VU VRIJE UNIVERSITEIT AMSTERDAM

The Transport Layer

(Part II)

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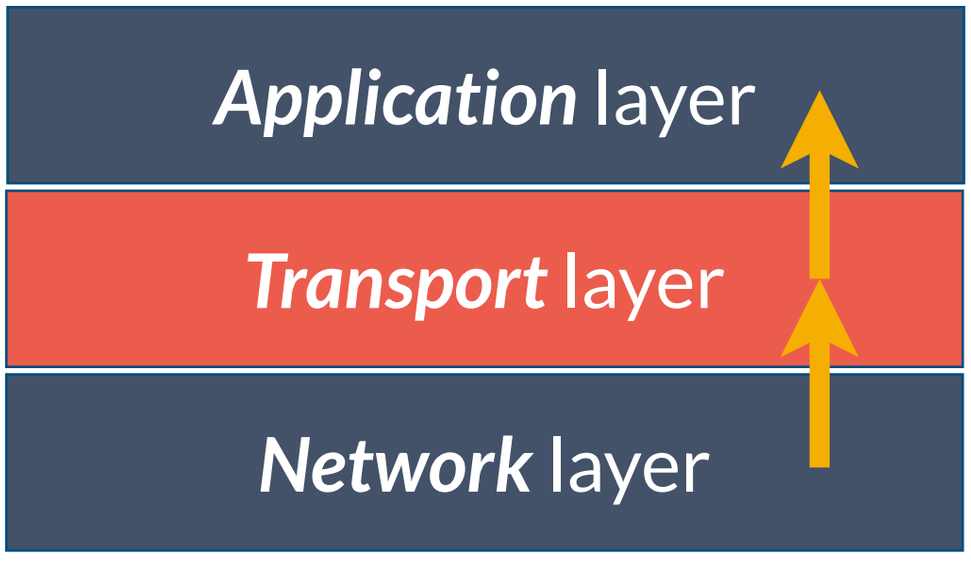
(Slides borrow content from lectures of Jennifer Rexford, Anja Feldmann, Bruce M. Maggs, and Jesse Donkervliet.)

Objectives

- Stream of Bytes Service
- RTT Estimation
- Flow Control
- Congestion Control

Recap

Transport layer



Offers various functionalities to the application

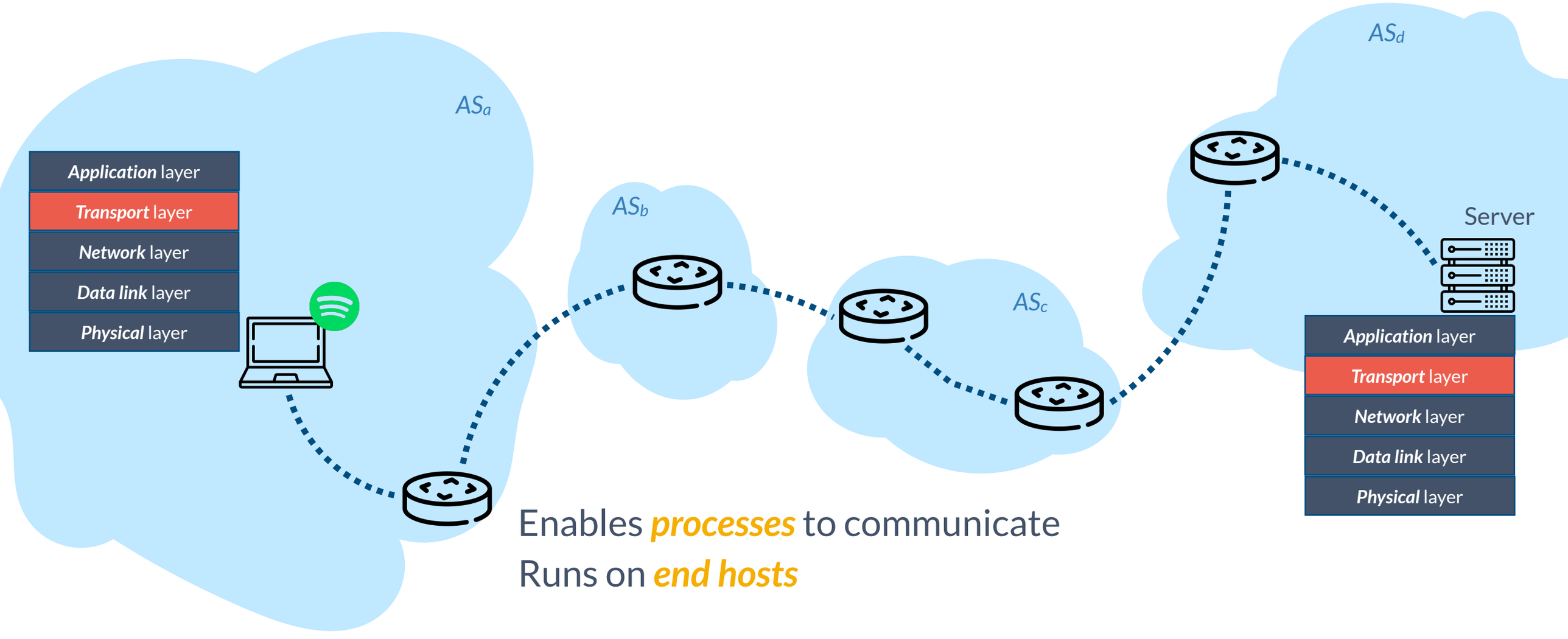
(reliable data transfer, congestion control, flow control, …)

Relies on *services* exposed by the network

(Network layer provides the path for the transport.)

Recap

End-to-End protocol



Enables ***processes*** to communicate

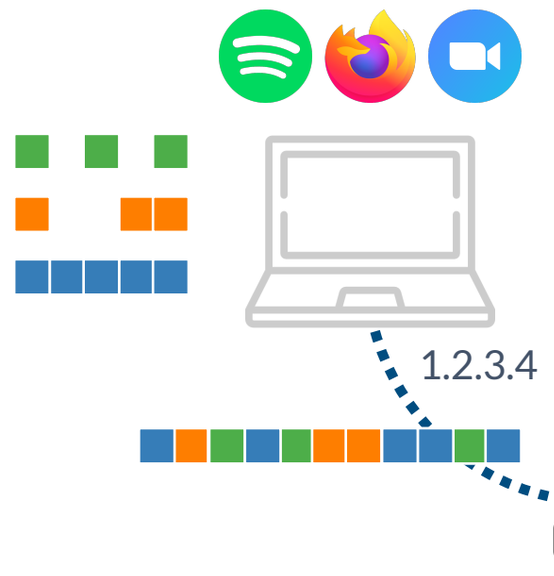
Runs on ***end hosts***

Recap

(De)Multiplexing traffic

- Different applications may generate different traffic workloads
  - Browsing: typically *bursty*

- *Statistical multiplexing*
  - Maximize *utilization* by multiplexing different applications' traffic



