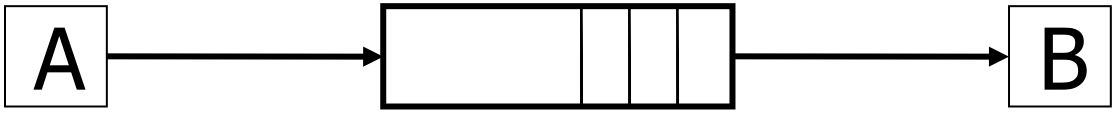
CS4700/CS5700
Fundamentals of Computer Networks

Lecture 15: Congestion Control

Slides used with permissions from Edward W. Knightly, T. S. Eugene Ng, Ion Stoica, Hui Zhang

Abstract View



Buffer in bottleneck Router

Sending Host

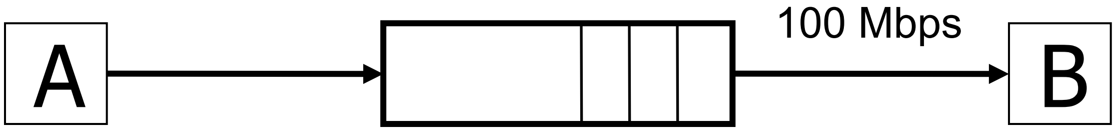
Receiving Host

- We ignore internal structure of network and model it as having a single bottleneck link

Three Congestion Control Problems

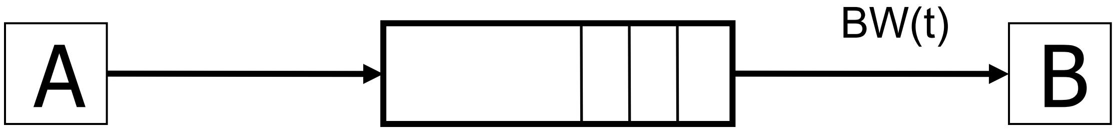
- Adjusting to bottleneck bandwidth
- Adjusting to variations in bandwidth
- Sharing bandwidth between flows

Single Flow, Fixed Bandwidth



- Adjust rate to match bottleneck bandwidth
  - without any *a priori* knowledge
  - could be gigabit link, could be a modem

Single Flow, Varying Bandwidth

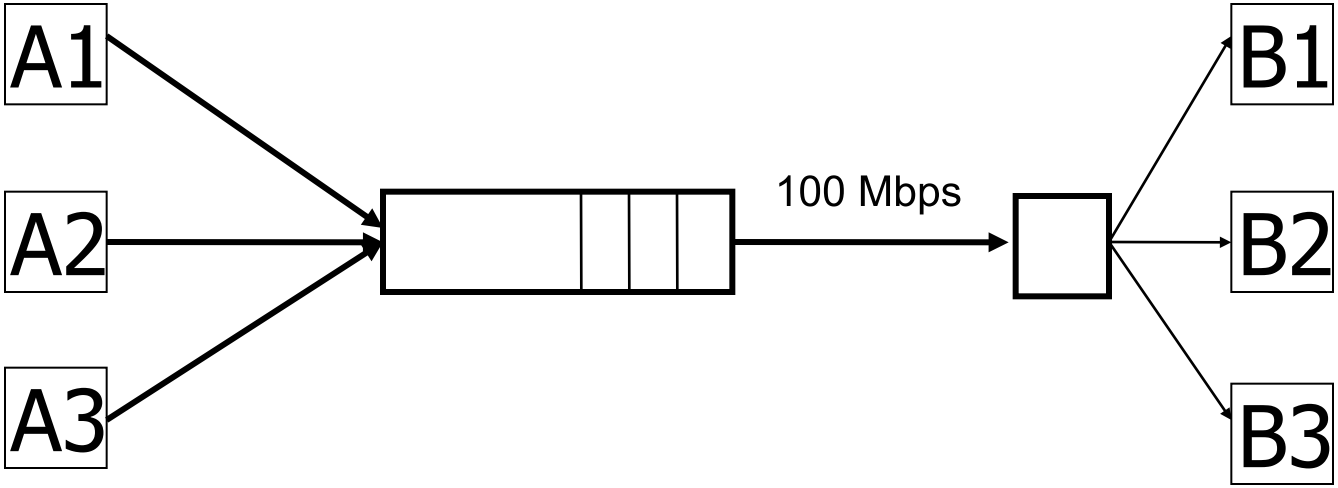


- Adjust rate to match instantaneous bandwidth
- Bottleneck can change because of a routing change

Multiple Flows

Two Issues:

- Adjust total sending rate to match bottleneck bandwidth
- Allocation of bandwidth between flows



General Approaches

- Send without care
  - many packet drops
  - could cause congestion collapse
- Reservations
  - pre-arrange bandwidth allocations
  - requires negotiation before sending packets
- Pricing
  - don’t drop packets for the high-bidders
  - requires payment model

General Approaches (cont'd)

- Dynamic Adjustment (TCP)
  - Every sender probe network to test level of congestion
  - speed up when no congestion
  - slow down when congestion
  - suboptimal, messy dynamics, simple to implement

  - Distributed coordination problem!

TCP Congestion Control

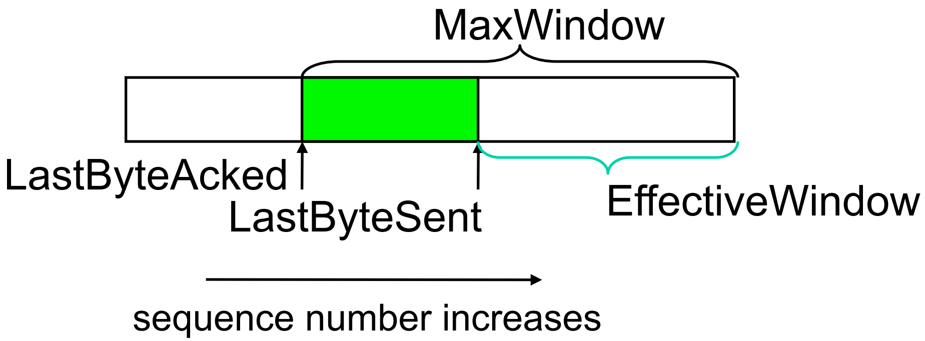
- TCP connection has window
  - controls number of unacknowledged packets
- Sending rate: ~Window/RTT
- Vary window size to control sending rate
- Introduce a new parameter called congestion window (cwnd) at the sender
  - Congestion control is mainly a sender-side operation

Congestion Window (*cwnd*)

- Limits how much data can be in transit
- Implemented as # of bytes
- Described as # packets in this lecture

MaxWindow = min(cwnd, AdvertisedWindow)

EffectiveWindow = MaxWindow – (LastByteSent – LastByteAcked)



Two Basic Components

- Detecting congestion
- Rate adjustment algorithm (change cwnd size)
  - depends on congestion or not

Detecting Congestion

Detecting Congestion

- Packet dropping is best sign of congestion
  - delay-based methods are hard and risky
- How do you detect packet drops? ACKs
  - TCP uses ACKs to signal receipt of data
  - ACK denotes last contiguous byte received
    - actually, ACKs indicate next segment expected
- Two signs of packet drops
  - No ACK after certain time interval: time-out
  - Several duplicate ACKs (ignore for now)

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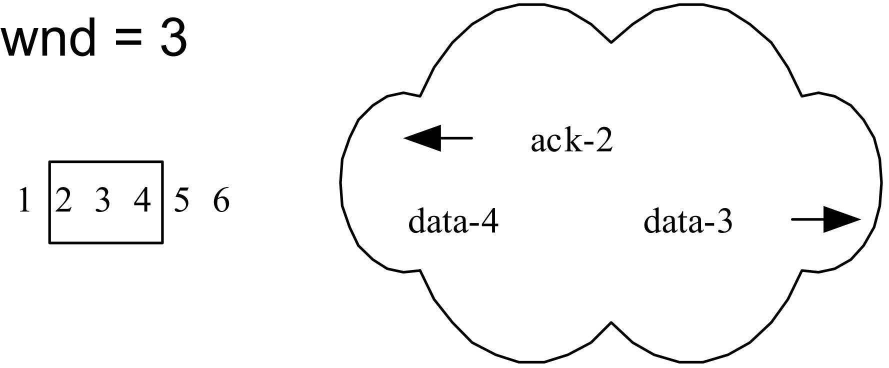
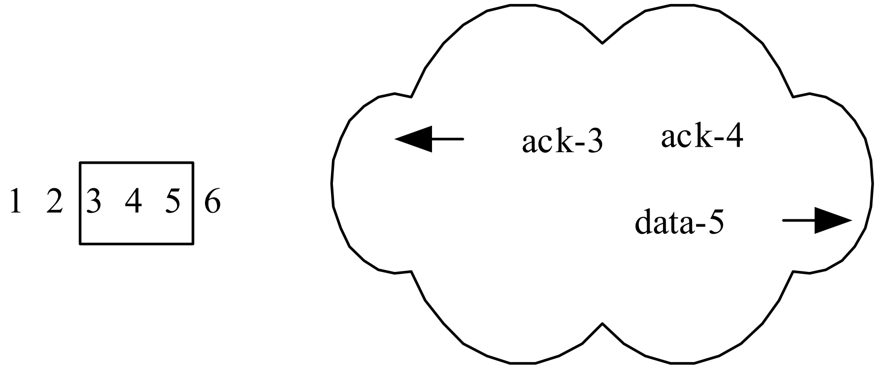
- May not work well for wireless networks, why?

Sliding (Congestion) Window

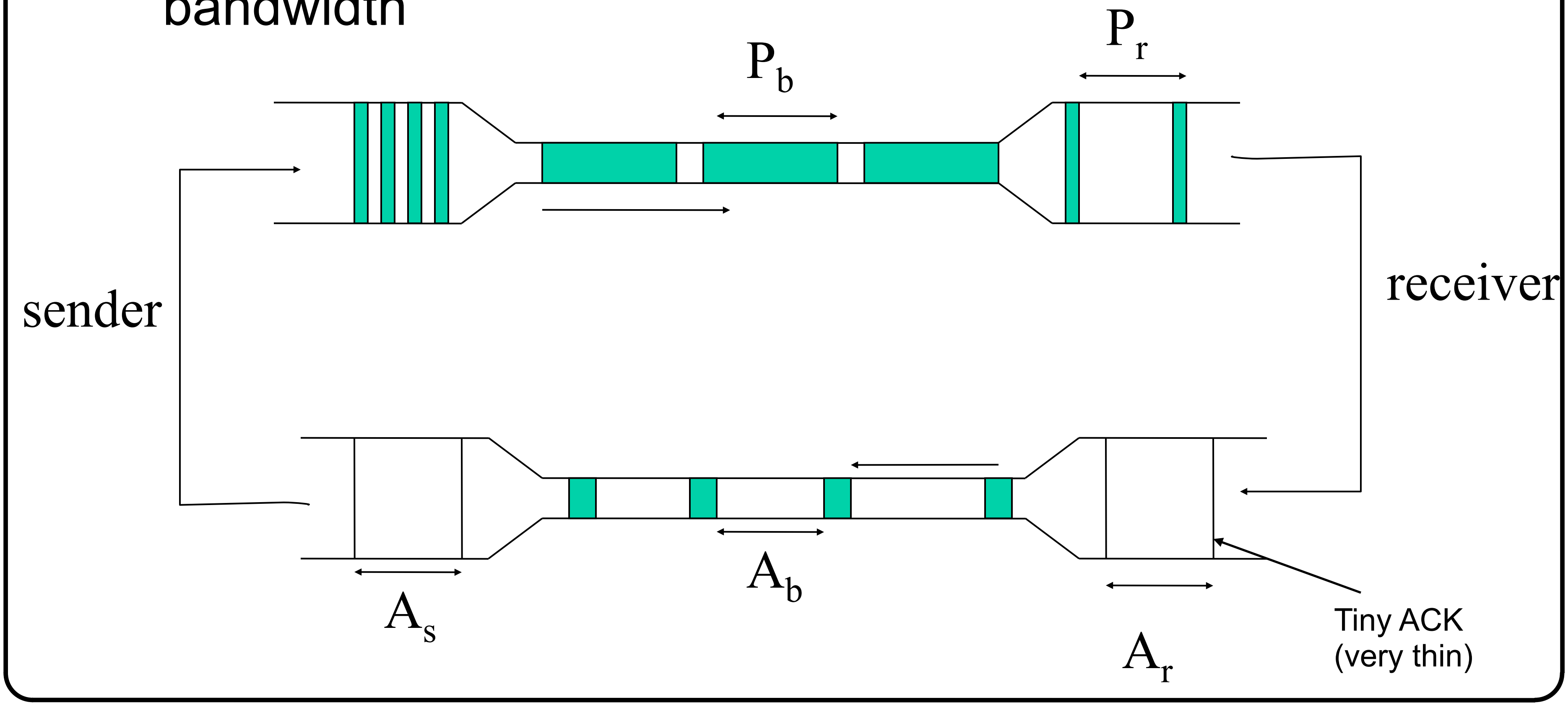
- Sliding window: each ACK = permission to send a new packet
  - Ex. cwnd = 3





Self-clocking

- If we have a large window, ACKs “self-clock” the data to the rate of the bottleneck link
- Observe: received ACK spacing ≅ bottleneck bandwidth

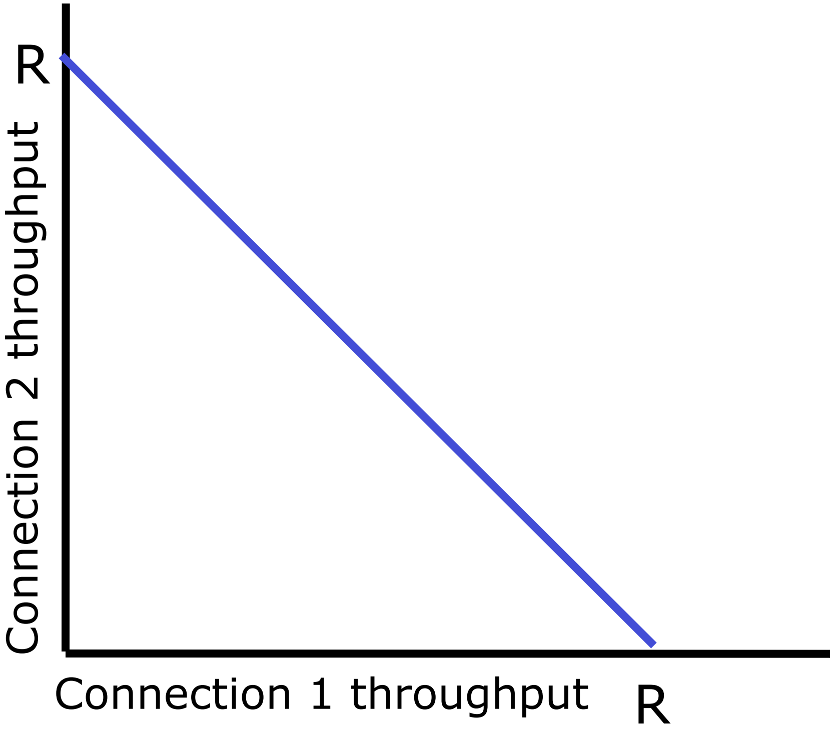


Rate Adjustment

- Basic structure:
  - Upon receipt of ACK (of new data): increase rate
    - Data successfully delivered, perhaps can send faster
  - Upon detection of loss: decrease rate

- But what increase/decrease functions should we use?
  - Depends on what problem we are solving

Fairness?



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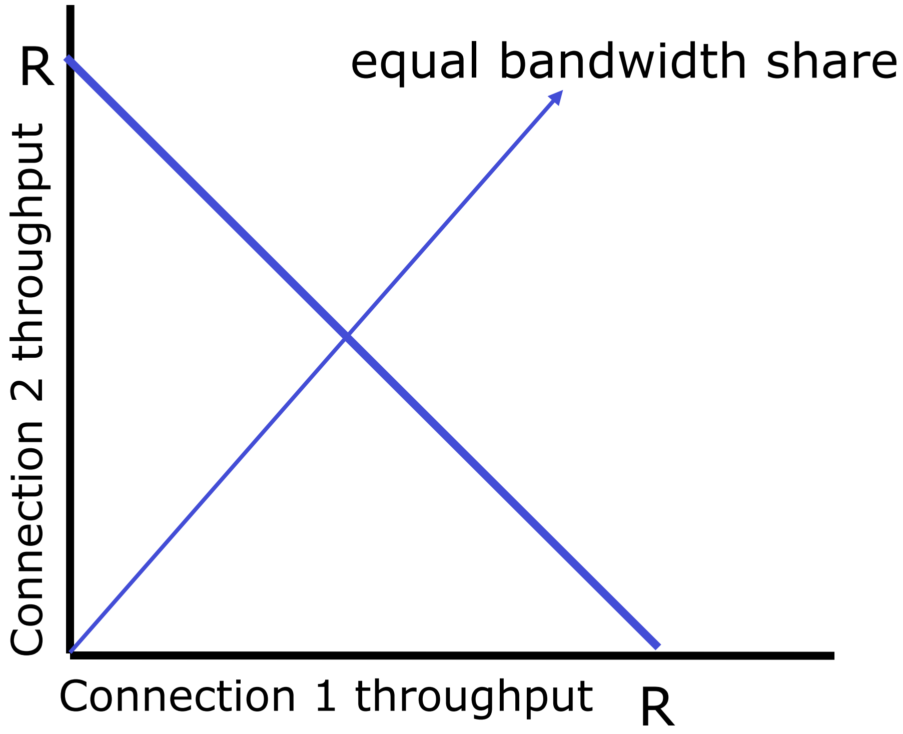
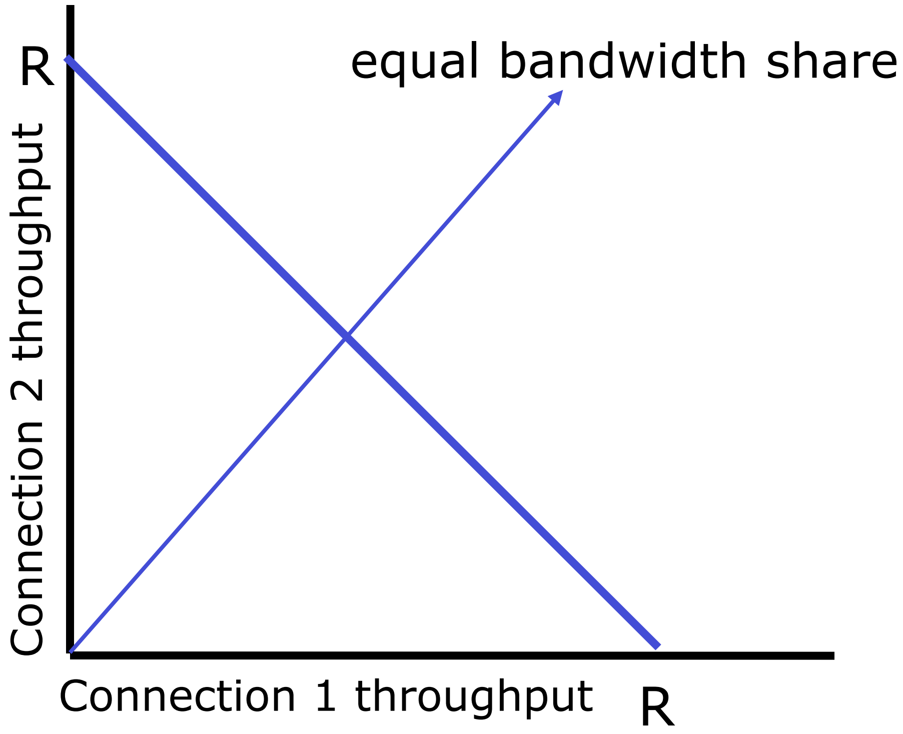

R
equal bandwidth share
Connection 2 throughput
Connection 1 throughput
R

Fairness?

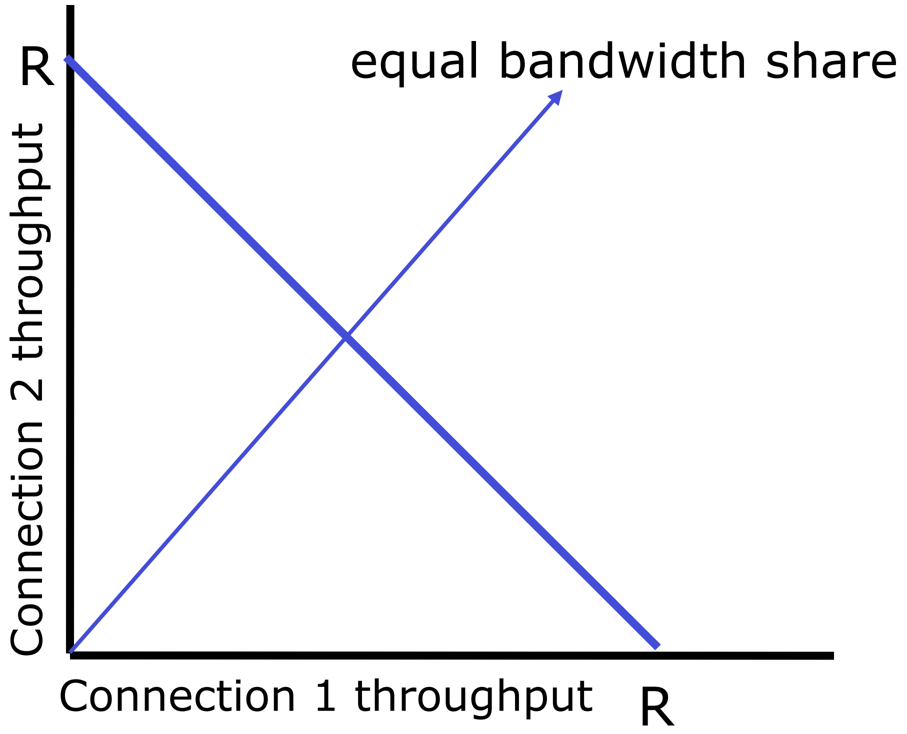
Two competing sessions:



Fairness?

