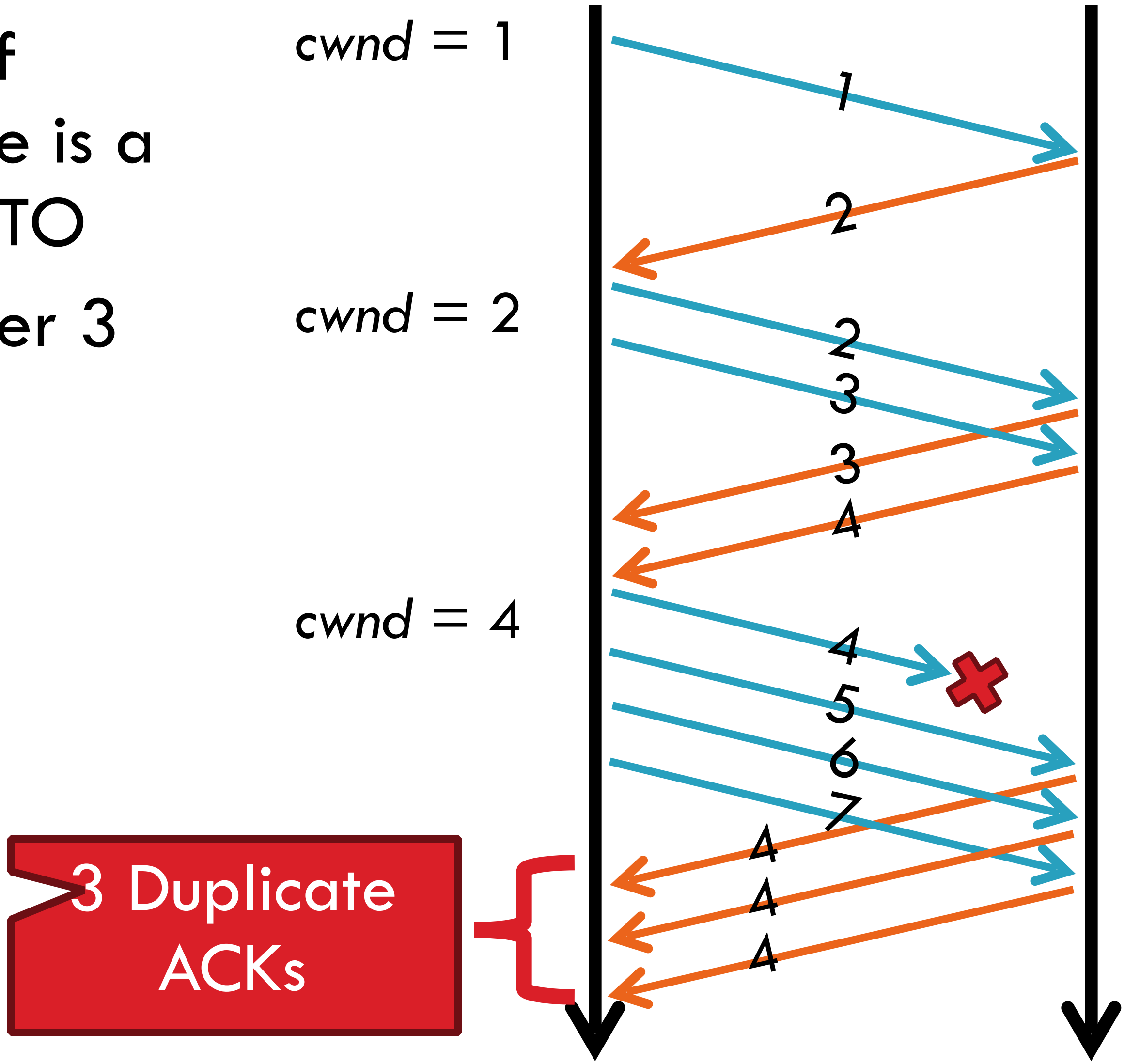
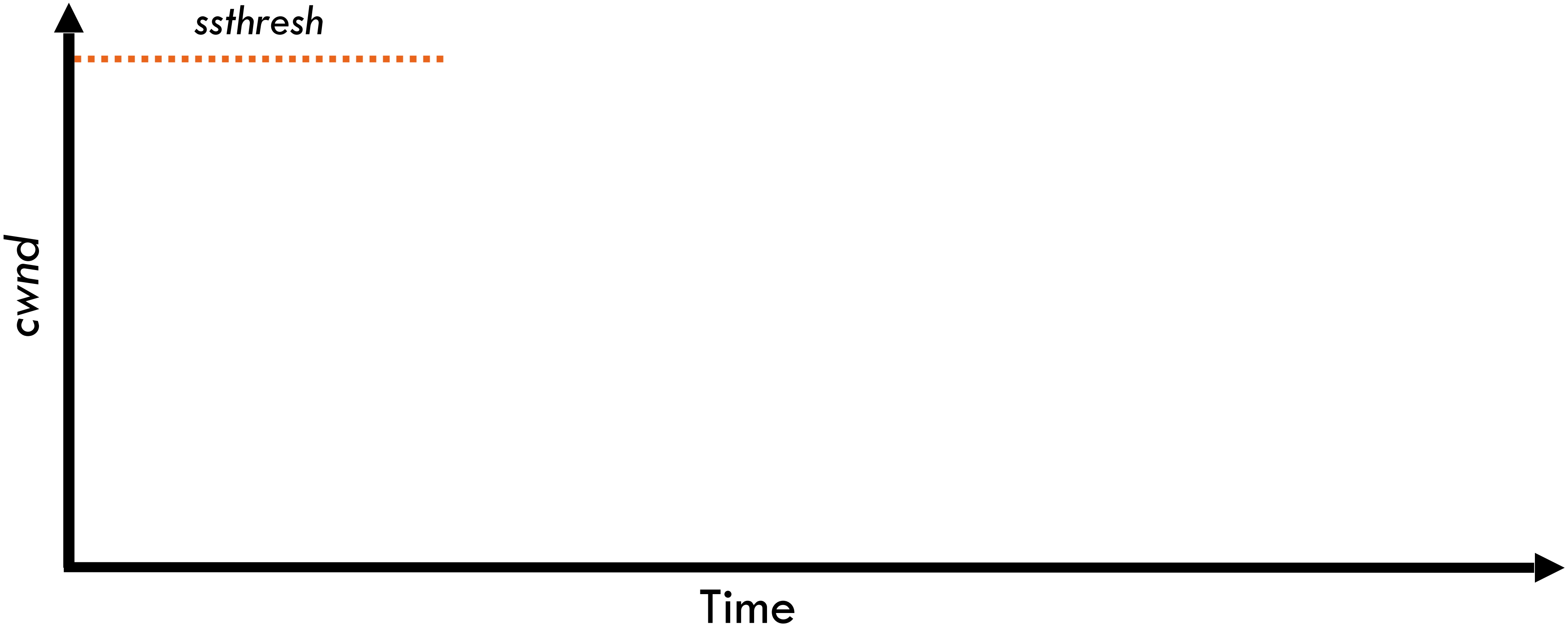


TCP Reno: Fast Recovery

- After a fast-retransmit set *cwnd* to *ssthresh/2*
  - i.e. don't reset *cwnd* to 1
  - Avoid unnecessary return to slow start
  - Prevents expensive timeouts
- But when RTO expires still do *cwnd* = 1
  - Return to slow start, same as Tahoe
  - Indicates packets aren't being delivered at all
  - i.e. congestion must be really bad

Fast Retransmit and Fast Recovery



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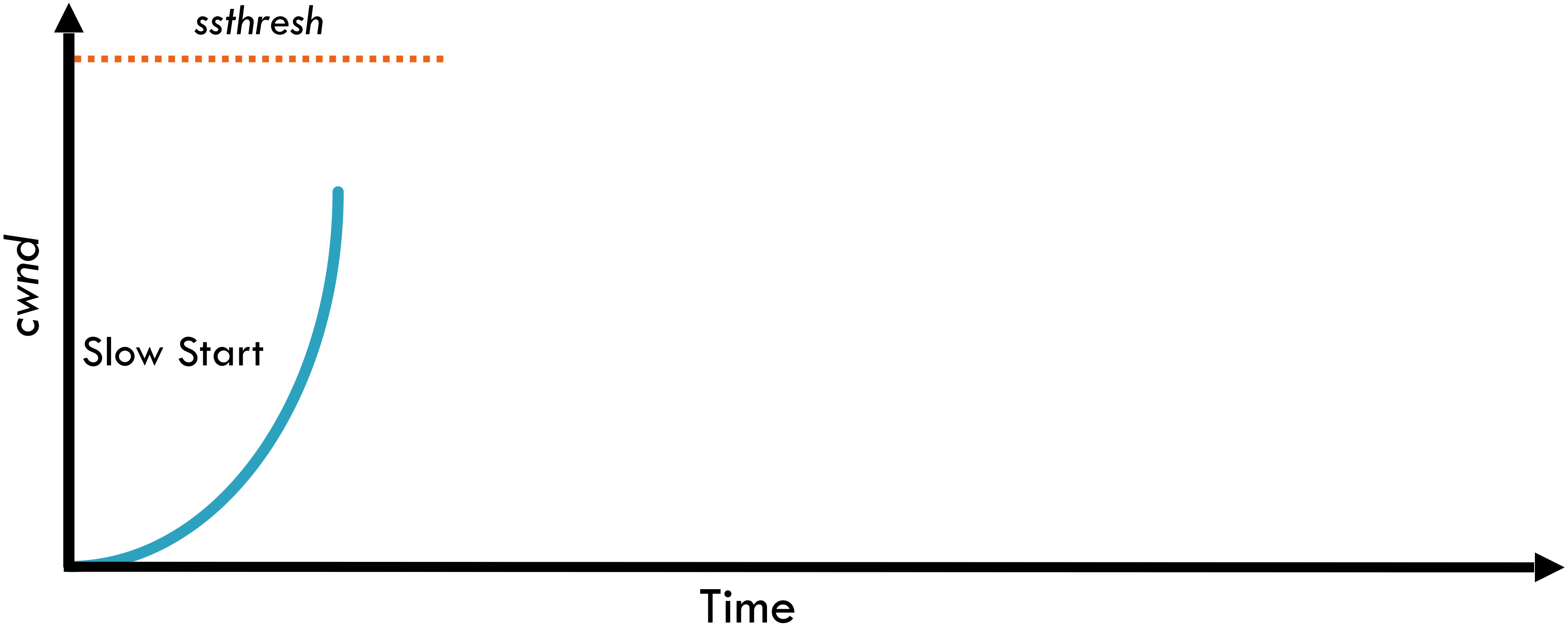

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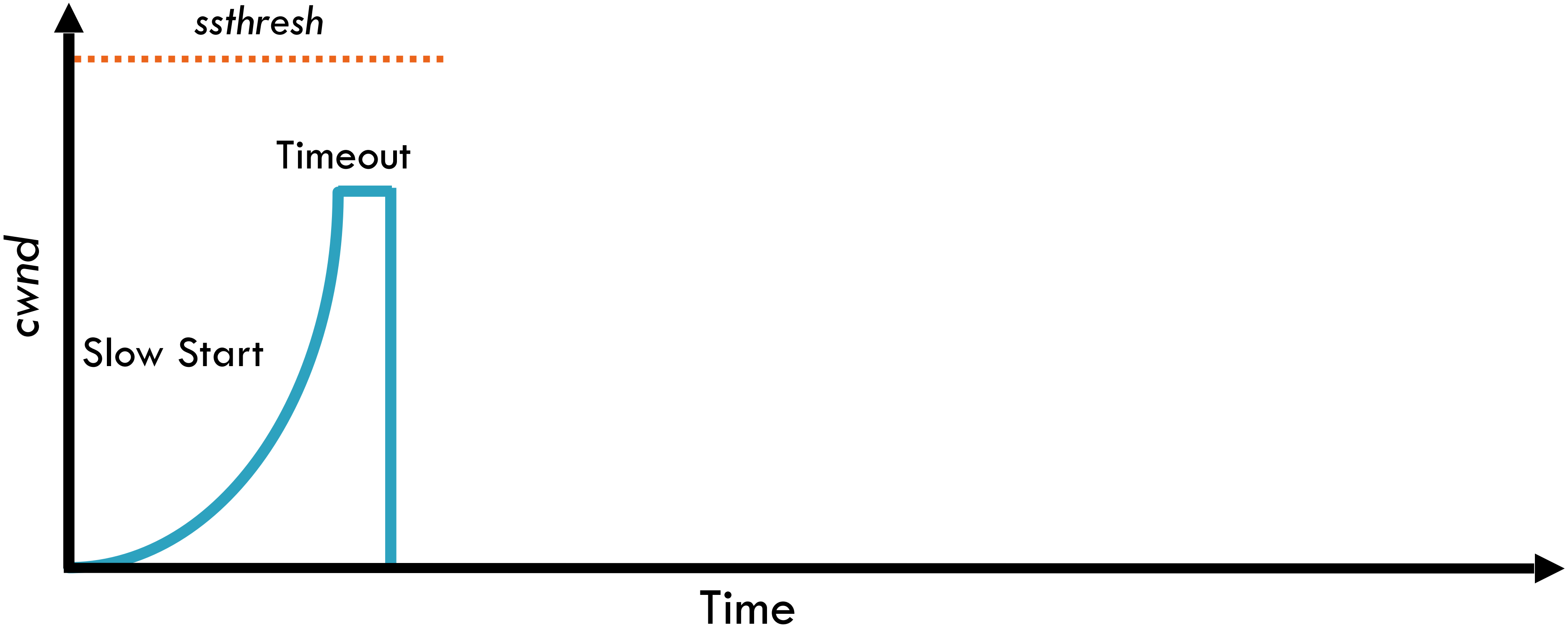

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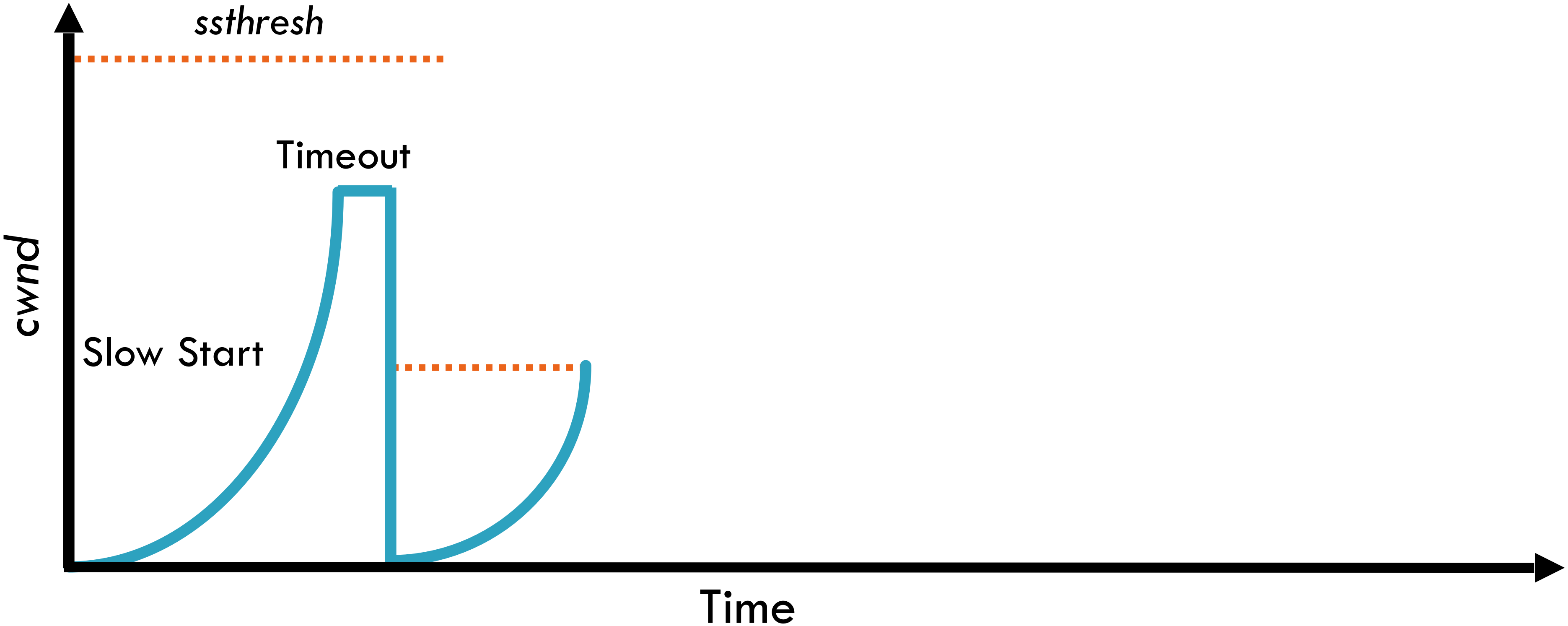

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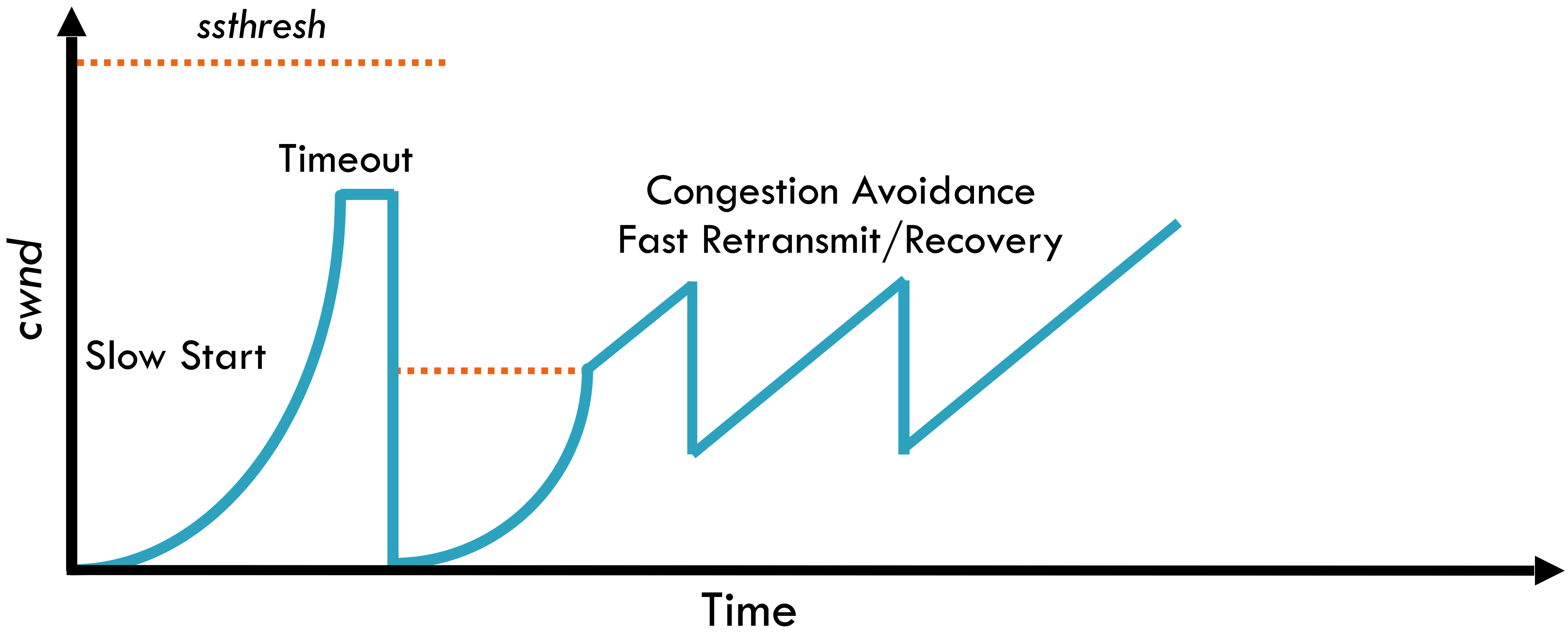

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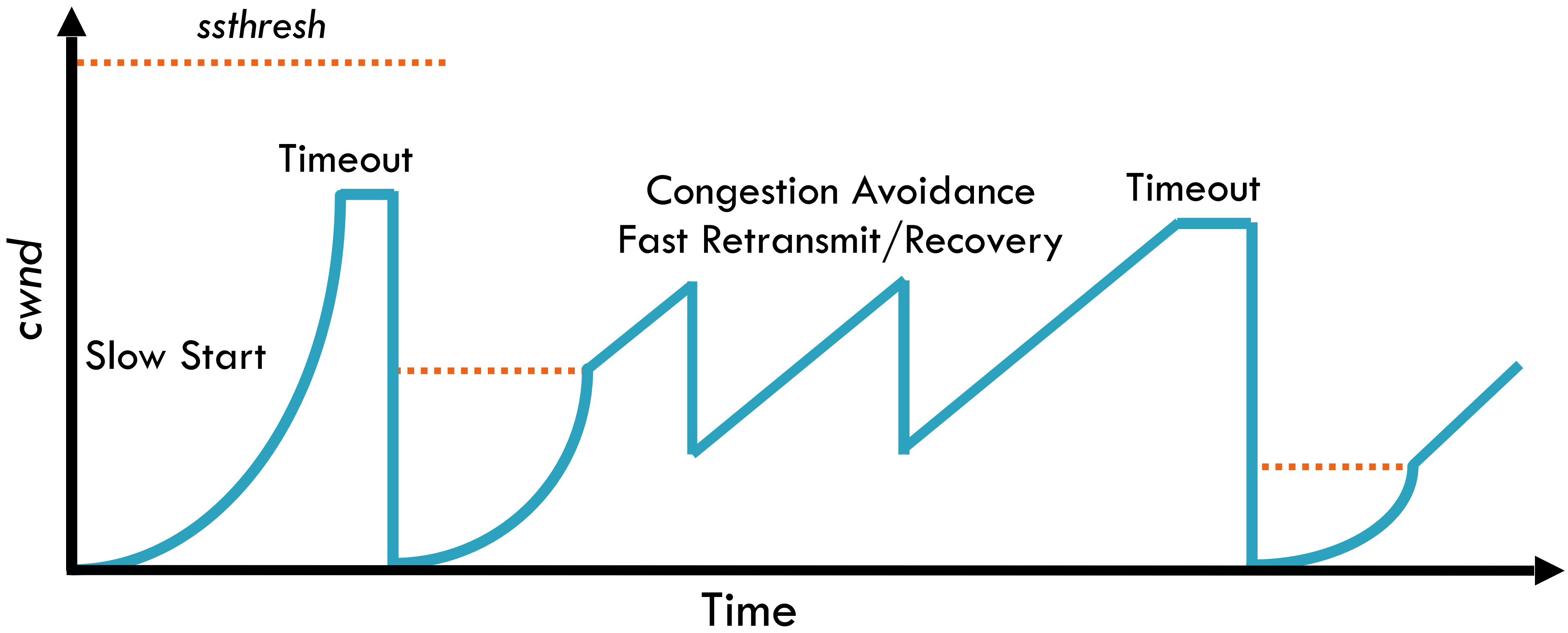

