Congestion Control

CS 168

Spring 2024

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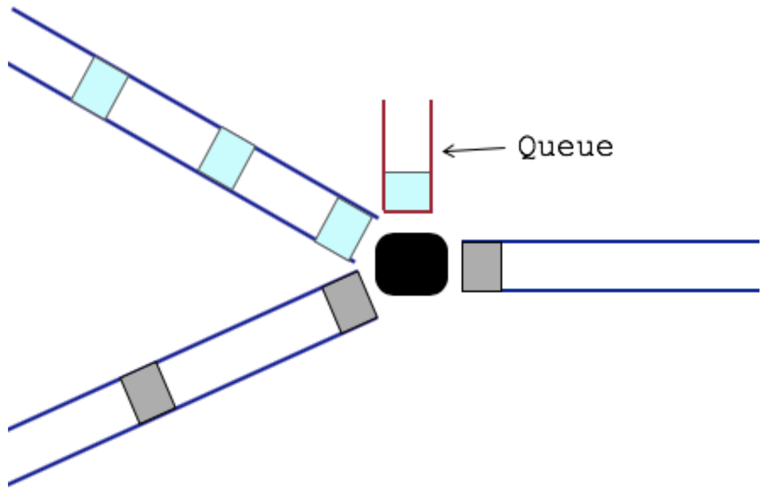
Today: Congestion Control

- One of the "core" topics in networking
- Today: concepts, design space, TCP’s approach
- Next lecture: implementation details and advanced topics

Recall: Lecture 3



- If two packets arrive at a router at the same time, the router will transmit one and buffer the other
- If many packets arrive close in time
  - the router cannot keep up → gets congested
  - causes packet delays and drops

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> In October of '86, the Internet had the first of what became a series of 'congestion collapses'. During this period, the data throughput from LBL to UC Berkeley (sites separated by 400 yards and two IMP hops) dropped from 32 Kbps to 40 bps. We were fascinated by this sudden factor-of-thousand drop in bandwidth and embarked on an investigation of why things had gotten so bad. In particular, we wondered if the 4.3BSD (Berkeley UNIX) TCP was mis-behaving or if it could be tuned to work better under abysmal network conditions. The answer to both of these questions was "yes".

-- Karels (UCB) and Jacobson (LBL)

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- Fixed by Karels and Jacobson's development of TCP's congestion control (CC) algorithms

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- Extensively researched and improved upon

Topics for today

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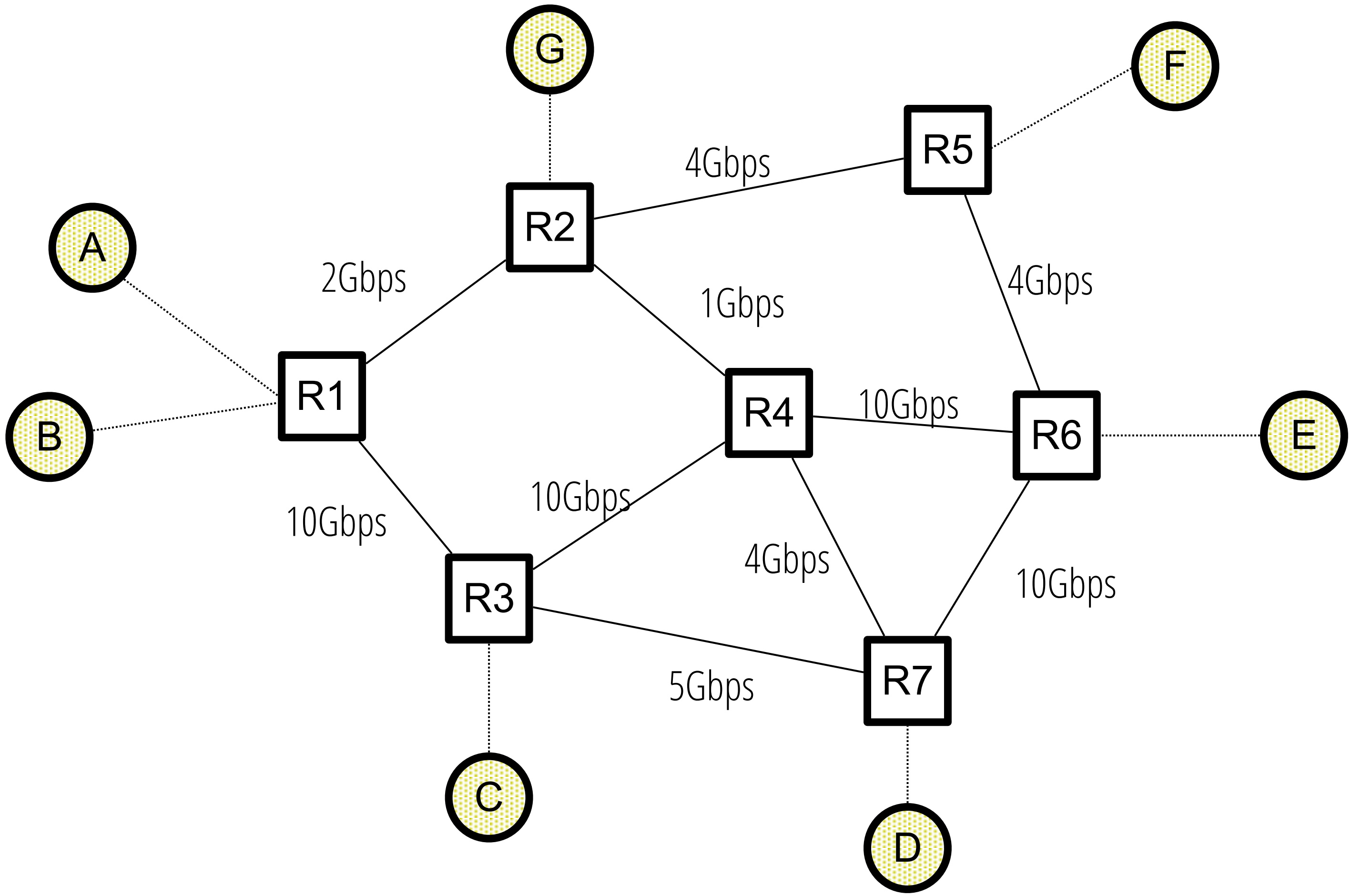
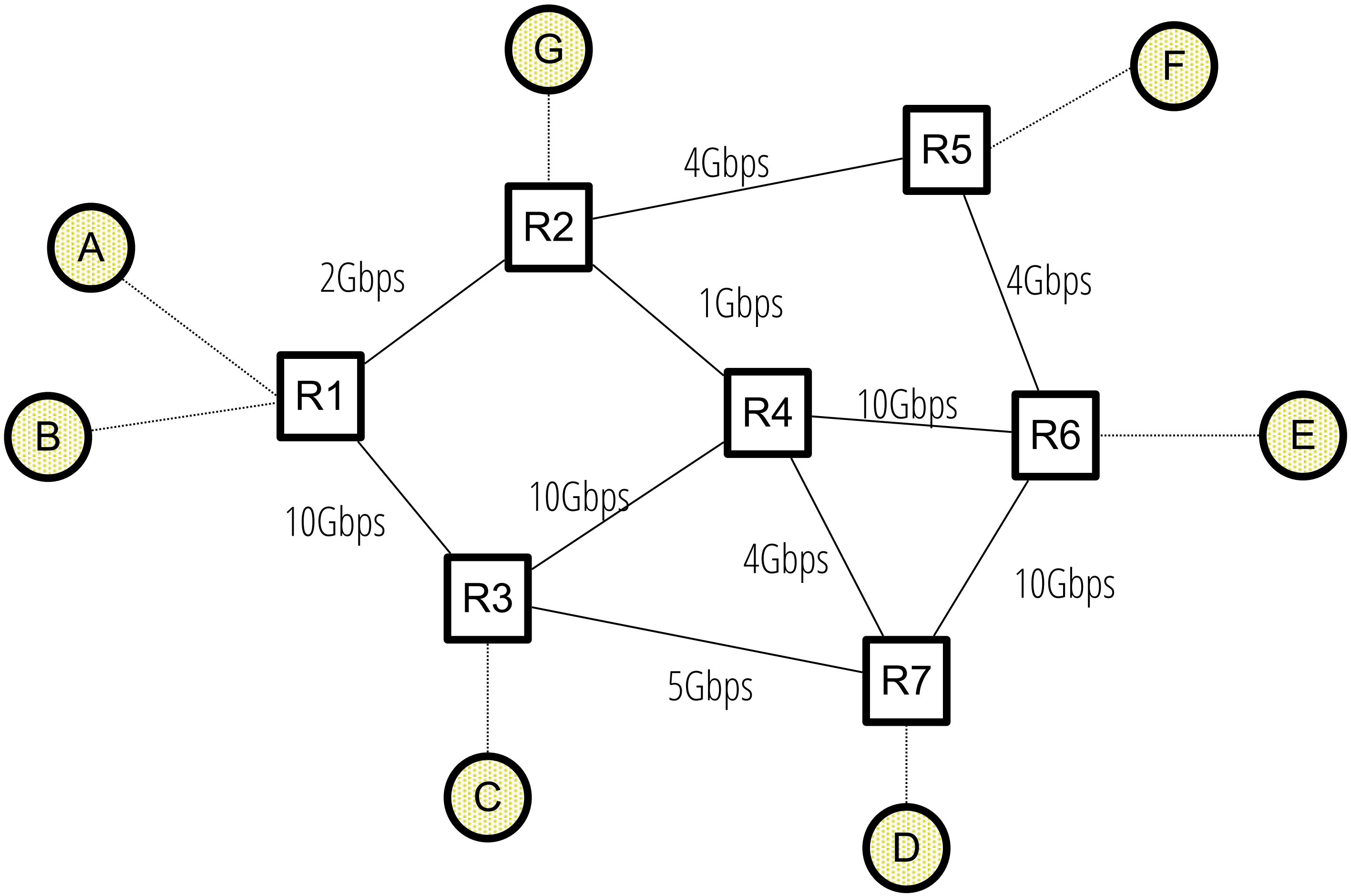
- Next lecture:
  - TCP CC in detail
  - Advanced topics in CC

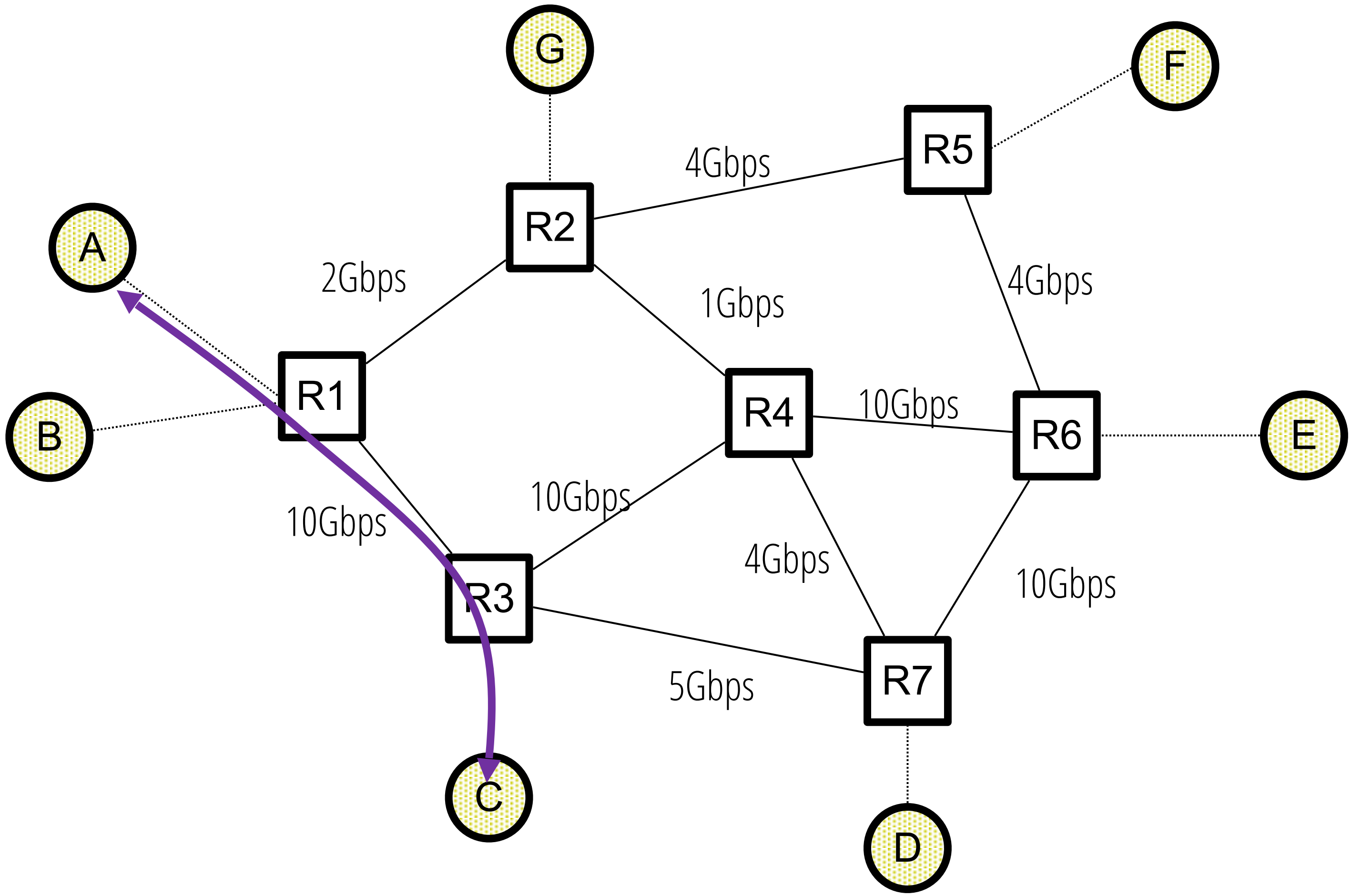


At what rate should Host A send traffic?

*For this example, we'll ignore the BW of links attaching hosts to routers



Depends on the destination



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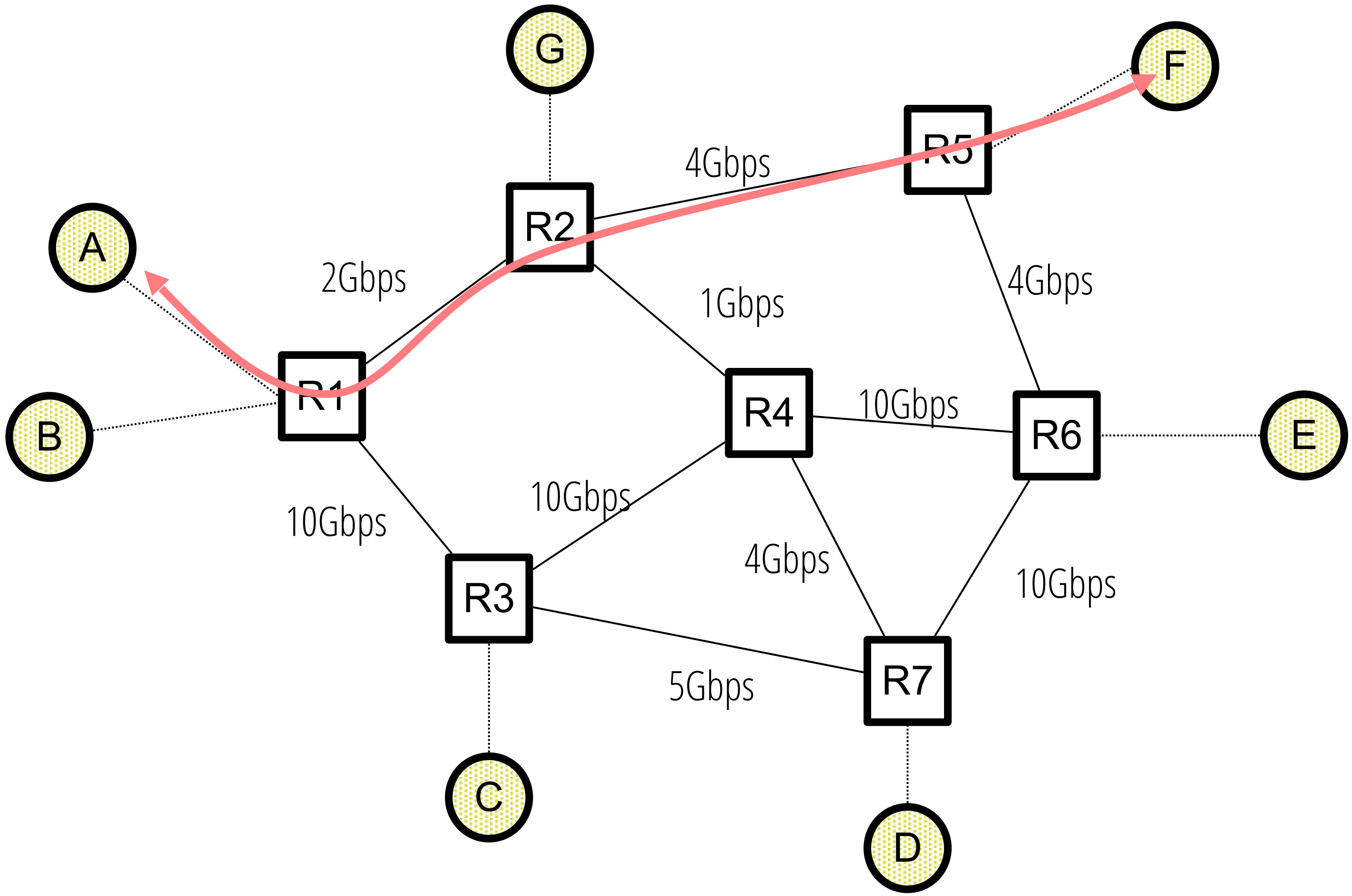

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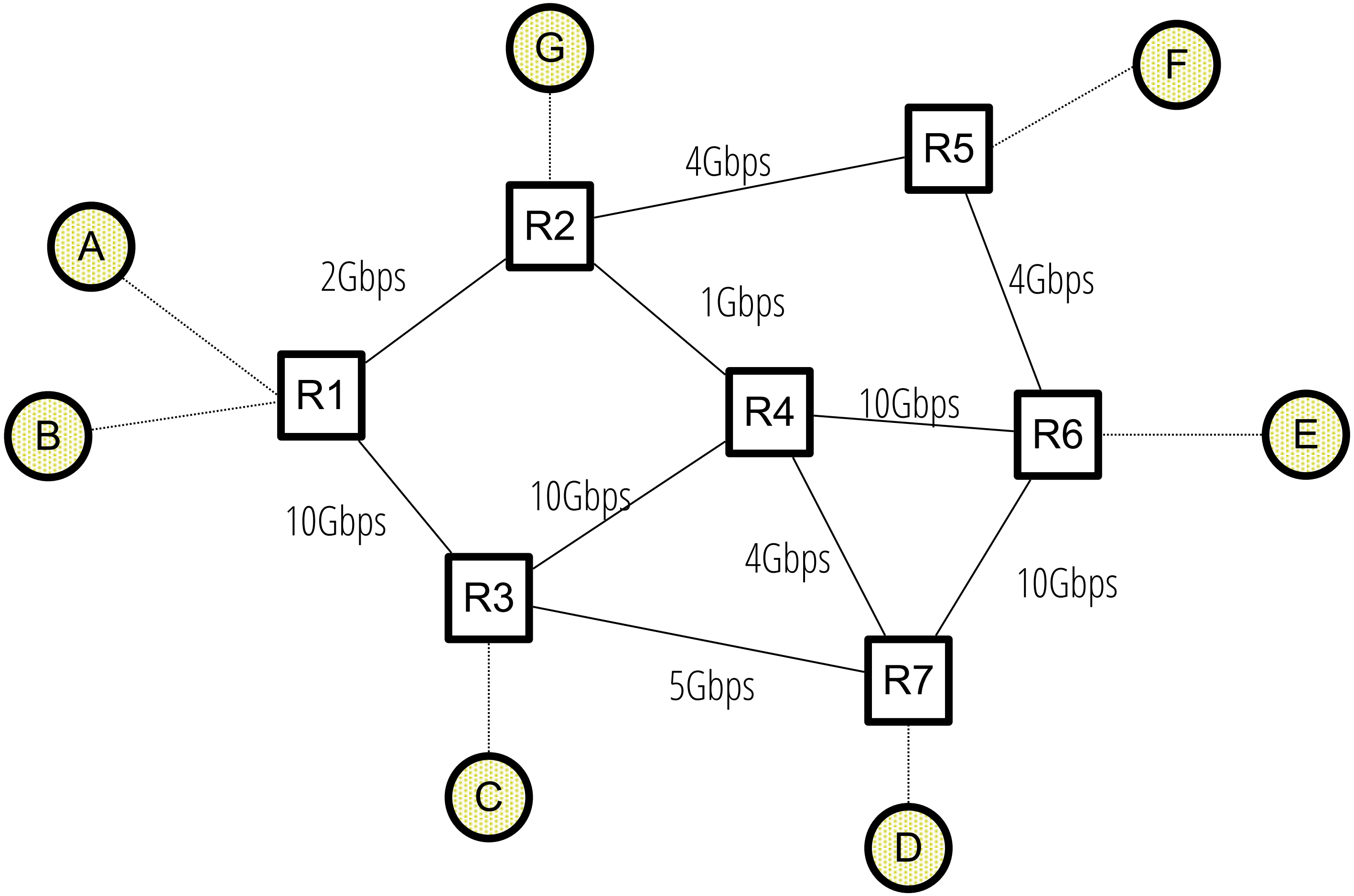
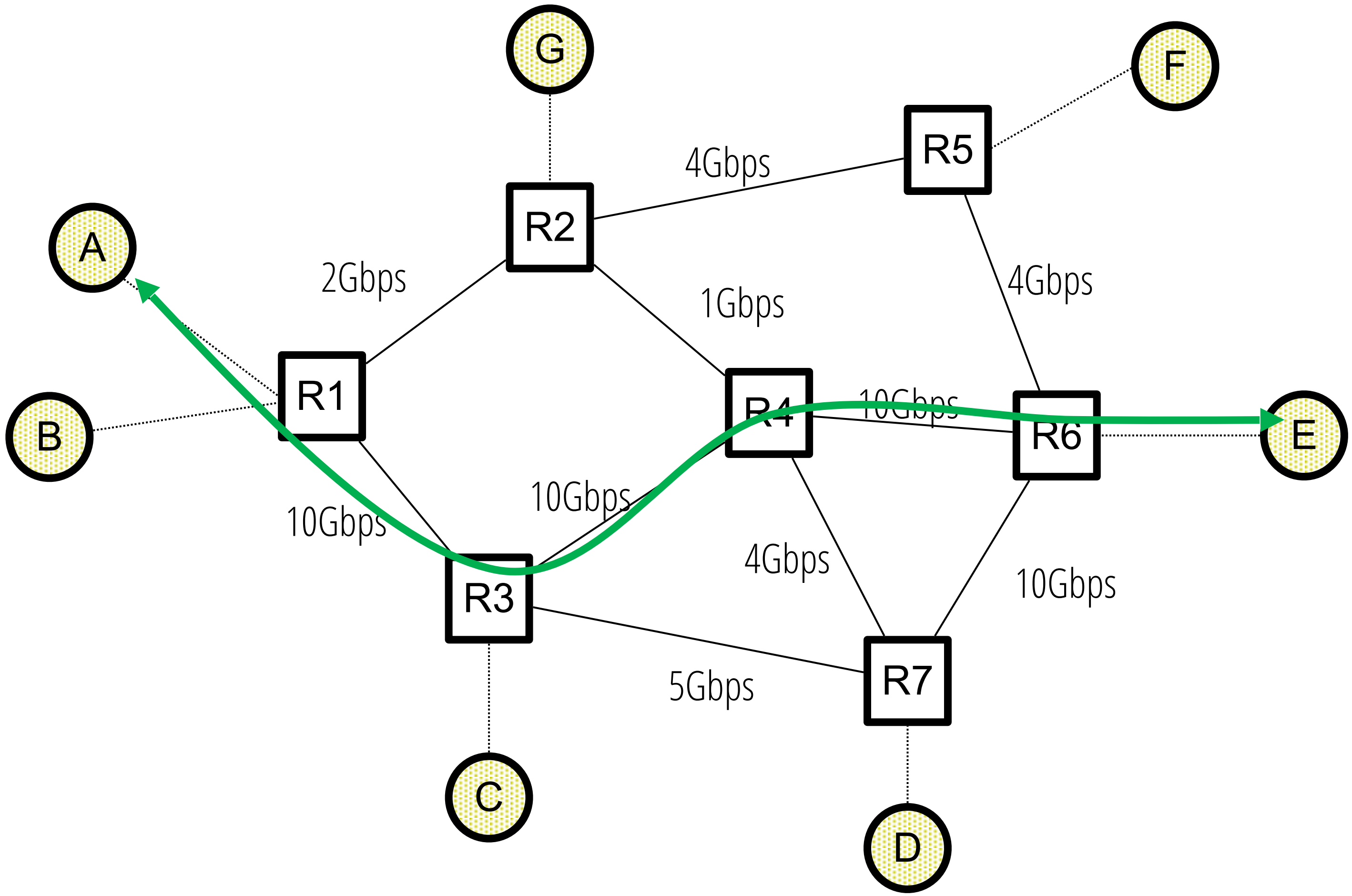


Changes with routing dynamics



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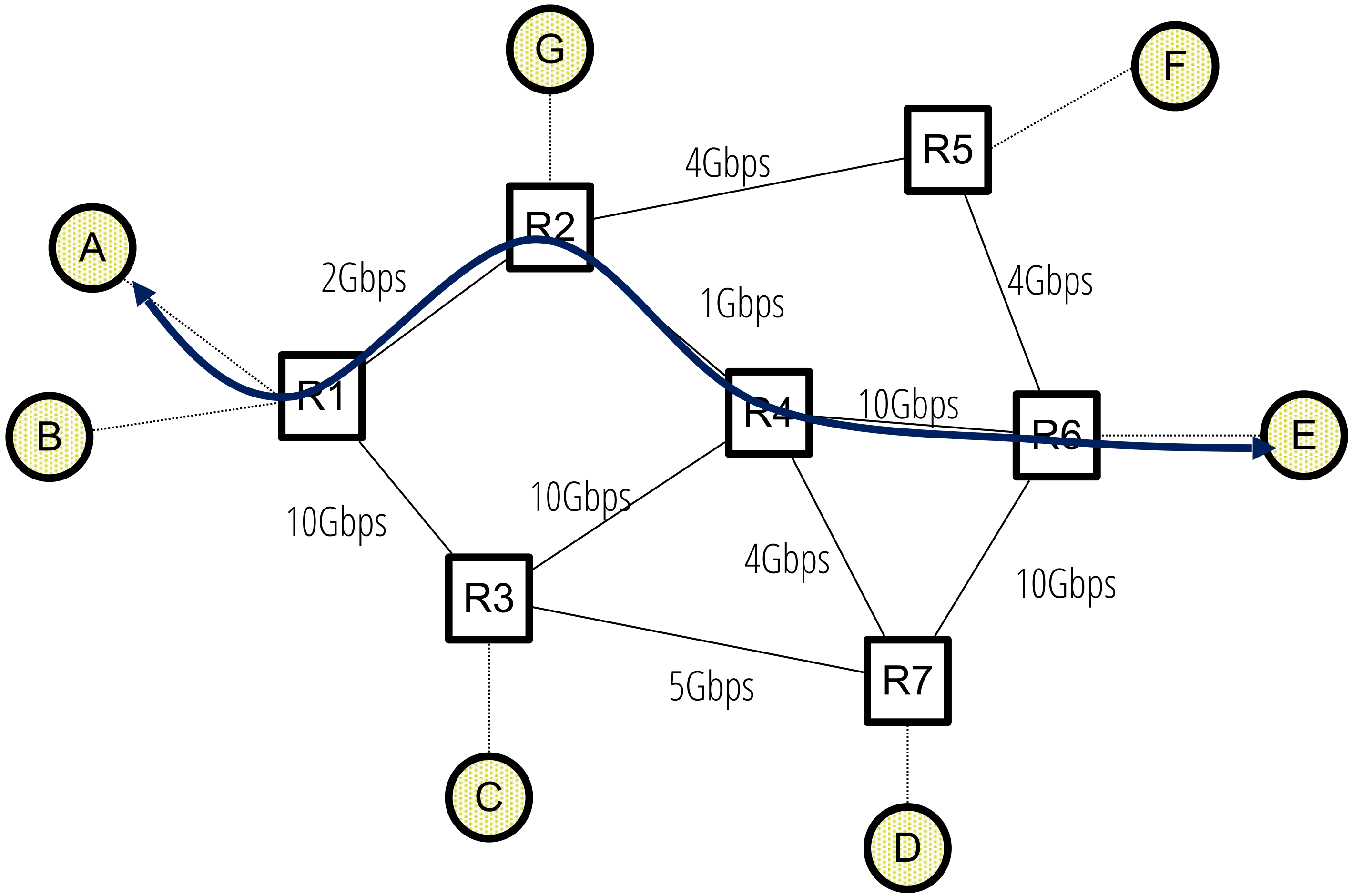

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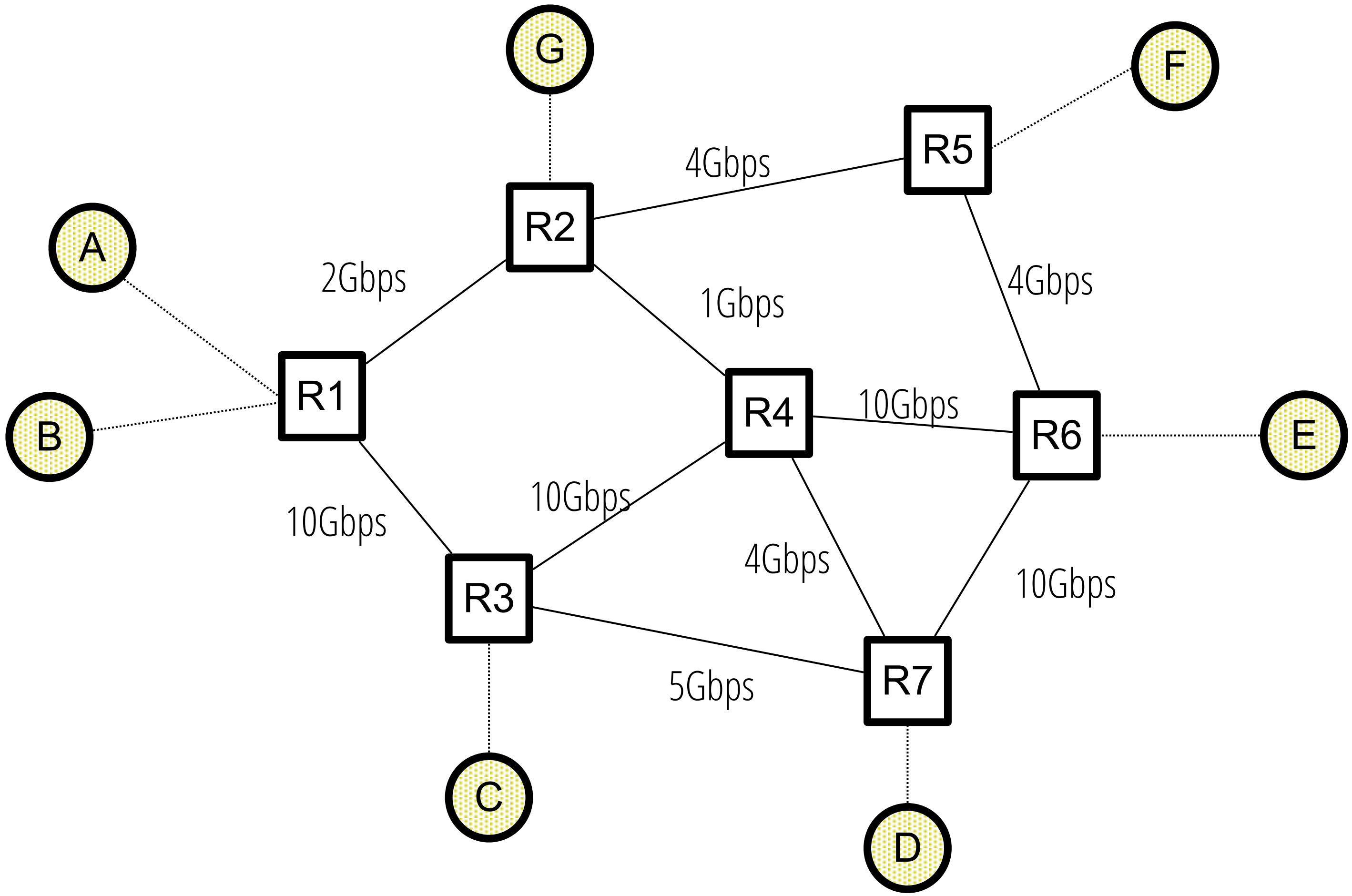
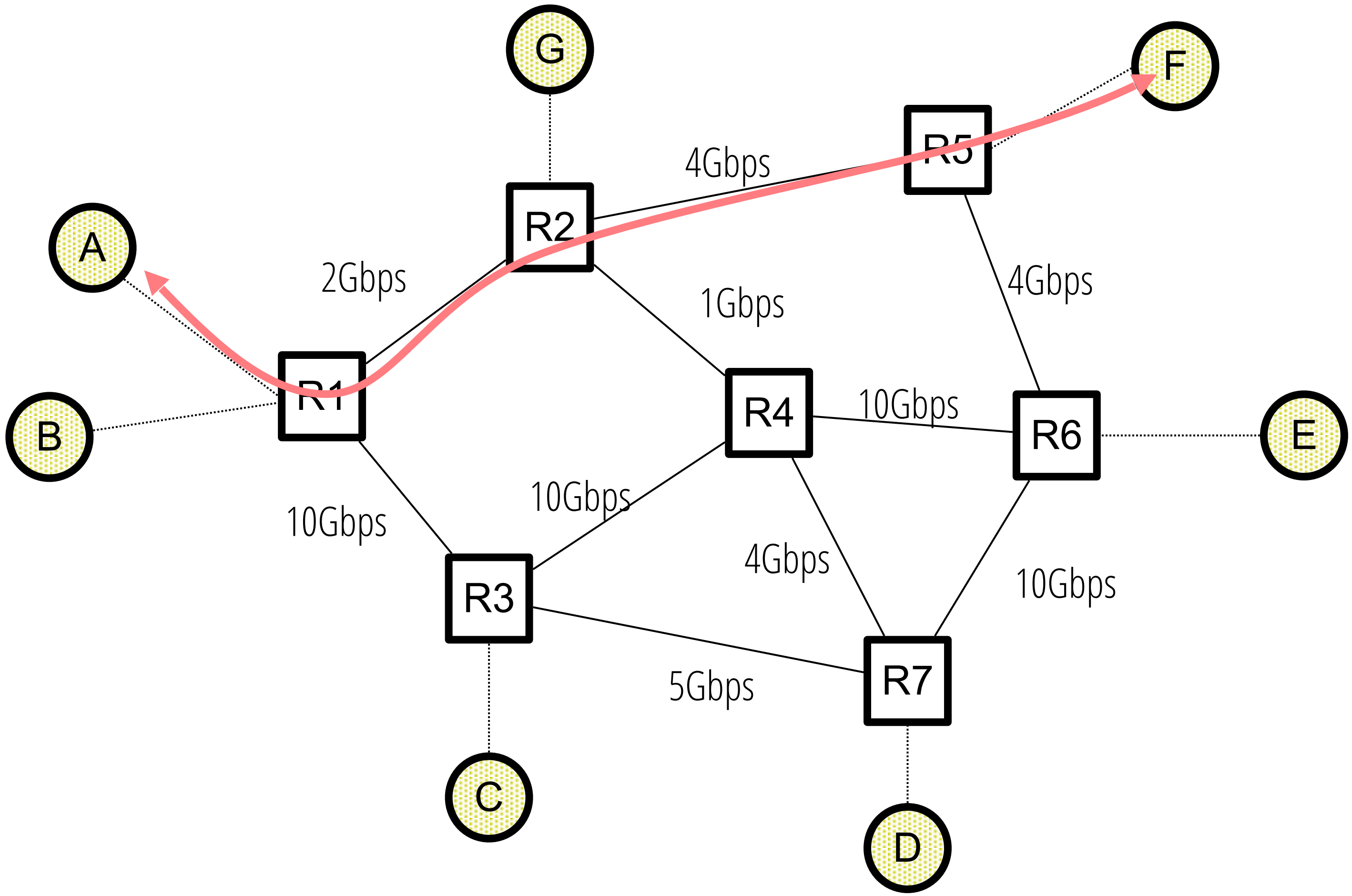


Depends on “competing” flows



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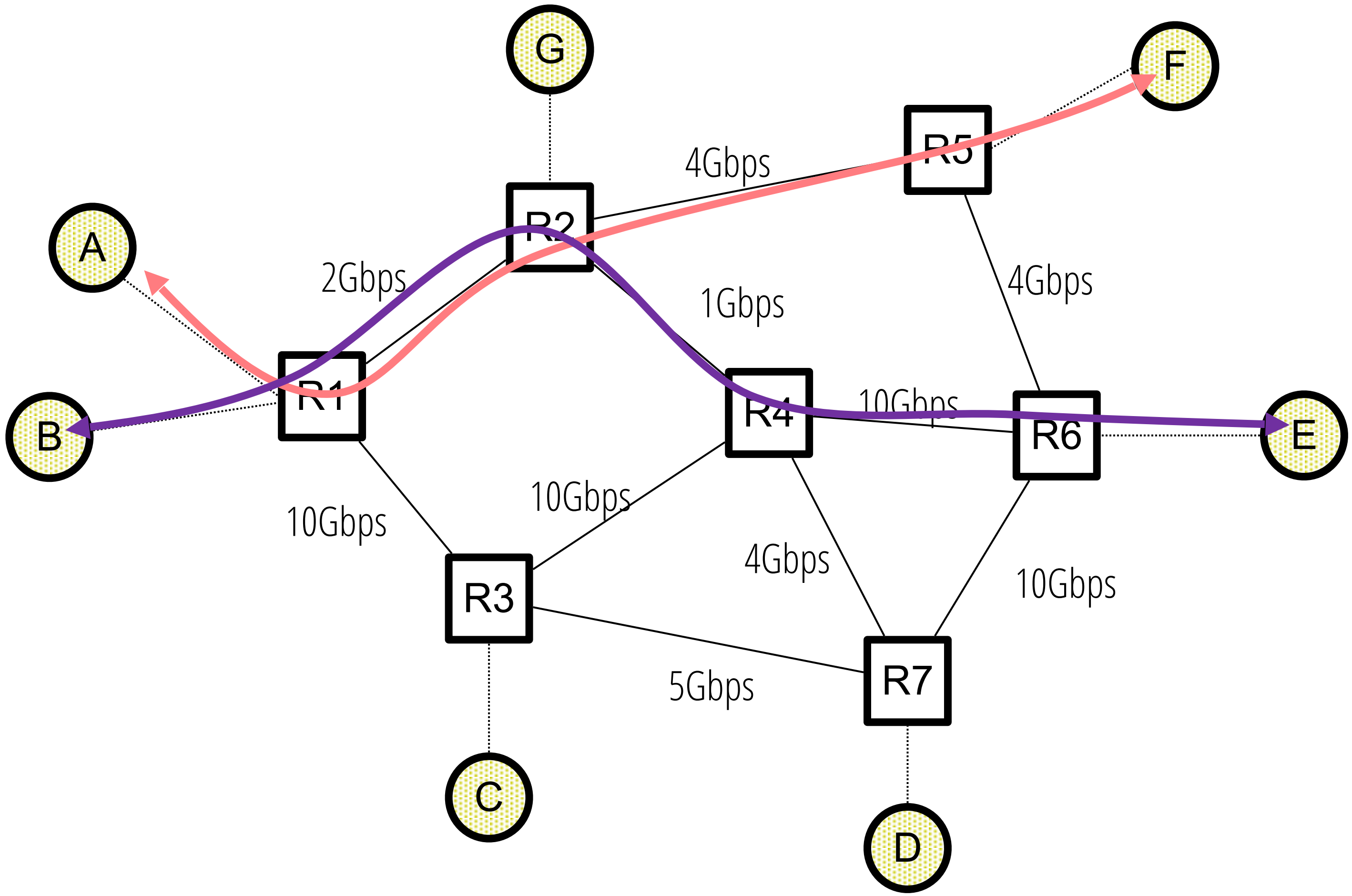