Two competing sessions:

- Additive increase (AI) gives slope of 1, as throughout increases



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Two competing sessions:

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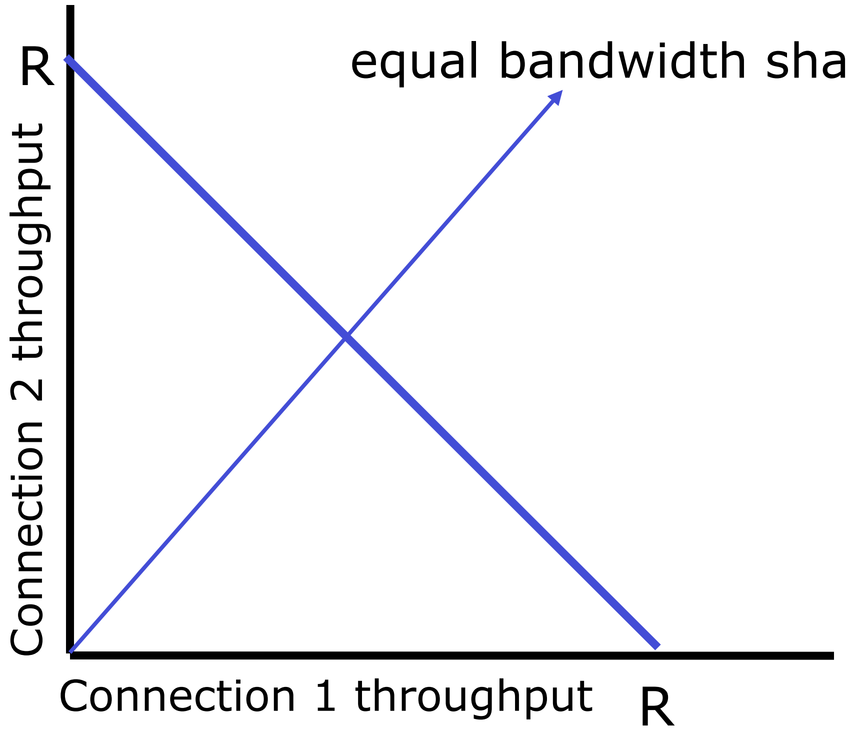
- multiplicative decrease (MD) decreases throughput proportionally



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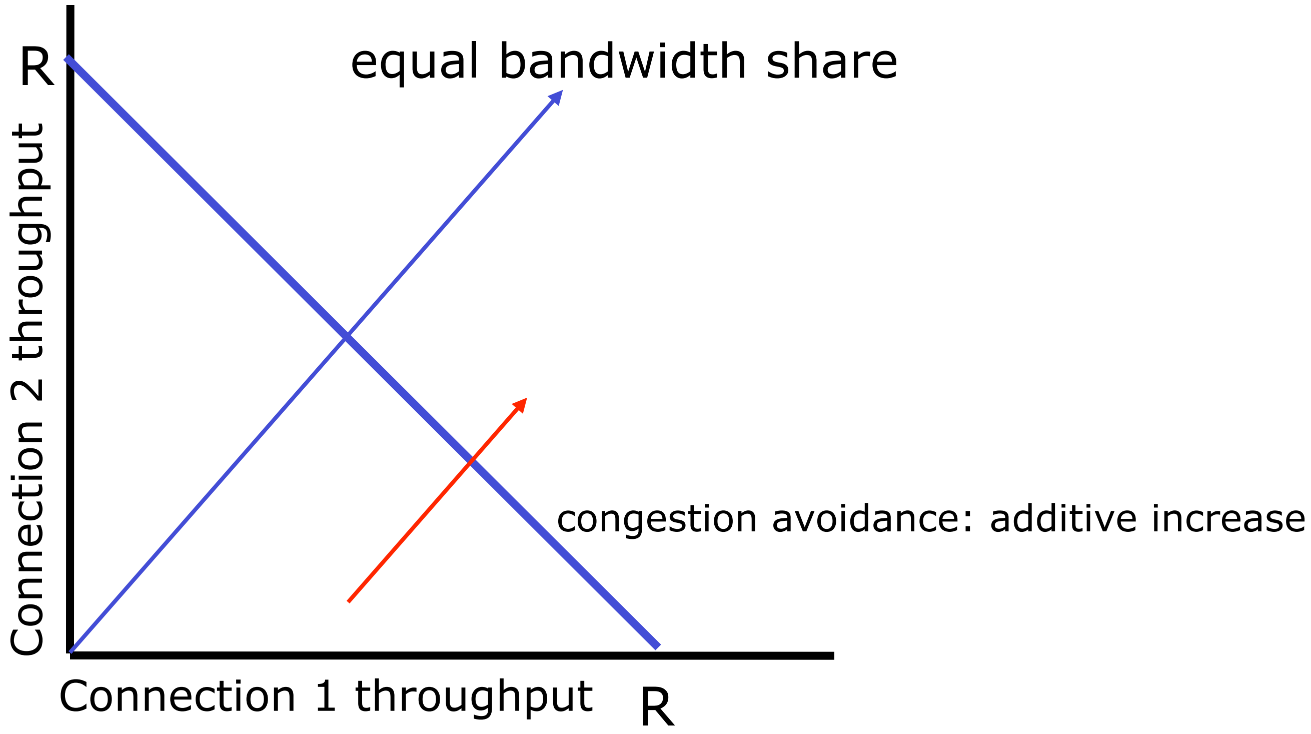

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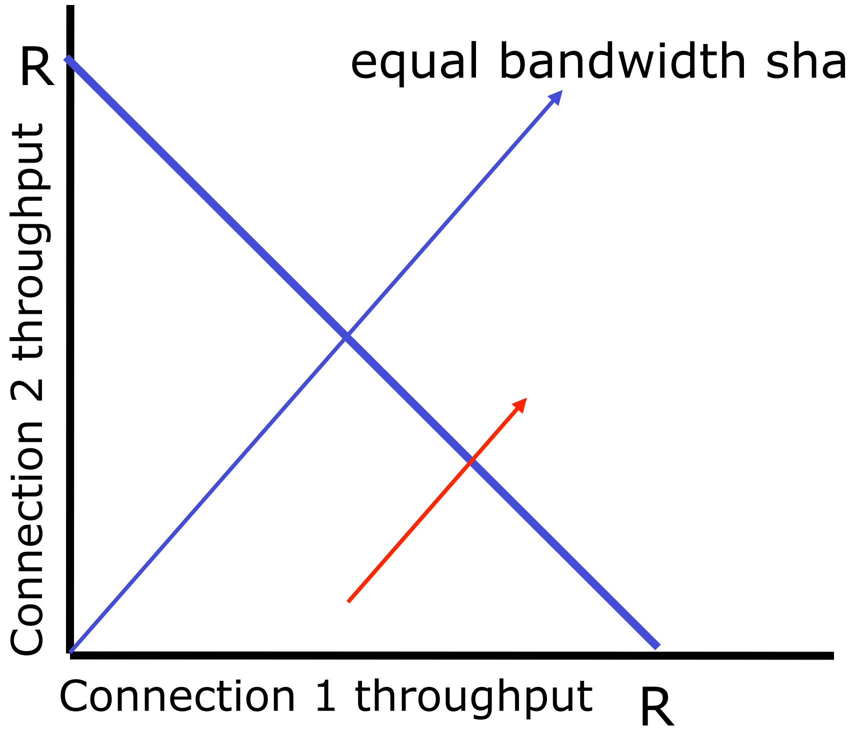

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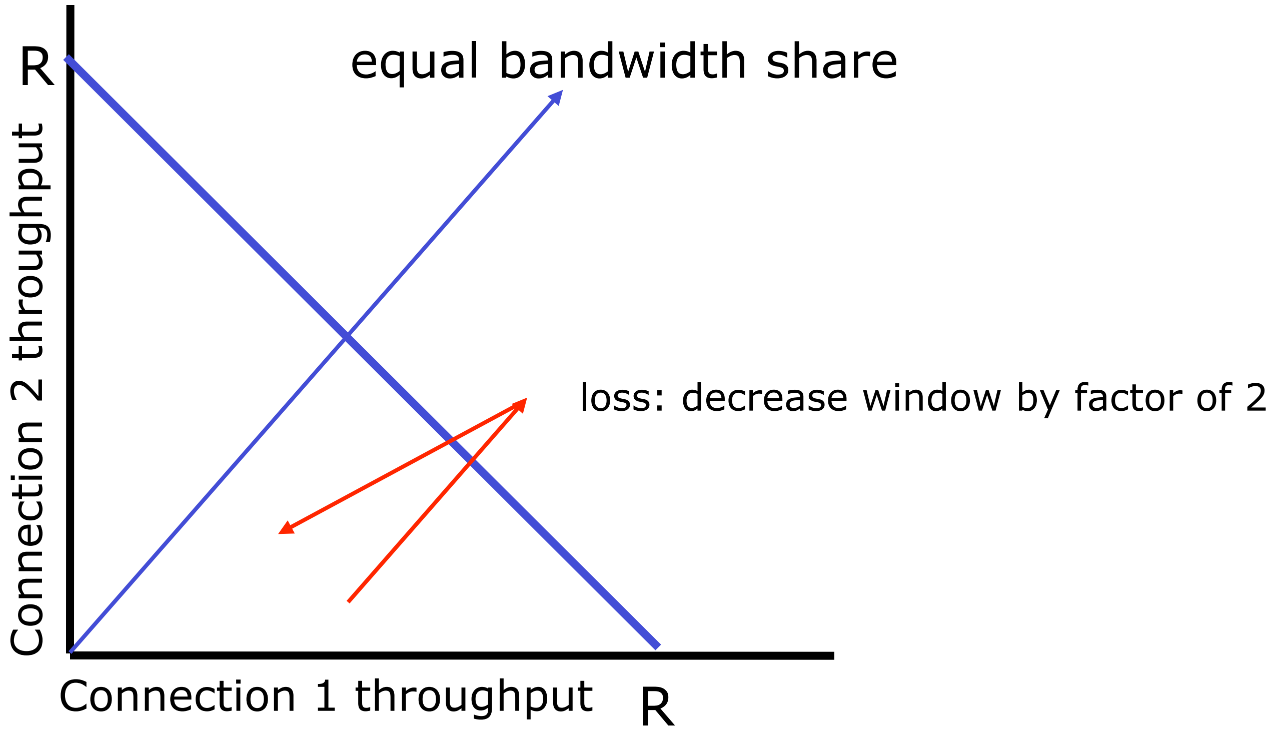

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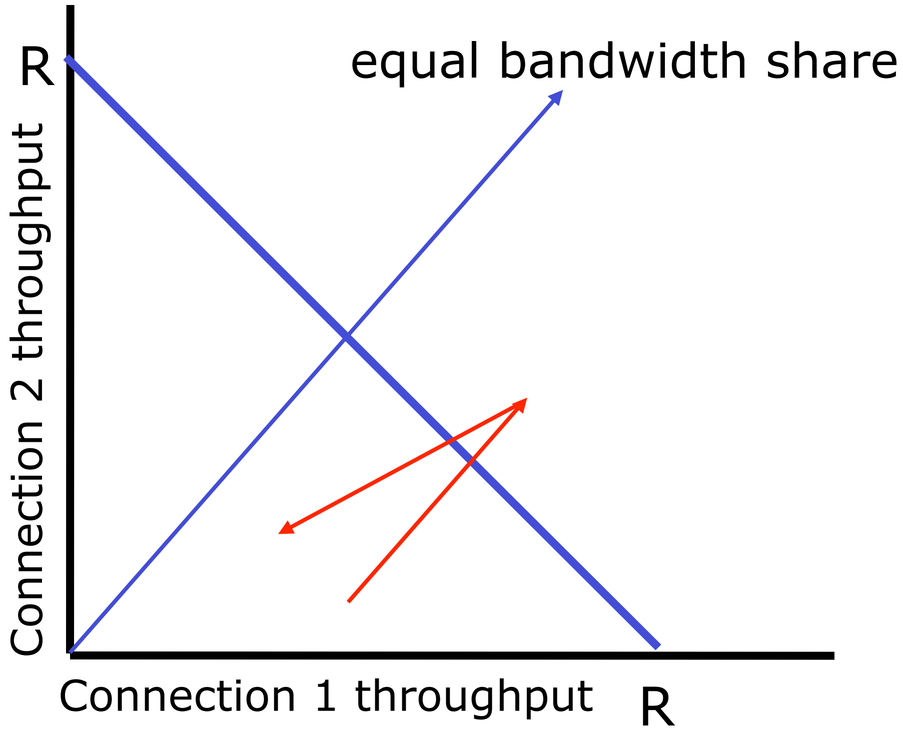

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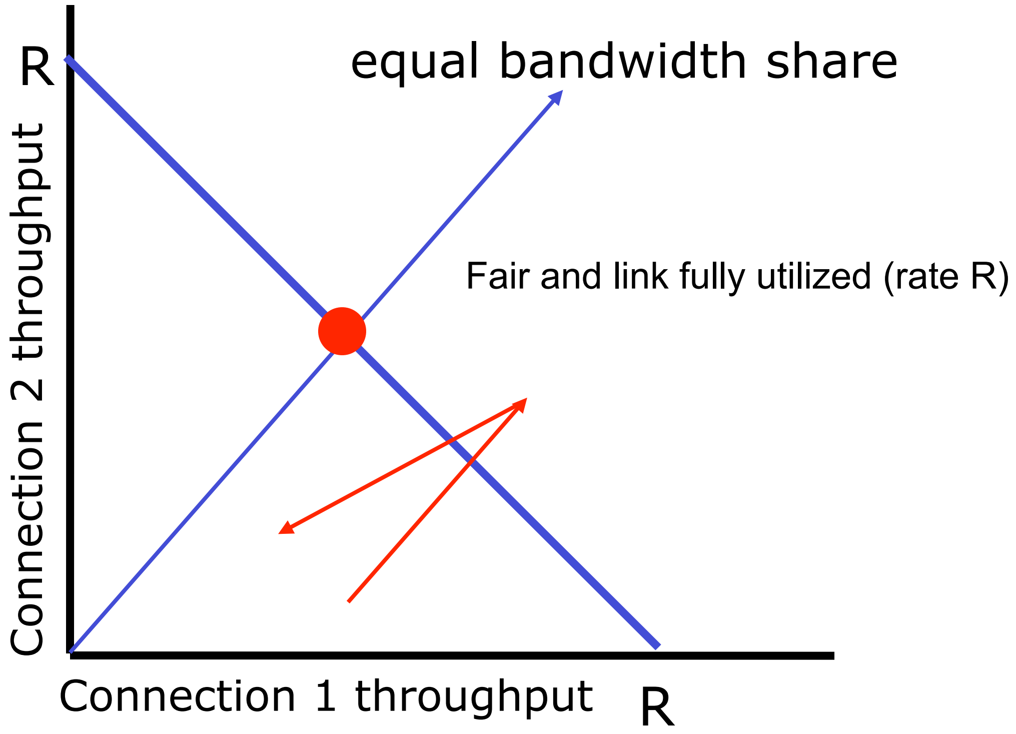
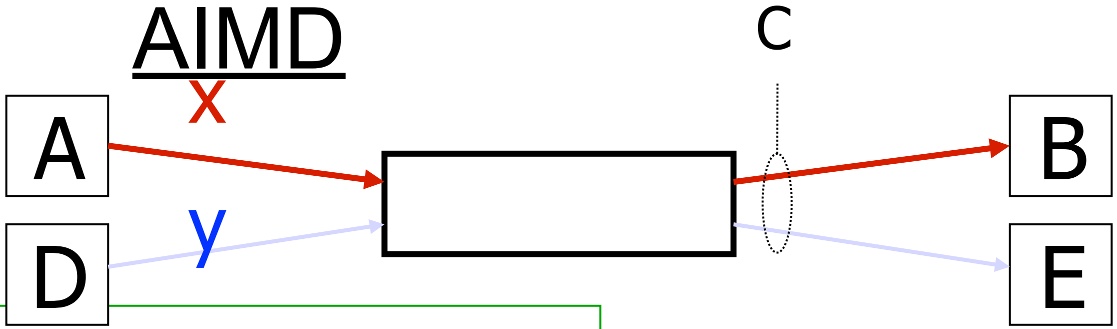
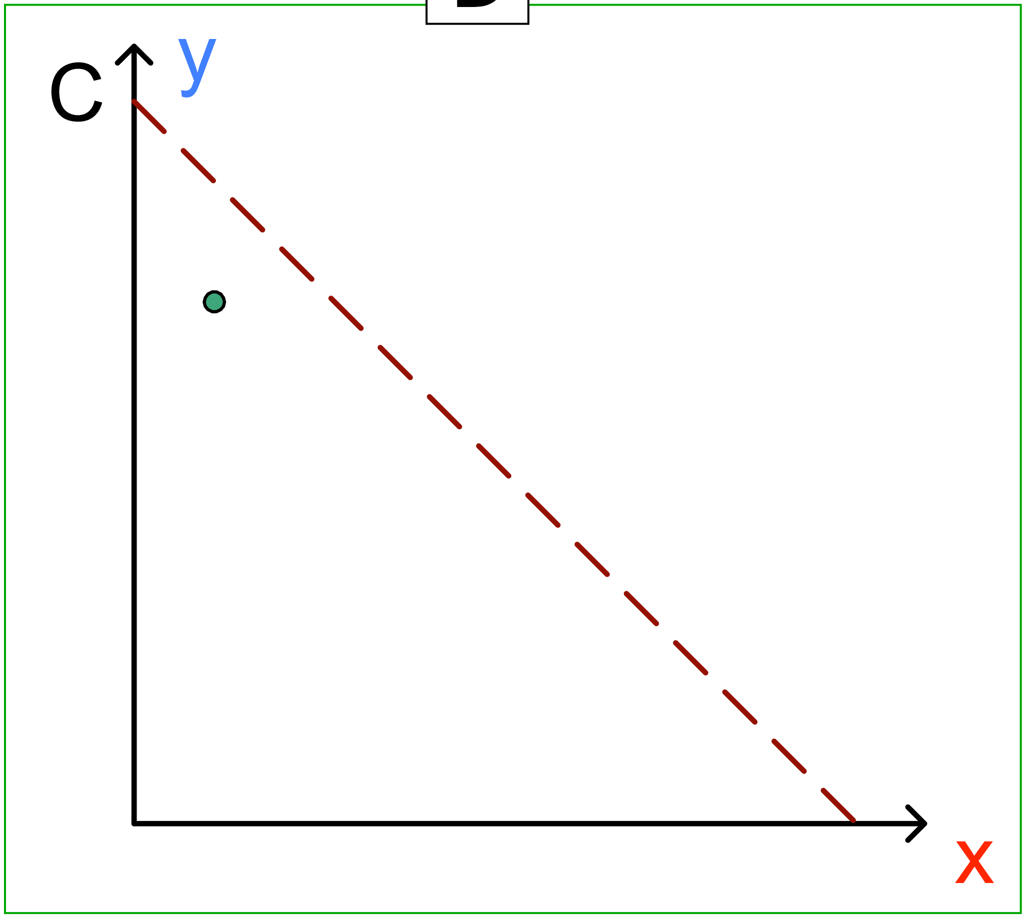


AIMD





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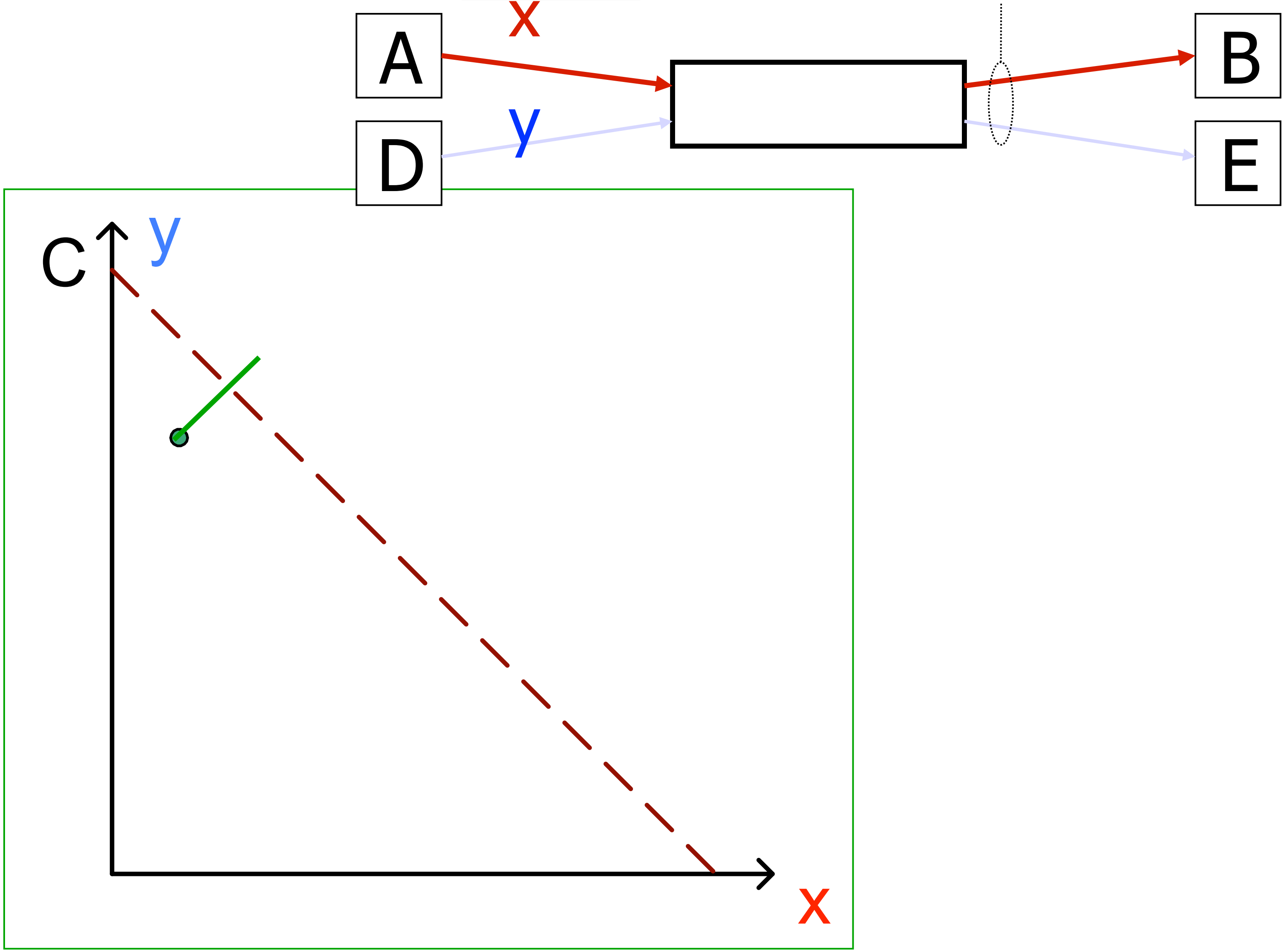