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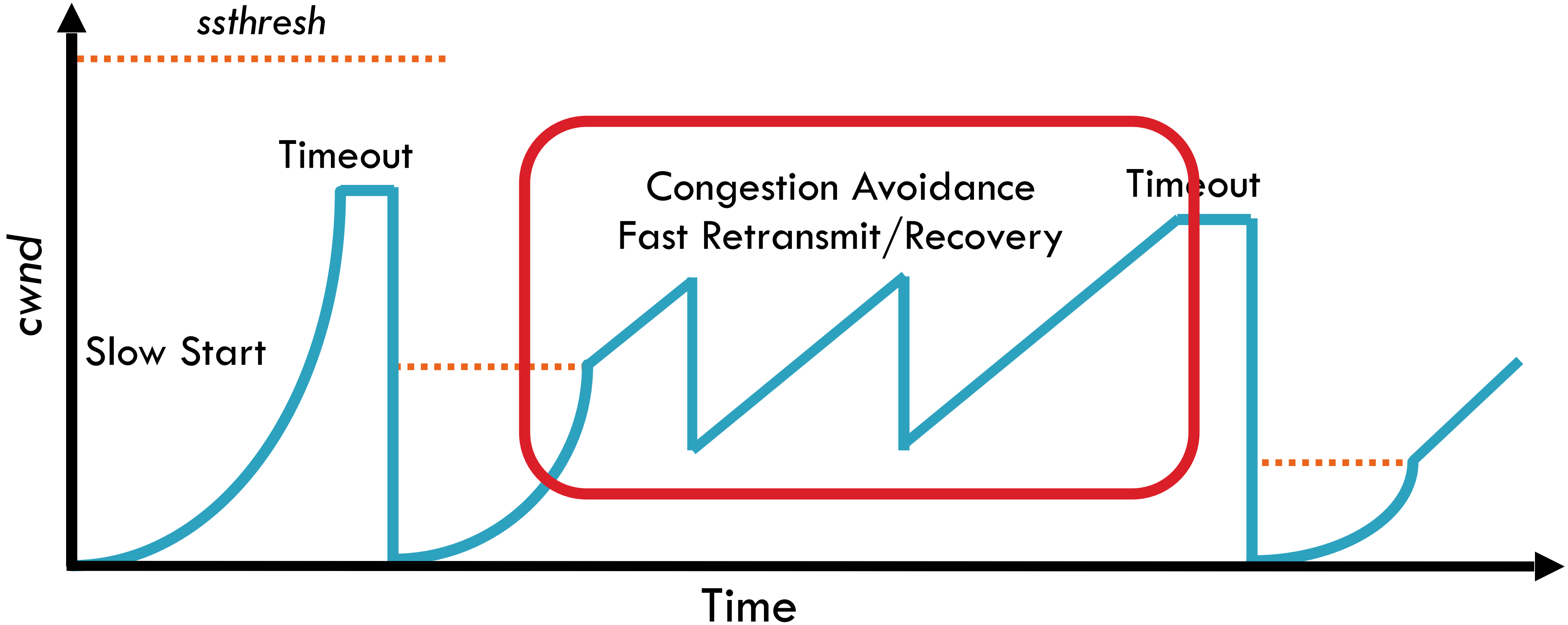
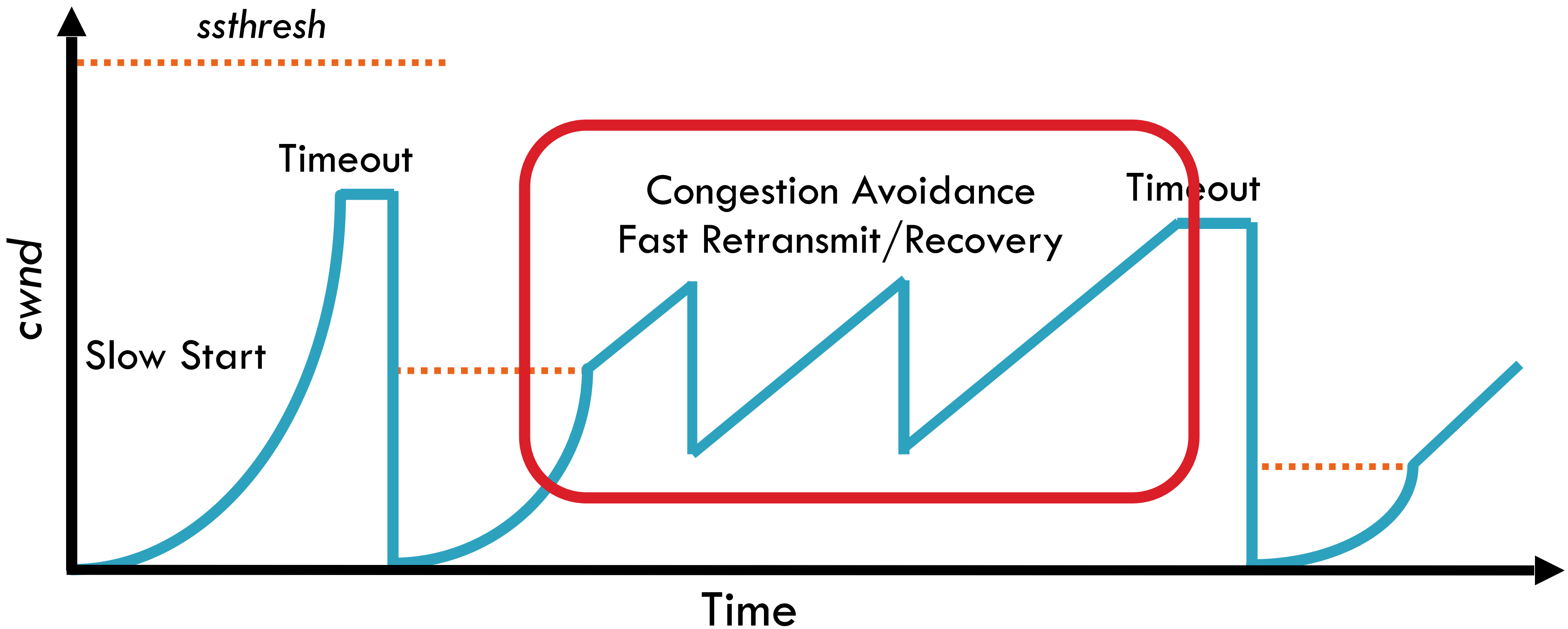


- At steady state, *cwnd* oscillates around the optimal window size

Fast Retransmit and Fast Recovery



- At steady state, *cwnd* oscillates around the optimal window size
- TCP always forces packet drops

Many TCP Variants…

- Tahoe: the original
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- And many, many, many more…

TCP in the Real World

- What are the most popular variants today?
  - Key problem: TCP performs poorly on high bandwidth-delay product networks (like the modern Internet)
  - Compound TCP (Windows)
    - Based on Reno
    - Uses two congestion windows: delay based and loss based
    - Thus, it uses a *compound* congestion controller
  - TCP CUBIC (Linux)
    - Enhancement of BIC (Binary Increase Congestion Control)
    - Window size controlled by cubic function
    - Parameterized by the time *T* since the last dropped packet

High Bandwidth-Delay Product

- Key Problem: TCP performs poorly when
  - The capacity of the network (bandwidth) is large
  - The delay (RTT) of the network is large
  - Or, when bandwidth * delay is large
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    - b * d = maximum amount of in-flight data in the network
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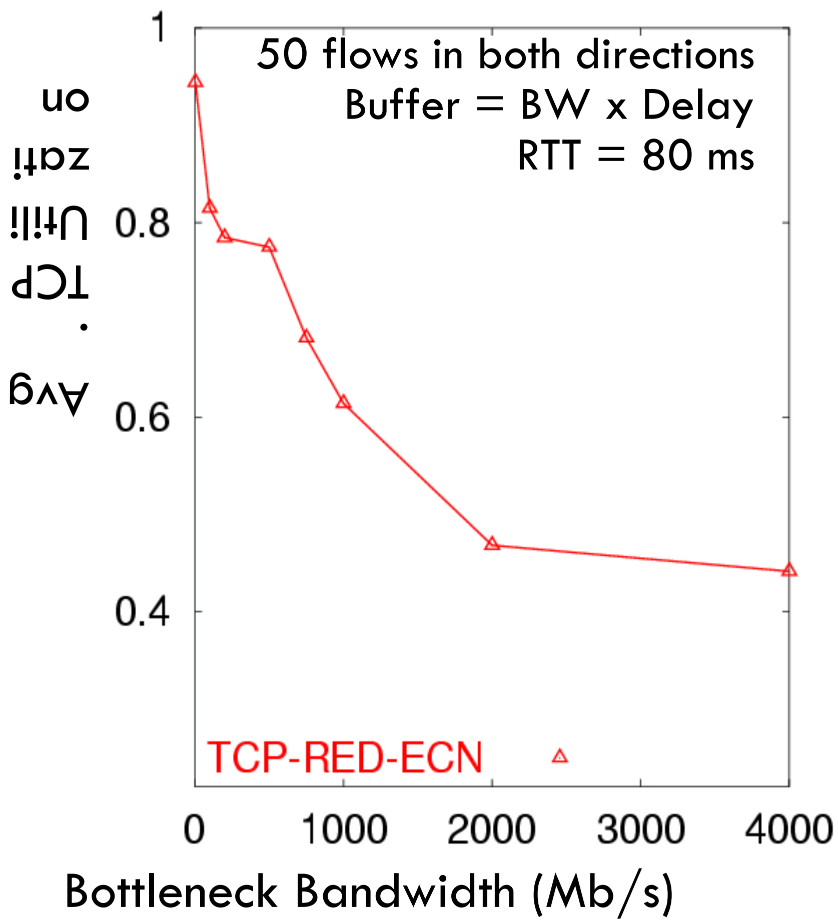
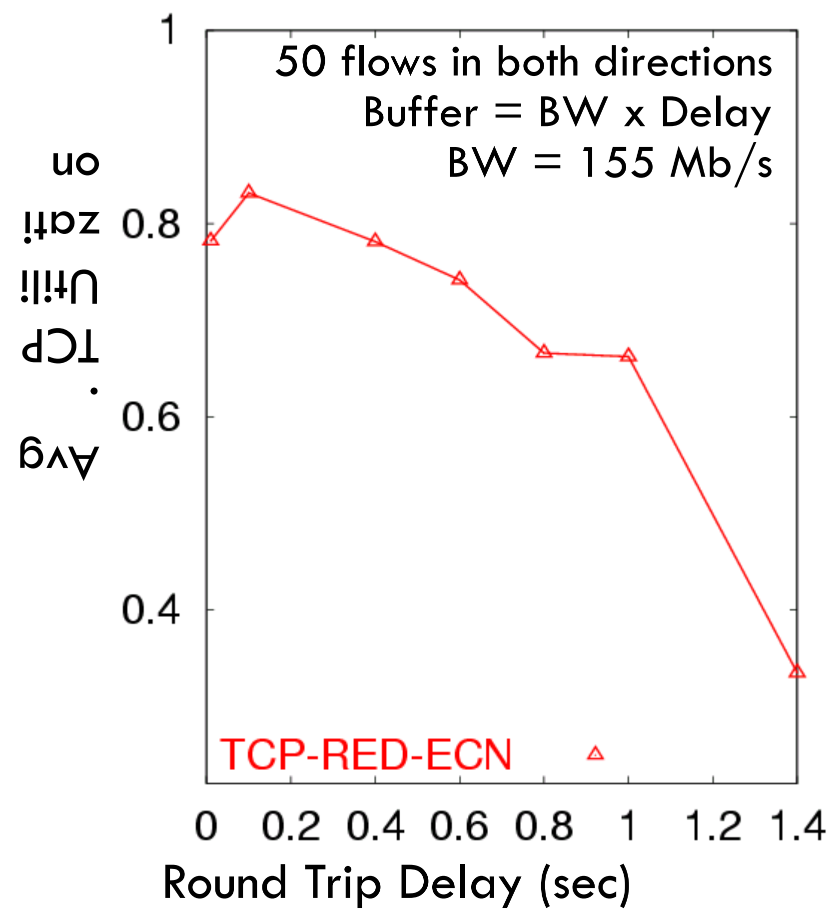
- Why does TCP perform poorly?
  - Slow start and additive increase are slow to converge
  - TCP is ACK clocked
    - i.e. TCP can only react as quickly as ACKs are received
    - Large RTT → ACKs are delayed → TCP is slow to react

Poor Performance of TCP Reno CC





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- Simple implementation

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- Default TCP implementation in Windows
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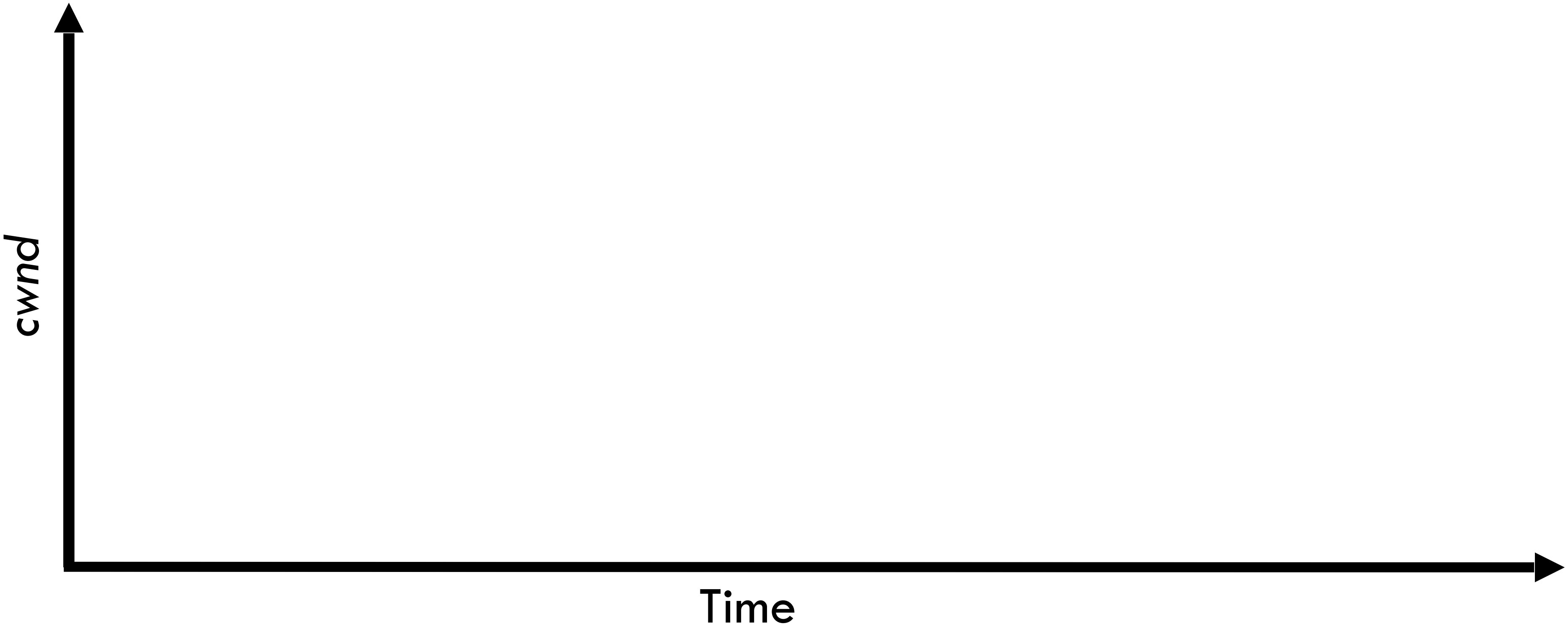
- *wnd* = min(*cwnd* + *dwnd*, *adv_wnd*)
  - *cwnd* is controlled by AIMD
  - *dwnd* is the delay window
- Rules for adjusting *dwnd:*
  - If RTT is increasing, decrease *dwnd* (*dwnd* >= 0)
  - If RTT is decreasing, increase *dwnd*
  - Increase/decrease are proportional to the rate of change

Compound TCP Example



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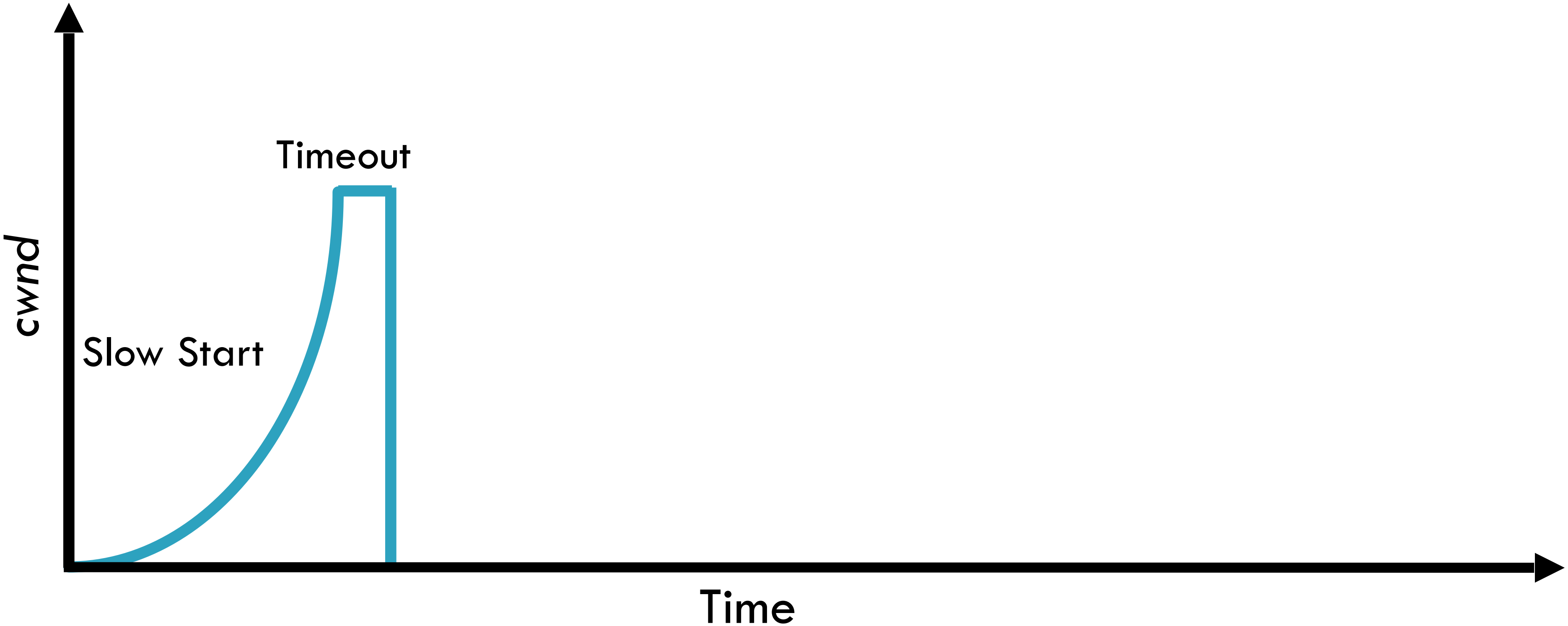

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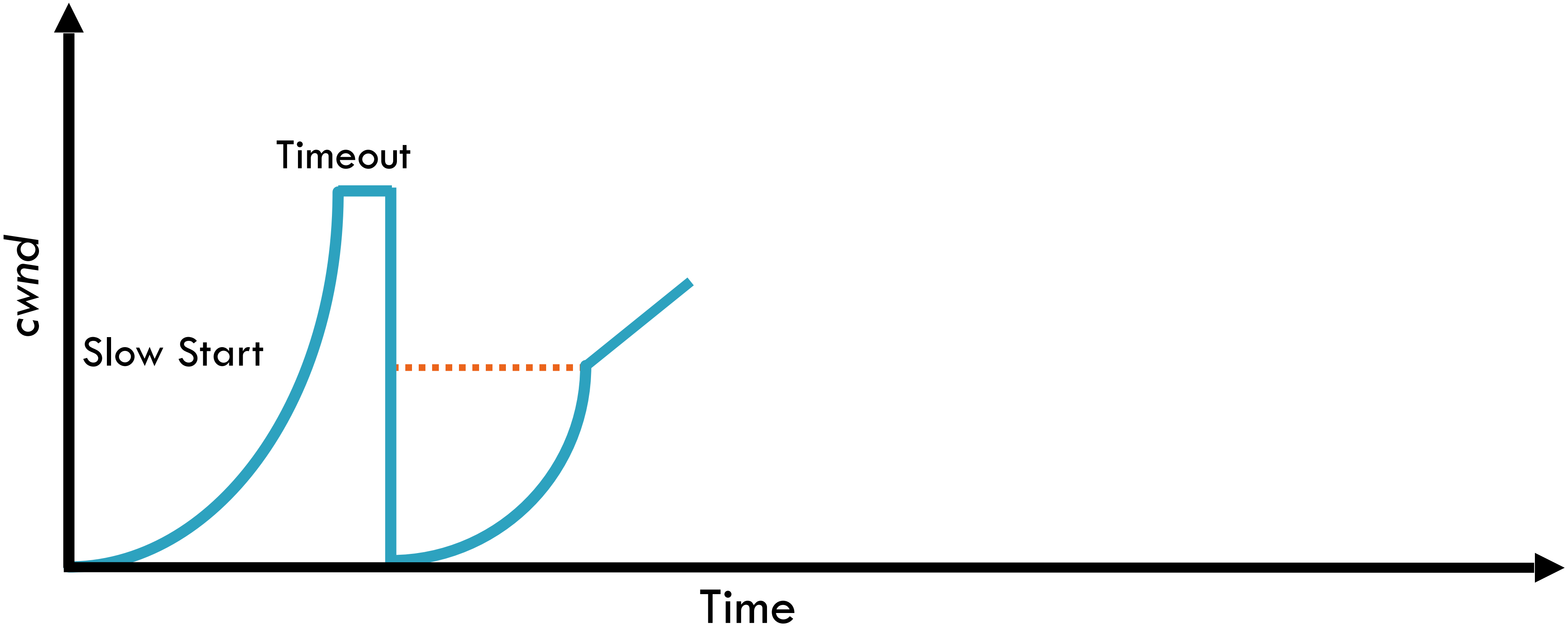

