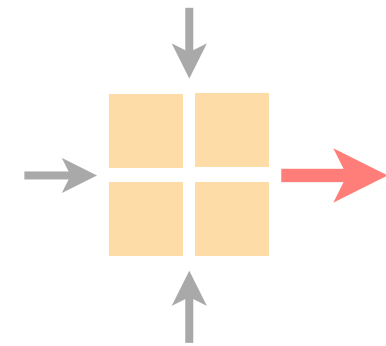


Communication Networks

Spring 2021



Laurent Vanbever

nsg.ee.ethz.ch

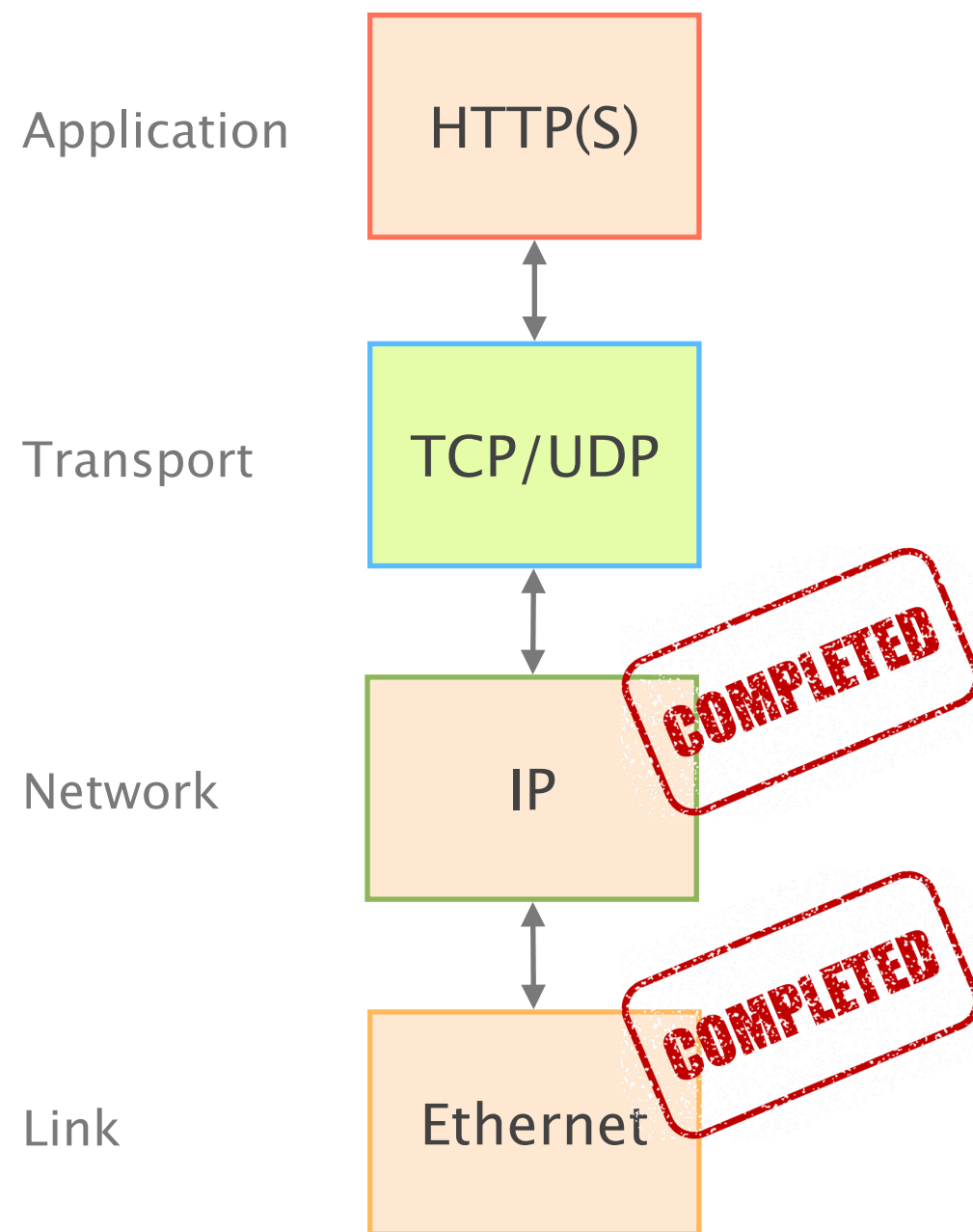
ETH Zürich (D-ITET)

May 10 2021

Materials inspired from Scott Shenker & Jennifer Rexford

Last week on
Communication Networks

We continued our journey up the layers,
and started to look at **the transport layer**



What Problems Should Be Solved Here?

Data delivering, to the *correct* application

- IP just points towards next protocol
- *Transport needs to demultiplex incoming data (ports)*

Files or bytestreams abstractions for the applications

- Network deals with packets
- *Transport layer needs to translate between them*

Reliable transfer (if needed)

Not overloading the receiver

Not overloading the network

UDP: Datagram messaging service

UDP provides a **connectionless, unreliable** transport service

- No-frills extension of “best-effort” IP
- UDP provides **only two services** to the App layer
 - Multiplexing/Demultiplexing among processes
 - Discarding corrupted packets (optional)

TCP: Reliable, in-order delivery

TCP provides a **connection-oriented, reliable, bytestream** transport service

What UDP provides, plus:

- Retransmission of lost and corrupted packets
- Flow control (to not overflow receiver)
- Congestion control (to not overload network)
- “Connection” set-up & tear-down

Sockets

A socket is a software abstraction by which an application process exchanges network messages with the (transport layer in the) operating system

- `socketID = socket(..., socket.TYPE)`
- `socketID.sendto(message, ...)`
- `socketID.recvfrom(...)`

Two important types of sockets

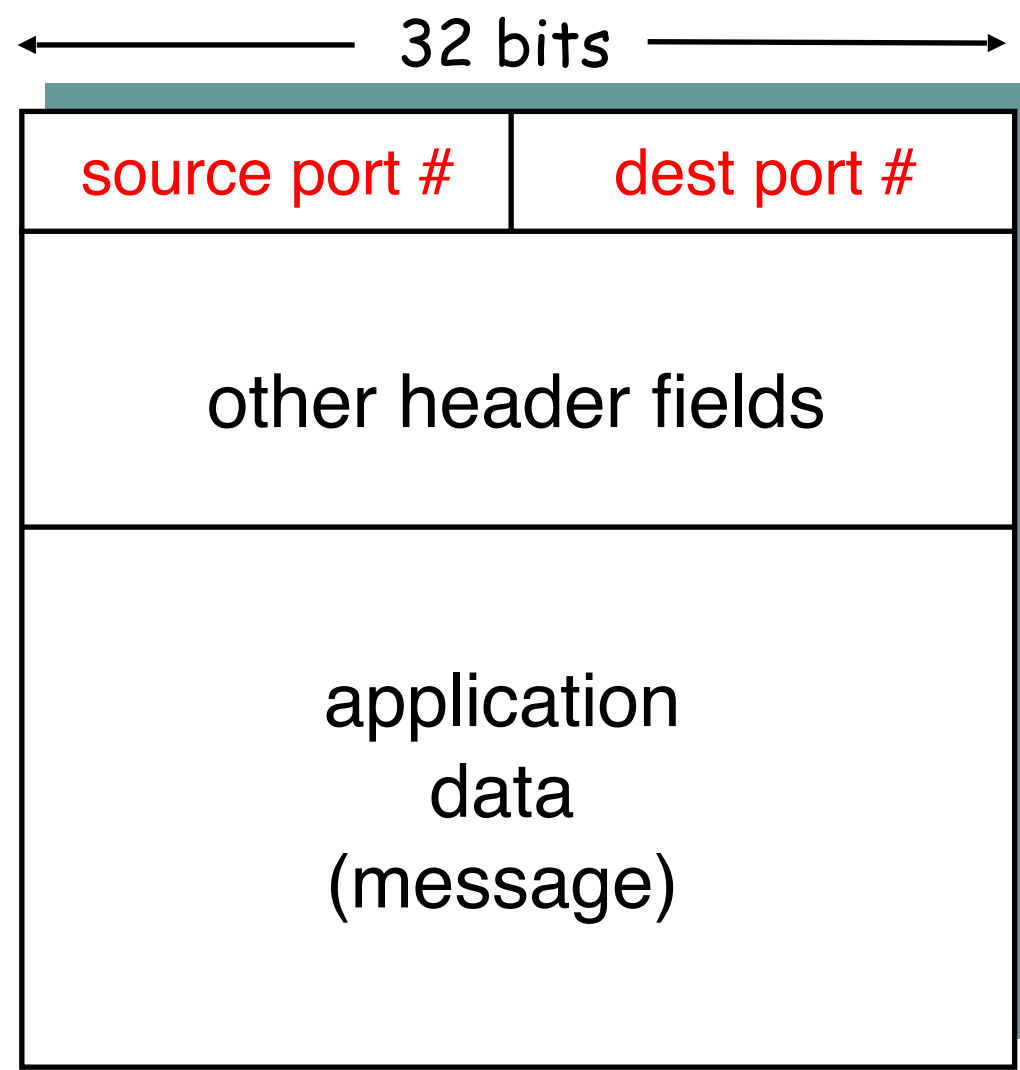
- UDP socket: TYPE is `SOCK_DGRAM`
- TCP socket: TYPE is `SOCK_STREAM`

Multiplexing and Demultiplexing

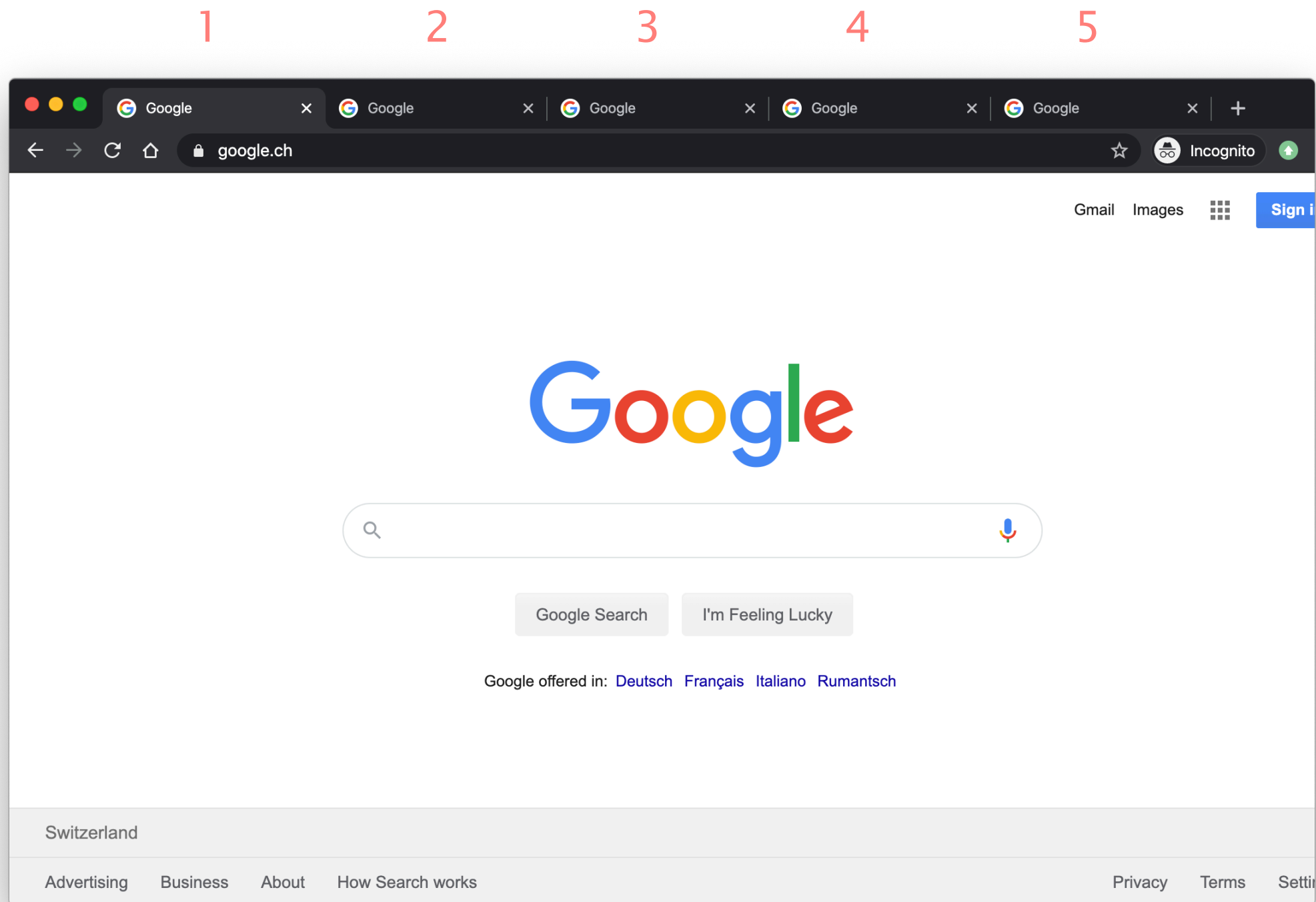
Host receives IP datagrams

- Each datagram has source and destination IP address,
- Each segment has source and destination port number

Host uses IP addresses *and* port numbers to direct the segment to appropriate socket



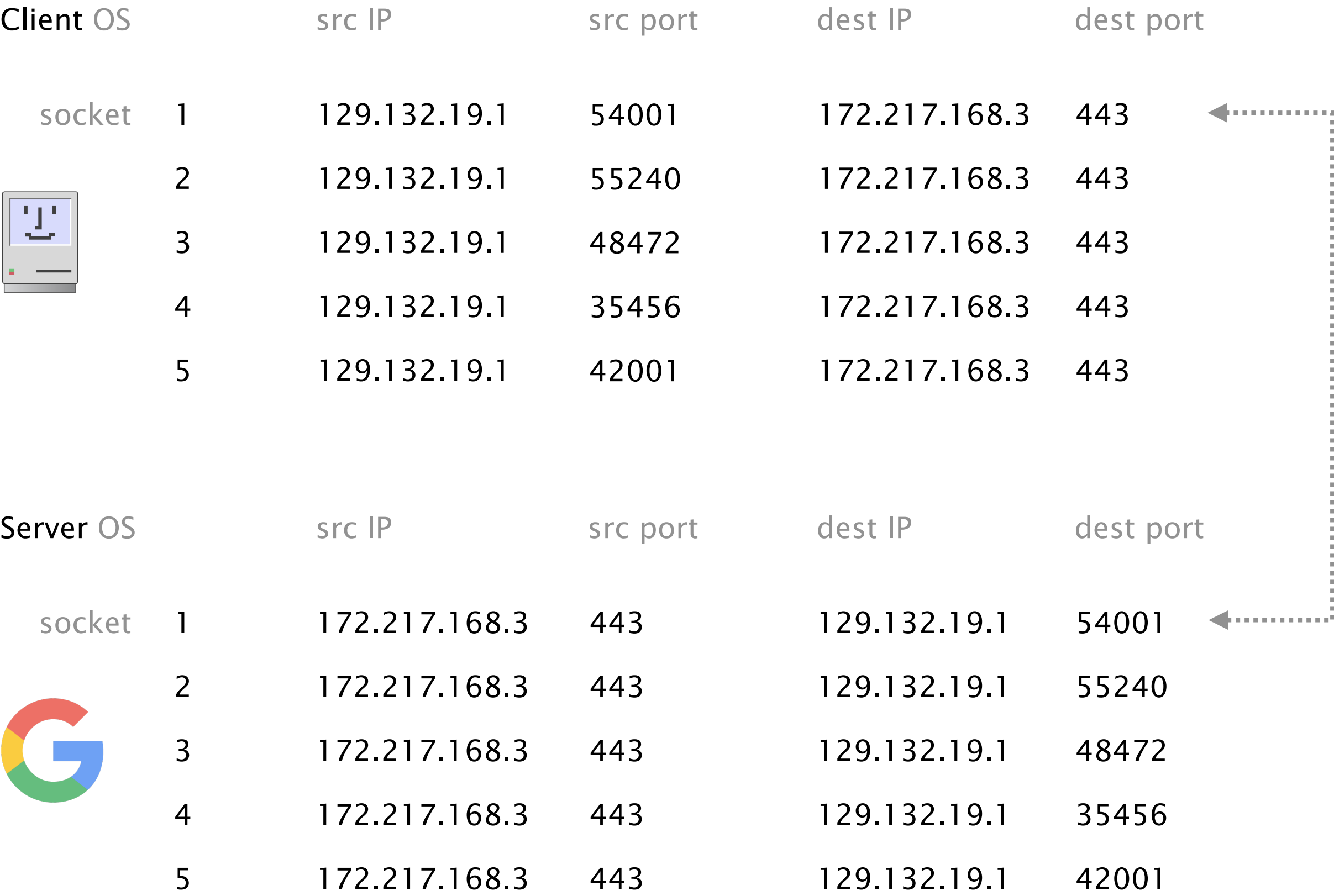
A TCP/UDP socket is identified by a 4-tuple:
(src IP, src port, dst IP, dest port)