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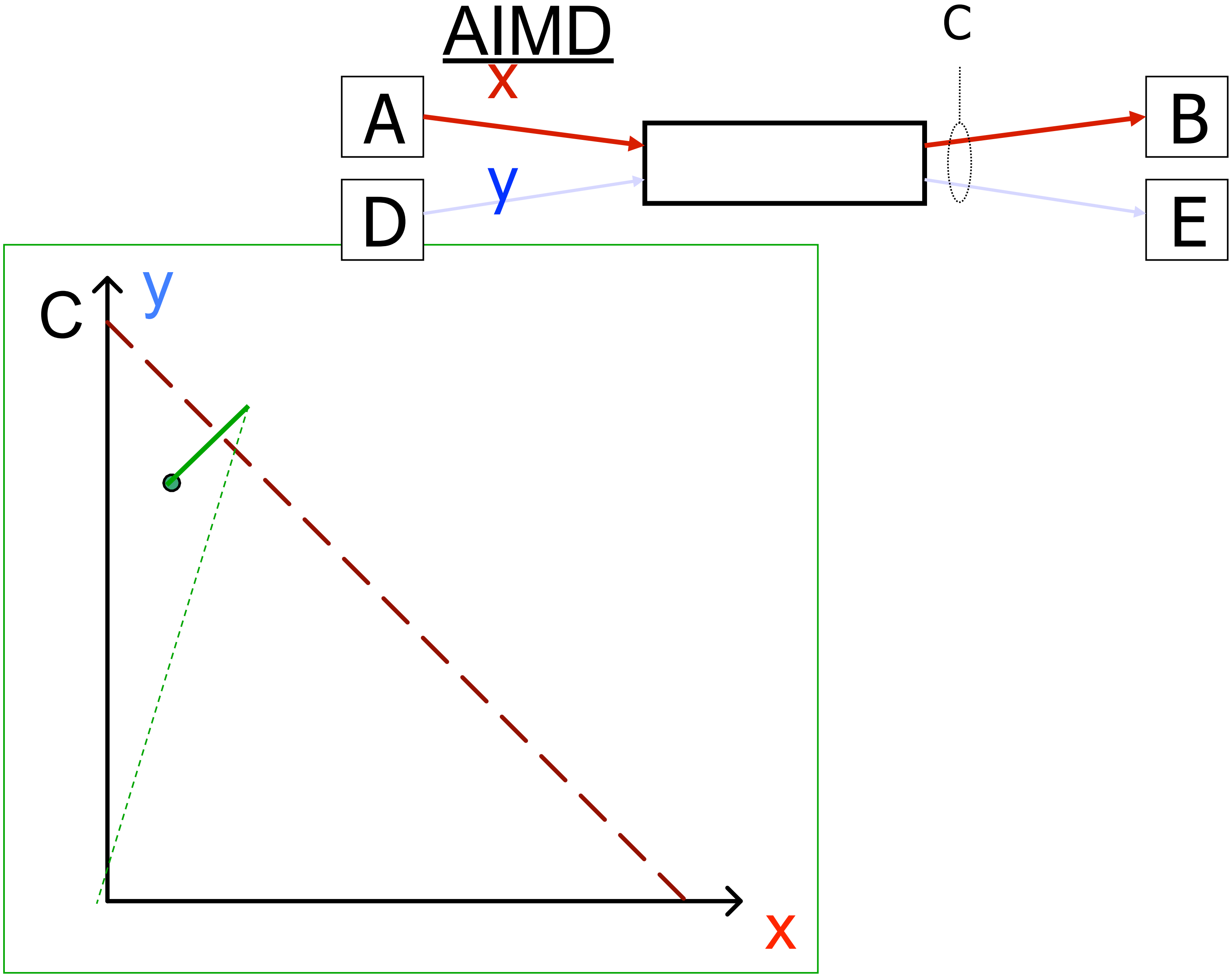

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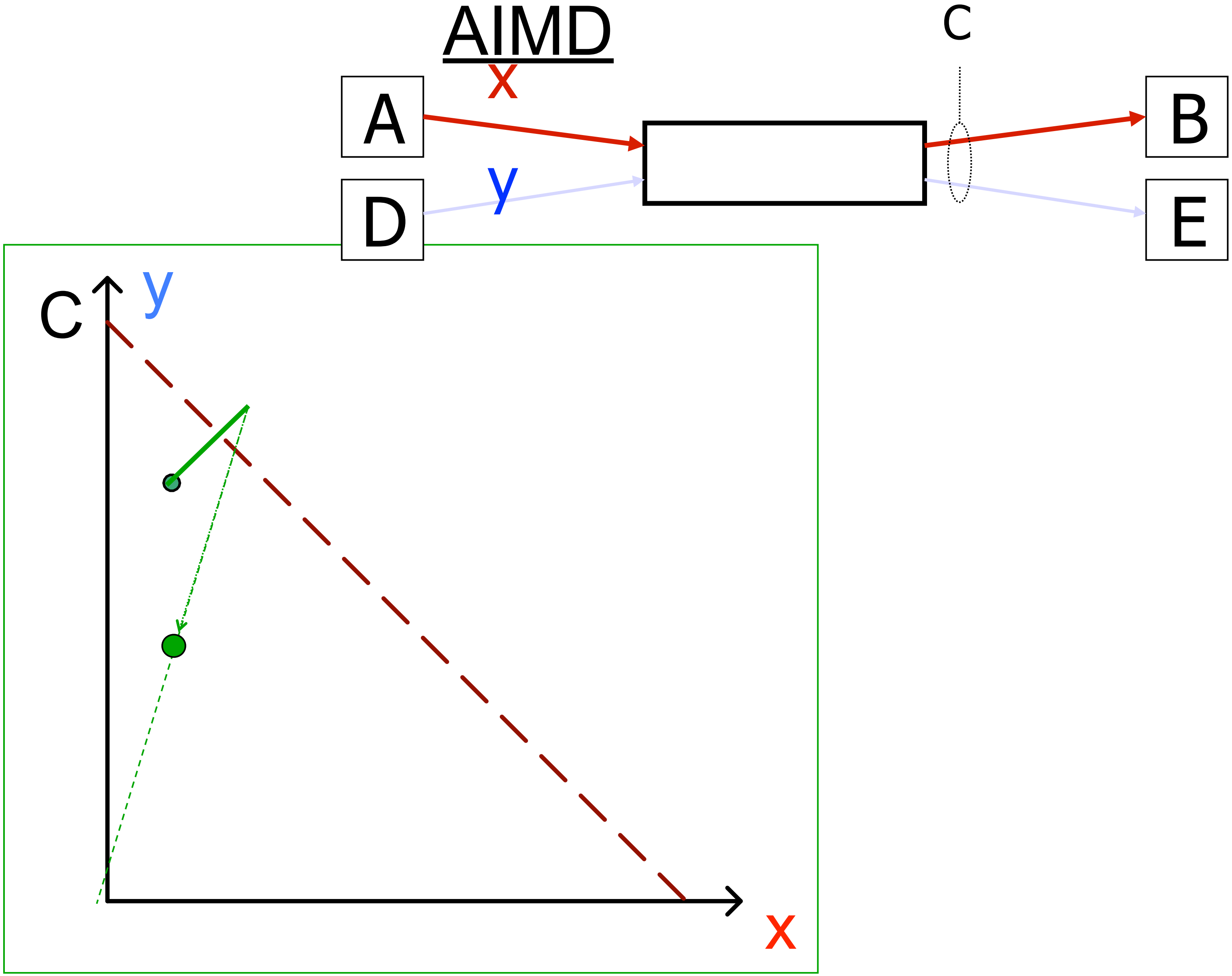

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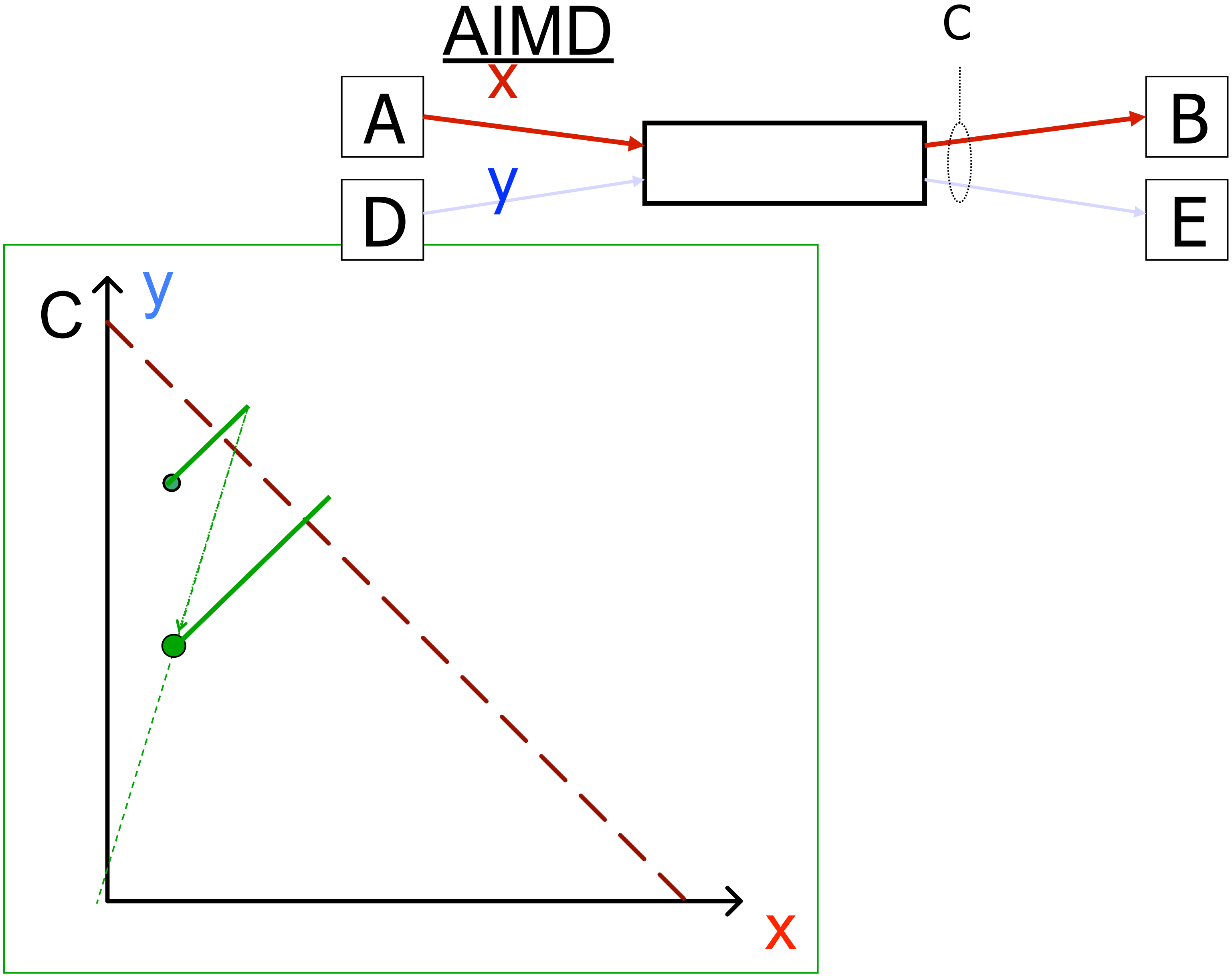

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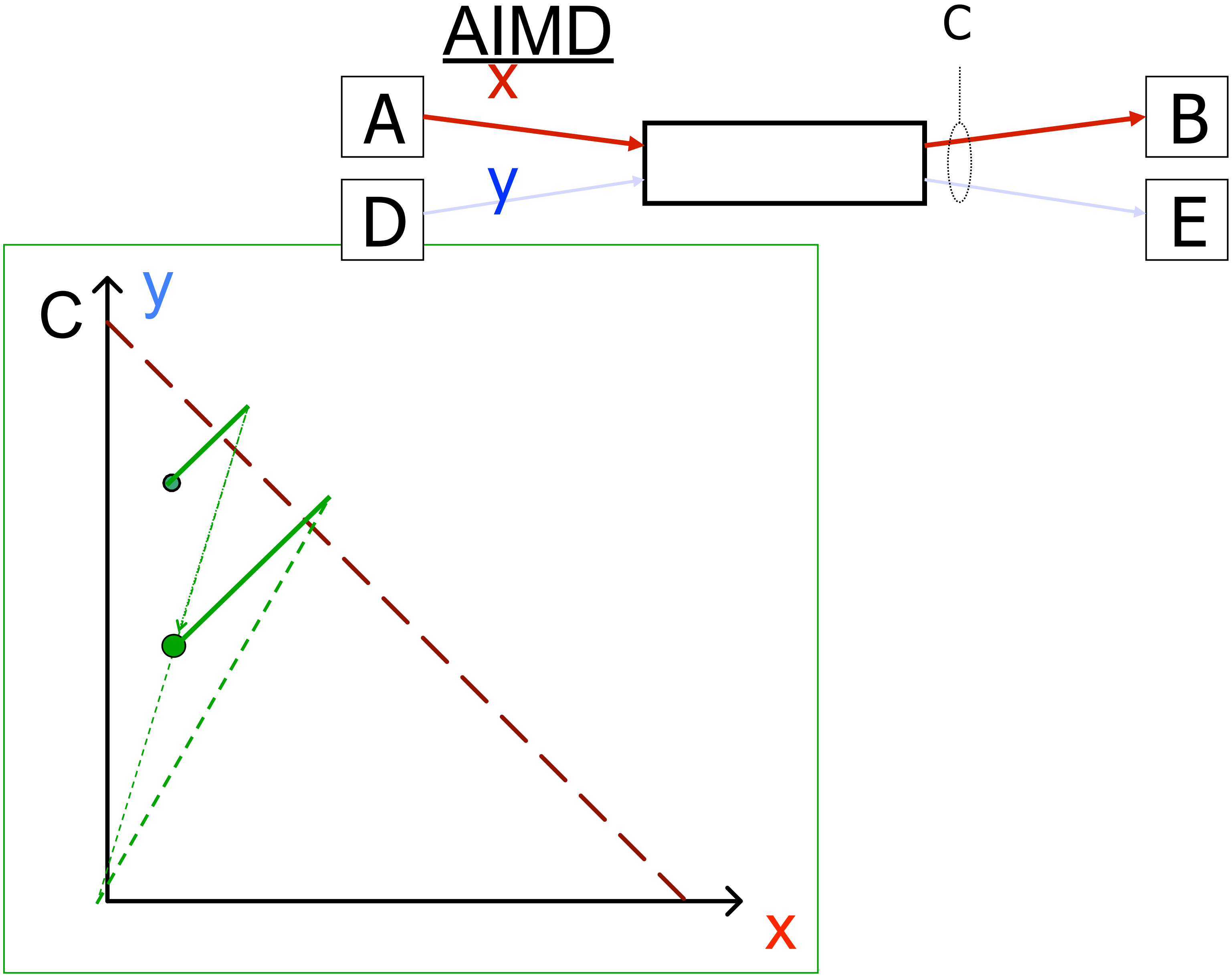

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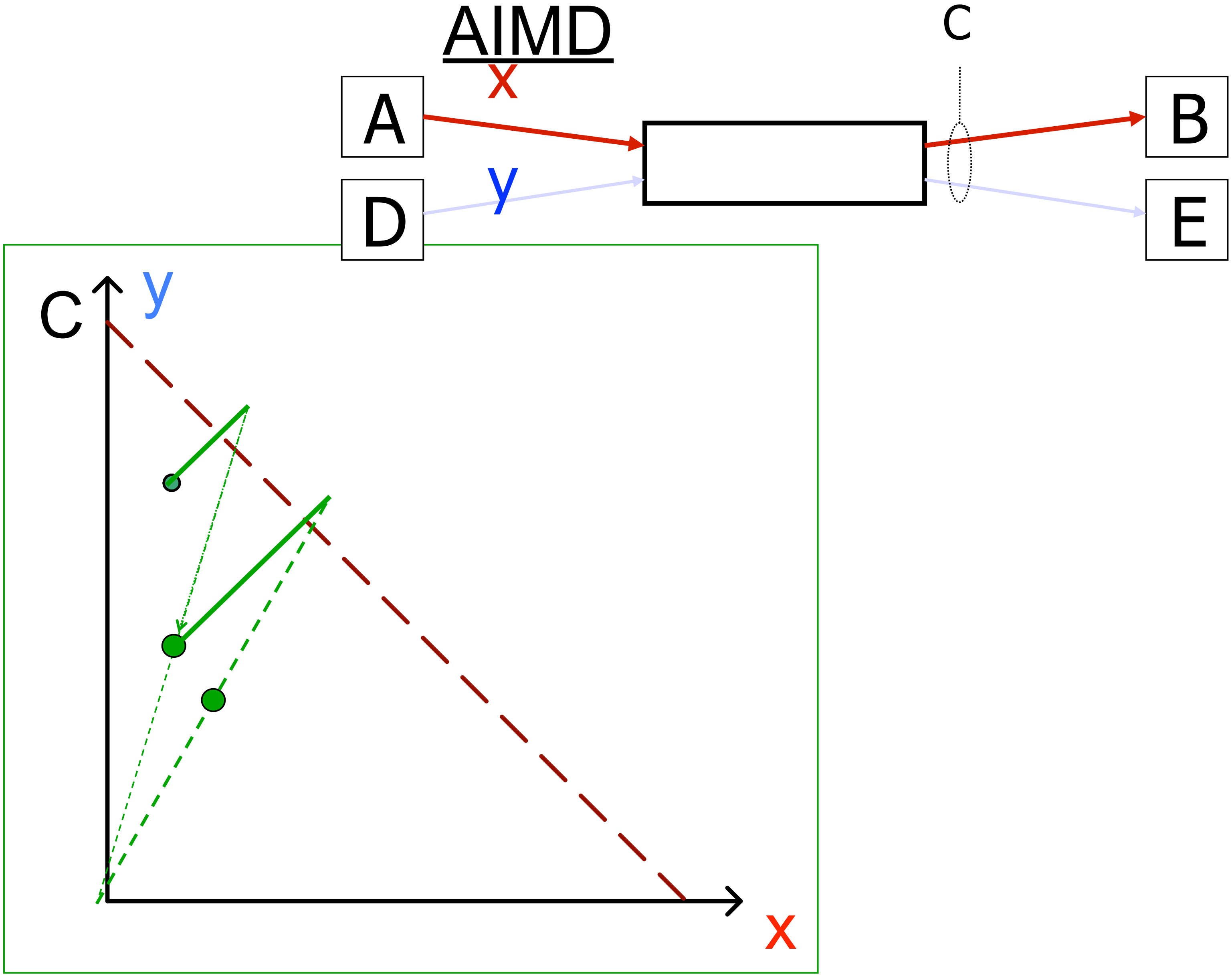

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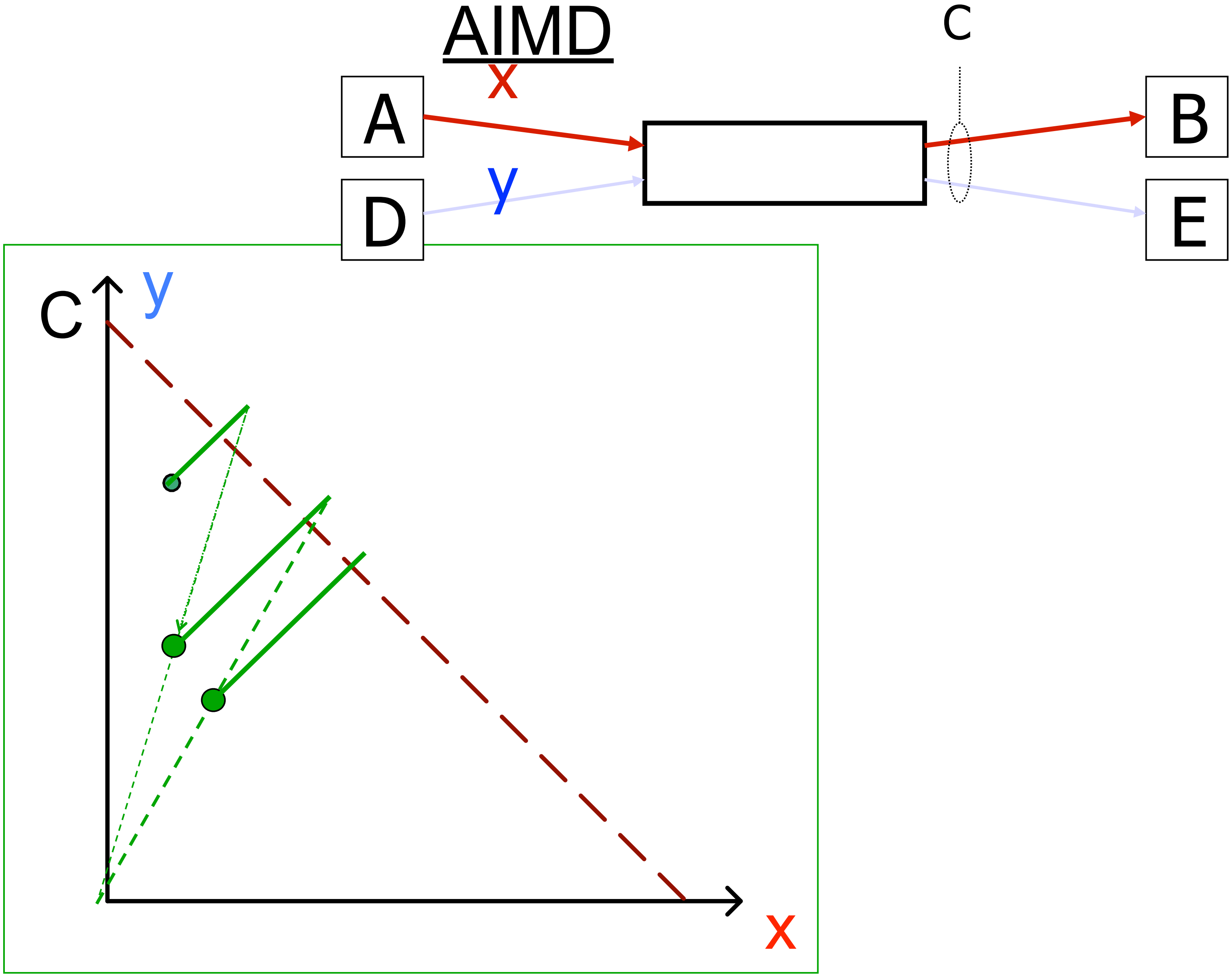