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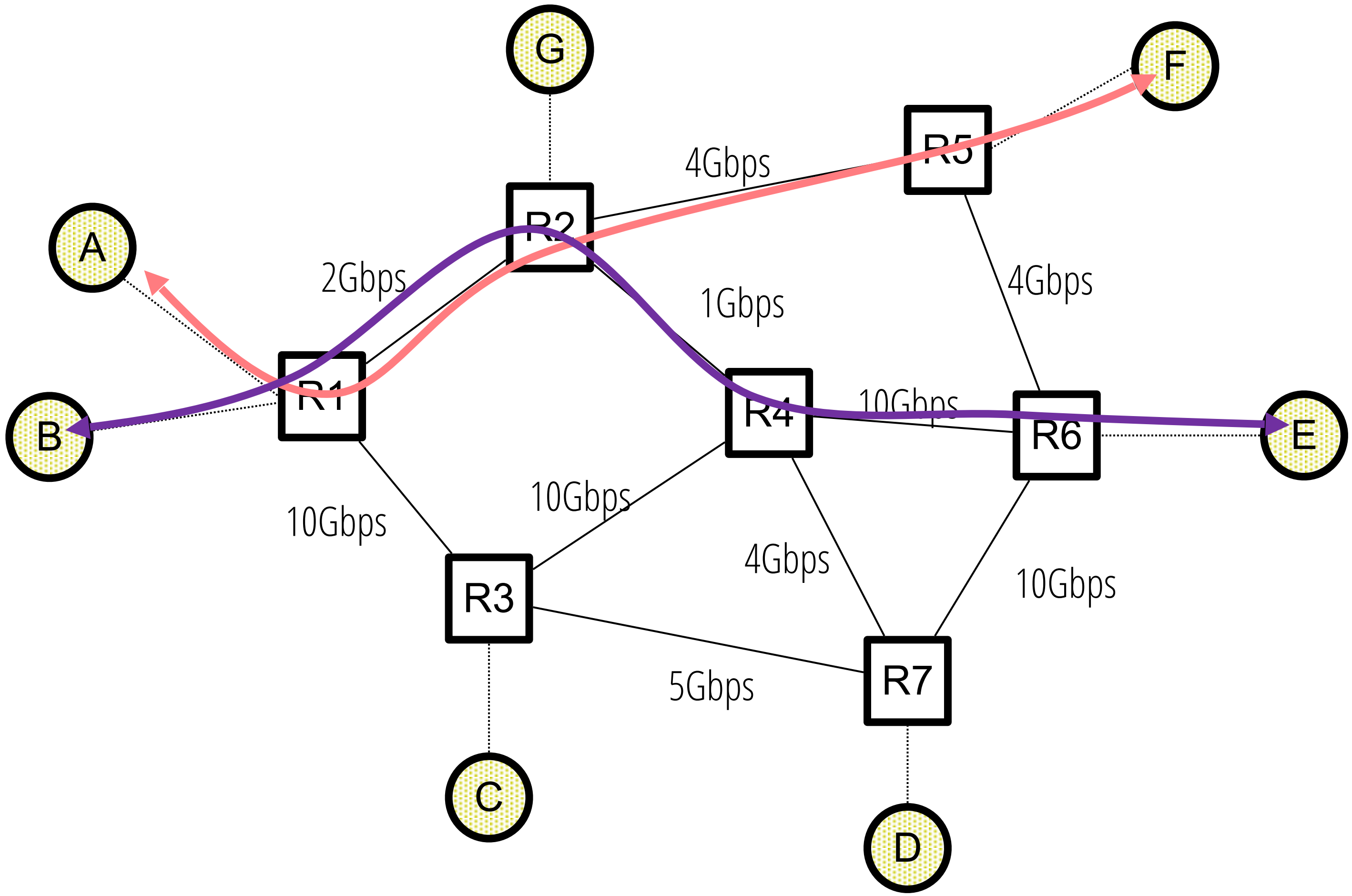

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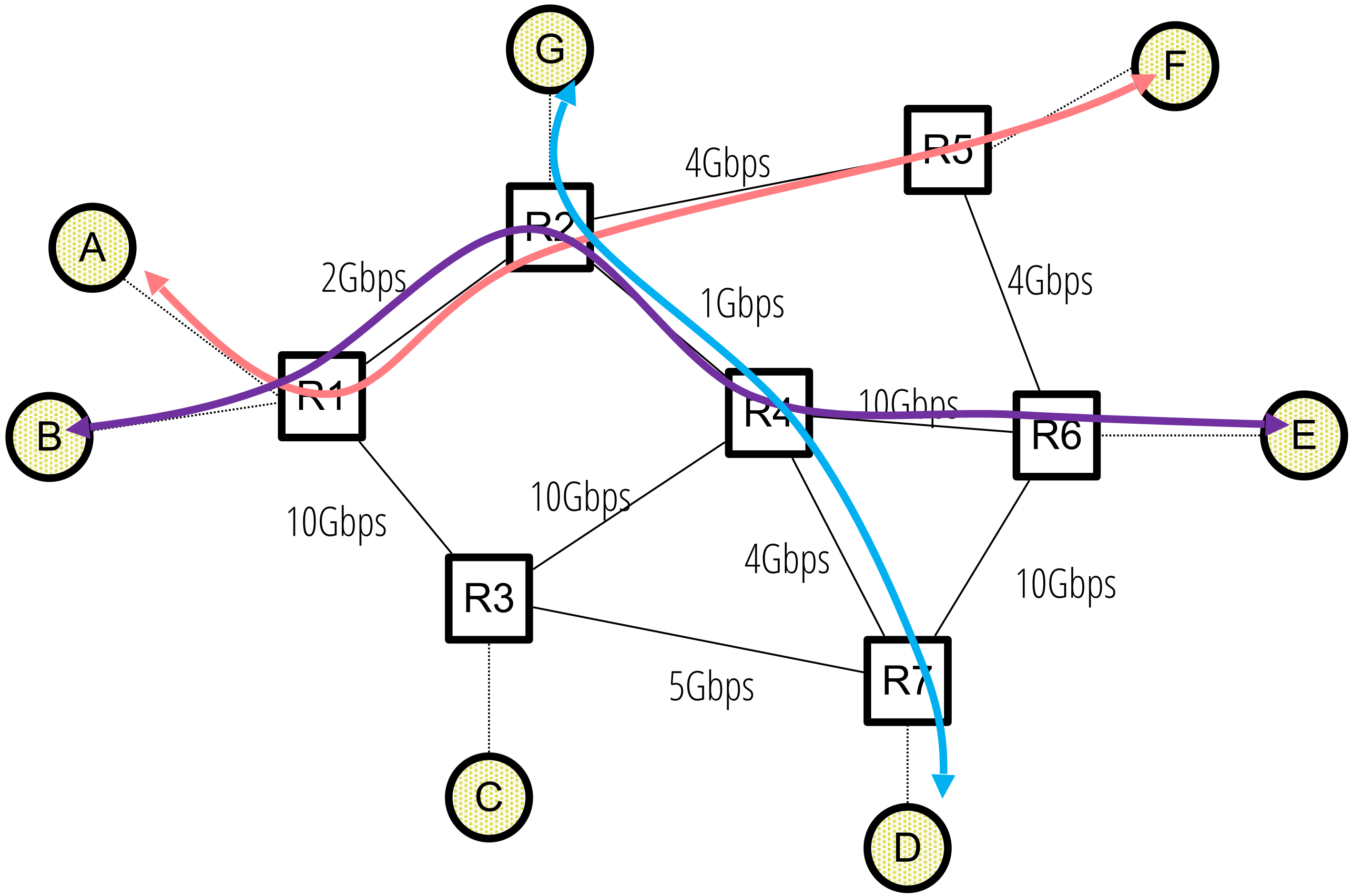
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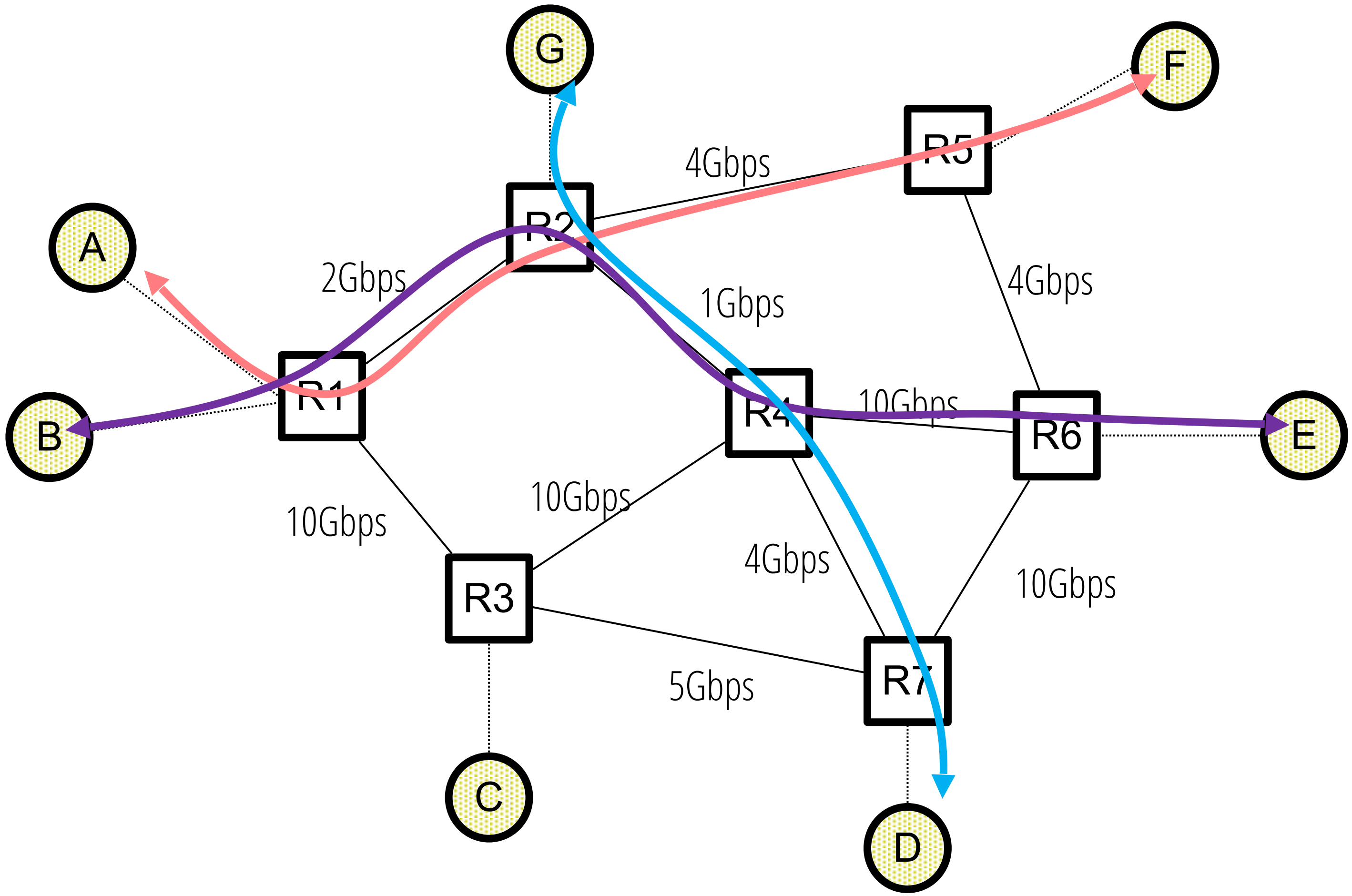

Including “indirect” competition!

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  - Changing one link's allocation can have <u>global</u> impact
  - And we're changing allocations on <u>every flow arrival/exit</u>
  - No single entity has a complete view or complete control!
- Allocations in our context are highly **interdependent**

Outline for today

- What makes CC a hard problem?
- Goals for a good solution
- Design space
- TCP’s approach (high level)
- Components of a solution

Goals

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- From a resource allocation perspective
  - Low packet delay and loss
  - High link utilization
  - “Fair” sharing across flows

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Aim: a good <u>tradeoff</u> between the above goals

Goals

- From a resource allocation perspective
  - Low packet delay and loss
  - High link utilization
  - “Fair” sharing across flows
- From a systems perspective
  - **Practical:** scalable, decentralized, adaptive, *etc.*

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Possible Approaches

(1) Reservations

- Pre-arrange bandwidth allocations
- Comes with all the problems we've discussed

Possible Approaches

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(2) Pricing / priorities

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- Charge users based on current congestion levels
- Requires payment model

Possible Approaches

(1) Reservations

(2) Pricing / priorities

(3) Dynamic Adjustment

- Hosts dynamically learn current level of congestion
- Adjust their sending rate accordingly

Possible Approaches

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In practice, the **generality** of dynamic adjustment has proven powerful

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Possible Approaches

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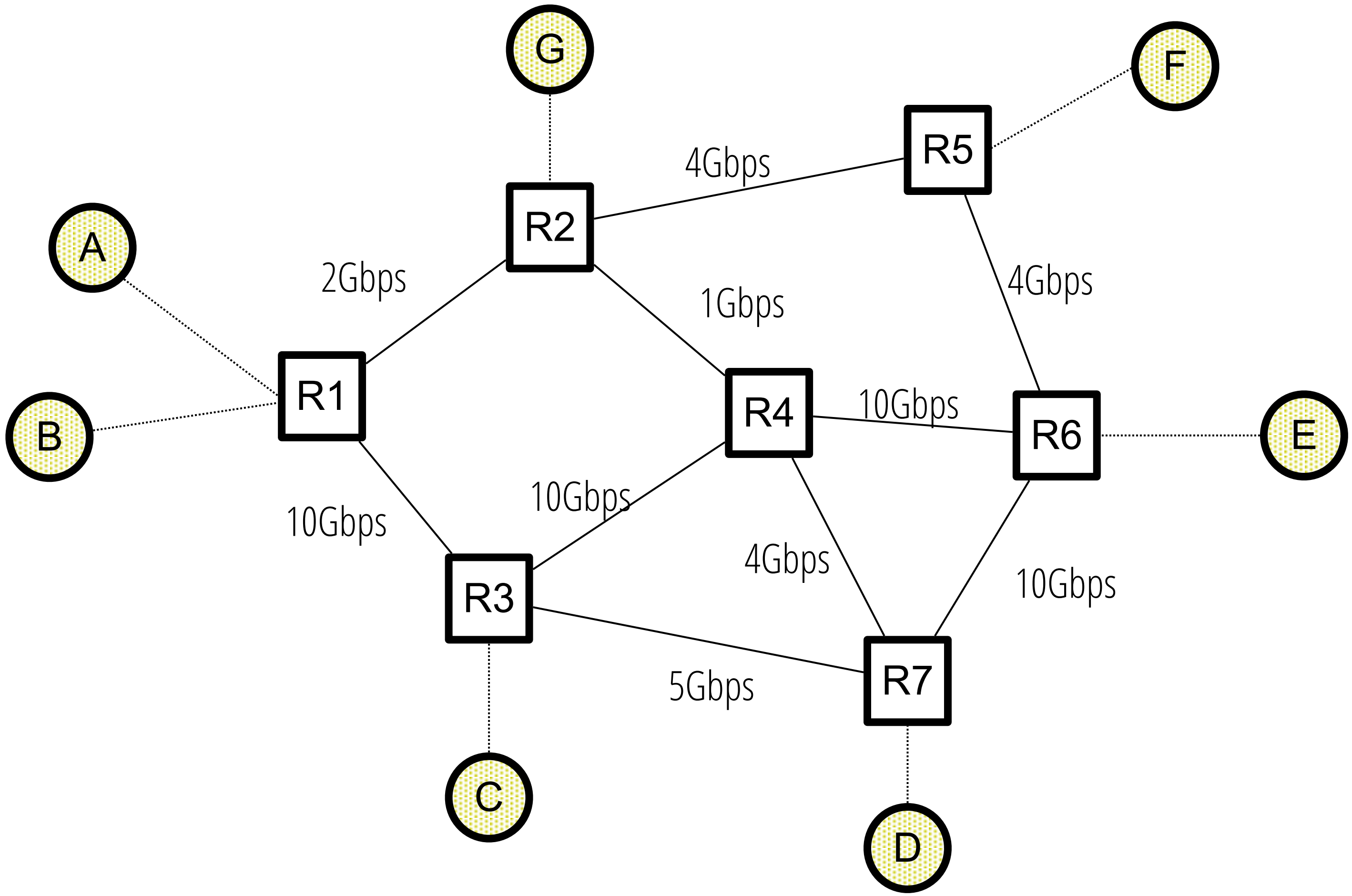
In practice, the **generality** of dynamic adjustment has proven powerful

- Doesn’t presume business model
- Doesn’t assume we know app/user requirements
- But does assume good citizenship!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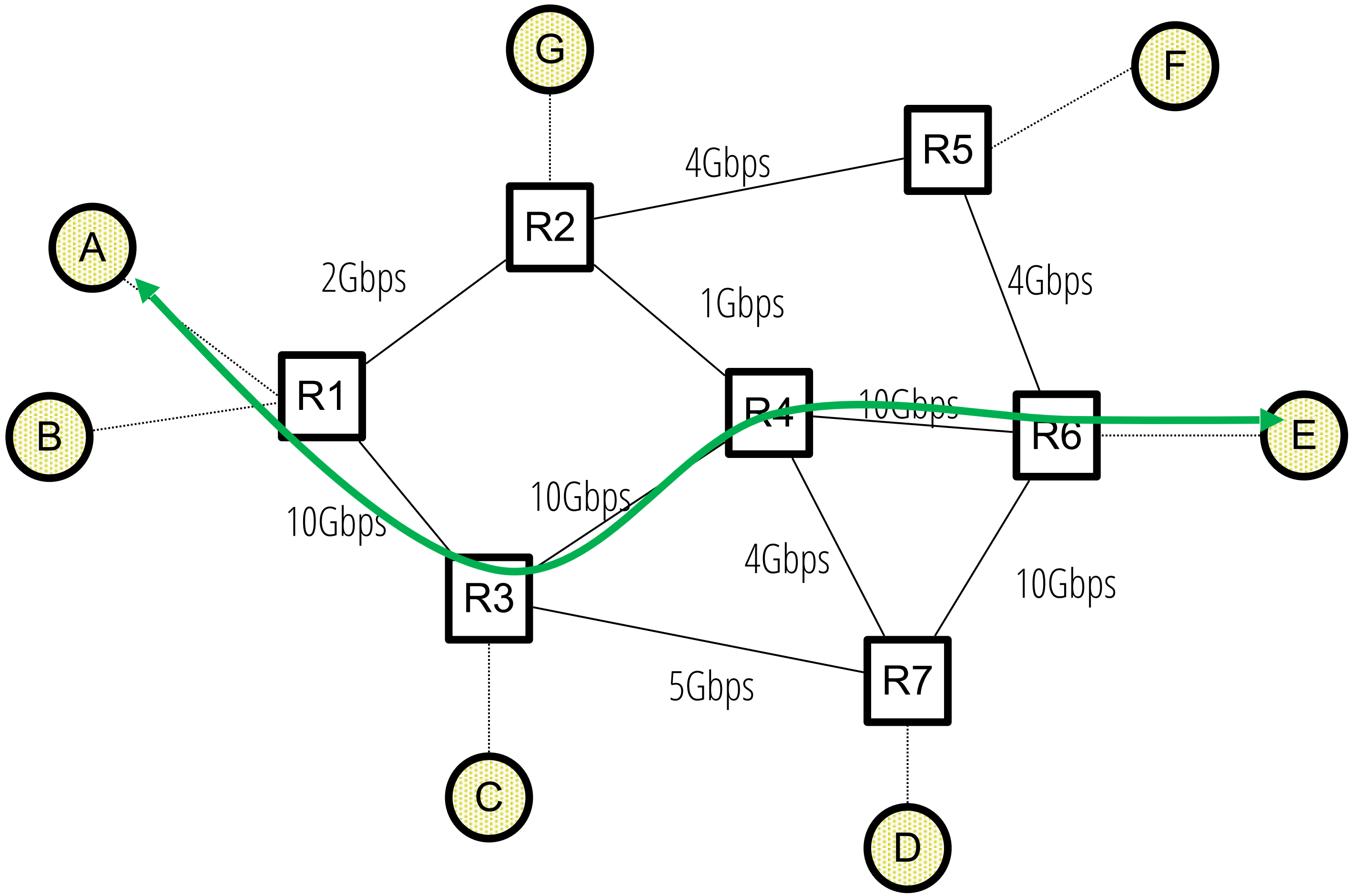
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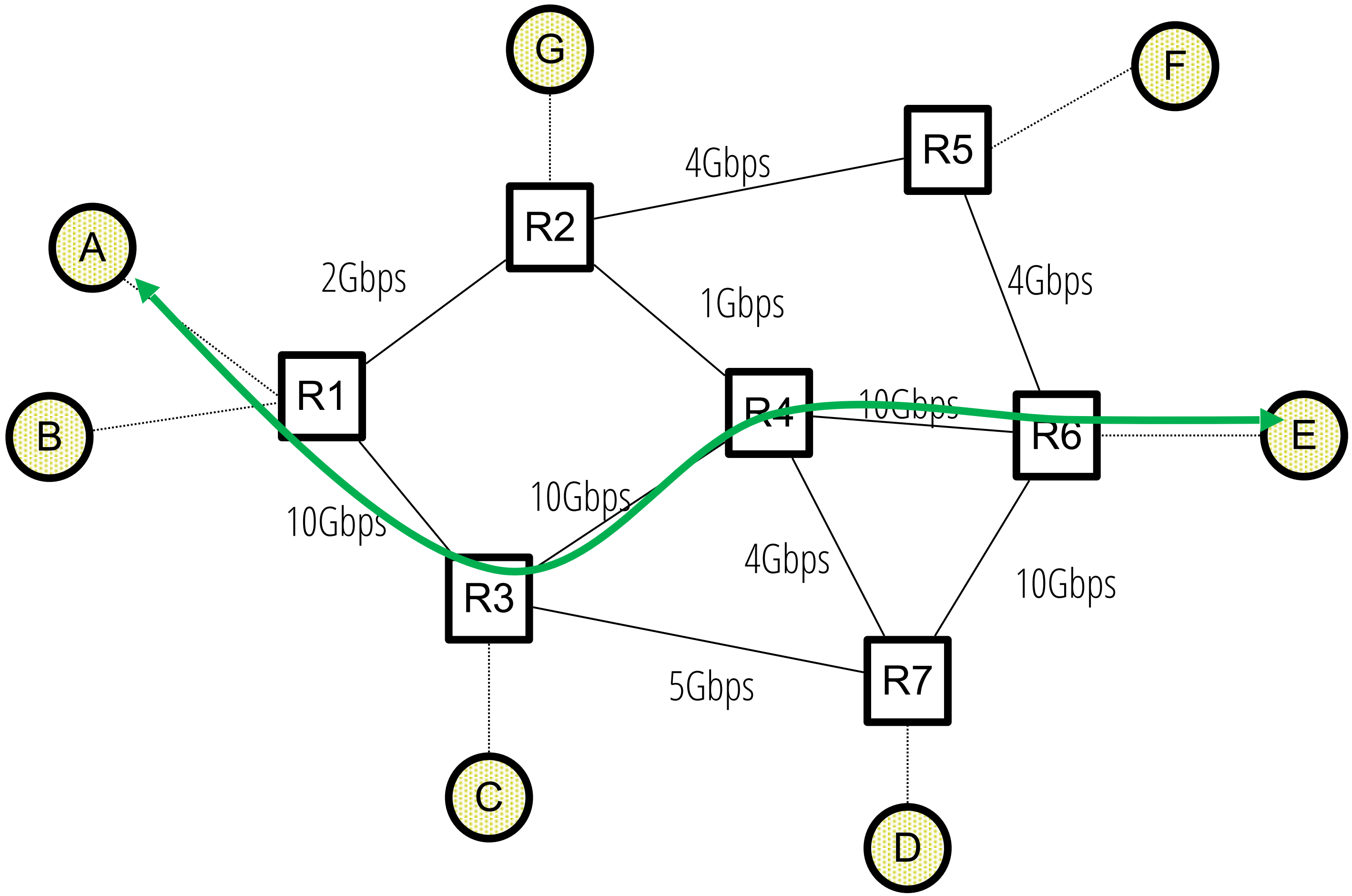
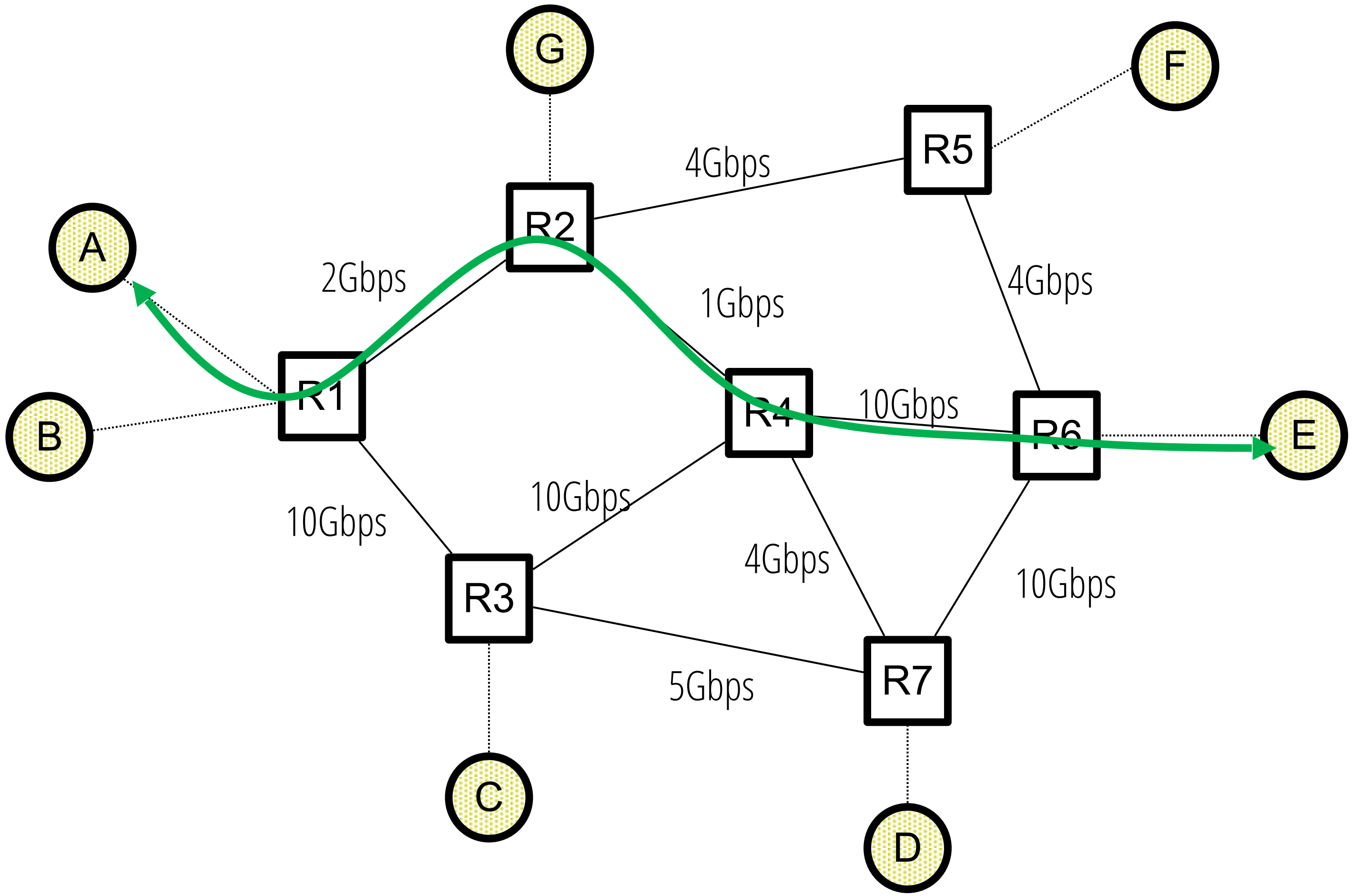


(1) First, host A discovers it can send at ~10Gbps



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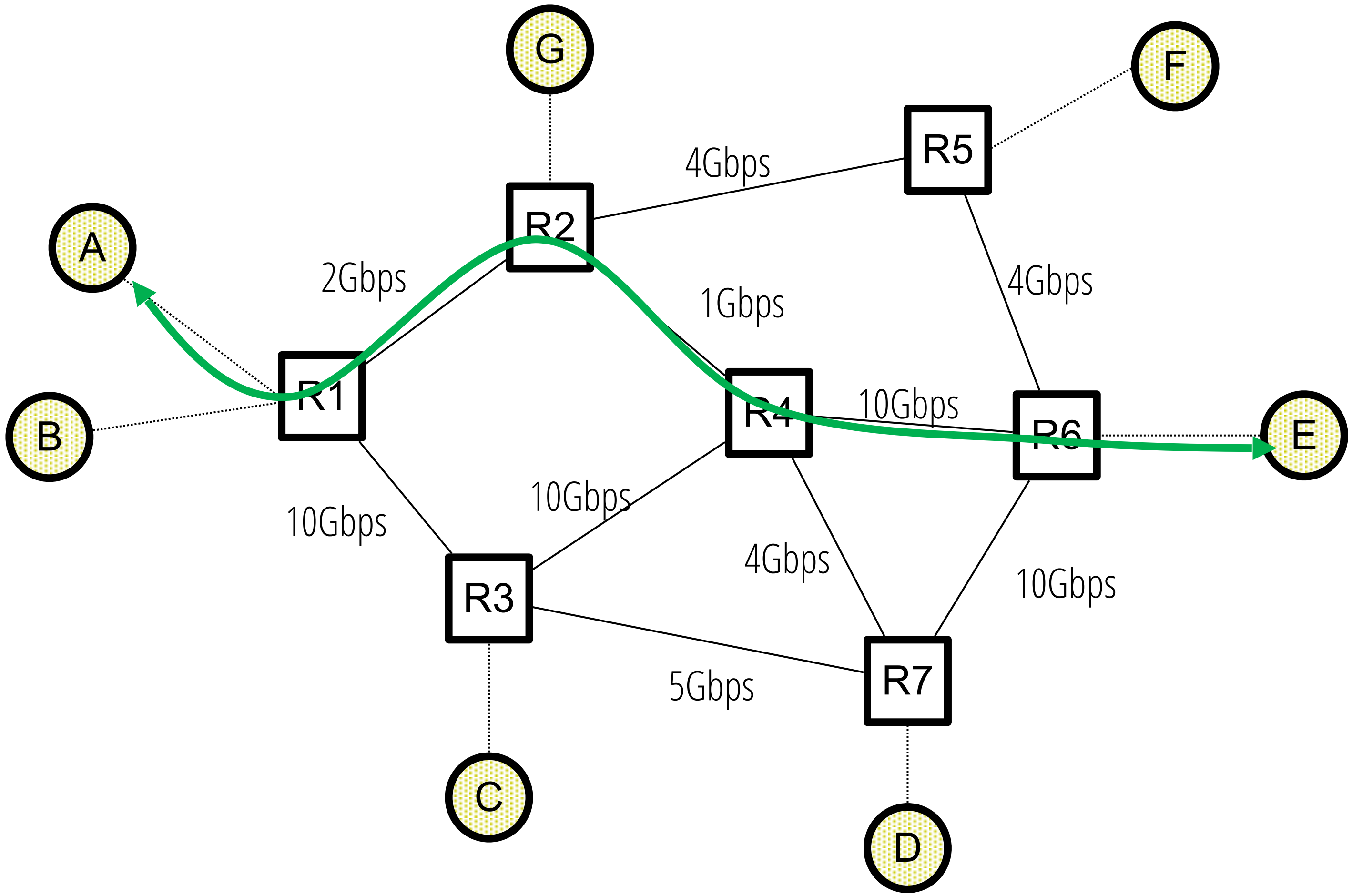

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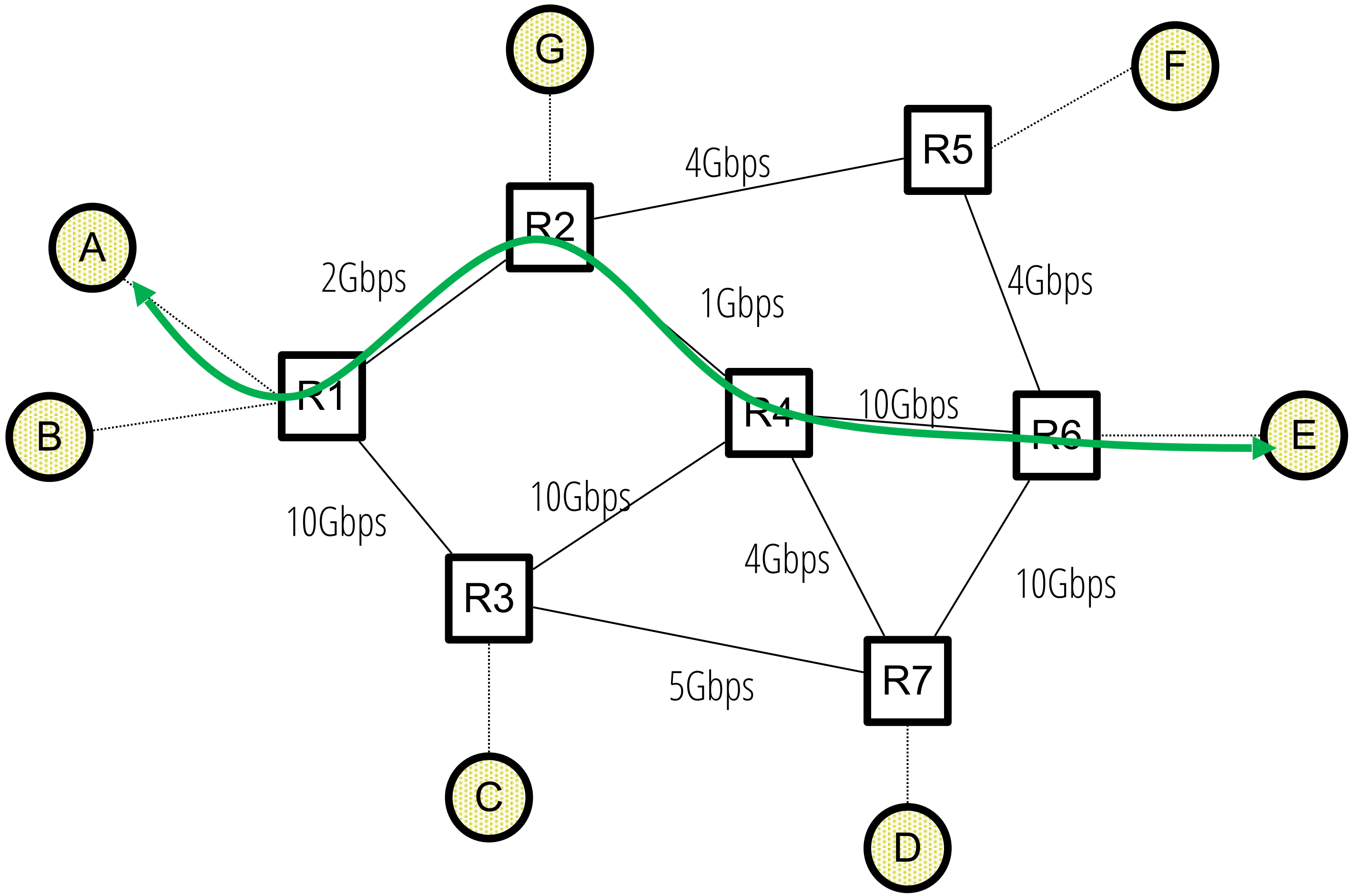

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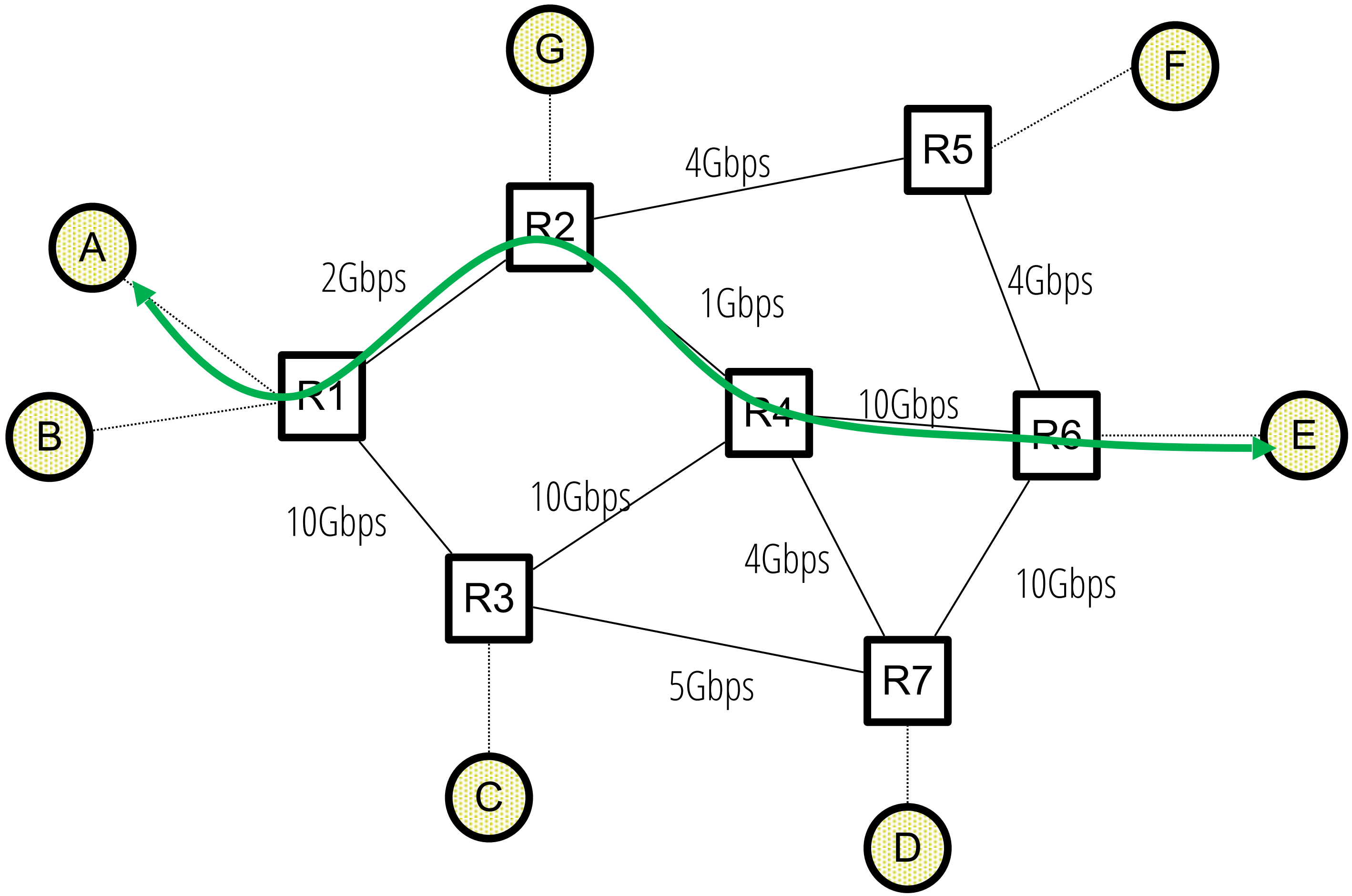