Let's say you open 5 tabs to google.ch

Your IP: 129.132.19.1

Google's IP: 172.217.168.3



This week on
Communication Networks

UDP / TCP

Congestion
Control

starting from
slide 51/107



CONGESTION
AHEAD
EXPECT DELAYS

UDP / TCP

Congestion
Control

starting from
slide 51/107

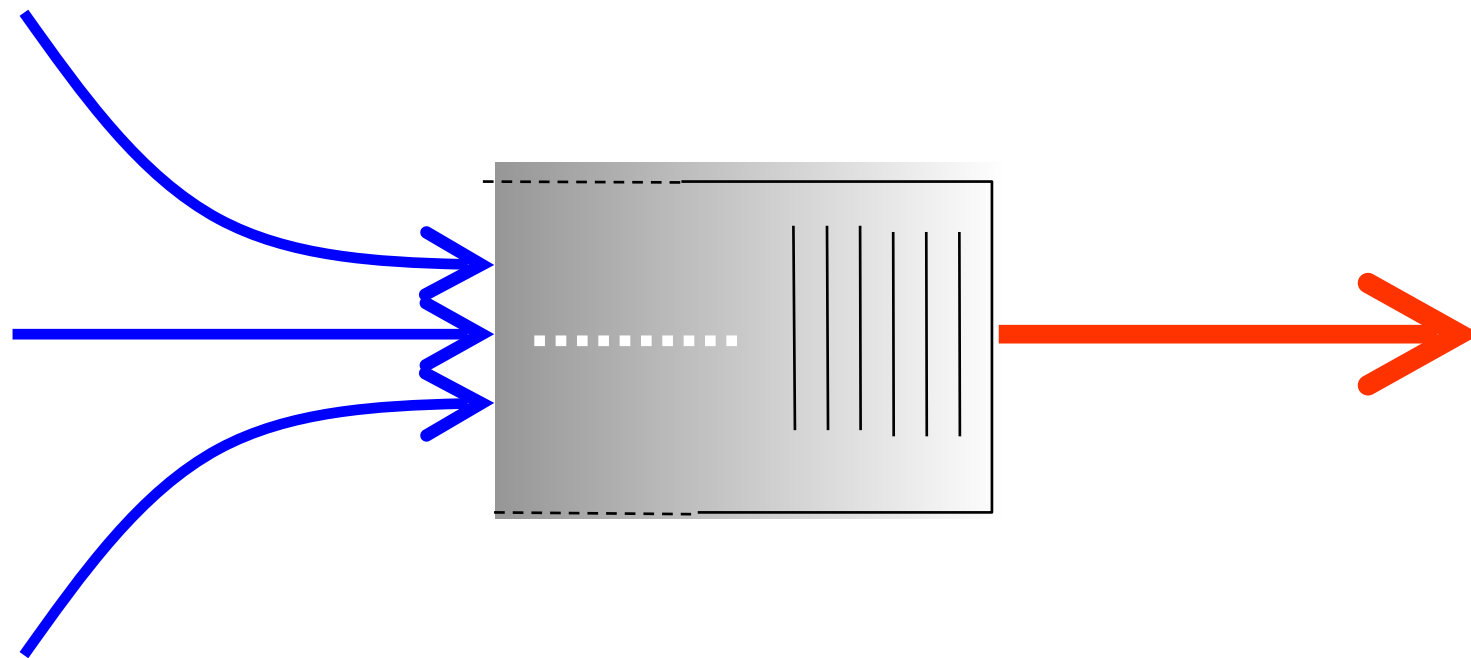
UDP / TCP

Congestion
Control



CONGESTION
AHEAD
EXPECT DELAYS

Because of traffic burstiness and lack of BW reservation,
congestion is inevitable



If many packets arrive within
a short period of time
the node cannot keep up anymore

Congestion is harmful

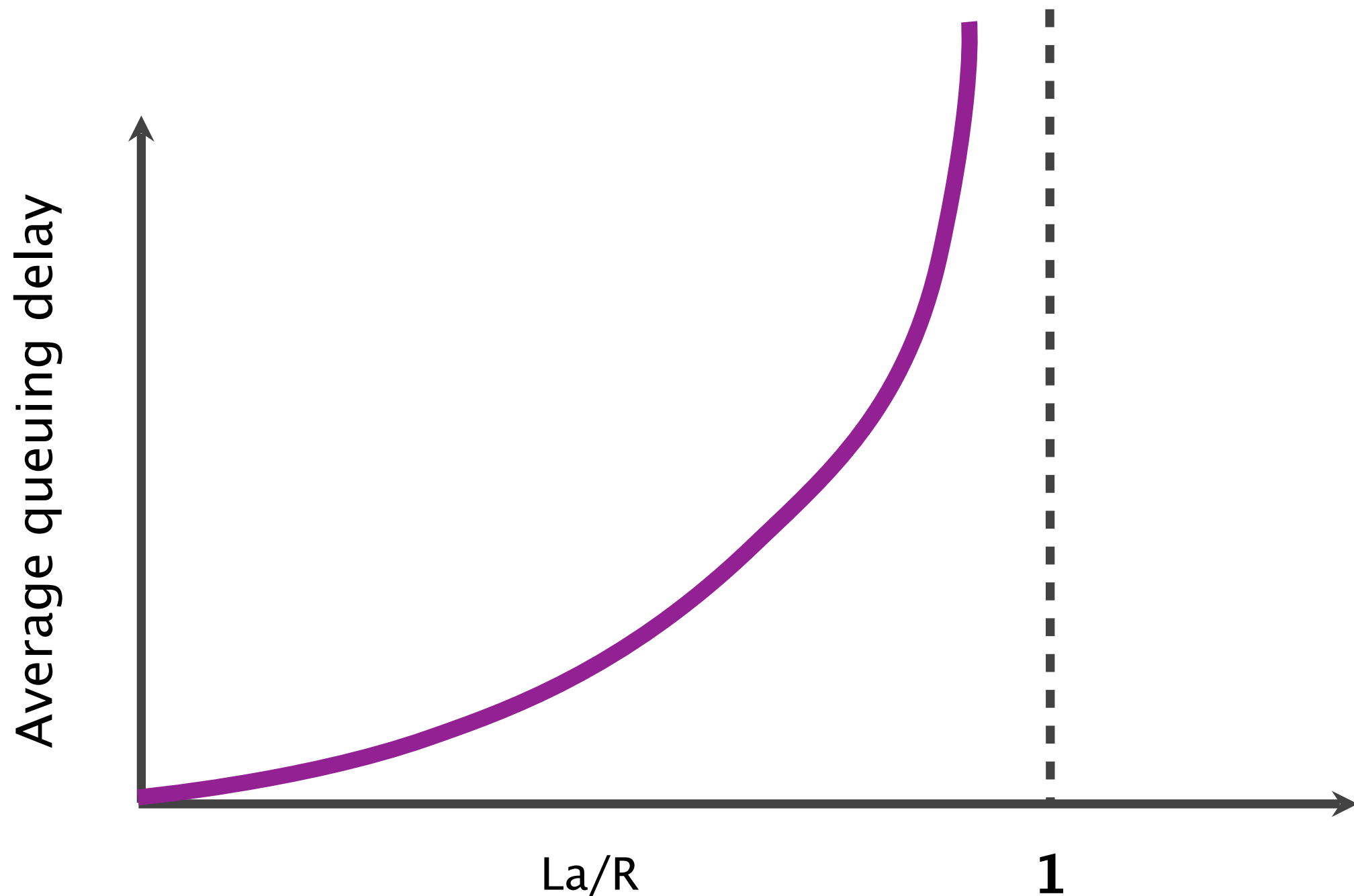
average packet arrival rate	a	[packet/sec]
transmission rate of outgoing link	R	[bit/sec]
fixed packets length	L	[bit
average bits arrival rate	La	[bit/sec]
traffic intensity	La/R	

When the **traffic intensity is >1** , the queue will increase without bound, and so does the queuing delay

Golden rule

Design your queuing system,
so that it operates far from that point

When the **traffic intensity** is ≤ 1 ,
queueing delay depends on the burst size



Congestion is **not a new problem**

The Internet almost died of congestion in 1986
throughput collapsed from 32 Kbps to... 40 bps

Van Jacobson saved us with Congestion Control
his solution went right into BSD

Recent resurgence of research interest after brief lag
new methods (ML), context (Data centers), requirements

The Internet almost died of congestion in 1986
throughput collapsed from 32 Kbps to... 40 bps

original
behavior

On connection,
nodes send full window of packets

Upon timer expiration,
retransmit packet immediately

meaning

sending rate only limited by flow control

net effect

window-sized burst of packets

Increase in network load results in
a **decrease** of useful work done

Sudden load increased the round-trip time (RTT)
faster than the hosts' measurements of it

As RTT exceeds the maximum retransmission interval,
hosts begin to retransmit packets

Hosts are sending each packet several times,
eventually some copies arrive at the destination.

This phenomenon is known as **congestion collapse**

Knee

point after which

throughput

increases

slowly

delay

increases

quickly

Cliff

point after which

throughput

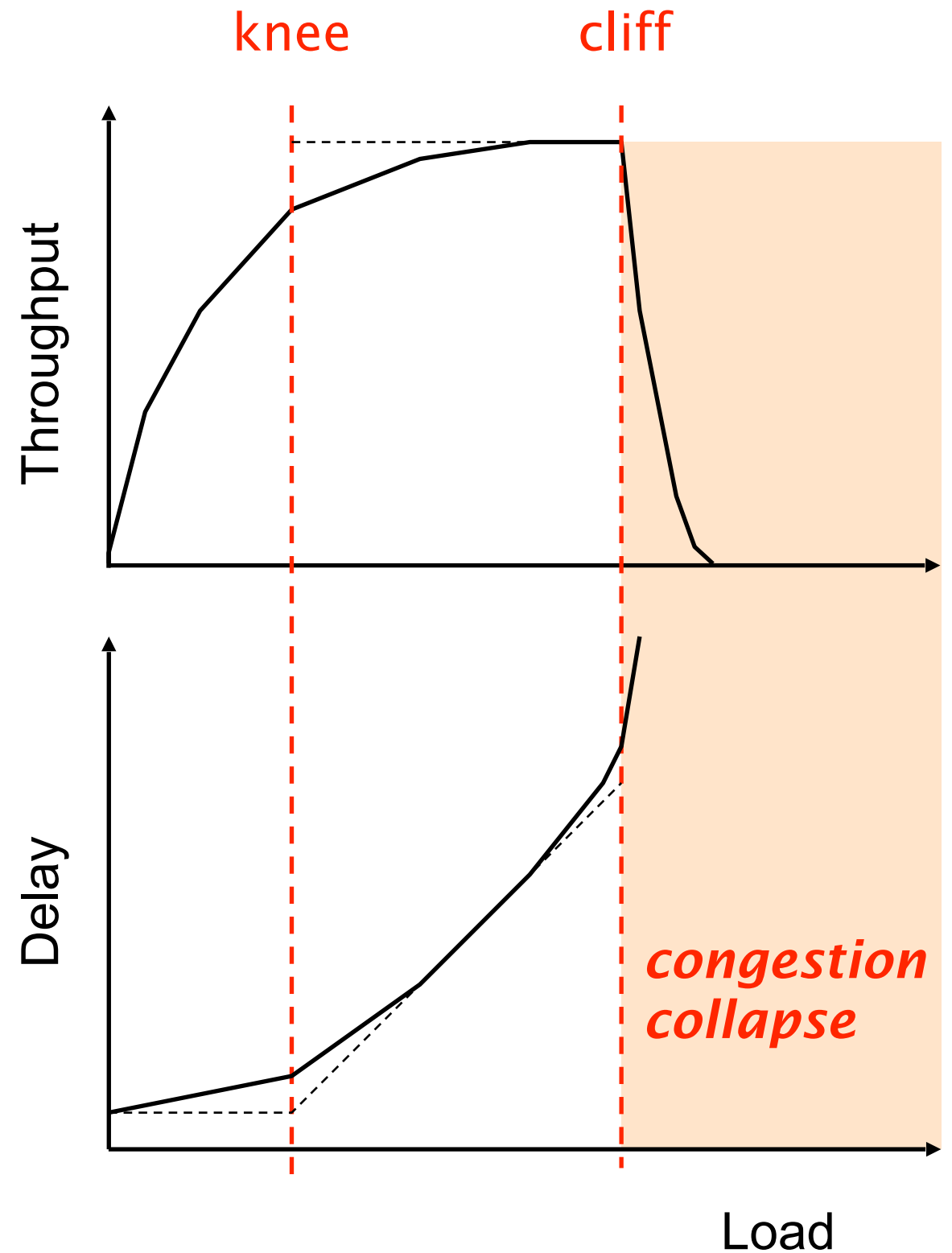
decreases

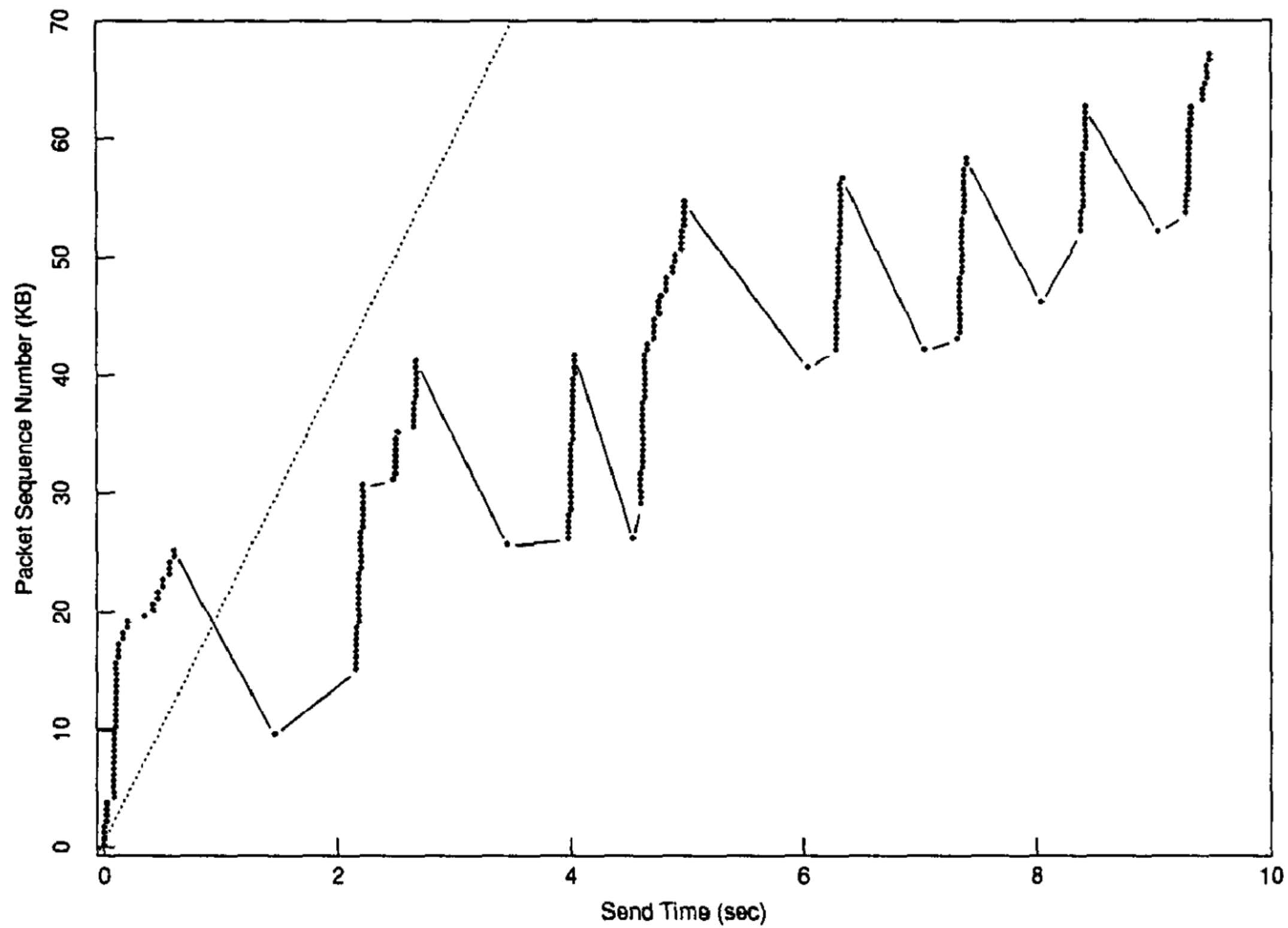
quickly

delay

tends to

infinity





Van Jacobson saved us with **Congestion Control**
his solution went right into BSD

Congestion control aims at solving three problems

- | | | |
|----|-------------------------|---|
| #1 | bandwidth
estimation | How to adjust the bandwidth of a single flow to the bottleneck bandwidth?

could be 1 Mbps or 1 Gbps... |
| #2 | bandwidth
adaptation | How to adjust the bandwidth of a single flow to variation of the bottleneck bandwidth? |
| #3 | fairness | How to share bandwidth "fairly" among flows, without overloading the network |

Congestion control differs from flow control

both are provided by TCP though

Flow control

prevents one fast sender from
overloading **a slow receiver**

Congestion control

prevents a set of senders from
overloading **the network**

TCP solves both using two distinct windows

Flow control

prevents one fast sender from
overloading a slow receiver

solved using a **receiving window**

Congestion control

prevents a set of senders from
overloading the network

solved using a **“congestion” window**

The sender adapts its sending rate based on these two windows

Receiving Window

RWND

How many bytes can be sent
without overflowing the receiver buffer?

based on the receiver input

Congestion Window

CWND

How many bytes can be sent
without overflowing the routers?

based on network conditions

Sender Window

minimum(**CWND**, **RWND**)

The 2 key mechanisms of Congestion Control

detecting
congestion

reacting to
congestion

The 2 key mechanisms of Congestion Control

detecting
congestion

reacting to
congestion

There are essentially three ways to detect congestion

Approach #1

Network could tell the source
but signal itself could be lost

Approach #2

Measure packet delay
but signal is noisy
delay often varies considerably

Approach #3

Measure packet loss
fail-safe signal that TCP already has to detect

Packet dropping is the best solution

delay- and signaling-based methods are hard & risky

Approach #3

Measure packet loss

fail-safe signal that TCP already has to detect

Detecting losses can be done using ACKs or timeouts,
the two signal differ in their degree of severity

duplicate ACKs

mild congestion signal

packets are still making it

timeout

severe congestion signal

multiple consequent losses

The 2 key mechanisms of Congestion Control

detecting
congestion

reacting to
congestion

TCP approach is to **gently increase** when not congested
and to **rapidly decrease** when congested

question

What **increase/decrease function**
should we use?

it depends on the problem we are solving...