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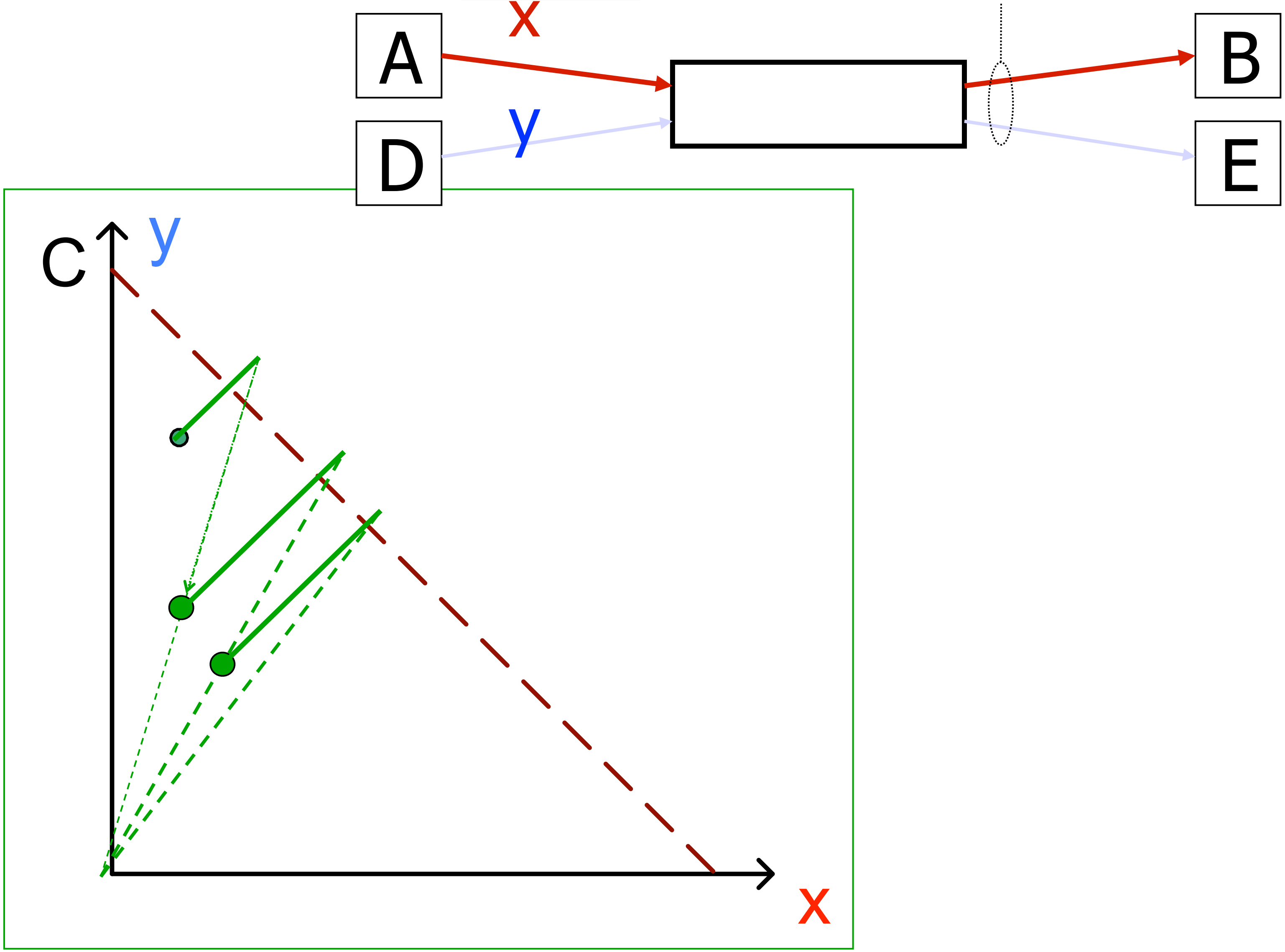

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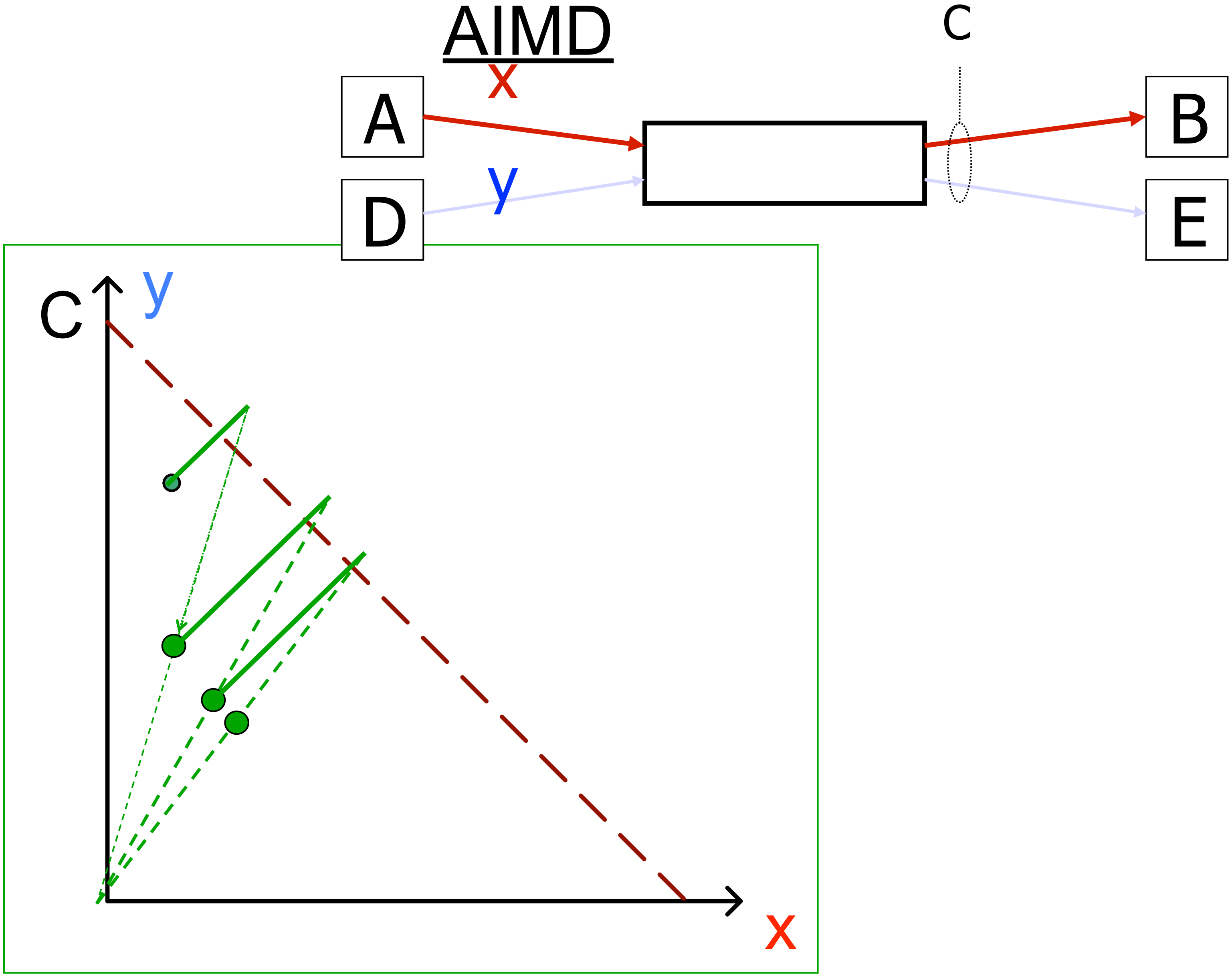

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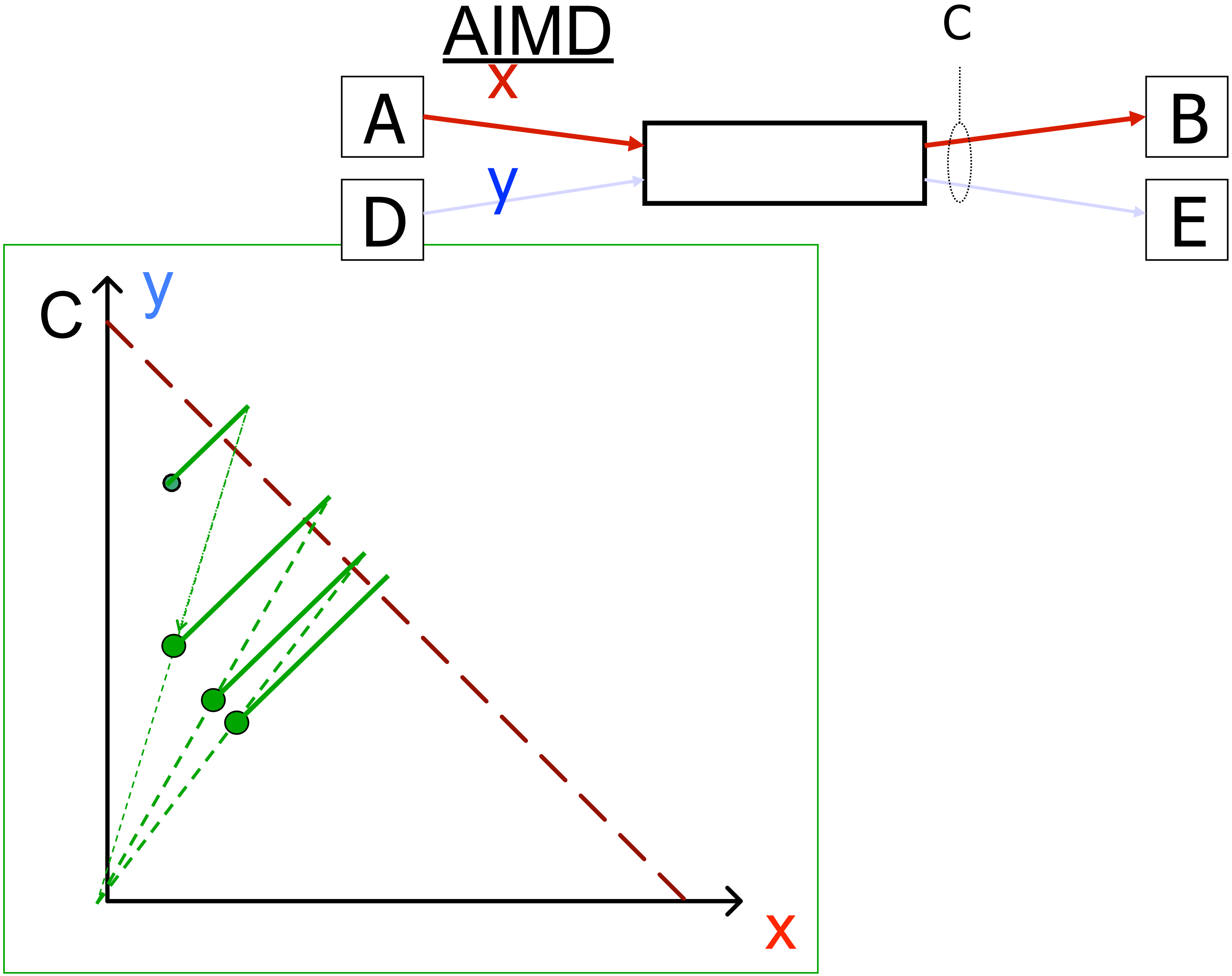

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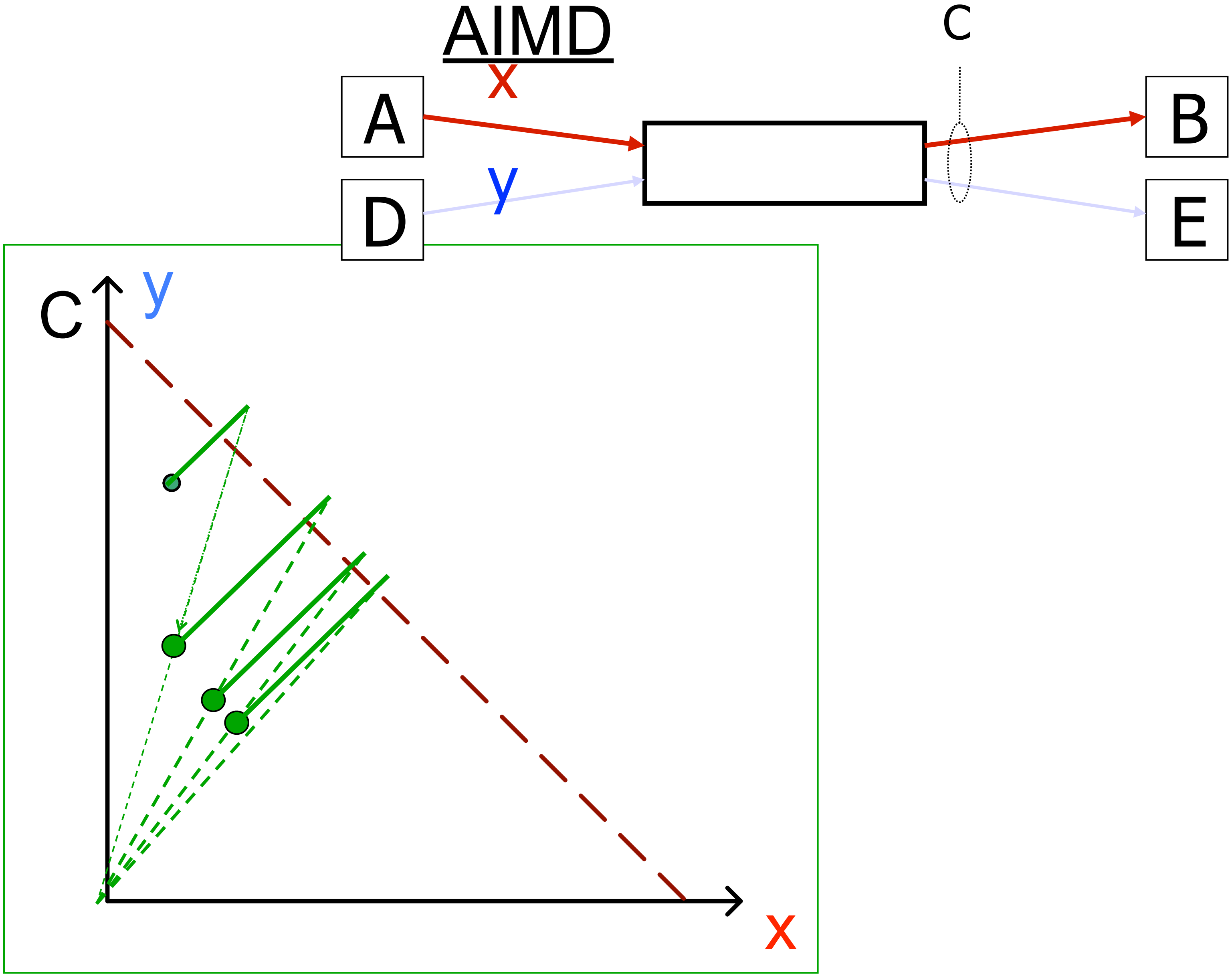

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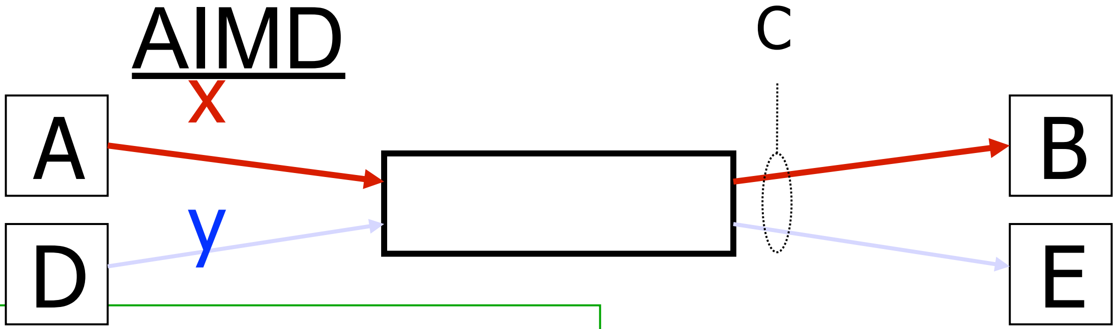

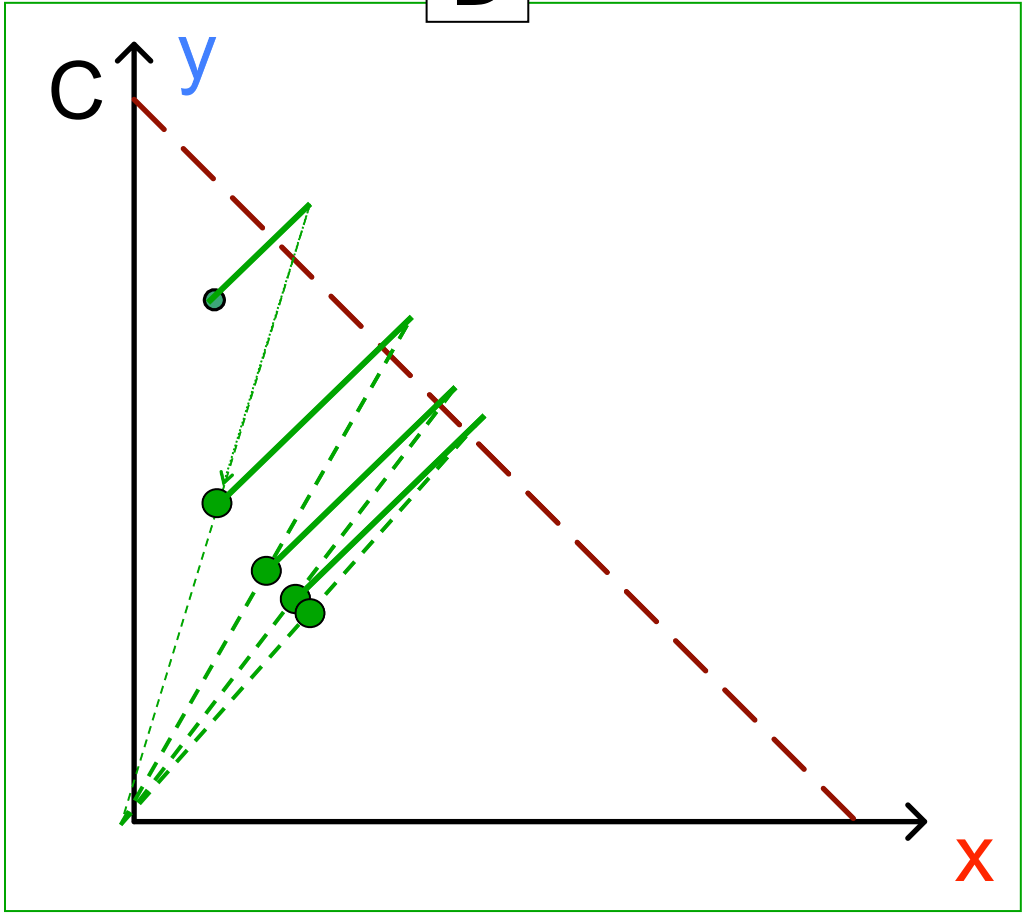

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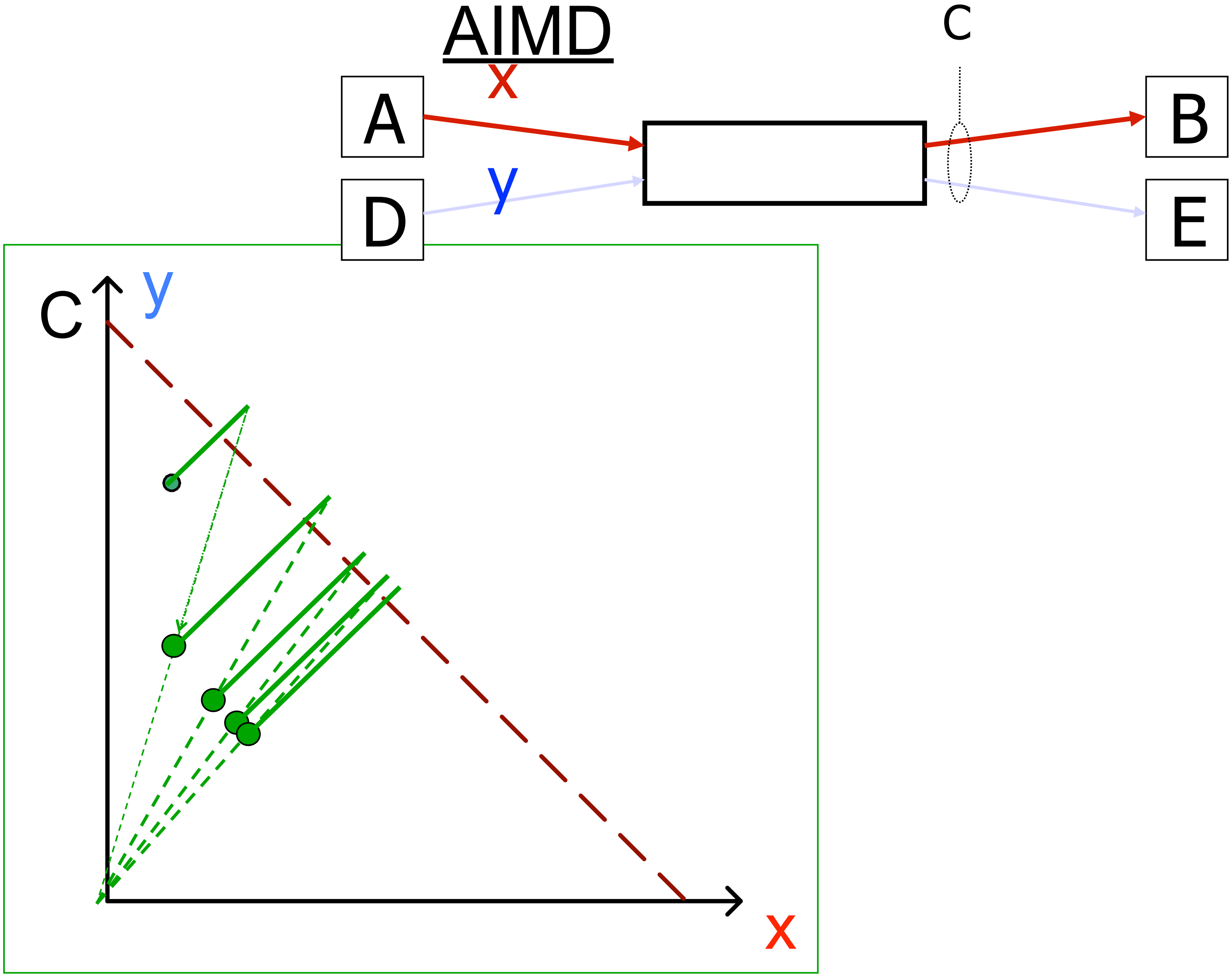