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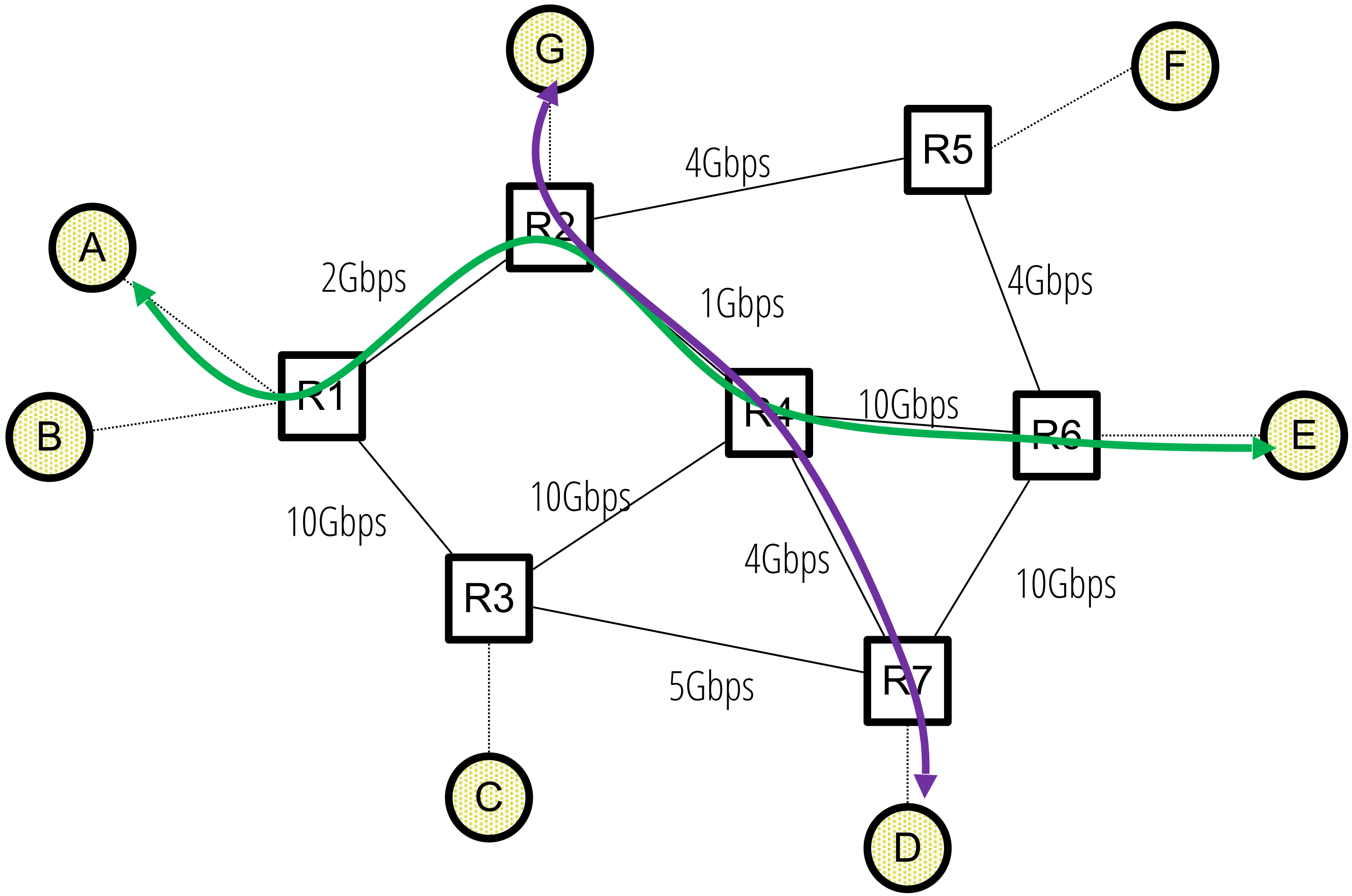
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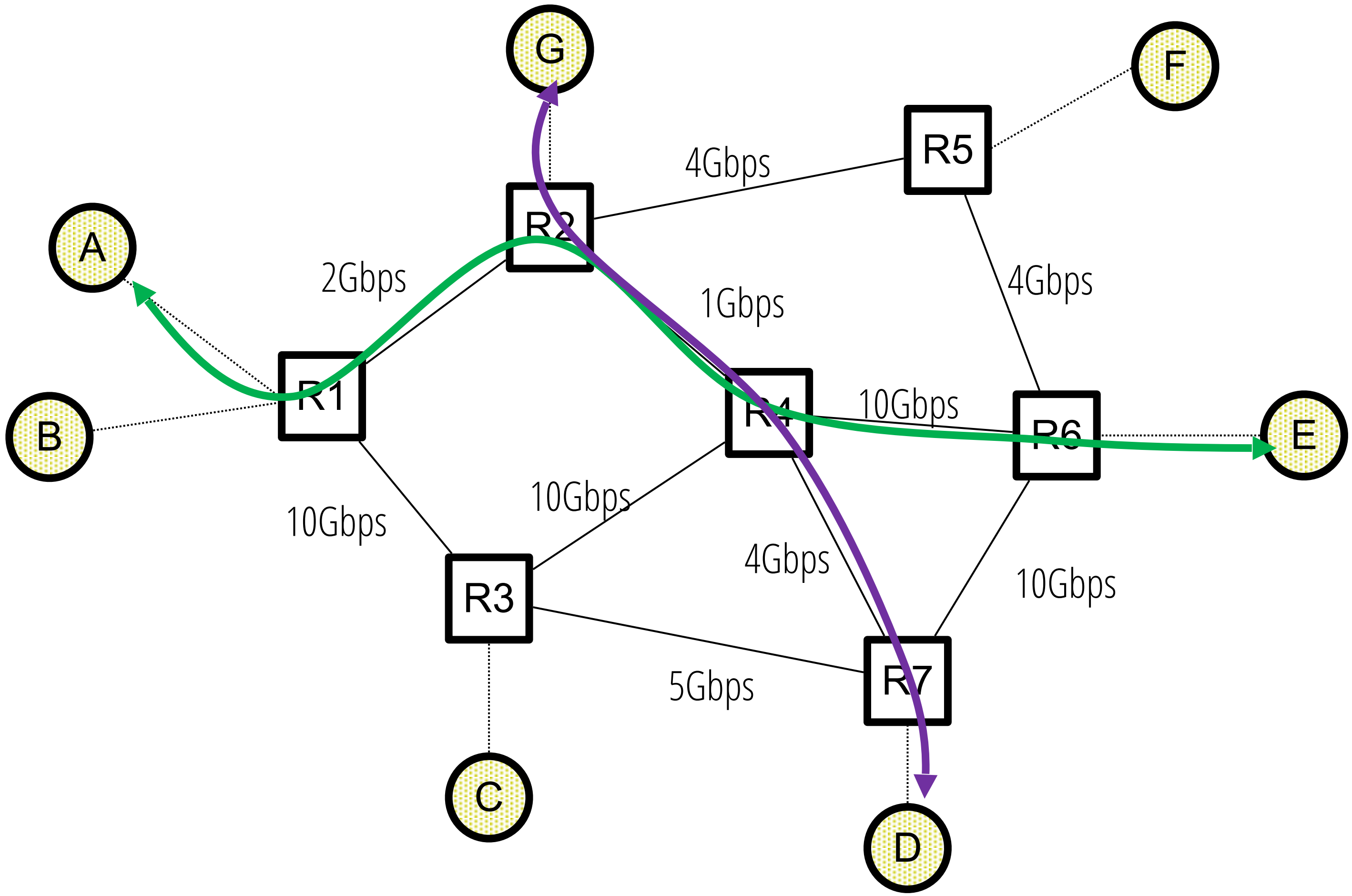

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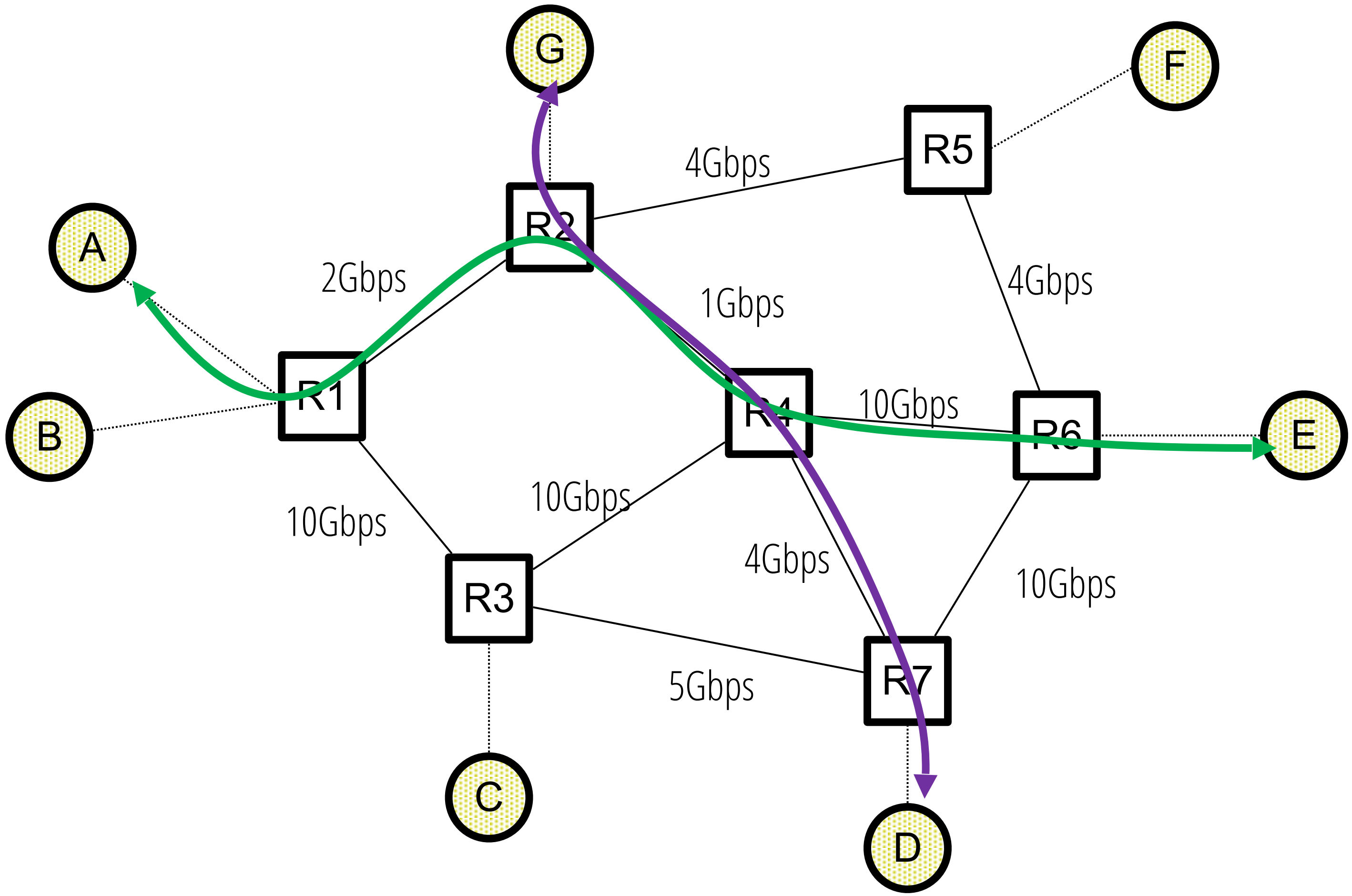

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(5) A figures out it should cut its rate to (say) ½ Gbps

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  - No special support from routers
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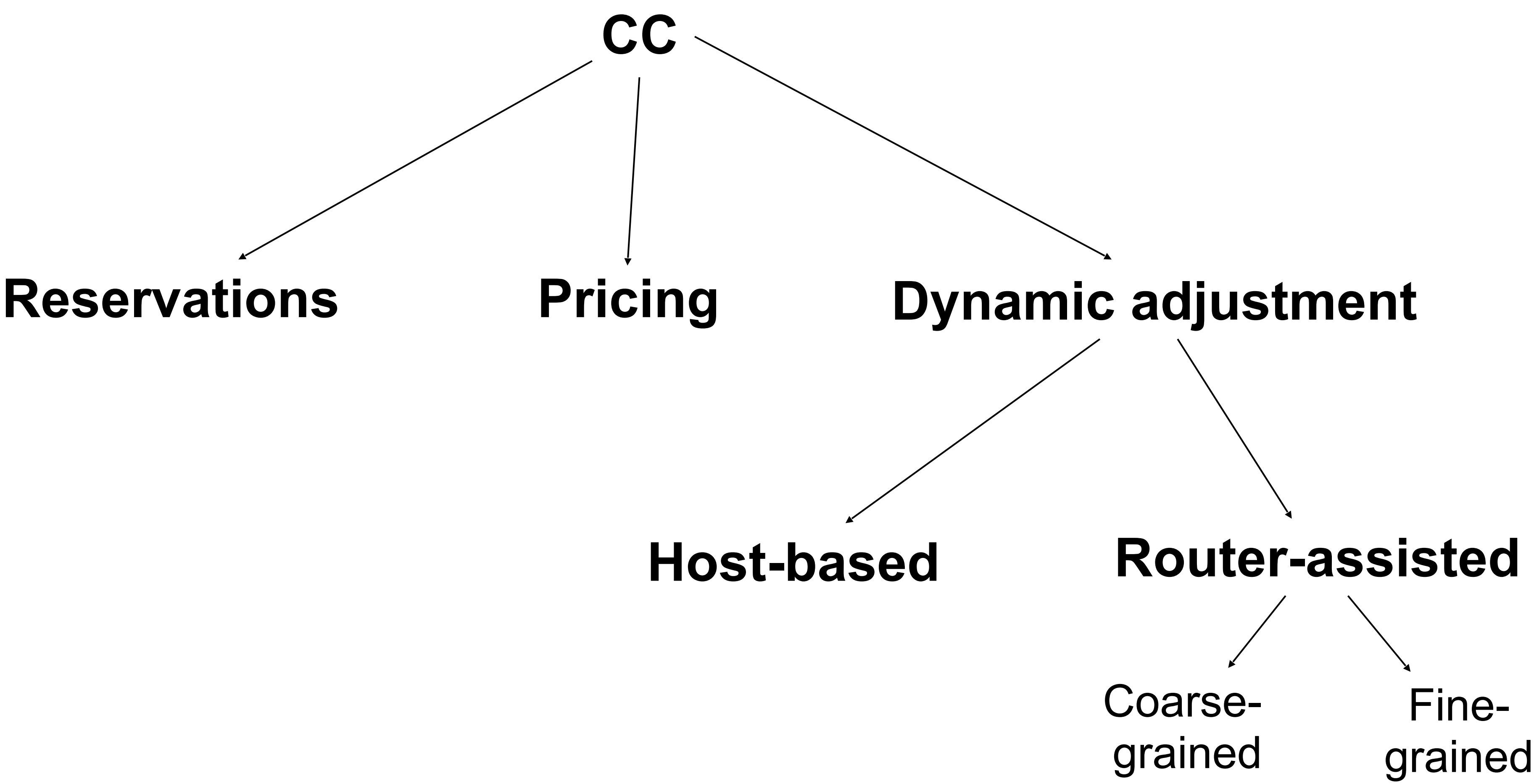
- We'll study TCP's host-based approach in detail and briefly touch on router-assisted CC

Taking stock:
where we are in the design space



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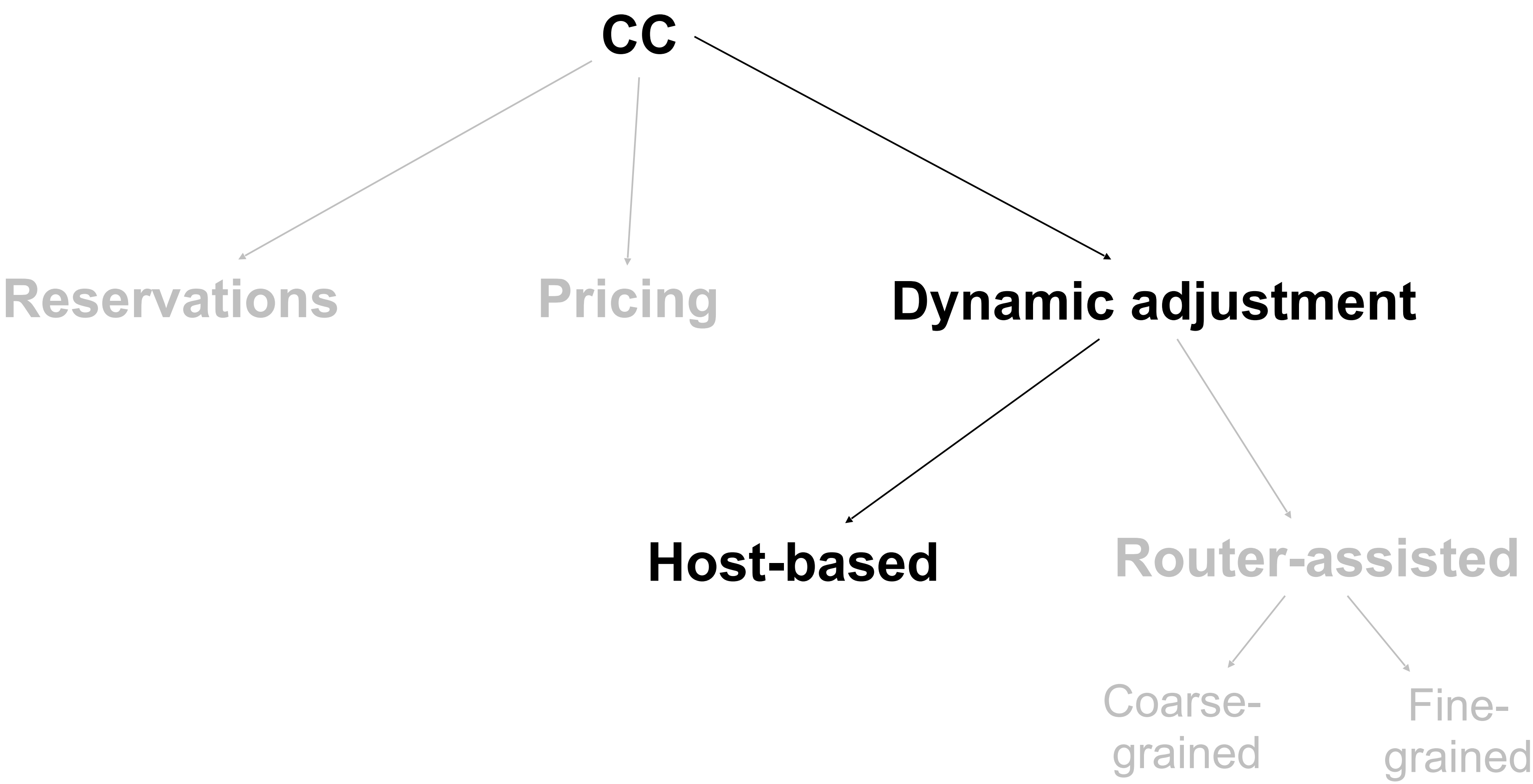

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    - If yes, reduce R
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  - Repeat

Sketch of a (host-based) solution

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How do we detect congestion

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- Discovering an initial rate
- Detecting congestion
- Reacting to congestion (or lack thereof)
  - Increase/decrease rules

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  - Already something TCP detects to implement reliability
- **Cons**
  - Complication: non-congestive loss (e.g., checksum err.)
  - Complication: reordering (e.g., with cumulative ACKs)
  - Detection occurs after packets have experienced delay

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- **Increase in packet delay**
  - Long considered tricky to get right: packet delay varies with queue size and competing traffic
  - Google's BBR protocol is challenging this assumption

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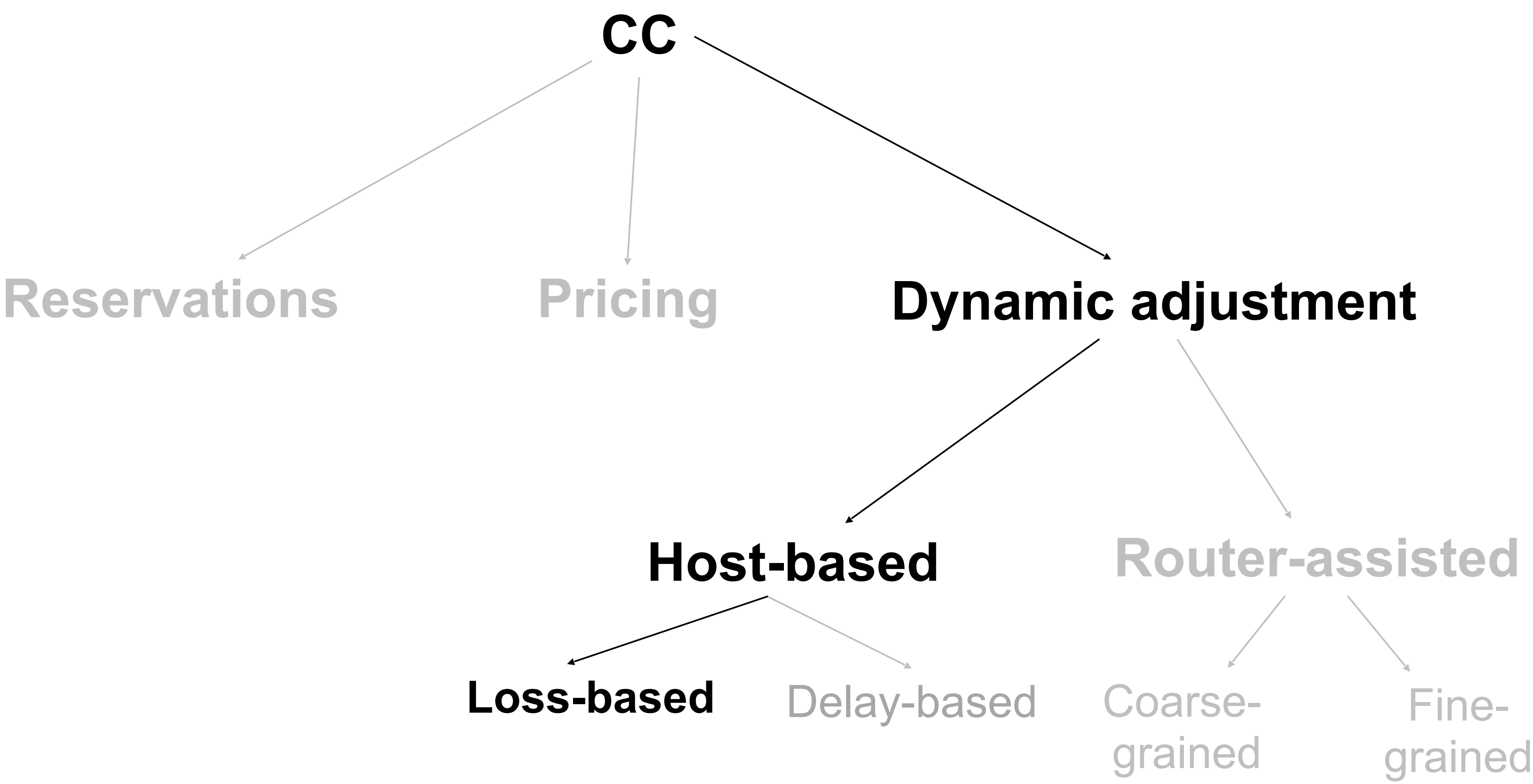

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- Goal: estimate available bandwidth
  - Start slow (for safety)
  - But ramp up quickly (for efficiency)
- Toy example of an inefficient solution
  - Add ½ Mbps every 100ms until we detect loss
  - If available BW is 1Mbps, will discover rate in 200ms
  - If available BW is 1Gbps, will take 200 seconds
  - Either is possible!

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  - Might be much less than actual bandwidth
  - Linear increase takes too long to ramp up
- Increase exponentially until first loss
  - E.g., double rate until first loss
- A ”safe” rate is half of that when first loss occurred
  - I.e., if first loss occurred at rate R, then R/2 is safe rate

Components of a Solution

- Discovering an initial rate
- Detecting congestion
- Reacting to congestion (or lack thereof)
  - Increase/decrease rules

Sketch of a solution

Each source independently runs the following:

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By how much should we increase/decrease?

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- Determines how effectively BW is consumed
- Determines how BW is shared (fairness)

Goals for rate adjustment

- **Efficiency**: High utilization of link bandwidth
- **Fairness**: Each flow gets equal share

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- Fast: **multiplicative** increase/decrease
  - E.g., increase/decrease by 2x (R → 2R or R/2)

How should we adjust rate?

- At the highest level: fast or slow

- Fast: **multiplicative** increase/decrease
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- Slow: **additive** increase/decrease
  - E.g., increase/decrease by +1 (R→ R+1 or R-1)

Leads to four alternatives

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- **AIAD**: gentle increase, gentle decrease
- **AIMD**: gentle increase, rapid decrease

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Why AIMD? Intuition

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- Consequences of sending too much are worse than sending too little
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- Consequences of sending too much are worse than sending too little
  - Too much: packets dropped and retransmitted
  - Too little: somewhat lower throughput
- General approach:
  - Gentle increase when uncongested (exploration)
  - Rapid decrease when congested

Why AIMD? In more detail...

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- Consider a simple model
  - Two flows going over single link of capacity C
  - Sending at rates X1 and X2 respectively

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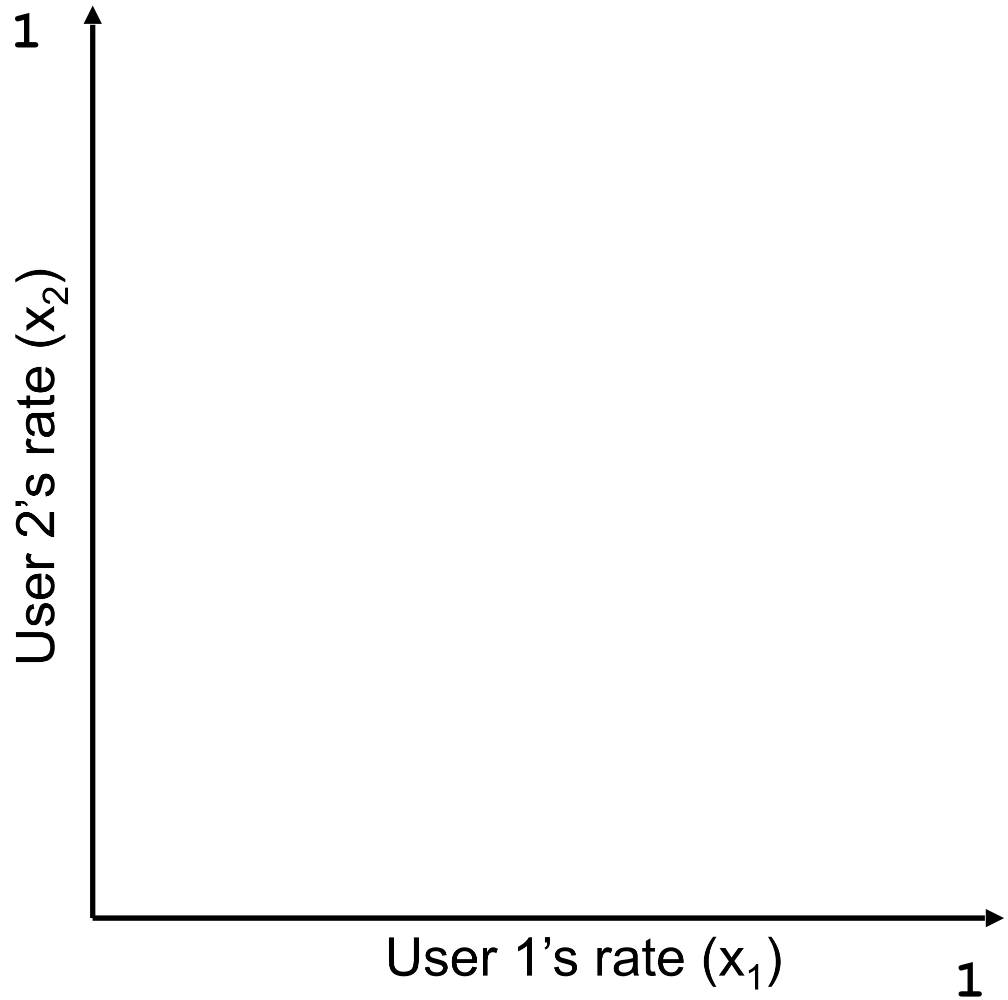
  - Sending at rates X1 and X2 respectively

- When X1+X2 > C, network is congested
- When X1+X2 < C, network is underloaded

- Would like *both*:
  - X1 + X2 = C → link is fully utilized with no congestion
  - X1 = X2 → sharing is “fair”

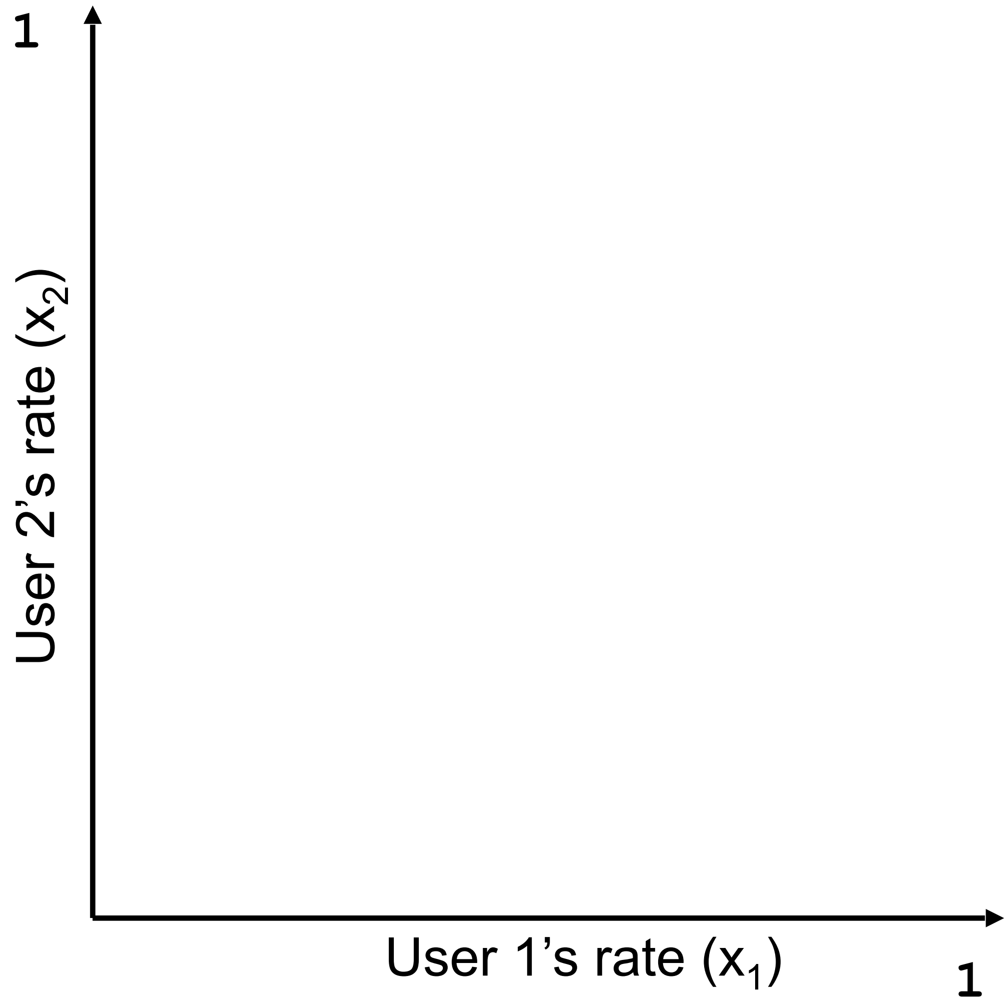
Simple Model, C=1

Simple Model, C=1



Simple Model, C=1

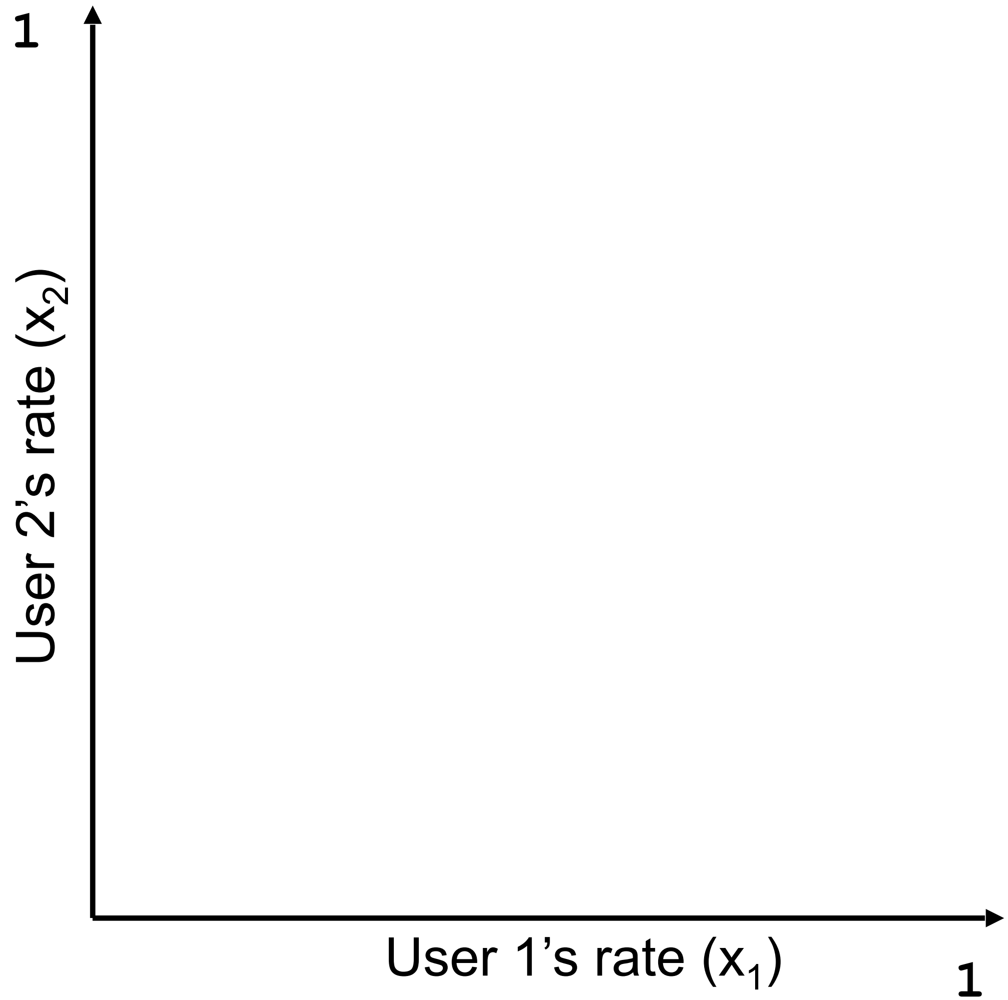
- Two users with rates x_1 and x_2



Simple Model, C=1

- Two users with rates x_1 and x_2

- Congestion when $x_1+x_2 > 1$



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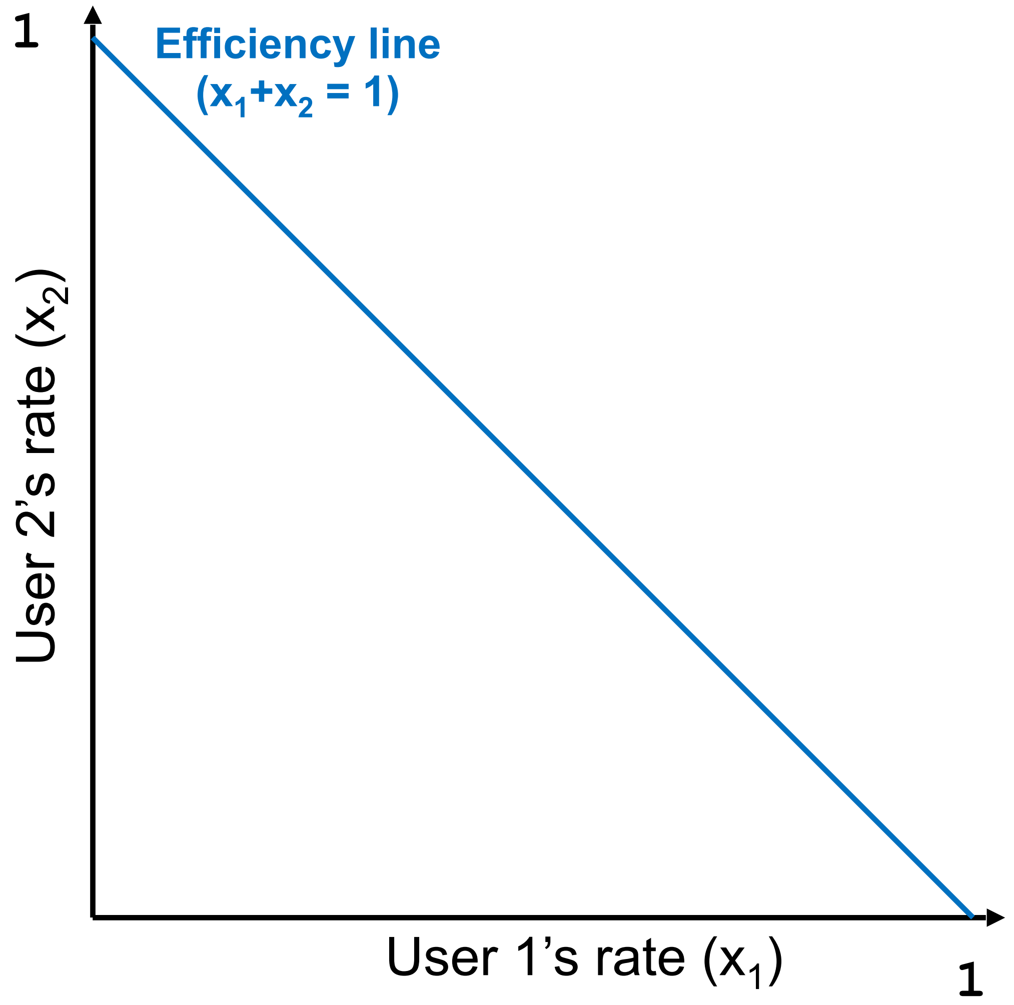

Simple Model, C=1

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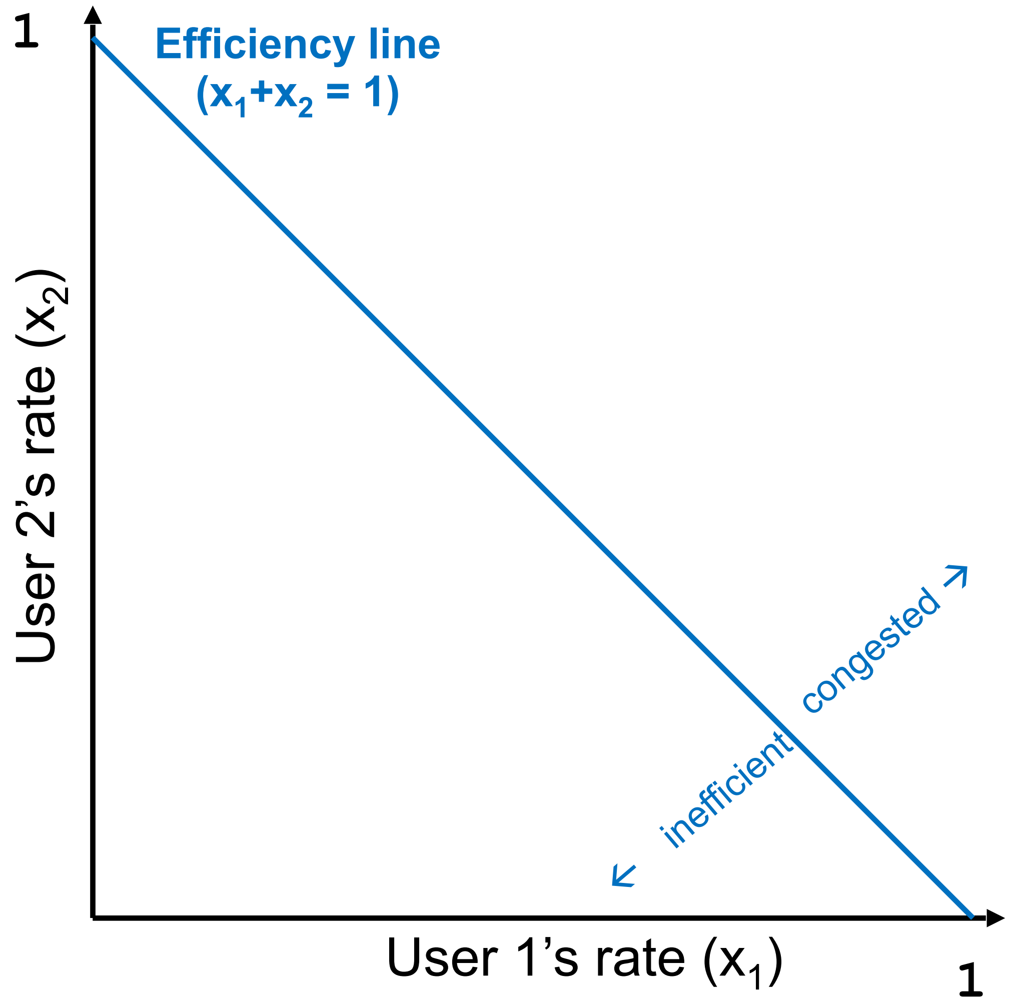

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- Two users with rates x_1 and x_2
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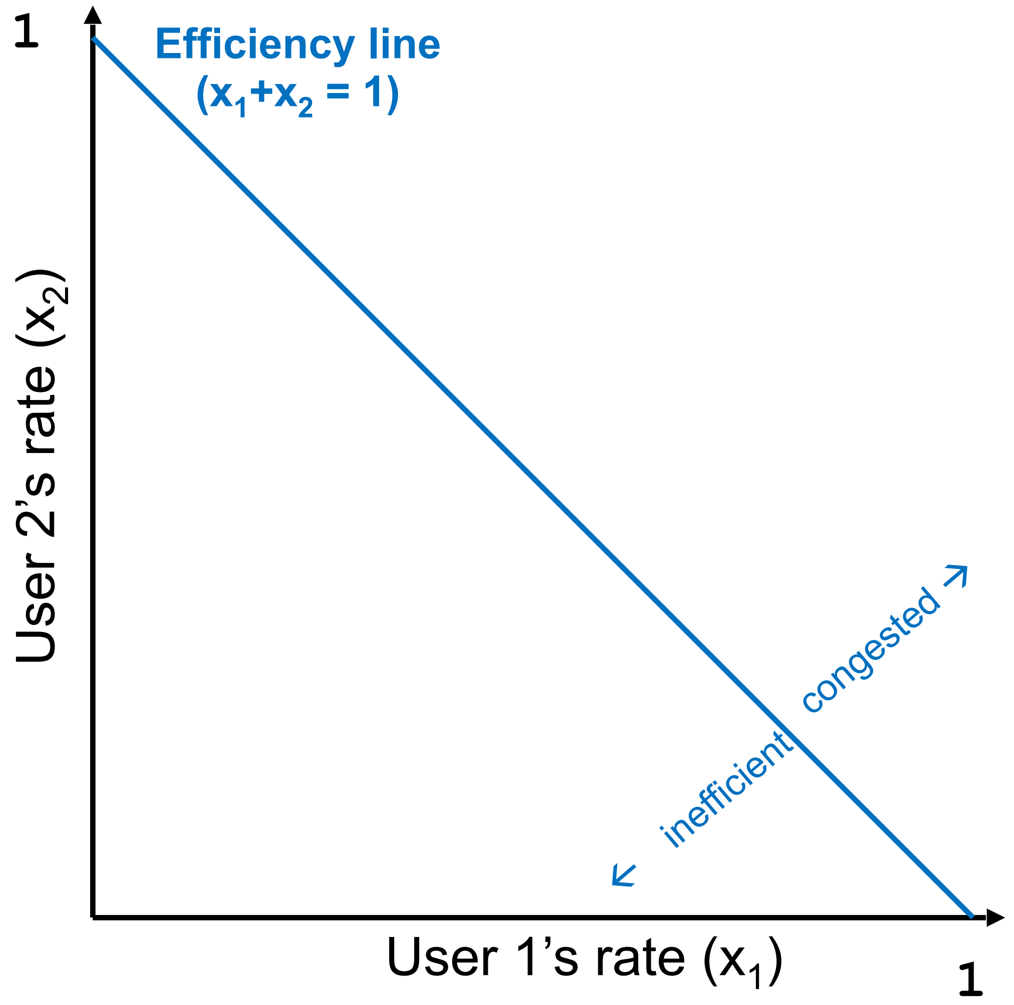