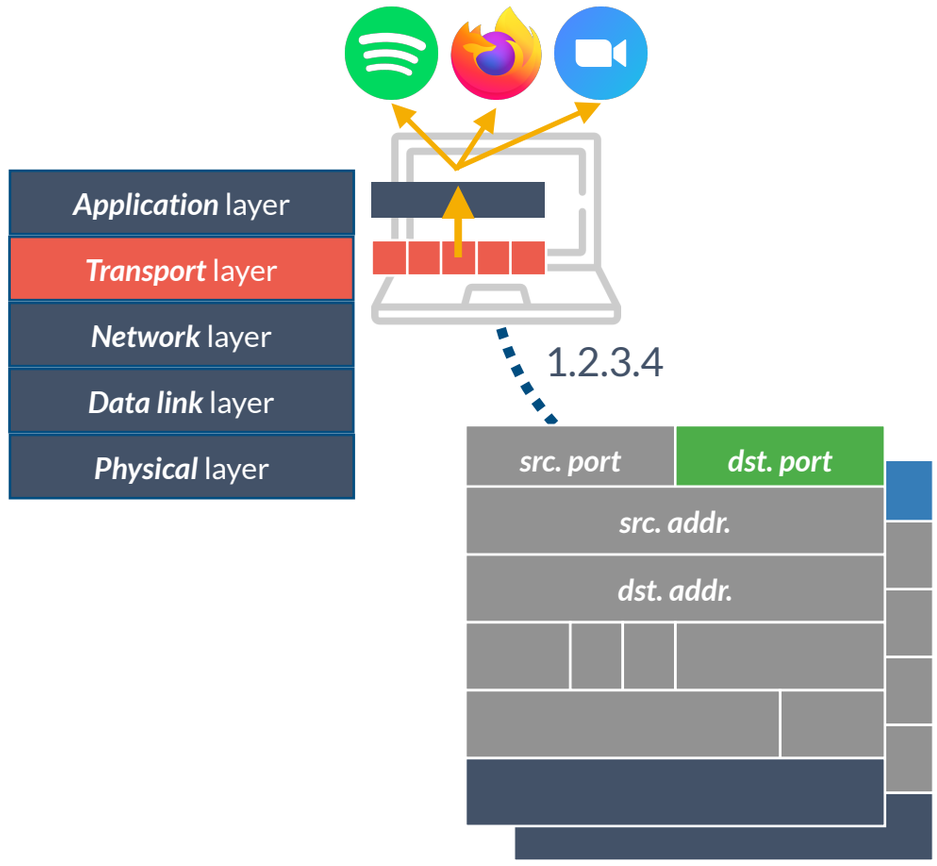
Recap

(De)Multiplexing traffic

- All applications running on the end host have the *same* IP address
  - Who should receive reassembled segments?
  - Transport layer needs more than IP addresses to identify *end points*

- Host receives IP *datagrams*, each of which
  - has a *source* and *destination* IP address
  - carries *one* transport *segment*

- Each *segment* has a *source* and *destination port* number

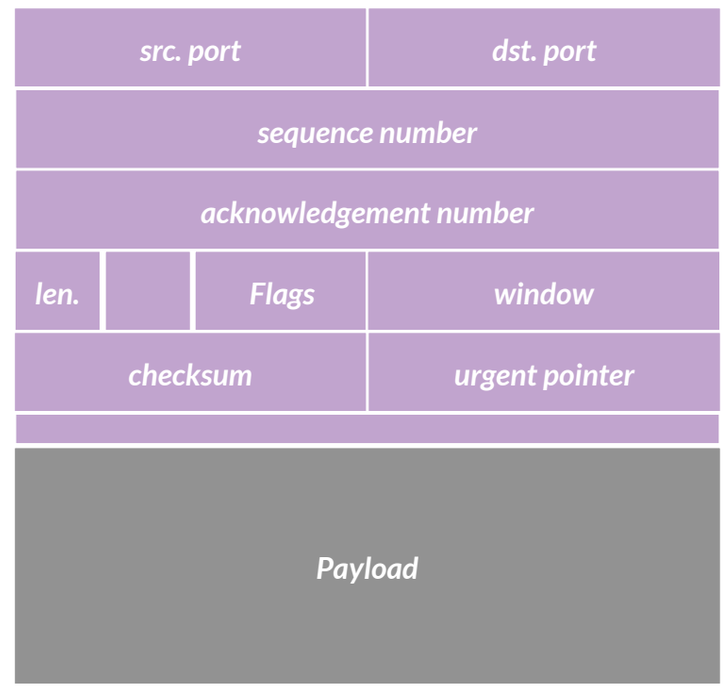


IP addresses and port numbers determine which application gets which segments.

Recap

Reliable data transfer

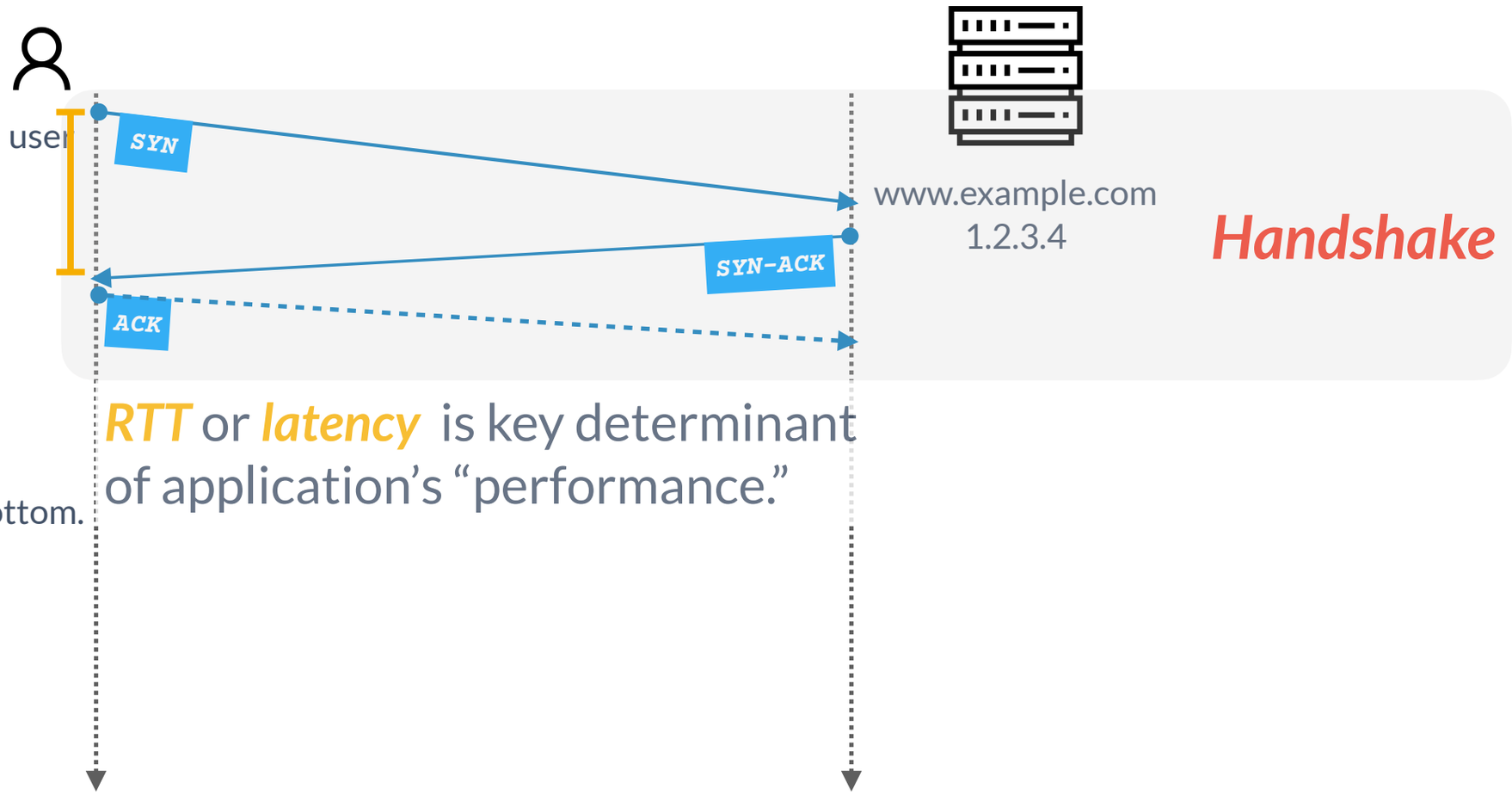
- *Transmission Control Protocol (TCP)*
  - Source and destination ports
  - Sequence and acknowledgement numbers
  - At least 20-bytes of header
- Rich protocol
  - *Connection-oriented*
  - *Stream-of-bytes* service
  - *Reliable*, *in-order* delivery
  - *Flow* control
  - *Congestion* control