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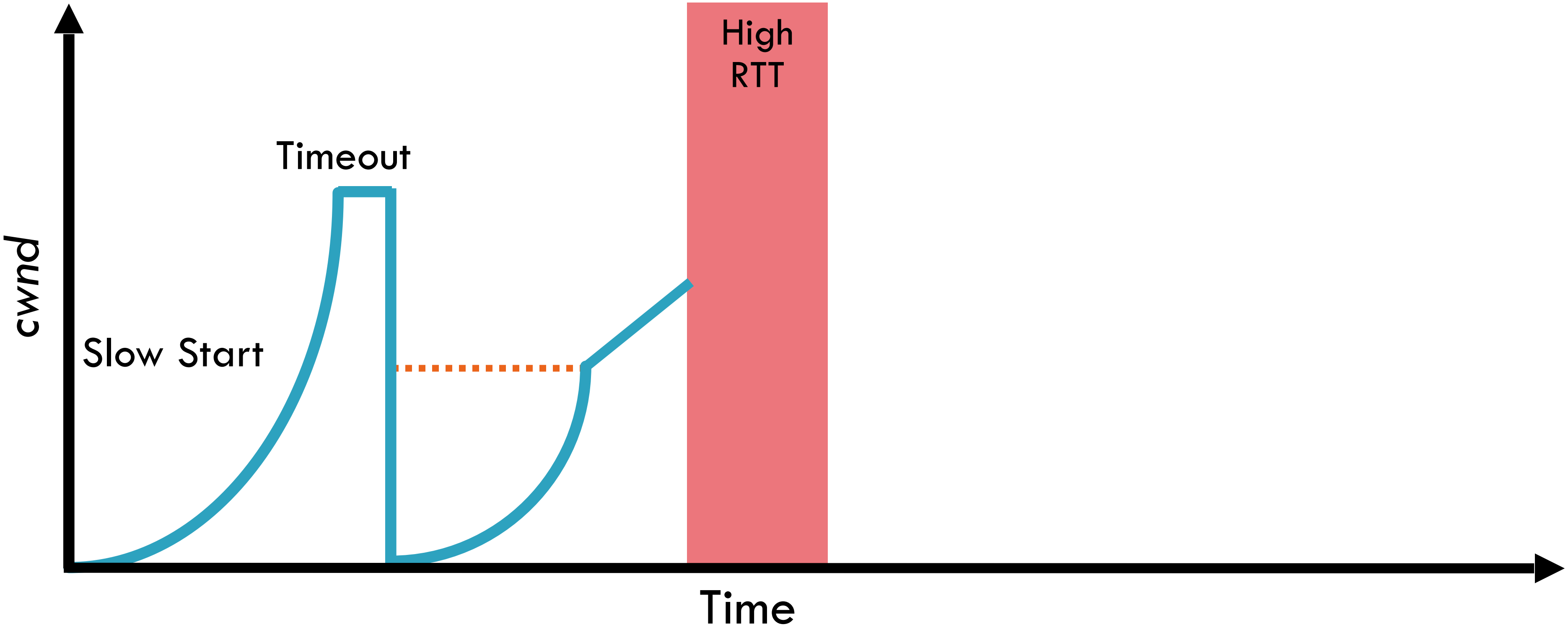

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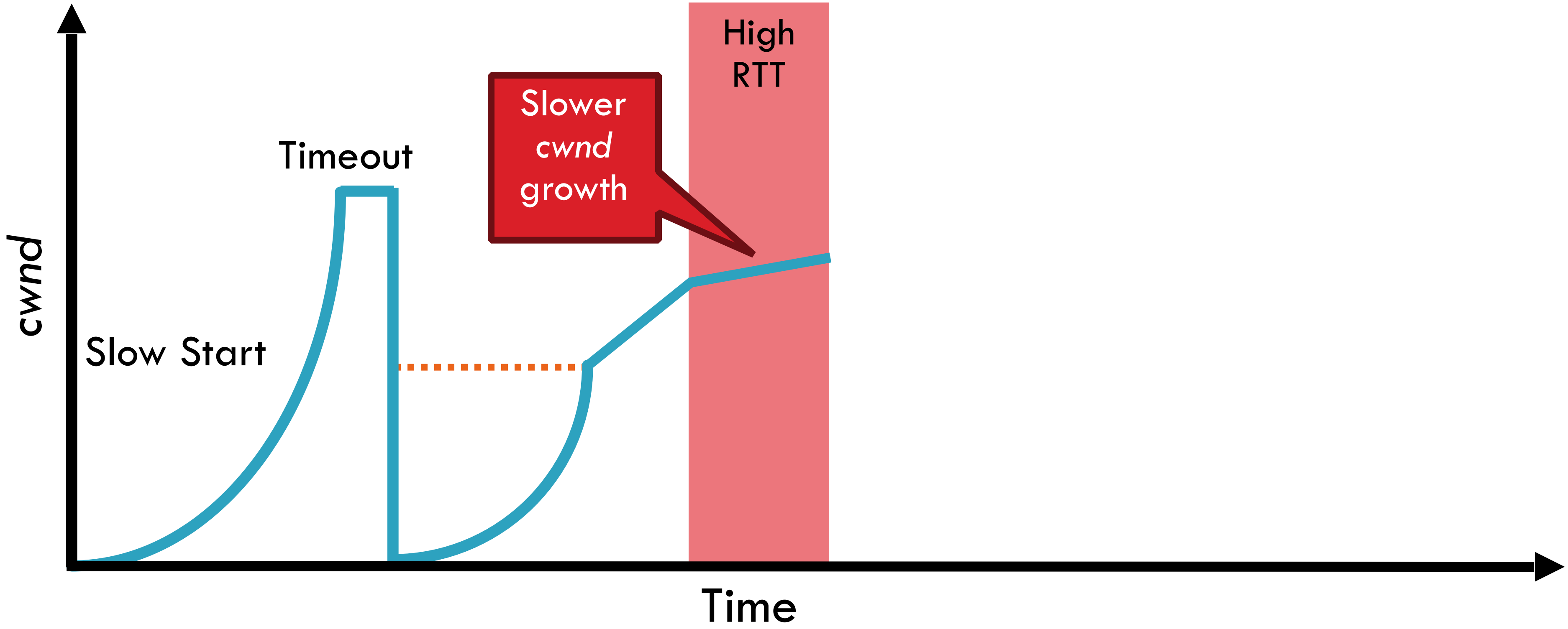

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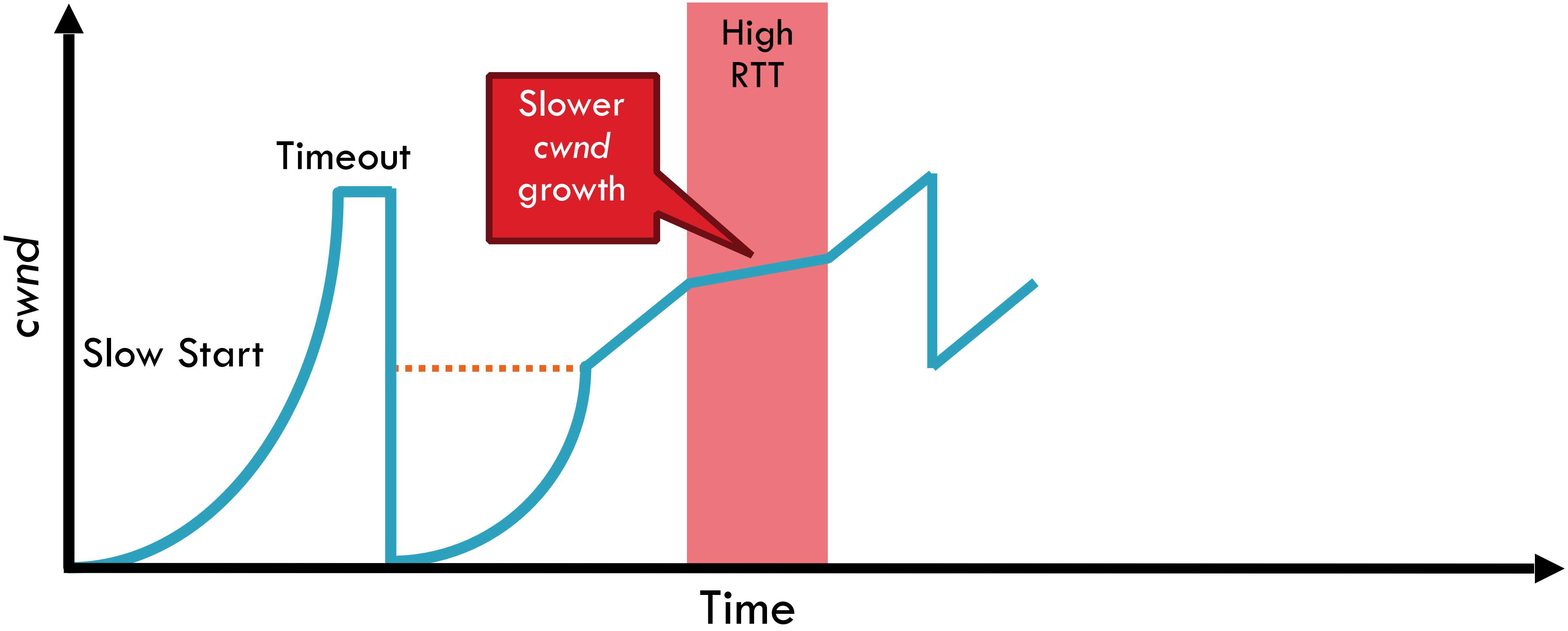

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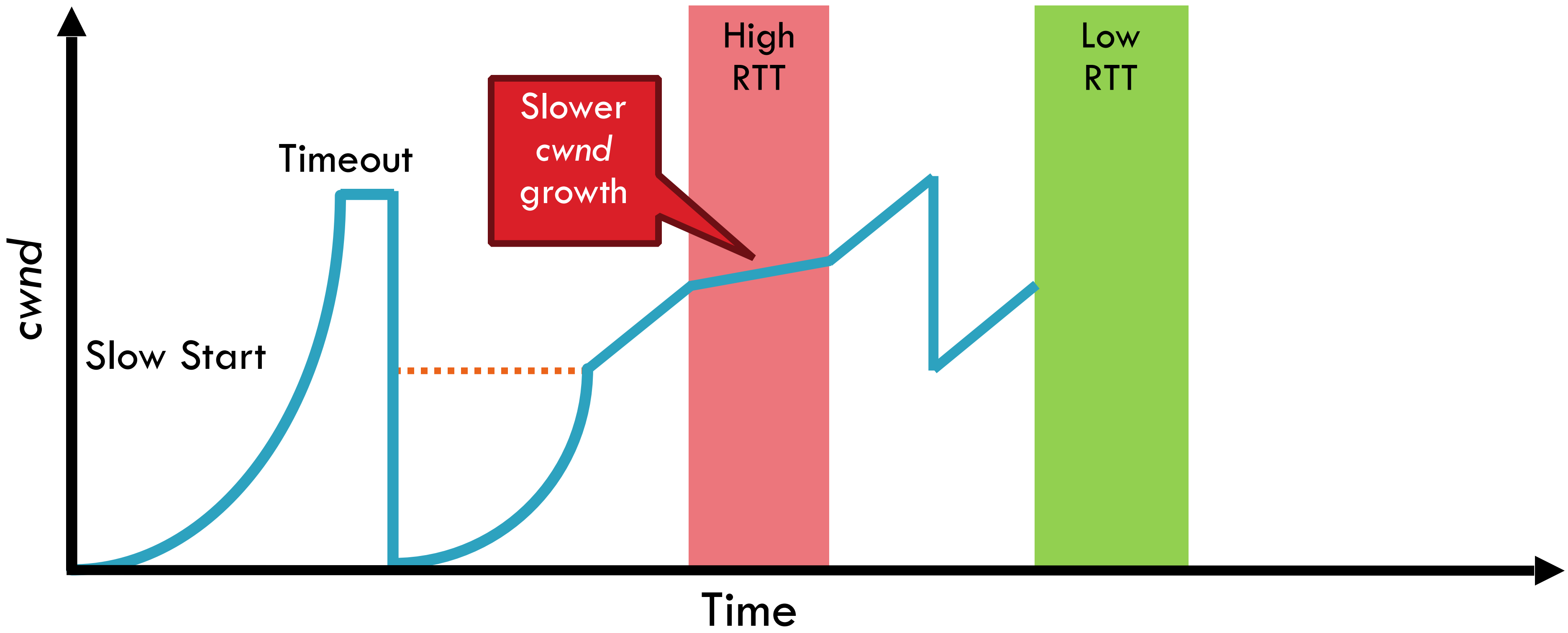

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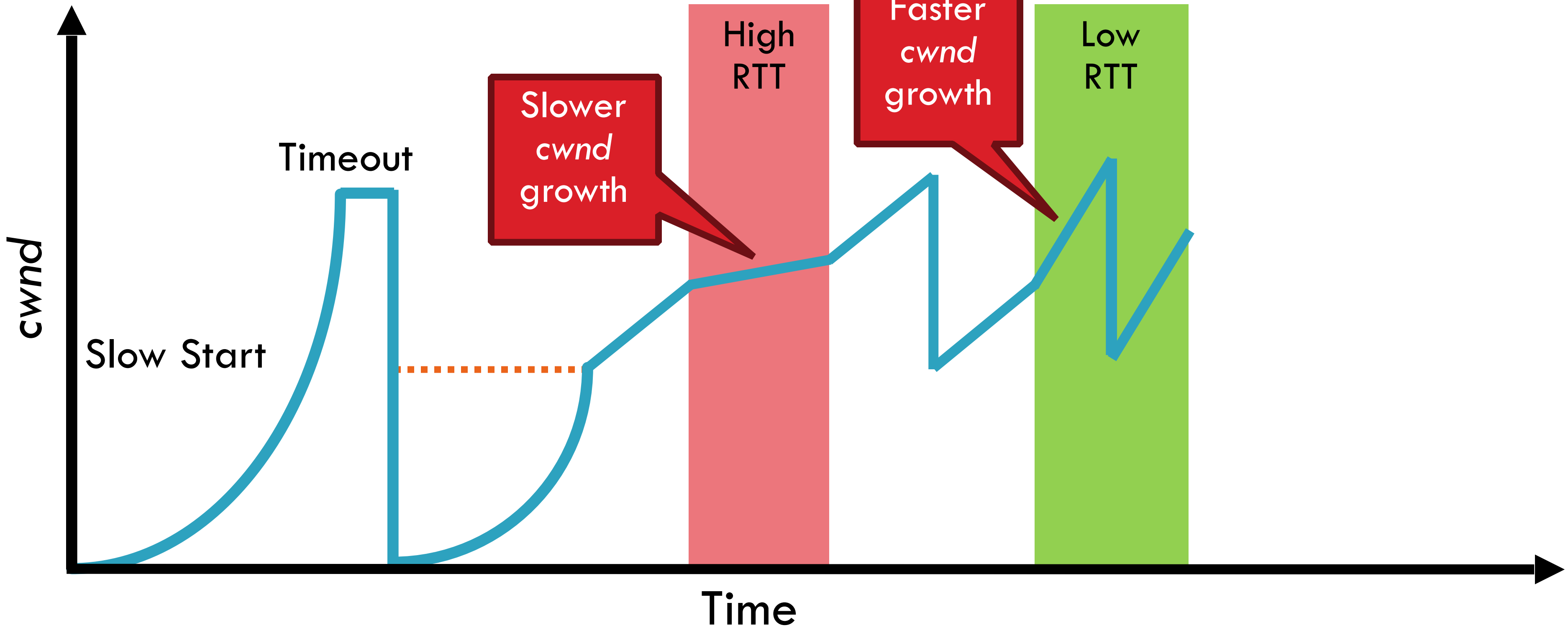

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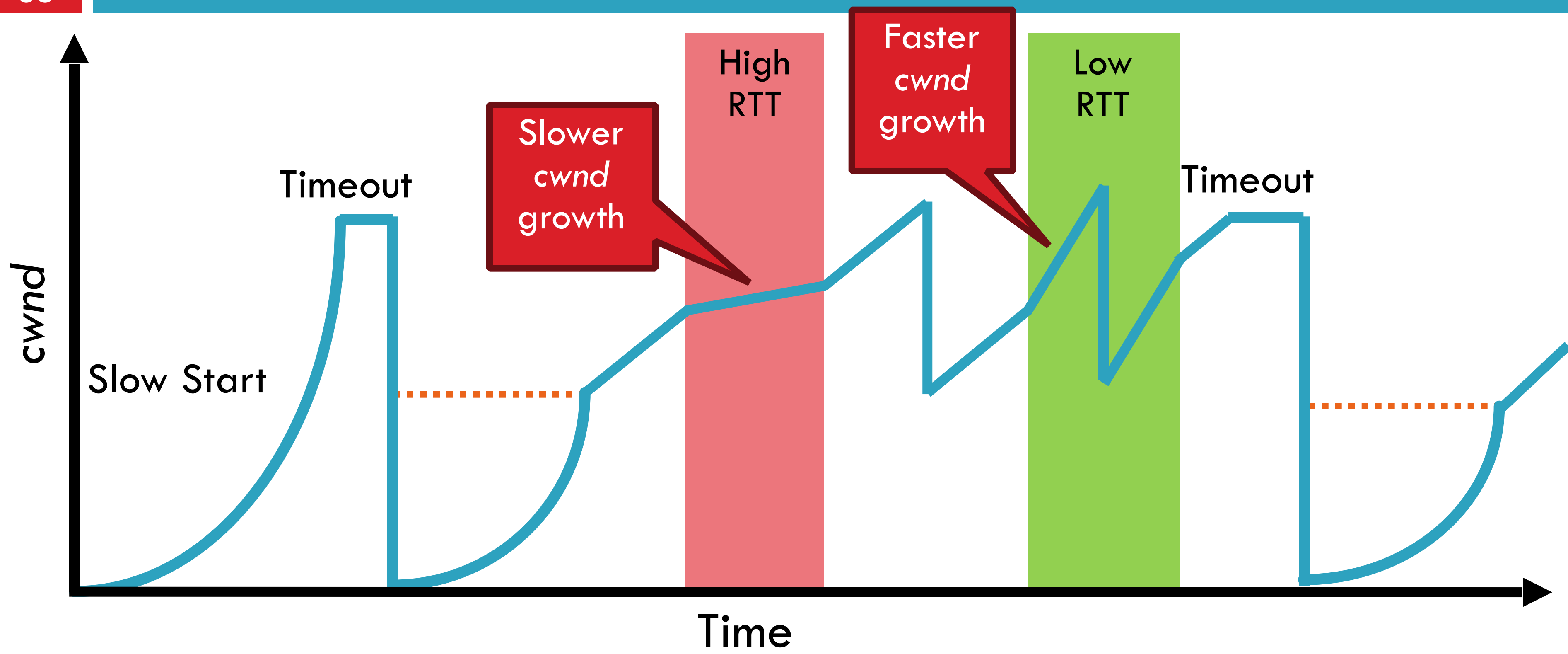

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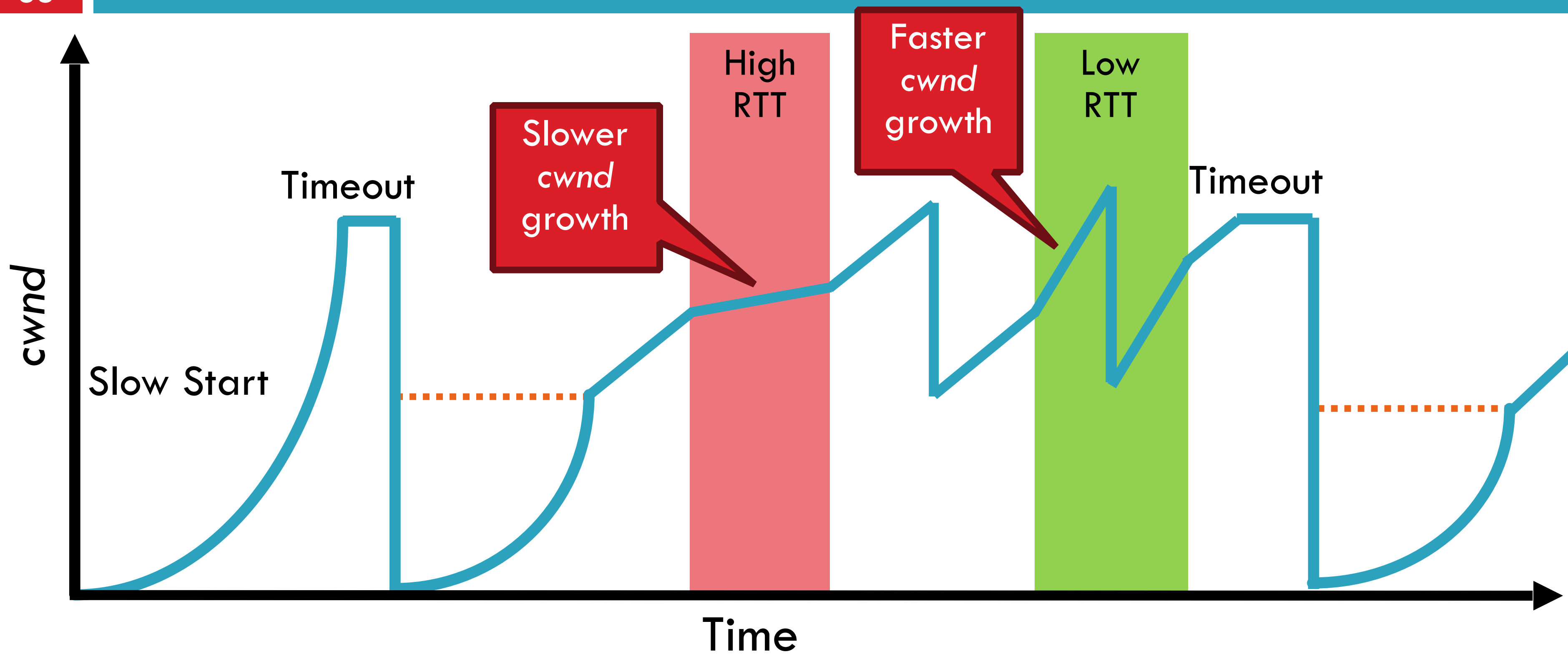