Remember that Congestion Control aims at solving three problems

- | | | |
|----|-------------------------|---|
| #1 | bandwidth
estimation | How to adjust the bandwidth of a single flow to the bottleneck bandwidth?

could be 1 Mbps or 1 Gbps... |
| #2 | bandwidth
adaptation | How to adjust the bandwidth of a single flow to variation of the bottleneck bandwidth? |
| #3 | fairness | How to share bandwidth "fairly" among flows, without overloading the network |

#1	bandwidth estimation	How to adjust the bandwidth of a single flow to the bottleneck bandwidth? could be 1 Mbps or 1 Gbps...
----	-------------------------	--

The goal here is to quickly get a first-order estimate of the available bandwidth

Intuition

Start slow but rapidly increase
until a packet drop occurs

Increase
policy

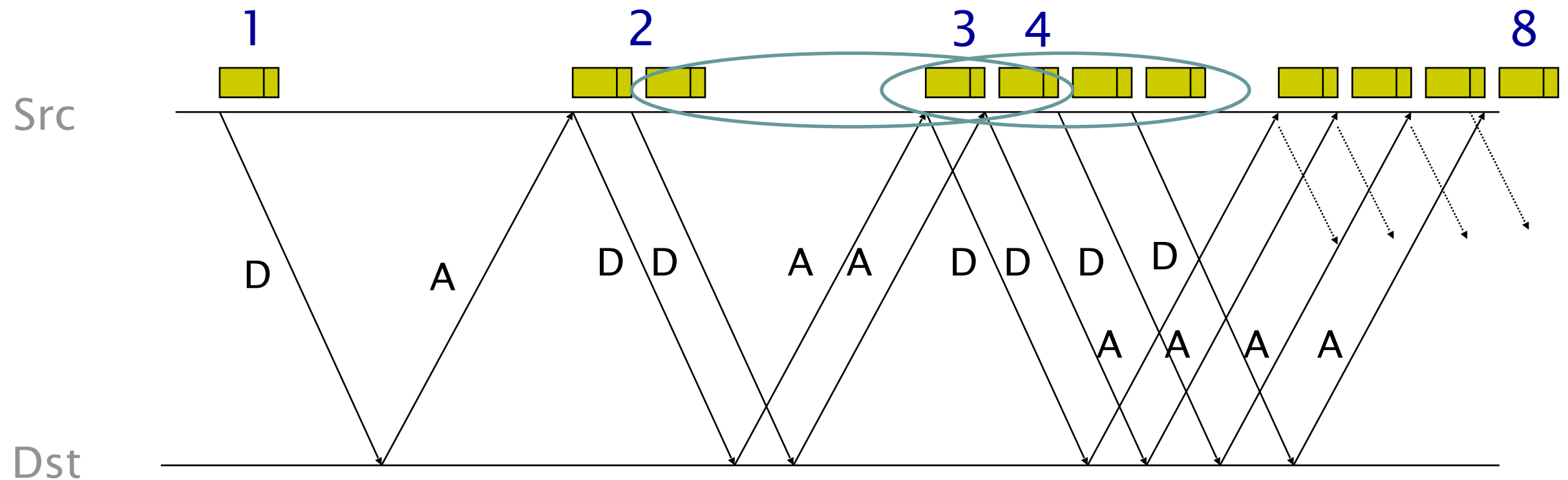
$\text{cwnd} = 1$

initially

$\text{cwnd} += 1$

upon receipt of an ACK

This increase phase, known as slow start,
corresponds to an... exponential increase of CWND!



slow start is called like this only because of starting point

The problem with slow start is that it can result in a full window of packet losses

Example

Assume that CWND is just enough to “fill the pipe”

After one RTT, CWND has doubled

All the excess packets are now dropped

Solution

We need a more gentle adjustment algorithm

once we have a rough estimate of the bandwidth

#2

bandwidth
adaptation

How to adjust the bandwidth of a single flow
to variation of the bottleneck bandwidth?

The goal here is to track the available bandwidth,
and oscillate around its current value

Two possible variations

- Multiplicative Increase or Decrease

$$cwnd = a * cwnd$$

- Additive Increase or Decrease

$$cwnd = b + cwnd$$

... leading to four alternative design

increase
behavior

decrease
behavior

AIAD

gentle

gentle

AIMD

gentle

aggressive

MIAD

aggressive

gentle

MIMD

aggressive

aggressive

To select one scheme, we need to consider
the 3rd problem: **fairness**

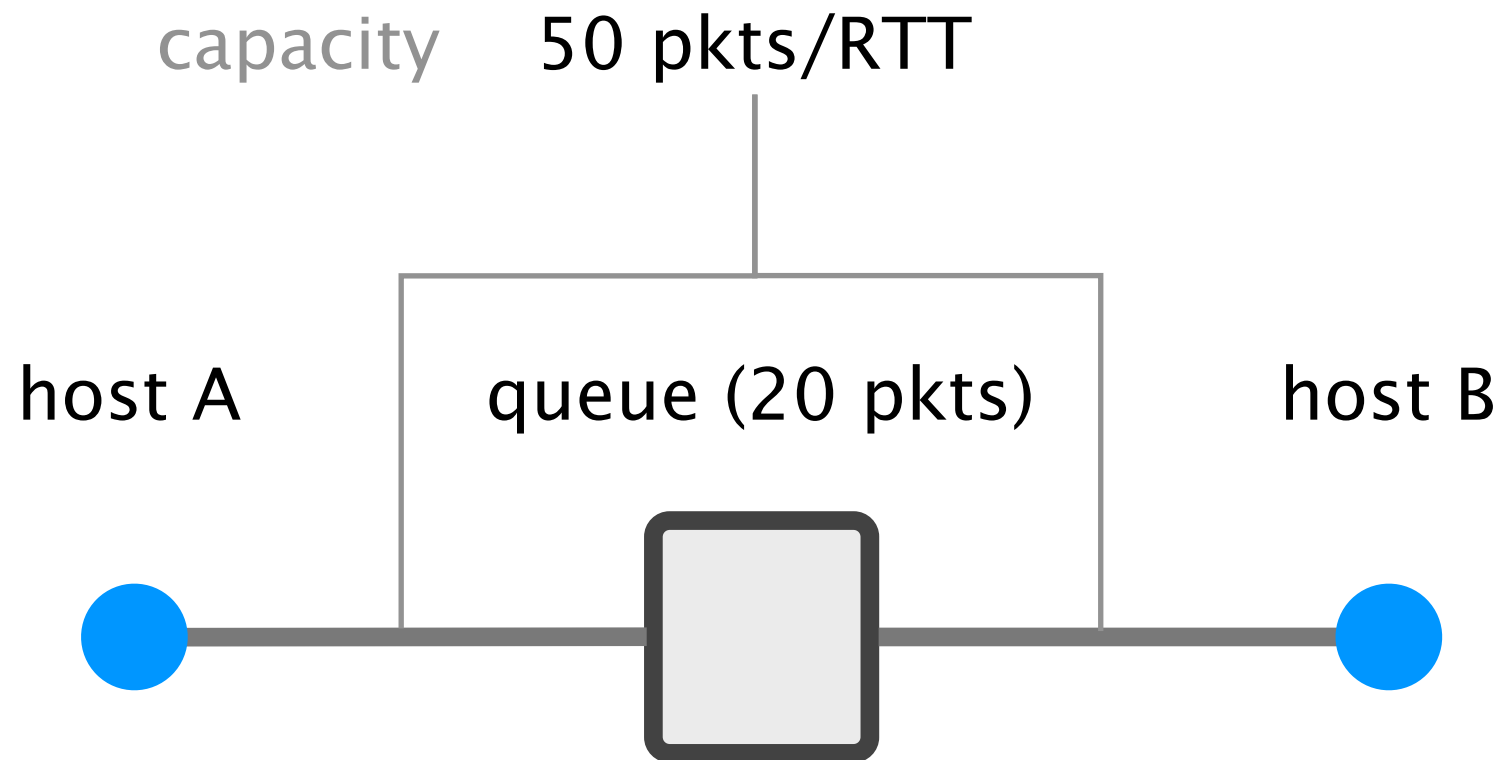
	increase behavior	decrease behavior
AIAD	gentle	gentle
AIMD	gentle	aggressive
MIAD	aggressive	gentle
MIMD	aggressive	aggressive

#3 fairness

How to share bandwidth “fairly” among flows,
without overloading the network

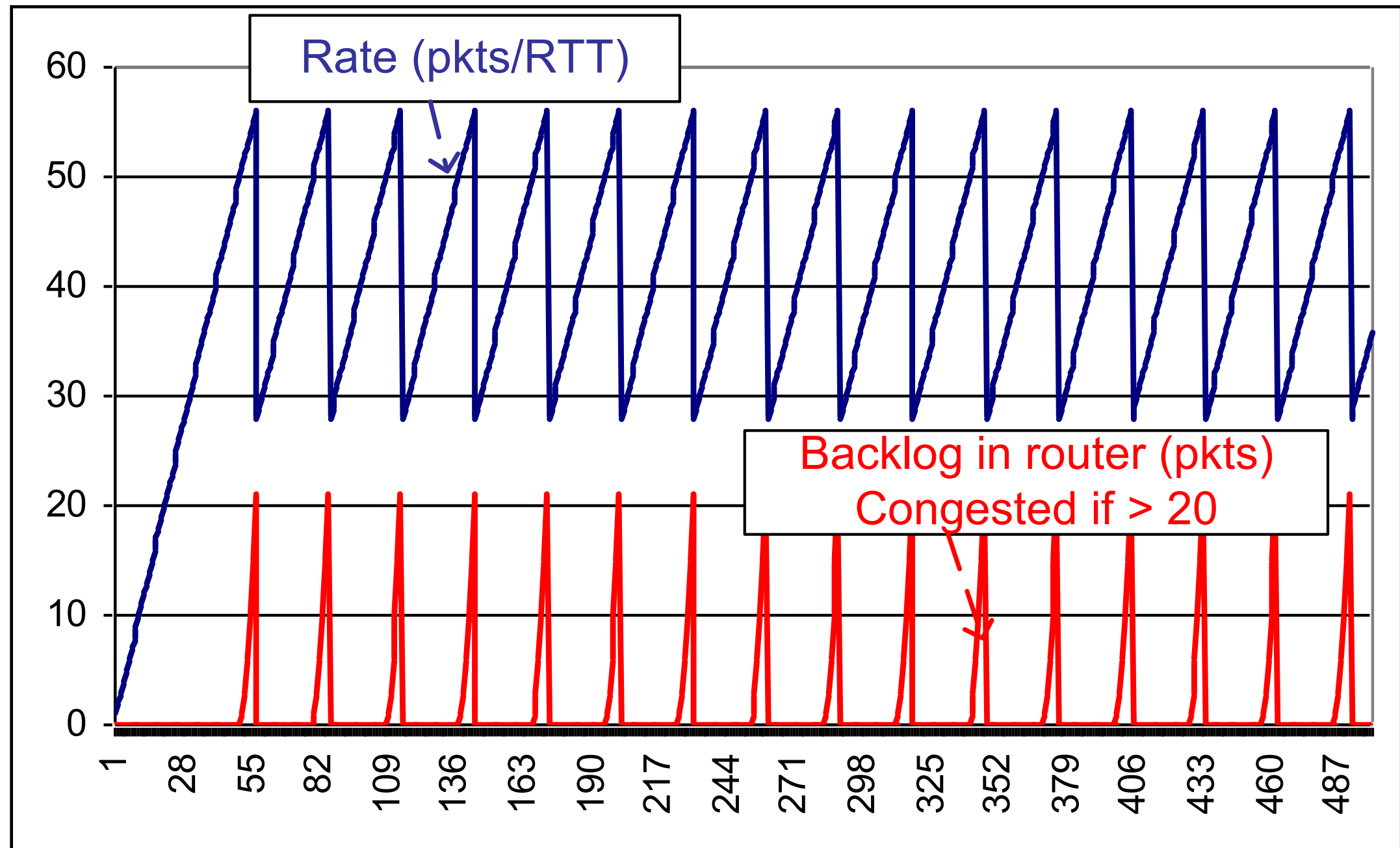
TCP notion of fairness: 2 identical flows
should end up with the same bandwidth