Recap

TCP “Handshake”

Round-trip time (RTT)

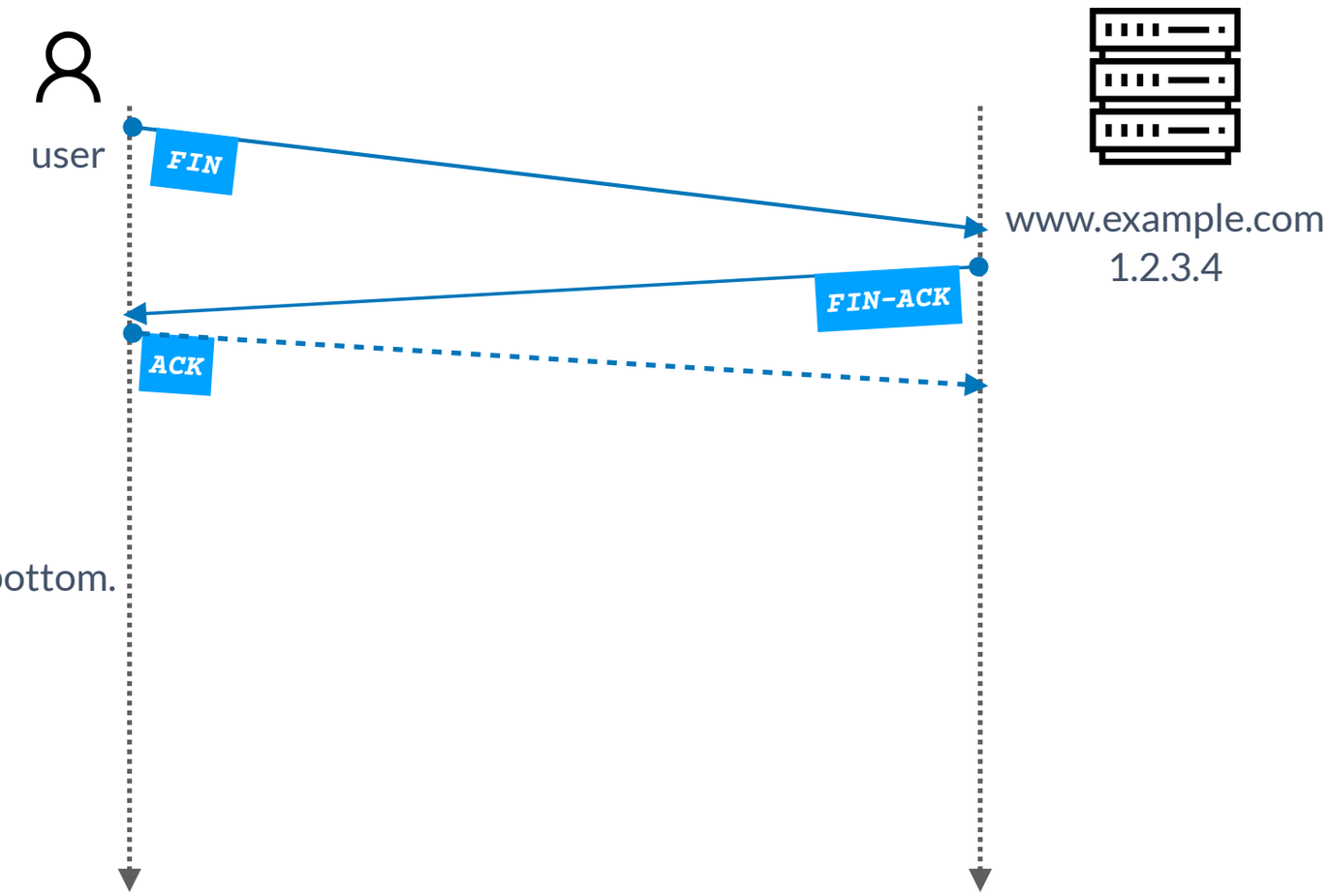


Time moves from top to bottom.

RTT or ***latency*** is key determinant of application’s “performance.”

Recap

Connection “tear down”

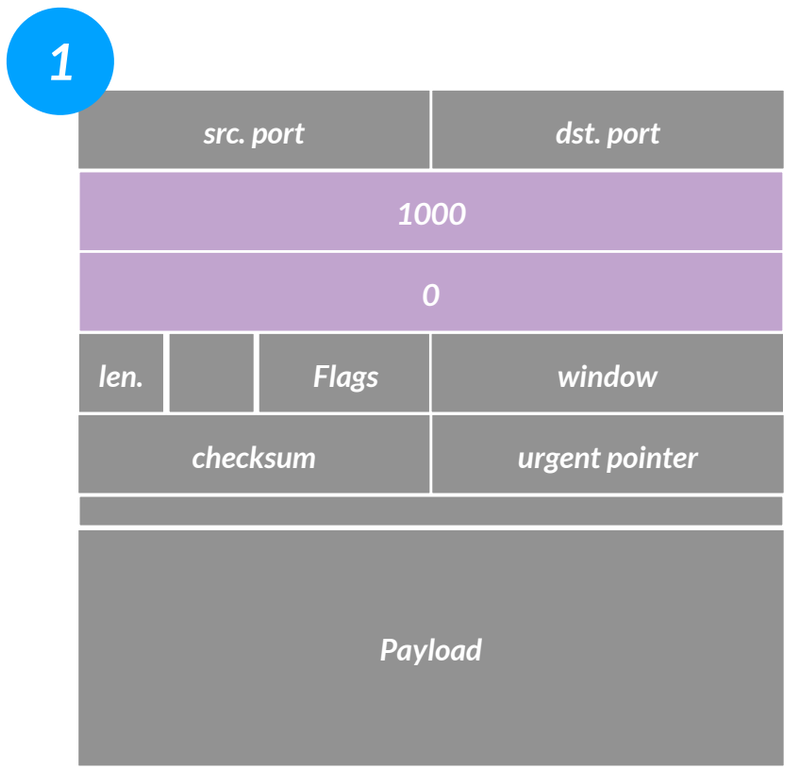


Time moves from top to bottom.