- Aggressiveness corresponds to changes in RTT

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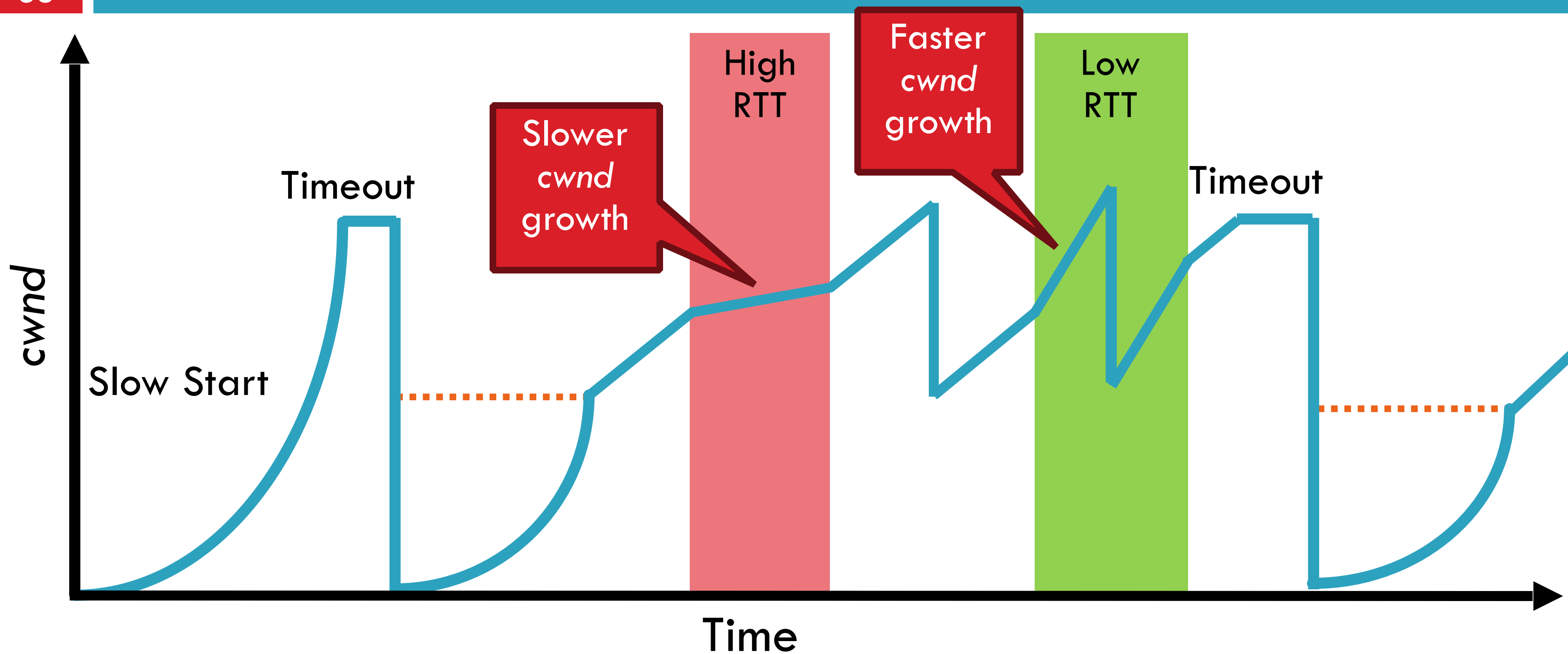

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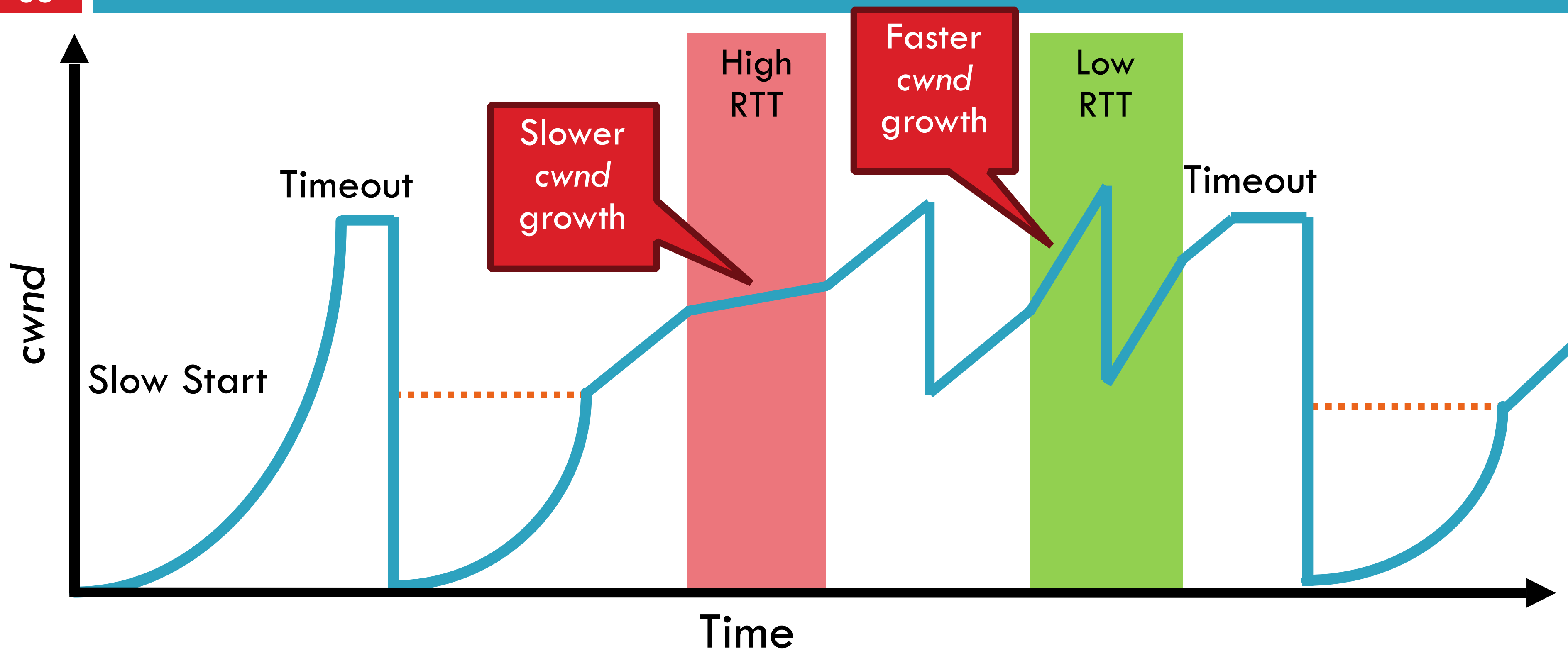


- Aggressiveness corresponds to changes in RTT
- Advantages: fast ramp up, more fair to flows with different RTTs
- Disadvantage: must estimate RTT, which is very challenging

TCP CUBIC Implementation

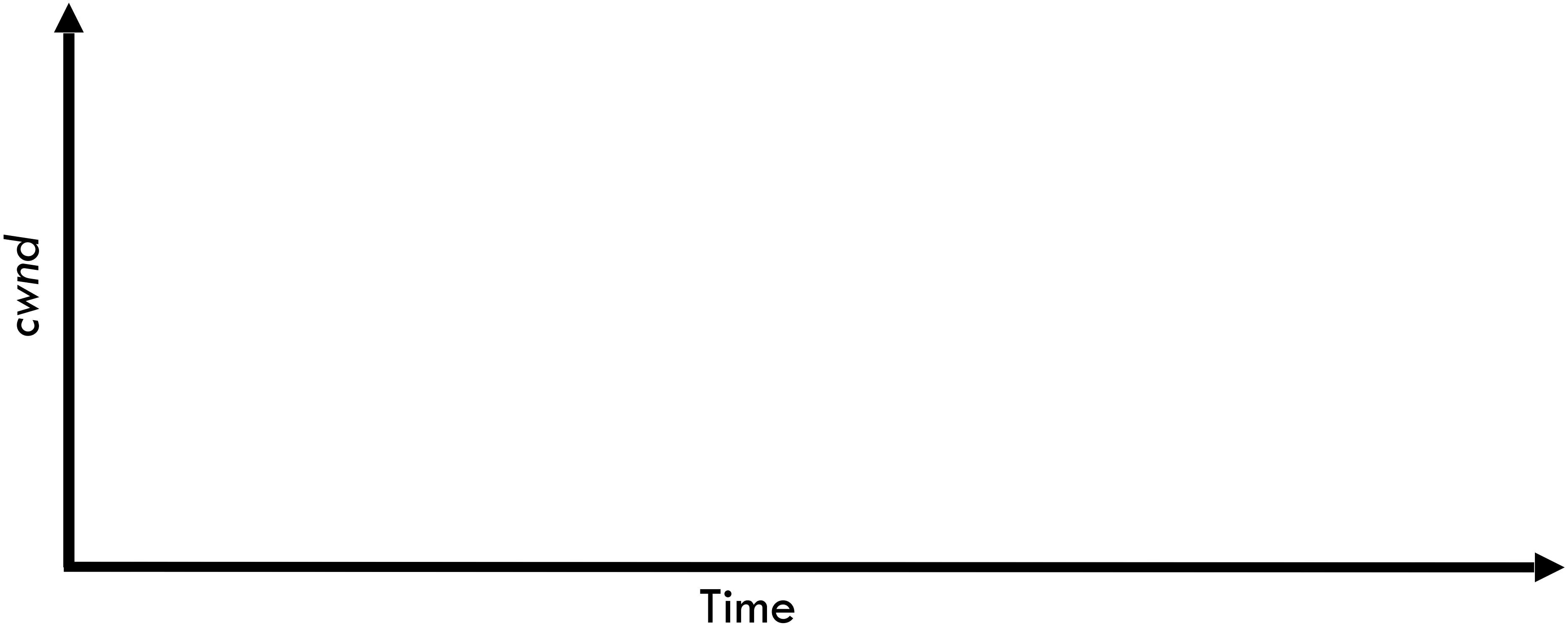
- Default TCP implementation in Linux
- Replace AIMD with cubic function

$$W_{cubic} = C(T - K)^3 + W_{max} \quad (1)$$

C is a scaling constant, and $K = \sqrt[3]{\frac{W_{max}\beta}{C}}$

  - B → a constant fraction for multiplicative increase
  - T → time since last packet drop
  - W_max → cwnd when last packet dropped

TCP CUBIC Example



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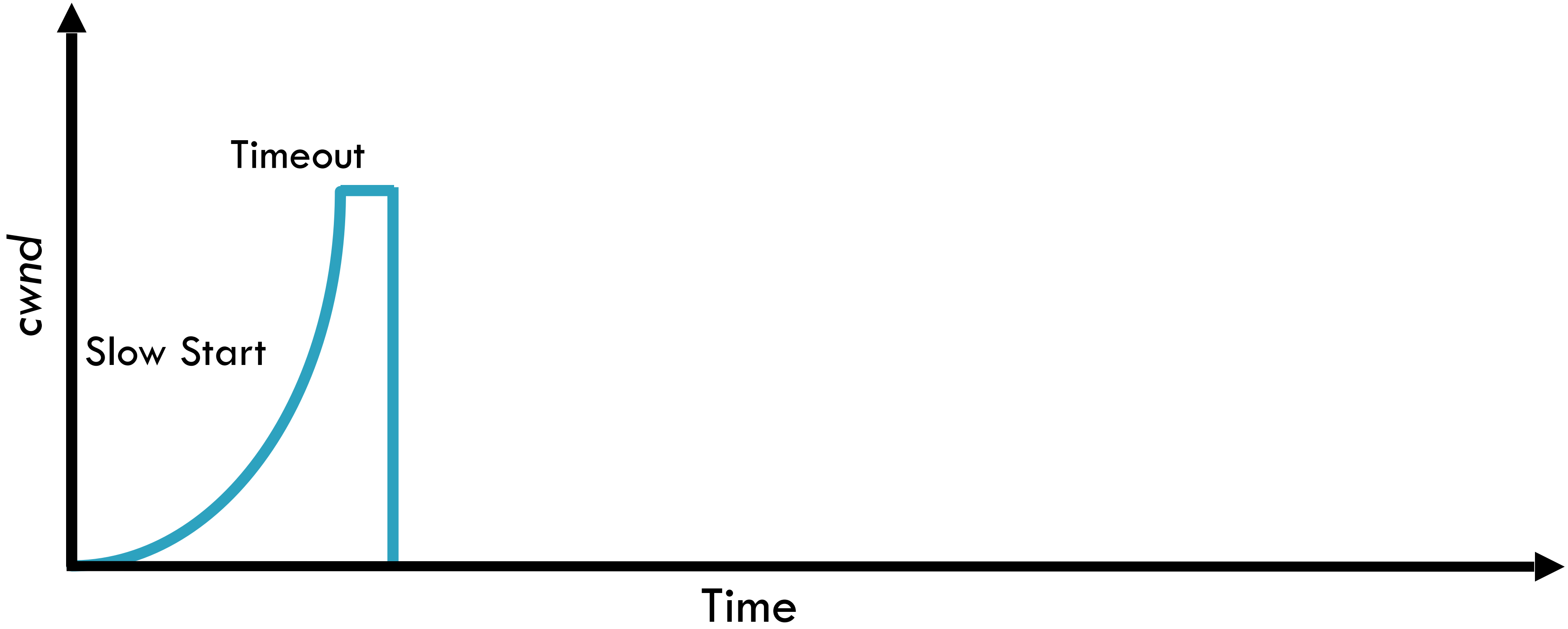

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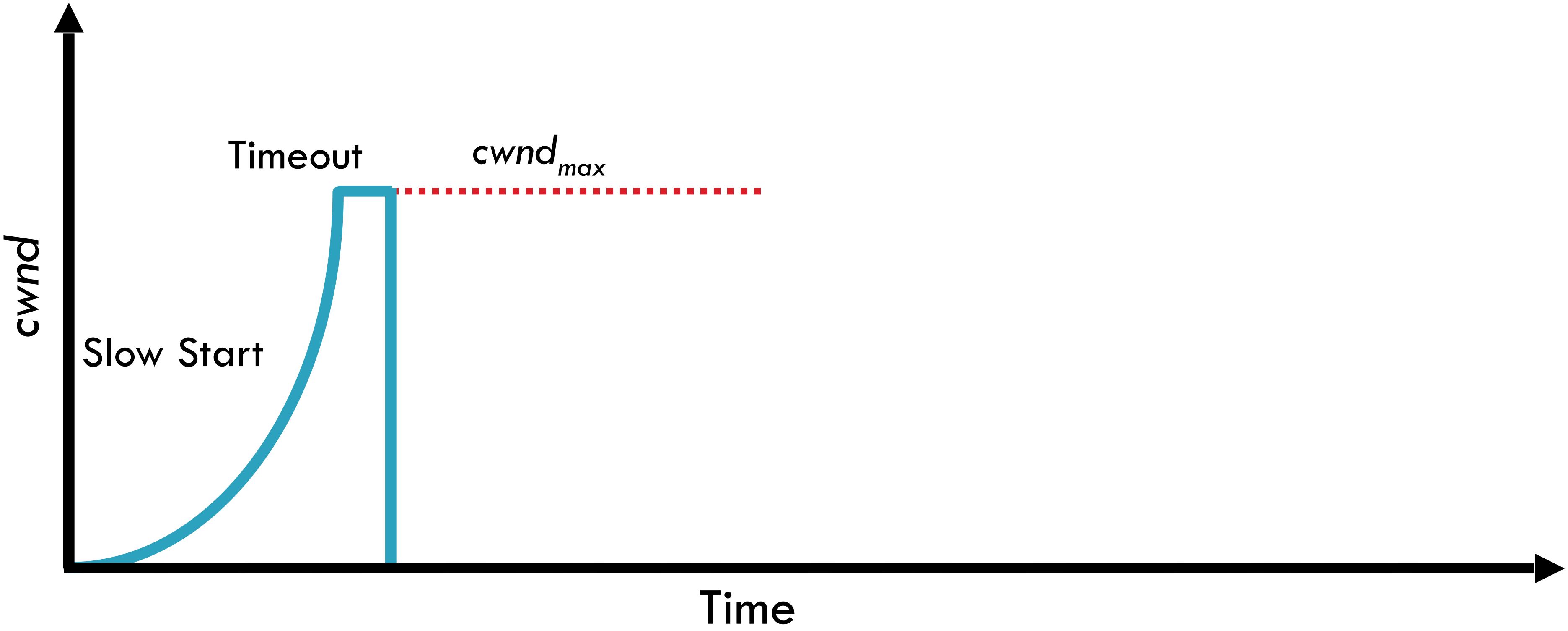

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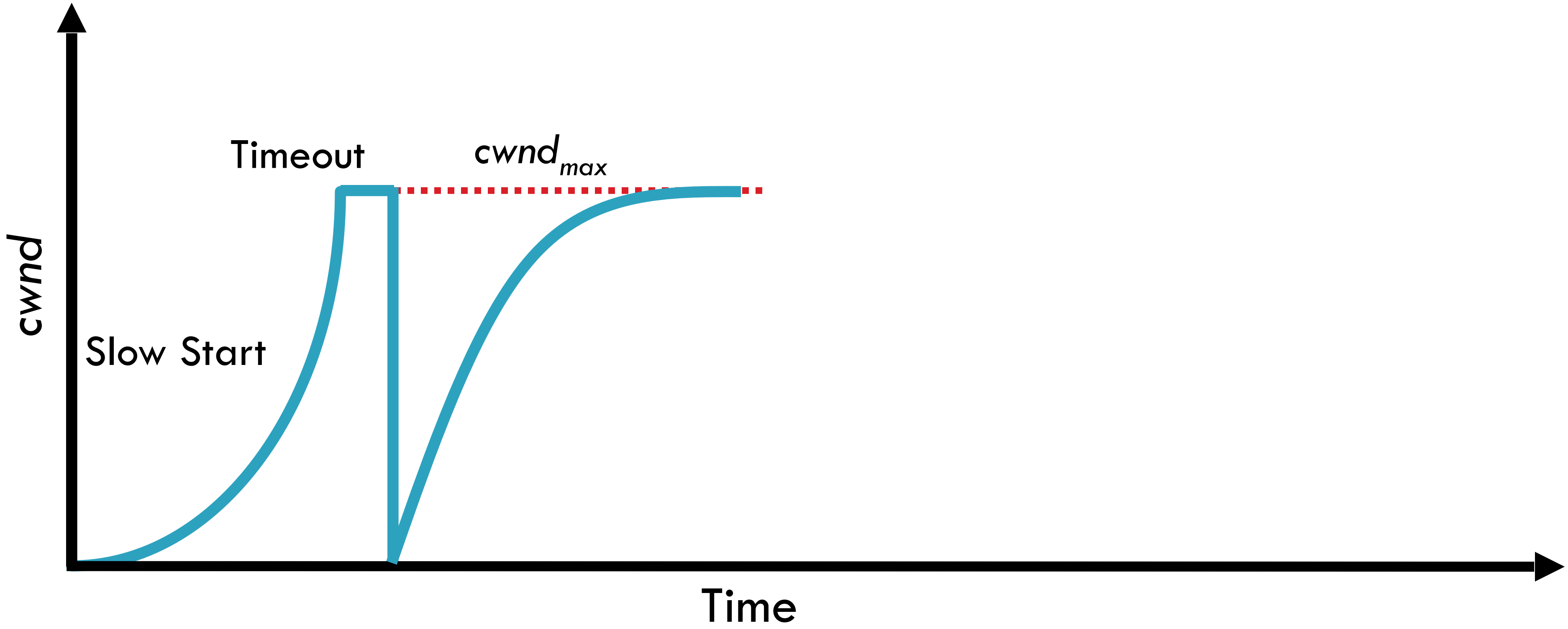

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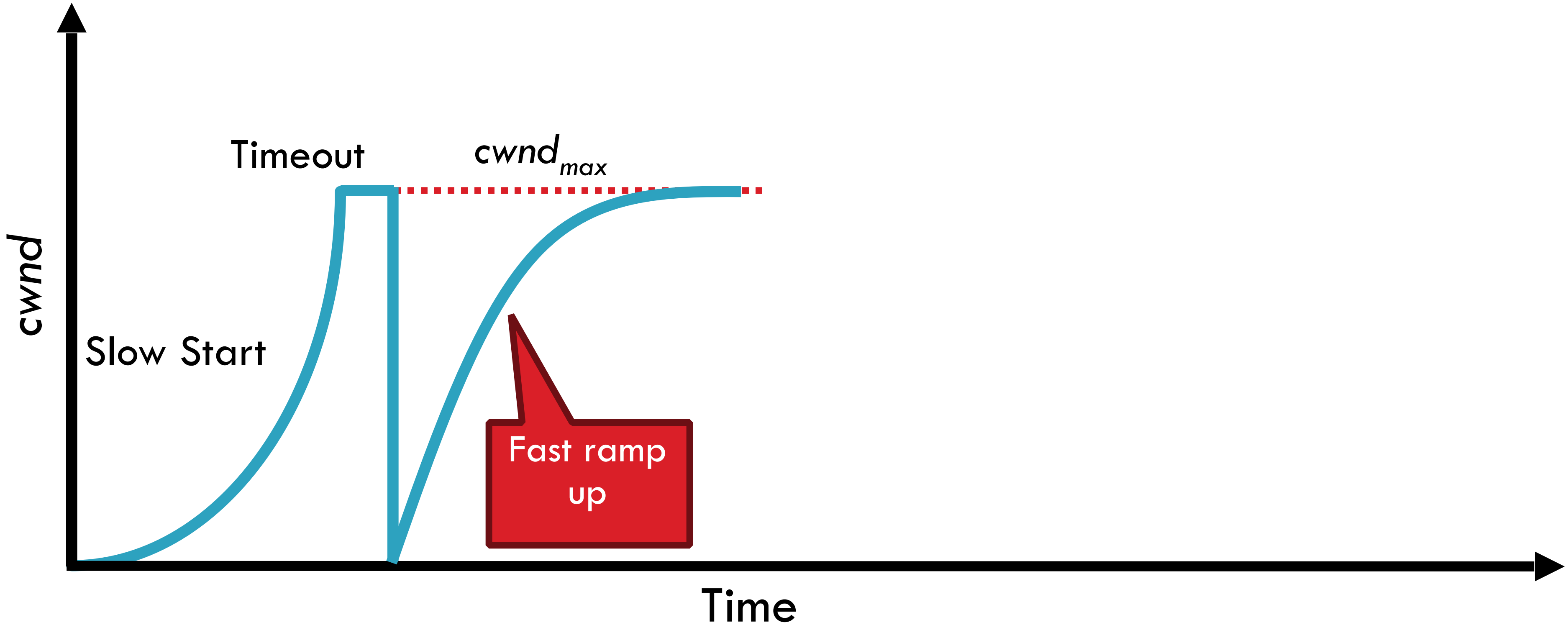