Simple Model, C=1

- Two users with rates x_1 and x_2
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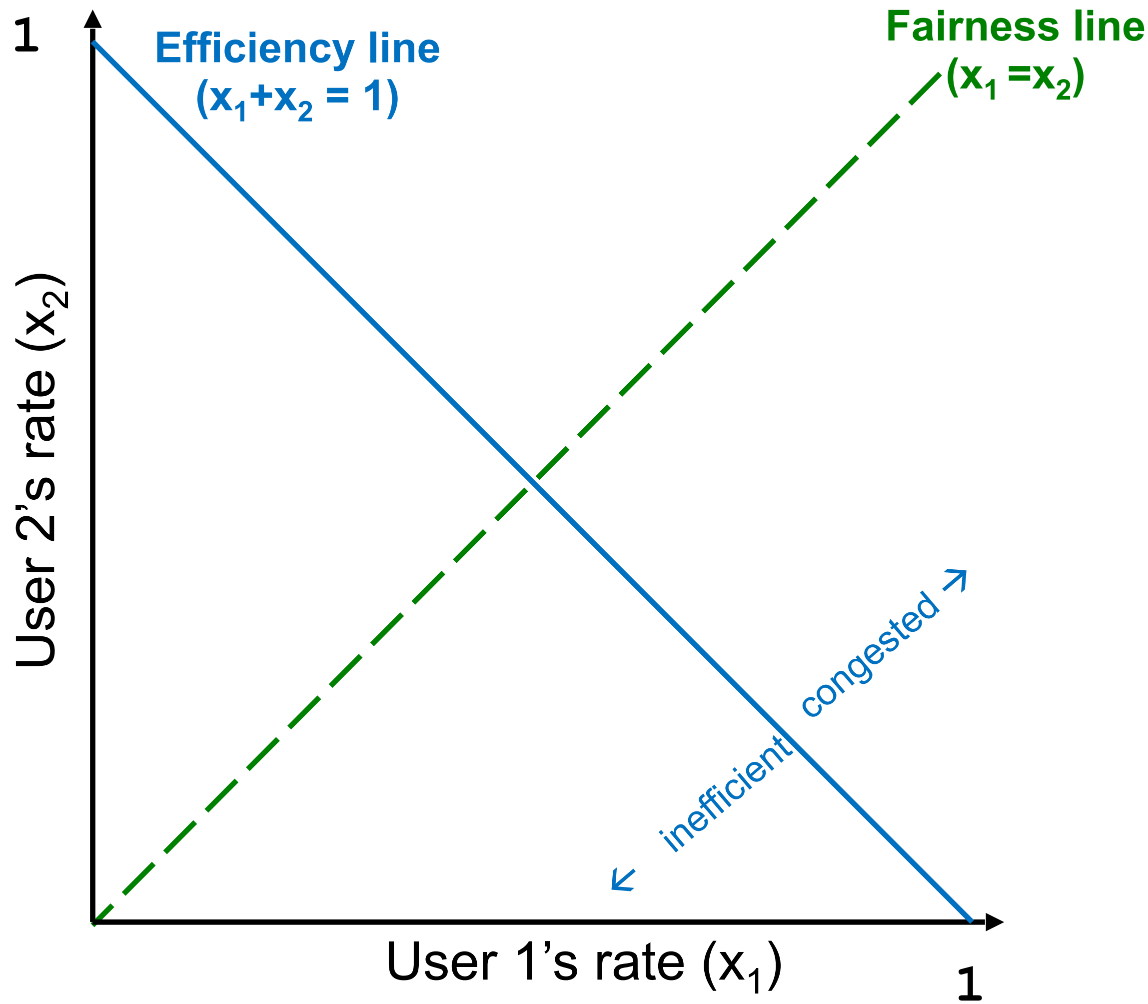
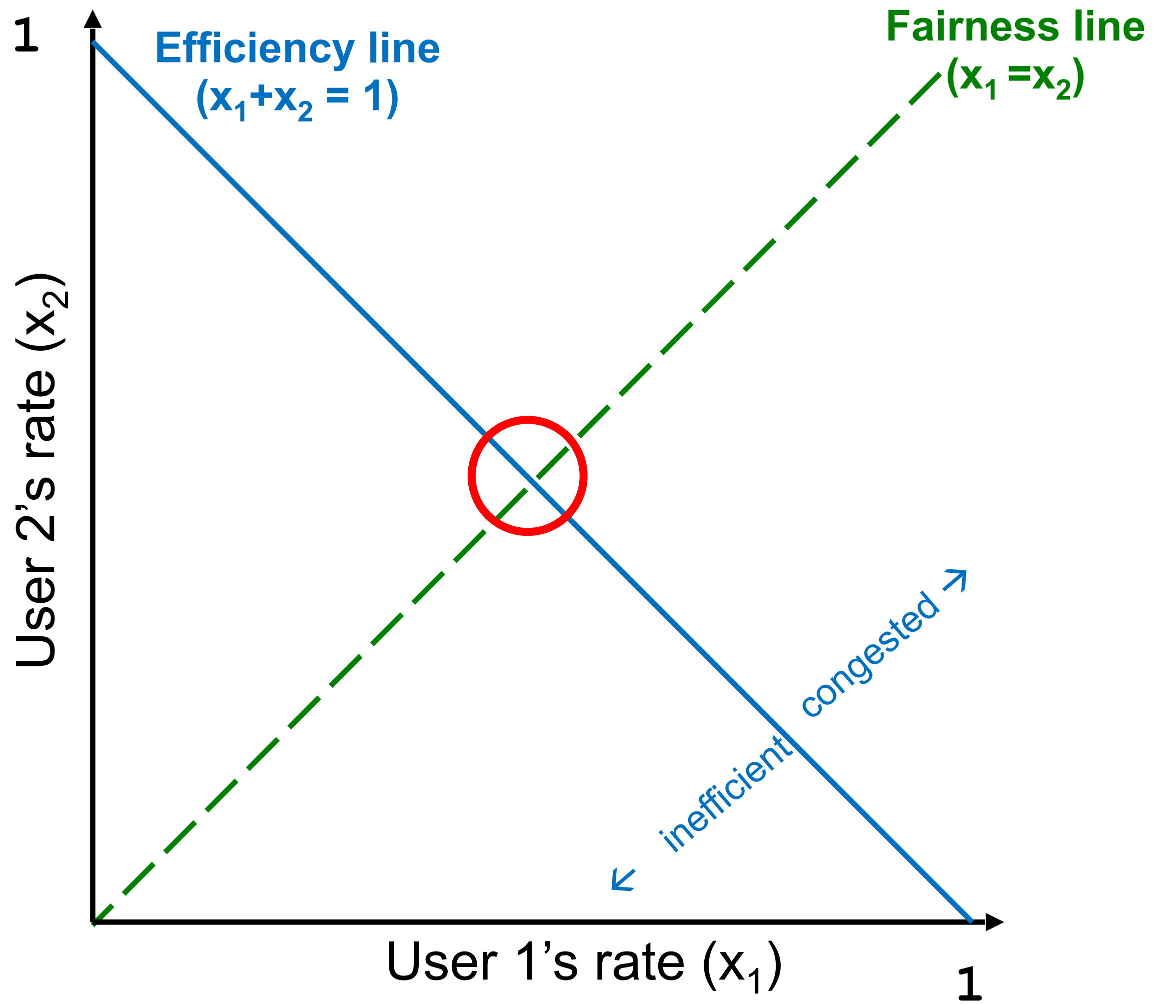
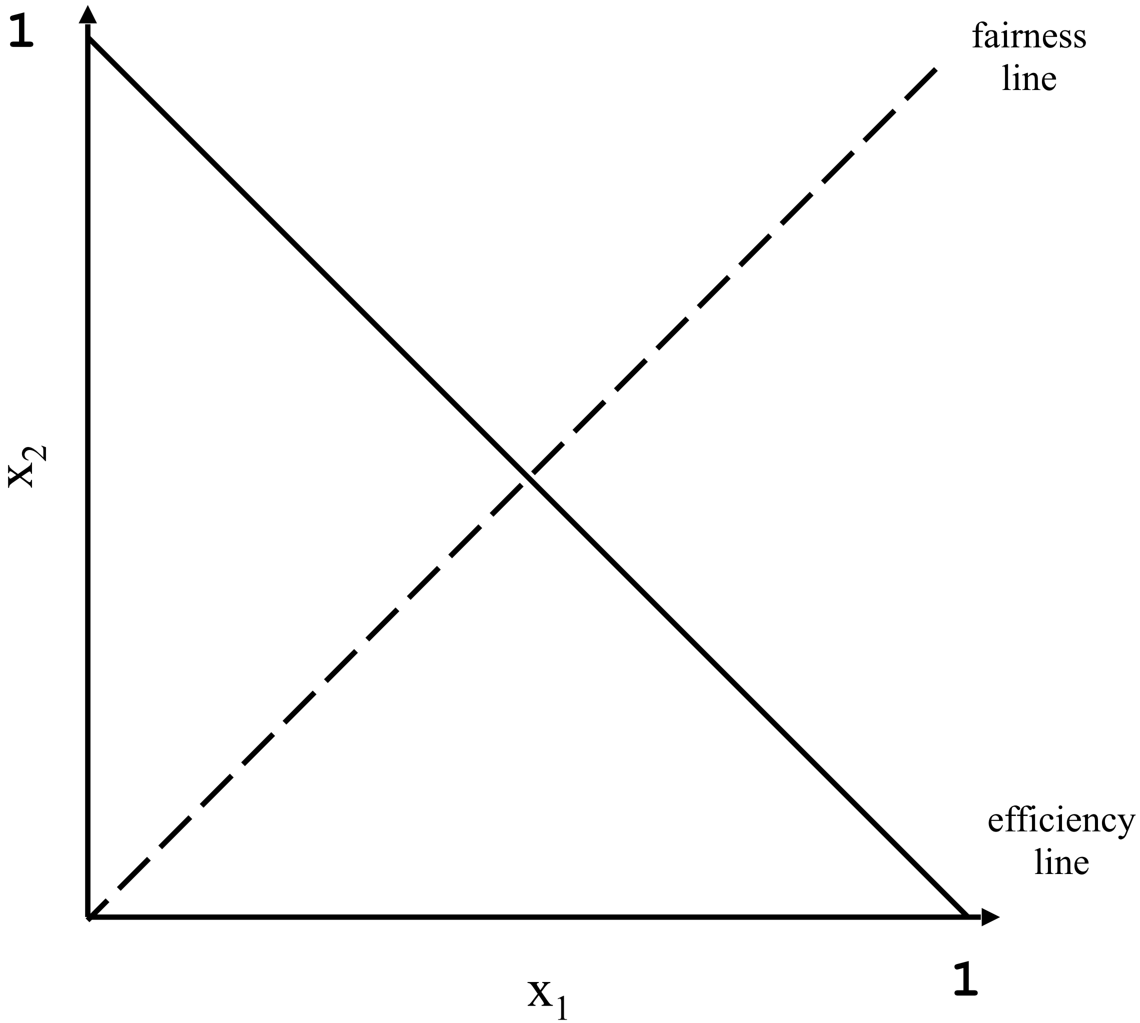


Simple Model, C=1

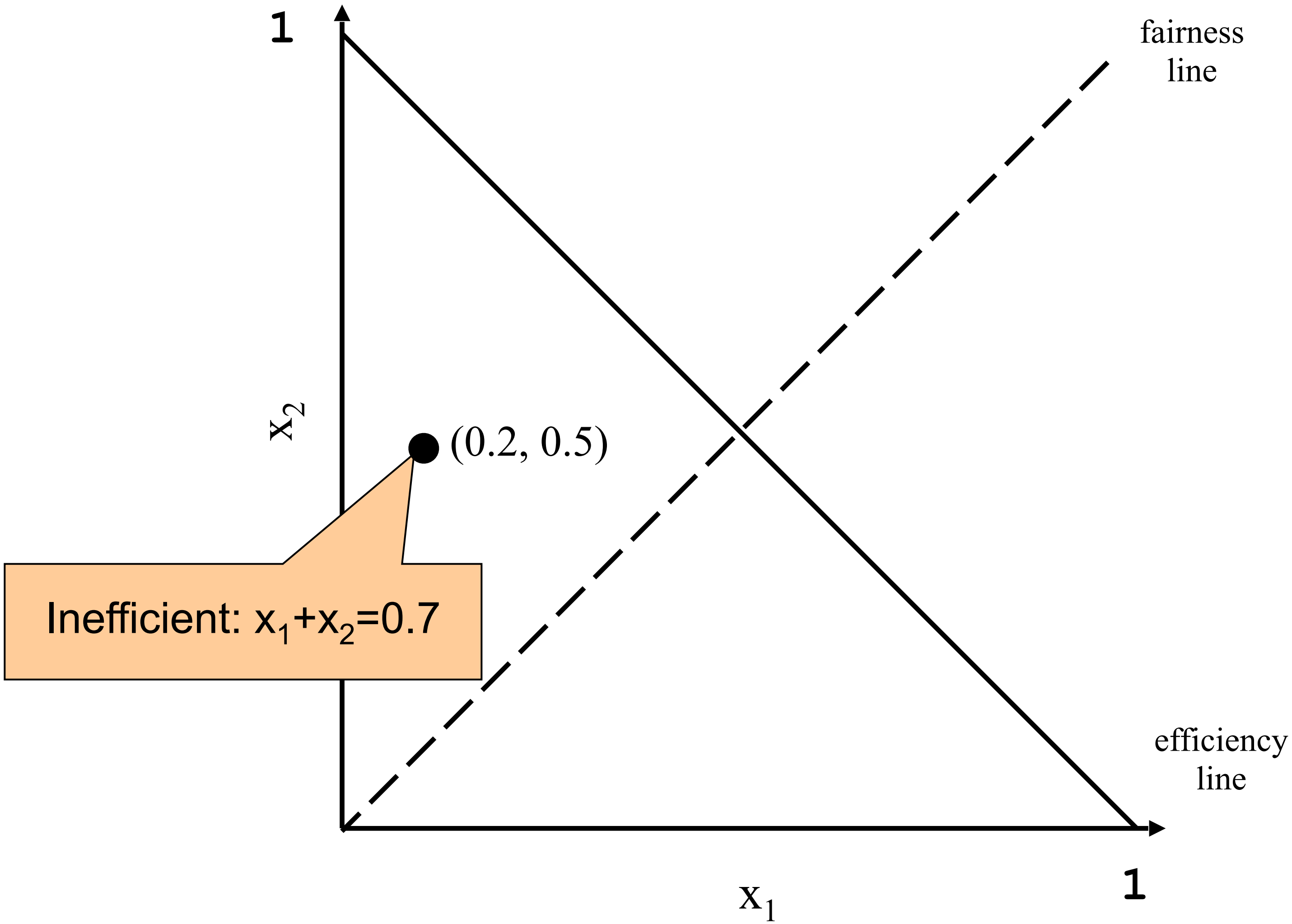
- Two users with rates x_1 and x_2
- Congestion when $x_1+x_2 > 1$
- Unused capacity when $x_1+x_2 < 1$
- Fair when $x_1 = x_2$



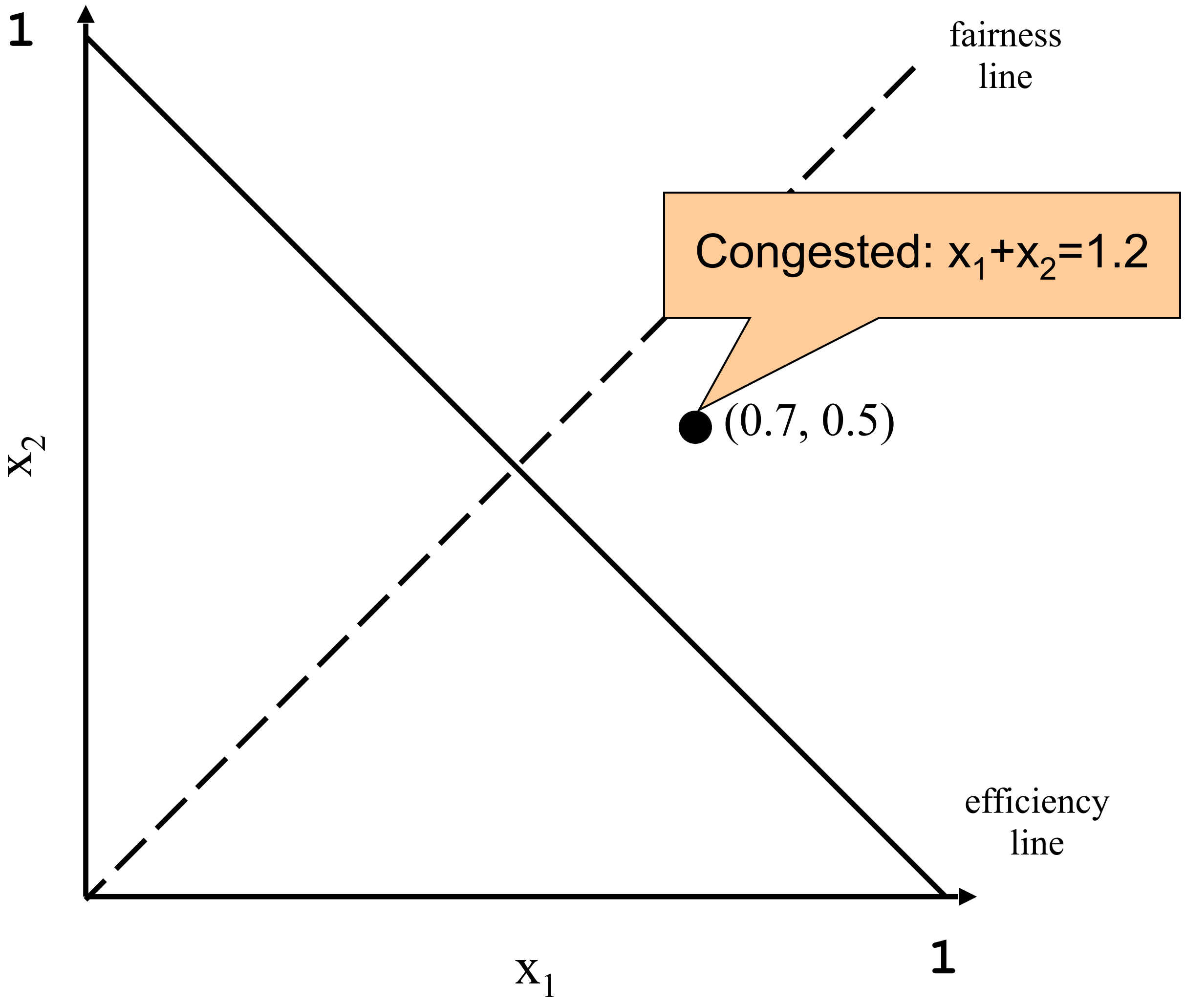
Example Allocations, C=1



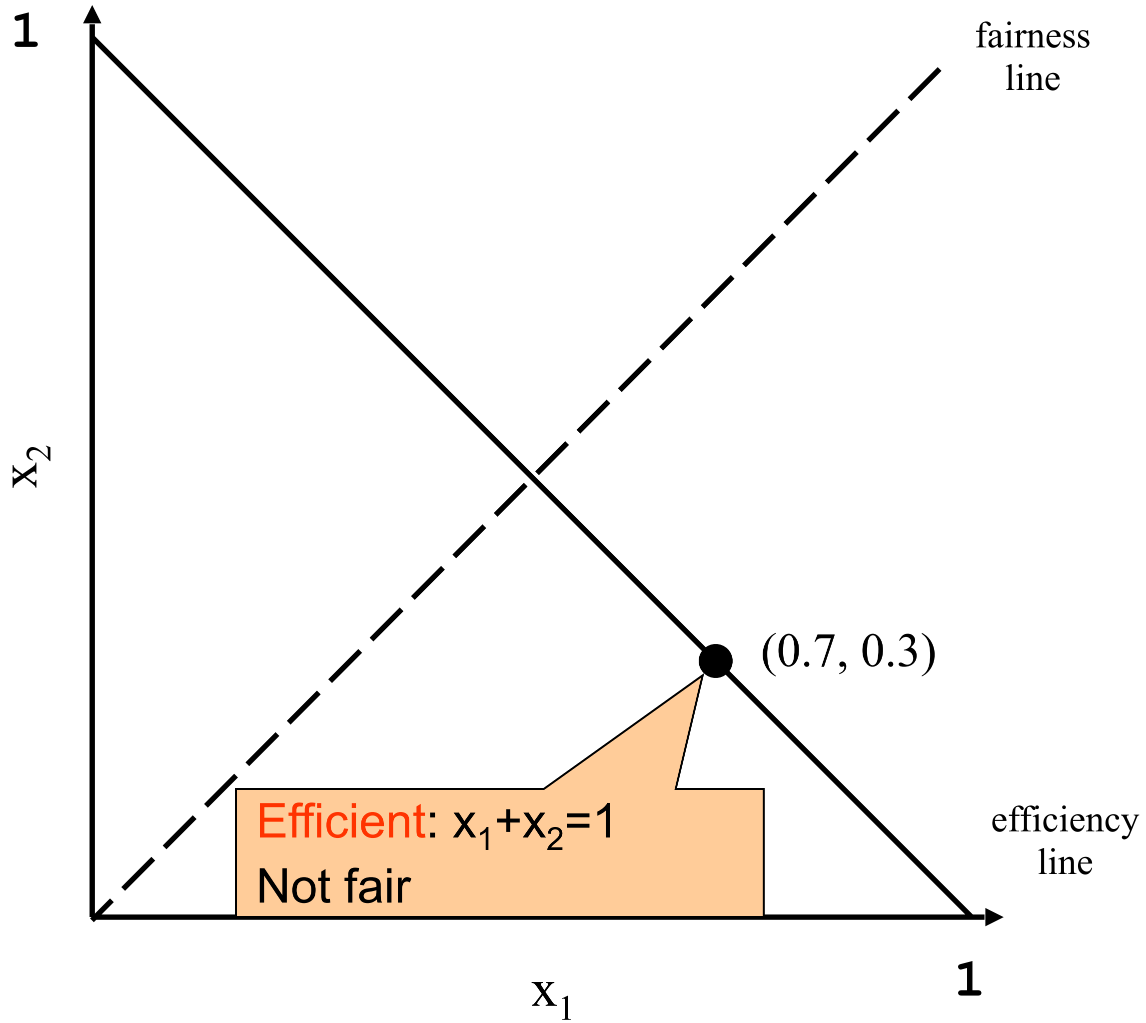
Example Allocations, C=1



Example Allocations, C=1



Example Allocations, C=1



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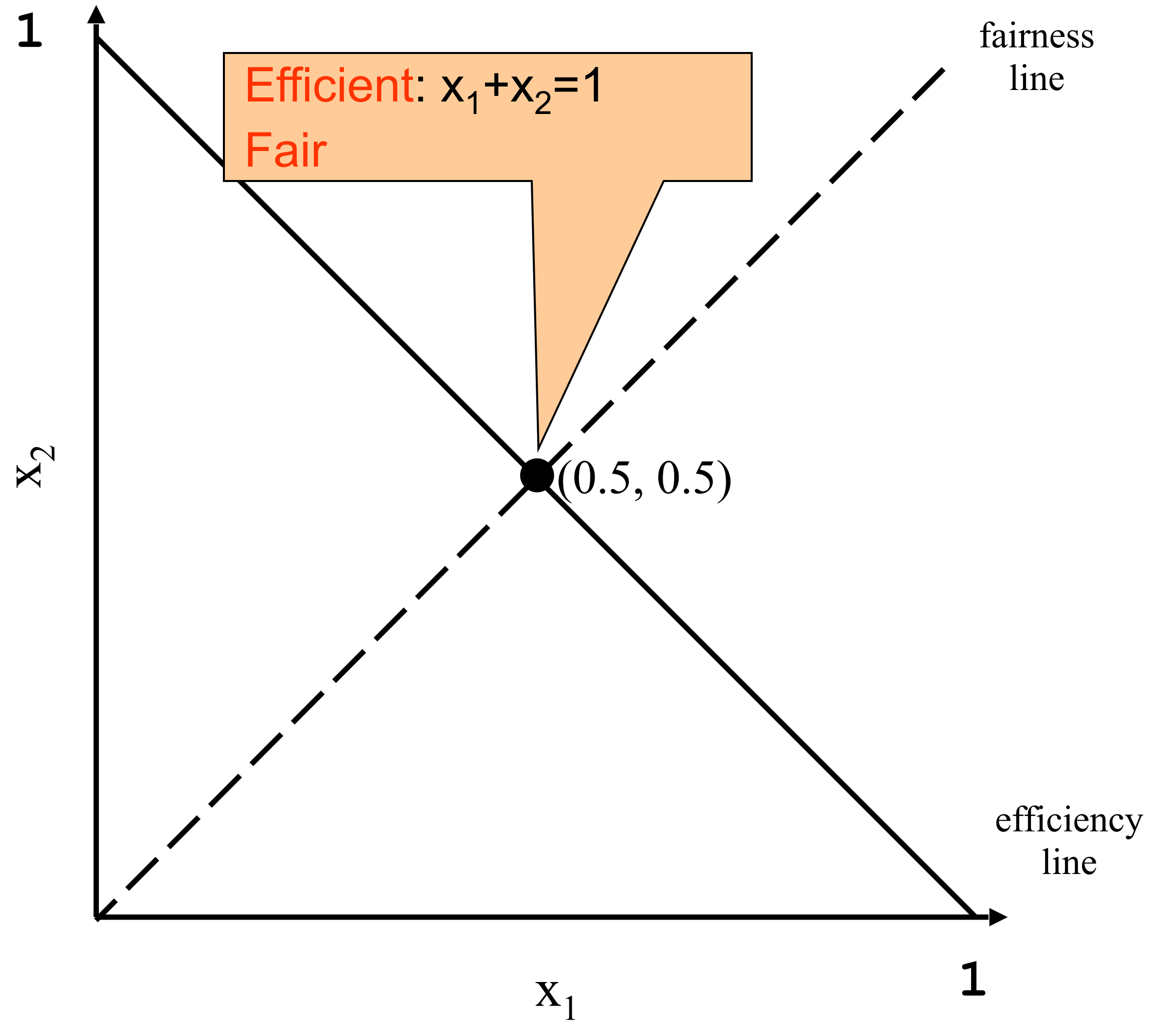
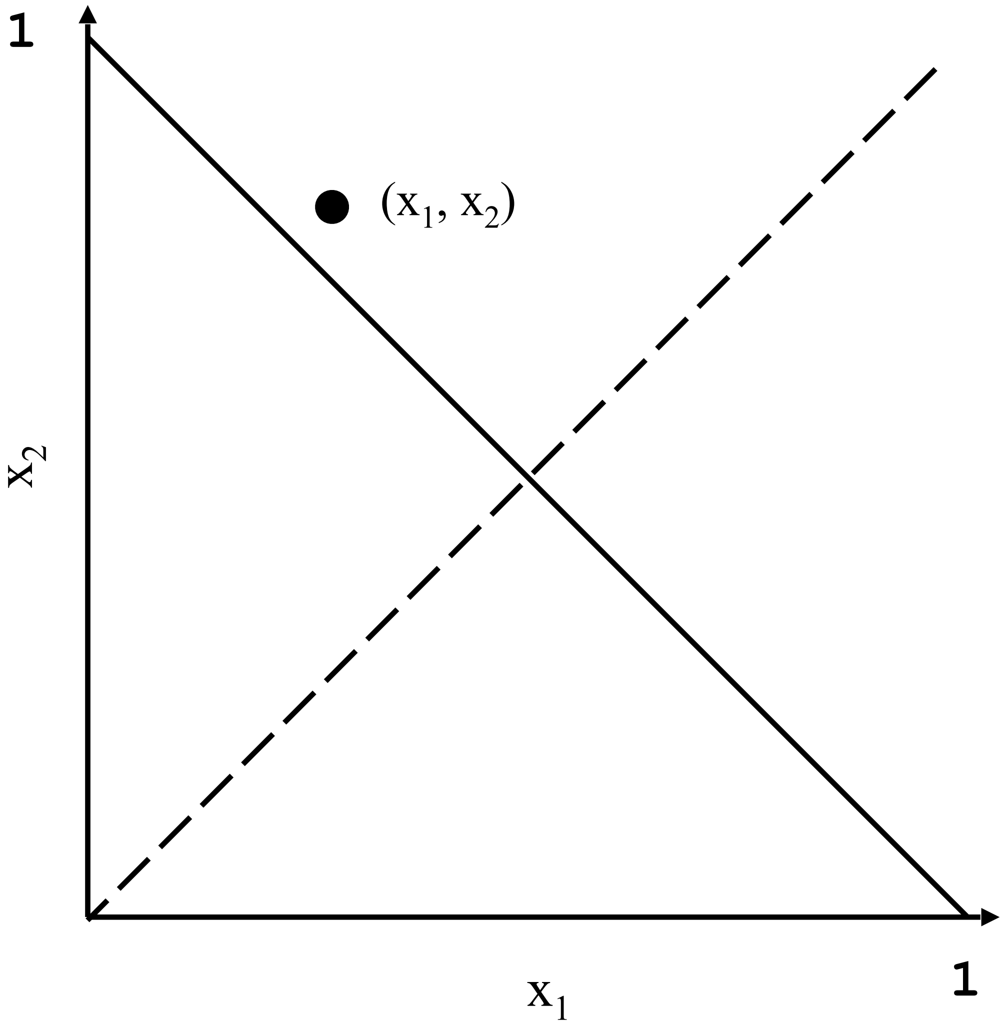


Example Adjustments



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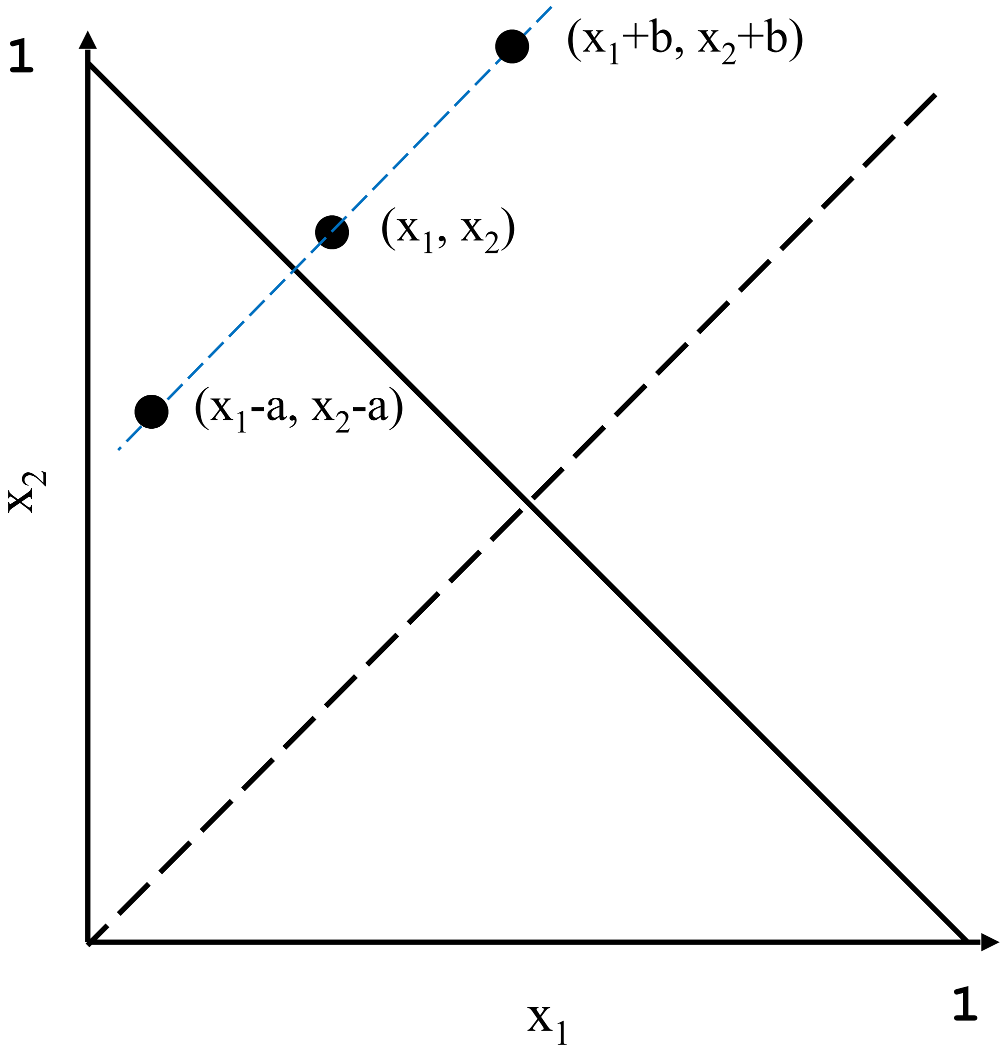

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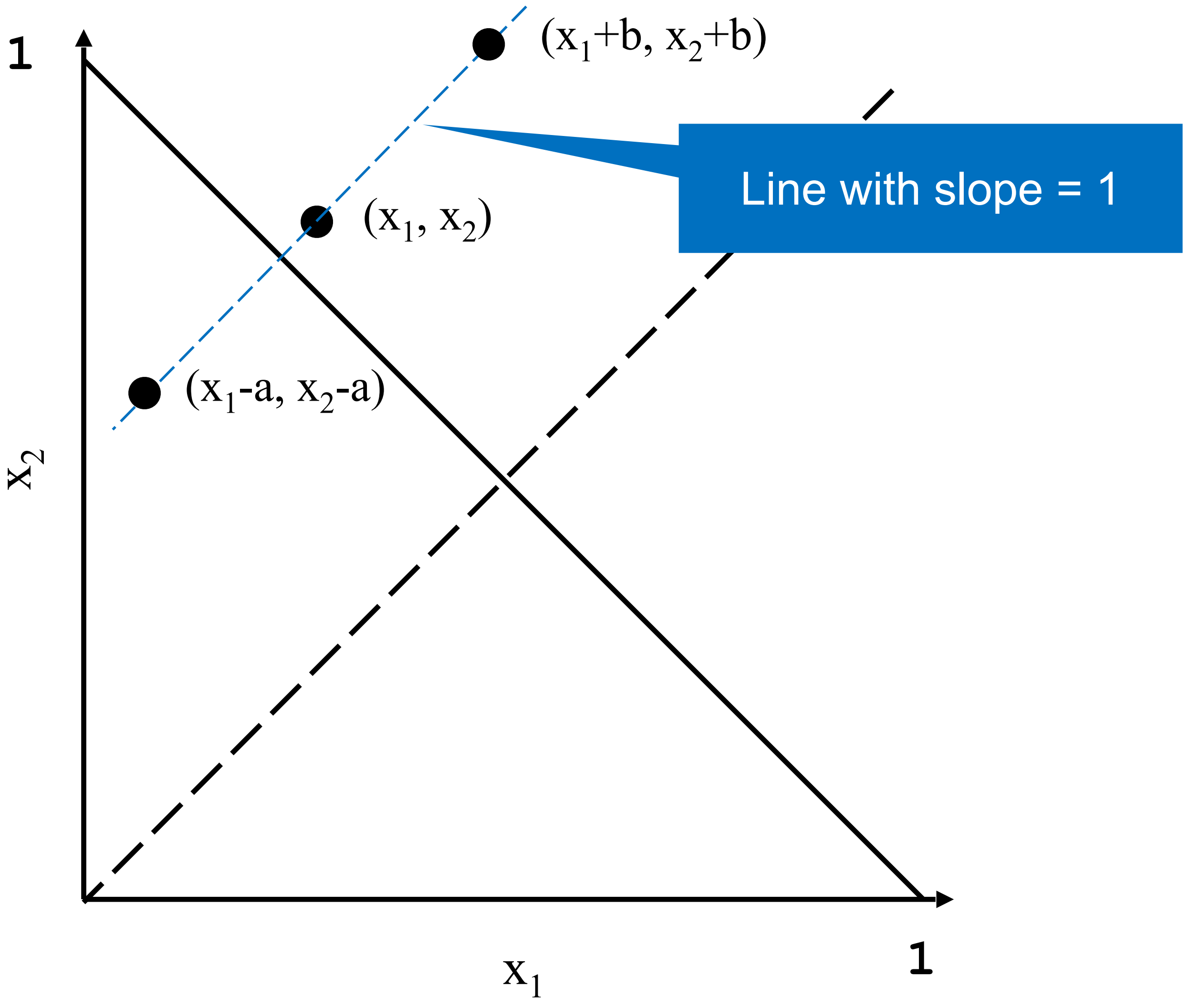

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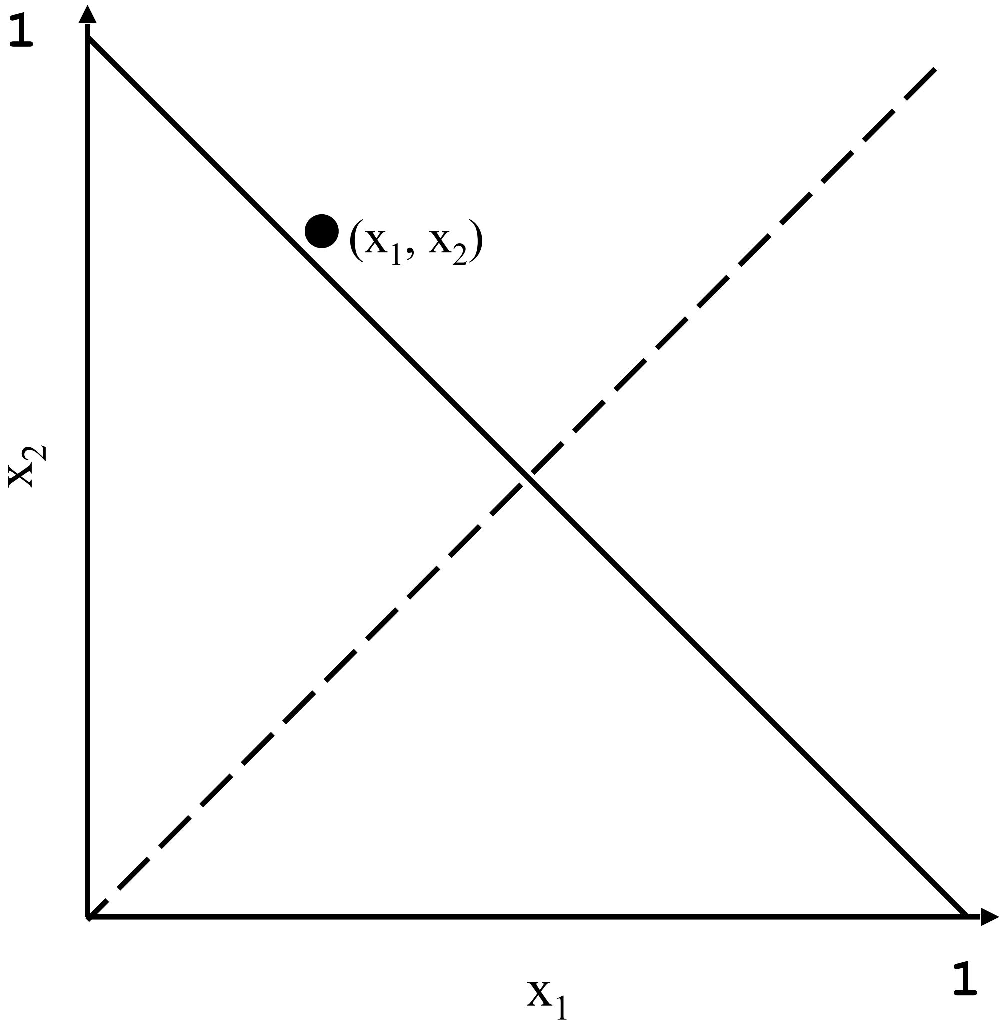