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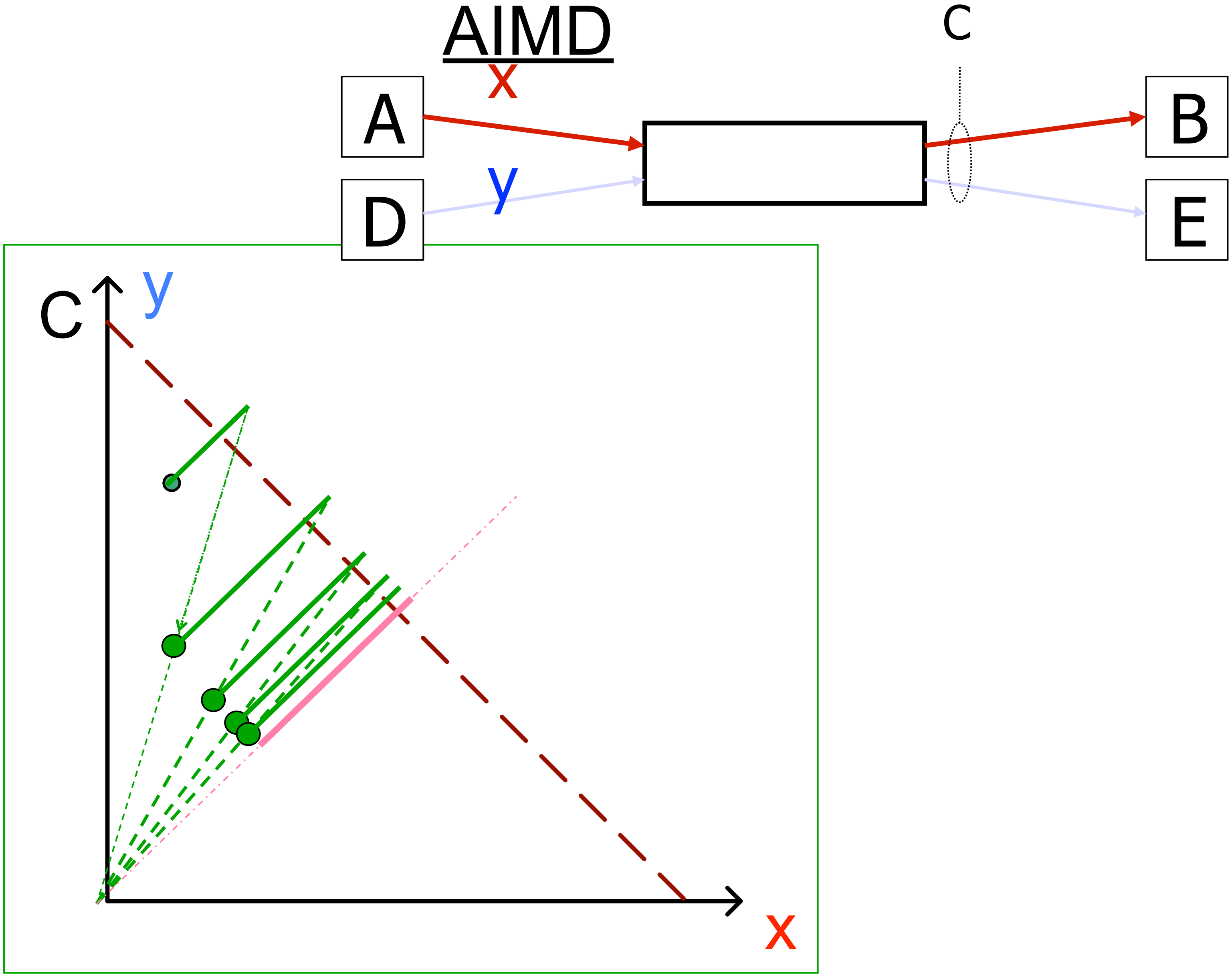

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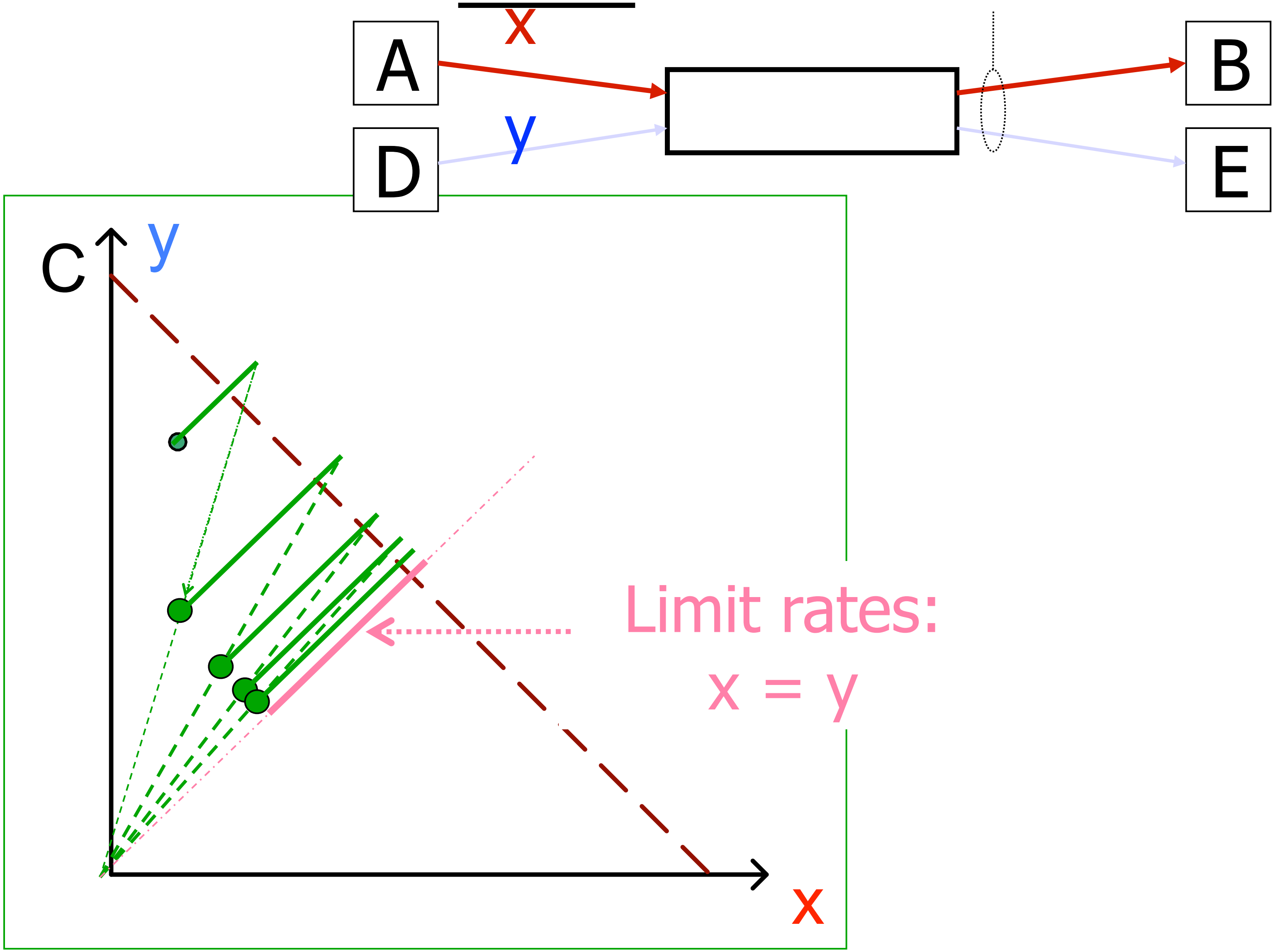
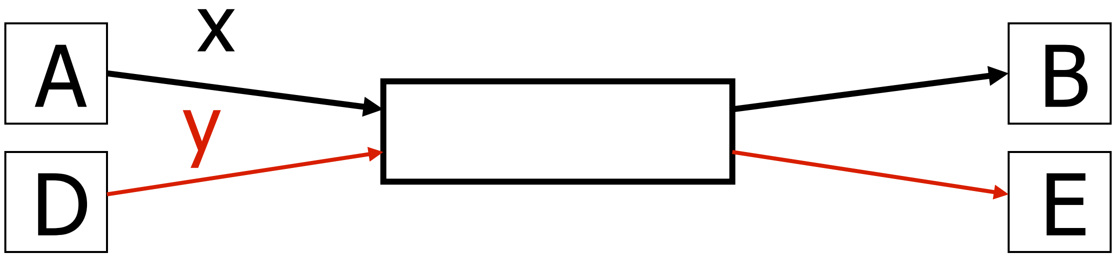
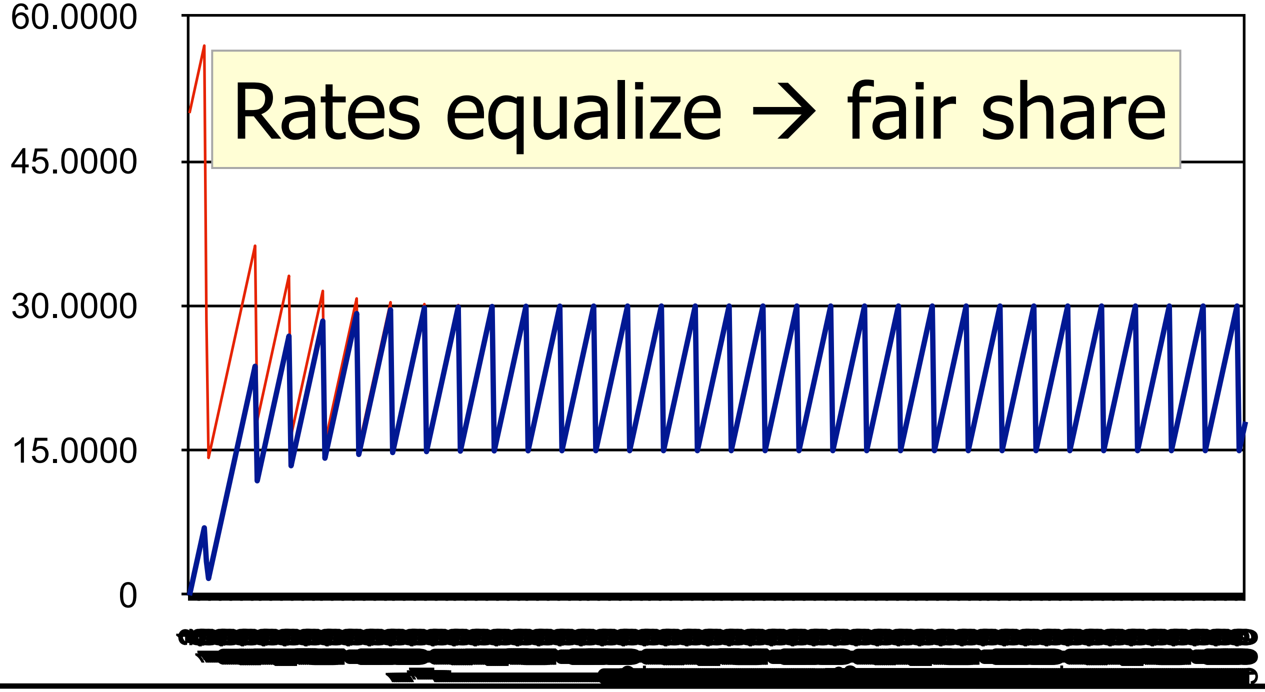


Limit rates:
x = y

AIMD Sharing Dynamics

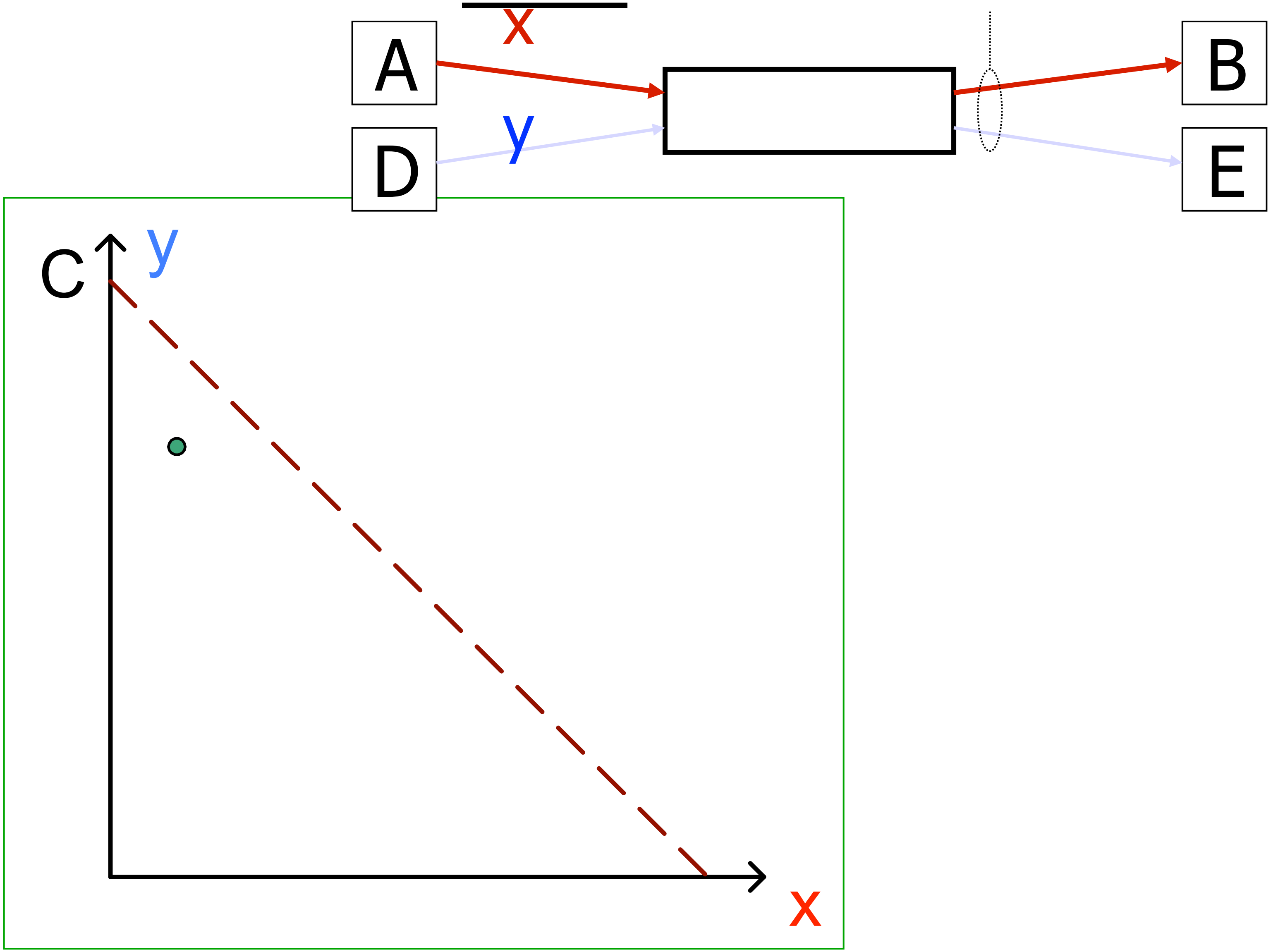


- No congestion → rate increases by one packet/RTT every RTT
- Congestion → decrease rate by factor 2



Rates equalize → fair share

AIAD



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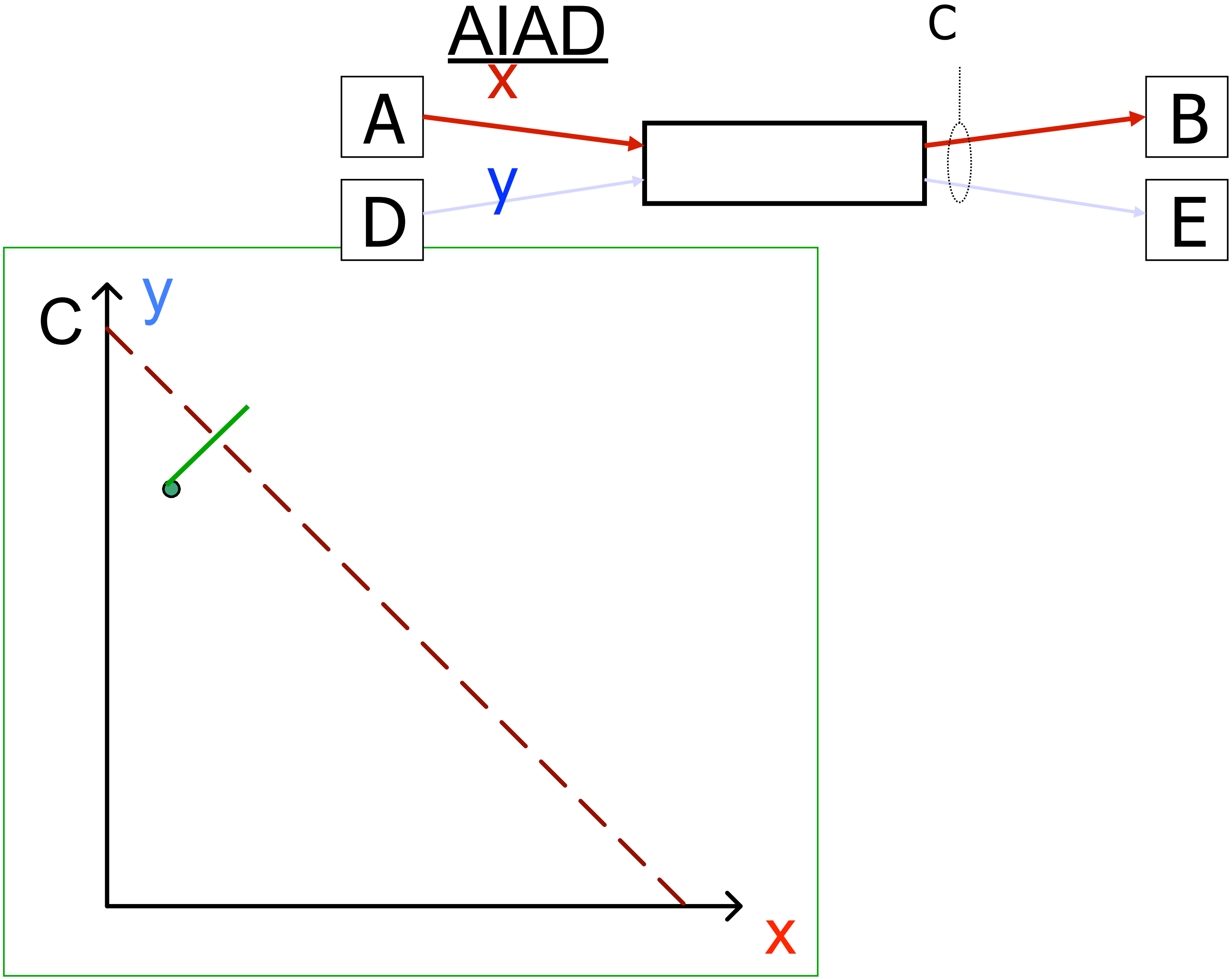

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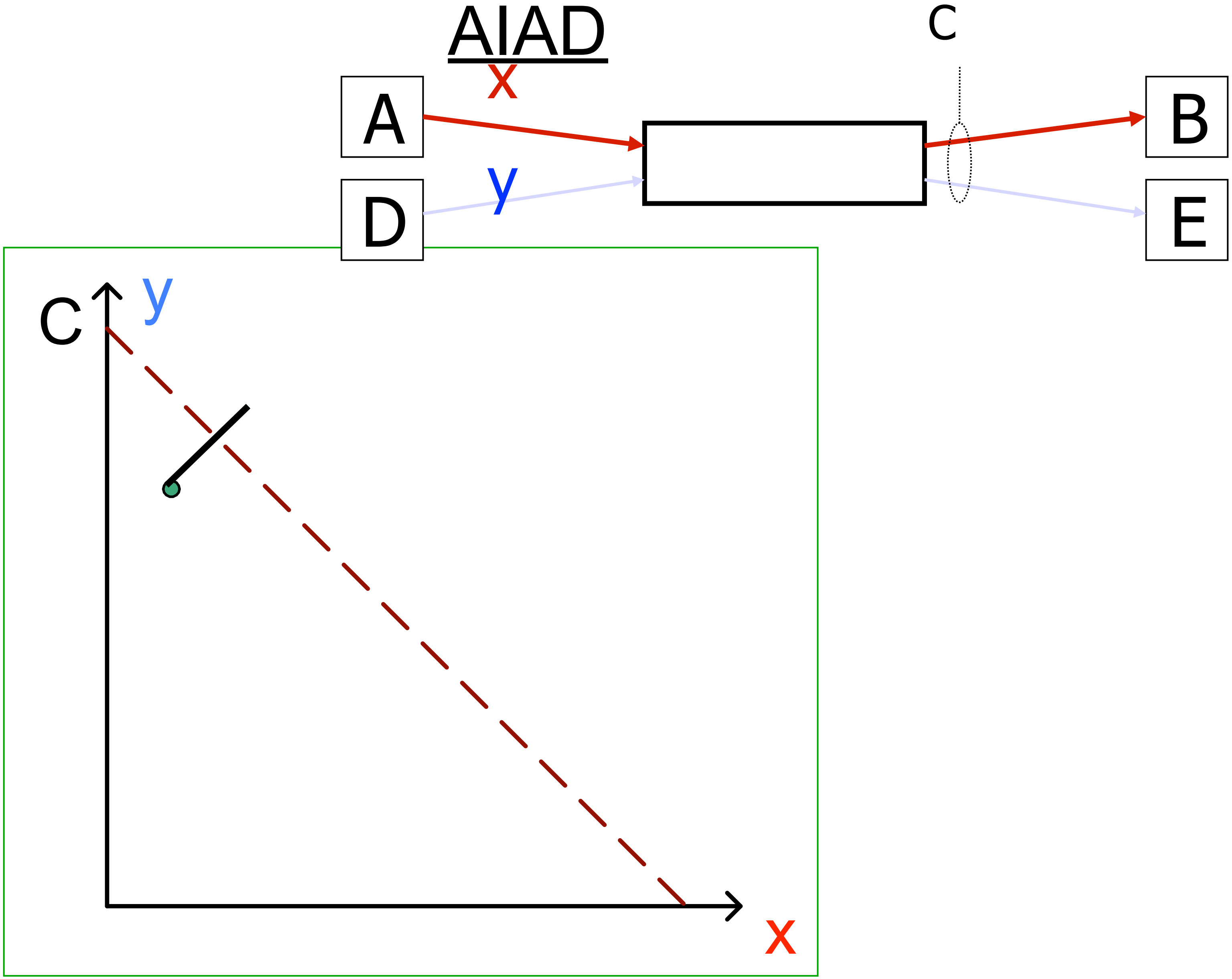