Consider first a single flow between A and B
and AIMD

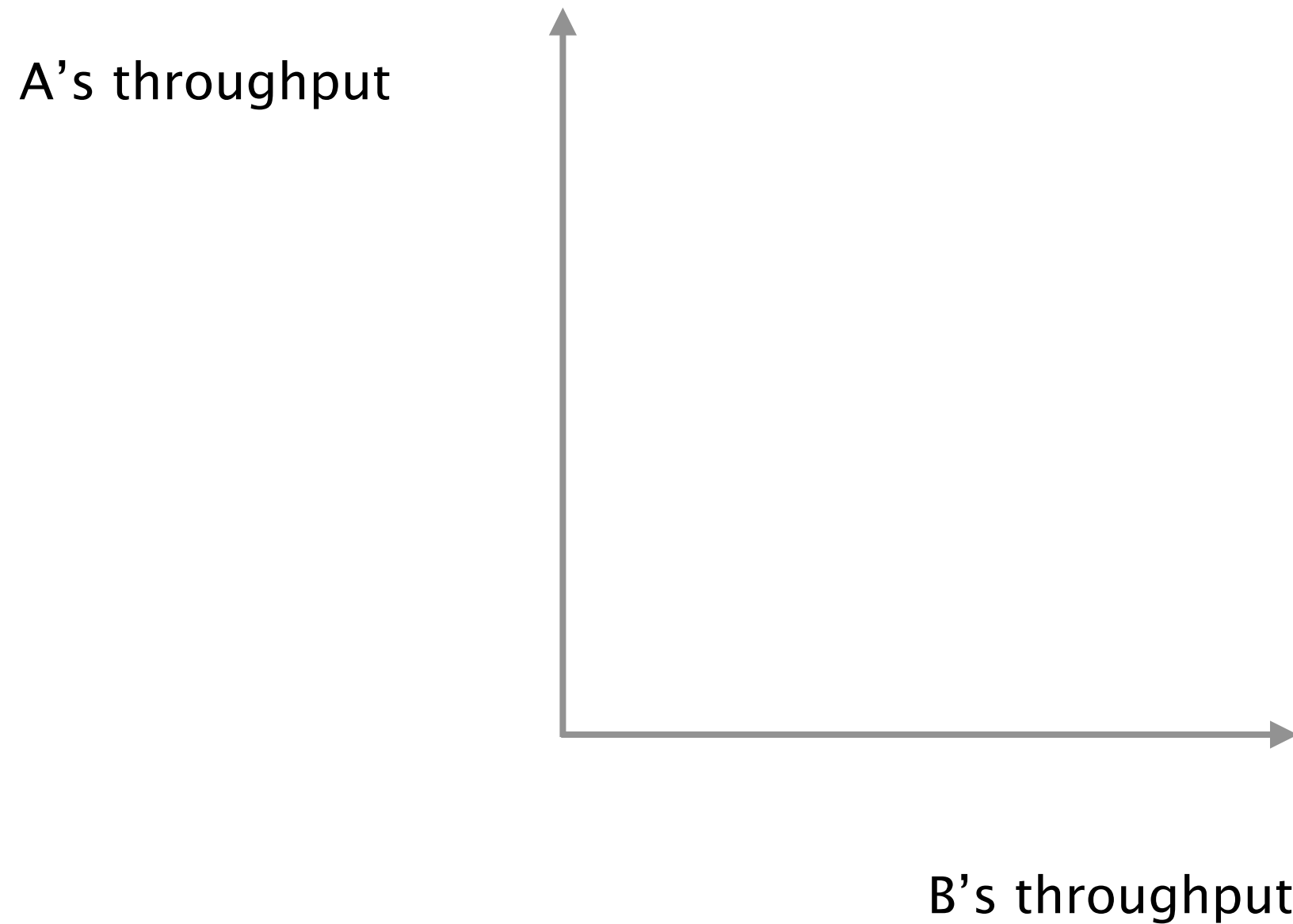


without congestion
upon congestion

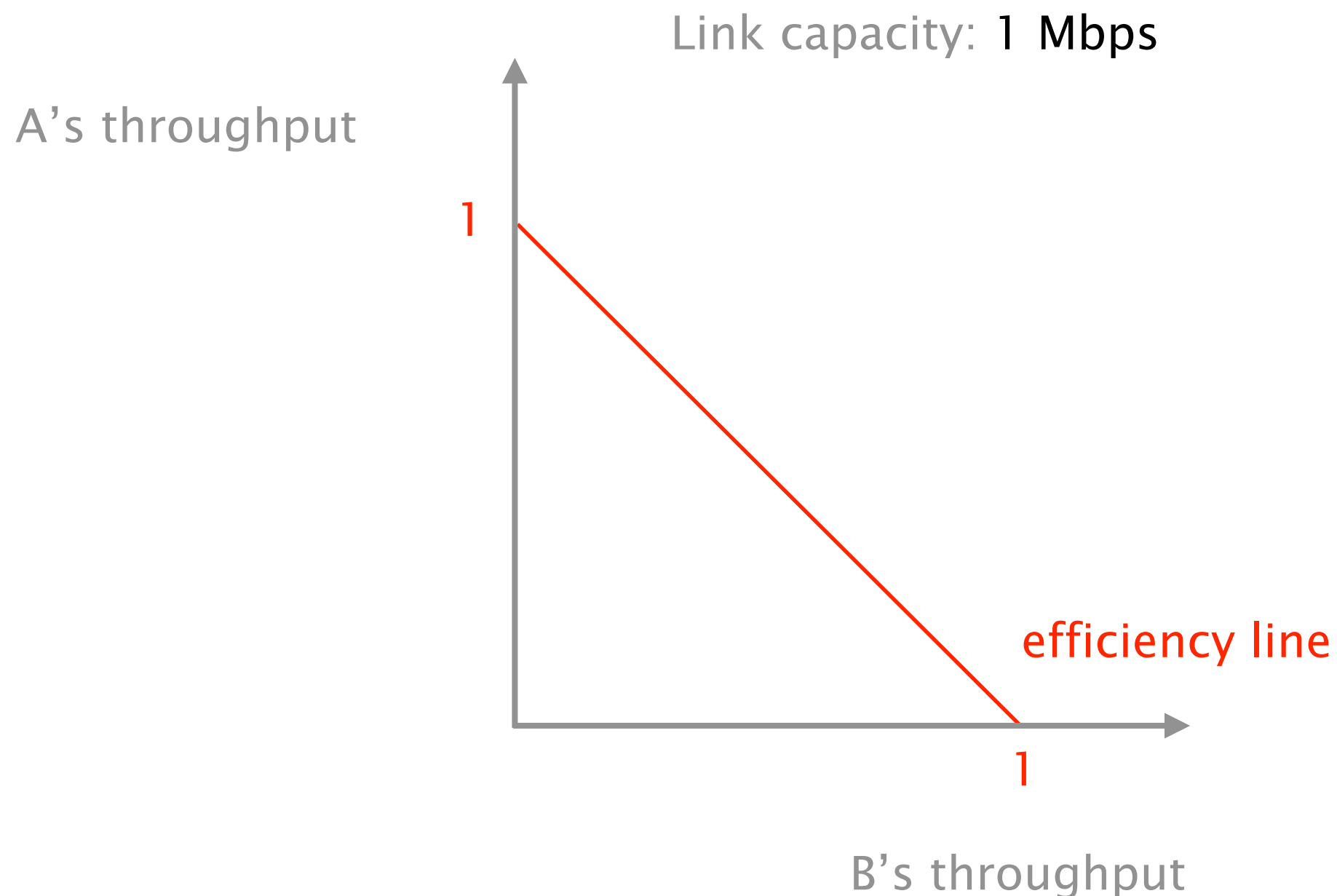
CWND increases by one packet every ACK
CWND decreases by a factor 2



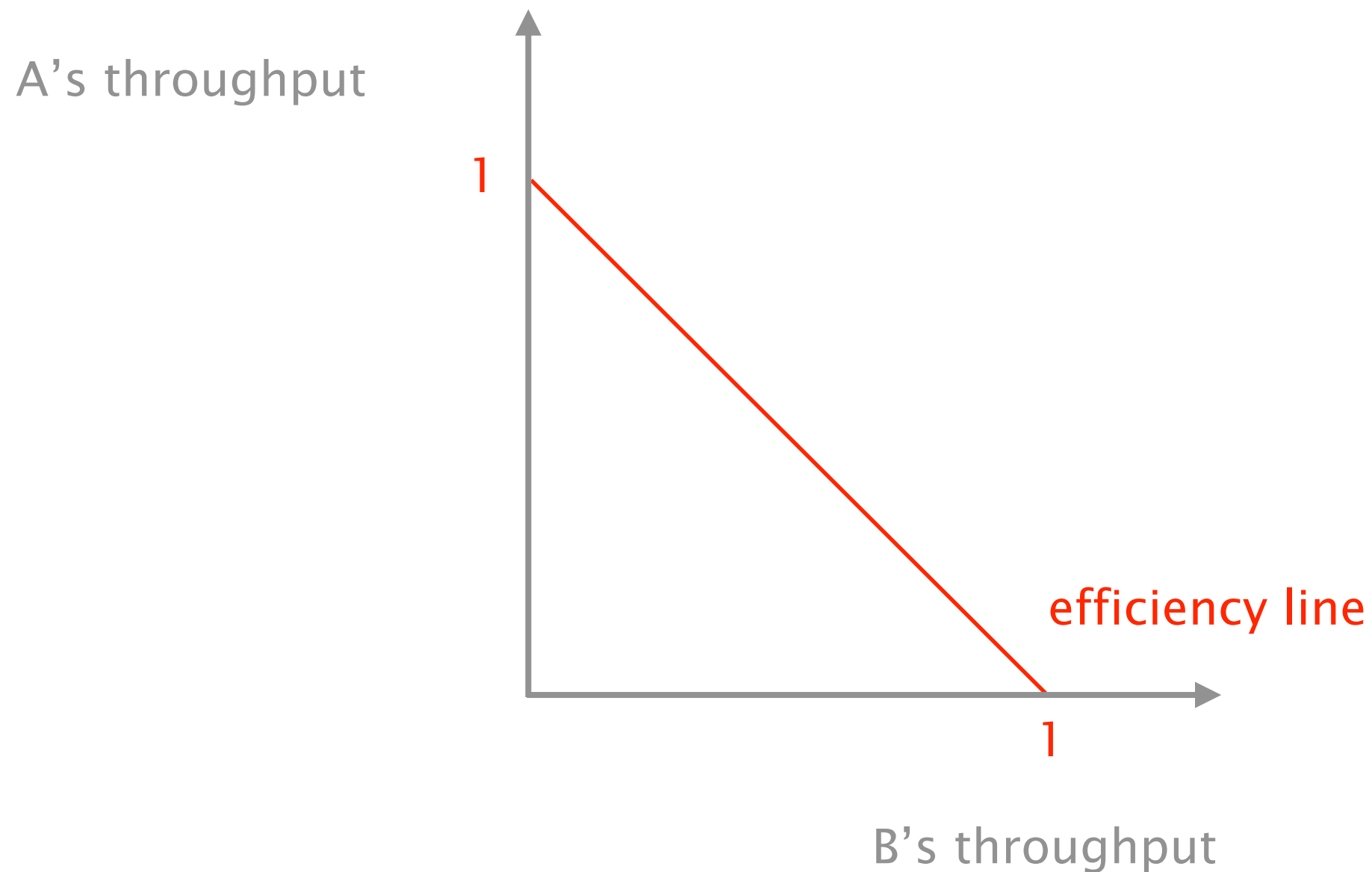
We can analyze the system behavior
using a system trajectory plot

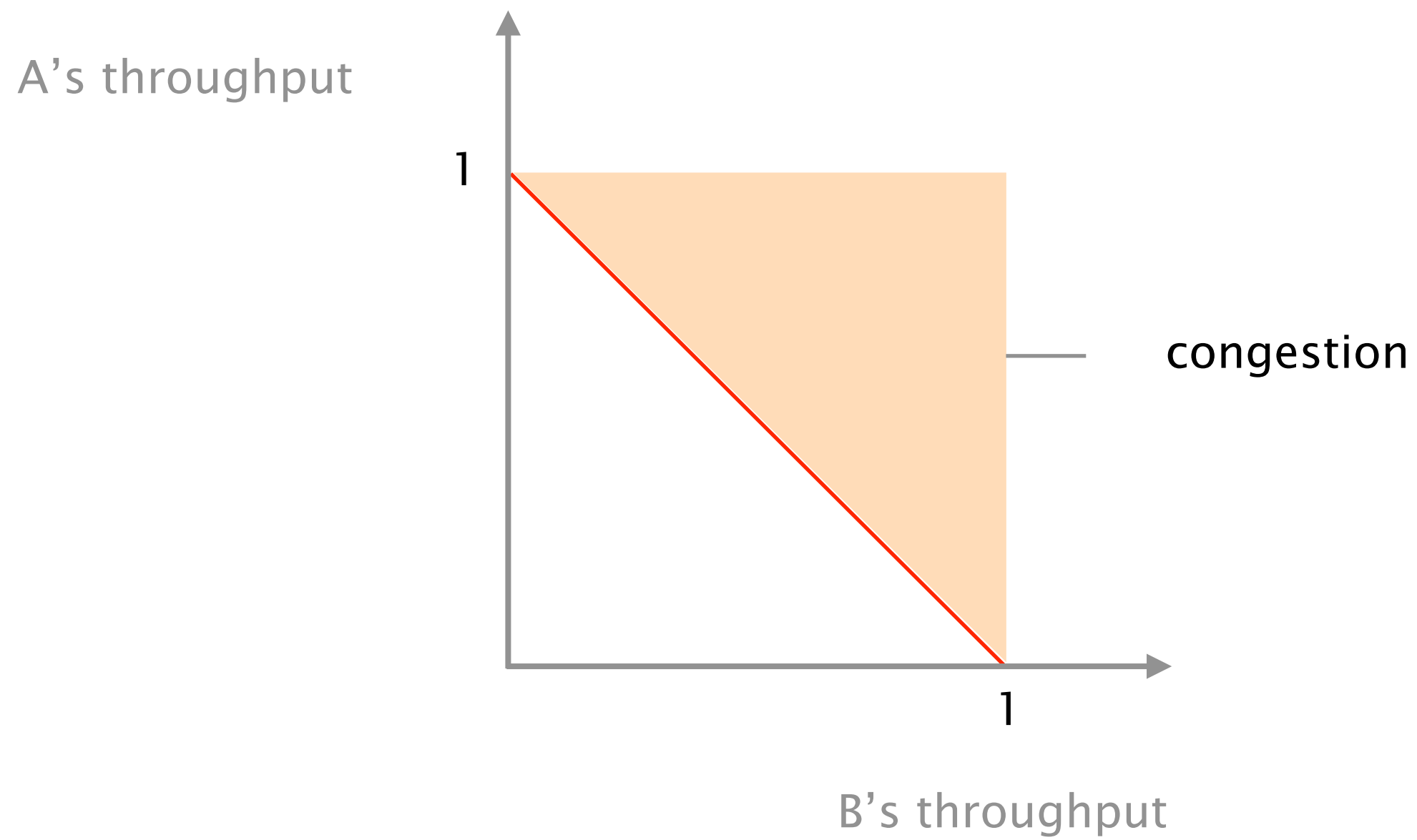


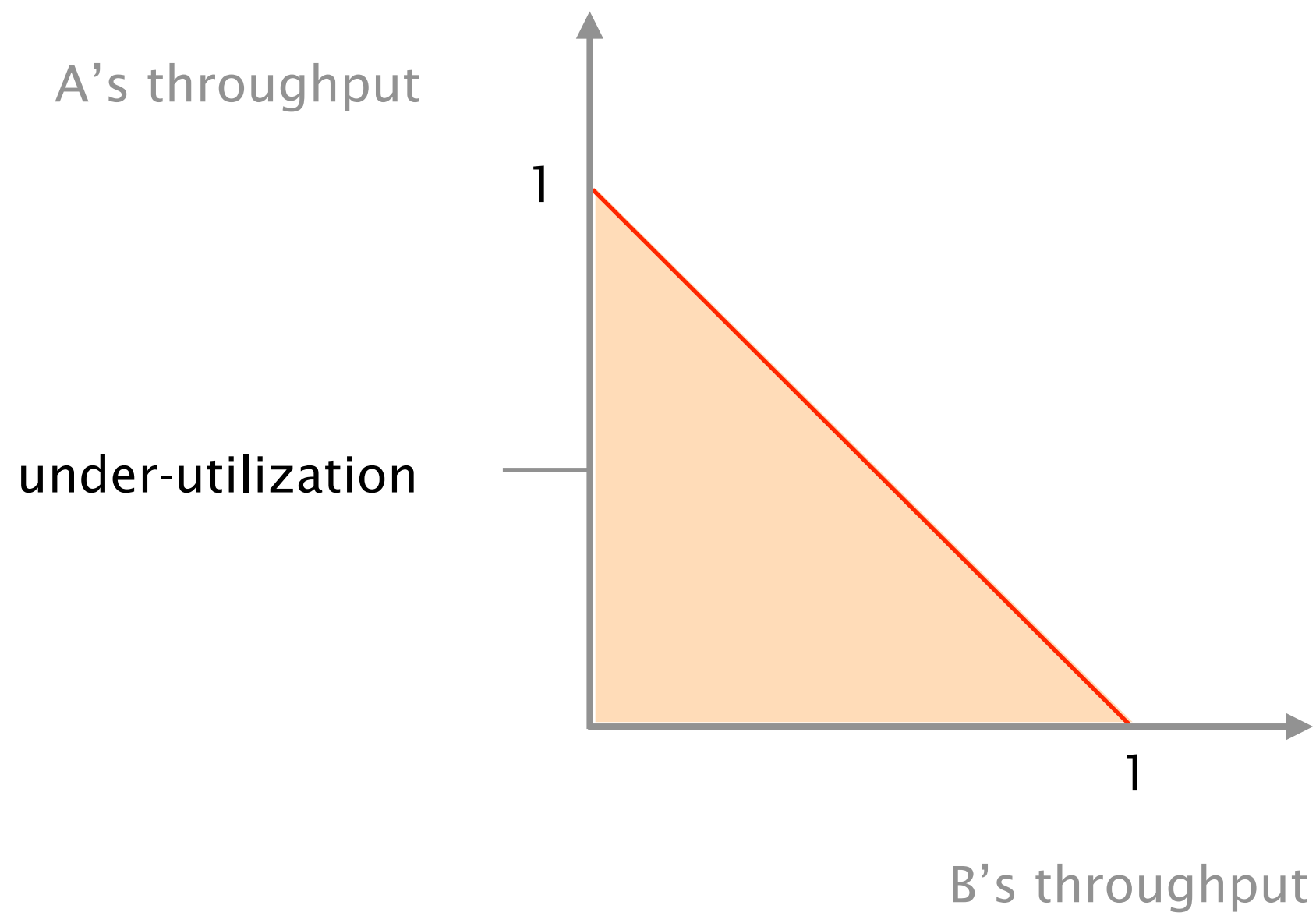
The system is efficient if the capacity is fully used, defining an **efficiency line** where $a + b = 1$