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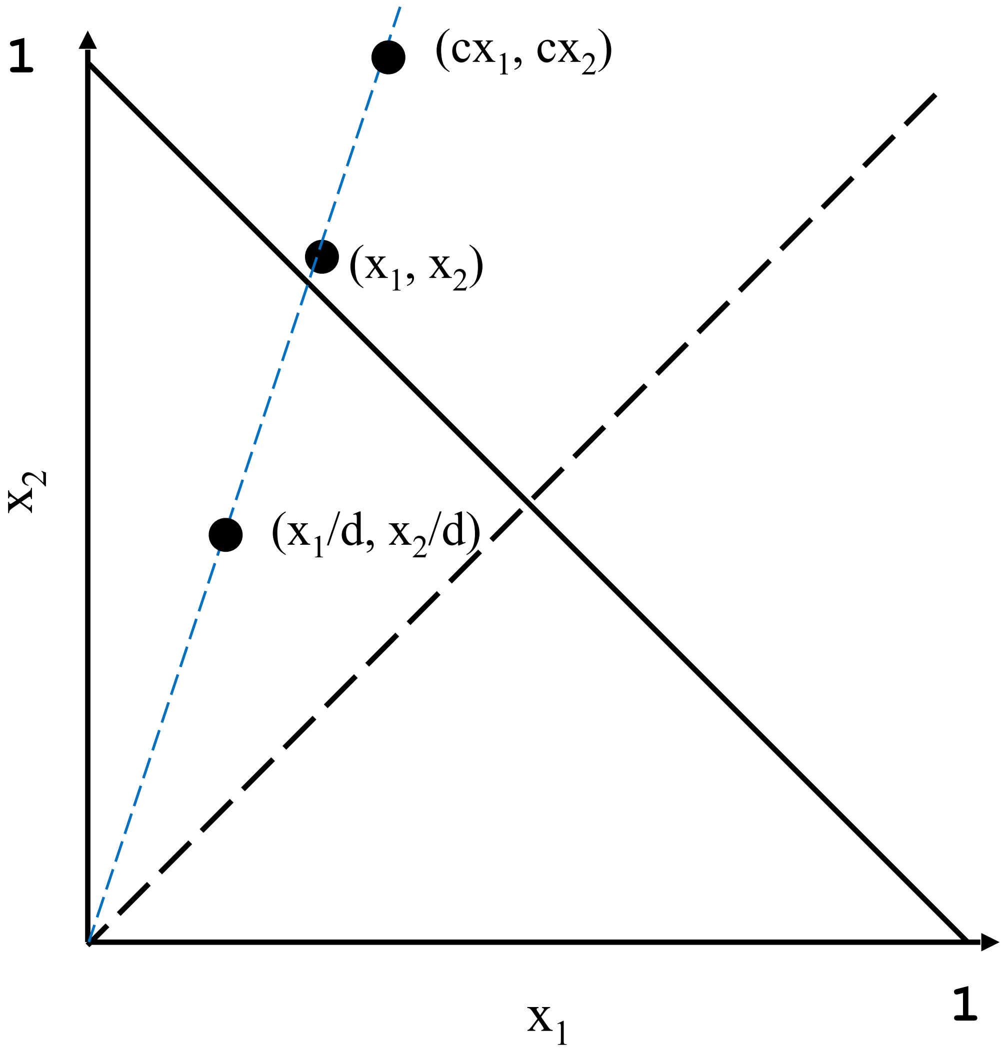

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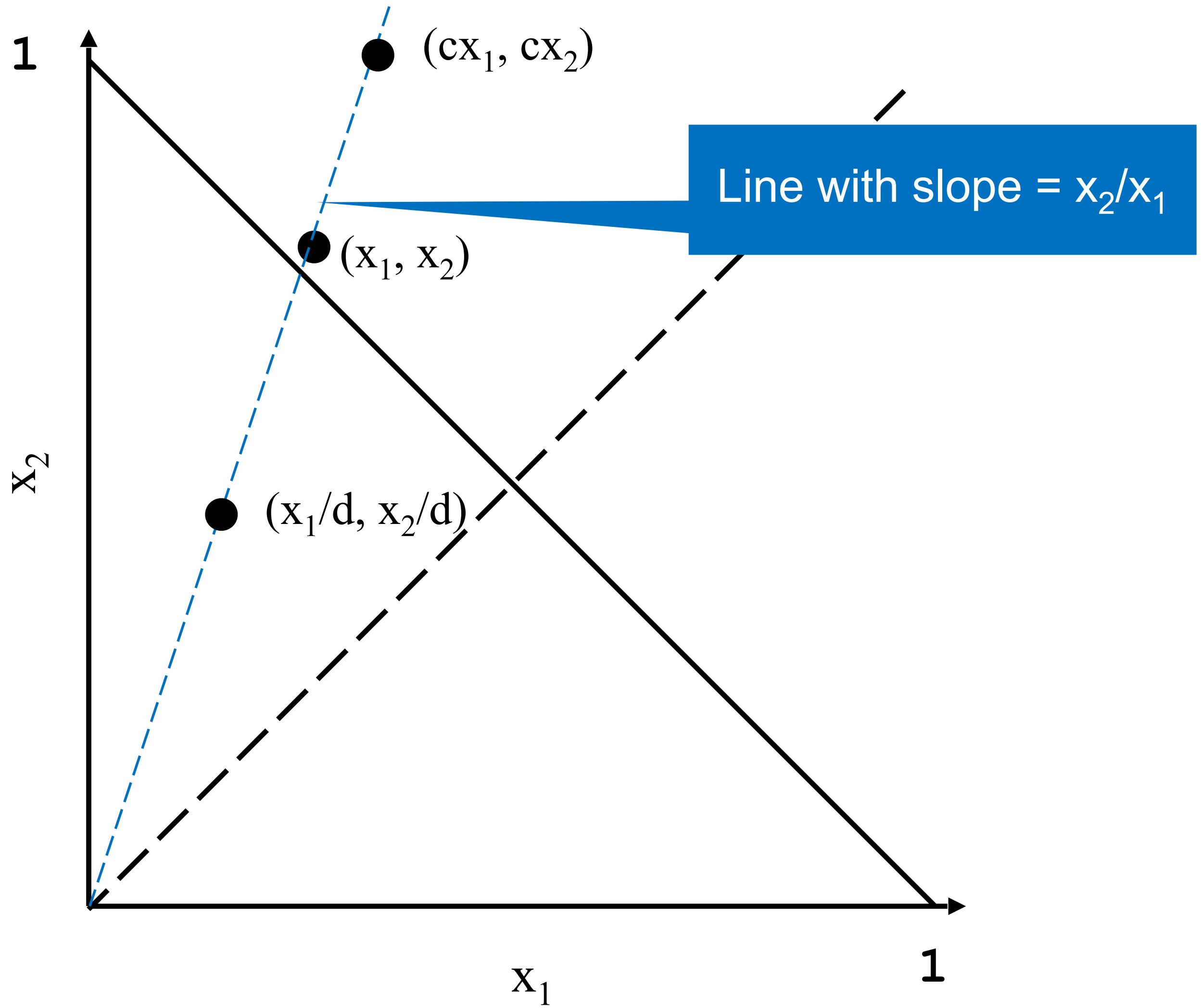

Our Four Options

Our Four Options

- AIAD: gentle increase, gentle decrease
- AIMD: gentle increase, rapid decrease
- MIAD: rapid increase, gentle decrease
- MIMD: rapid increase, rapid decrease
- **And now apply our simple model!**

AIAD Dynamics

AIAD Dynamics

- Consider: Increase: +1   Decrease: -2

AIAD Dynamics

- Consider: Increase: +1 Decrease: -2
- Start at X1 = 1, X2 = 3, with C = 5
- First iteration: no congestion
  - X1 → 2, X2 → 4

AIAD Dynamics

- Consider: Increase: +1 Decrease: -2
- Start at X1 = 1, X2 = 3, with C = 5
- First iteration: no congestion
  - X1 → 2, X2 → 4
- Second iteration: congestion
  - X1 → 0, X2 → 2

AIAD Dynamics

- Consider: Increase: +1 Decrease: -2
- Start at X1 = 1, X2 = 3, with C = 5
- First iteration: no congestion
  - X1 → 2, X2 → 4
- Second iteration: congestion
  - X1 → 0, X2 → 2
- Third iteration: no congestion
  - X1 → 1, X2 → 3

AIAD Dynamics

- Consider: Increase: +1 Decrease: -2
- Start at X1 = 1, X2 = 3, with C = 5
- First iteration: no congestion
  - X1 → 2, X2 → 4
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  - X1 → 1, X2 → 3
- …

AIAD Dynamics

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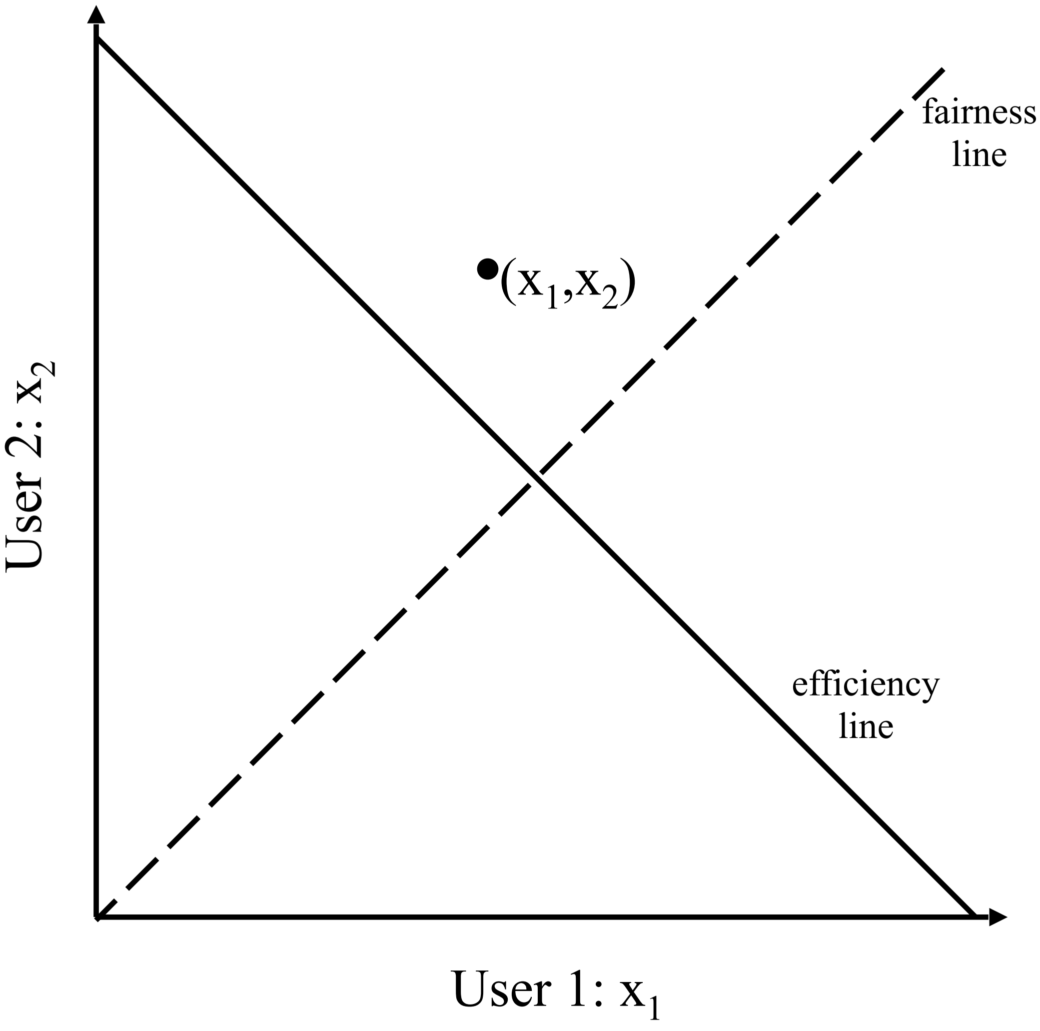
- Start at X1 = 1, X2 = 3, with C = 5
- First iteration: no congestion
  - X1 → 2, X2 → 4
- Second iteration: congestion
  - X1 → 0, X2 → 2
- Third iteration: no congestion
  - X1 → 1, X2 → 3
- …

Back where we started!
→ Gap between X1 and X2 didn't change at all

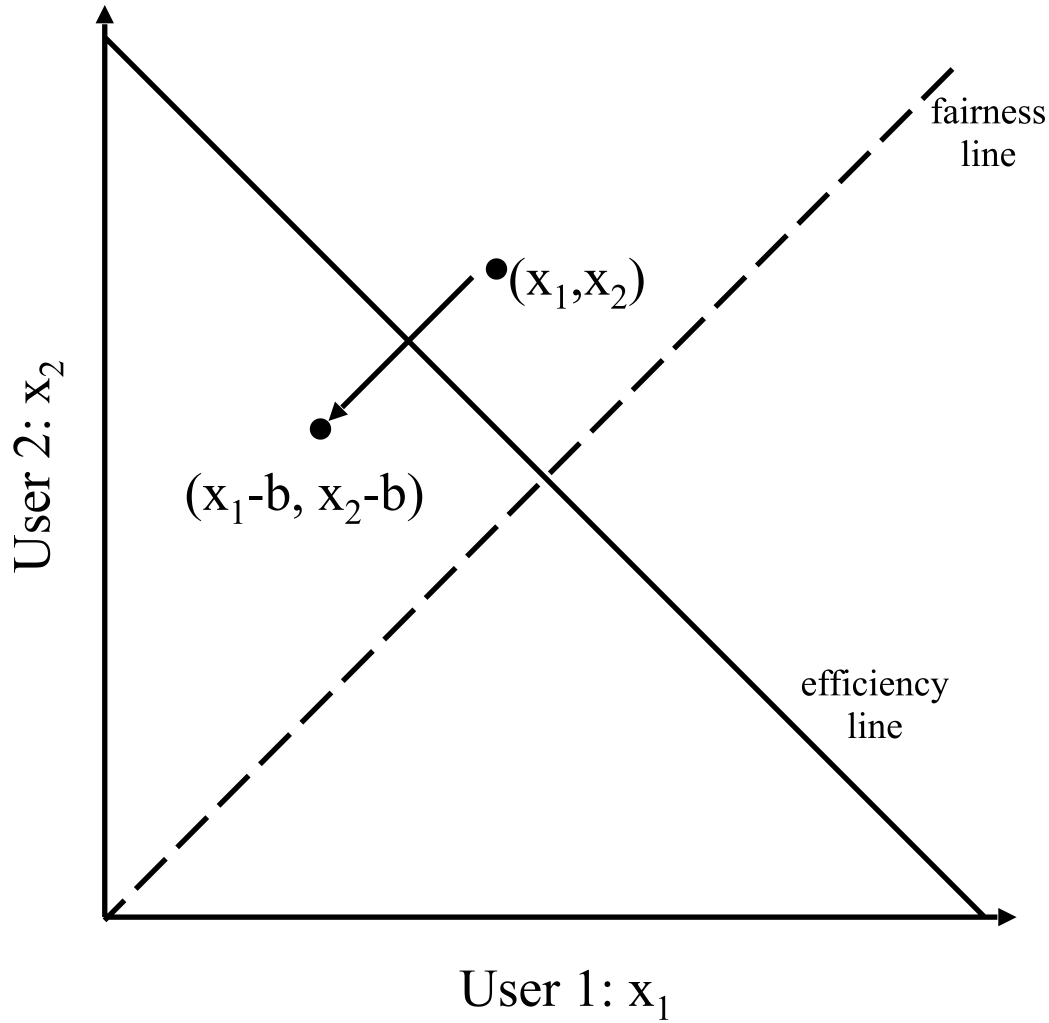
AIAD

- Increase: $x + a$
- Decrease: $x - b$



AIAD

- Increase: $x + a$
- Decrease: $x - b$



AIAD

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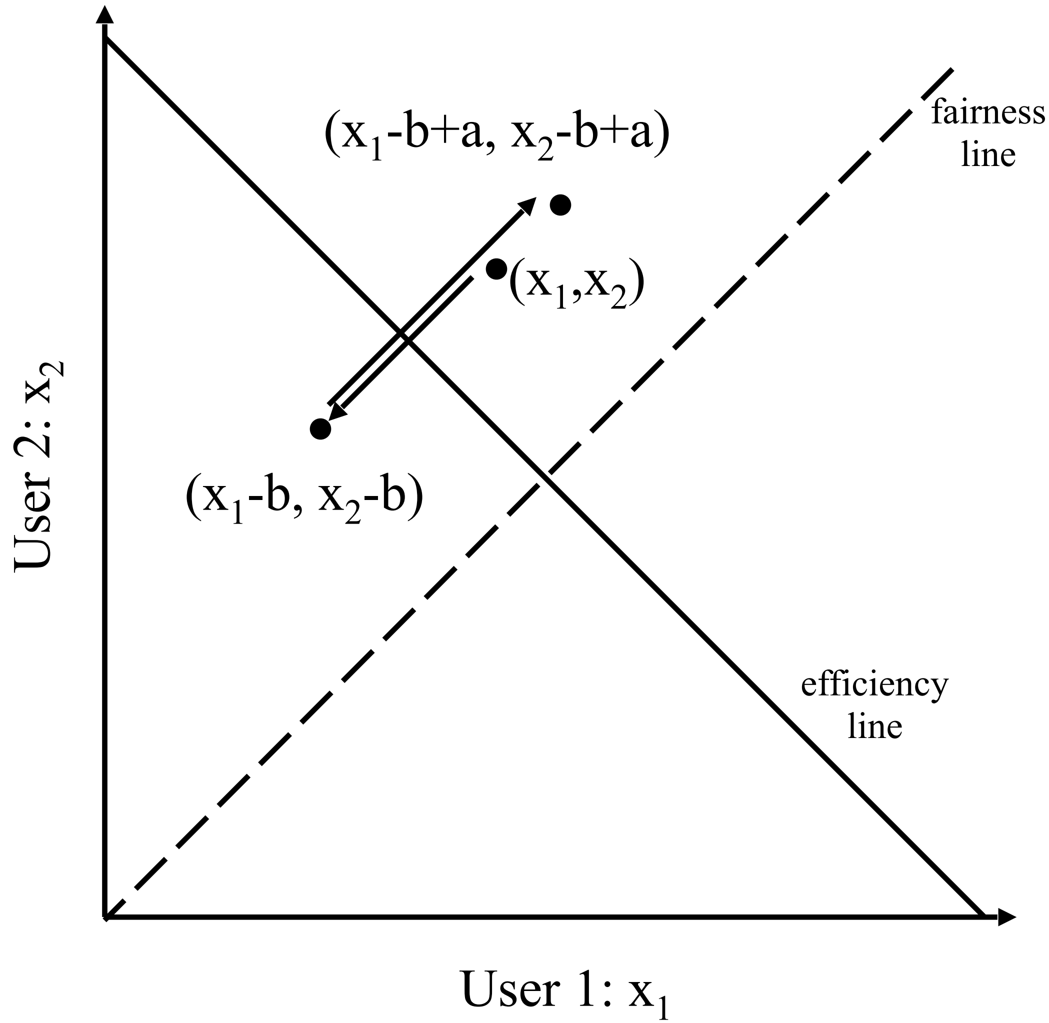
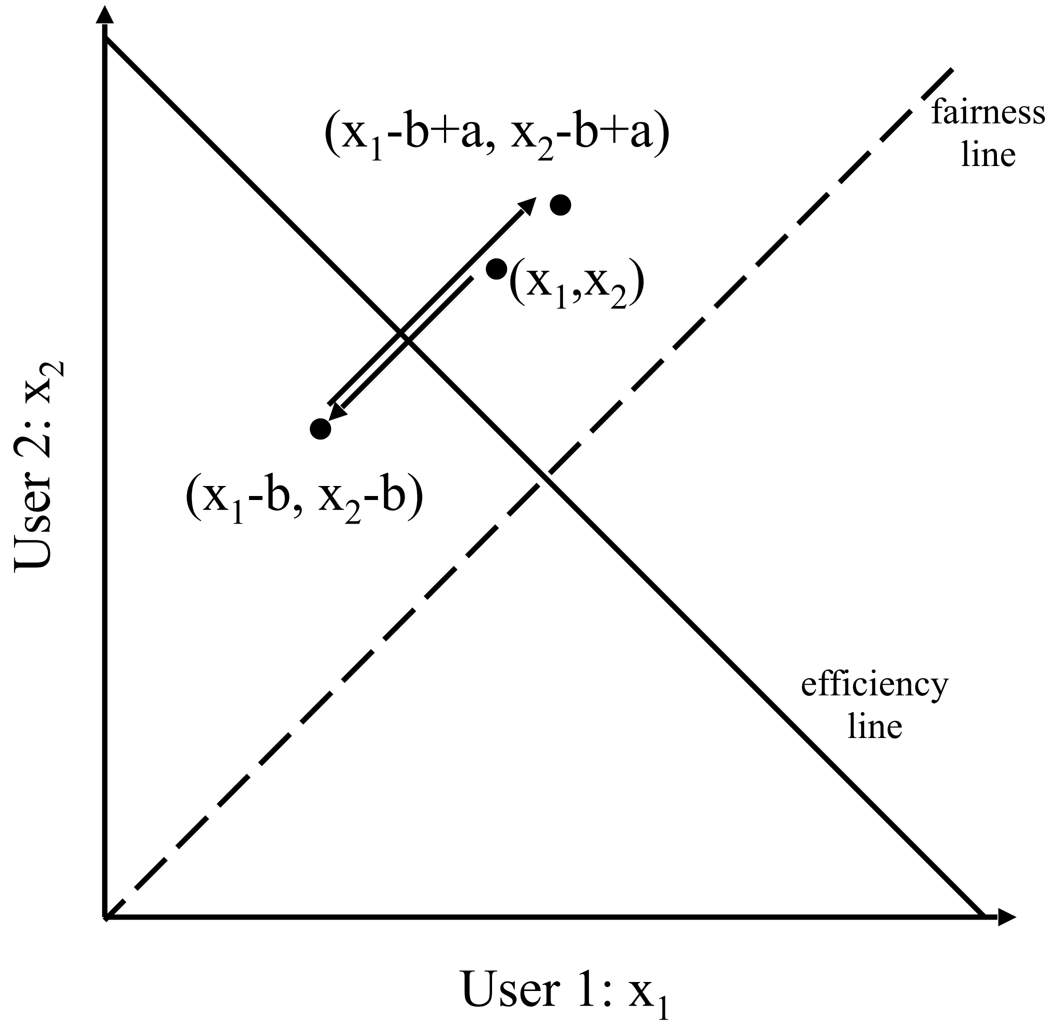


AIAD

- Increase: $x + a$
- Decrease: $x - b$

- Does not converge to fairness



MIMD Dynamics

MIMD Dynamics

- Consider: Increase: $\times 2$ Decrease: $\div 4$
- Start at X1 = ½, X2 = 1, with C = 5

MIMD Dynamics

- Consider: Increase: $\times 2$ Decrease: $\div 4$
- Start at X1 = ½, X2 = 1, with C = 5
- First iteration: no congestion
  - X1 → 1, X2 → 2
- Second iteration: no congestion
  - X1 → 2, X2 → 4

MIMD Dynamics

- Consider: Increase: $\times 2$ Decrease: $\div 4$
- Start at X1 = ½, X2 = 1, with C = 5
- First iteration: no congestion
  - X1 → 1, X2 → 2
- Second iteration: no congestion
  - X1 → 2, X2 → 4
- Third iteration: congestion
  - X1 → ½ , X2 → 1

MIMD Dynamics

- Consider: Increase: $\times 2$ Decrease: $\div 4$
- Start at X1 = ½, X2 = 1, with C = 5
- First iteration: no congestion
  - X1 → 1, X2 → 2
- Second iteration: no congestion
  - X1 → 2, X2 → 4
- Third iteration: congestion
  - X1 → ½ , X2 → 1
- …

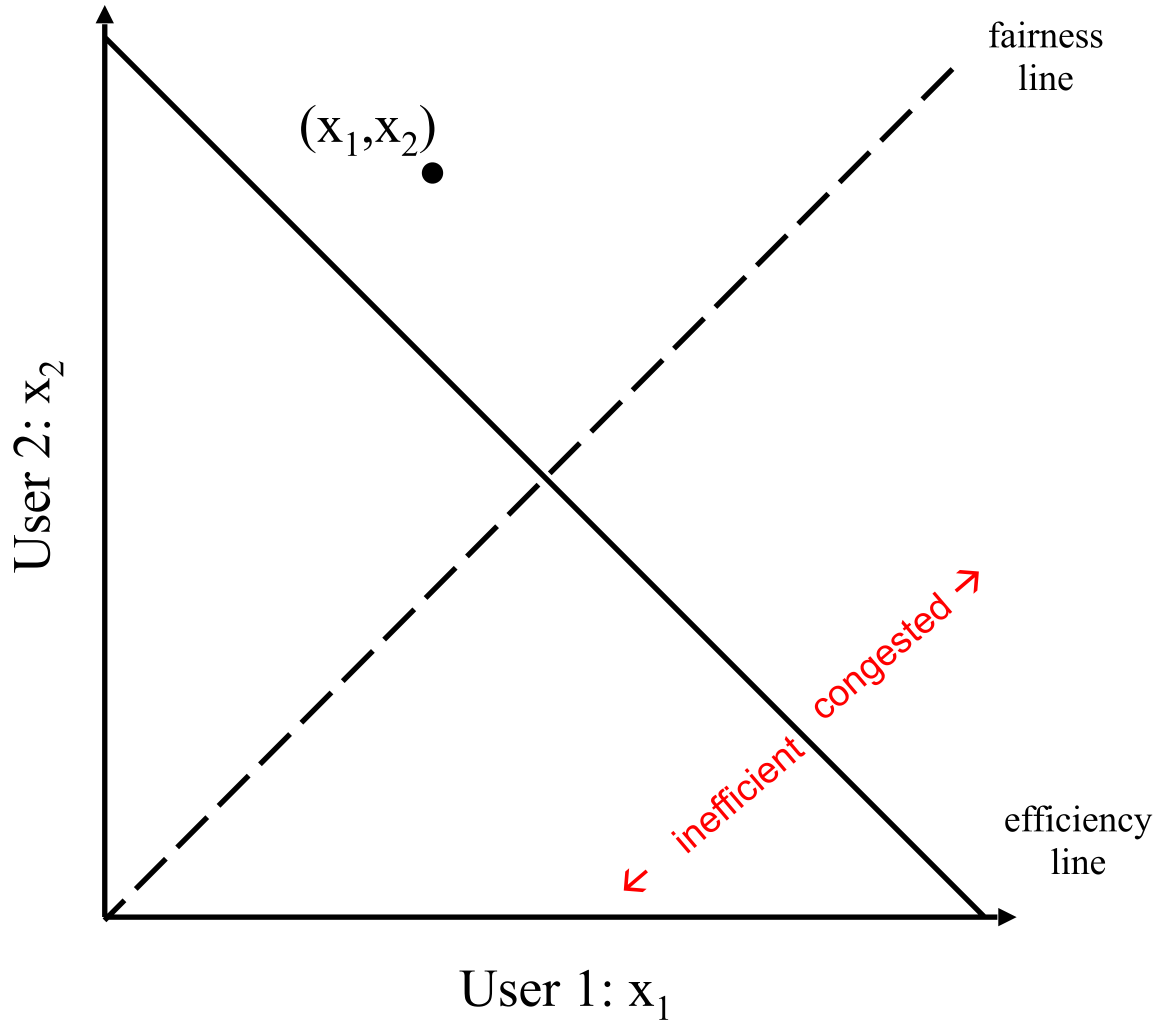
MIMD Dynamics

- Consider: Increase: $\times 2$ Decrease: $\div 4$
- Start at X1 = ½, X2 = 1, with C = 5
- First iteration: no congestion
  - X1 → 1, X2 → 2
- Second iteration: no congestion
  - X1 → 2, X2 → 4
- Third iteration: congestion
  - X1 → ½ , X2 → 1
- …

Again, no improvement in fairness

MIMD

- Increase: $x \times b_I$
- Decrease: $x \times b_D$



MIMD

- Increase: $x \times b_I$
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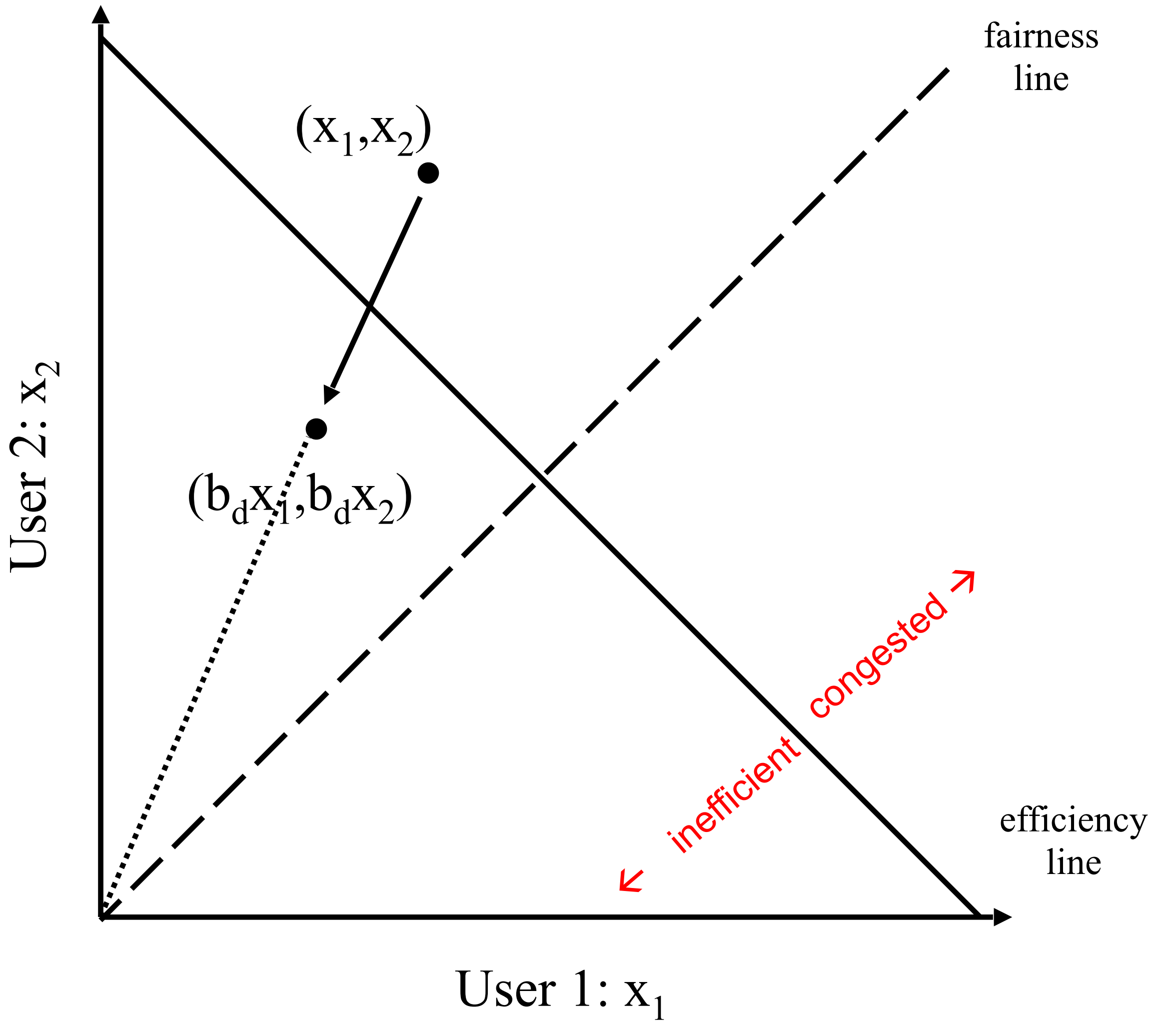
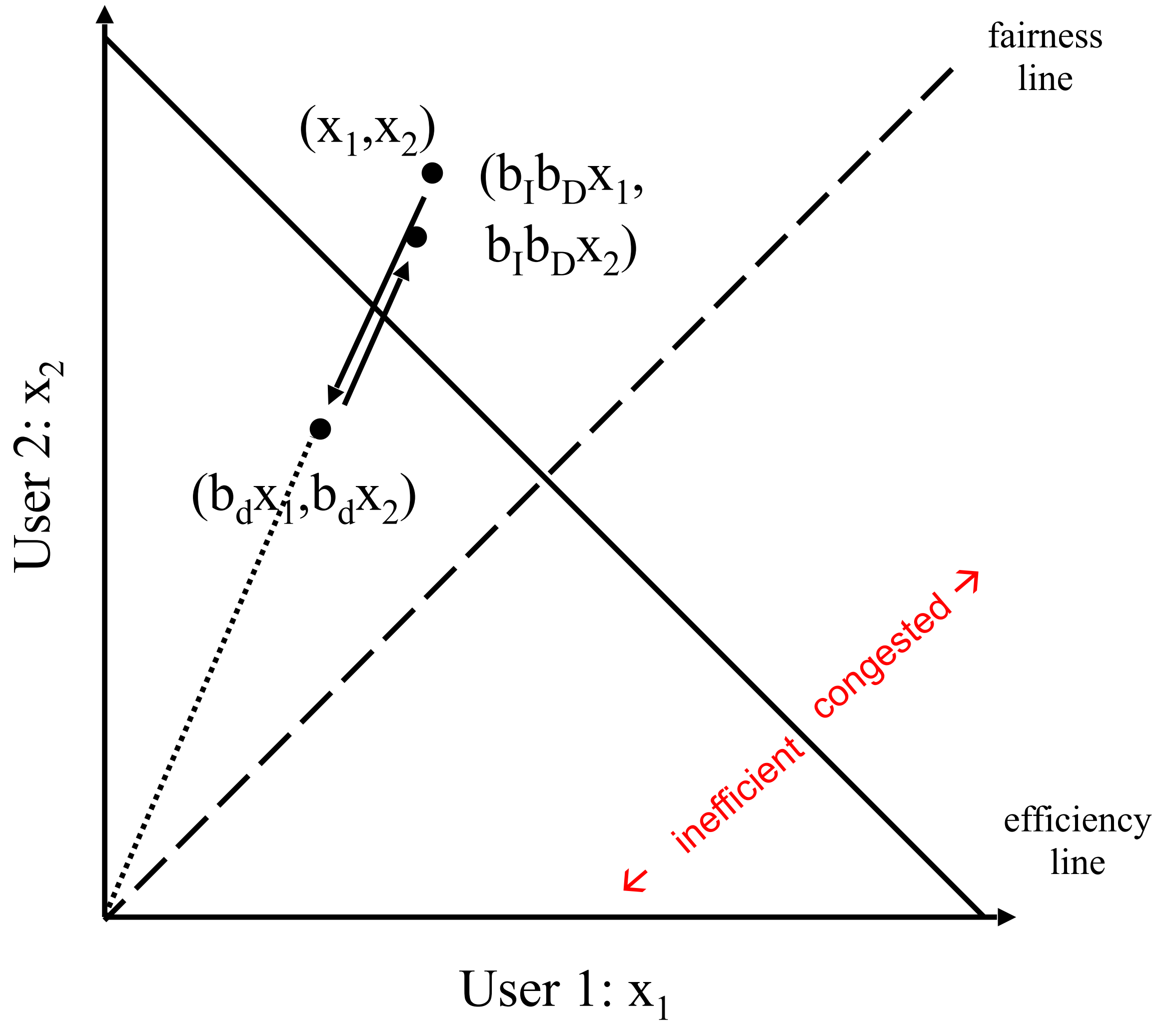


MIMD

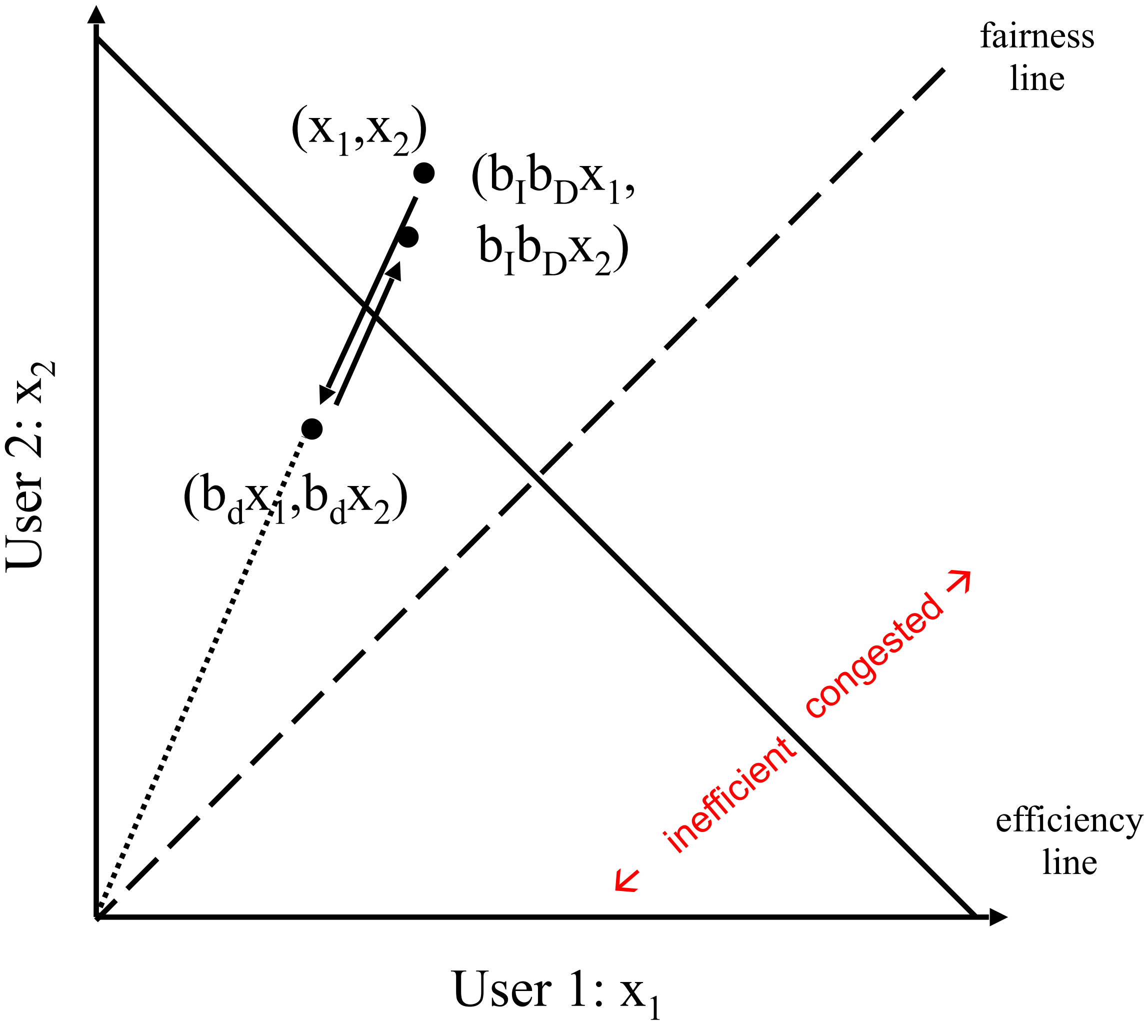
- Increase: $x \times b_I$
- Decrease: $x \times b_D$



MIMD

- Increase: $x \times b_I$
- Decrease: $x \times b_D$

- Does not converge to fairness



MIAD Dynamics

MIAD Dynamics

- Consider: Increase: $\times 2$ Decrease: -1

MIAD Dynamics

- Consider: Increase: $\times 2$ Decrease: -1
- Start at X1 = 1, X2 = 3, with C = 5
- First iteration: no congestion; X1 $\rightarrow$ 2, X2 $\rightarrow$ 6

MIAD Dynamics

- Consider: Increase: $\times 2$ Decrease: -1
- Start at X1 = 1, X2 = 3, with C = 5

- First iteration: no congestion; X1 $\rightarrow$ 2, X2 $\rightarrow$ 6
- Second iteration: congestion; X1 $\rightarrow$ 1, X2 $\rightarrow$ 5

MIAD Dynamics

- Consider: Increase: $\times 2$ Decrease: -1
- Start at X1 = 1, X2 = 3, with C = 5

- First iteration: no congestion; X1 $\rightarrow$ 2, X2 $\rightarrow$ 6
- Second iteration: congestion; X1 $\rightarrow$ 1, X2 $\rightarrow$ 5
- Third iteration: congestion; X1 $\rightarrow$ 0, X2 $\rightarrow$ 4

MIAD Dynamics

- Consider: Increase: $\times 2$ Decrease: -1
- Start at X1 = 1, X2 = 3, with C = 5

- First iteration: no congestion; X1 $\rightarrow$ 2, X2 $\rightarrow$ 6
- Second iteration: congestion; X1 $\rightarrow$ 1, X2 $\rightarrow$ 5
- Third iteration: congestion; X1 $\rightarrow$ 0, X2 $\rightarrow$ 4
- Fourth iteration: no congestion; X1 $\rightarrow$ 0, X2 $\rightarrow$ 8

MIAD Dynamics

- Consider: Increase: $\times 2$ Decrease: -1
- Start at X1 = 1, X2 = 3, with C = 5

- First iteration: no congestion; X1 $\rightarrow$ 2, X2 $\rightarrow$ 6
- Second iteration: congestion; X1 $\rightarrow$ 1, X2 $\rightarrow$ 5
- Third iteration: congestion; X1 $\rightarrow$ 0, X2 $\rightarrow$ 4
- Fourth iteration: no congestion; X1 $\rightarrow$ 0, X2 $\rightarrow$ 8

X1 pegged at 0; MIAD is maximally unfair!