Recap

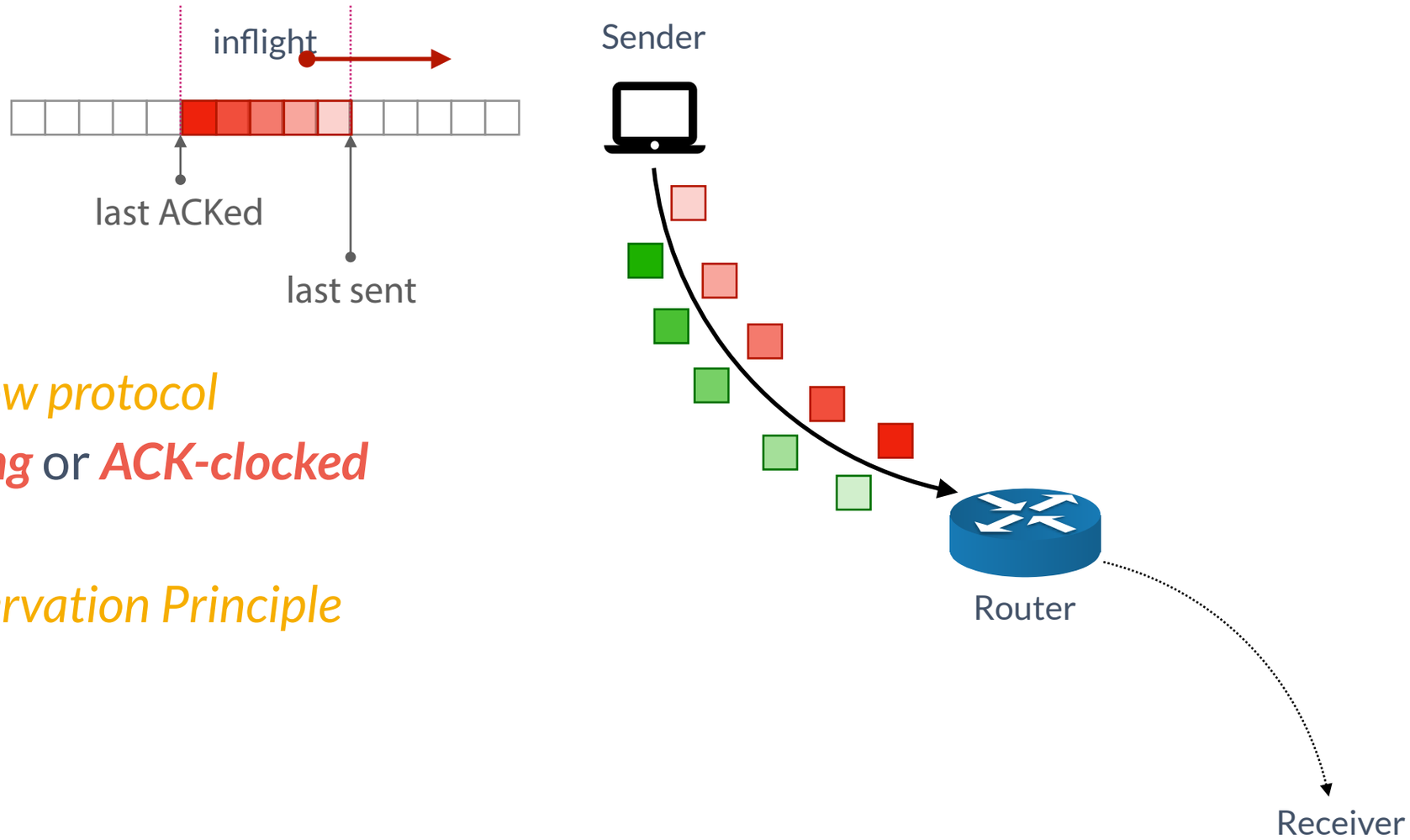
Stream of Bytes Service

- SYN
  - Sender's *initial* SEQ number
  - Pick a *random* number
  - Set *acknowledgement (ACK)* number to *zero*
- SYN-ACK
  - Receiver's *random* initial SEQ number
  - Set ACK number to *Sender's SEQ number + 1*