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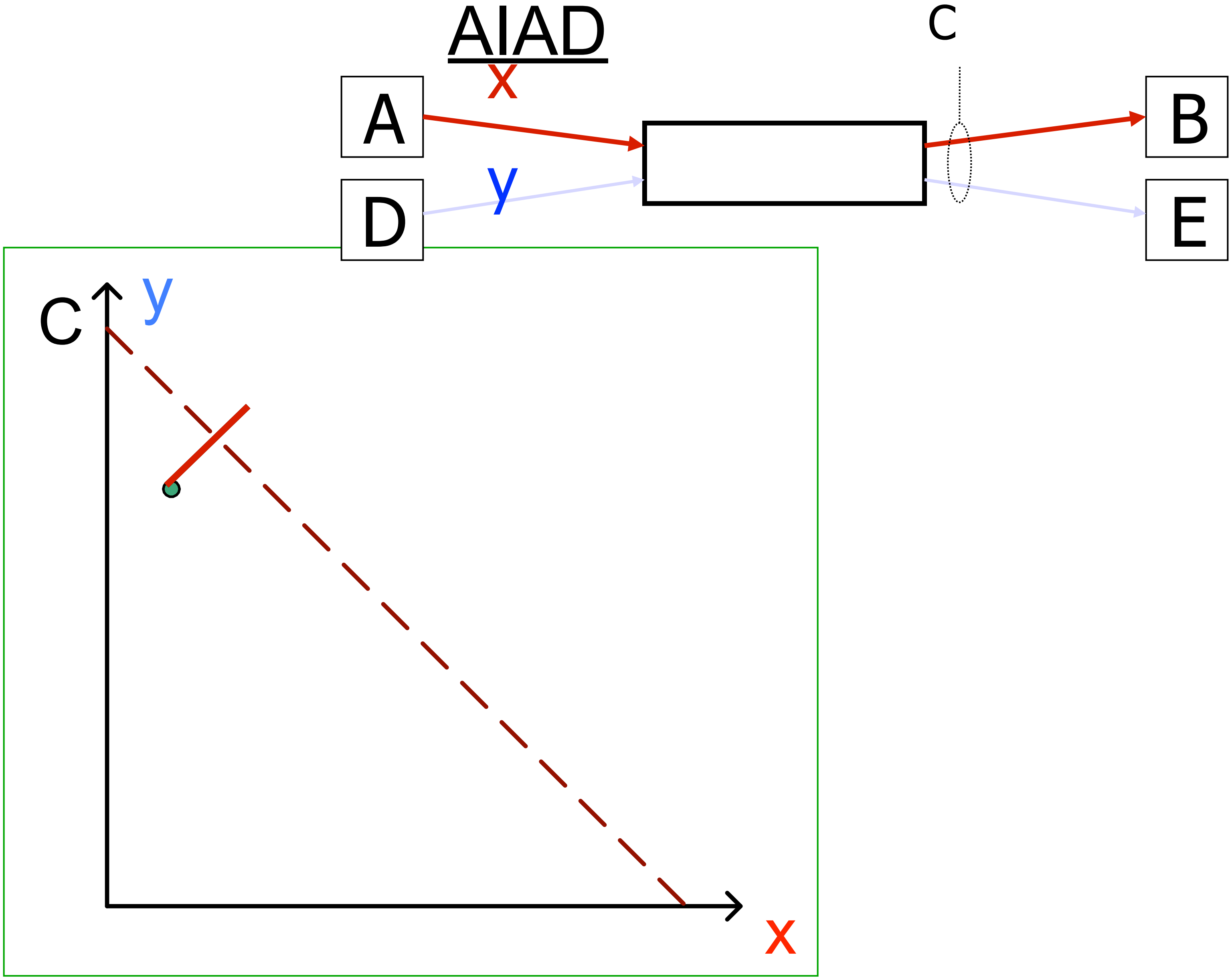

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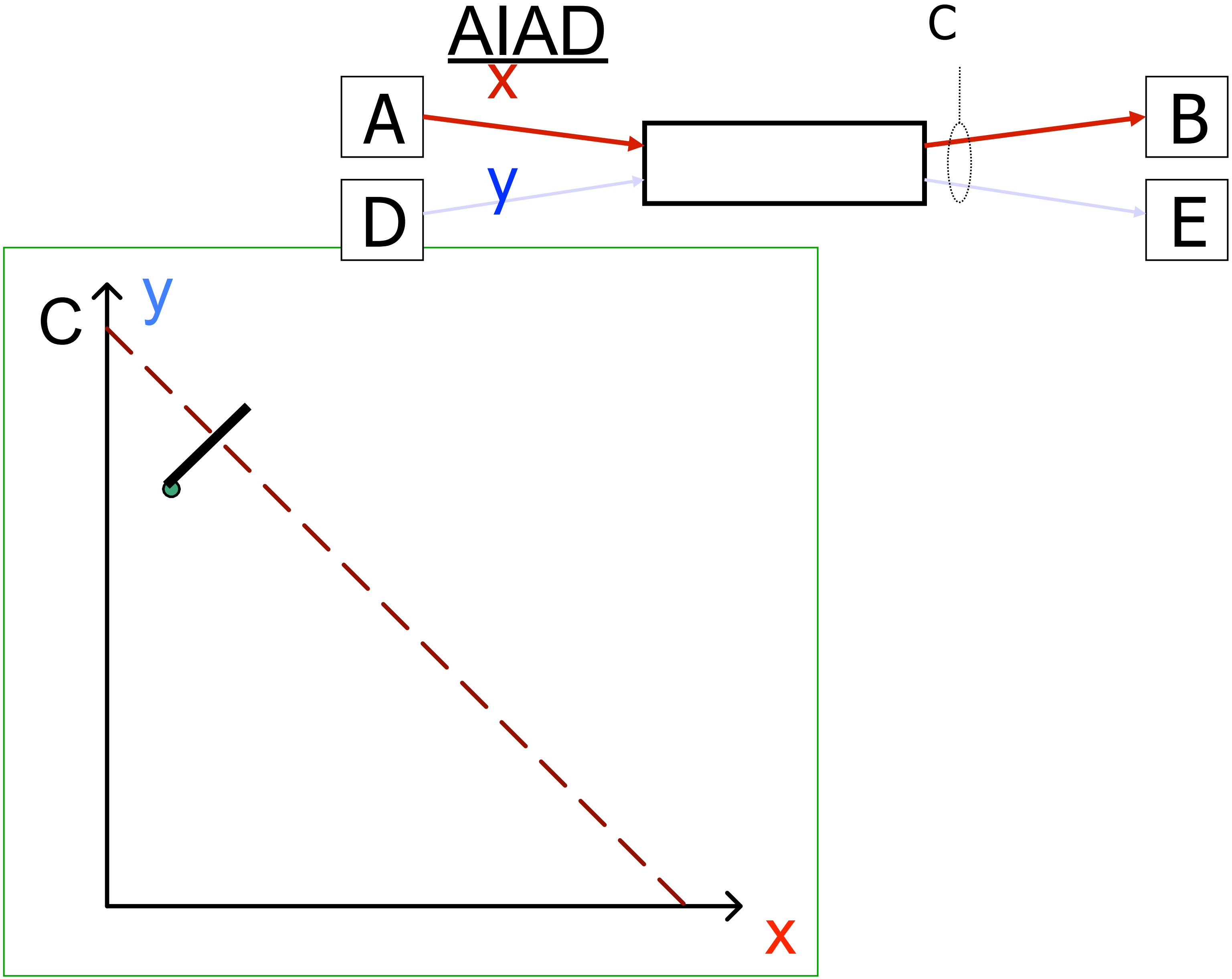

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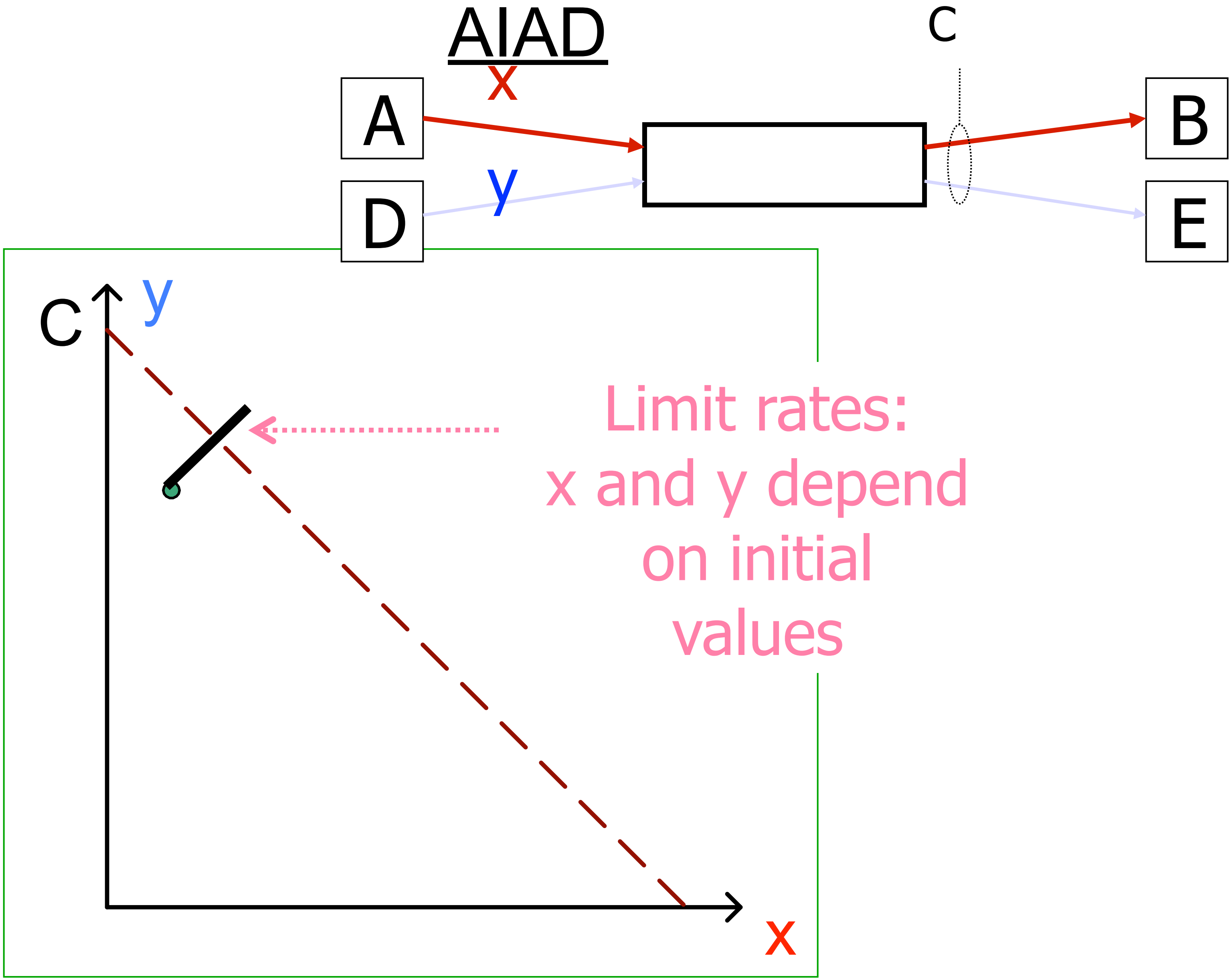
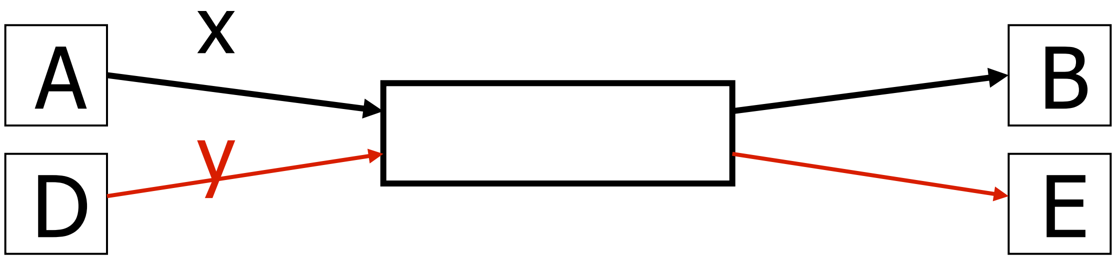


Limit rates:
x and y depend
on initial
values

AIAD Sharing Dynamics



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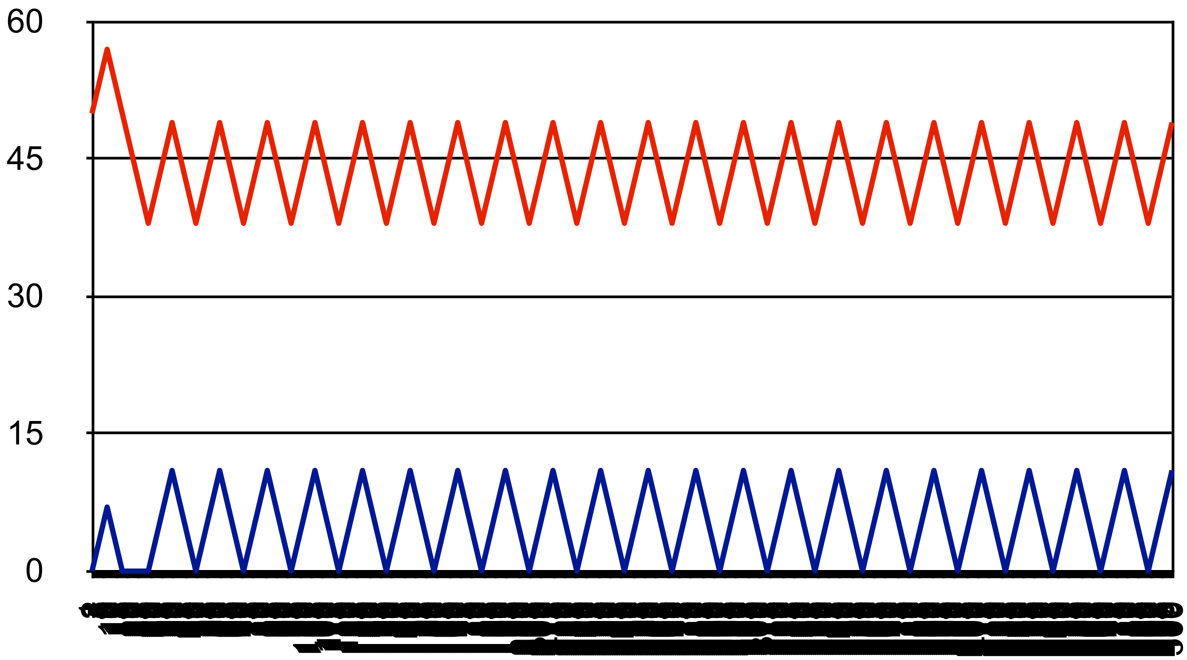
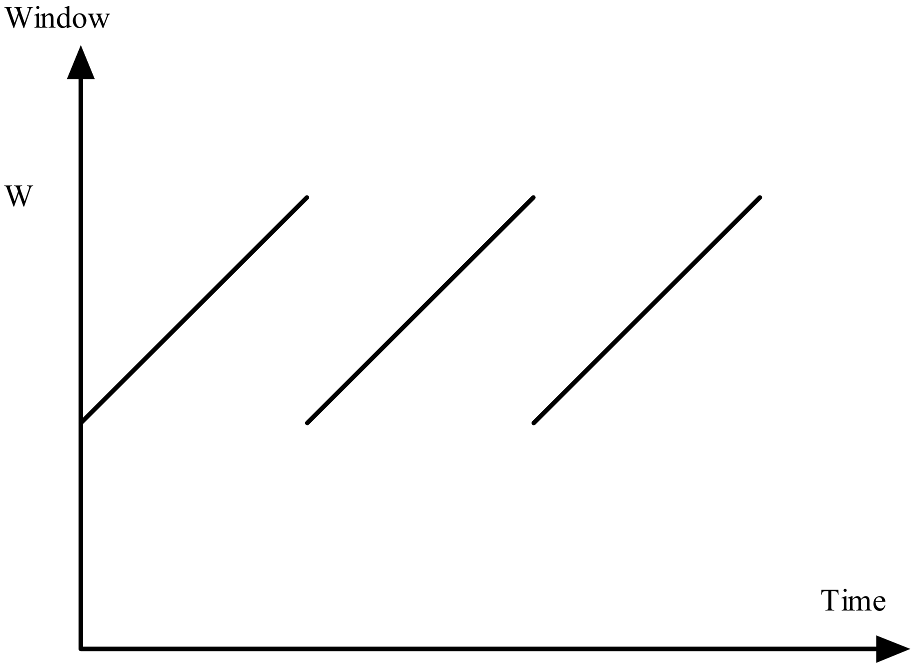


TCP Model

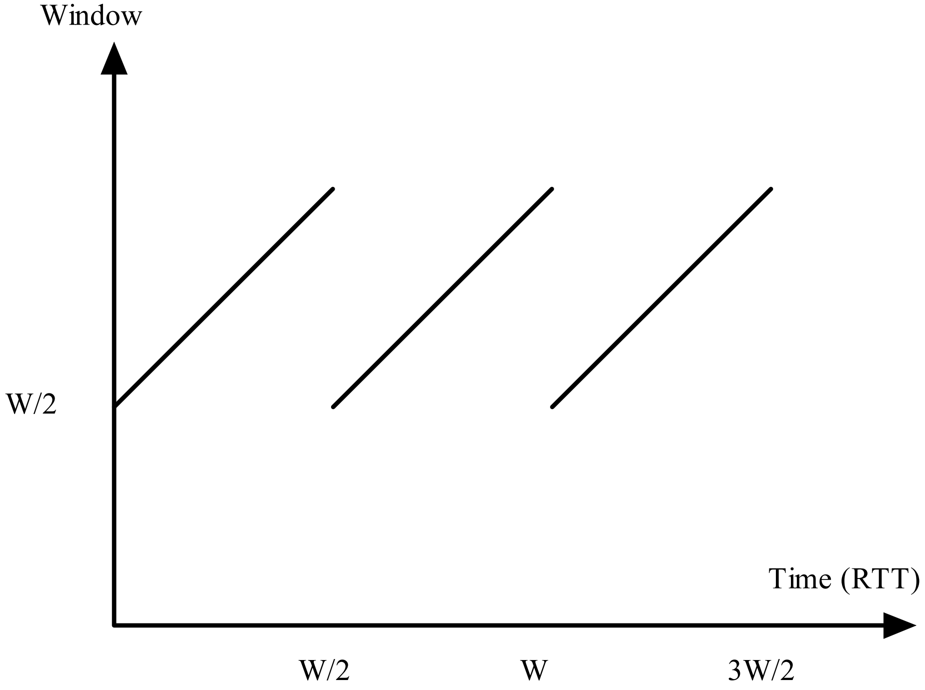
- Derive an expression for the steady state throughput as a function of
  - RTT
  - Loss probability
- Assumptions
  - Each packet dropped with *iid* probability p
- Methodology: analyze “average” cycle in steady state
  - How many packets are transmitted per cycle?
  - What is the duration of a cycle?

Cycles in Steady State



- Denote *W* as the (mean) maximum achieved window
- What is the slope of the line?
- What are the key values on the time axis?

Cycle Analysis



W increase by 1 per RTT

$$\text{pkts xmitted/cycle} = \text{area} = \left(\frac{W}{2}\right)^2 + \frac{1}{2}\left(\frac{W}{2}\right)^2 = \frac{3}{8}W^2$$

Throughput

$$\text{throughput} = \frac{\text{pkts xmitted/cycle}}{\text{time/cycle}} = \frac{\frac{3}{8}W^2}{RTT\left(\frac{W}{2}\right)}$$

- What is *W* as a function of p?

  How long does a cycle last until a drop?

Cycle Length

Let α index packet loss that ends cycle.

$$P(\alpha = k) = P(k-1 \text{ pkts not lost}, k\text{th pkt lost})$$

$$= (1-p)^{k-1} p$$

$$\Rightarrow \quad E(\alpha) = \sum_{k=1}^{\infty} k(1-p)^{k-1} p = \frac{1}{p}$$

$$\Rightarrow \quad \frac{1}{p} = \frac{3}{8} W^2 \qquad \Rightarrow \quad W = \sqrt{\frac{8}{3p}}$$

TCP Model

$$\text{throughput T(p)} = \frac{1/p}{RTT \times \frac{1}{2}\sqrt{\frac{8}{3p}}} = \frac{1}{RTT\sqrt{\frac{2}{3}p}}$$

- Note role of RTT. Is it “fair”?
- A “macroscopic” model
- Achieving this throughput is referred to as “TCP Friendly”

Adapting cwin

- So far: sliding window + self-clocking of ACKs
- How to know the best cwnd (and best transmission rate)?

- Phases of TCP congestion control

1. Slow start (getting to equilibrium)
    1. Want to find this very very fast and not waste time
2. Congestion Avoidance
    - Additive increase - gradually probing for additional bandwidth
    - Multiplicative decrease - decreasing cwnd upon loss/ timeout

Phases of Congestion Control

- **Congestion Window (cwnd)**
  Initial value is 1 MSS (=maximum segment size) counted as bytes
- **Slow-start threshold Value (ss_thresh)**
  Initial value is the advertised window size

- **slow start** (cwnd < ssthresh)
- **congestion avoidance** (cwnd >= ssthresh)

TCP: Slow Start

- Goal: discover roughly the proper sending rate quickly

- Whenever starting traffic on a new connection, or whenever increasing traffic after congestion was experienced:
    - Intialize *cwnd* =1
    - Each time a segment is acknowledged, increment *cwnd* by one (*cwnd*++).