AIMD Dynamics

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5
- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

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- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3
- Fifth: congestion: X1 → 1.25, X2 → 1.5

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3
- Fifth: congestion: X1 → 1.25, X2 → 1.5
- Sixth: no congestion: X1 → 2.25, X2 → 2.5

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3
- Fifth: congestion: X1 → 1.25, X2 → 1.5
- Sixth: no congestion: X1 → 2.25, X2 → 2.5
- Seventh: no congestion: X1 → 3.25, X2 → 3.5

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3
- Fifth: congestion: X1 → 1.25, X2 → 1.5
- Sixth: no congestion: X1 → 2.25, X2 → 2.5
- Seventh: no congestion: X1 → 3.25, X2 → 3.5
- Eighth: congestion: X1 → 1.625, X2 → 1.75

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3
- Fifth: congestion: X1 → 1.25, X2 → 1.5
- Sixth: no congestion: X1 → 2.25, X2 → 2.5
- Seventh: no congestion: X1 → 3.25, X2 → 3.5
- Eighth: congestion: X1 → 1.625, X2 → 1.75
- Ninth: no congestion: X1 →2.625, X2→ 2.75

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5

Diff = 1

- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3
- Fifth: congestion: X1 → 1.25, X2 → 1.5
- Sixth: no congestion: X1 → 2.25, X2 → 2.5
- Seventh: no congestion: X1 → 3.25, X2 → 3.5
- Eighth: congestion: X1 → 1.625, X2 → 1.75
- Ninth: no congestion: X1 →2.625, X2→ 2.75

AIMD Dynamics

- Consider: Increase: $+1$ Decrease: $\div 2$
- Start at X1 = 1, X2 = 2, with C = 5 — Diff = 1

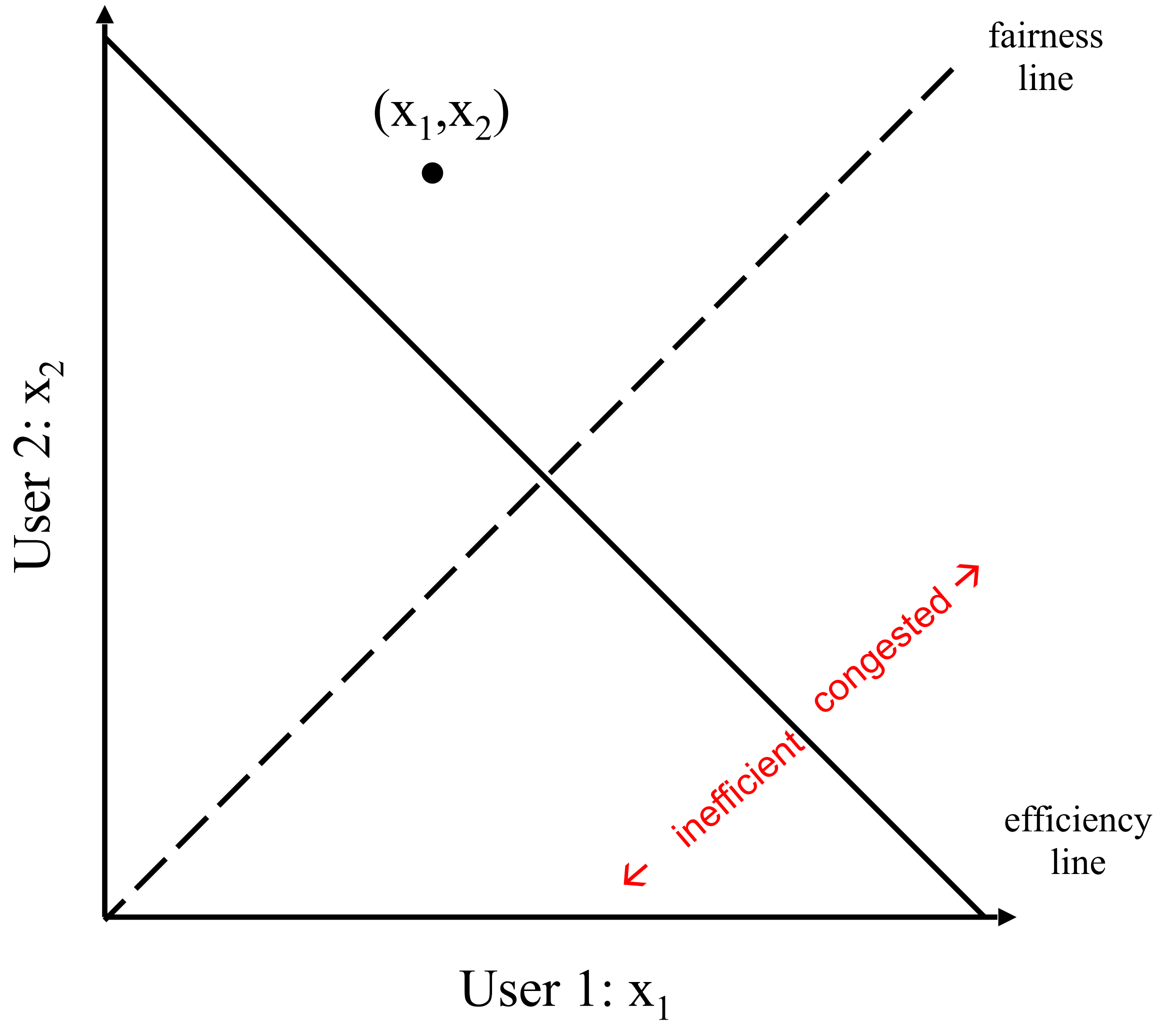
- First iteration: no congestion: X1 $\rightarrow$ 2, X2 $\rightarrow$ 3 — Diff = 1
- Second: no congestion: X1 $\rightarrow$ 3, X2 $\rightarrow$ 4 — Diff = 1
- Third: congestion: X1 $\rightarrow$ 1.5, X2 $\rightarrow$ 2 — Diff = 0.5
- Fourth: no congestion: X1 $\rightarrow$ 2.5, X2 $\rightarrow$ 3 — Diff = 0.5
- Fifth: congestion: X1 → 1.25, X2 → 1.5 — Diff = 0.25
- Sixth: no congestion: X1 → 2.25, X2 → 2.5 — Diff = 0.25
- Seventh: no congestion: X1 → 3.25, X2 → 3.5 — Diff = 0.25
- Eighth: congestion: X1 → 1.625, X2 → 1.75 — Diff = 0.125
- Ninth: no congestion: X1 →2.625, X2→ 2.75 — Diff = 0.125

AIMD

- Difference between X1 and X2 decreasing!
  - Difference stays constant when increasing
  - Halves every time there is a decrease

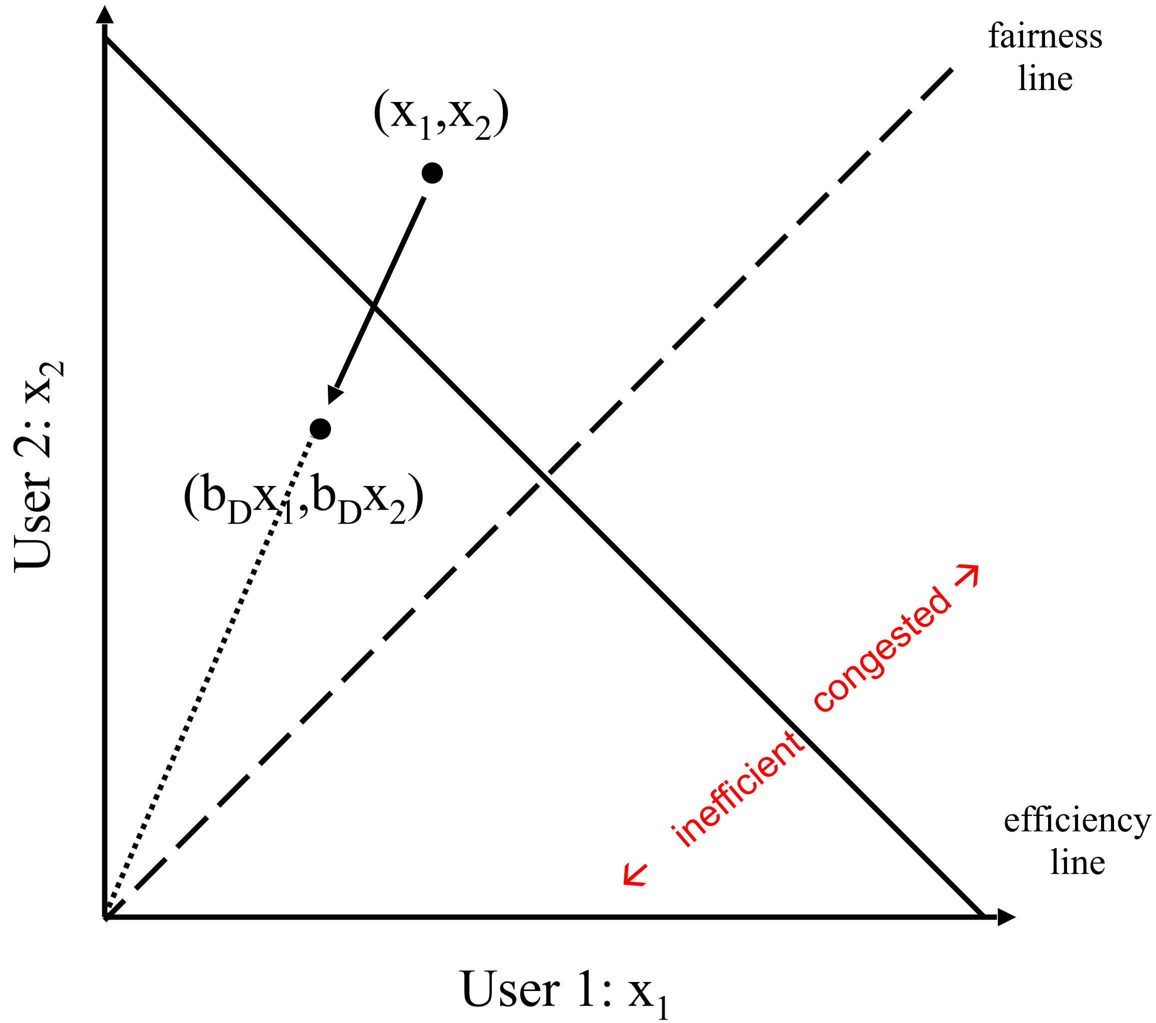
AIMD

- Increase: $x+a_I$
- Decrease: $x*b_D$



AIMD

- Increase: $x+a_I$
- Decrease: $x*b_D$



AIMD

- Increase: $x+a_I$
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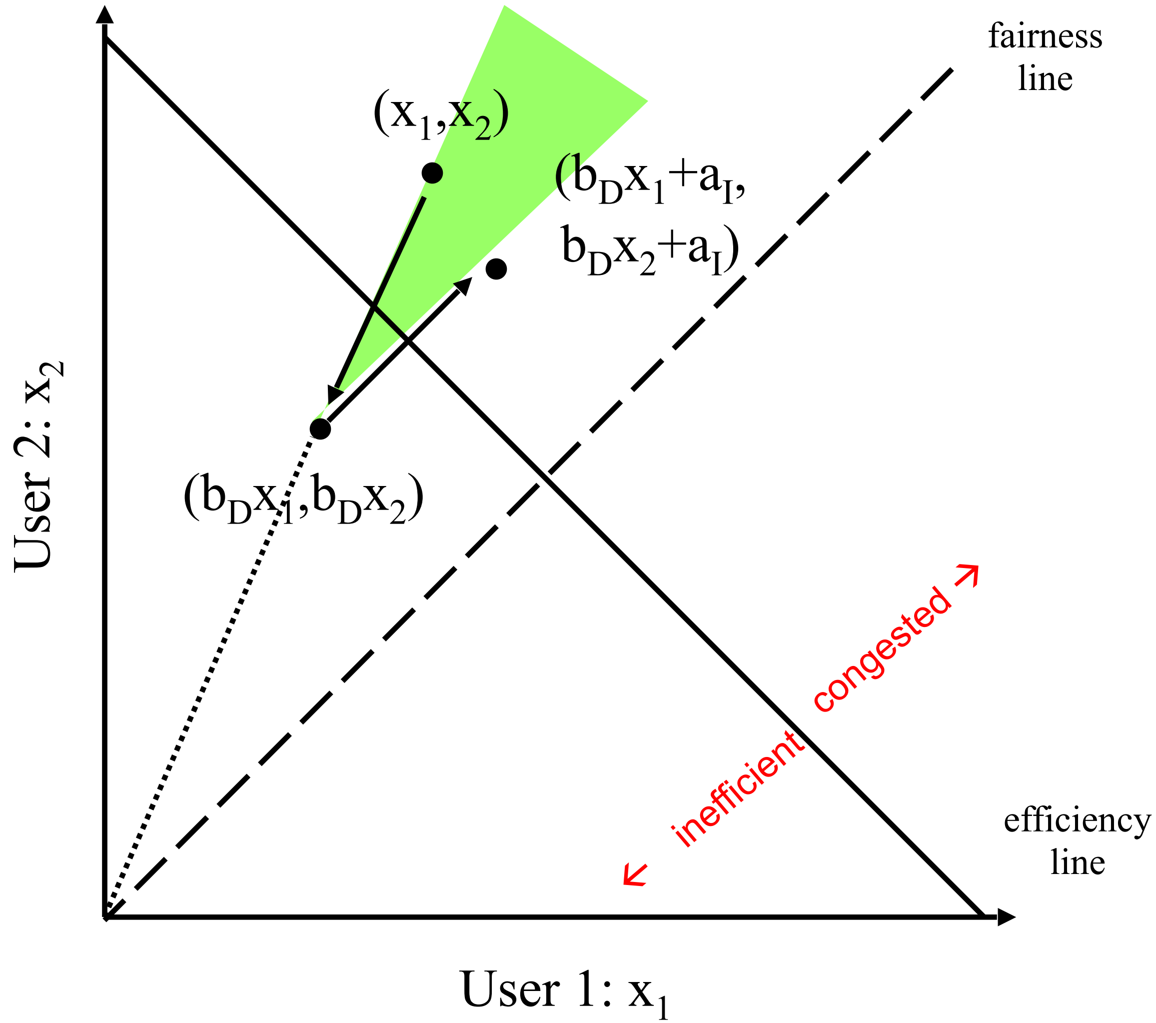

AIMD

- Increase: $x+a_I$
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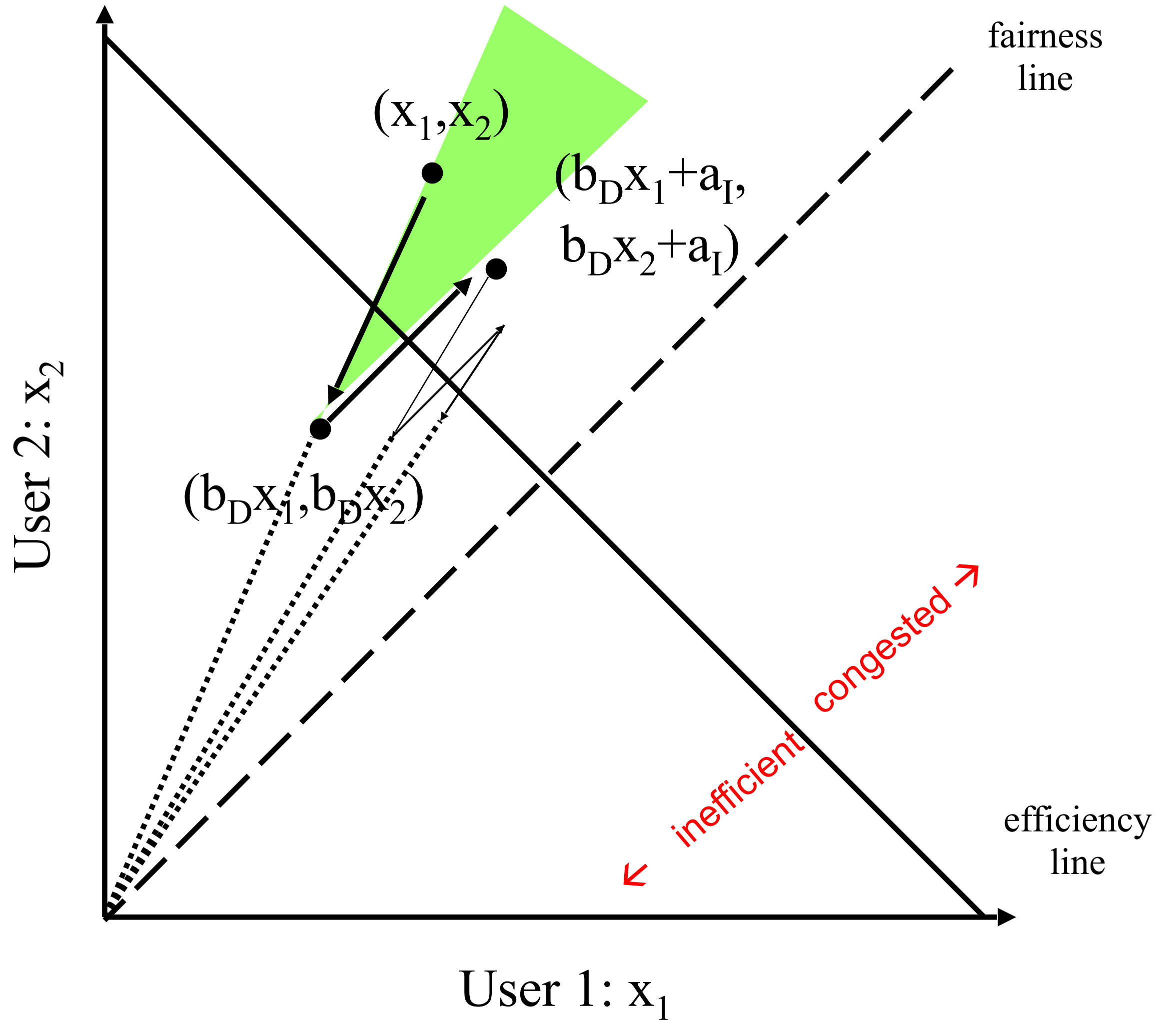
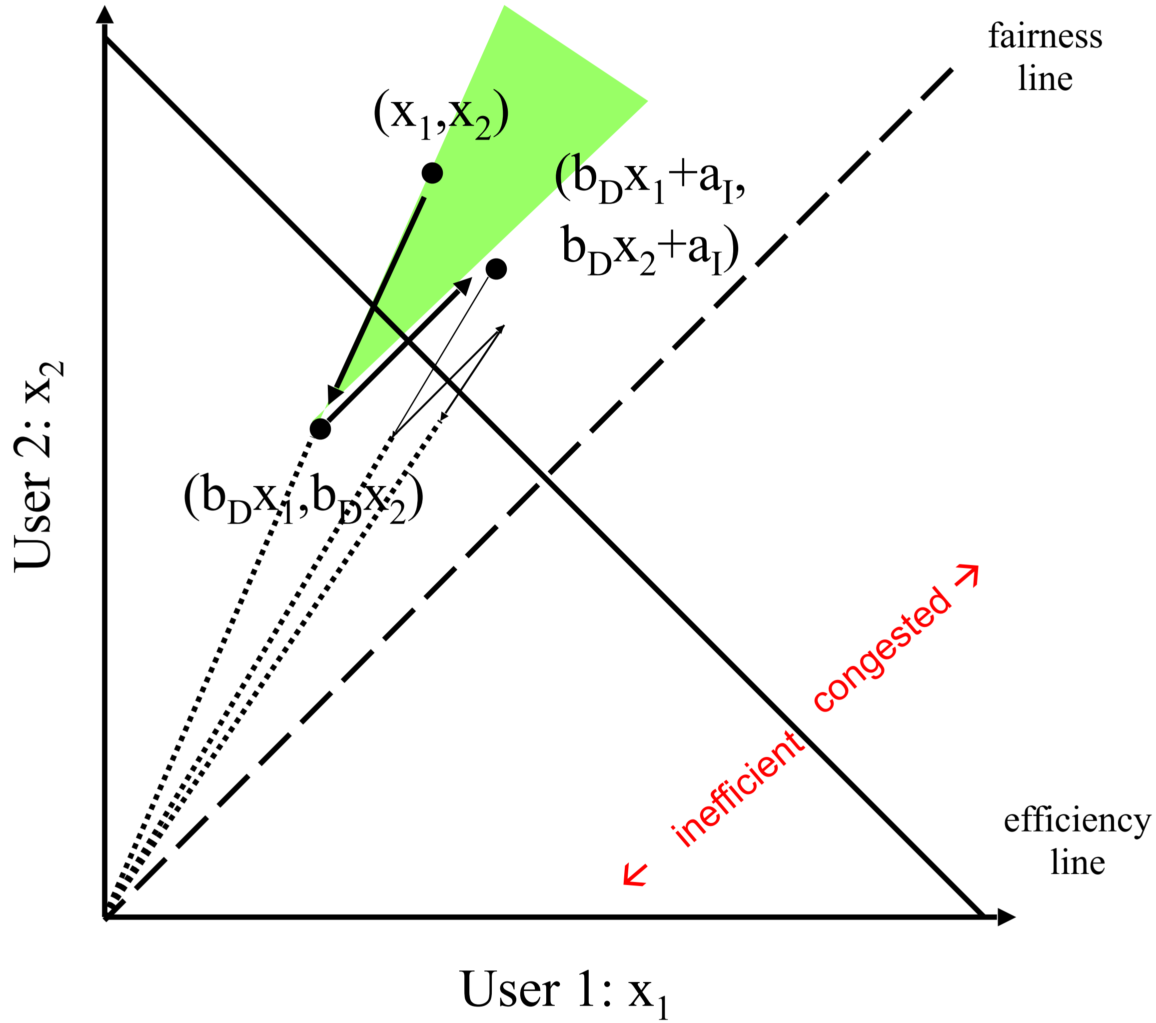


AIMD

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



Answer to Why AIMD?

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- AIMD embodies gentle increase, rapid decrease

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- AIMD embodies gentle increase, rapid decrease
- AIMD only choice that drives us towards “fairness”

Answer to Why AIMD?

- AIMD embodies gentle increase, rapid decrease

- AIMD only choice that drives us towards "fairness"

- Out of the four options
  - AIAD, MIMD: retain unfairness
  - MIAD: maximally unfair
  - AIMD: fair and appropriate gentle/rapid actions

Any Questions?

Sketch of a solution

Sketch of a solution

Each source independently runs the following:

Sketch of a solution

Each source <u>independently</u> runs the following:

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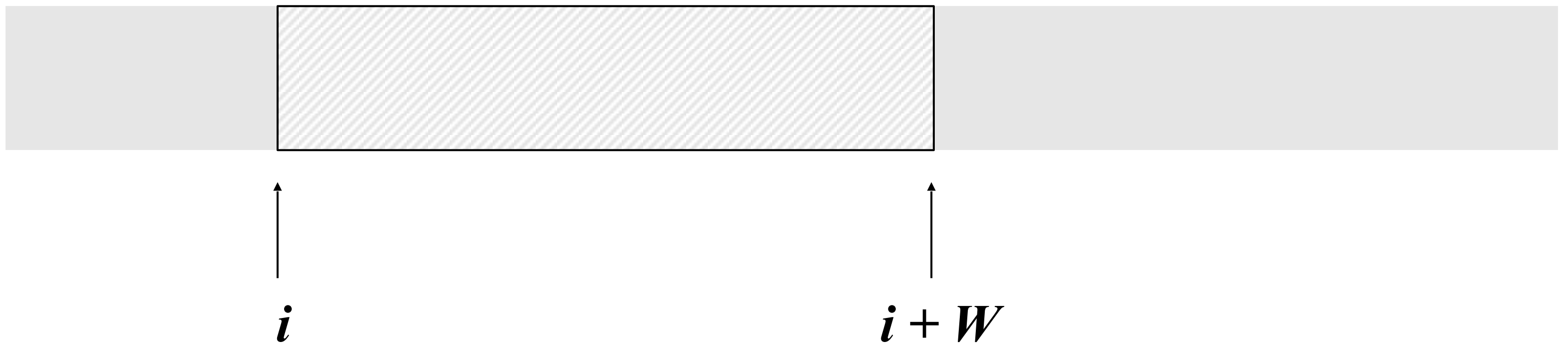
- **Sender-side window = min{CWND, RWND}**
  - Assume for this lecture that RWND > CWND

Note

- **Recall: TCP operates on bytestreams**
- **Hence, real implementations maintain CWND in bytes**
- **This lecture will talk about CWND in units of MSS**
  - MSS: Maximum Segment Size, the max number of bytes of data that one TCP packet can carry in its payload
  - This is only for pedagogical purposes

Review:



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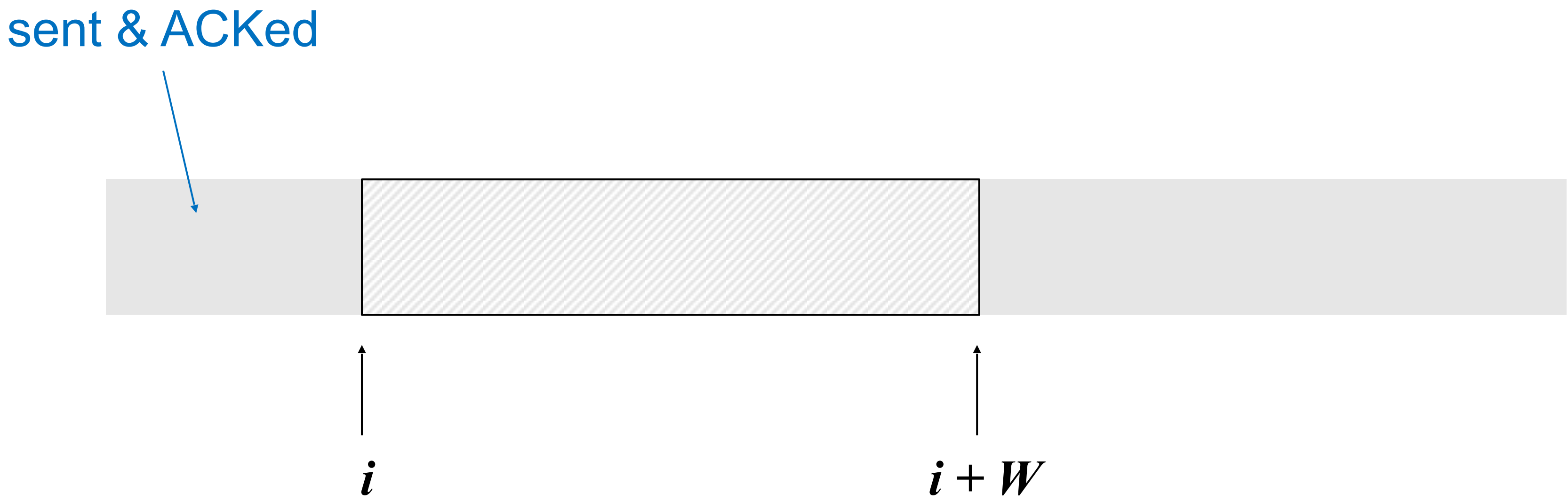

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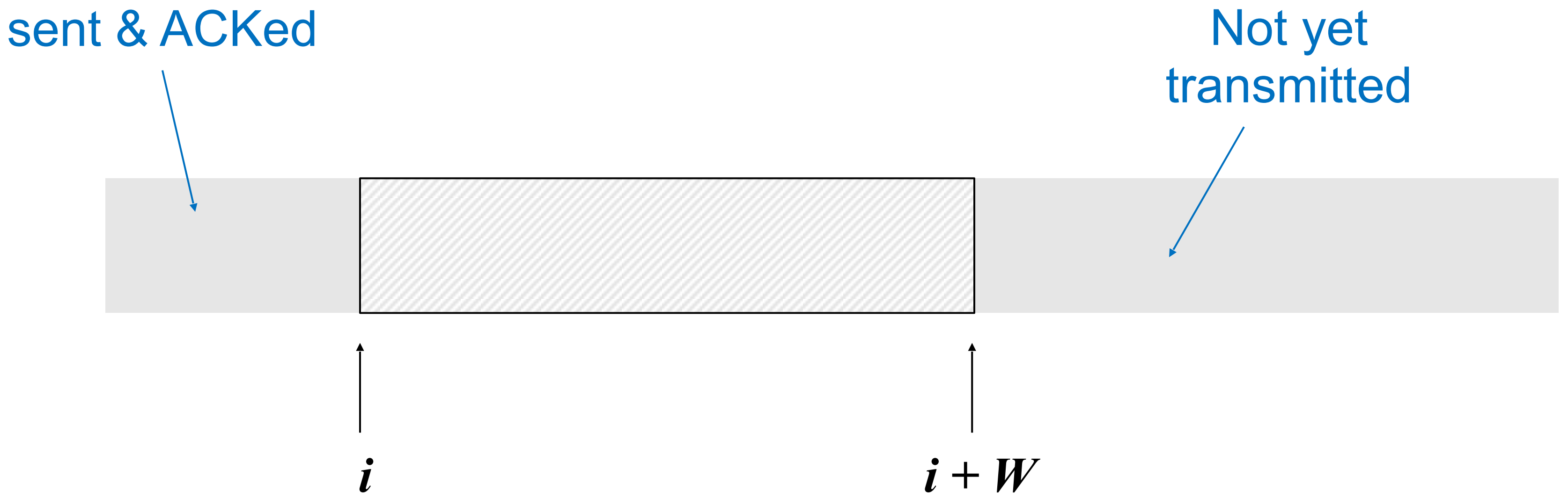

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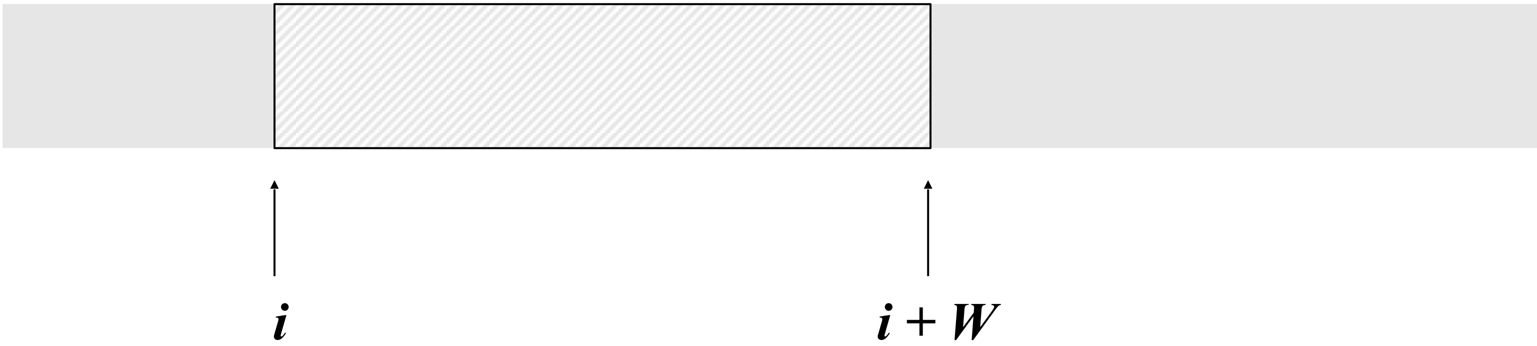

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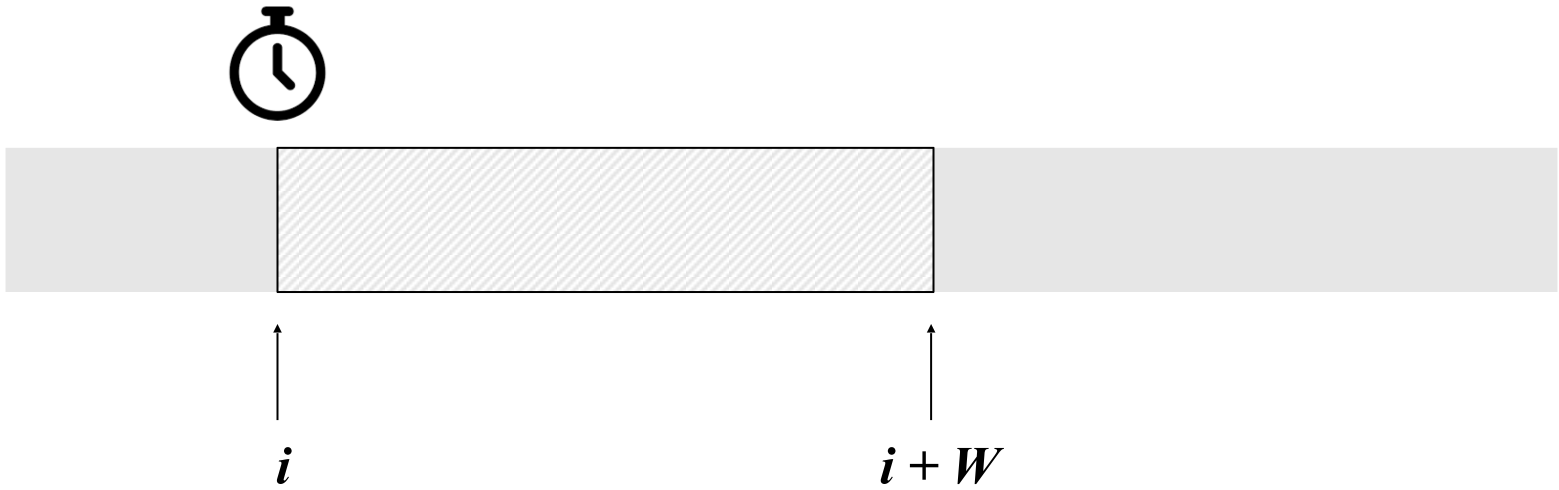

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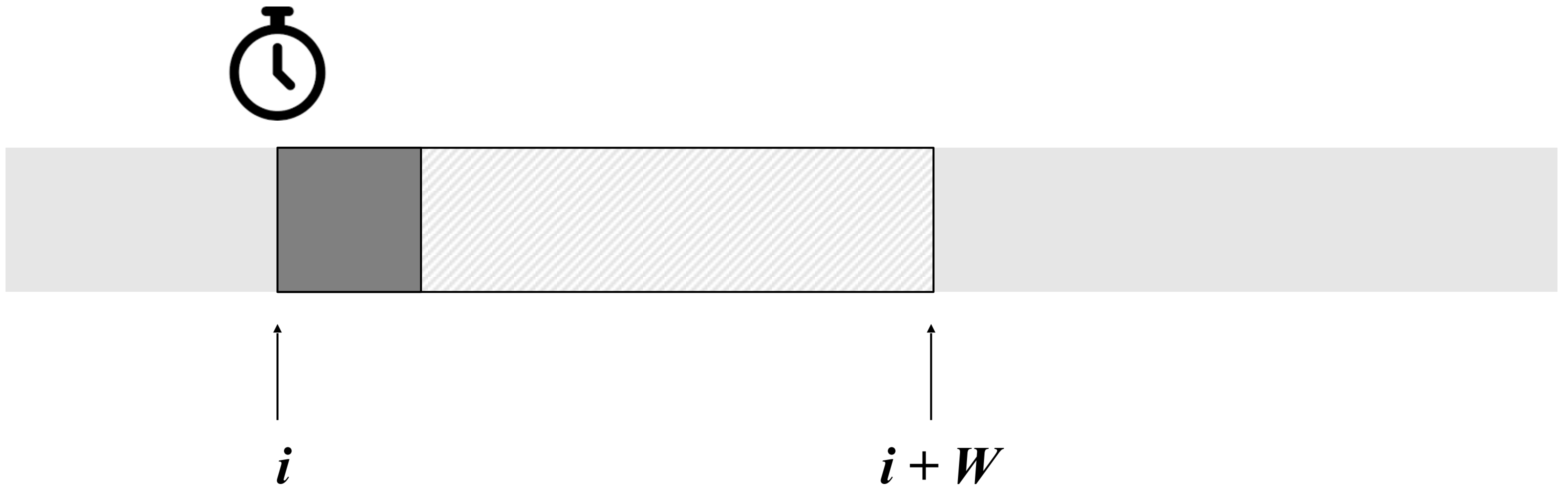

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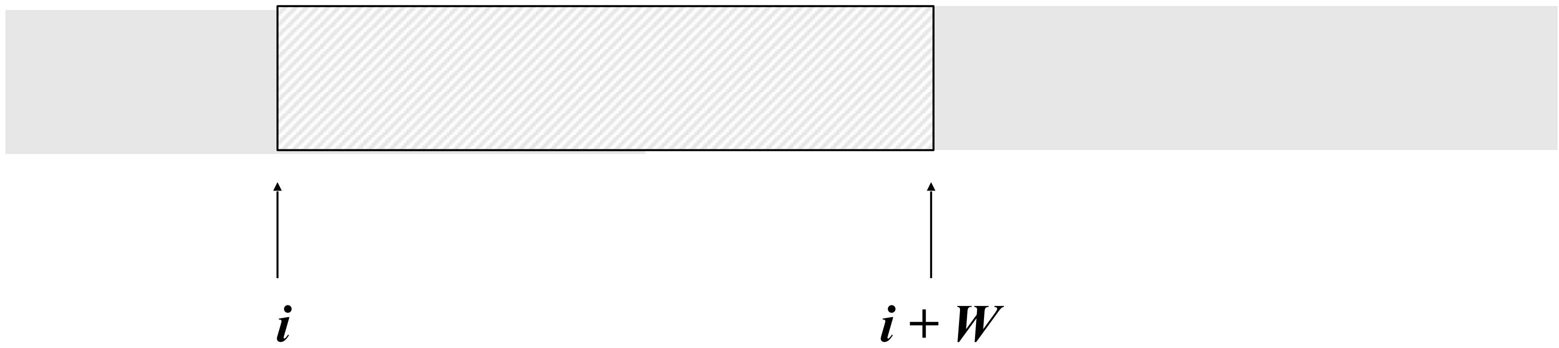

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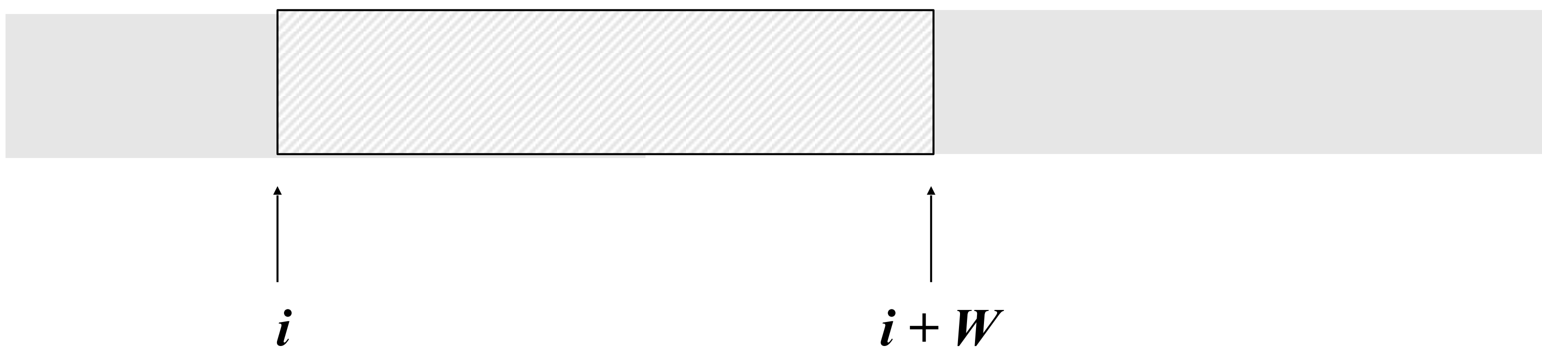

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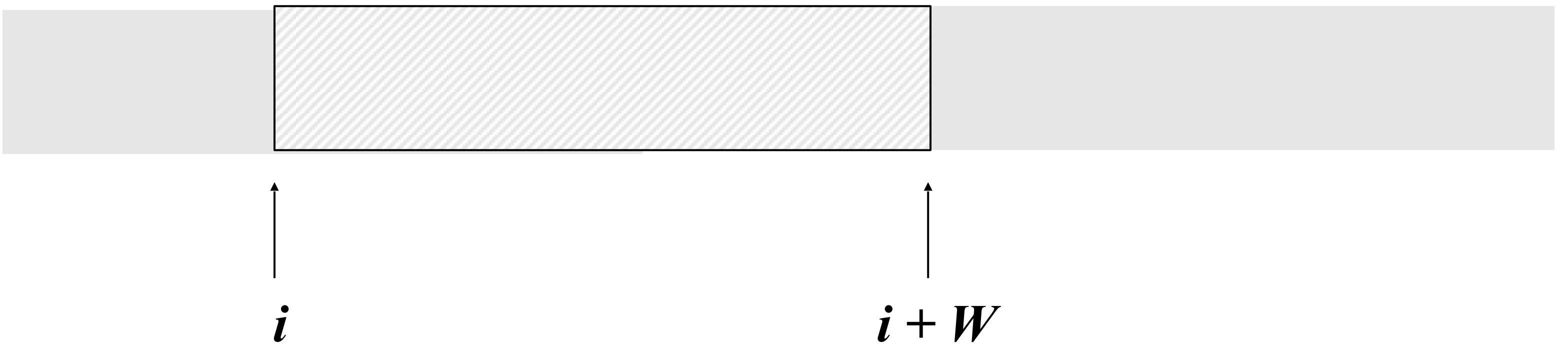