Recap

Sliding Window

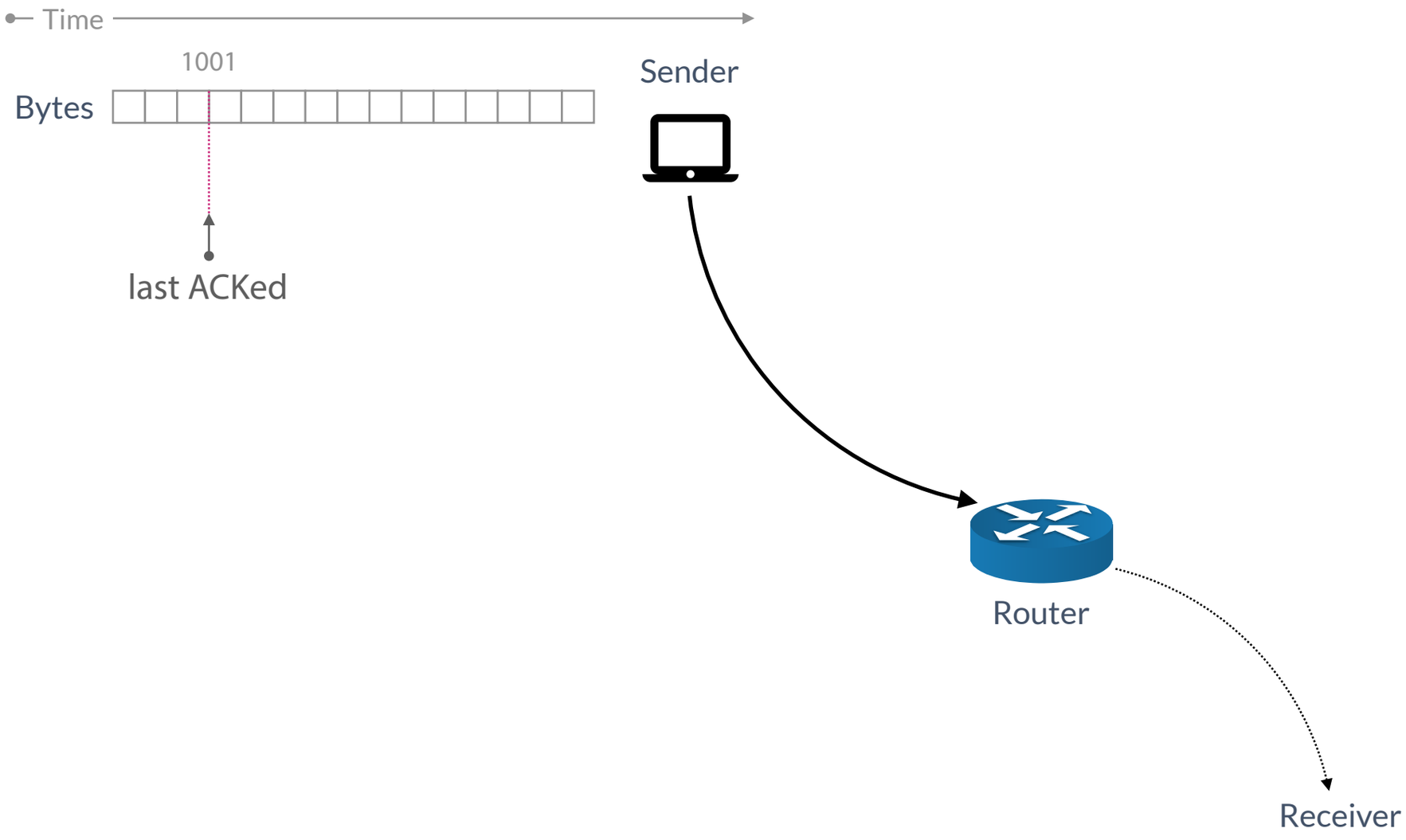


Sliding window protocol

Self-clocking or ***ACK-clocked***

Packet Conservation Principle

Stream of Bytes Service



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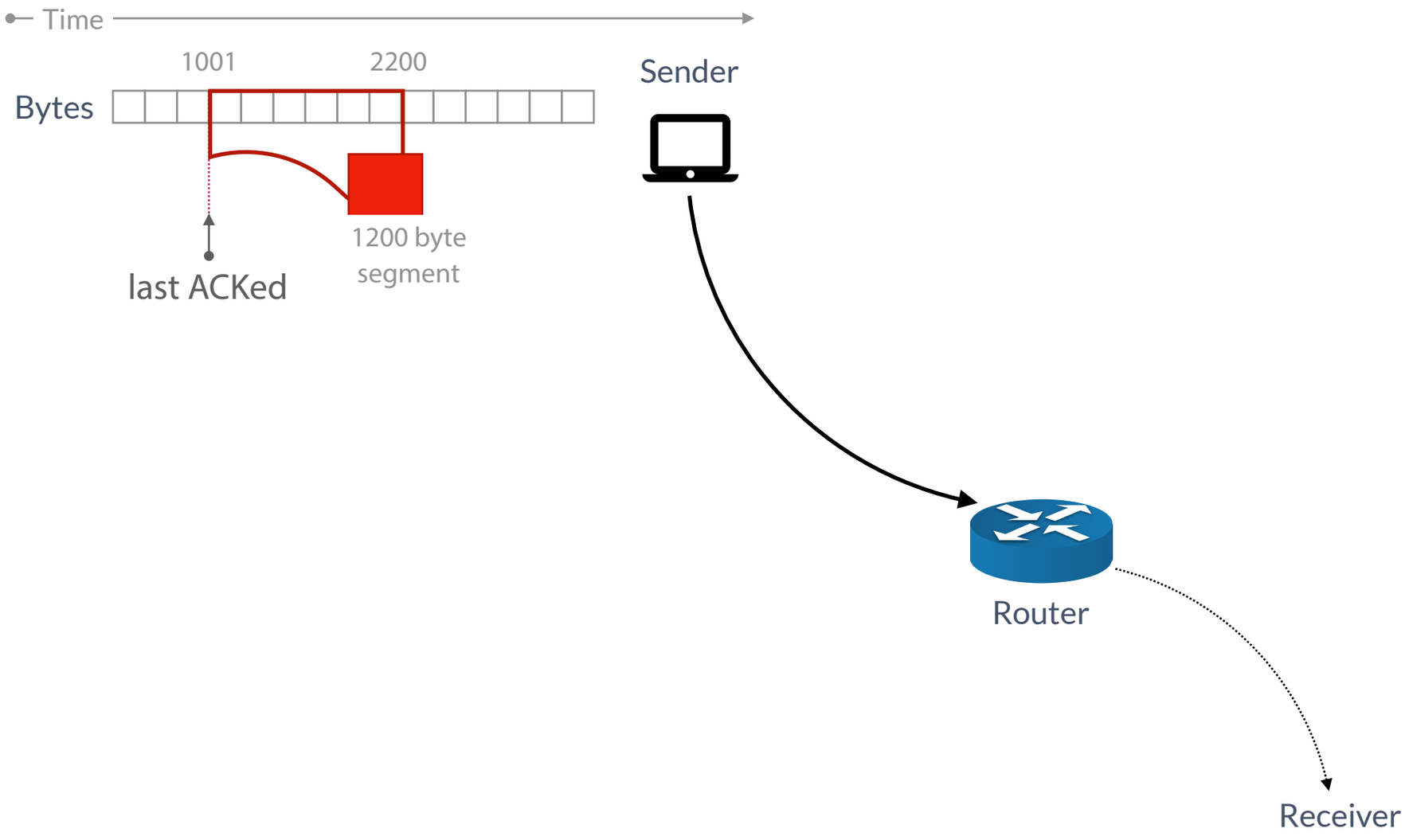

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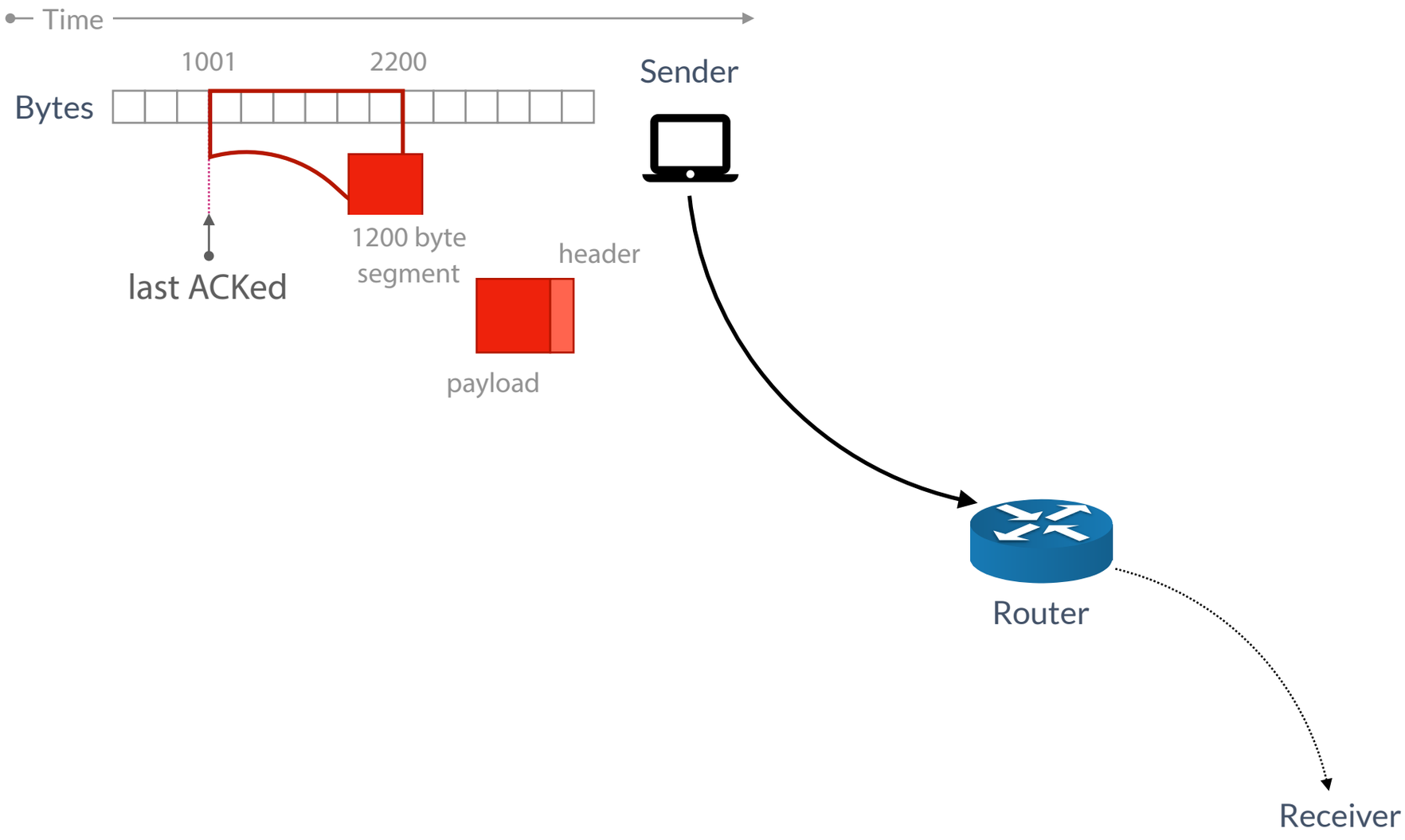