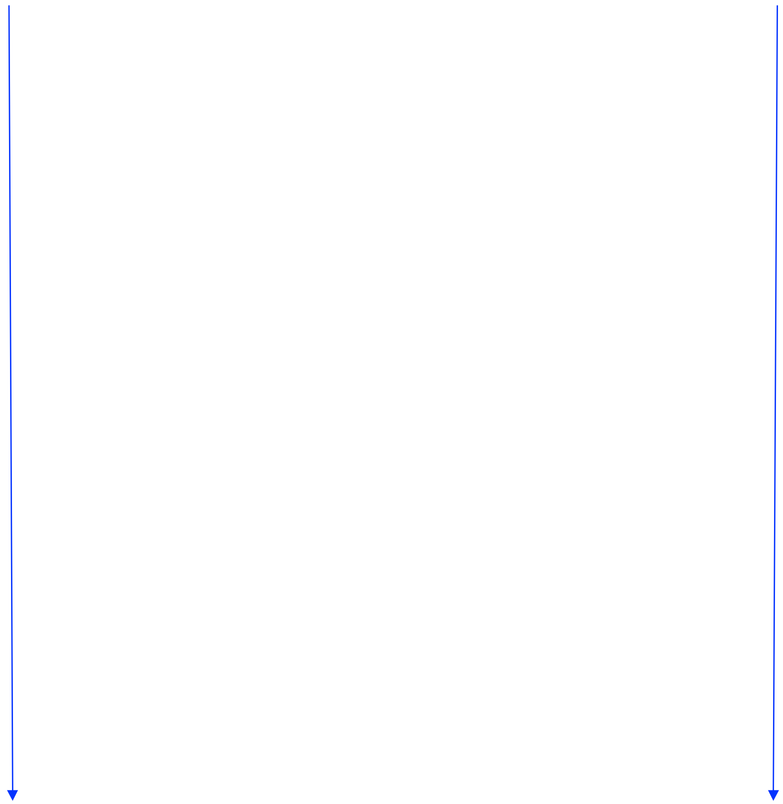
- Continue until
    - Reach ss_thresh
    - Packet loss

Slow Start Illustration

- The congestion window size grows very rapidly

- TCP slows down the increase of *cwnd* when ***cwnd >= ss_thresh***

- Observe:
  - Each ACK generates two packets
  - slow start increases rate exponentially fast (doubled every RTT)!



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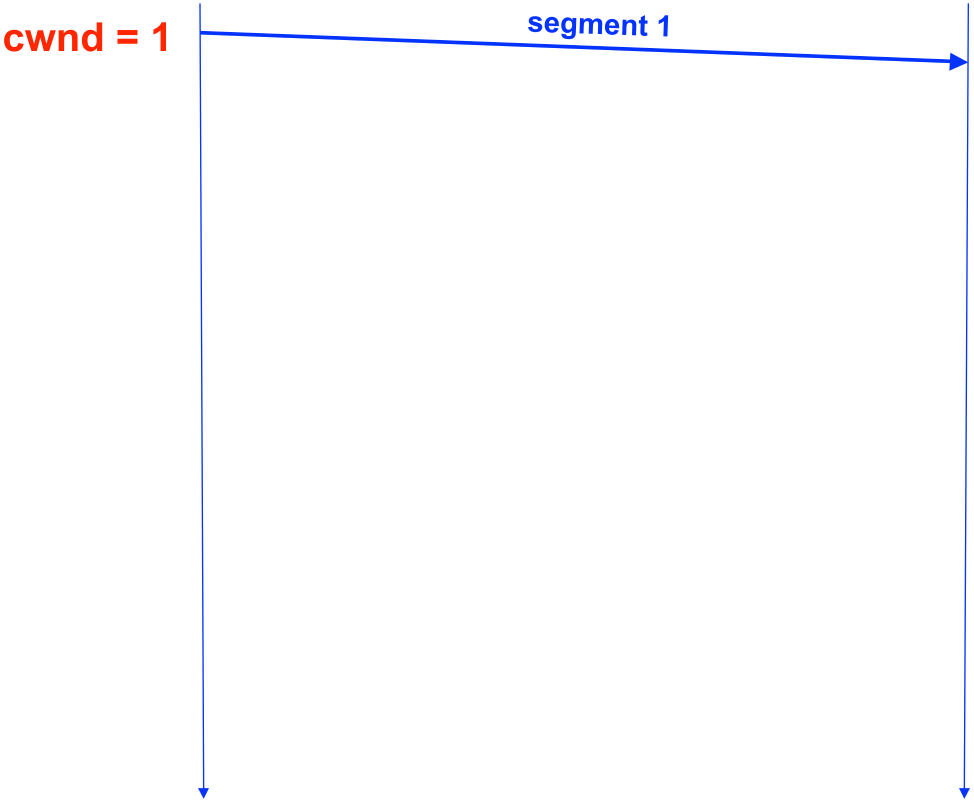

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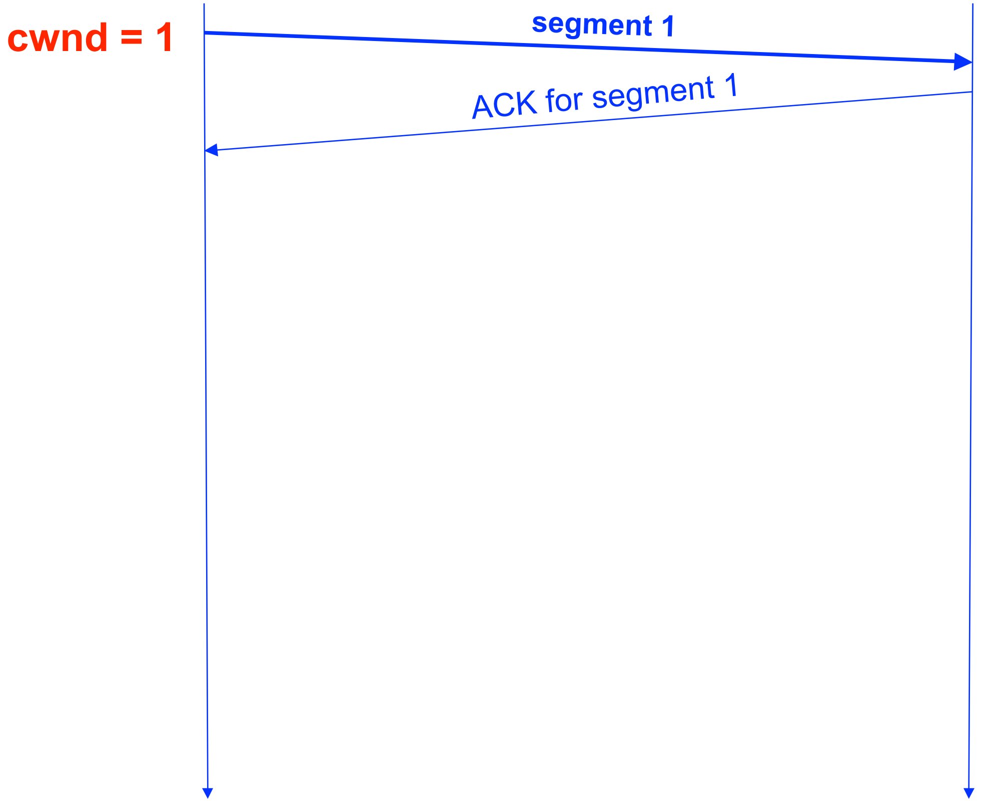

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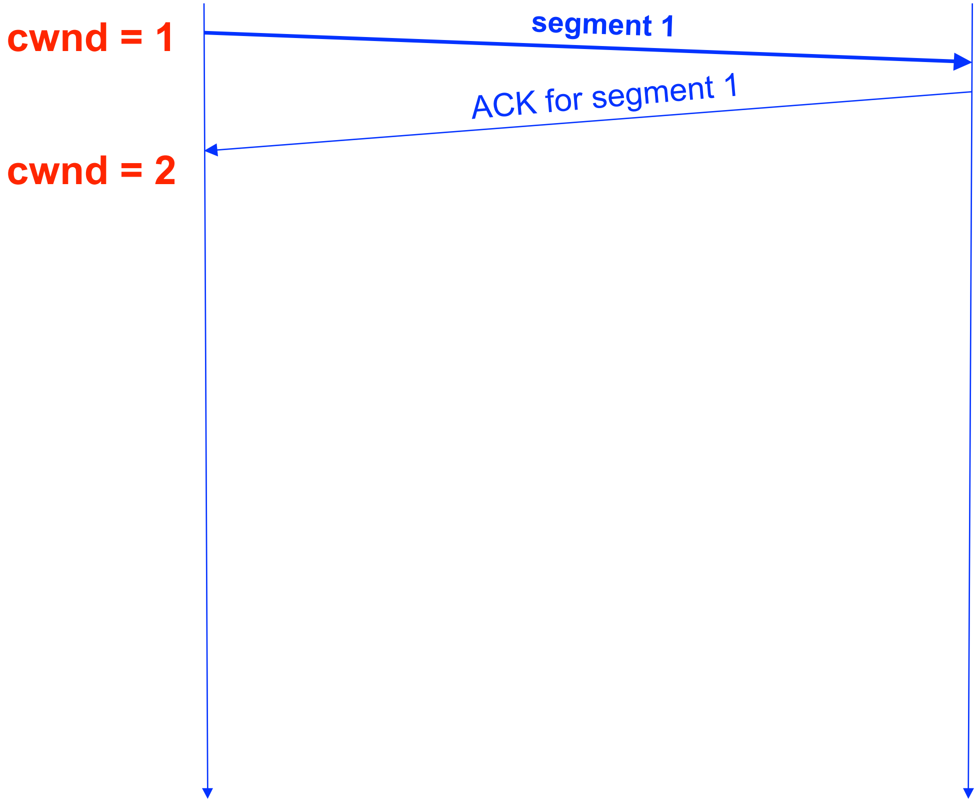

Slow Start Illustration

- The congestion window size grows very rapidly

- TCP slows down the increase of *cwnd* when ***cwnd >= ss_thresh***

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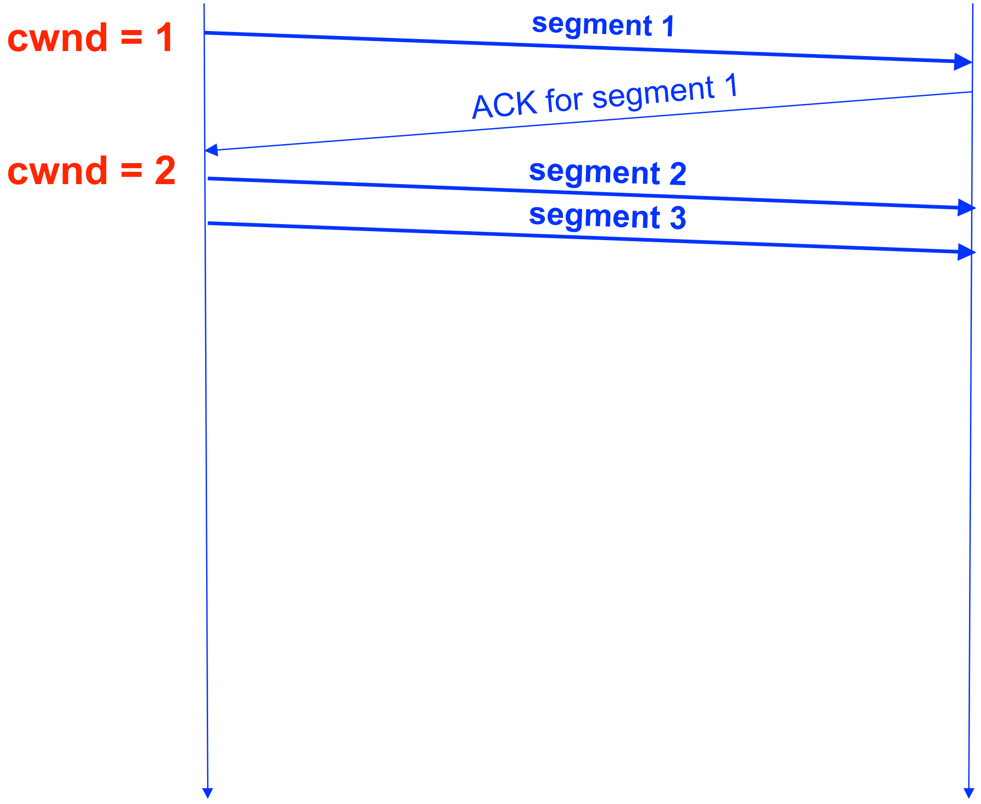

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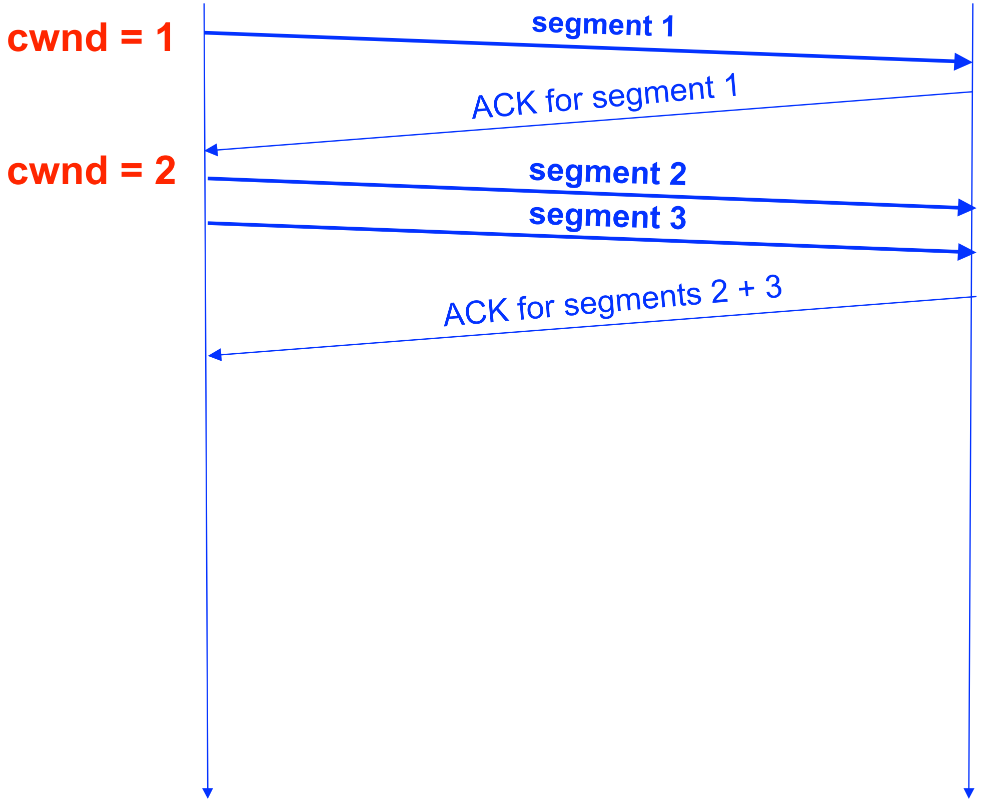

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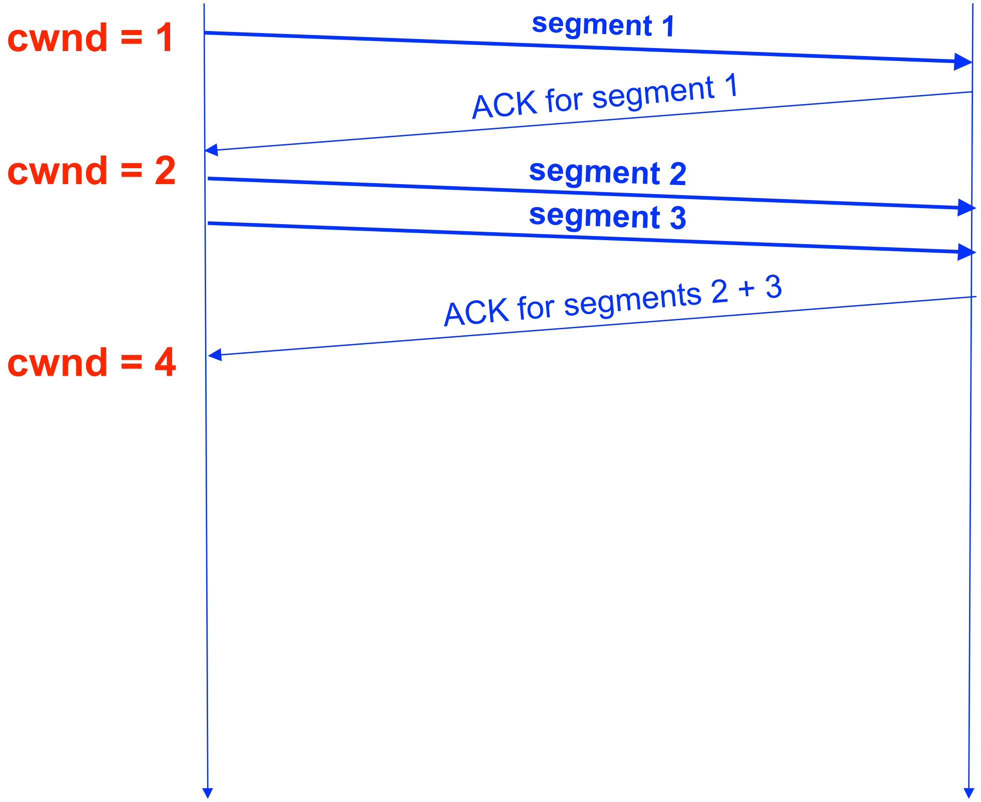

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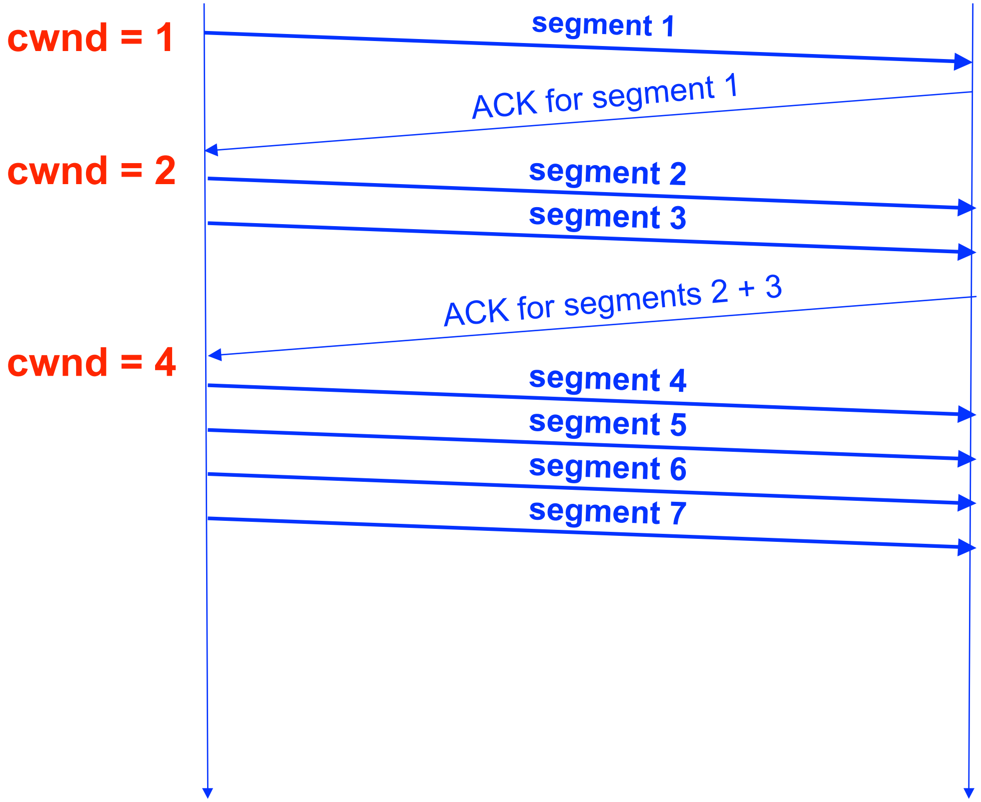

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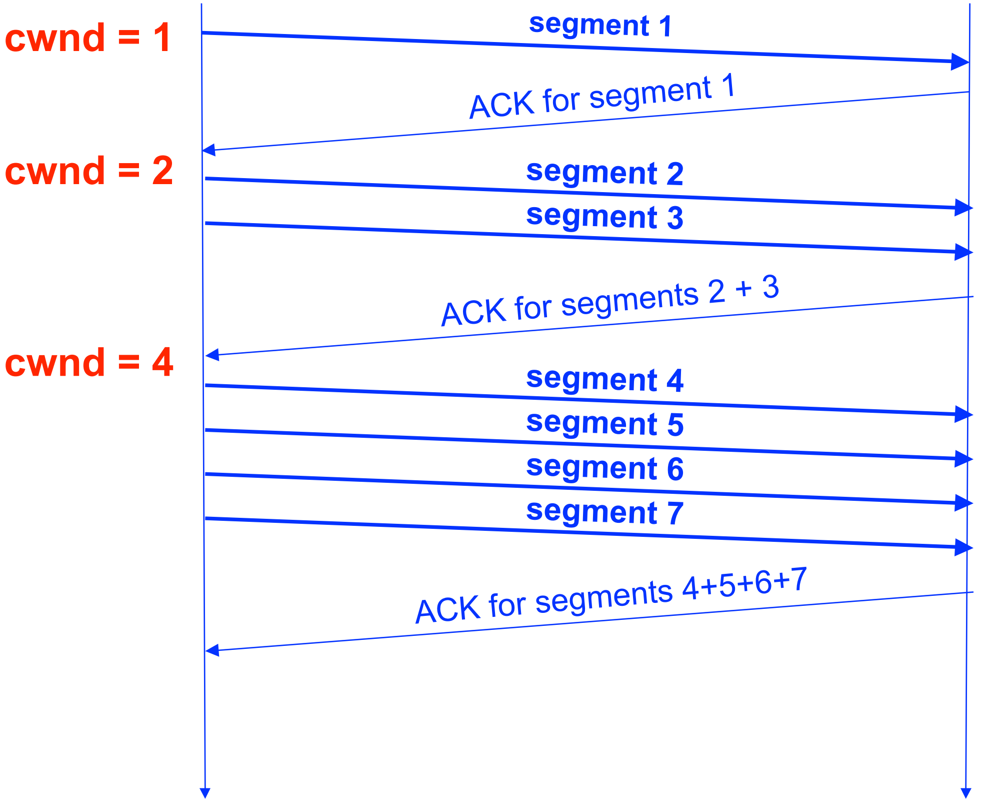

cwnd = 1

segment 1

ACK for segment 1

cwnd = 2

segment 2

segment 3

ACK for segments 2 + 3

cwnd = 4

segment 4

segment 5

segment 6

segment 7

ACK for segments 4+5+6+7

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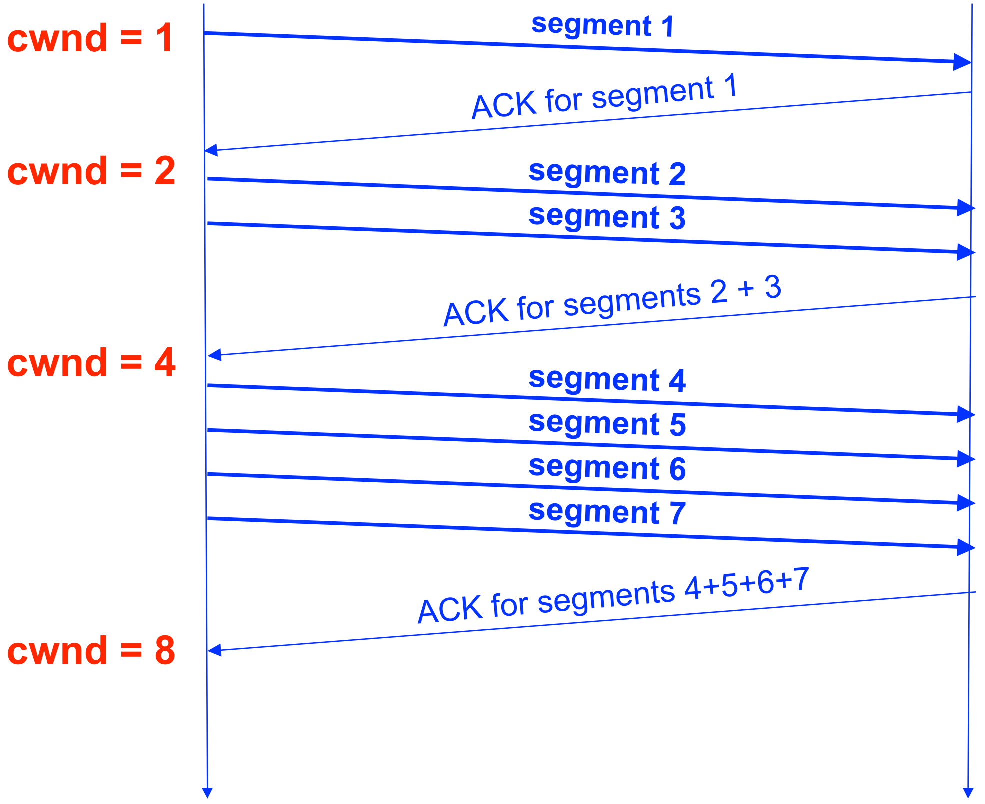