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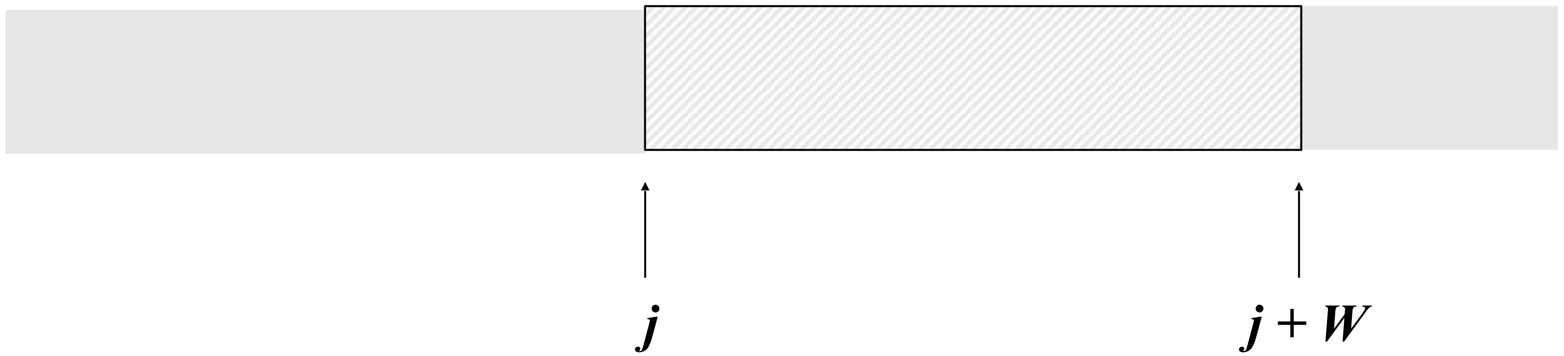

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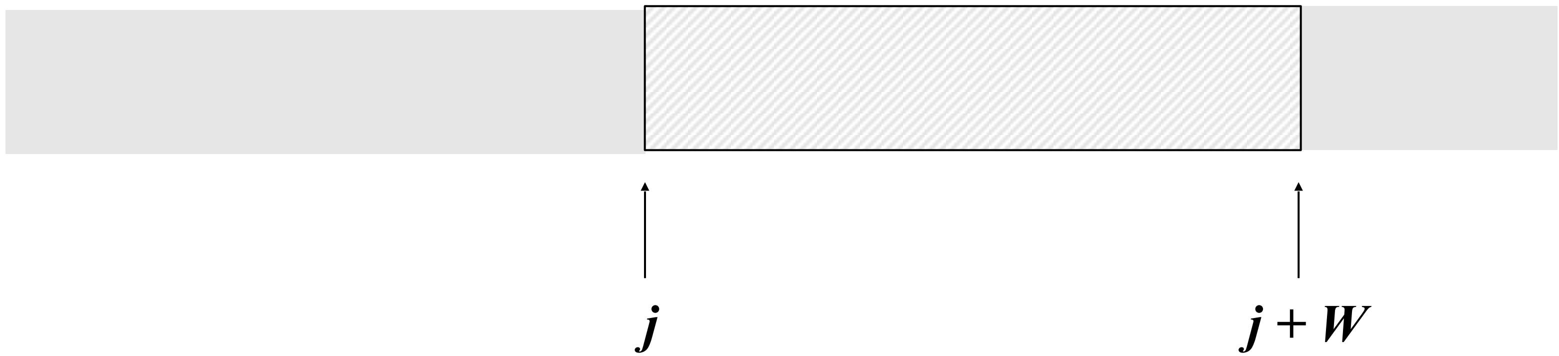

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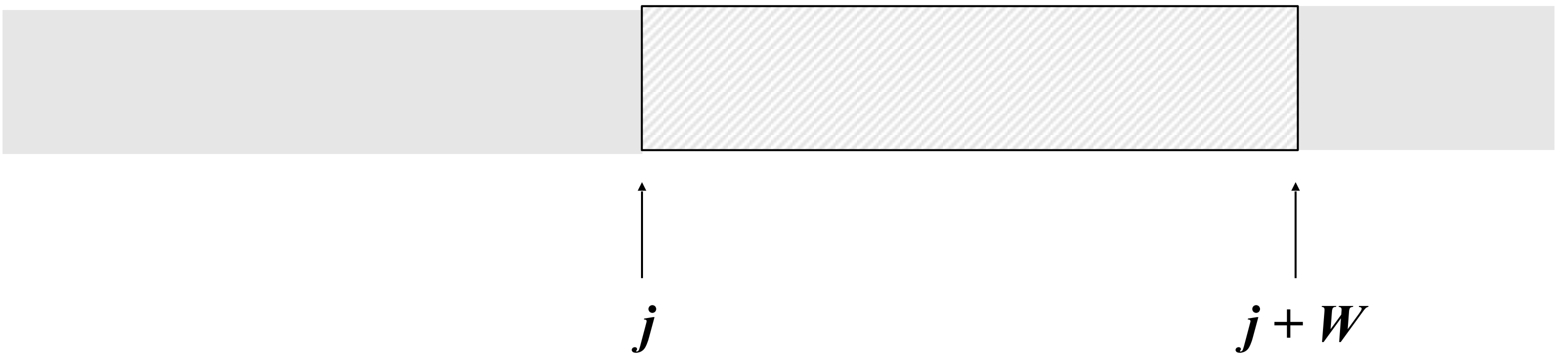

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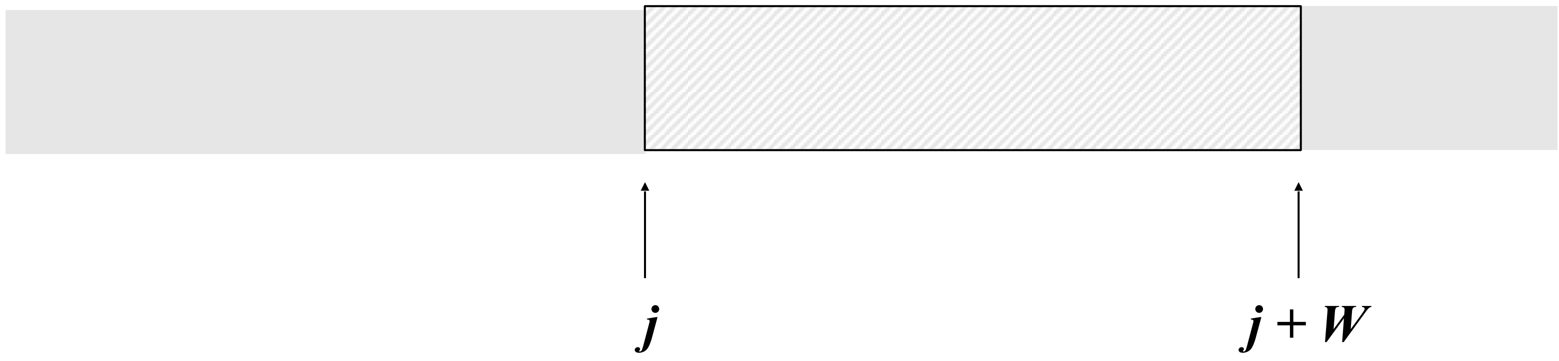

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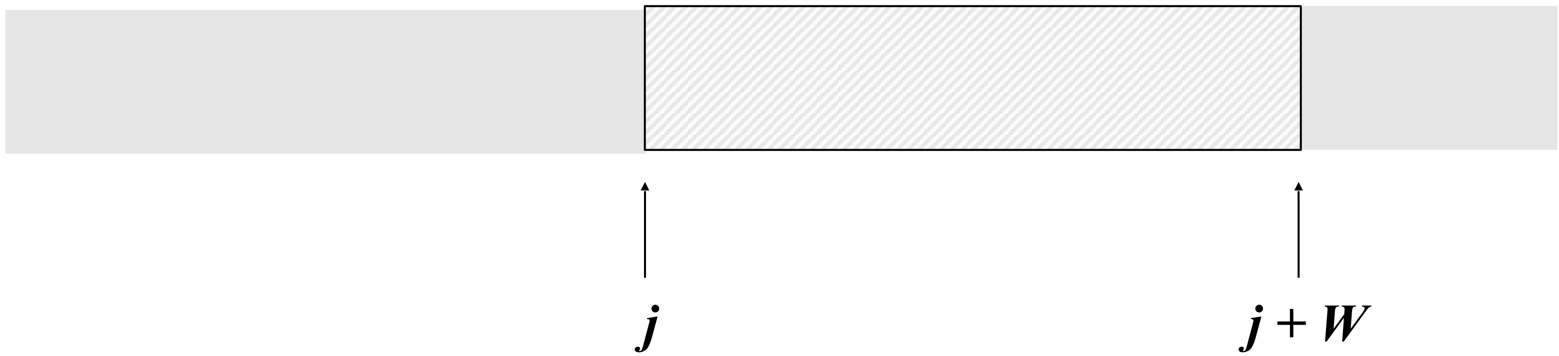

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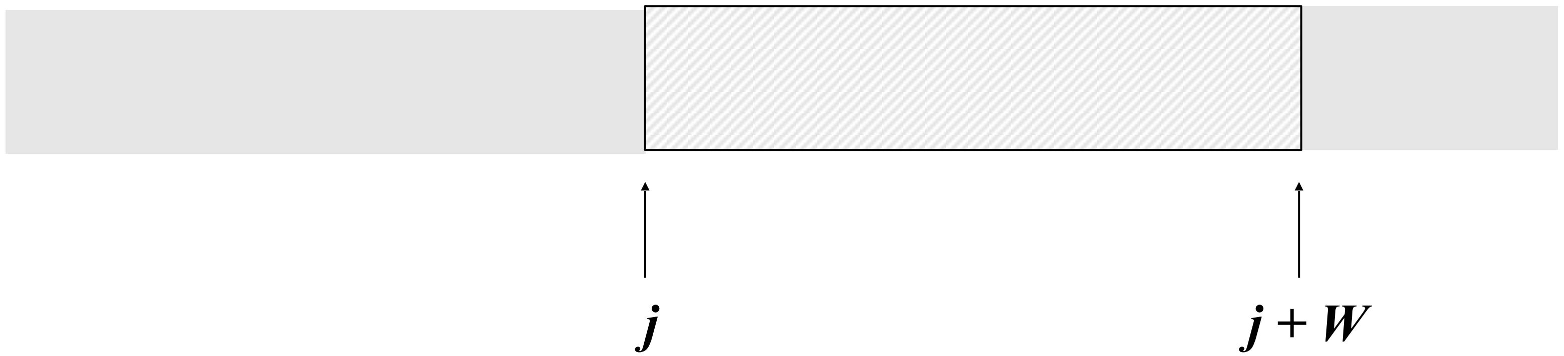

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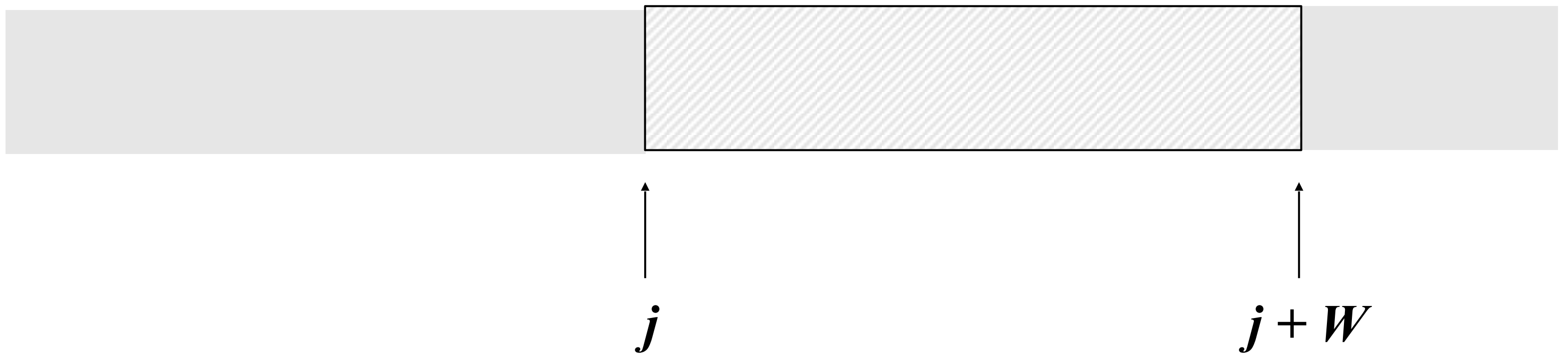

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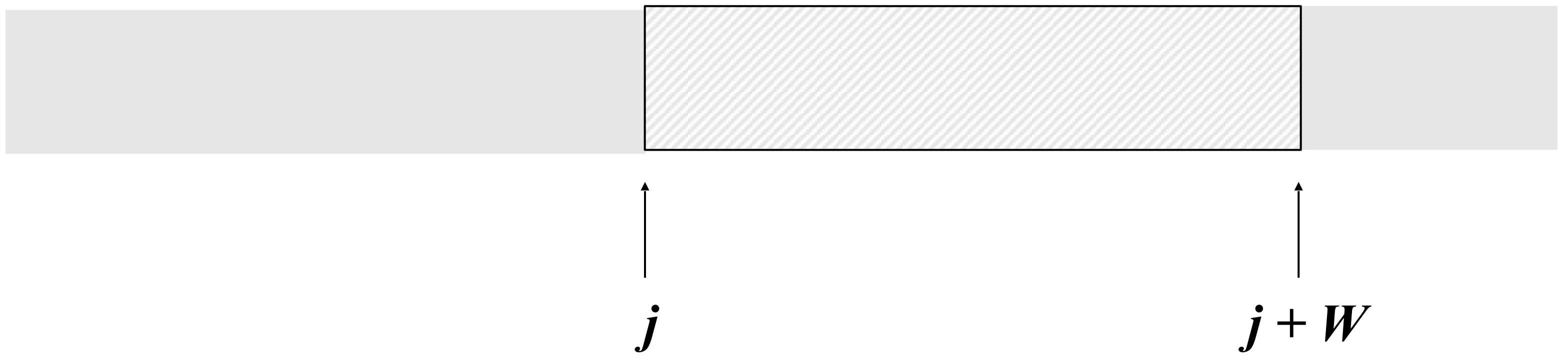

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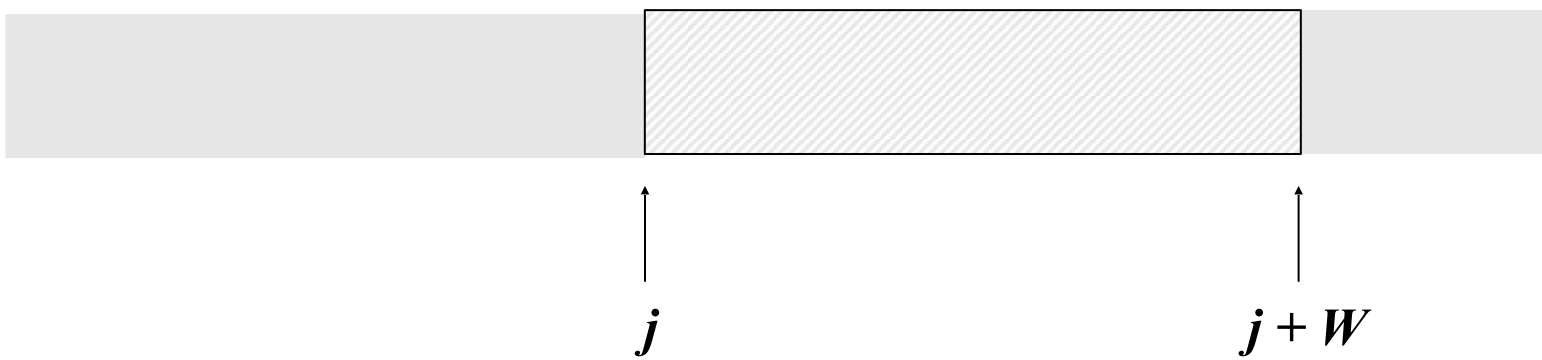

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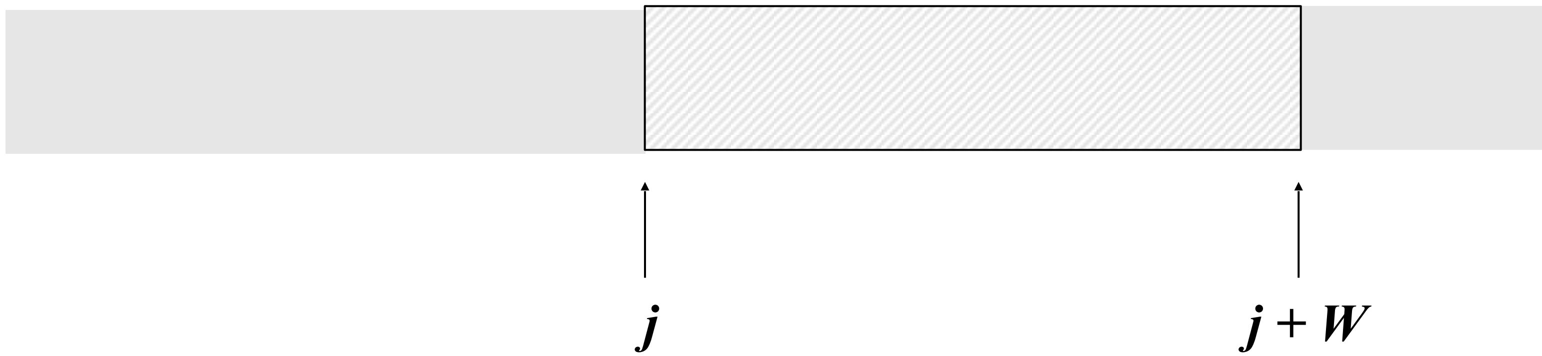

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- Adapting CWND → adapting sender's rate

Recall: how we adapt rate

- Detecting congestion
  - **Loss-based**
- Discovering an initial rate
  - **Slow start**
- Adapting rate to congestion (or lack thereof)
  - **AIMD**

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- Three types of events relevant to CC
  - New ACK
  - k(=3) duplicate ACKs
  - Timeout

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- Let's take a closer look at how this is implemented...

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Slow Start in Action

Goal: Double CWND every round-trip time

Simple implementation: On each ACK, CWND += 1 (MSS)

Src

Dest

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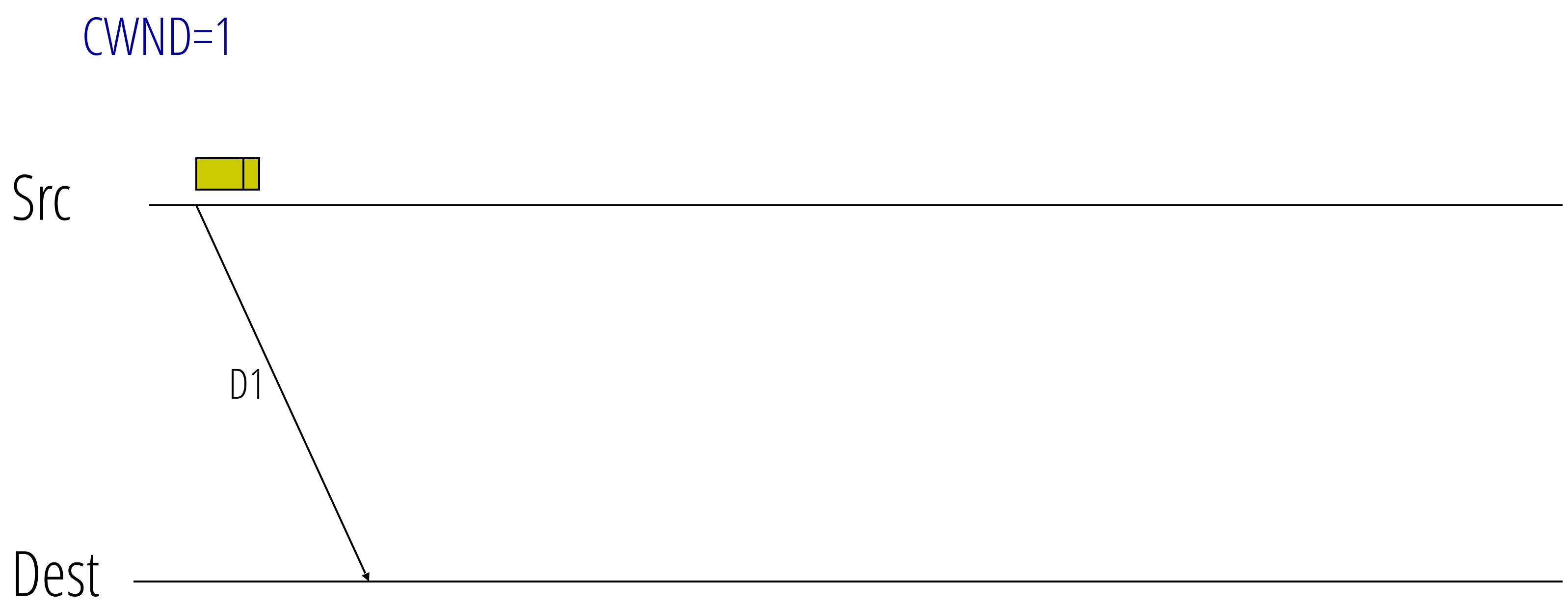

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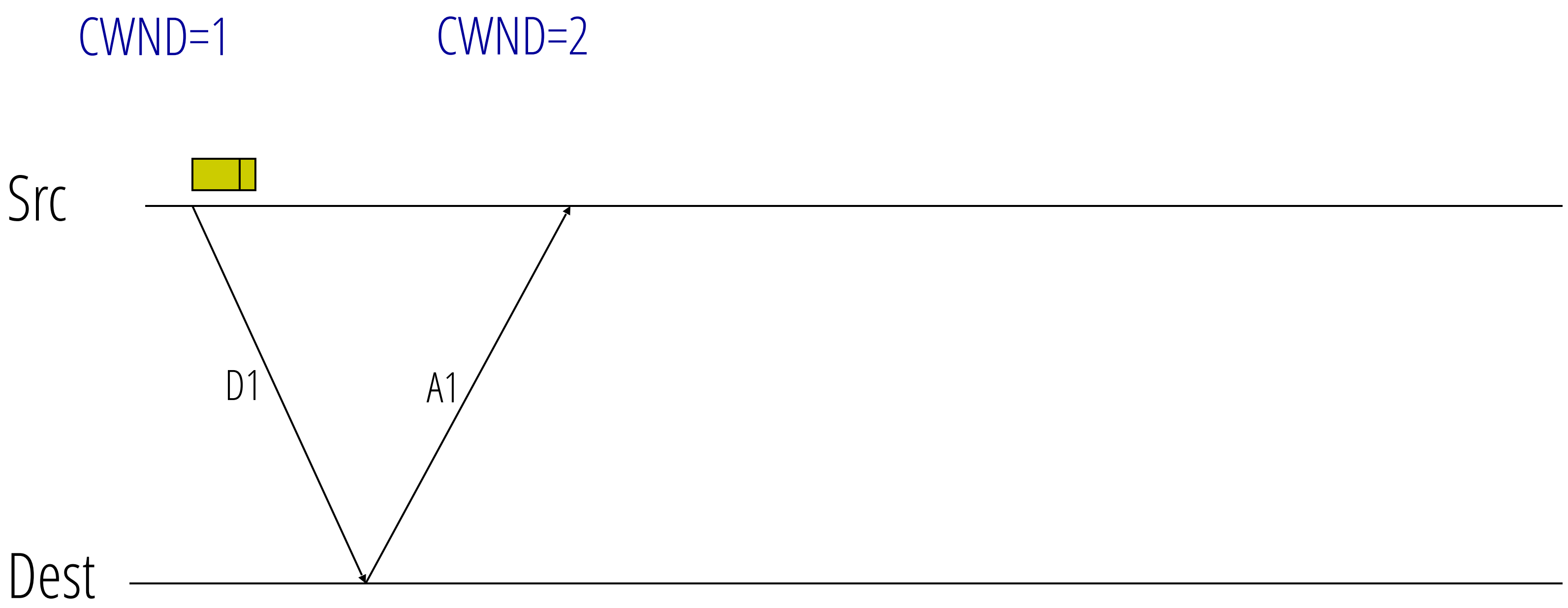

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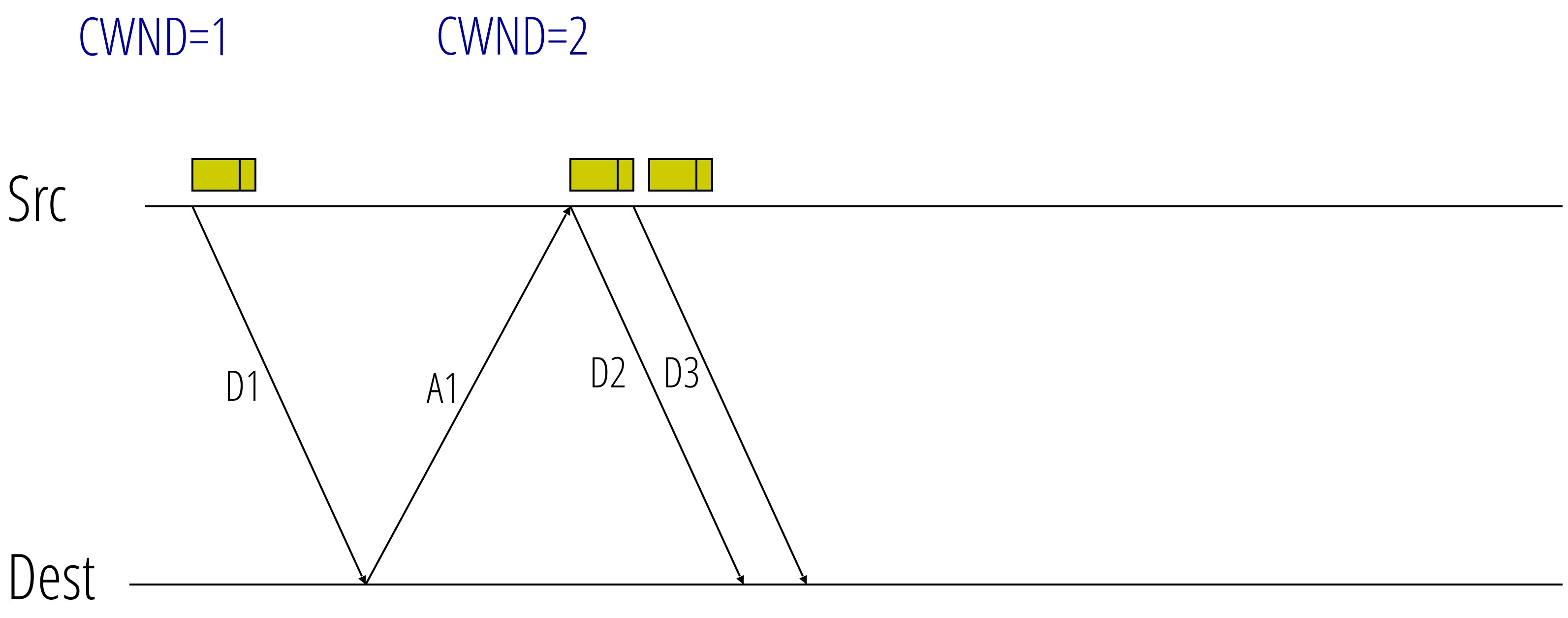

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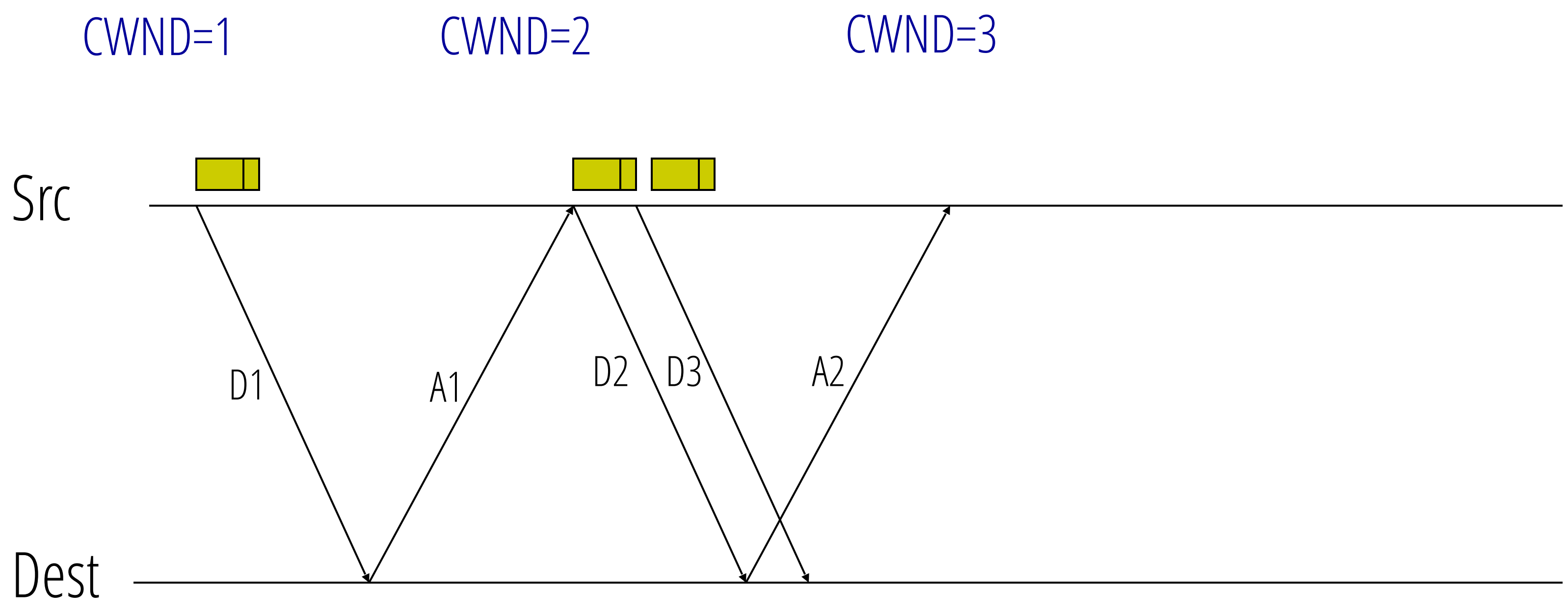

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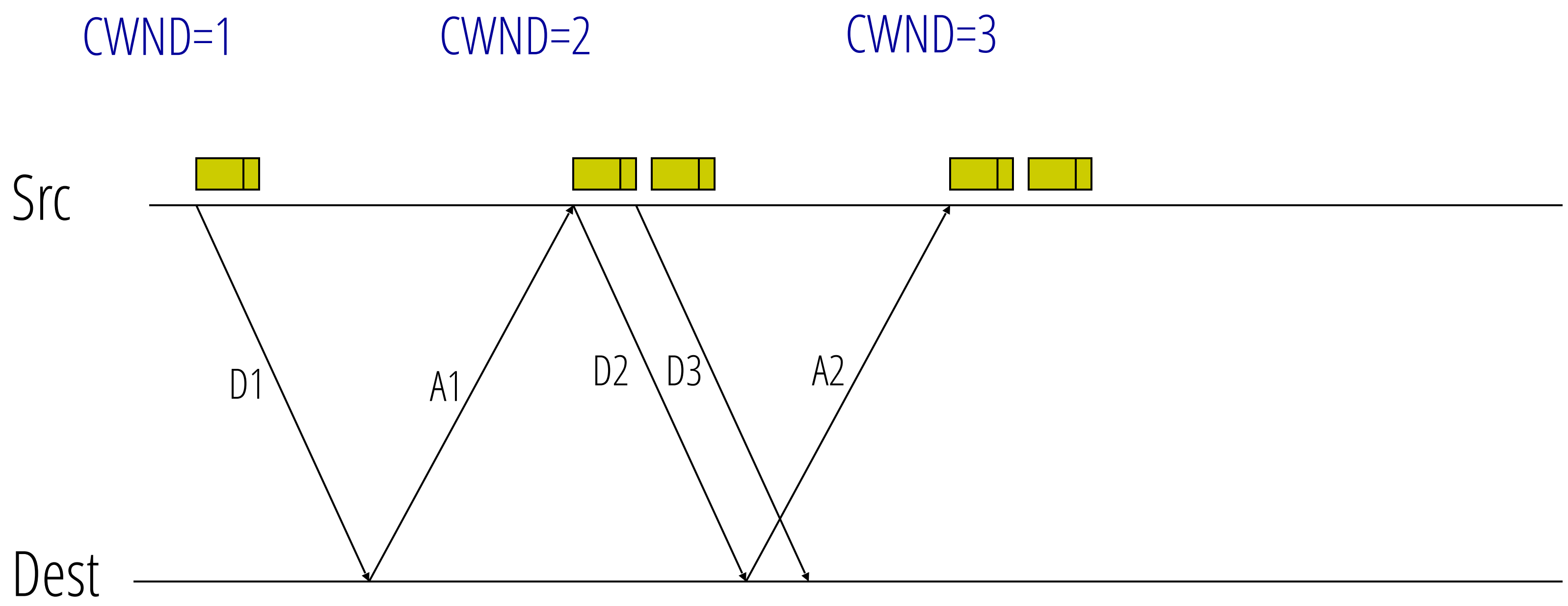

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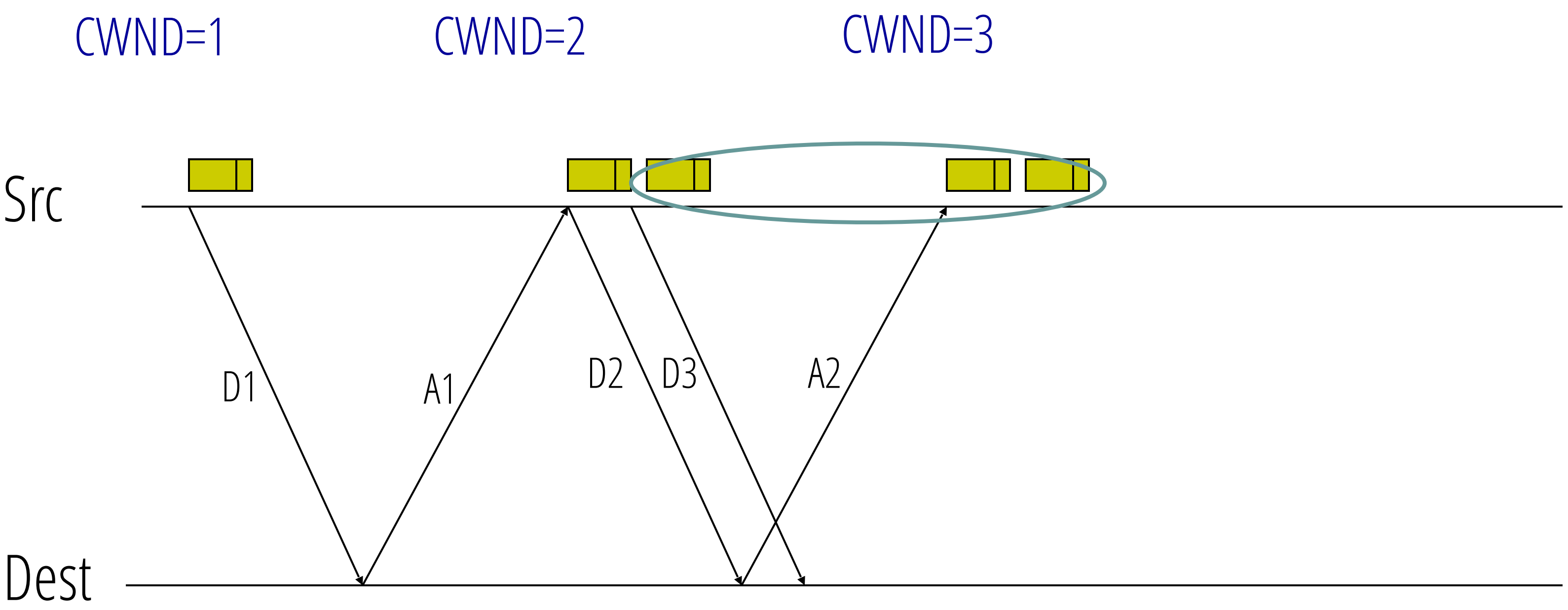

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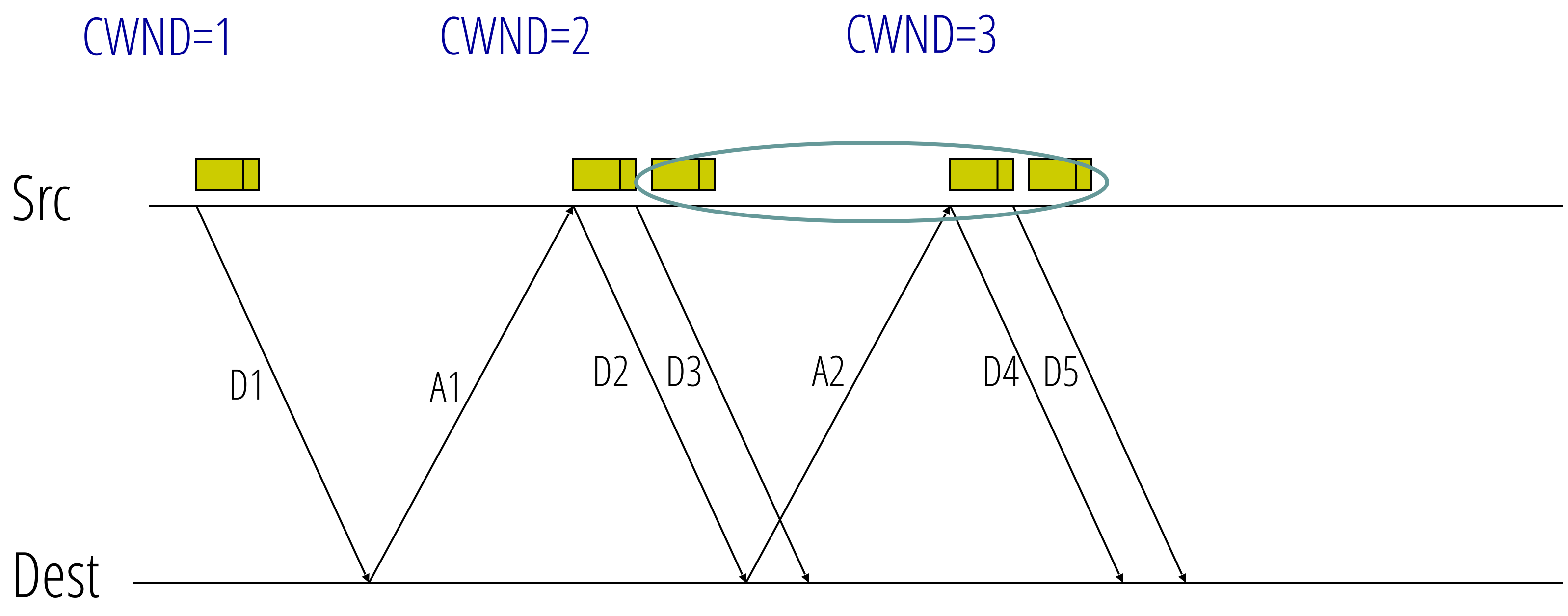