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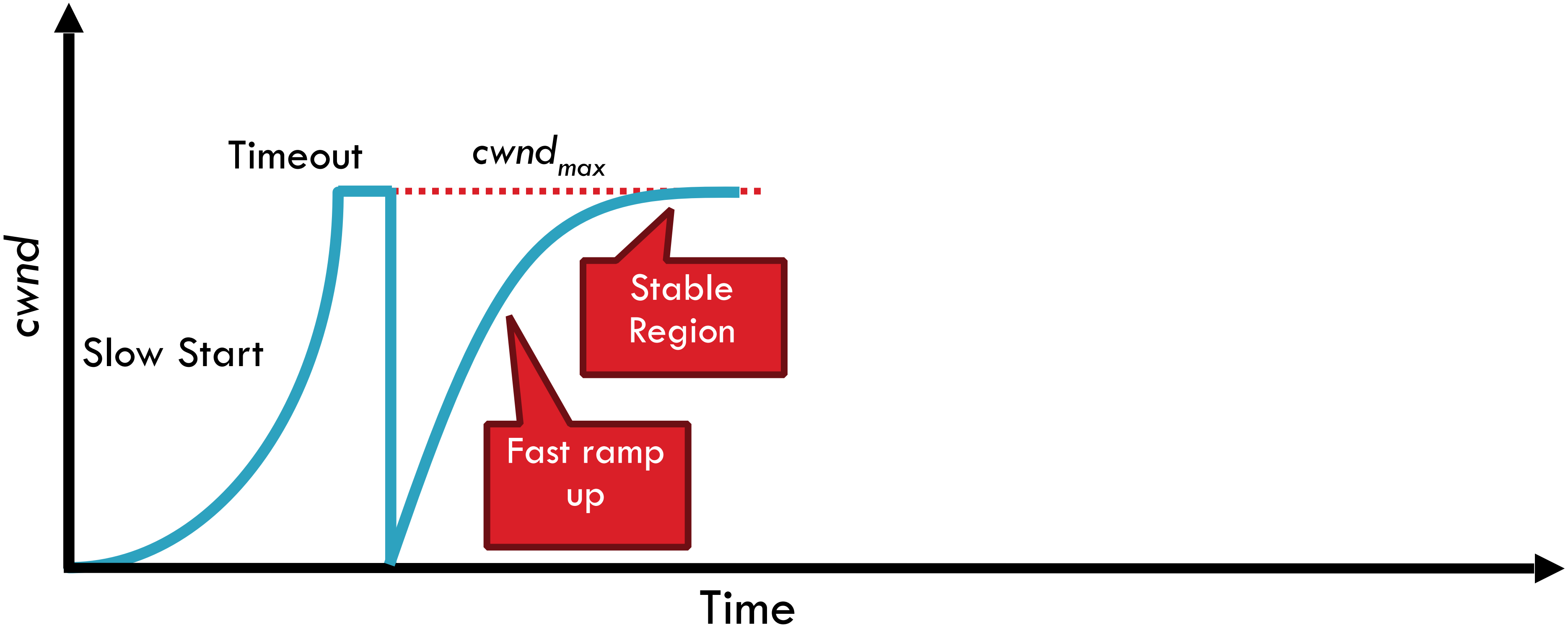

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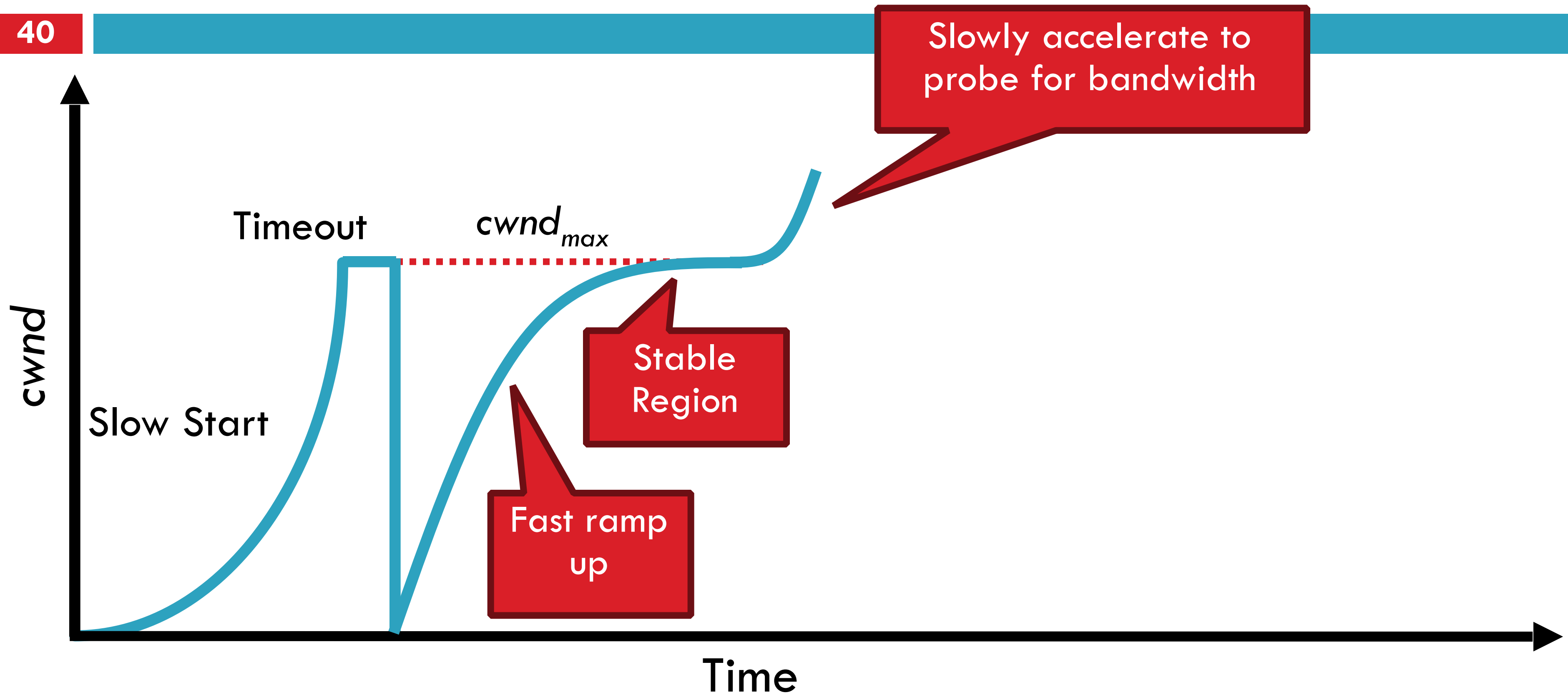

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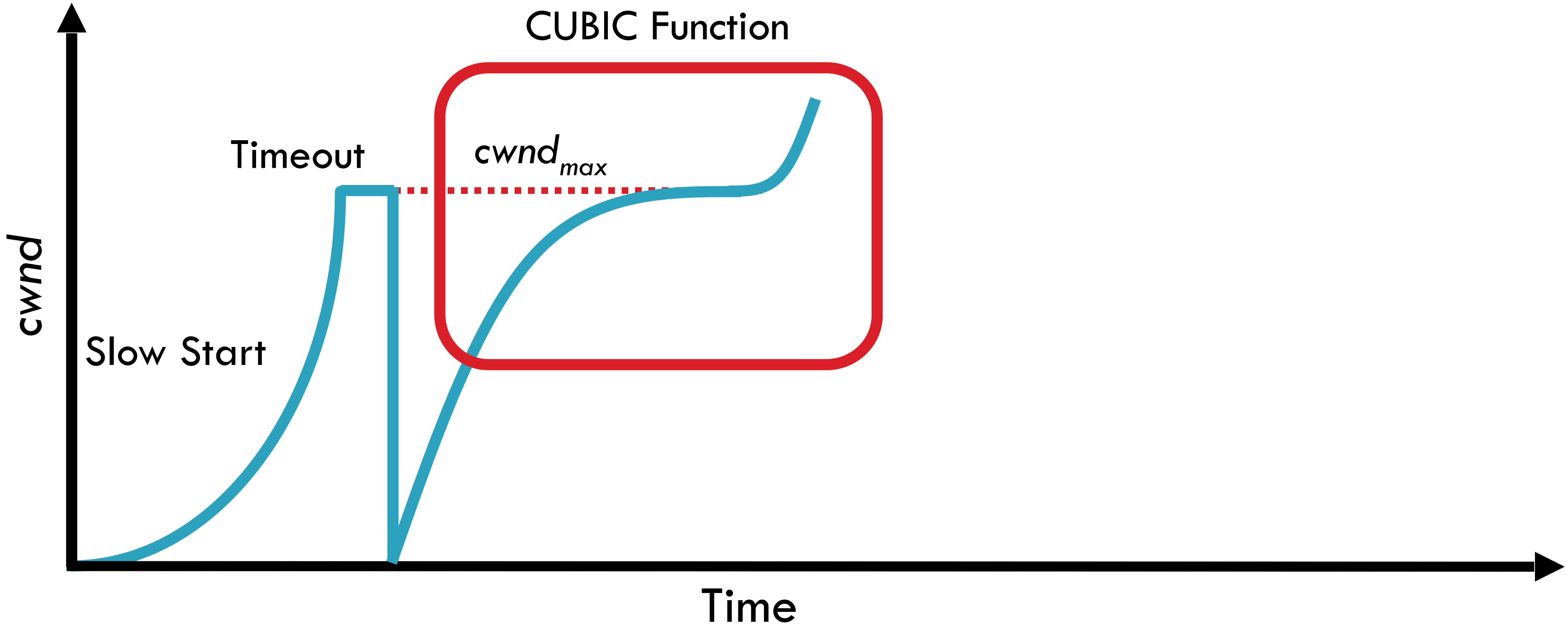

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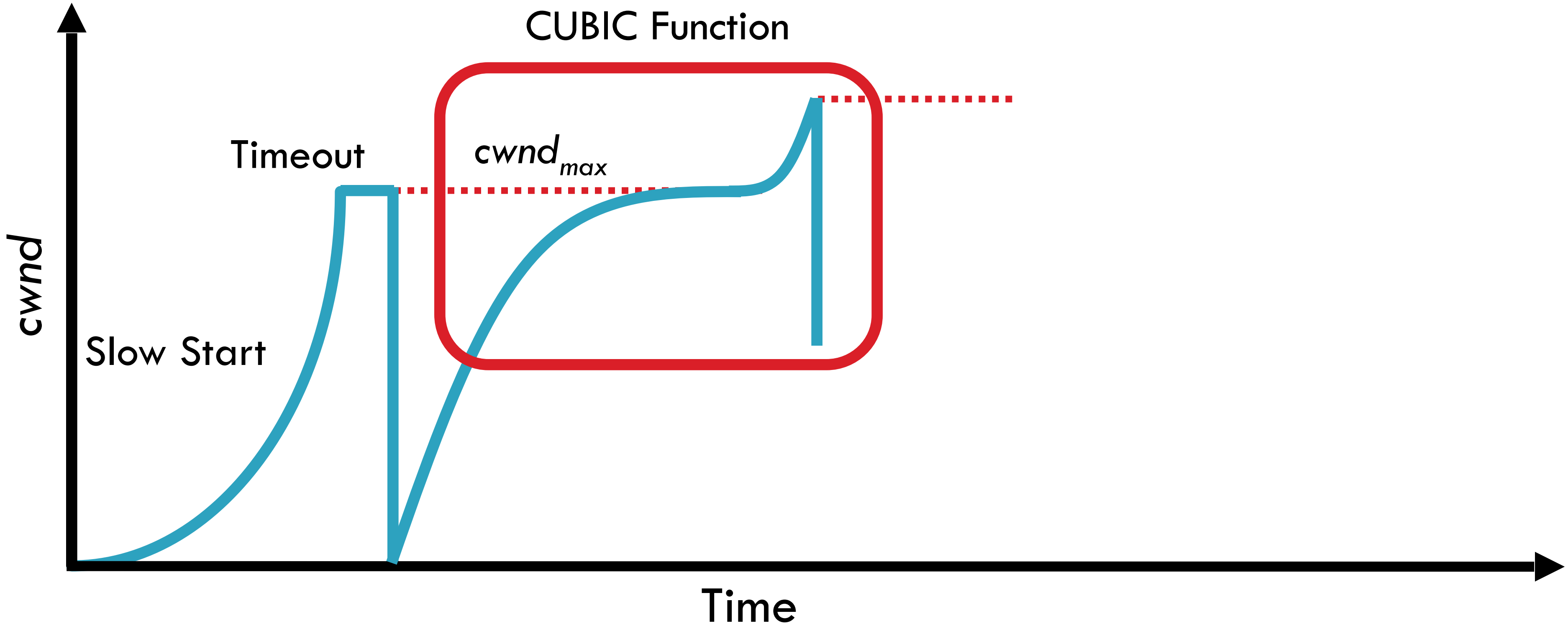

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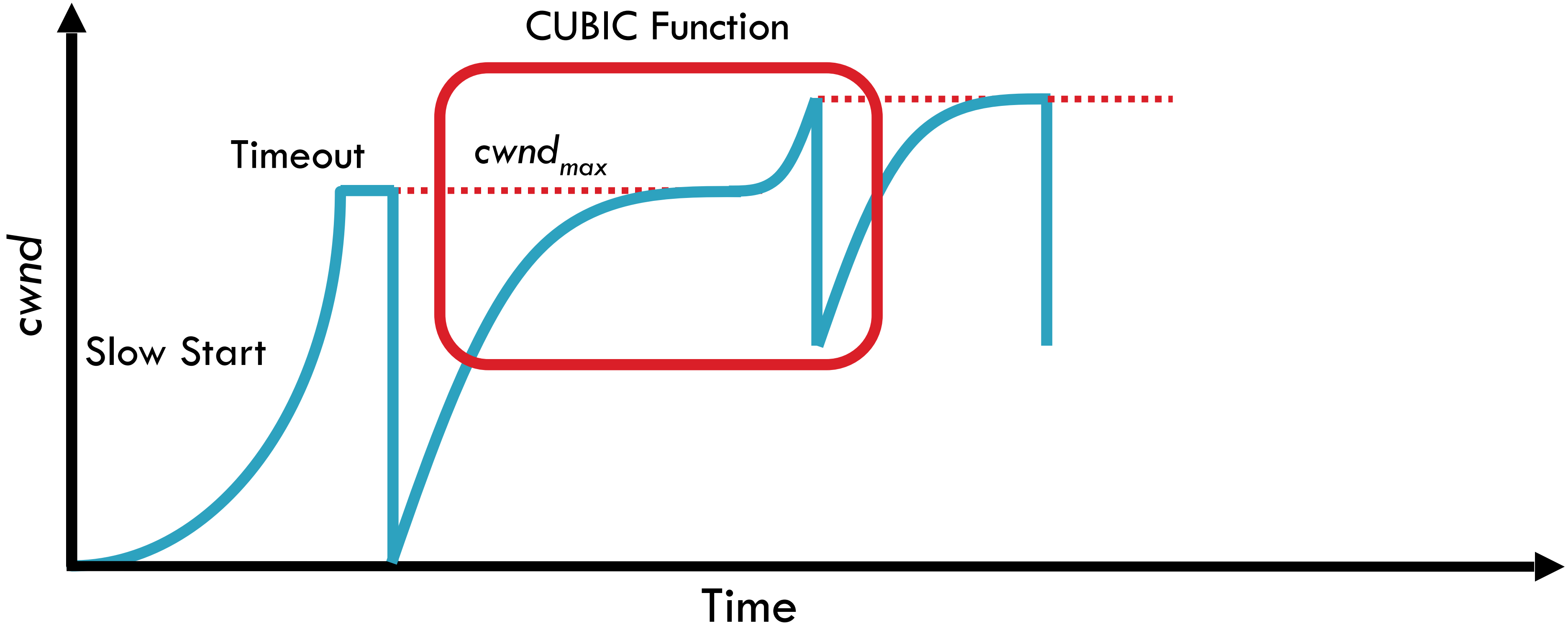

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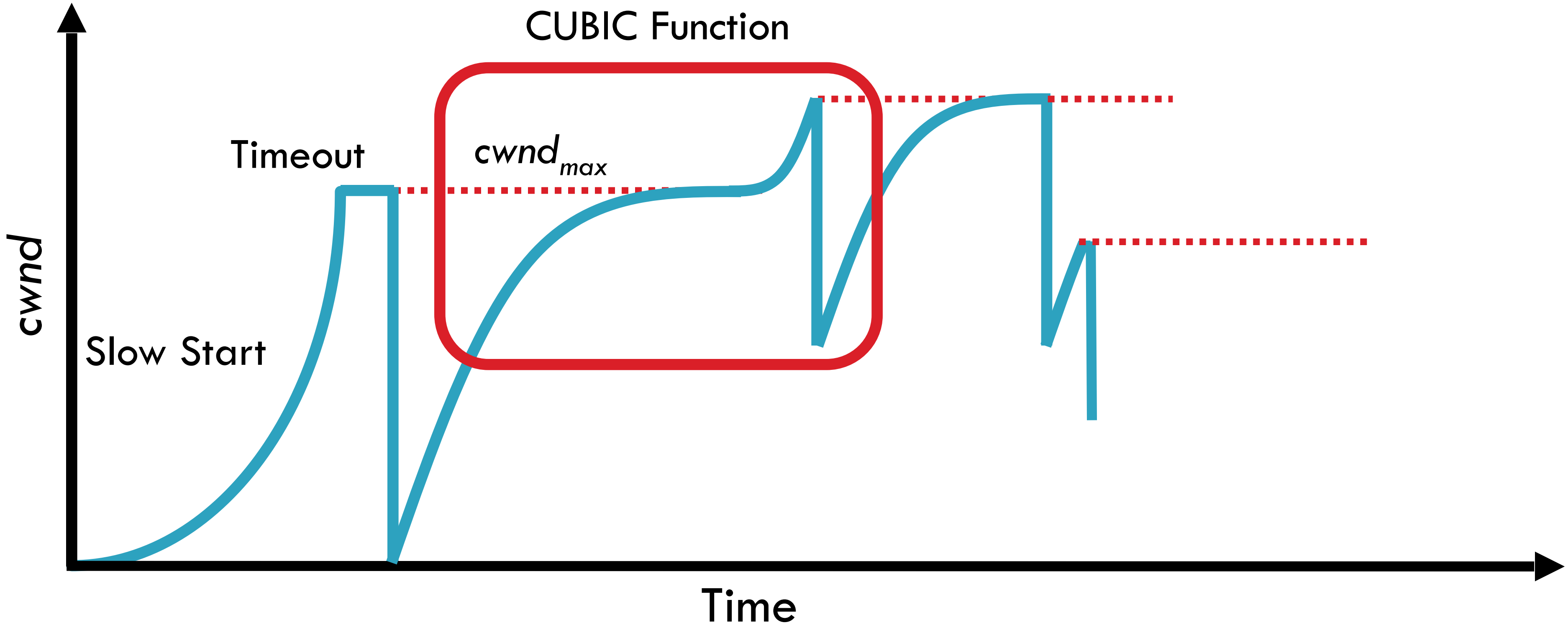

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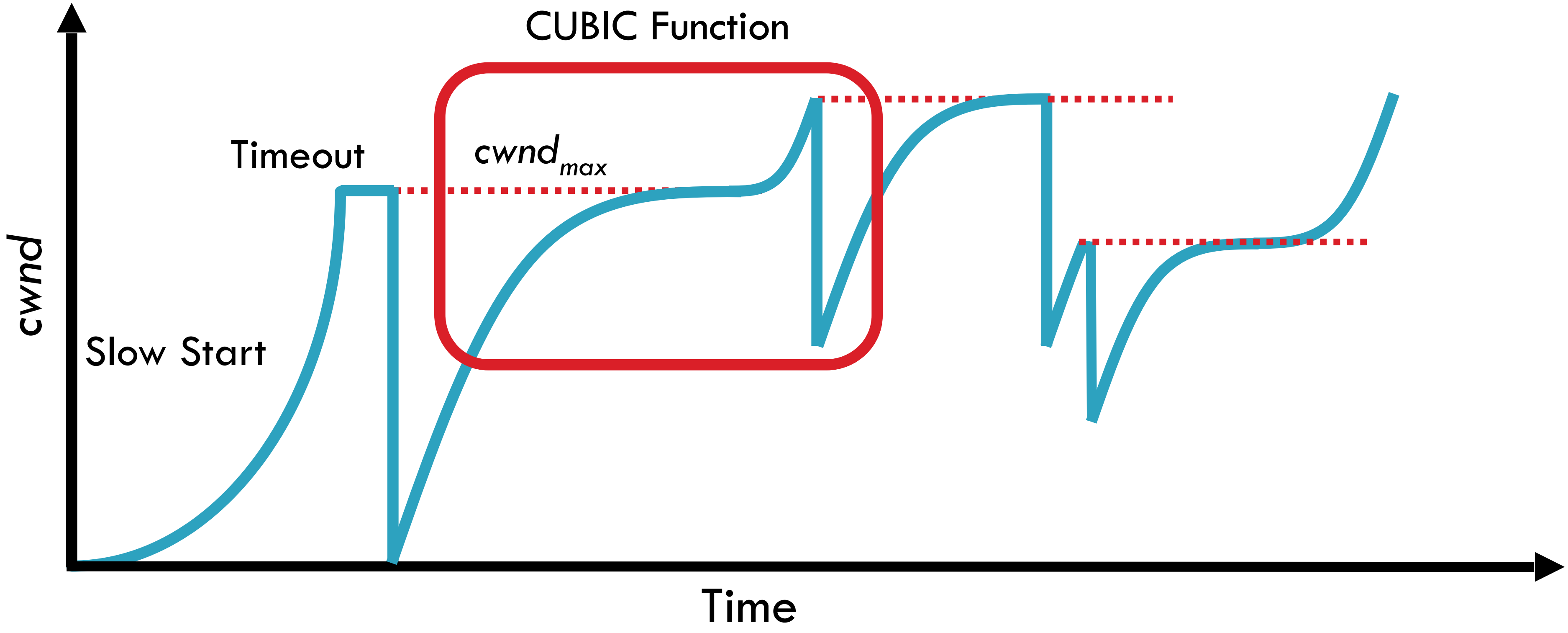