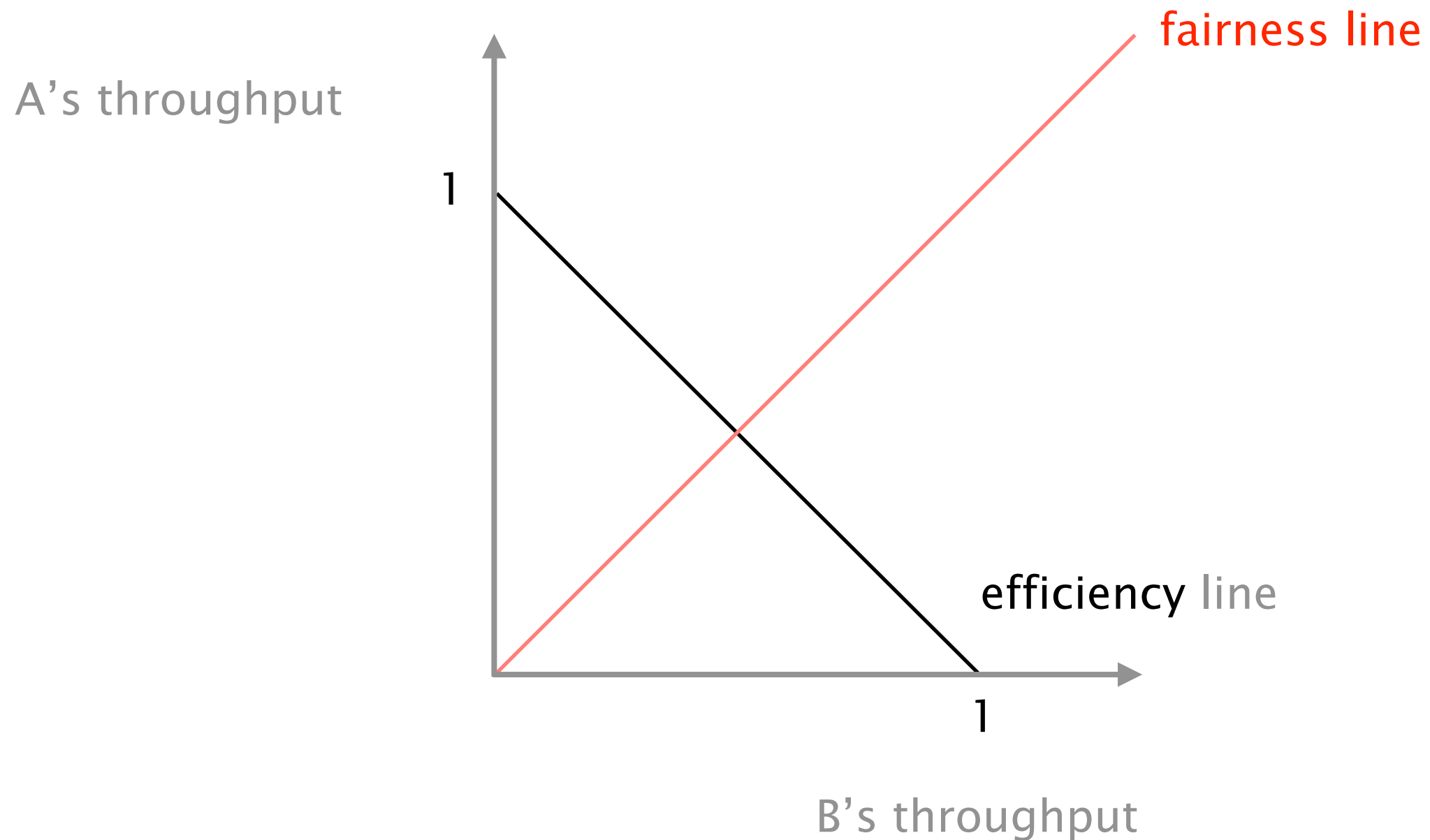
The goal of congestion control is to bring the system as close as possible to this line, and stay there

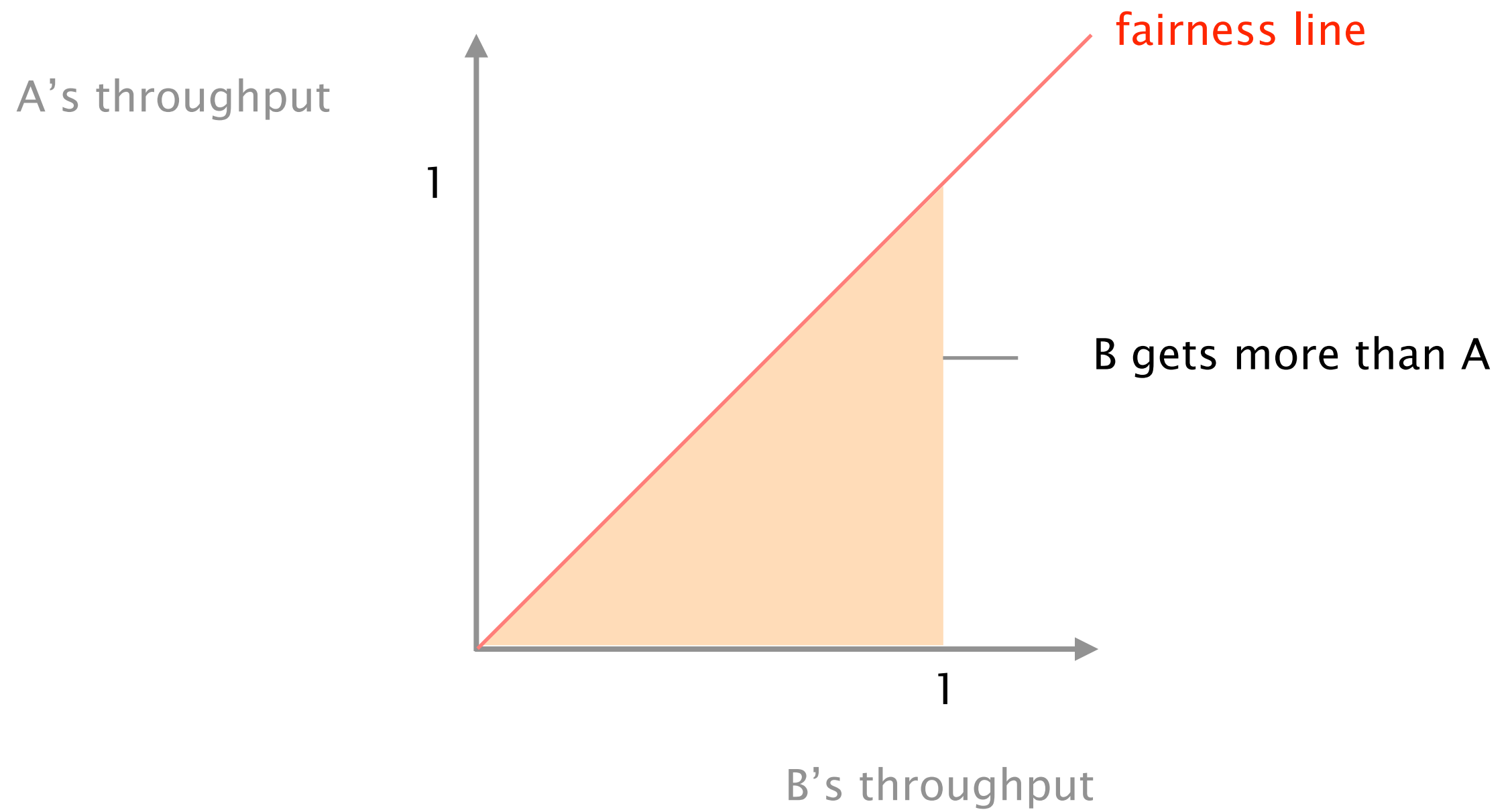


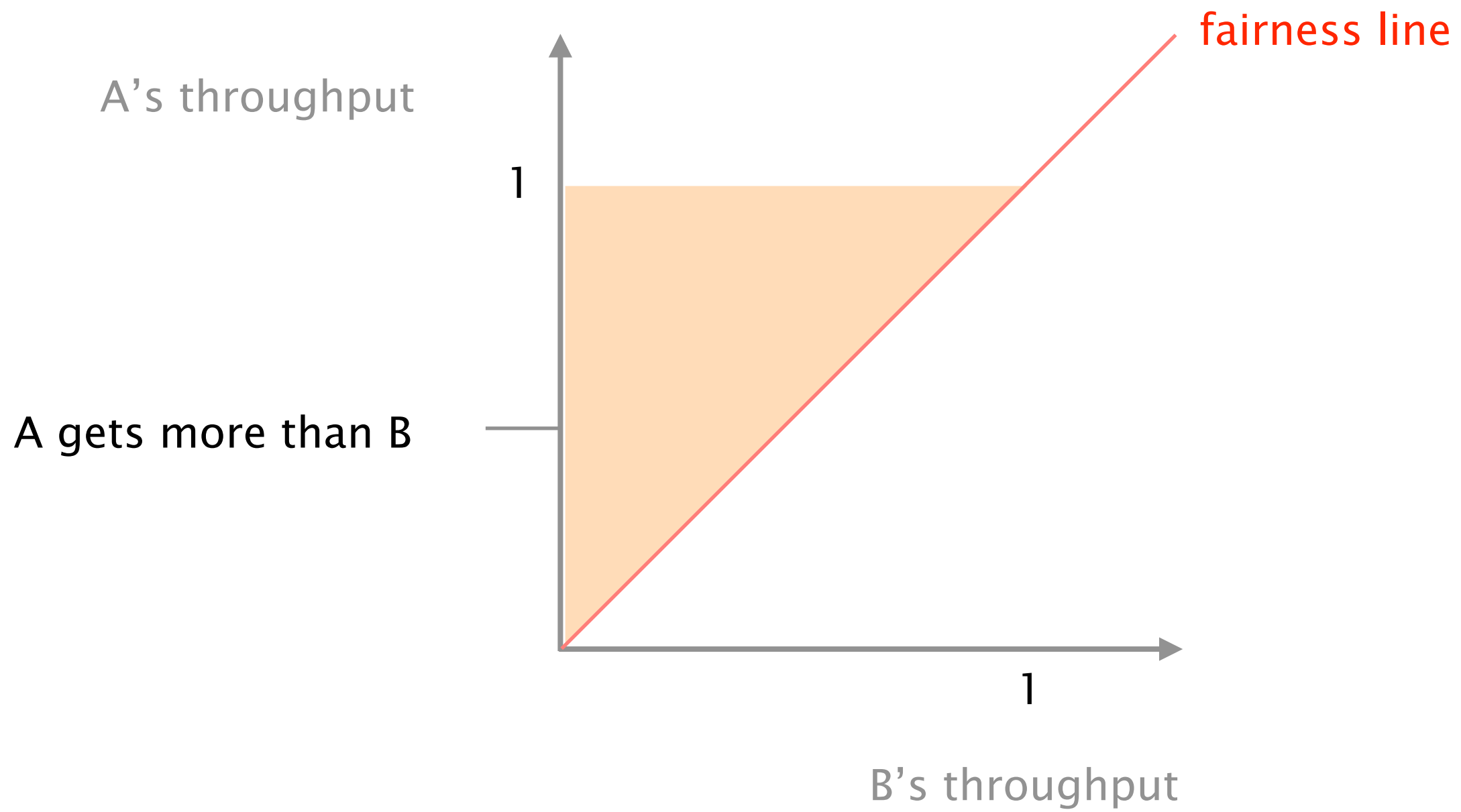


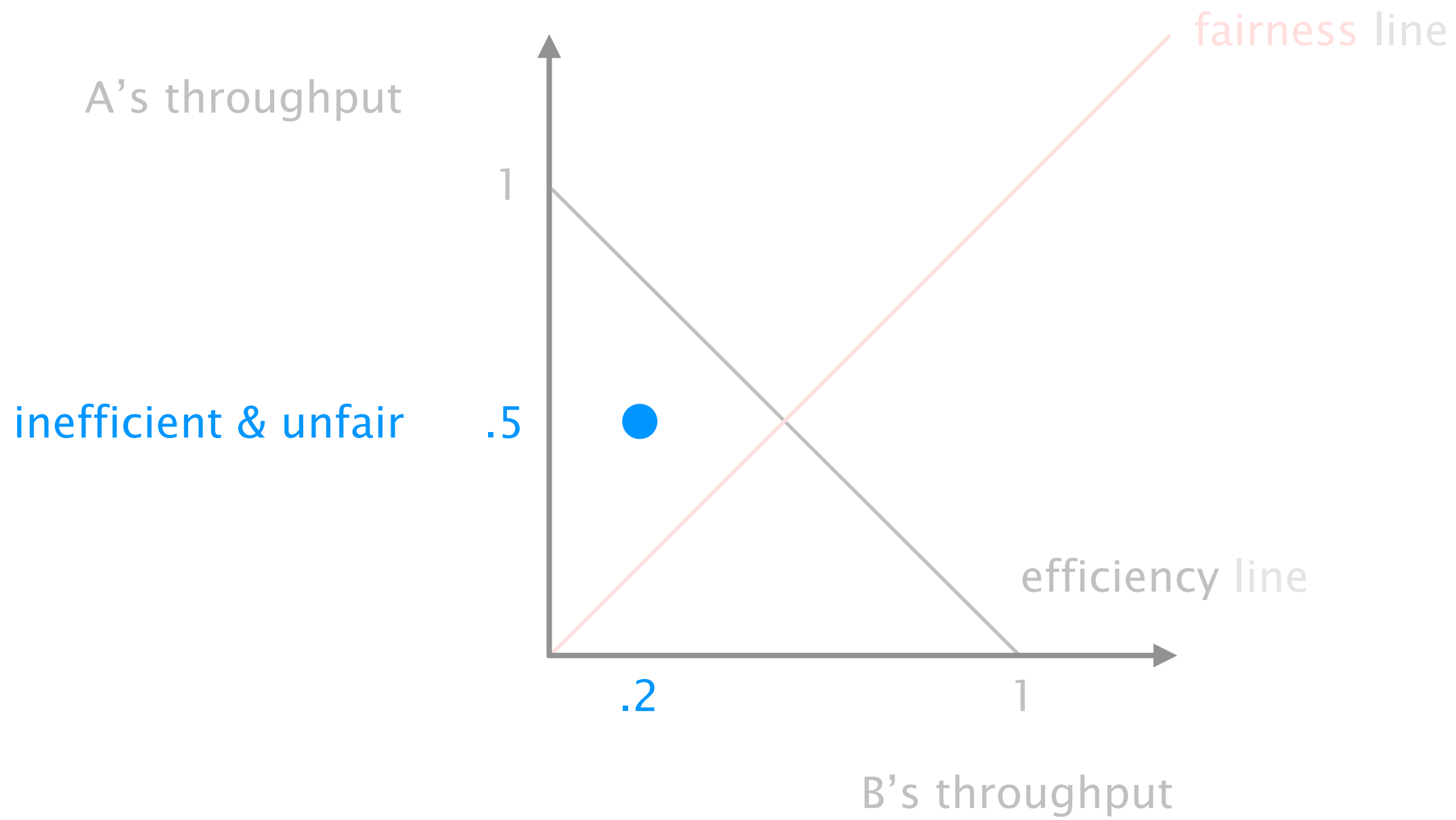


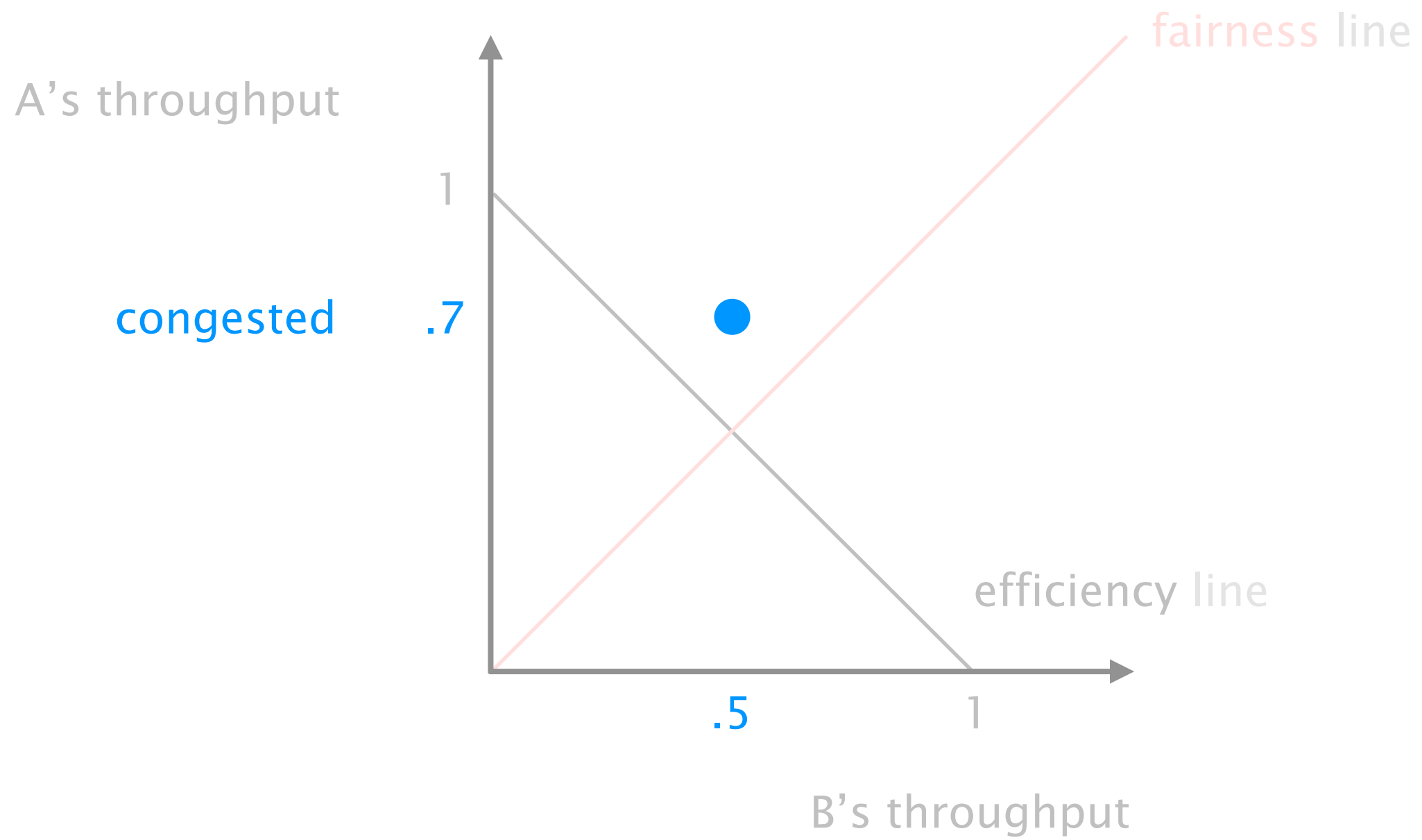
The system is fair whenever A and B have equal throughput, defining a **fairness line** where $a = b$