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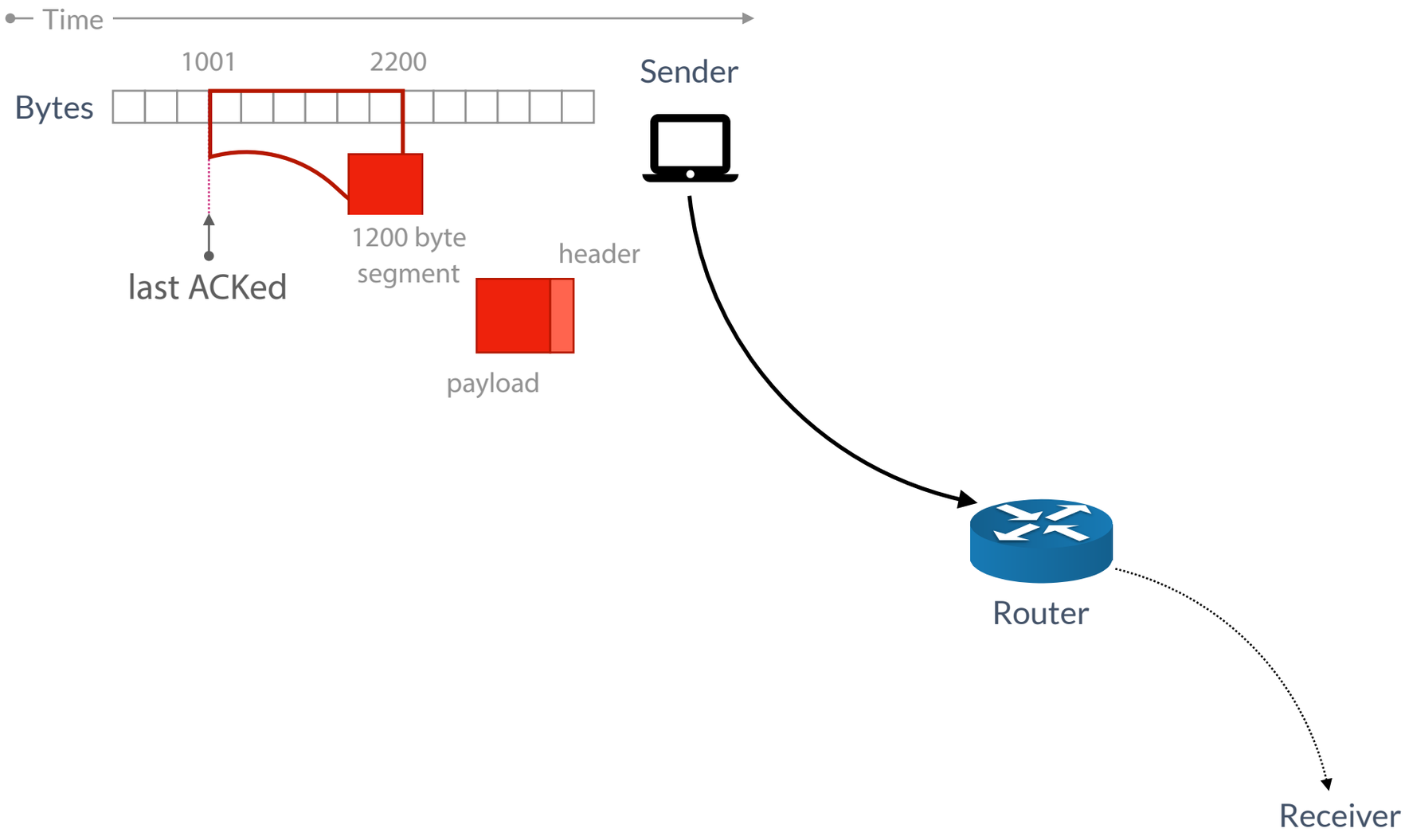

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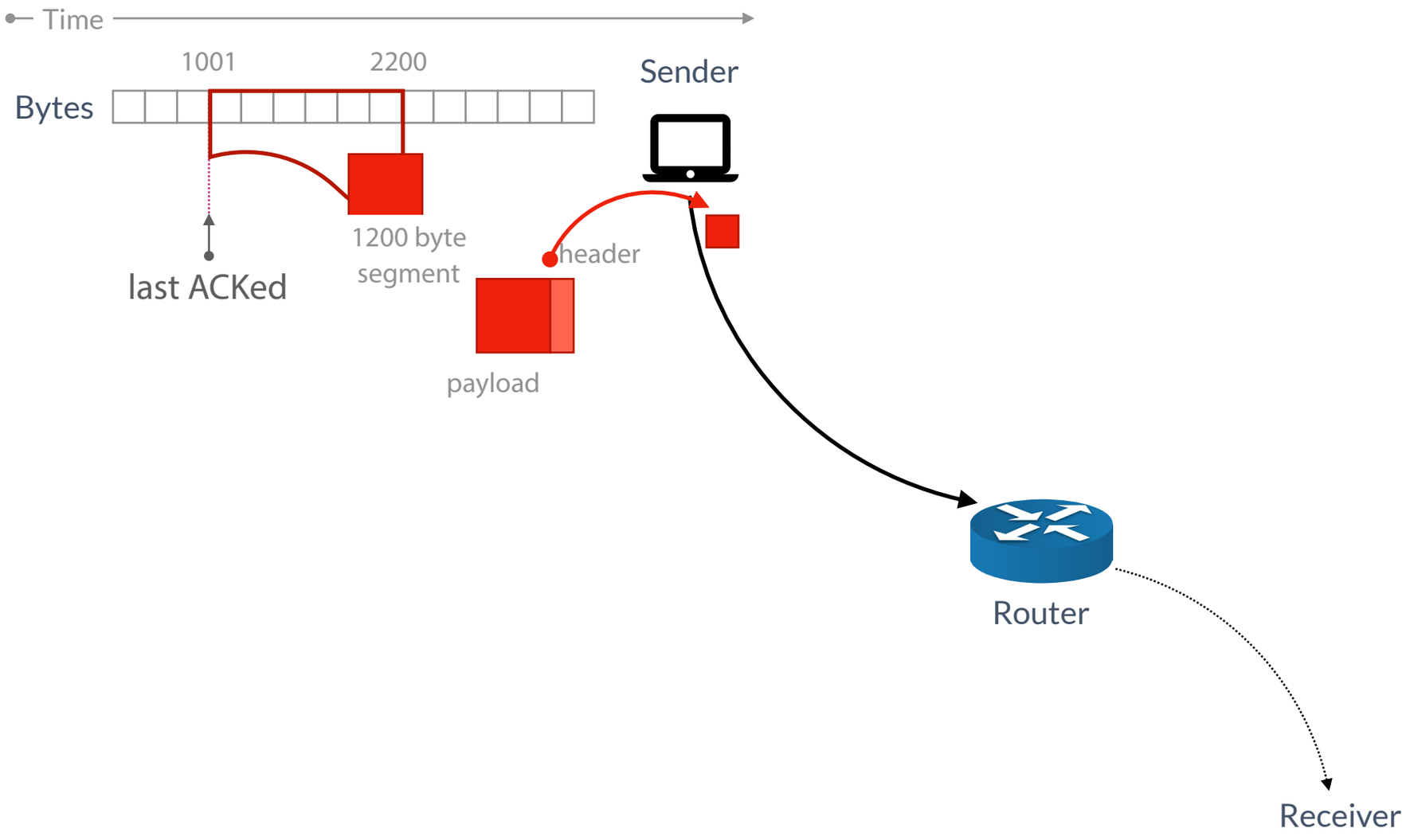