Congestion Avoidance (After Slow Start)

- Slow Start figures out roughly the rate at which the network starts getting congested
- Congestion Avoidance continues to react to network condition
  - Probes for more bandwidth, increase cwnd if more bandwidth available
  - If congestion detected, aggressive cut back cwnd

Congestion Avoidance: Additive Increase

- After exiting slow start, slowly increase cwnd to probe for additional available bandwidth
  - Competing flows may end transmission
  - May have been "unlucky" with an early drop

- **If** *cwnd > ss_thresh* **then**

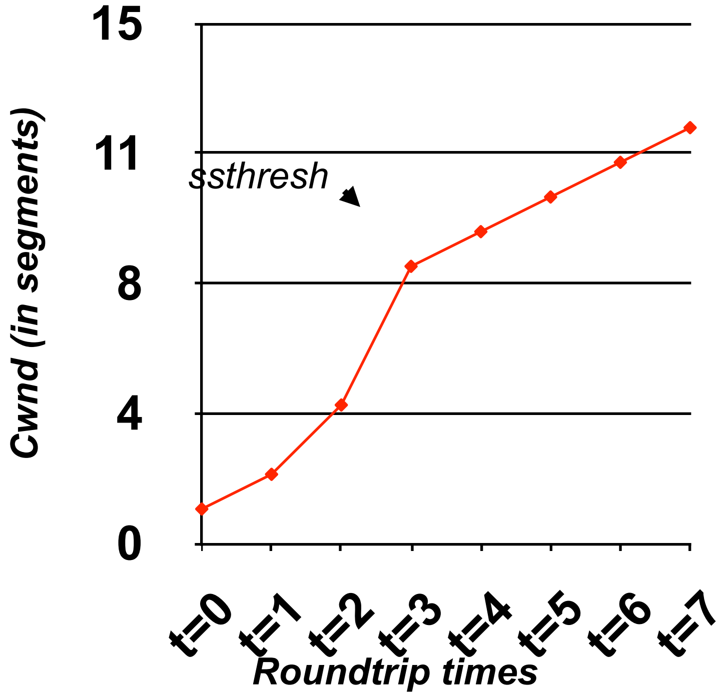
  each time a segment is acknowledged

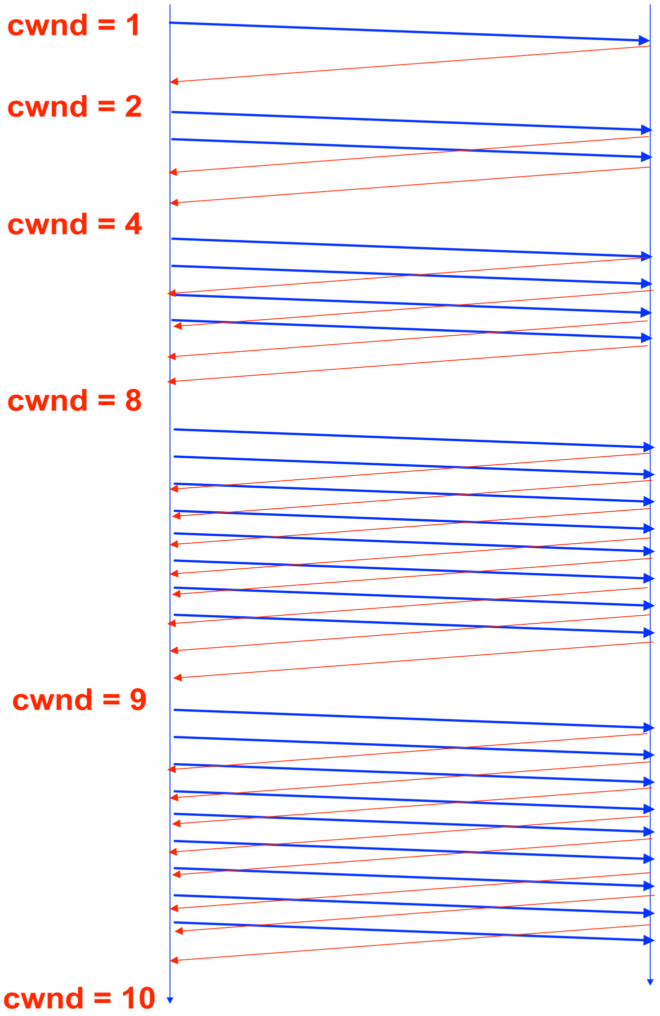
  increment *cwnd* by *1/cwnd* (*cwnd += 1/cwnd*).

- *cwnd* is increased by one only if all segments have been acknowledged
  - Increases by 1 per RTT, vs. doubling per RTT

Example of Slow Start + Congestion Avoidance

Assume that *ss_thresh = 8*





Detecting Congestion via Timeout

- If there is a packet loss, the ACK for that packet will not be received

- The packet will eventually timeout
  - No ack is seen as a sign of congestion

Congestion Avoidance: Multiplicative Decrease

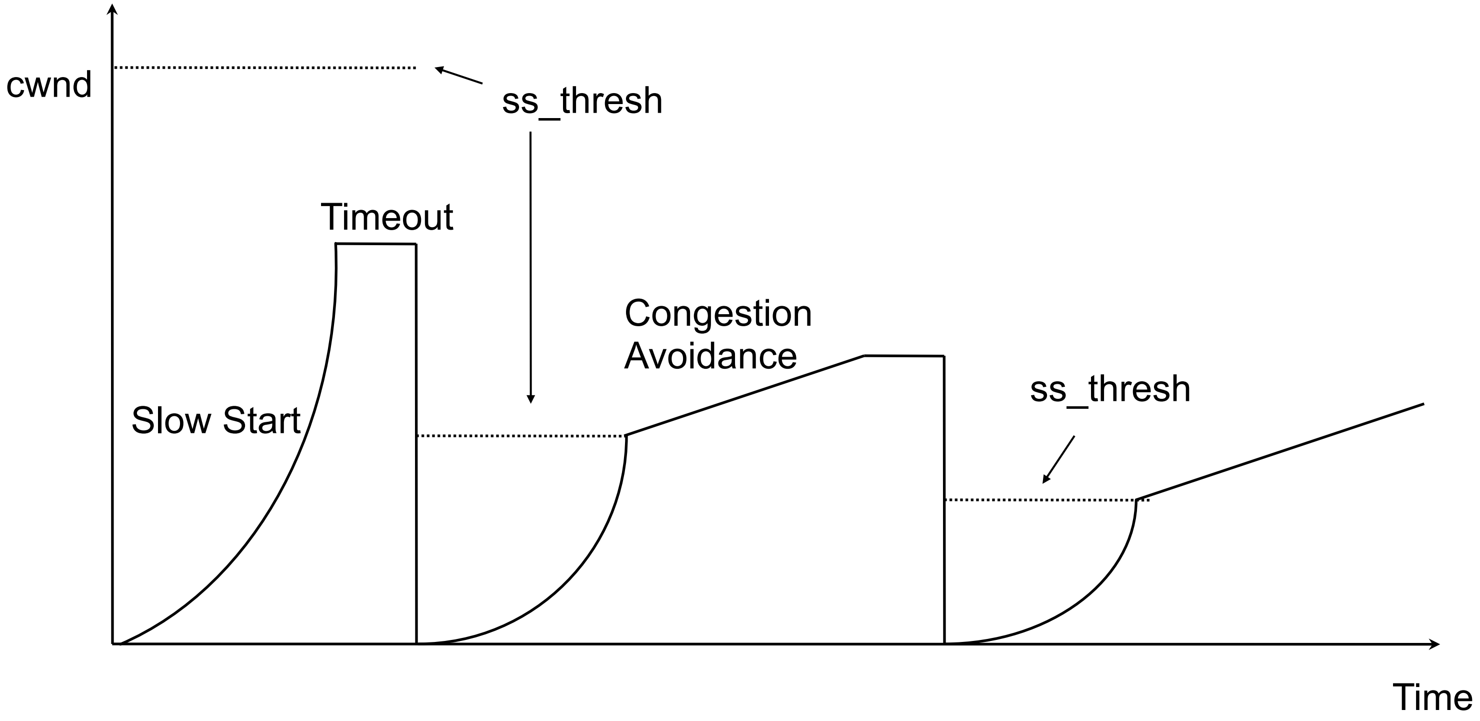
- Timeout = congestion

- Each time when congestion occurs,
  - ss_thresh is set to half the current size of the congestion window:

    ss_thresh = cwnd / 2
  - cwnd is reset to one:

    cwnd = 1
  - and slow-start is entered

TCP illustration



Responses to Congestion (Loss)

- There are algorithms developed for TCP to respond to congestion
  - **TCP Tahoe** - the basic algorithm (discussed previously)
  - **TCP Reno** - Tahoe + fast retransmit & fast recovery
    - Most end hosts today implement TCP Reno
- and many more:
  - TCP Vegas (research: use timing of ACKs to avoid loss)
  - TCP SACK (future deployment: selective ACK)

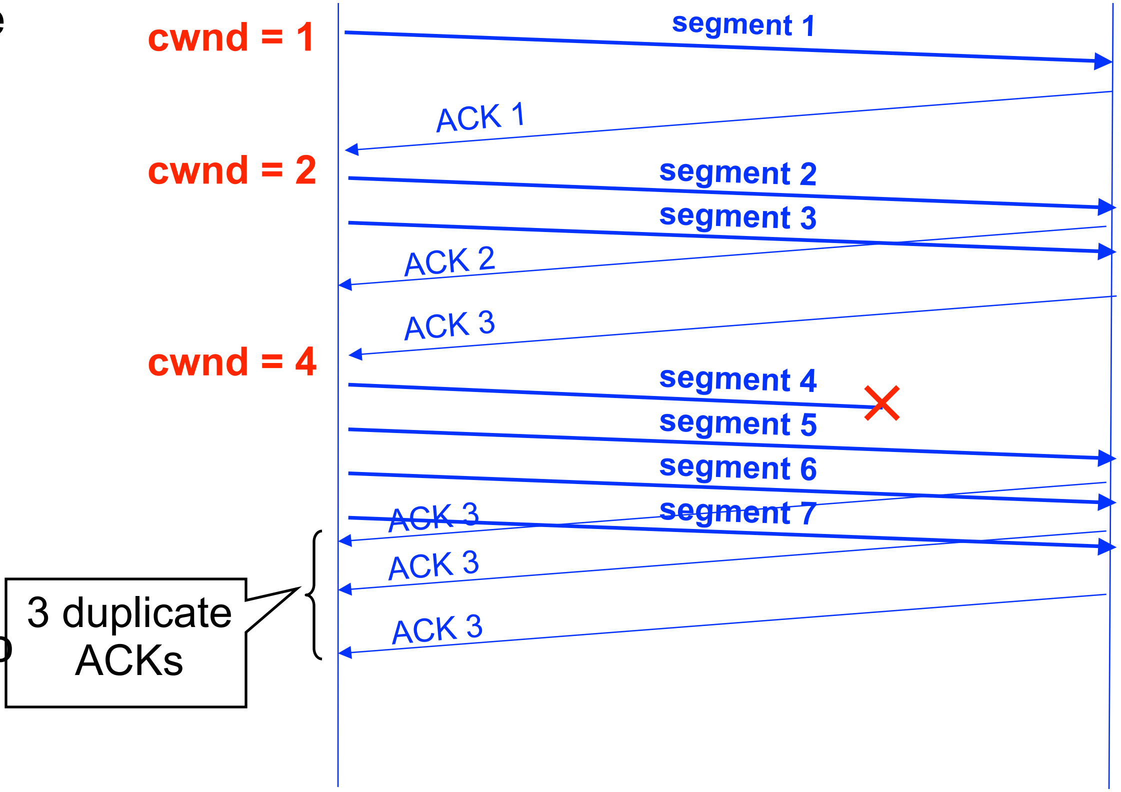
TCP Reno

- Problem with Tahoe: If a segment is lost, there is a long wait until timeout
- Reno adds a **fast retransmit** and **fast recovery mechanism**

- Upon receiving 3 duplicate ACKs, retransmit the presumed lost segment ("fast retransmit")
- But do not enter slow-start. Instead enter congestion avoidance ("fast recovery")

Fast Retransmit

- Resend a segment after 3 duplicate ACKs
  - remember a duplicate ACK means that an out-of sequence segment was received
  - ACK-n means packets 1, …, n all received



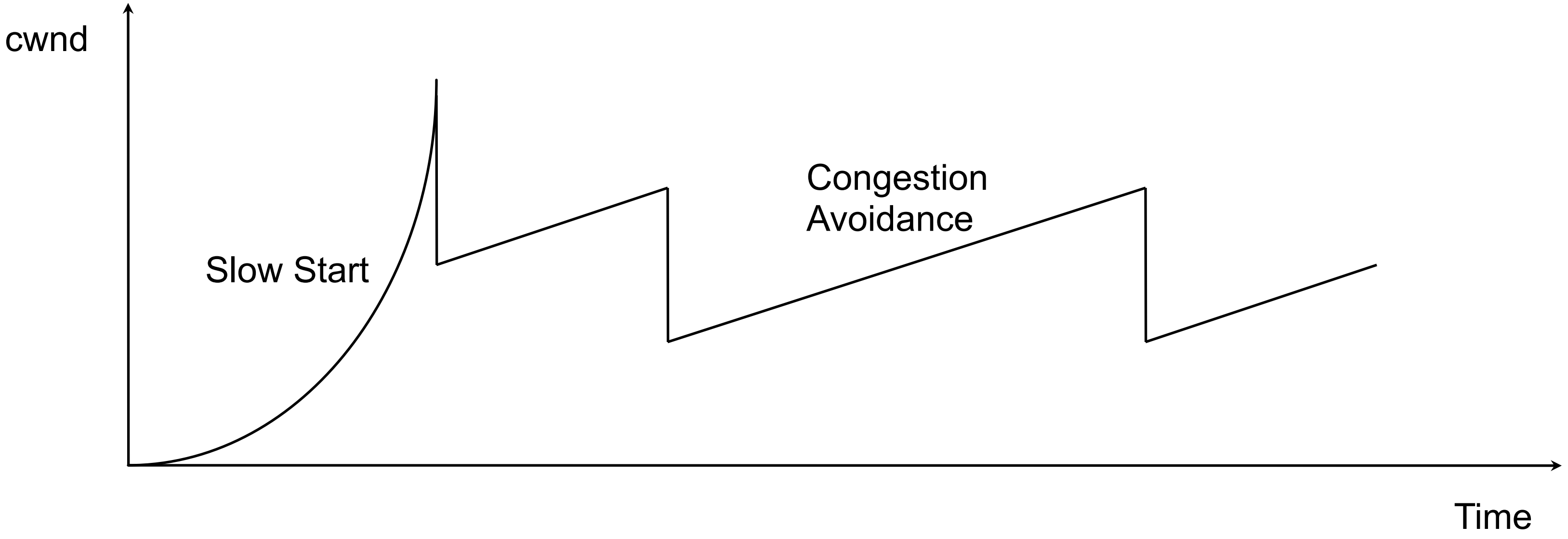
- Notes:
  - duplicate ACKs due to packet reordering!

Fast Recovery

- After a fast-retransmit
  - cwnd = *cwnd/2* (vs. 1 in Tahoe)
  - ss_thresh = cwnd
  - i.e. starts congestion avoidance at new cwnd
    - Not slow start from cwnd = 1

- After a timeout
  - *ss*_thresh = *cwnd/2*
  - cwnd = 1
  - Do slow start
  - Same as Tahoe

Fast Retransmit and Fast Recovery



- Retransmit after 3 duplicate ACKs
  - prevent expensive timeouts
- Slow start only once per session (if no timeouts)
- In steady state, *cwnd* oscillates around the ideal window size.

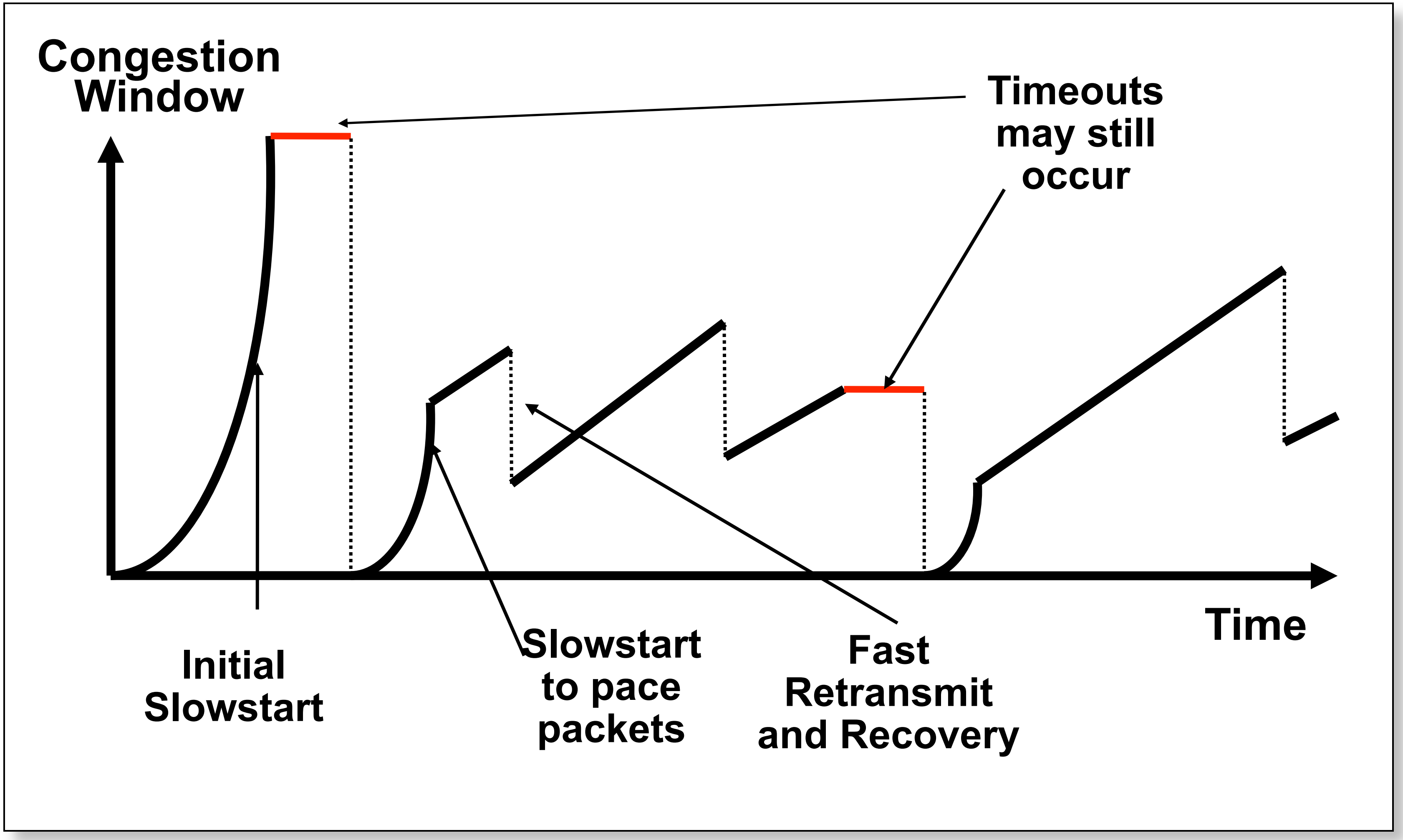
TCP Congestion Control Summary

- Measure available bandwidth
  - slow start: fast, hard on network
  - AIMD: slow, gentle on network
- Detecting congestion
  - timeout based on RTT
    - robust, causes low throughput
  - Fast Retransmit: avoids timeouts when few packets lost
    - can be fooled, maintains high throughput
- Recovering from loss
  - Fast recovery: don’t set cwnd=1 with fast retransmits

TCP Reno Quick Review

- Slow-Start if cwnd < ss_thresh
  - cwnd++ upon every new ACK (exponential growth)
  - Timeout: ss_thresh = cwnd/2 and cwnd = 1
- Congestion avoidance if cwnd >= ss_thresh
  - Additive Increase Multiplicative Decrease (AIMD)
  - ACK: cwnd = cwnd + 1/cwnd
  - Timeout: ss_thresh = cwnd/2 and cwnd = 1
- Fast Retransmit & Recovery
  - 3 duplicate ACKS (interpret as packet loss)
  - Retransmit lost packet
  - cwnd=cwnd/2, ss_thresh = cwnd

TCP Reno Saw Tooth Behavior



Summary

- TCP Reno is the *de facto* standard for congestion control on the Internet

- AIMD or “TCP friendliness” is expected of distributed applications