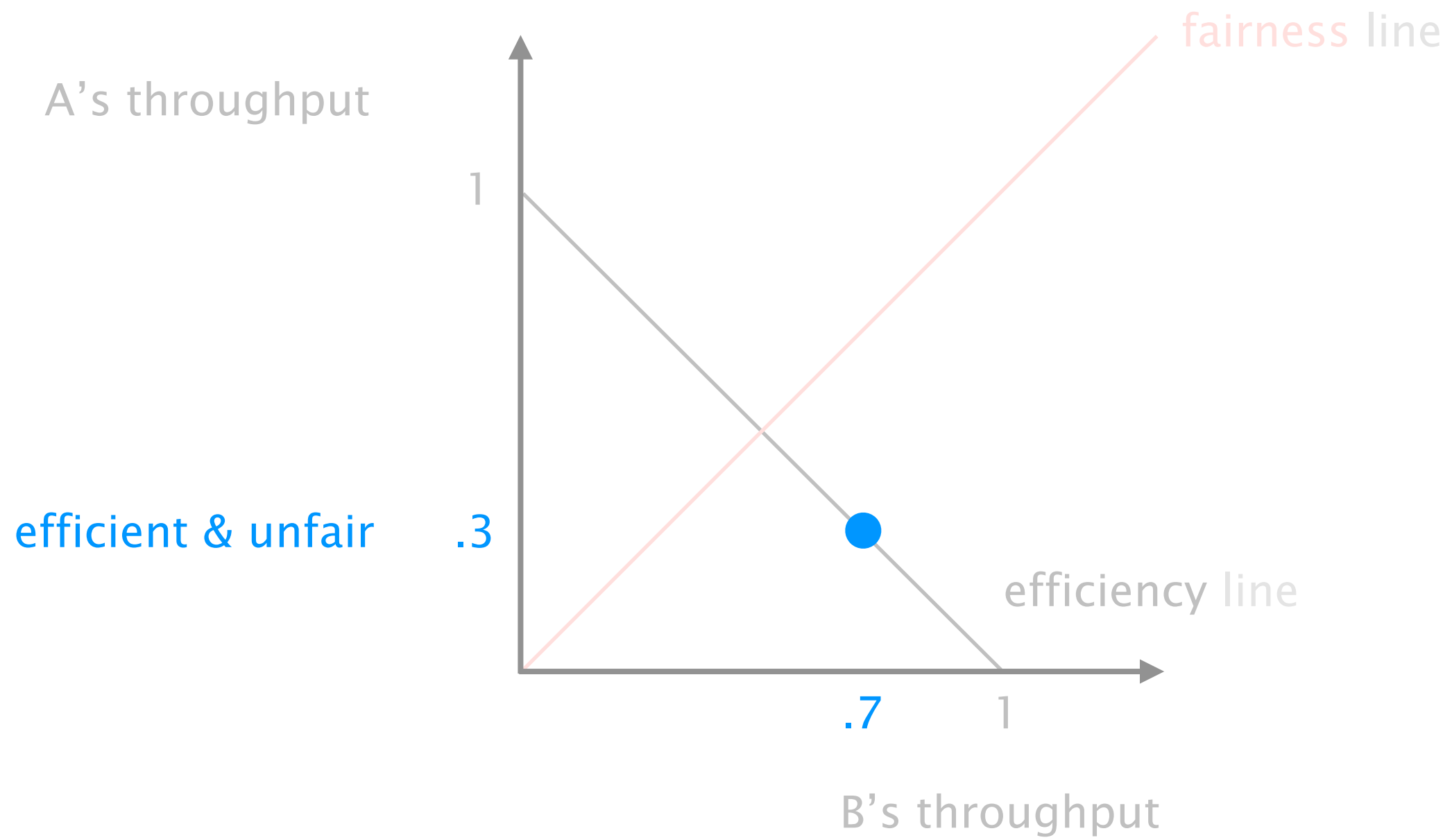


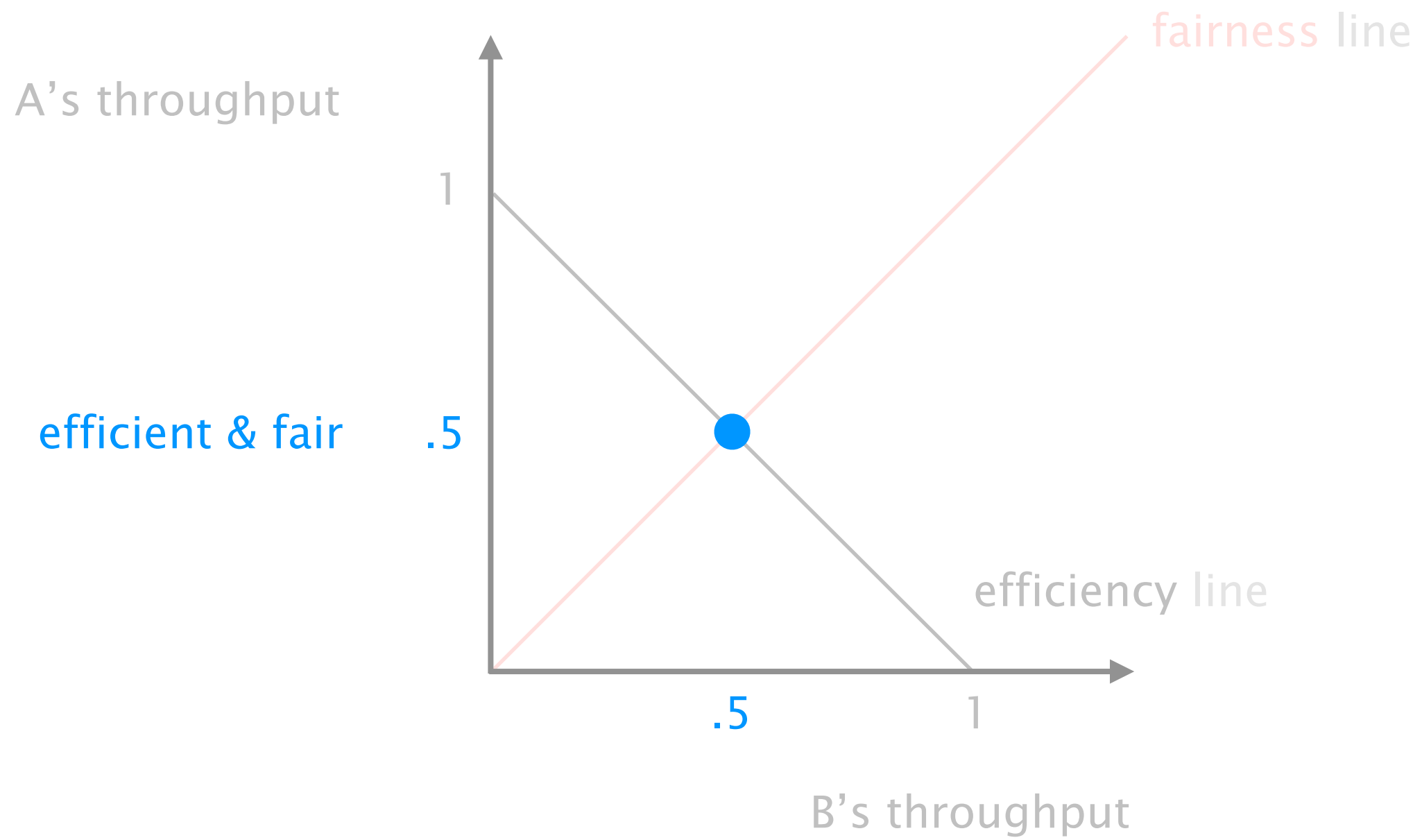












increase
behavior

decrease
behavior

AIAD

gentle

gentle

AIMD

gentle

aggressive

MIAD

aggressive

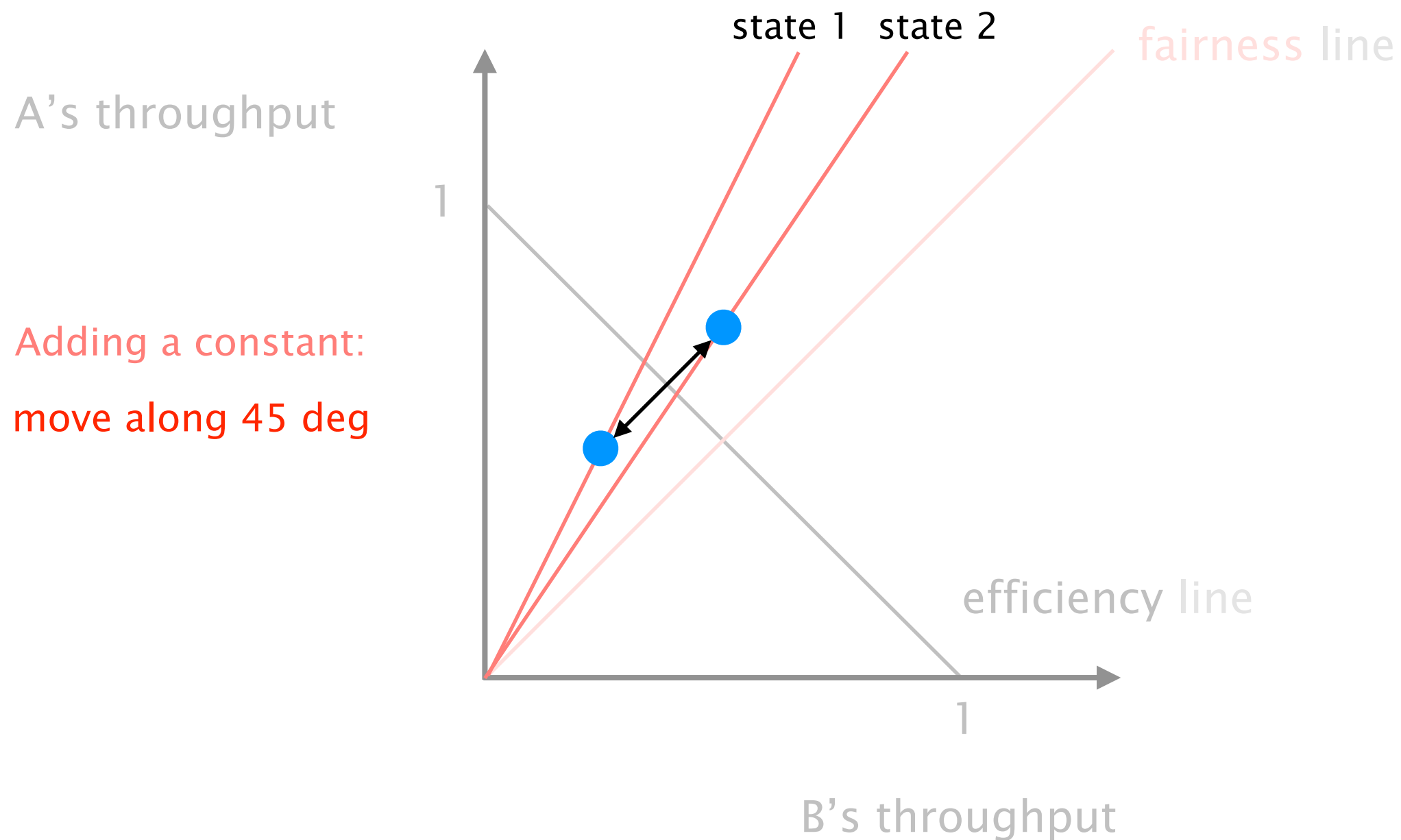
gentle

MIMD

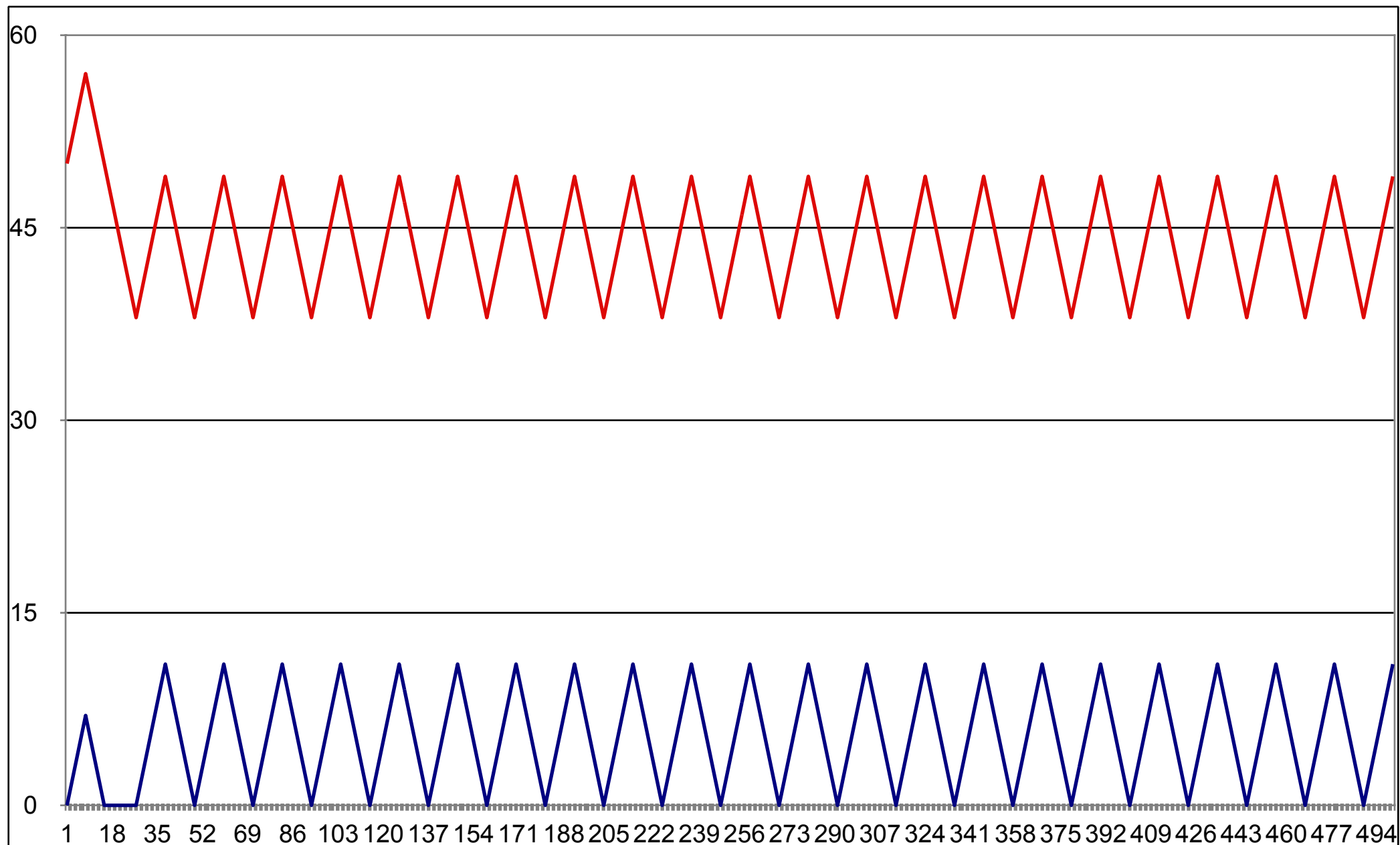
aggressive

aggressive

AIAD does not converge to fairness, nor efficiency:
the system fluctuates between two fairness states