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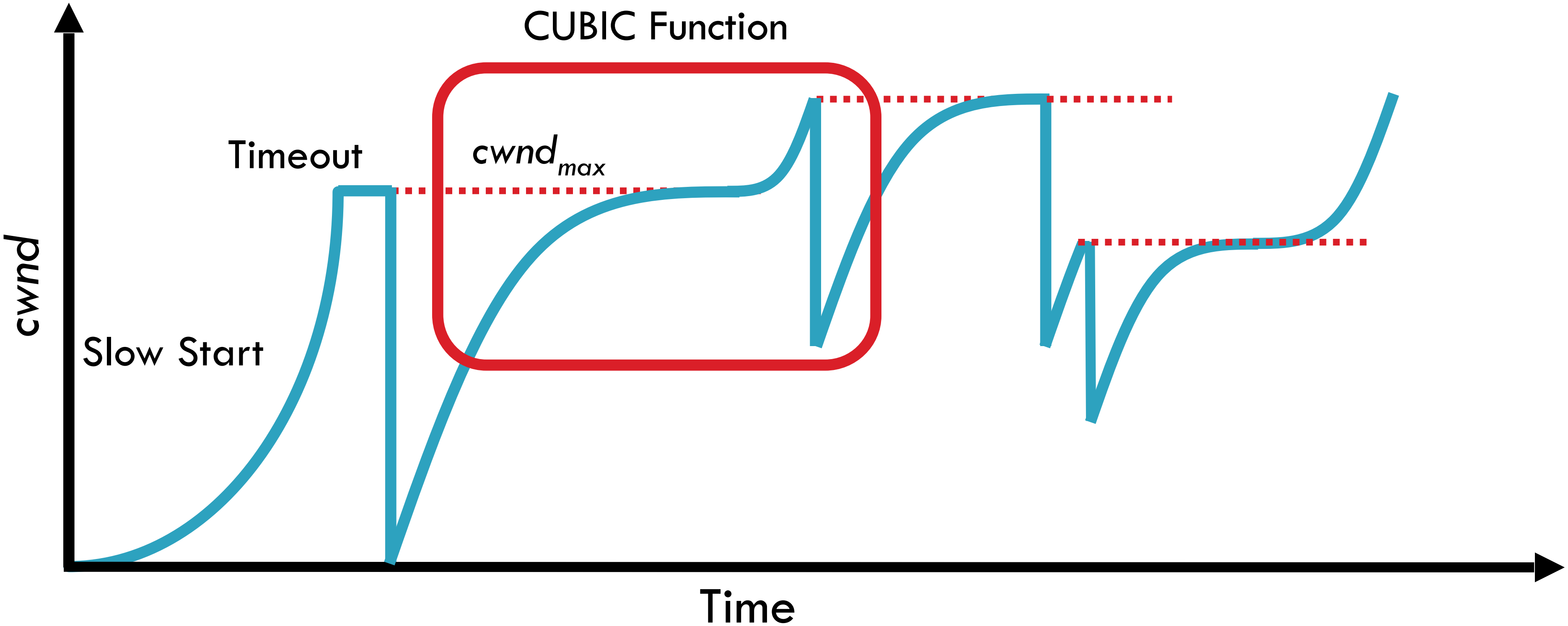
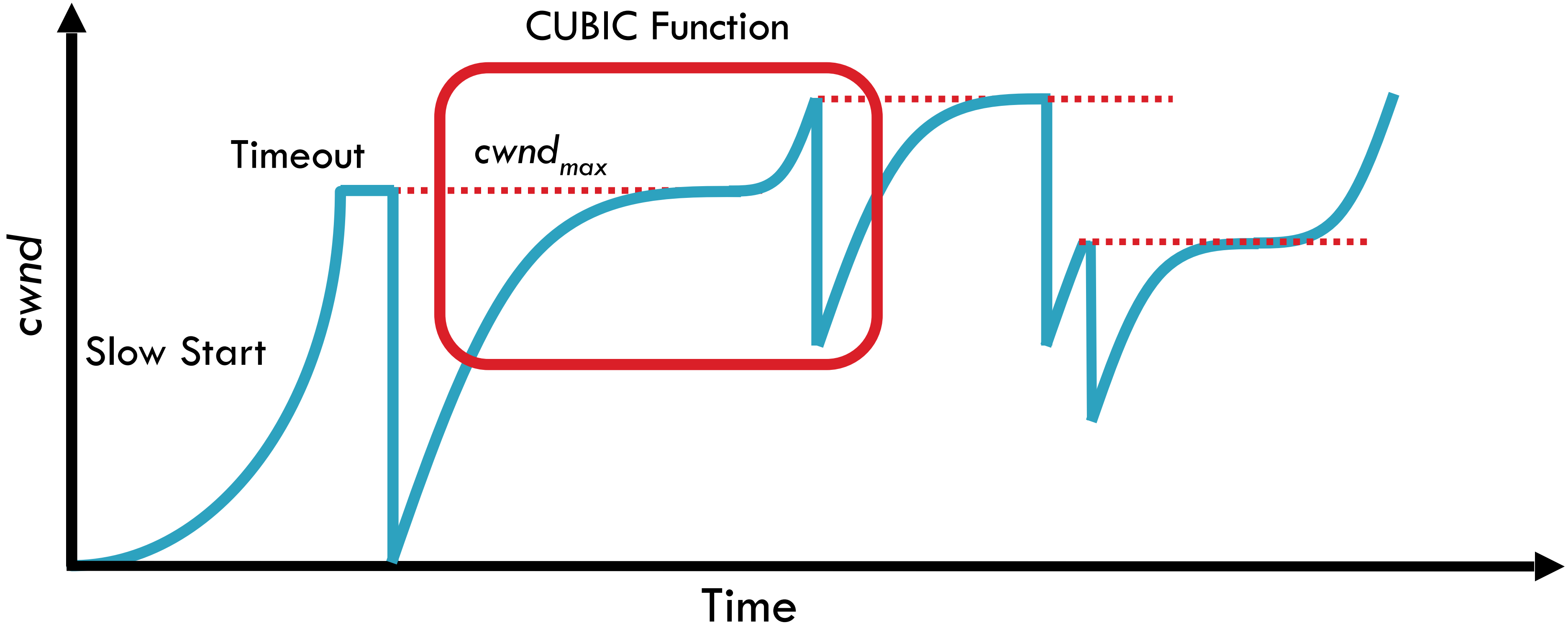


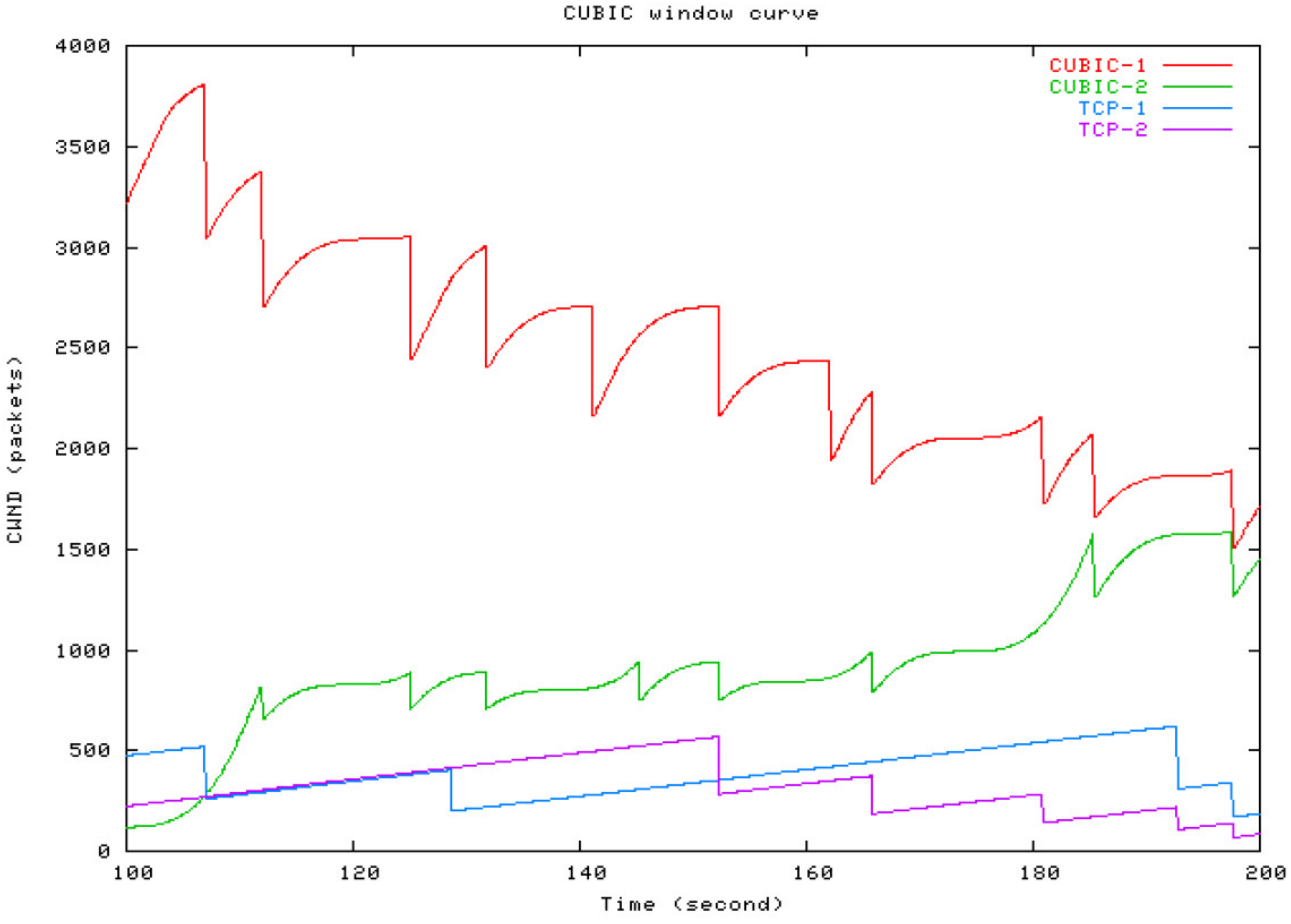
- Less wasted bandwidth due to fast ramp up

TCP CUBIC Example



- Less wasted bandwidth due to fast ramp up
- Stable region and slow acceleration help maintain fairness
  - Fast ramp up is more aggressive than additive increase
  - To be fair to Tahoe/Reno, CUBIC needs to be less aggressive

Simulations of CUBIC Flows



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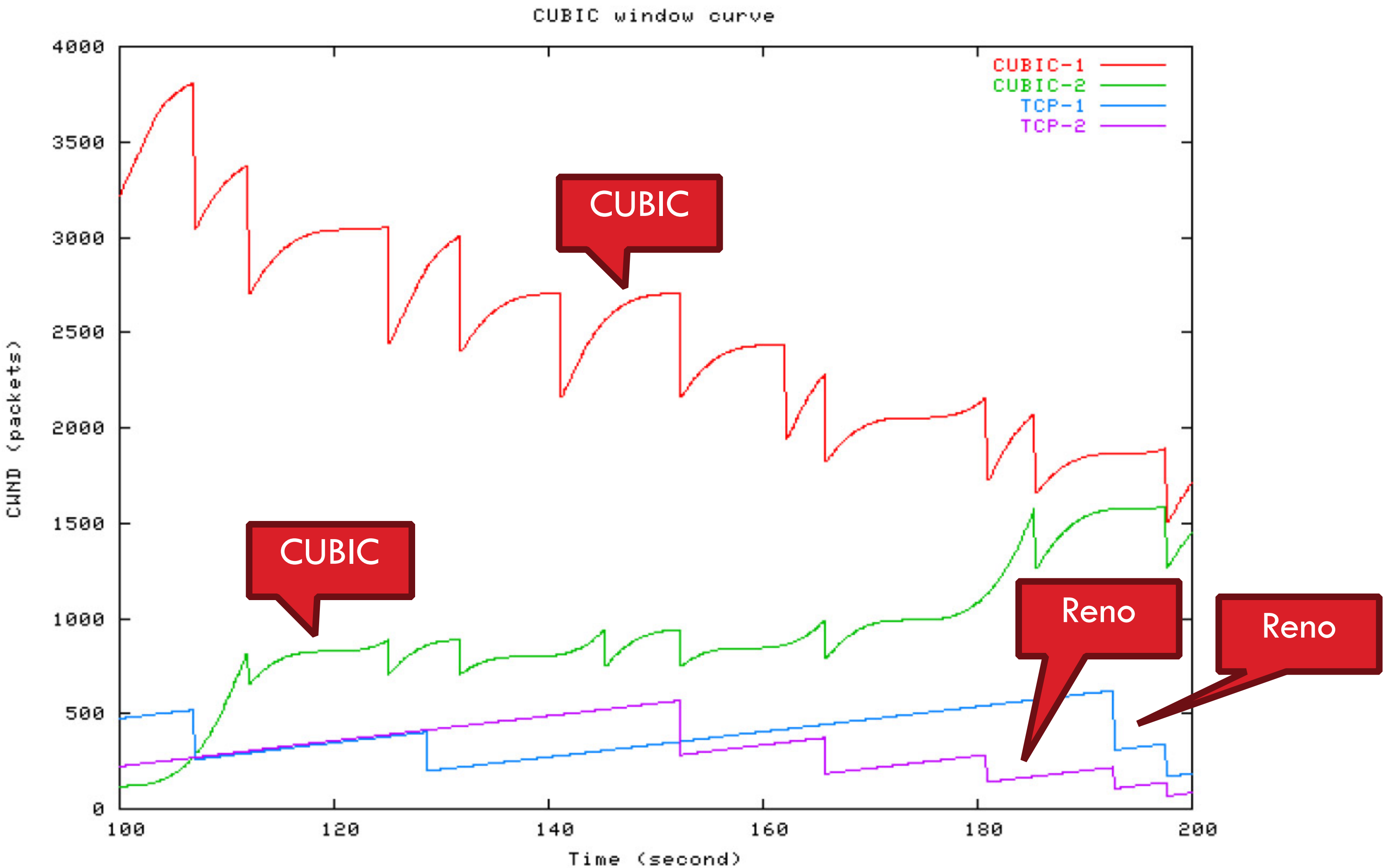

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- TCP assumes all flows employ TCP-like congestion control
  - TCP-friendly or TCP-compatible
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- TCP assumes all flows employ TCP-like congestion control
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- If new congestion control algorithms are developed, they must be TCP-friendly
- Be wary of unforeseen interactions
  - Variants work well with others like themselves
  - Different variants competing for resources may trigger unfair, pathological behavior

TCP Perspectives

- Cerf/Kahn
  - Provide flow control
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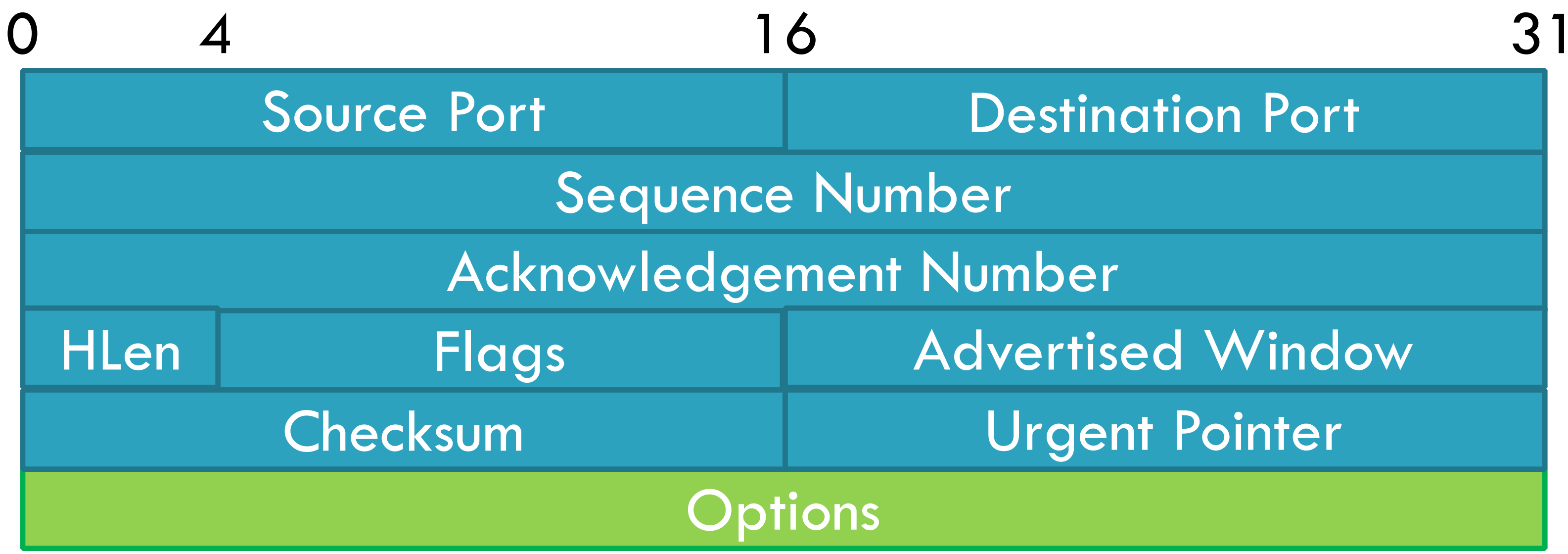
- Winstein/Balakrishnan
  - TCP is maximizing an objective function
    - Fairness/efficiency
    - Throughput/delay
  - Let a machine pick the best fit for your environment

Outline

- Congestion Control
- Evolution of TCP
- Problems with TCP

Common TCP Options



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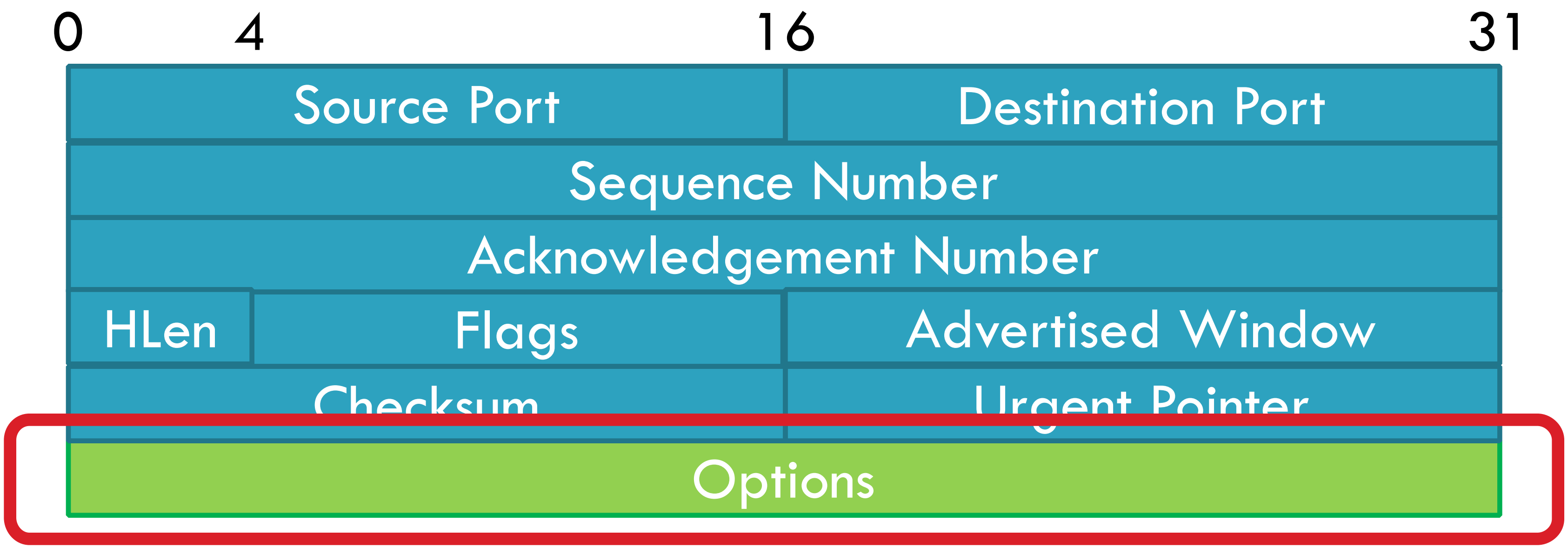

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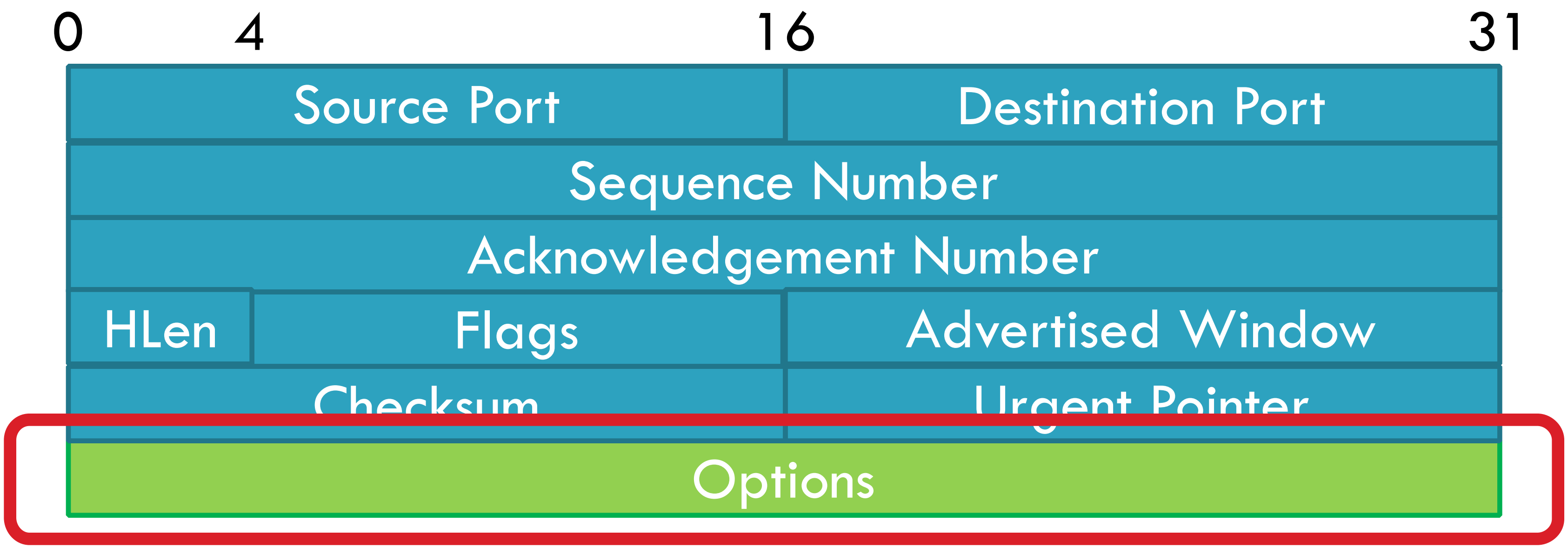