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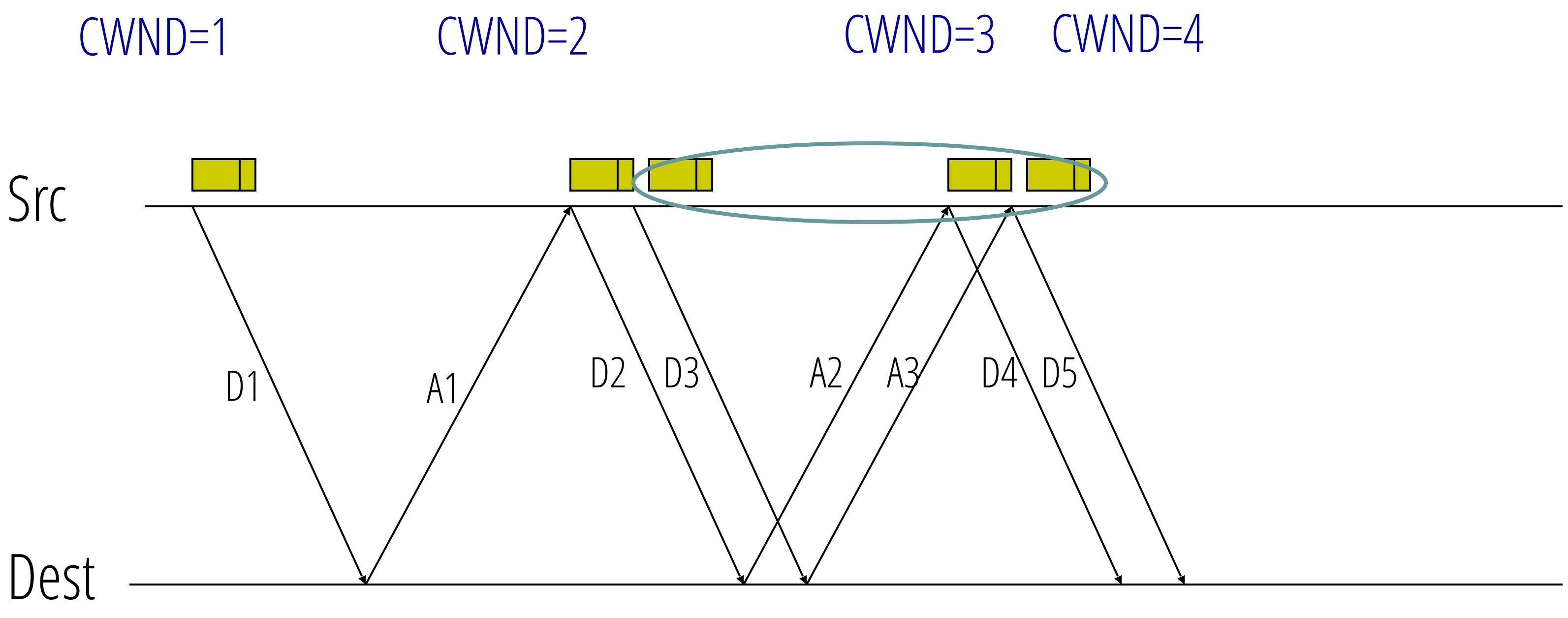

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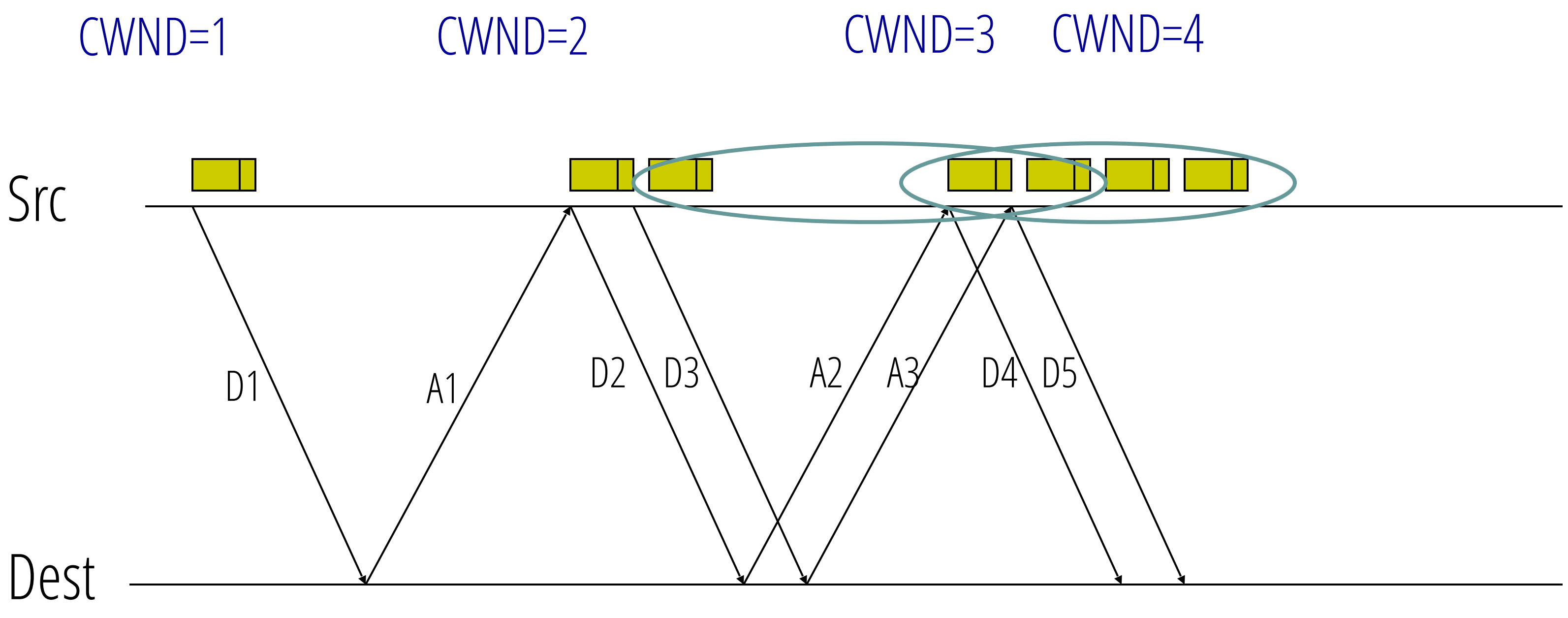

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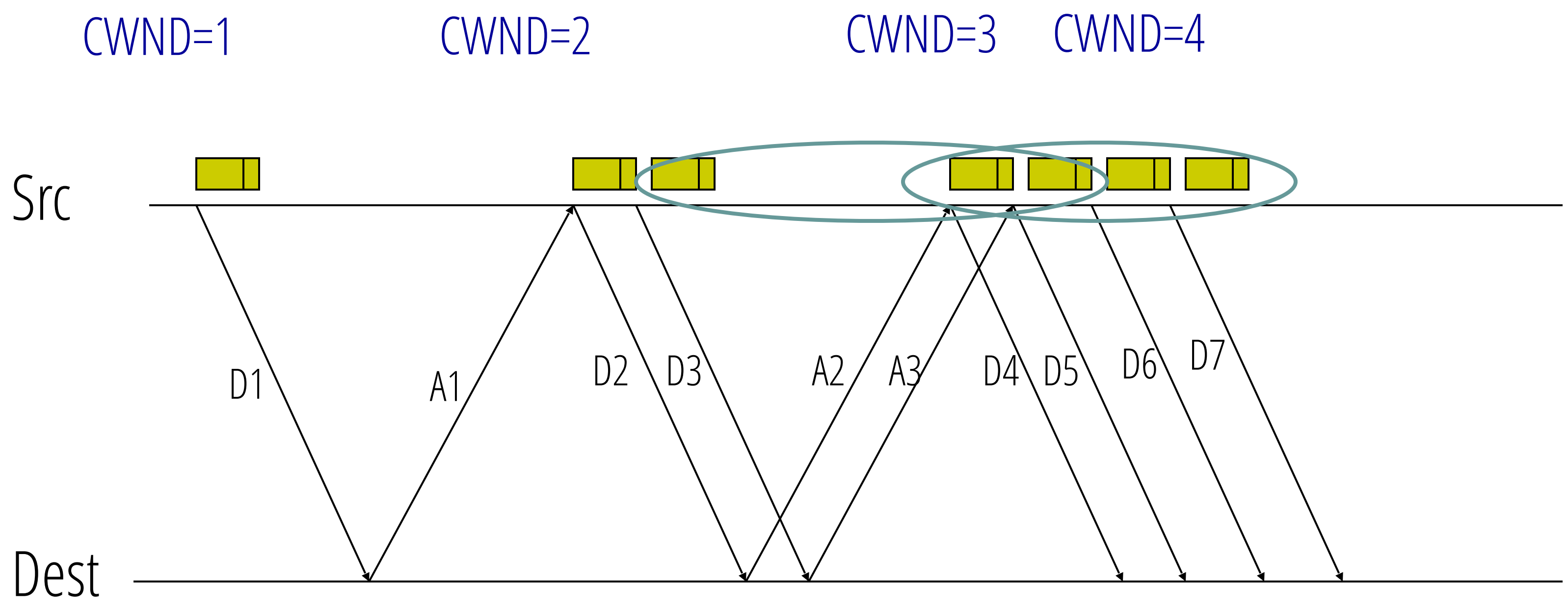

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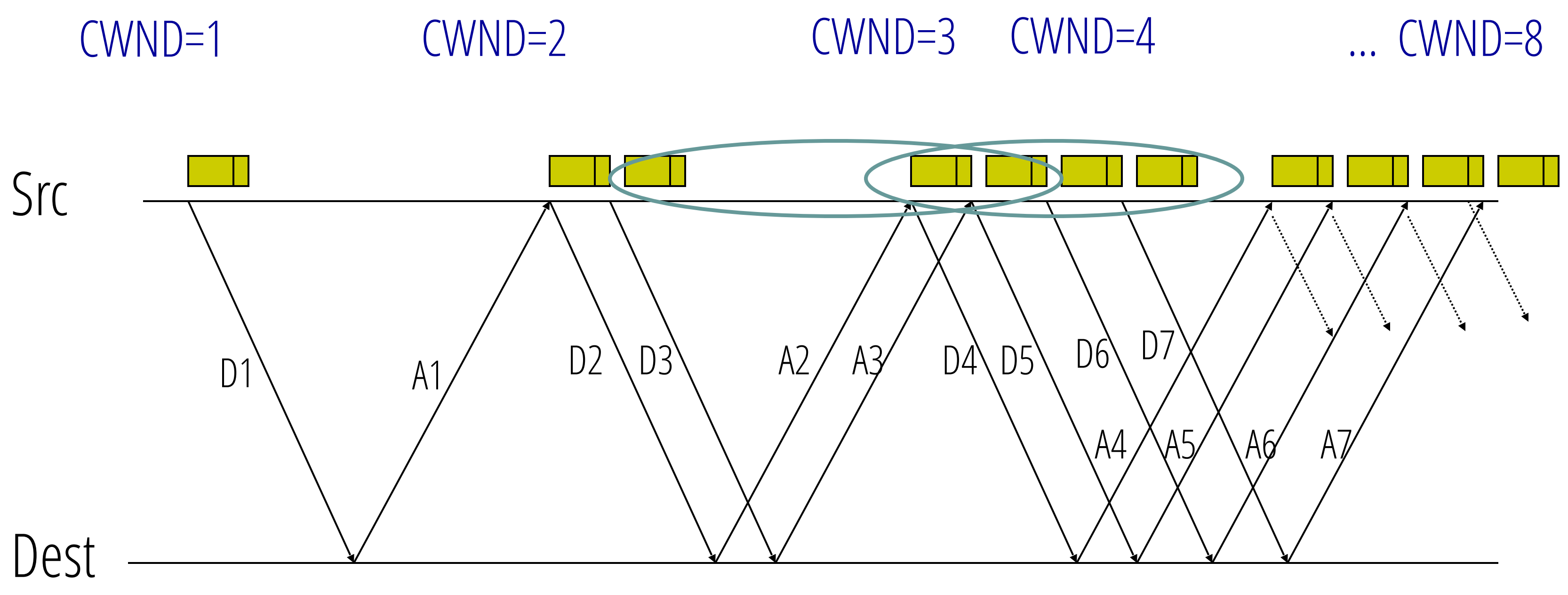

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- Introduce a “slow start threshold” parameter
  - SSTHRESH, used to remember last “safe” rate
- On first loss: SSTHRESH = CWND/2

AIMD in TCP

- Additive increase:
  - No loss → increase CWND by **1 MSS every RTT**

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- NOTE: after full window, CWND increases by 1 MSS
  - Thus, CWND increases by 1 MSS per RTT

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- Additive increase:
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- Multiplicative decrease
  - Loss detected by 3 dupACKs → divide CWND in **half**

Implementing Multiplicative Decrease

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- On receiving 3rd dupACK:
  - $$CWND \rightarrow \frac{CWND}{2}$$

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- Hence, on timeout:
  - Set SSTHRESH $\leftarrow \frac{CWND}{2}$
  - Set CWND $\leftarrow$ 1 MSS & enter Slow Start mode

Slow-Start vs. AIMD

- When does a sender stop Slow-Start and start Additive Increase?

Slow-Start vs. AIMD

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Slow-Start vs. AIMD

- When does a sender stop Slow-Start and start Additive Increase?
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- When CWND > SSTHRESH, sender switches from slow-start to AIMD’s additive increase

Recap: TCP congestion control

- Detecting congestion
  - **Loss-based**
- Discovering an initial rate
  - **Slow start**
- Adapting rate to congestion (or lack thereof)
  - **AIMD**

TCP implements the above by updating CWND on ACK arrivals and timeouts

Next Time

- TCP: reliability and CC together
- Analyzing TCP
- Router-assisted CC

BACKUP

Note: TCP is “ACK Clocked”

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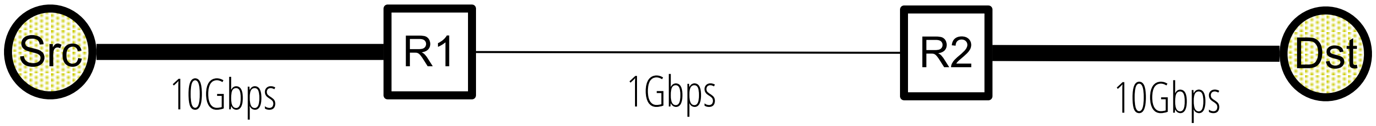
- A new ACK advances the sliding window and lets a new data segment enter the network
  - I.e., ACKs "clock" data segments

- What's the benefit of ACK clocking?

ACK Clocking



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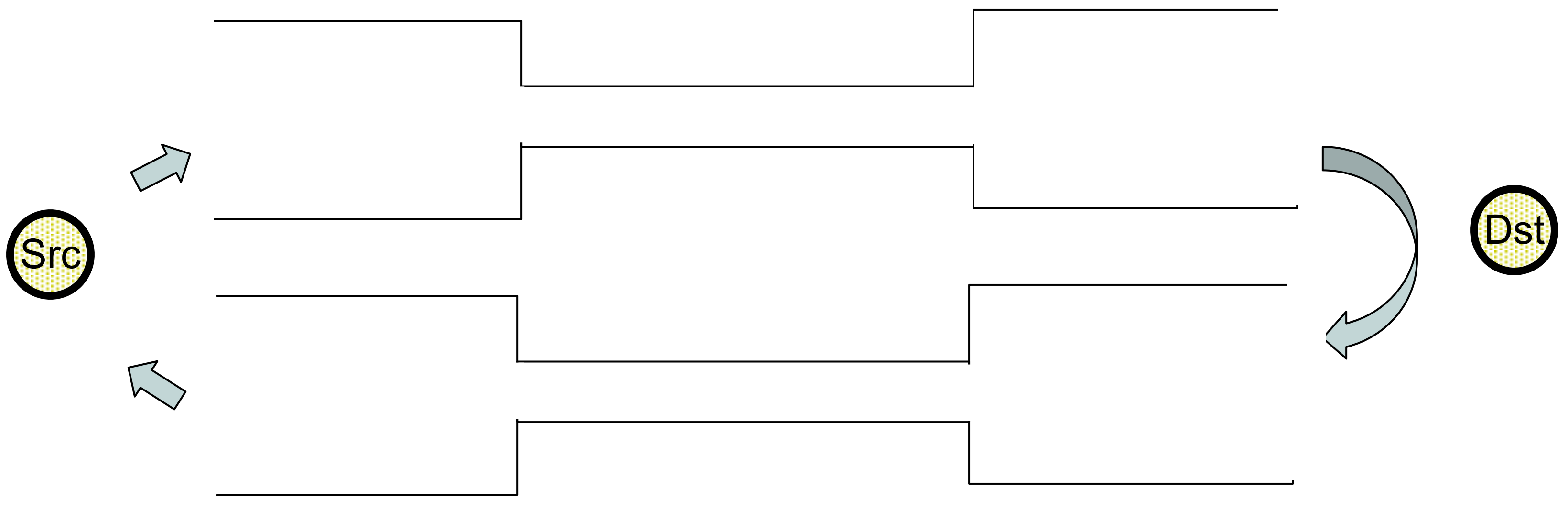

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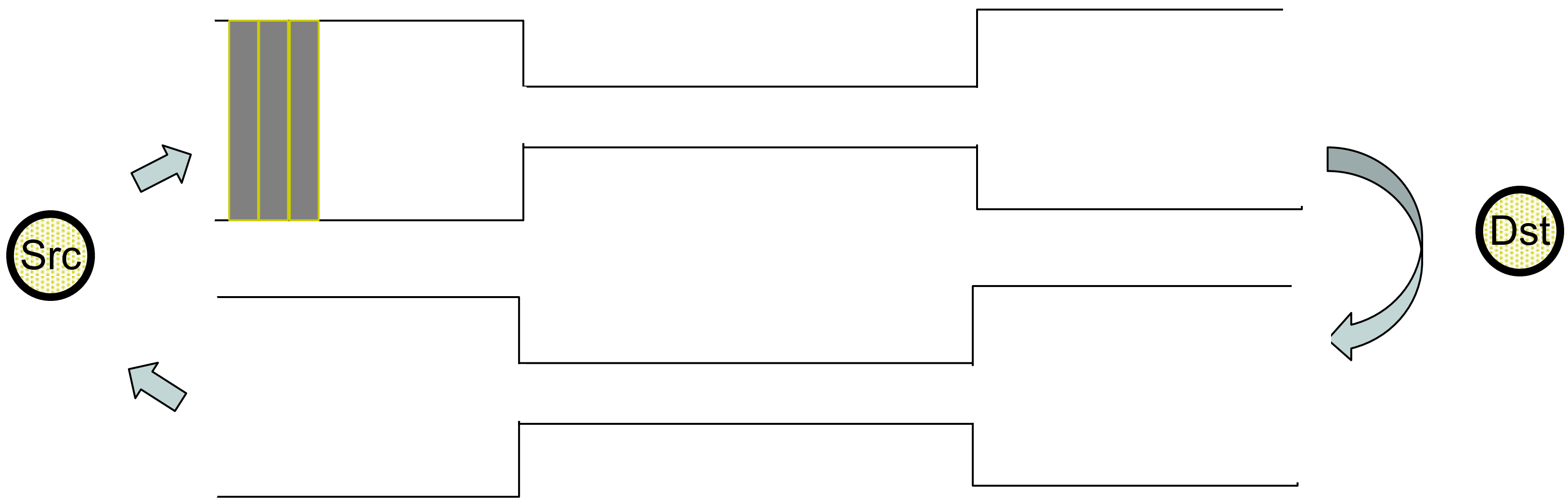

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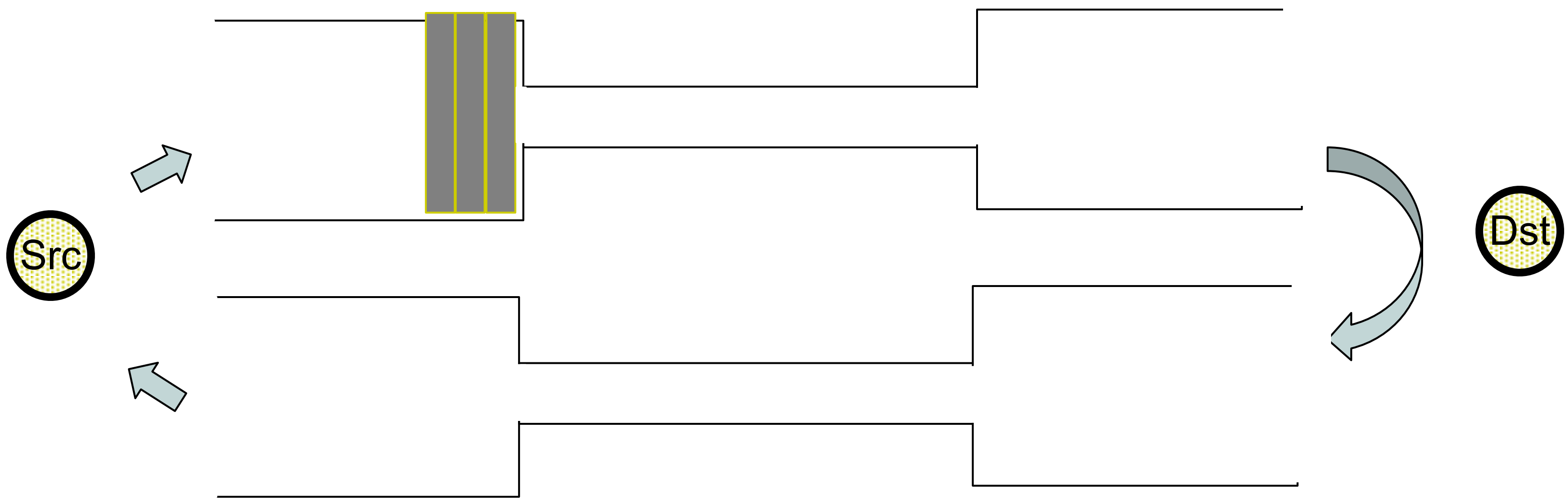
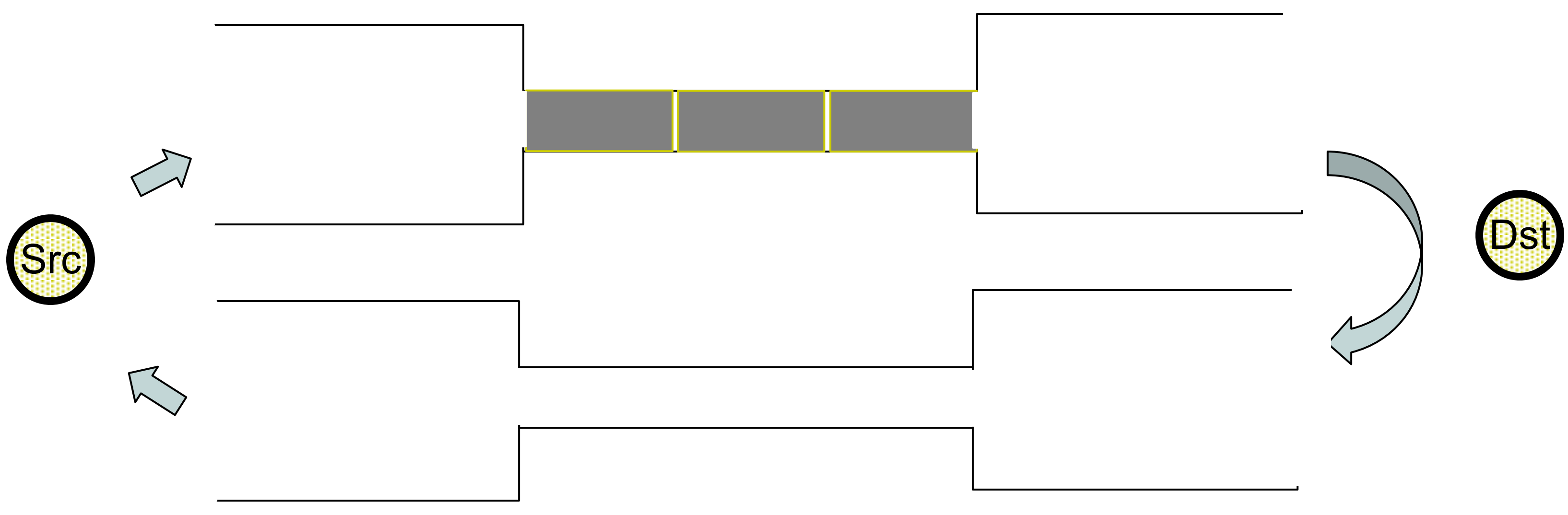


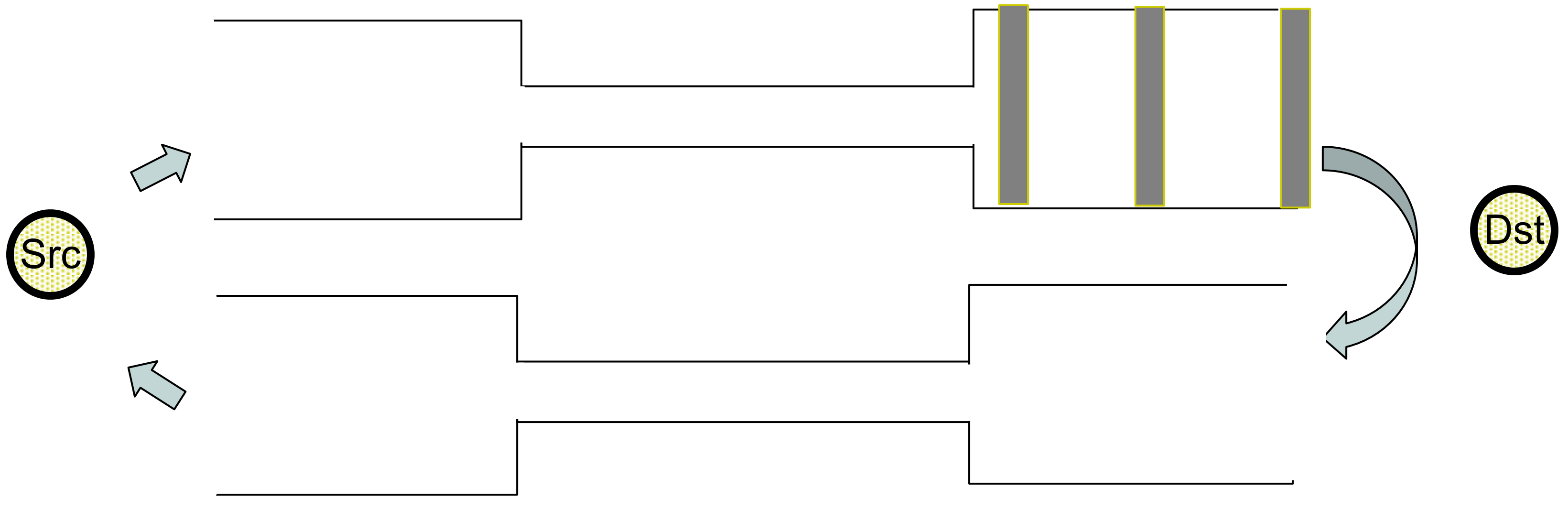
Consider: source sends a burst of packets

ACK Clocking

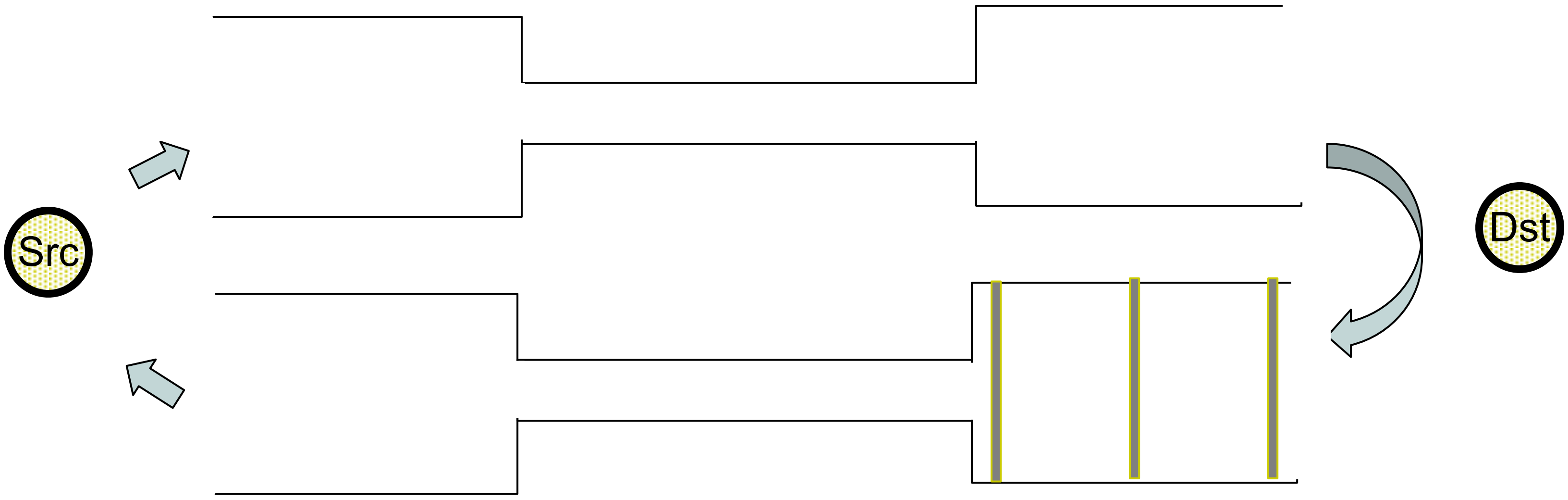


Packets are queued and "spread out" at slow link

ACK Clocking

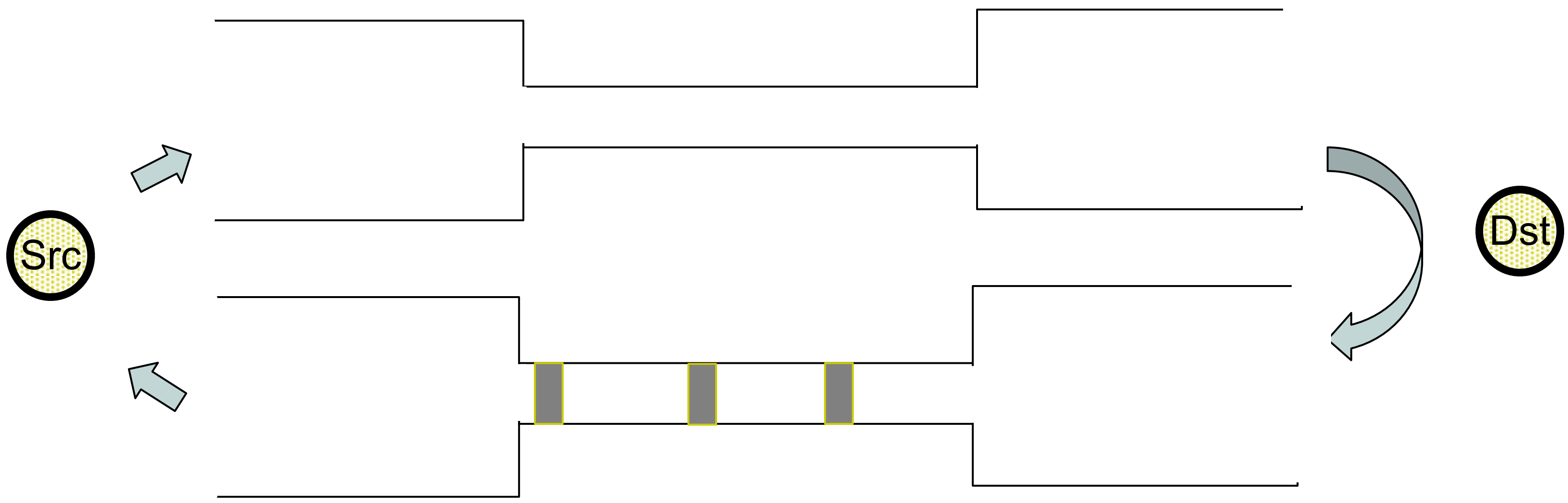


ACK Clocking



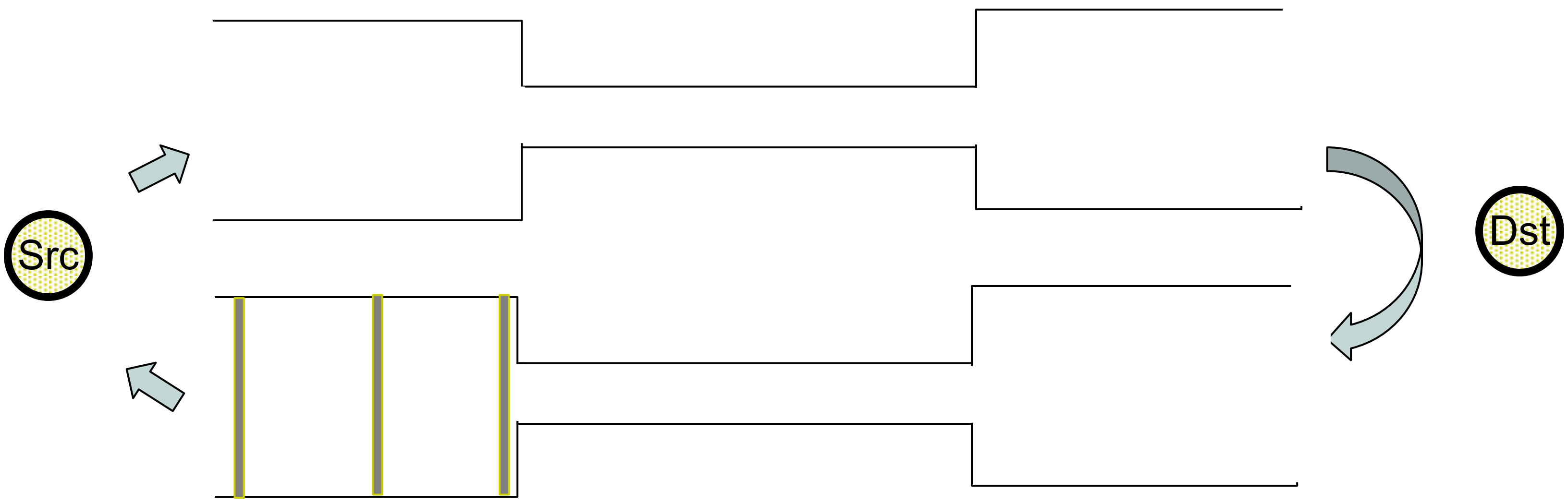
ACKs maintain the spread on the return path

ACK Clocking



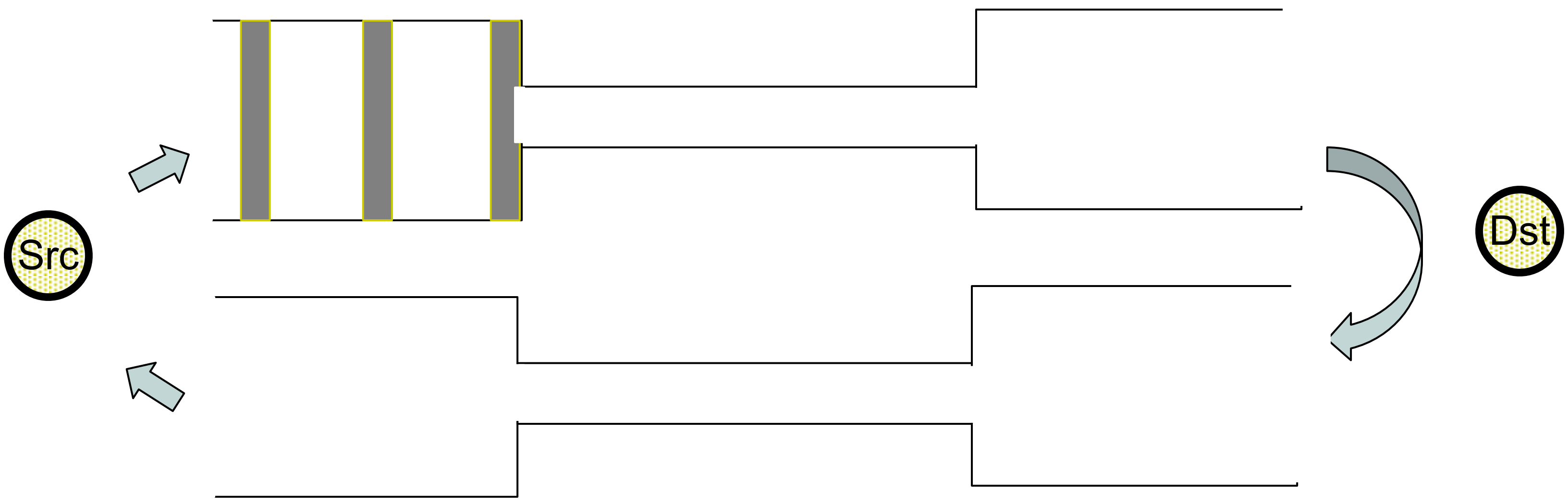
ACKs maintain the spread on the return path

ACK Clocking



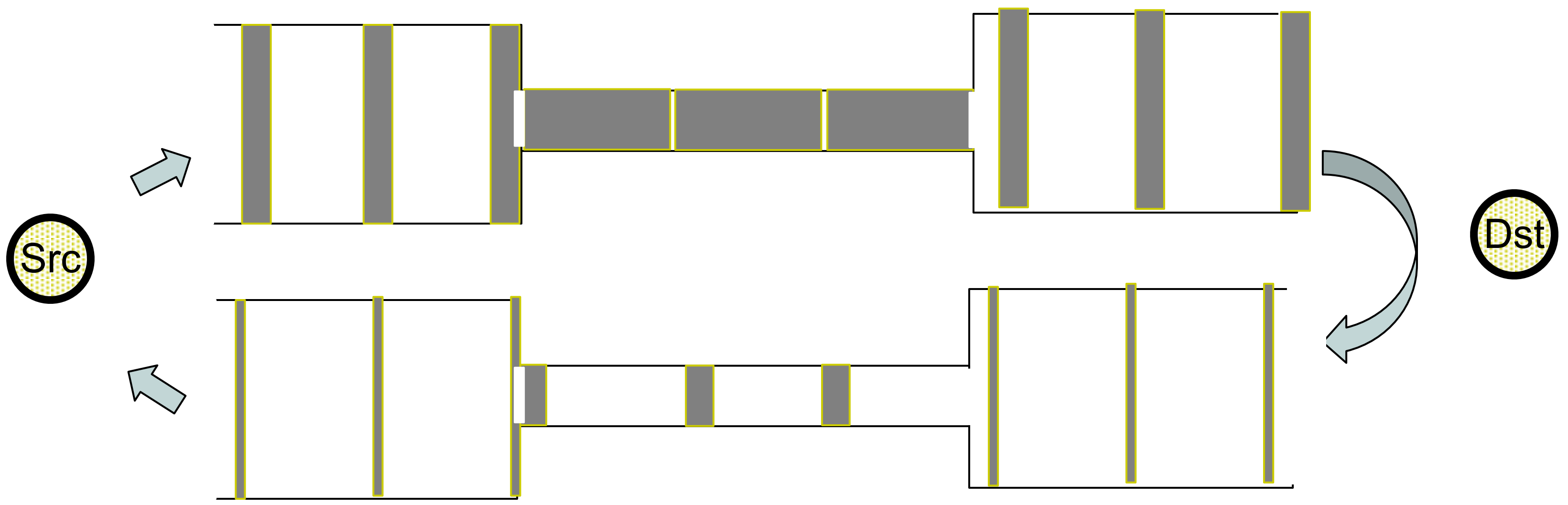
ACKs maintain the spread on the return path

ACK Clocking



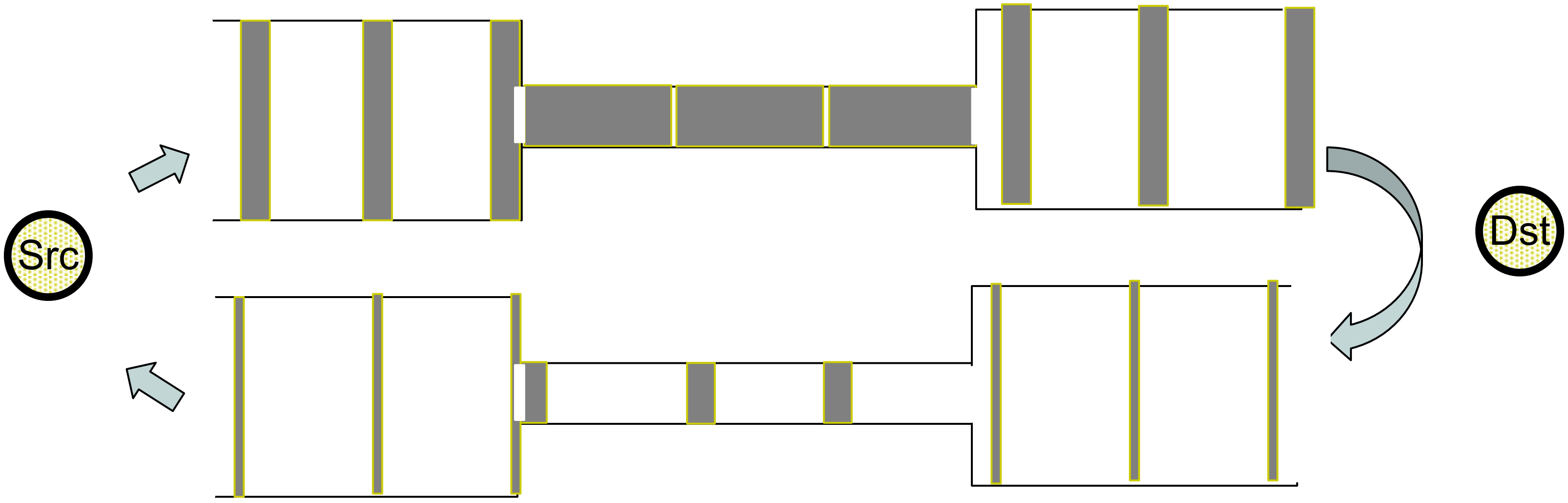
Sender clocks new packets with the spread

ACK Clocking



Sender clocks new packets with the spread

ACK Clocking



Sender clocks new packets with the spread

Now sending without queuing at the bottleneck link!