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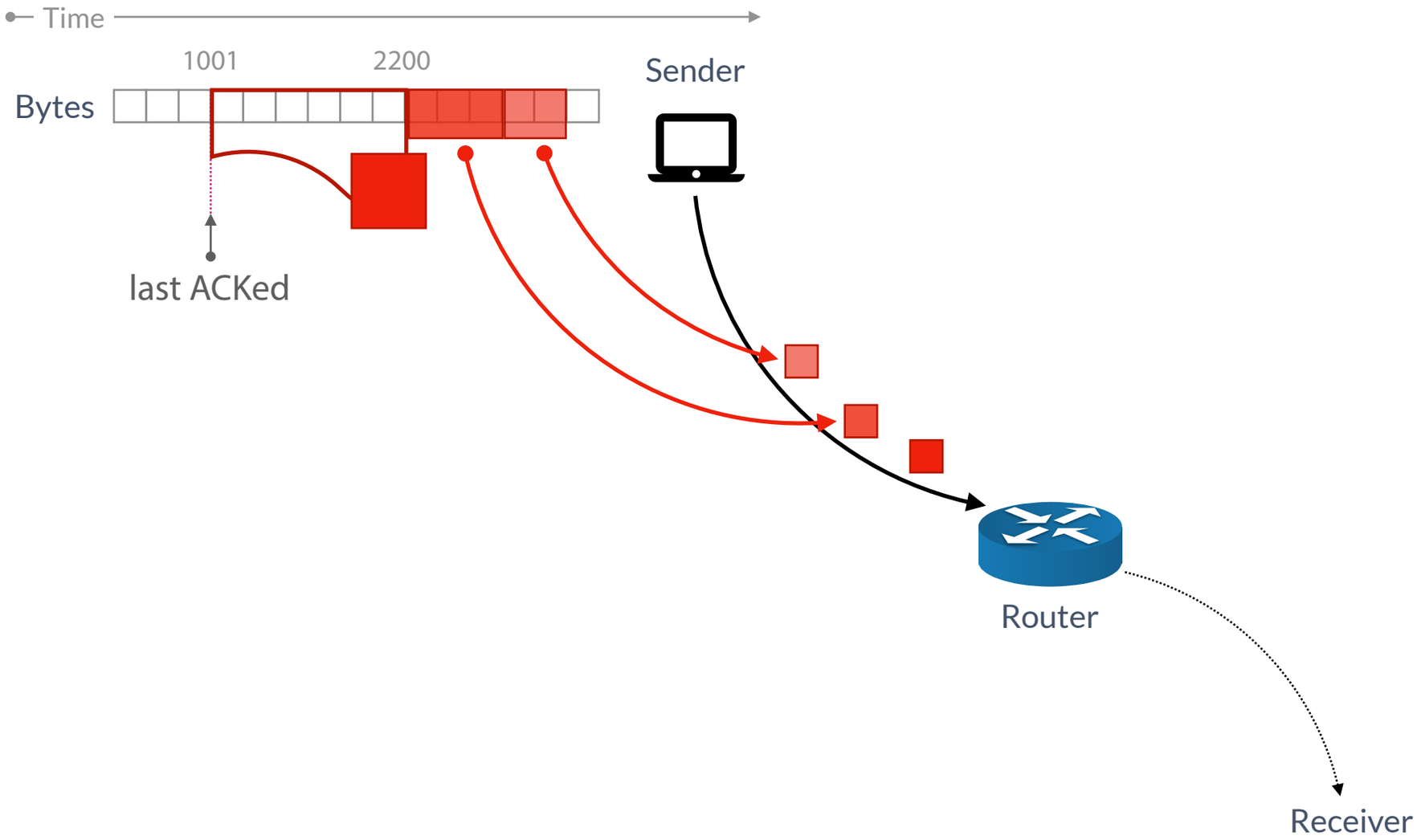

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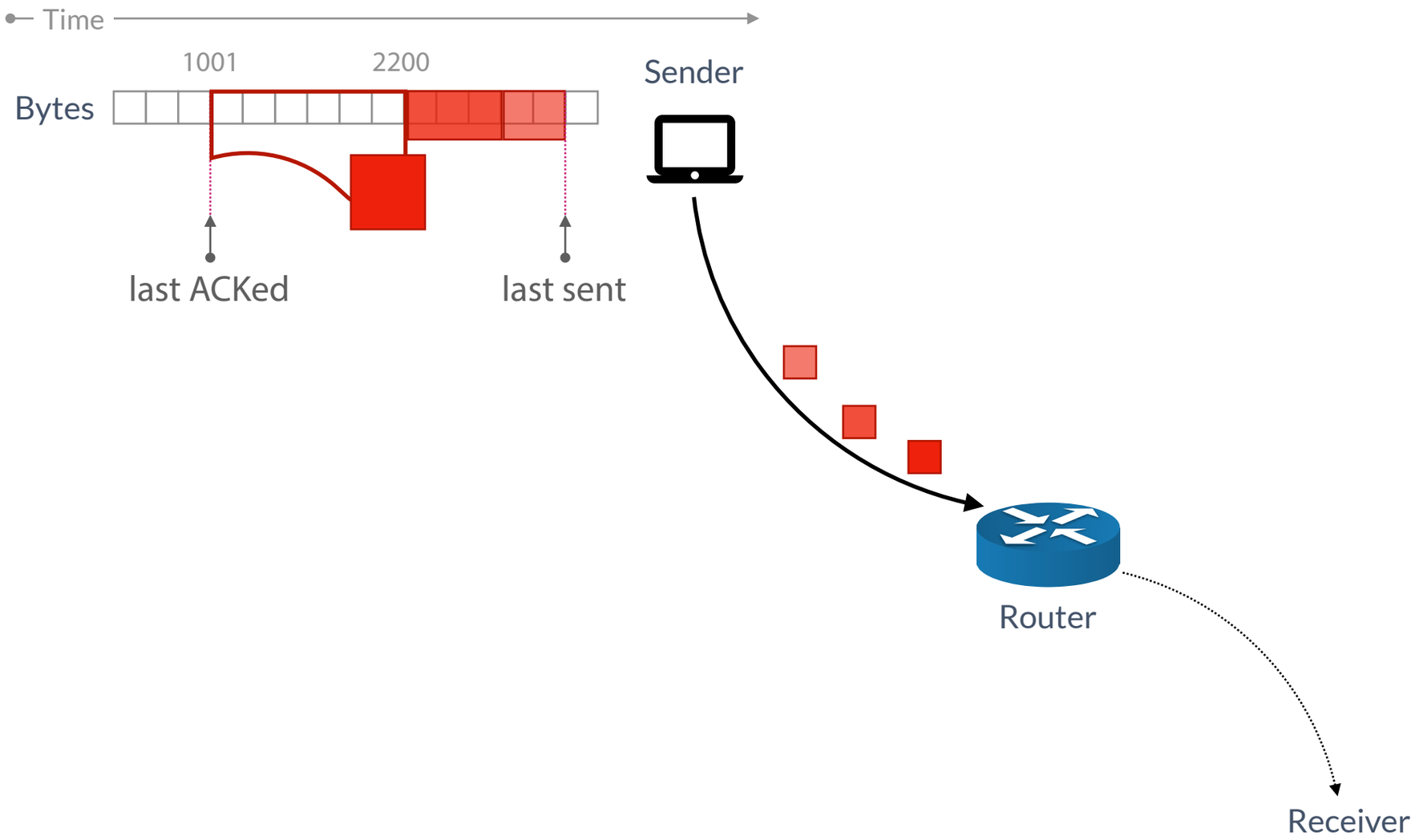