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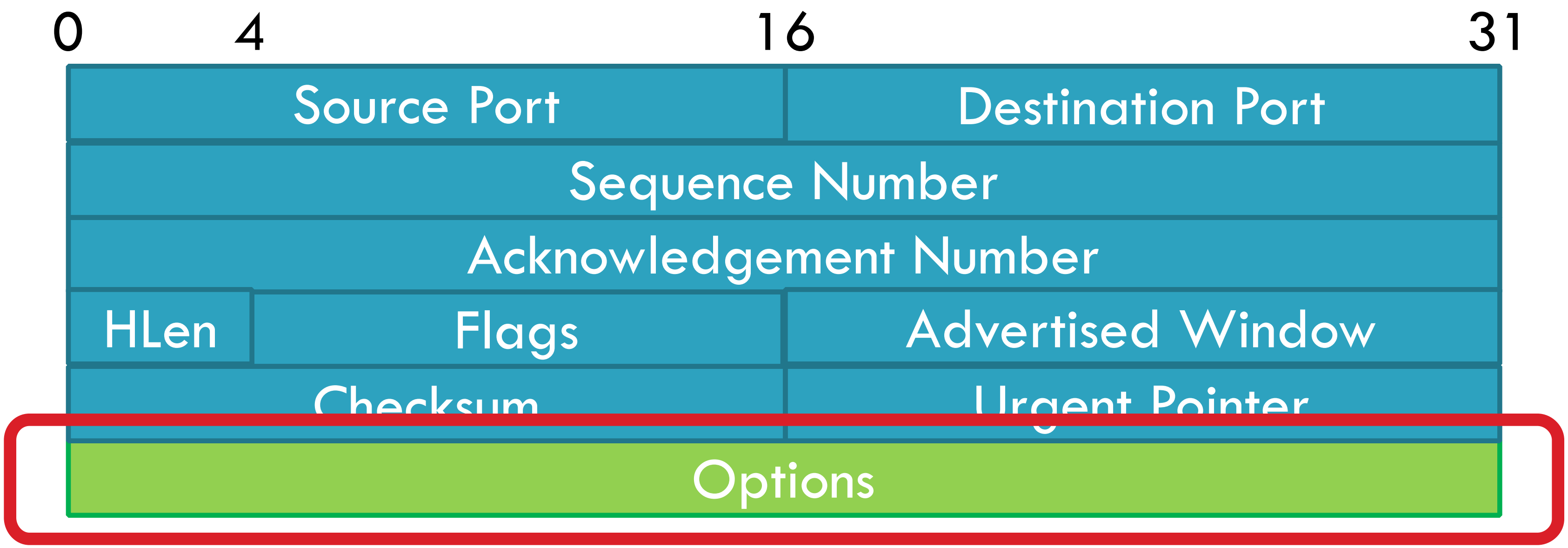

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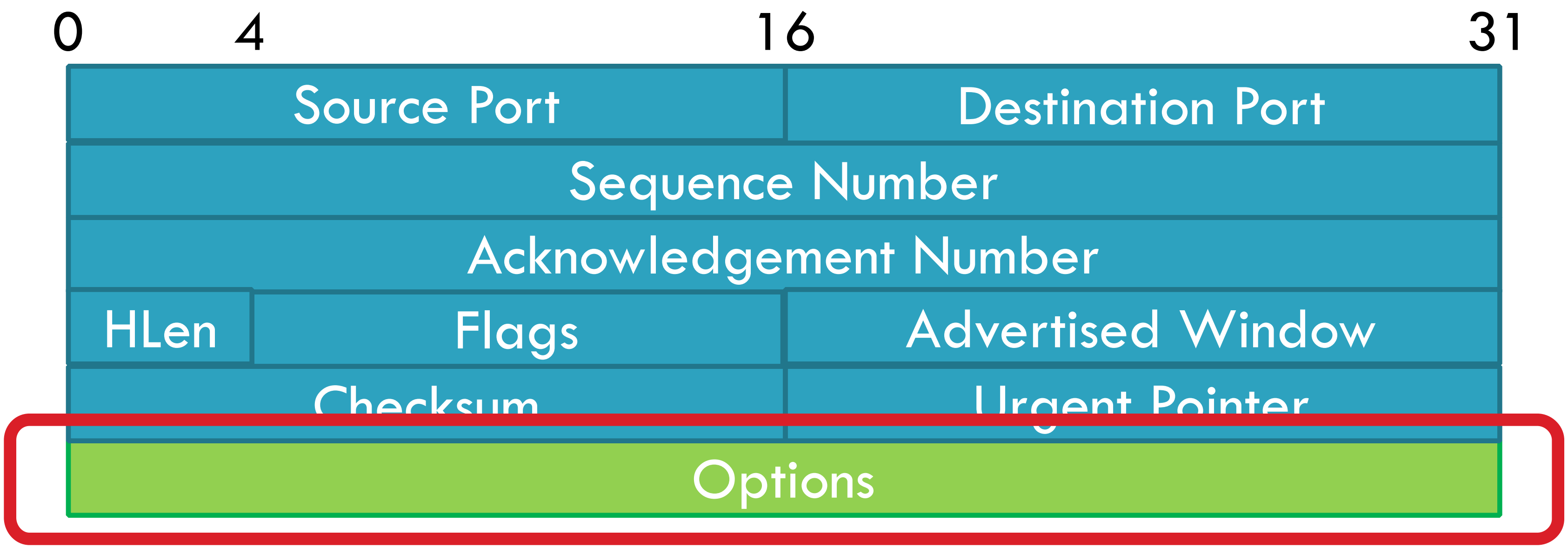

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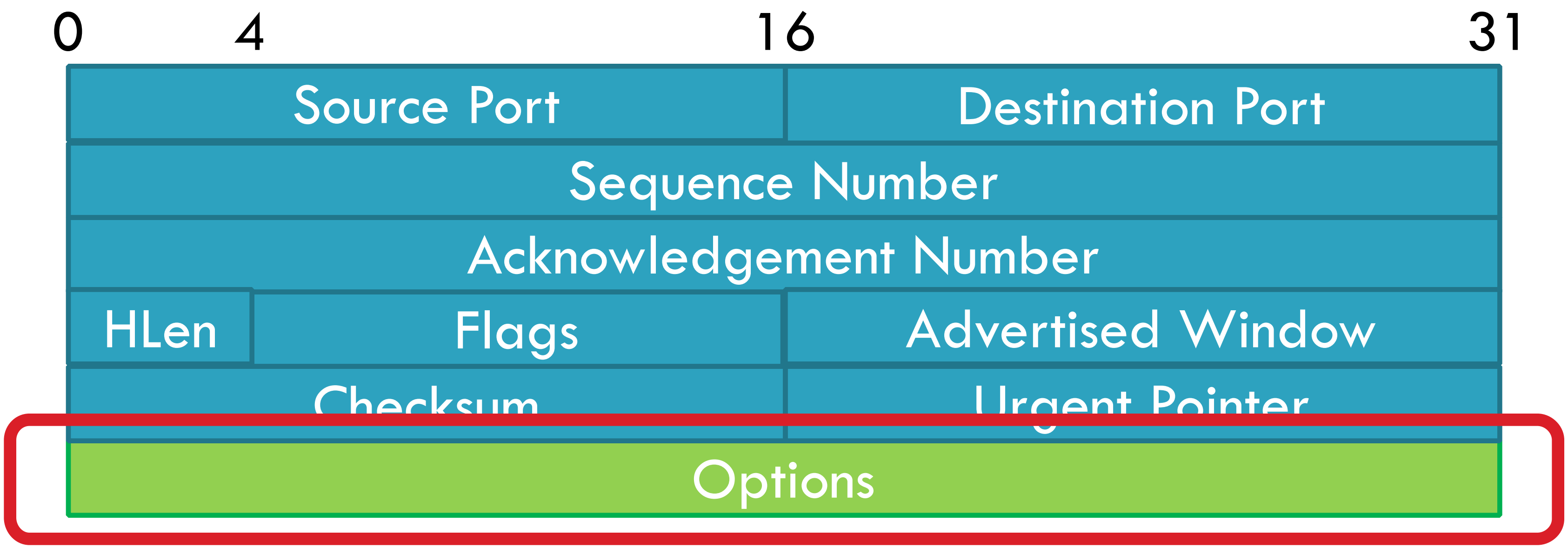

- Window scaling
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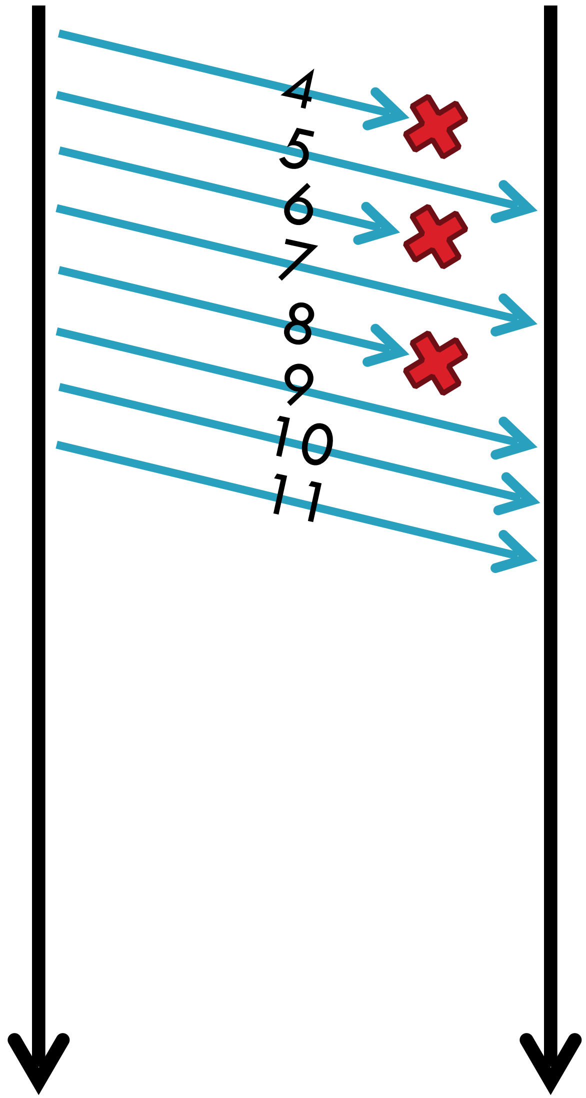
- Solution: introduce a window scaling value
  - *wnd = adv_wnd << wnd_scale;*
  - Maximum shift is 14 bits, 1GB maximum window

SACK: Selective Acknowledgment



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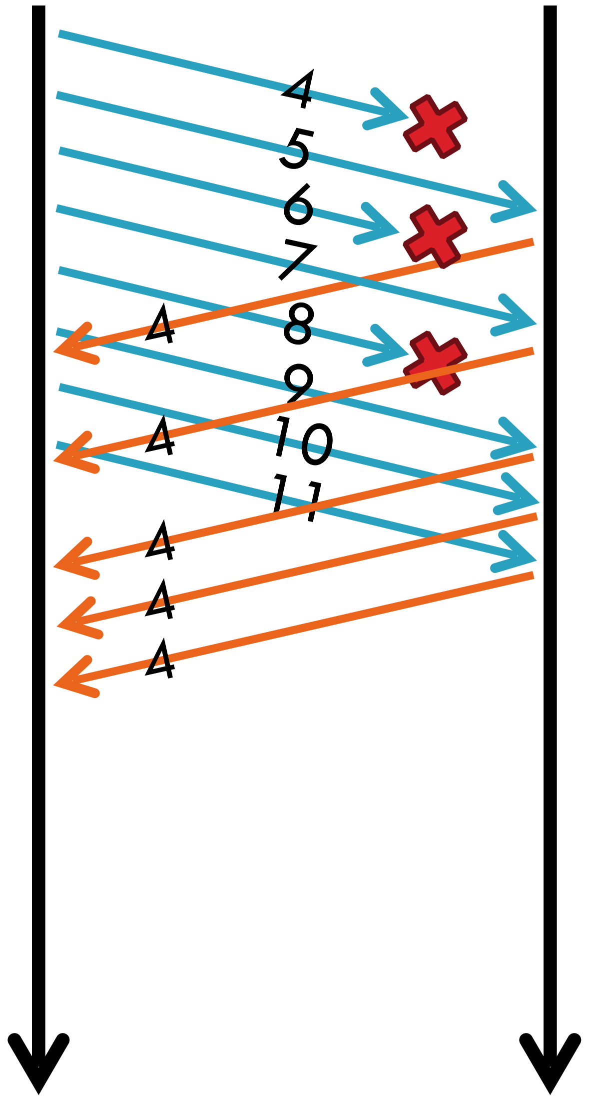
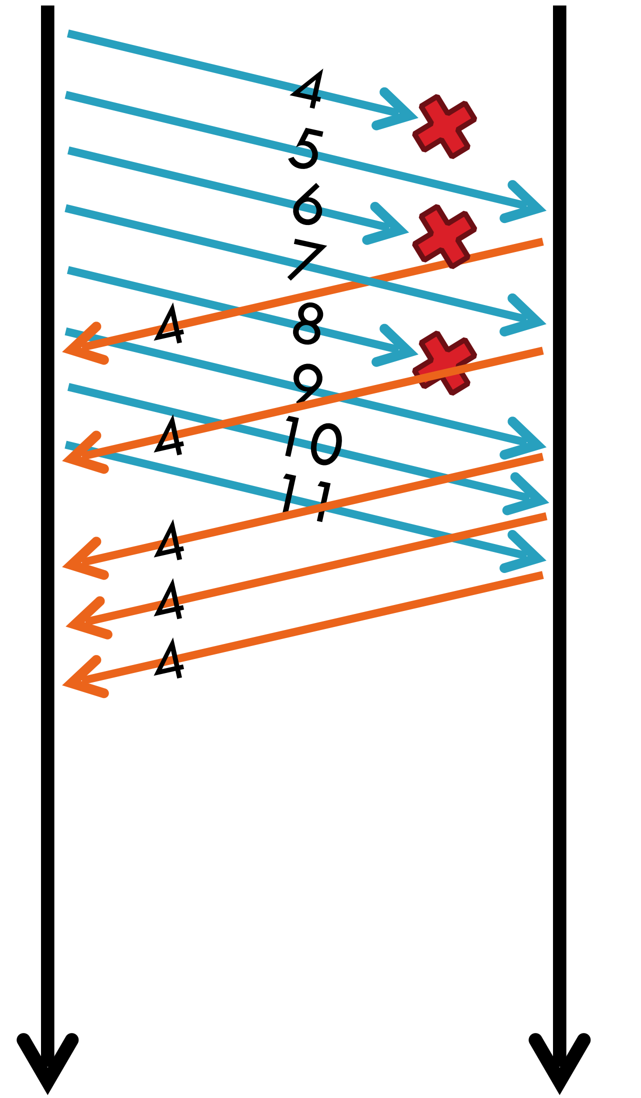


SACK: Selective Acknowledgment

- Problem: duplicate ACKs only tell us about 1 missing packet
  - Multiple rounds of dup ACKs needed to fill all holes
- Solution: selective ACK
  - Include received, out-of-order sequence numbers in TCP header
  - Explicitly tells the sender about holes in the sequence



Other Common Options

- Maximum segment size (MSS)
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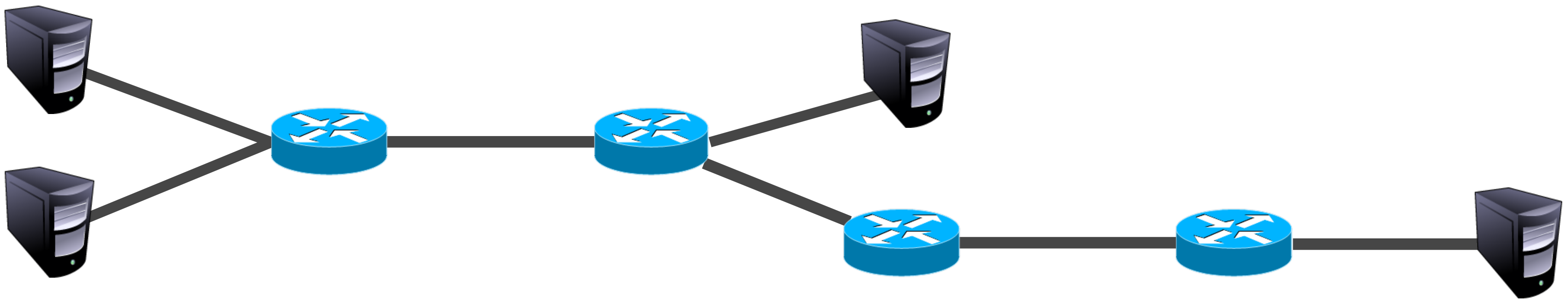
- Maximum segment size (MSS)
  - Essentially, what is the hosts MTU
  - Saves on path discovery overhead
- Timestamp
  - When was the packet sent (approximately)?
  - Used to prevent sequence number wraparound
  - PAWS algorithm

Issues with TCP

- The vast majority of Internet traffic is TCP
- However, many issues with the protocol
  - Lack of fairness
  - Synchronization of flows
  - Poor performance with small flows
  - Really poor performance on wireless networks
  - Susceptibility to denial of service

Fairness

- Problem: TCP throughput depends on RTT



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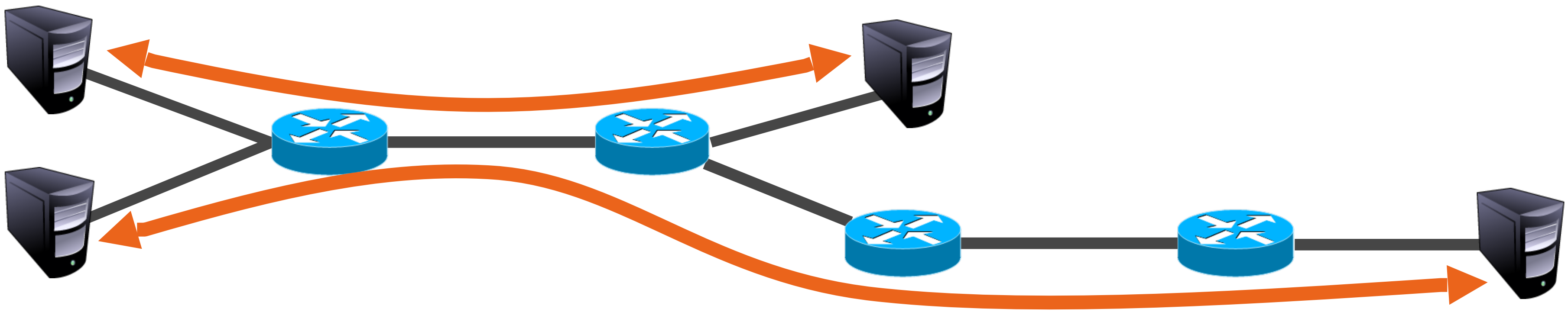

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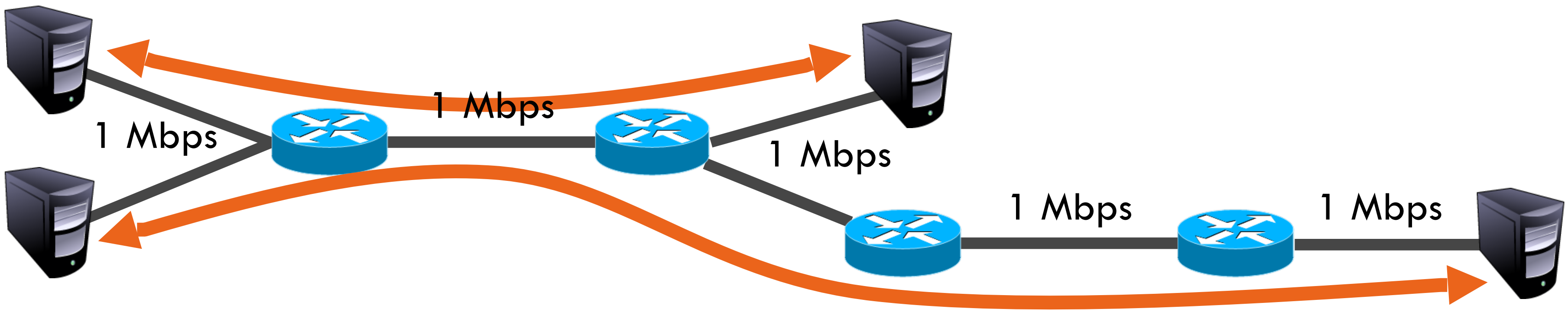

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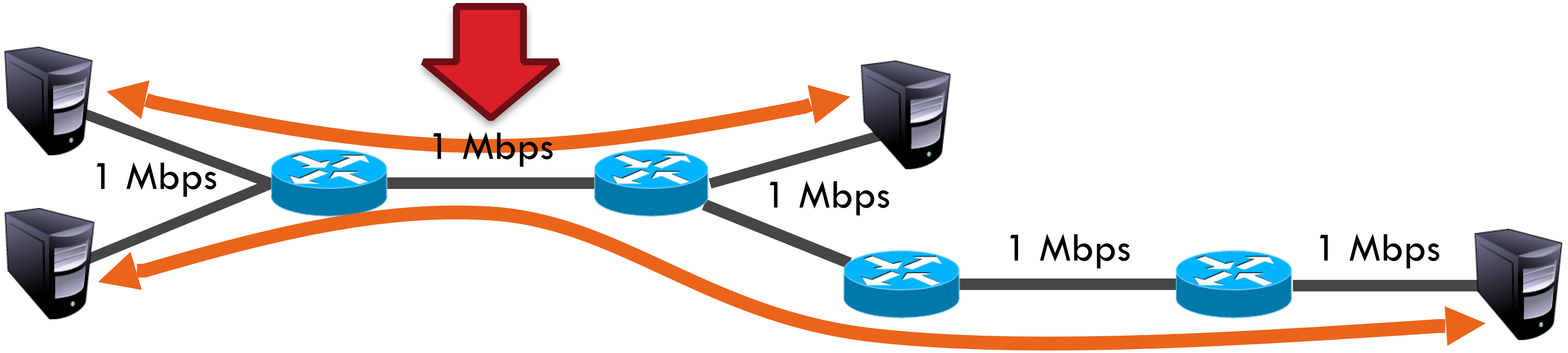