AIAD does not converge to fairness, nor efficiency:
the system fluctuates between two fairness states



increase
behavior

decrease
behavior

AIAD

gentle

gentle

AIMD

gentle

aggressive

MIAD

aggressive

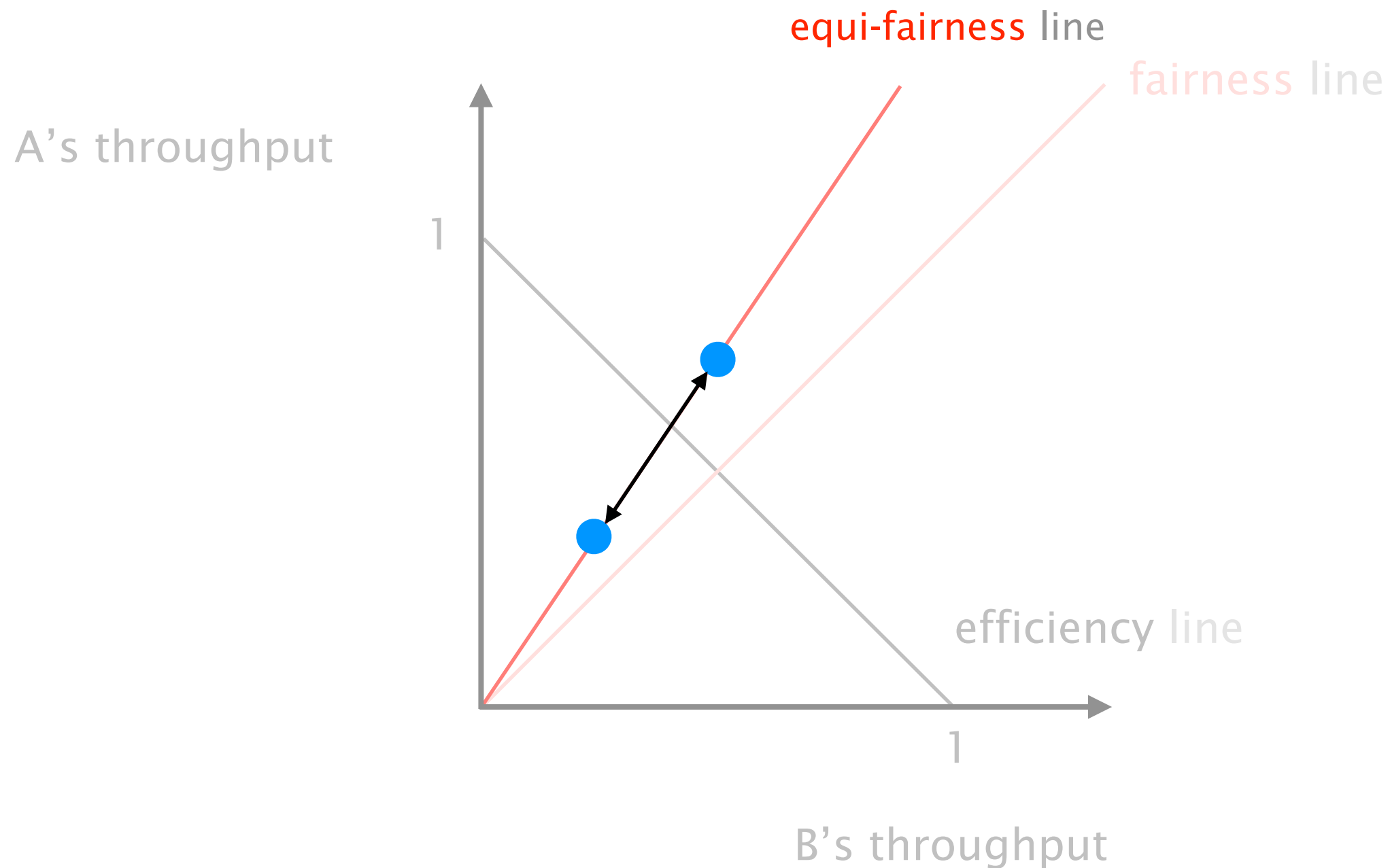
gentle

MIMD

aggressive

aggressive

MIMD does not converge to fairness, nor efficiency:
the system fluctuates along a equi-fairness line



increase
behavior

decrease
behavior

AIAD

gentle

gentle

AIMD

gentle

aggressive

MIAD

aggressive

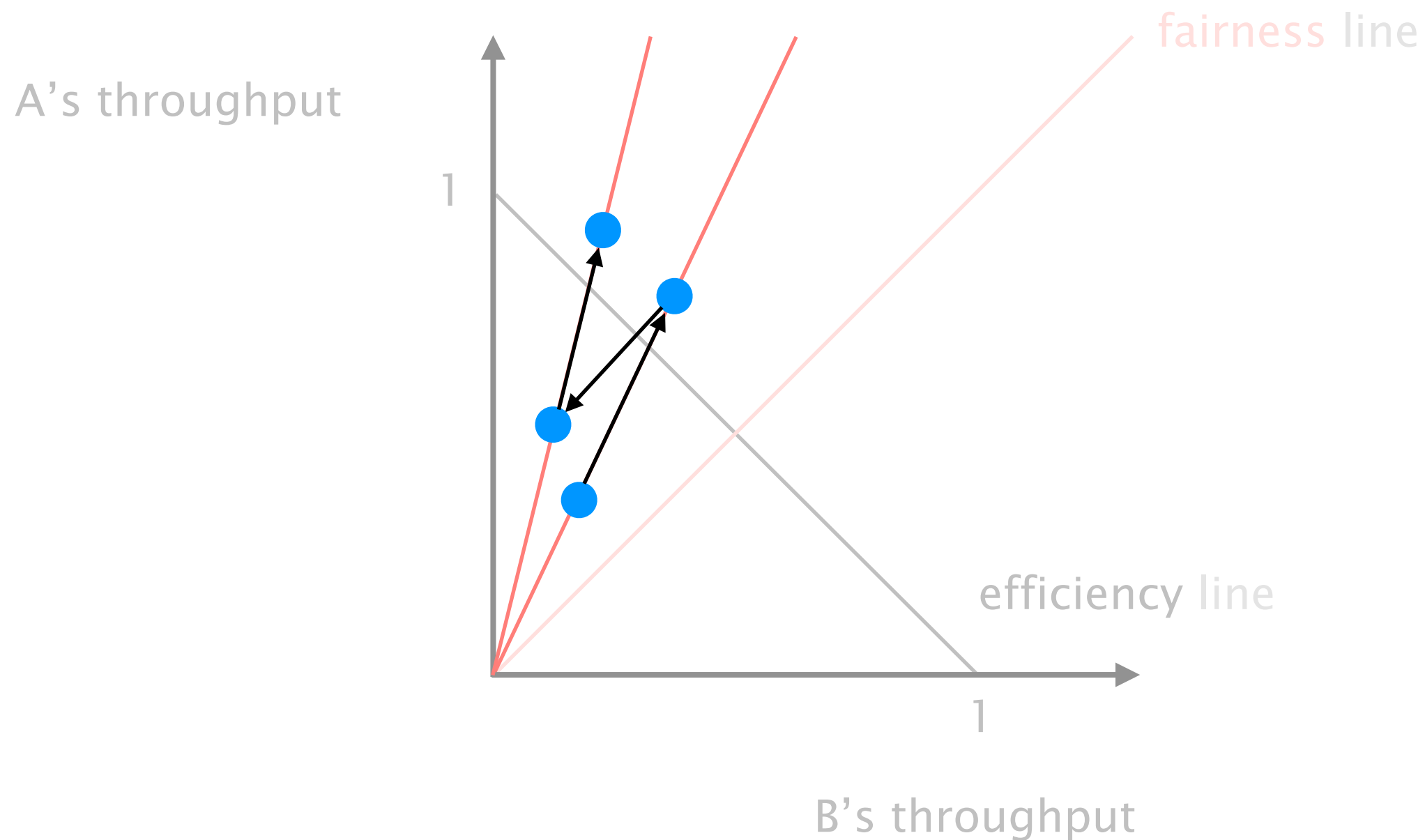
gentle

MIMD

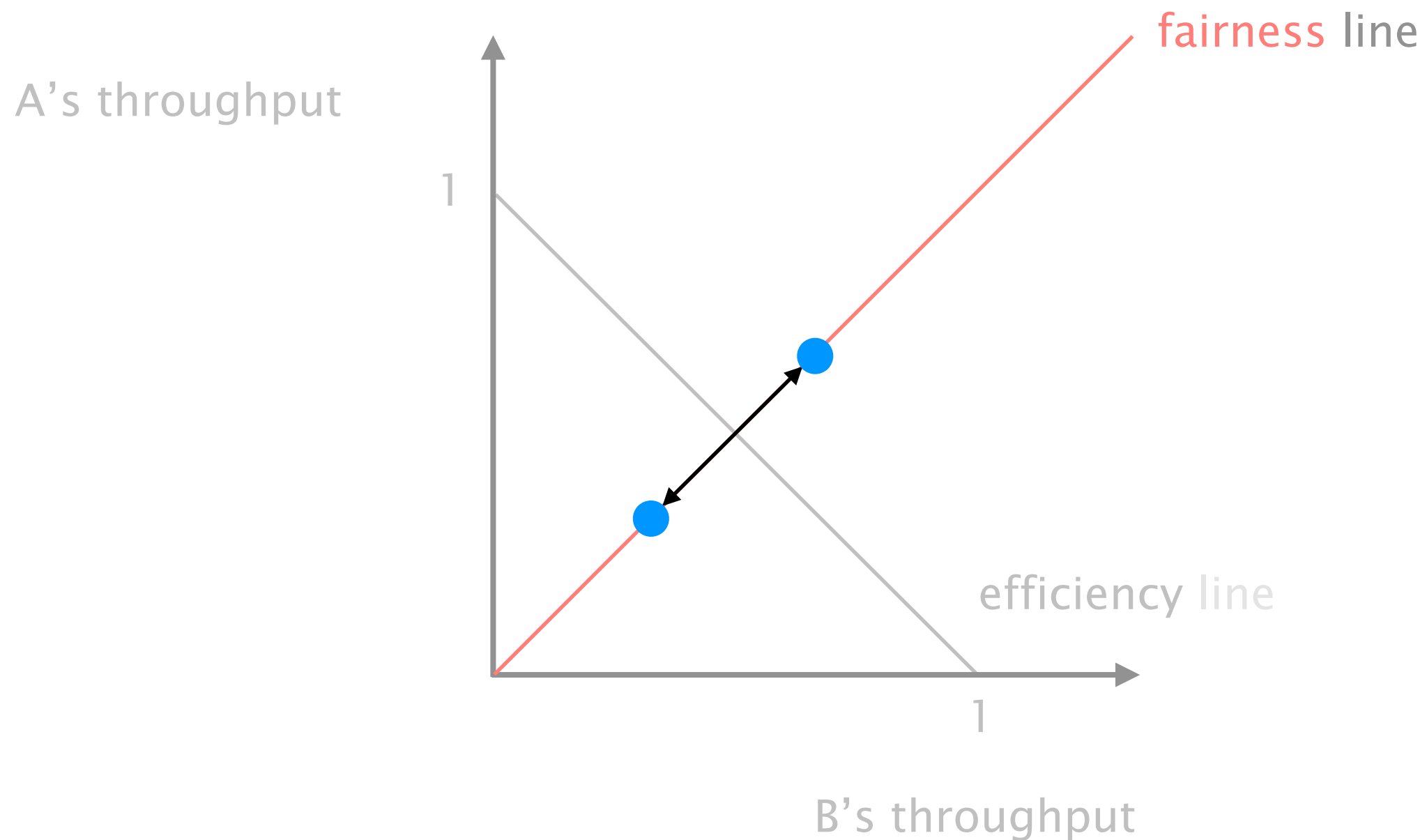
aggressive

aggressive

MIAD converges to a totally unfair allocation,
favoring the flow with a greater rate at the beginning



If flows start along the fairness line, MIAD fluctuates along it, **yet deviating from it at the slightest change**



increase
behavior

decrease
behavior

AIAD

gentle

gentle

AIMD

gentle

aggressive

MIAD

aggressive

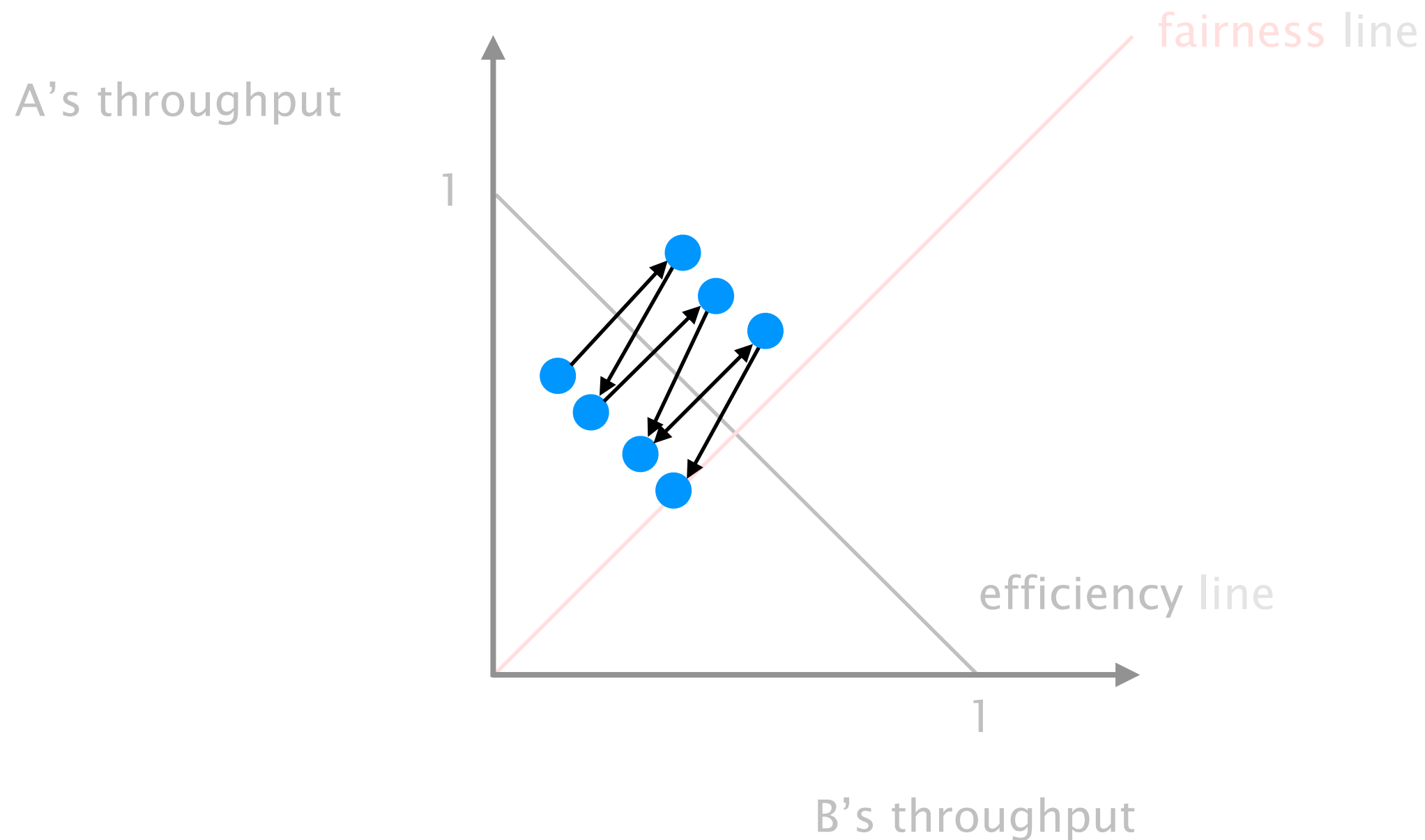
gentle

MIMD

aggressive

aggressive

AIMD converge to fairness and efficiency,
it then fluctuates around the optimum (in a stable way)



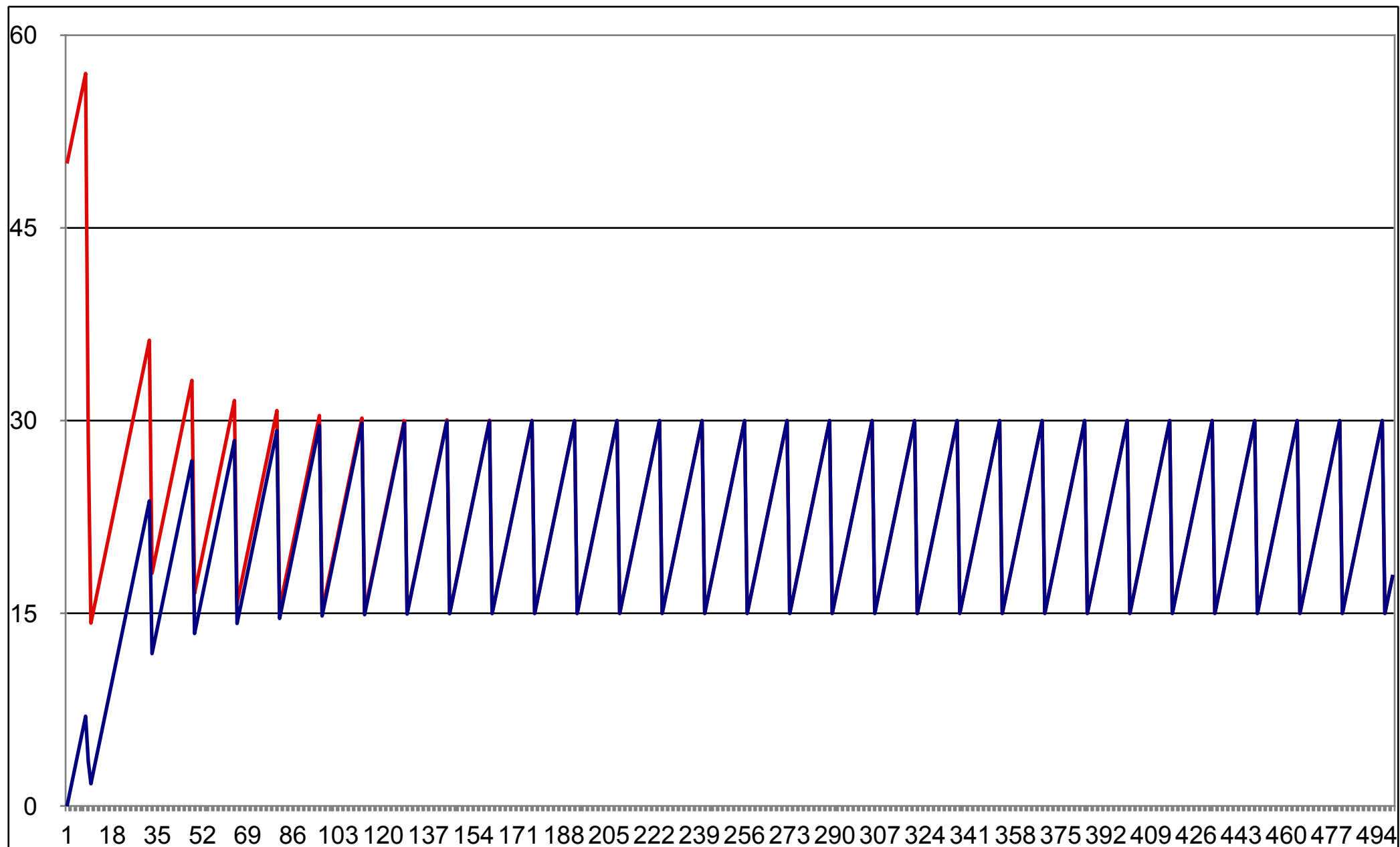
AIMD converge to fairness and efficiency,
it then fluctuates around the optimum (in a stable way)

Intuition

During increase,
both flows gain bandwidth at the same rate

During decrease,
the faster flow releases more

AIMD converge to fairness and efficiency,
it then fluctuates around the optimum (in a stable way)



In practice,
TCP implements AIMD

	increase behavior	decrease behavior
AIAD	gentle	gentle
AIMD	gentle	aggressive
MIAD	aggressive	gentle
MIMD	aggressive	aggressive

In practice, TCP implements AIMD

Implementation

After each ACK,

Increment cwnd by $1/\text{cwnd}$

linear increase of max. 1 per RTT

Question

When does a sender leave slow-start and start AIMD?

Introduce a slow start threshold,
adapt it in function of congestion:

on timeout, $\text{ssthresh} = \text{CWND}/2$

TCP congestion control in less than 10 lines of code

Initially:

`cwnd = 1`

`ssthresh = infinite`

New ACK received:

`if (cwnd < ssthresh):`

`/* Slow Start*/`

`cwnd = cwnd + 1`

`else:`

`/* Congestion Avoidance */`

`cwnd = cwnd + 1/cwnd`

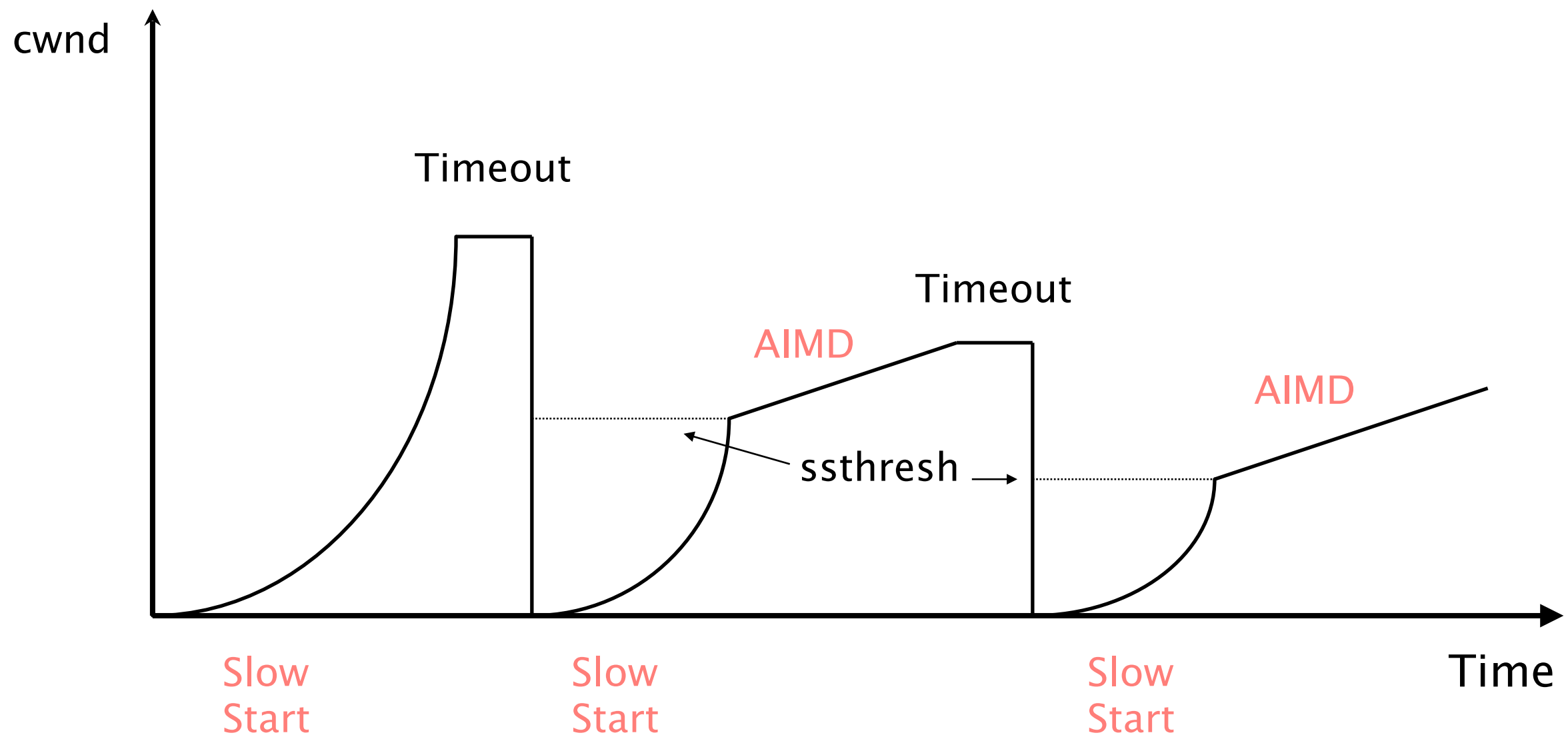
Timeout:

`/* Multiplicative decrease */`

`ssthresh = cwnd/2`

`cwnd = 1`

The congestion window of a TCP session typically undergoes multiple cycles of slow-start/AIMD



Going back all the way back to 0 upon timeout
completely destroys throughput

solution

Avoid timeout expiration...
which are usually $>500\text{ms}$

Detecting losses can be done **using ACKs** or timeouts,
the two signals differ in their degree of severity

duplicate ACKs

mild congestion signal

packets are still making it

timeout

severe congestion signal

multiple consequent losses

TCP automatically resends a segment
after receiving 3 duplicates ACKs for it

this is known as a “fast retransmit”

After a fast retransmit, TCP switches back to AIMD,
without going all way the back to 0

this is known as “fast recovery”

TCP congestion control (almost complete)

Initially:

$\text{cwnd} = 1$

$\text{ssthresh} = \text{infinite}$

New ACK received:

if ($\text{cwnd} < \text{ssthresh}$):

/ Slow Start */*

$\text{cwnd} = \text{cwnd} + 1$

else:

/ Congestion Avoidance */*

$\text{cwnd} = \text{cwnd} + 1/\text{cwnd}$

$\text{dup_ack} = 0$

Timeout:

/ Multiplicative decrease */*

$\text{ssthresh} = \text{cwnd}/2$

$\text{cwnd} = 1$

Duplicate ACKs received:

$\text{dup_ack} ++;$

if ($\text{dup_ack} \geq 3$):

/ Fast Recovery */*

$\text{ssthresh} = \text{cwnd}/2$

$\text{cwnd} = \text{ssthresh}$

Initially:

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

New ACK received:

```
  if (cwnd < ssthresh):  
    /* Slow Start */  
    cwnd = cwnd + 1  
  else:  
    /* Congestion Avoidance */  
    cwnd = cwnd + 1/cwnd
```

dup_ack = 0

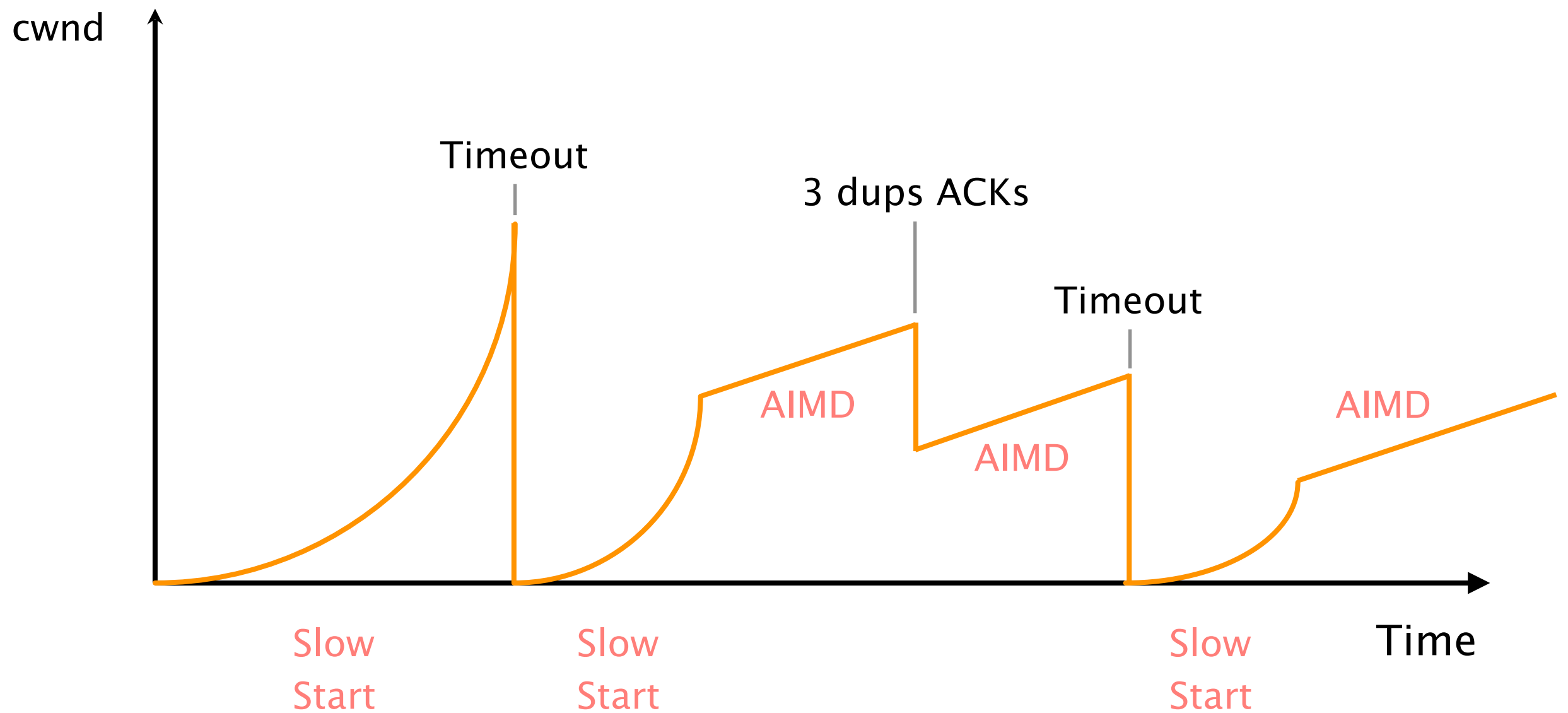
Timeout:

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

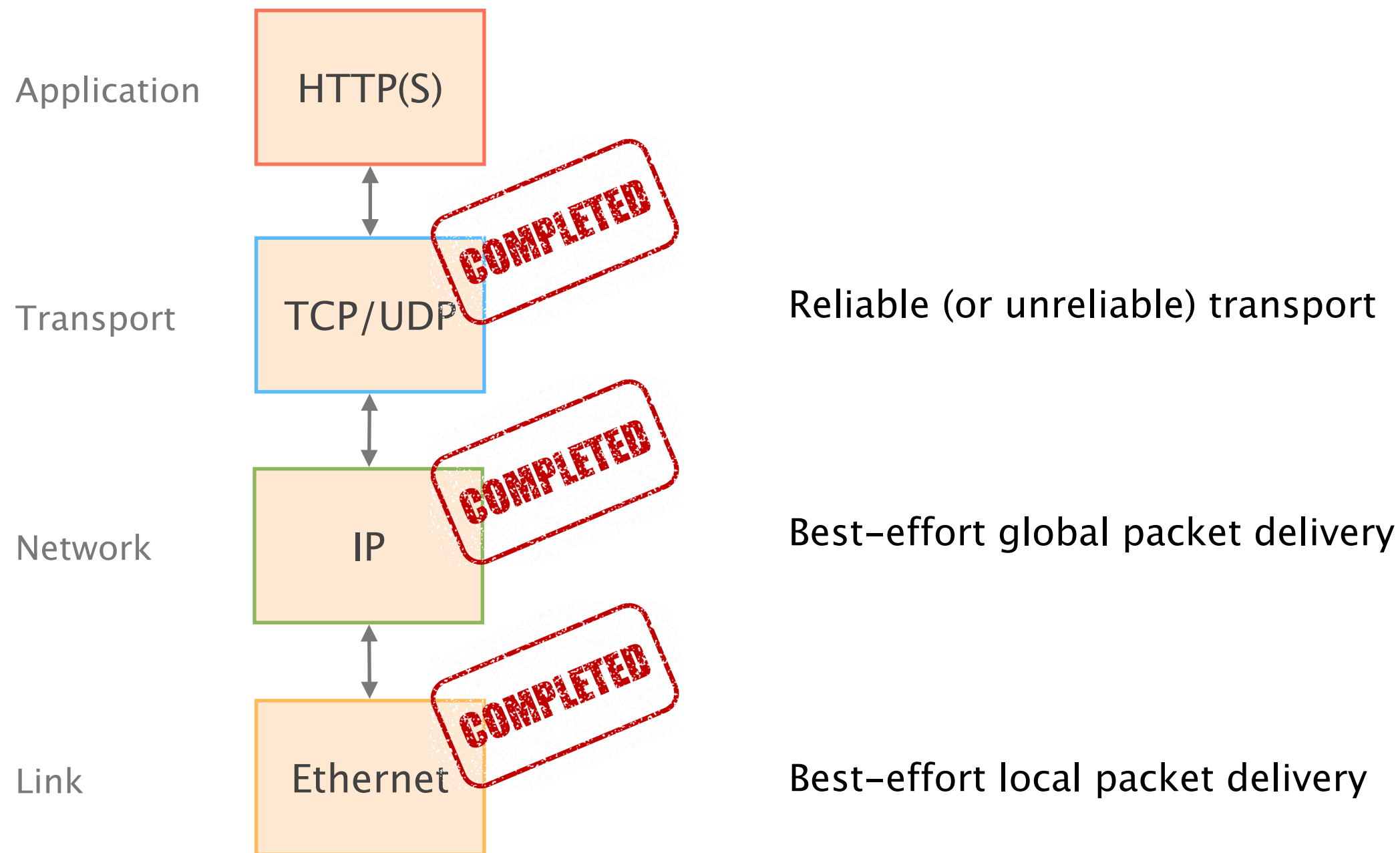
Duplicate ACKs received:

```
  dup_ack ++;  
  if (dup_ack >= 3):  
    /* Fast Recovery */  
    ssthresh = cwnd/2  
    cwnd = ssthresh
```

Congestion control makes TCP throughput look like a “sawtooth”

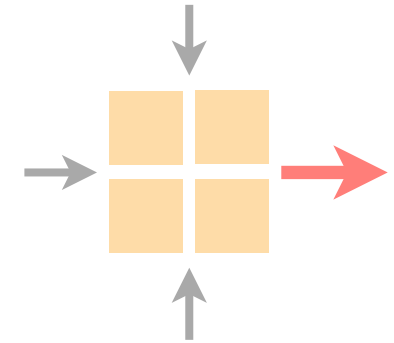


We now have completed **the transport layer (!)**



Communication Networks

Spring 2021



Laurent Vanbever

nsg.ee.ethz.ch

ETH Zürich (D-ITET)

May 10 2021