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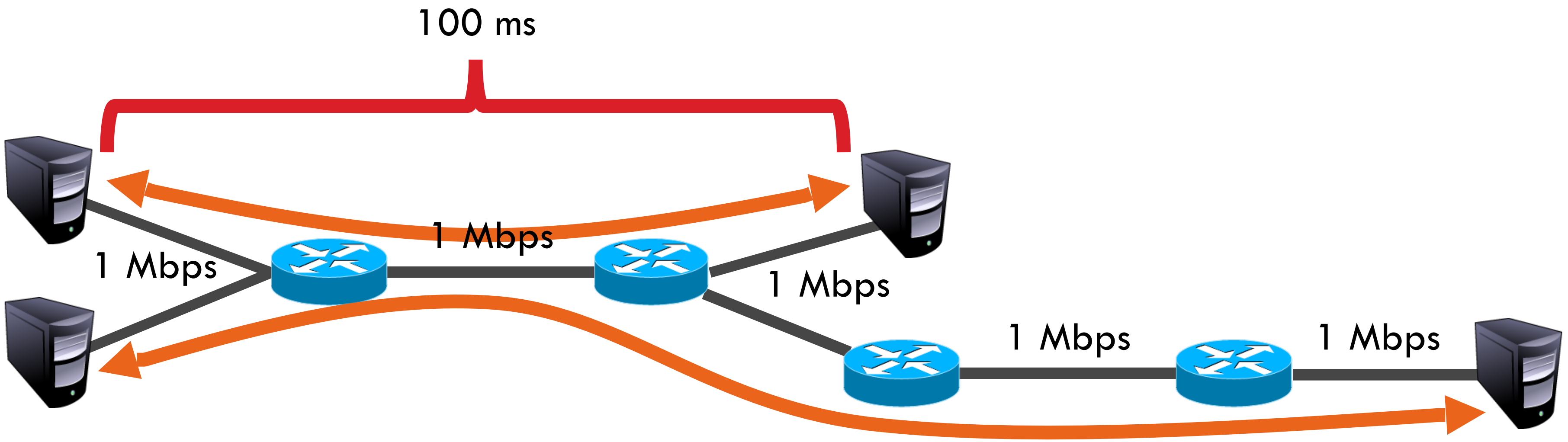

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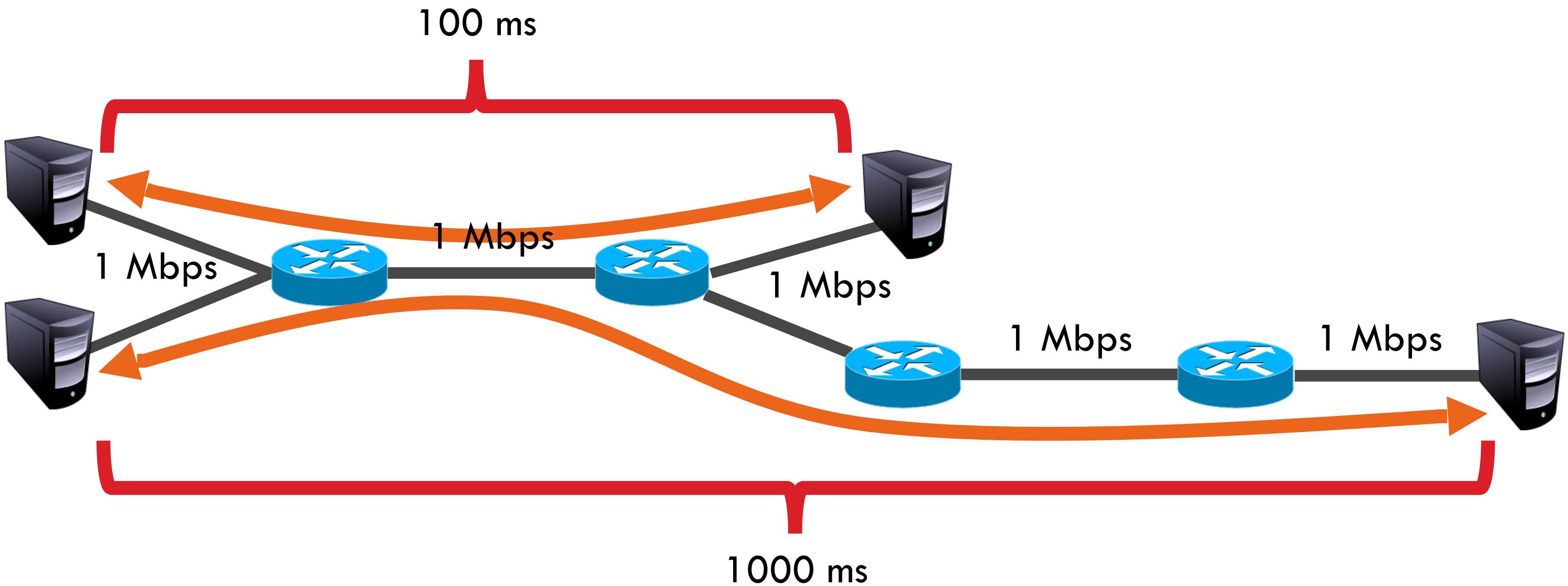

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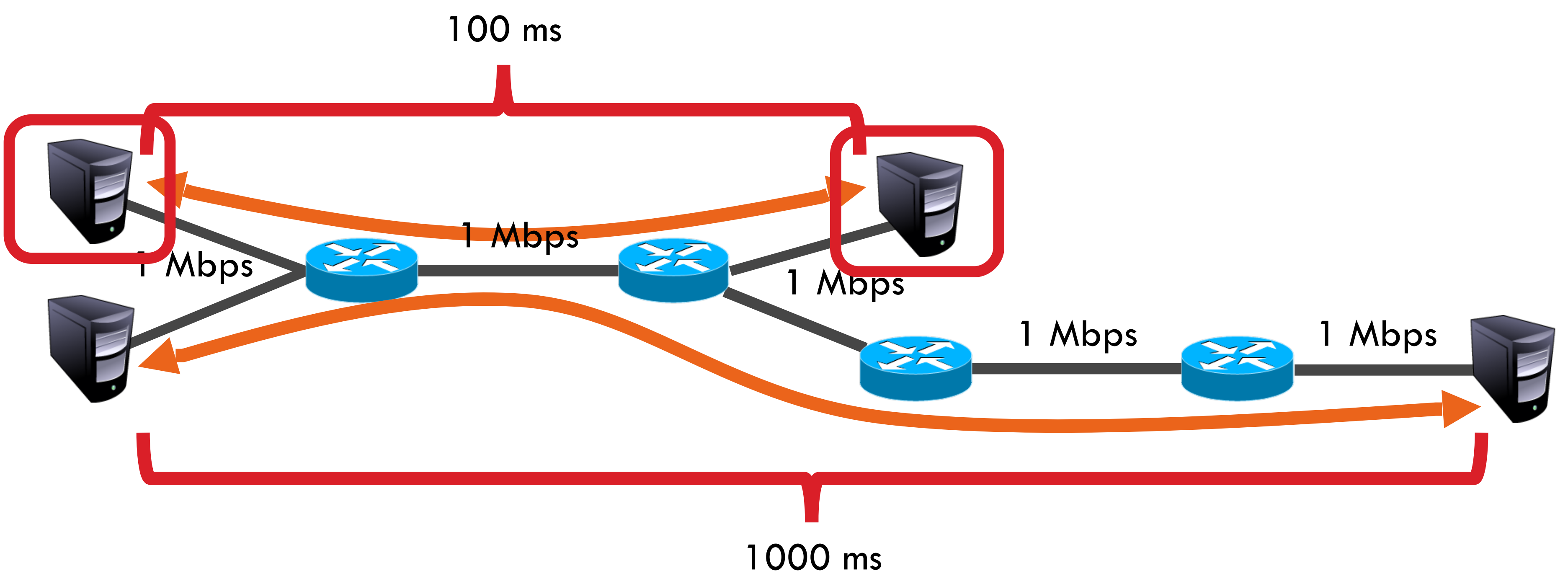

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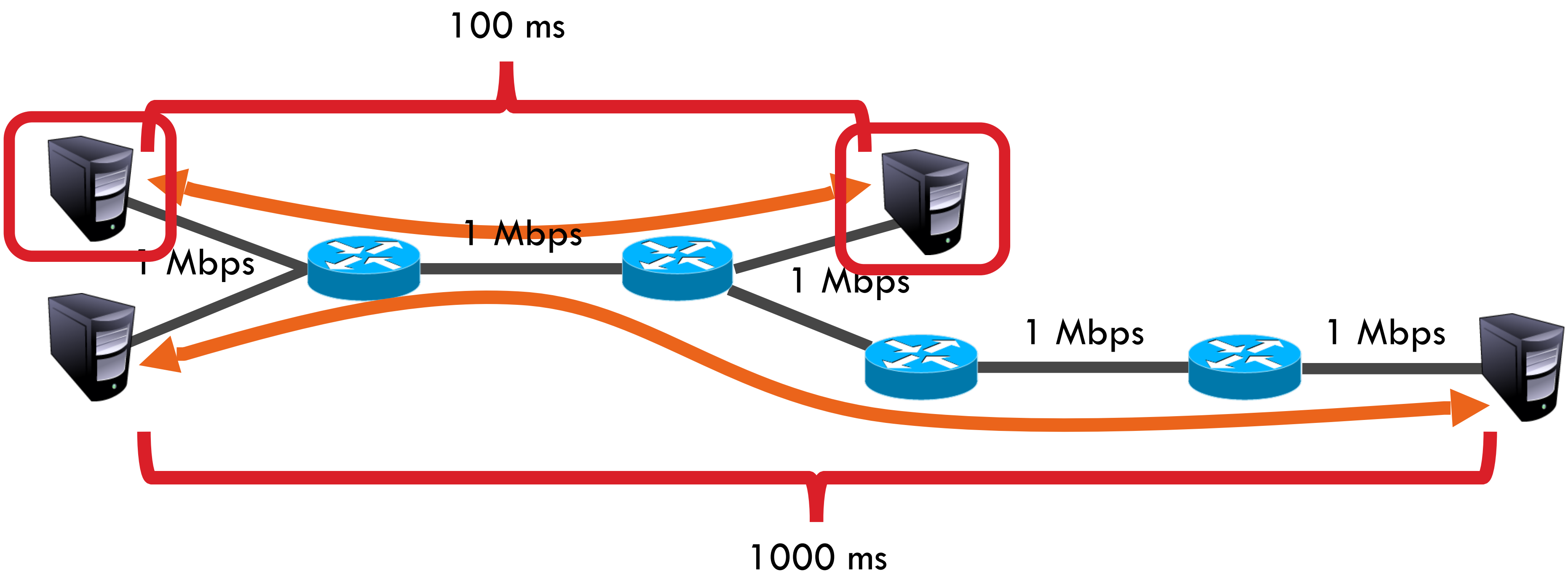

- ACK clocking makes TCP inherently unfair
- Possible solution: maintain a separate delay window
  - Implemented by Microsoft's Compound TCP

Synchronization of Flows

- Ideal bandwidth sharing

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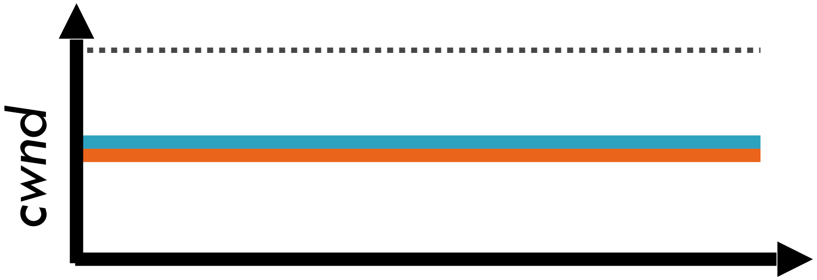

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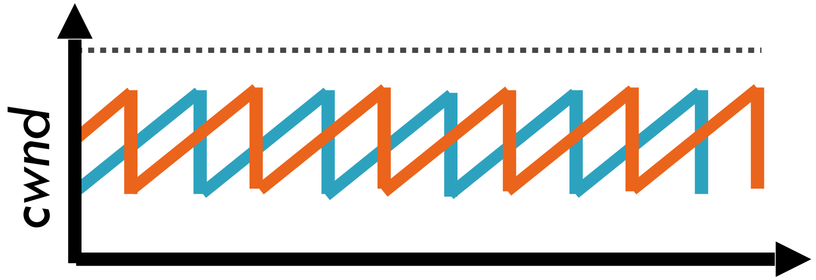

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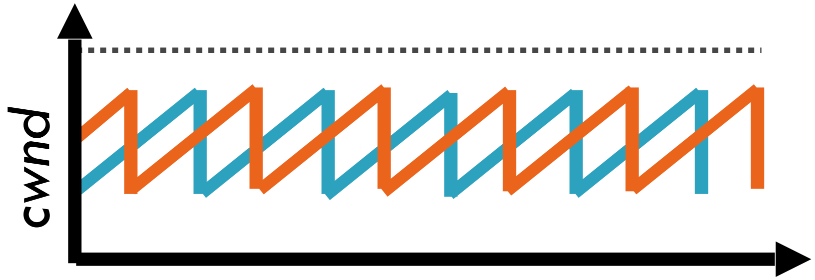

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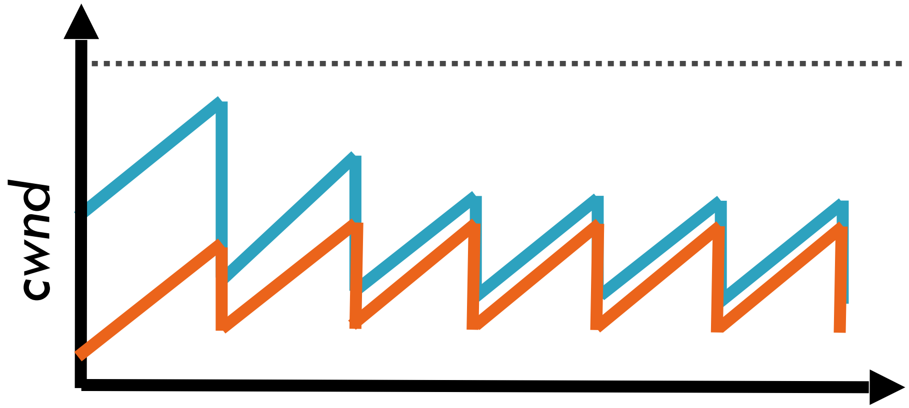

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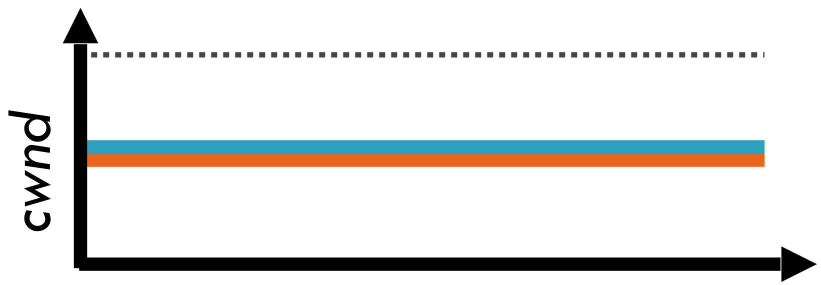

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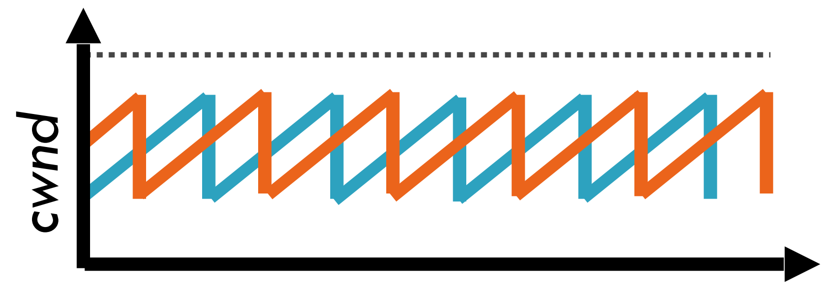

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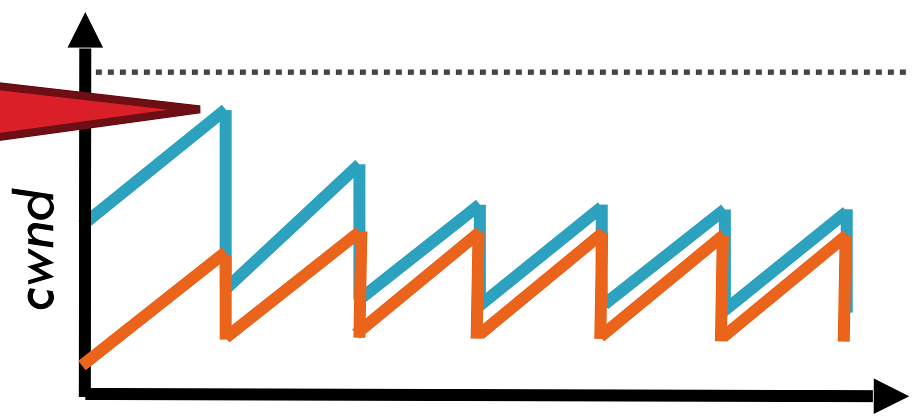
One flow causes all flows to drop packets



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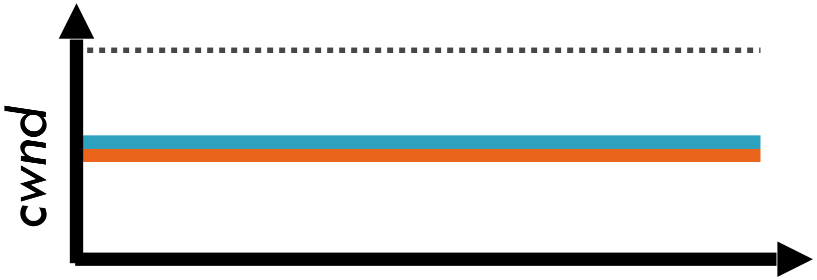

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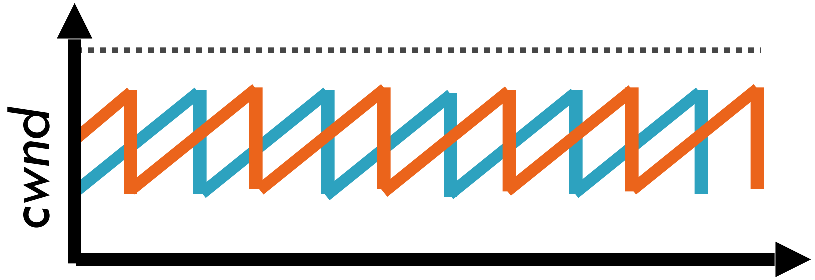

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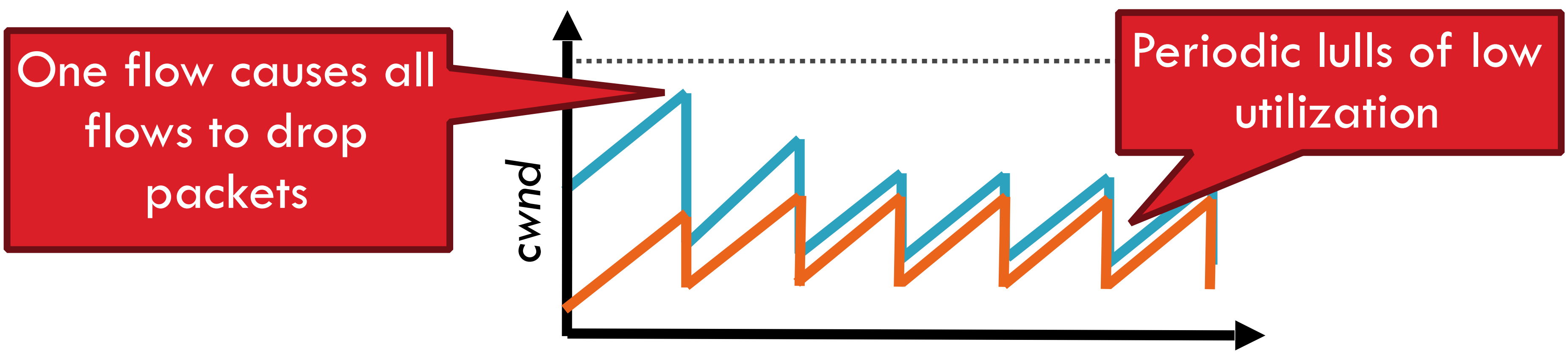

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- Vast majority of Internet traffic is short flows
  - Mostly HTTP transfers, <100KB
  - Most TCP flows never leave slow start!
- Proposed solutions (driven by Google):
  - Increase initial *cwnd* to 10
  - TCP Fast Open: use cryptographic hashes to identify receivers, eliminate the need for three-way handshake

Wireless Networks

- Problem: Tahoe and Reno assume loss = congestion
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- TCP throughput ~ 1/sqrt(drop rate)
  - Even a few interference drops can kill performance
- Possible solutions:
  - Break layering, push data link info up to TCP
  - Use delay-based congestion detection (TCP Vegas)
  - Explicit congestion notification (ECN)

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- SYN flood: send enough SYNs to a server to allocate all memory/meltdown the kernel
- Solution: SYN cookies
  - Idea: don't store initial state on the server
  - Securely insert state into the SYN/ACK packet
  - Client will reflect the state back to the server

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- Did the client really send me a SYN recently?
  - Timestamp: freshness check
  - Cryptographic hash: prevents spoofed packets
- Maximum segment size (MSS)
  - Usually stated by the client during initial SYN
  - Server should store this value…
  - Reflect the clients value back through them

SYN Cookies in Practice

- Advantages
  - Effective at mitigating SYN floods
  - Compatible with all TCP versions
  - Only need to modify the server
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- Advantages
  - Effective at mitigating SYN floods
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  - Only need to modify the server
  - No need for client support
- Disadvantages
  - MSS limited to 3 bits, may be smaller than clients actual MSS
  - Server forgets all other TCP options included with the client's SYN
    - SACK support, window scaling, etc.