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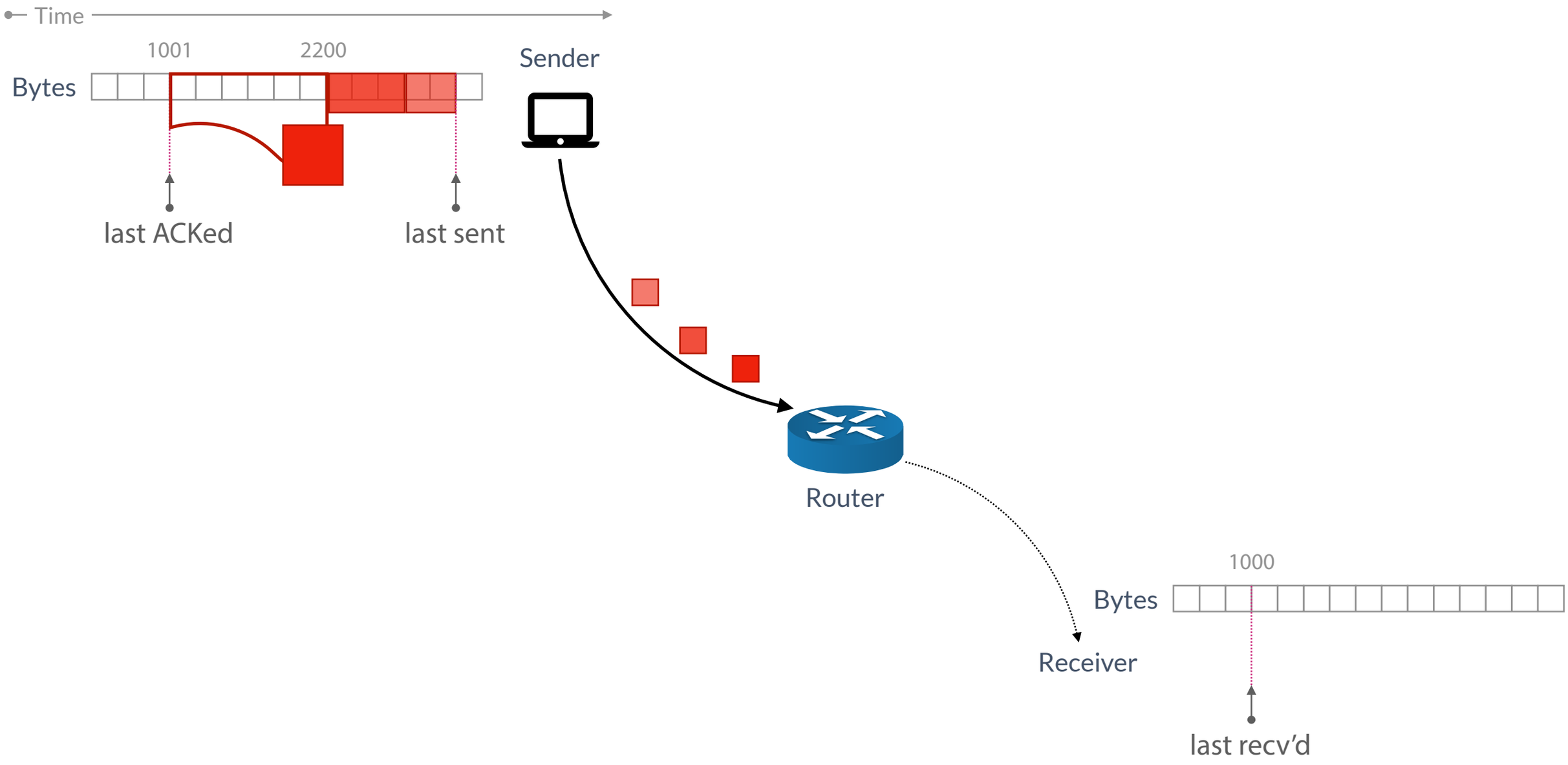

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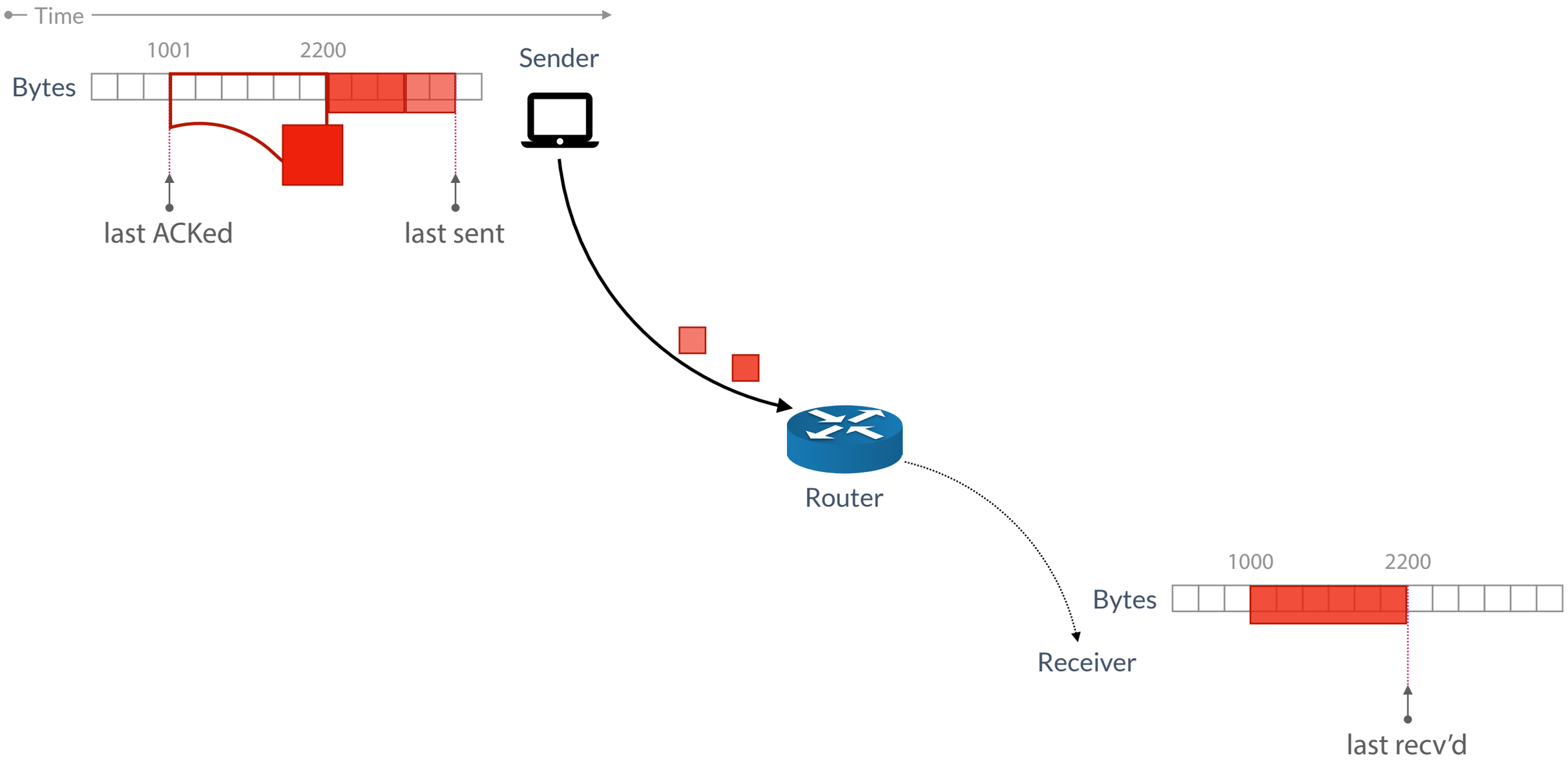

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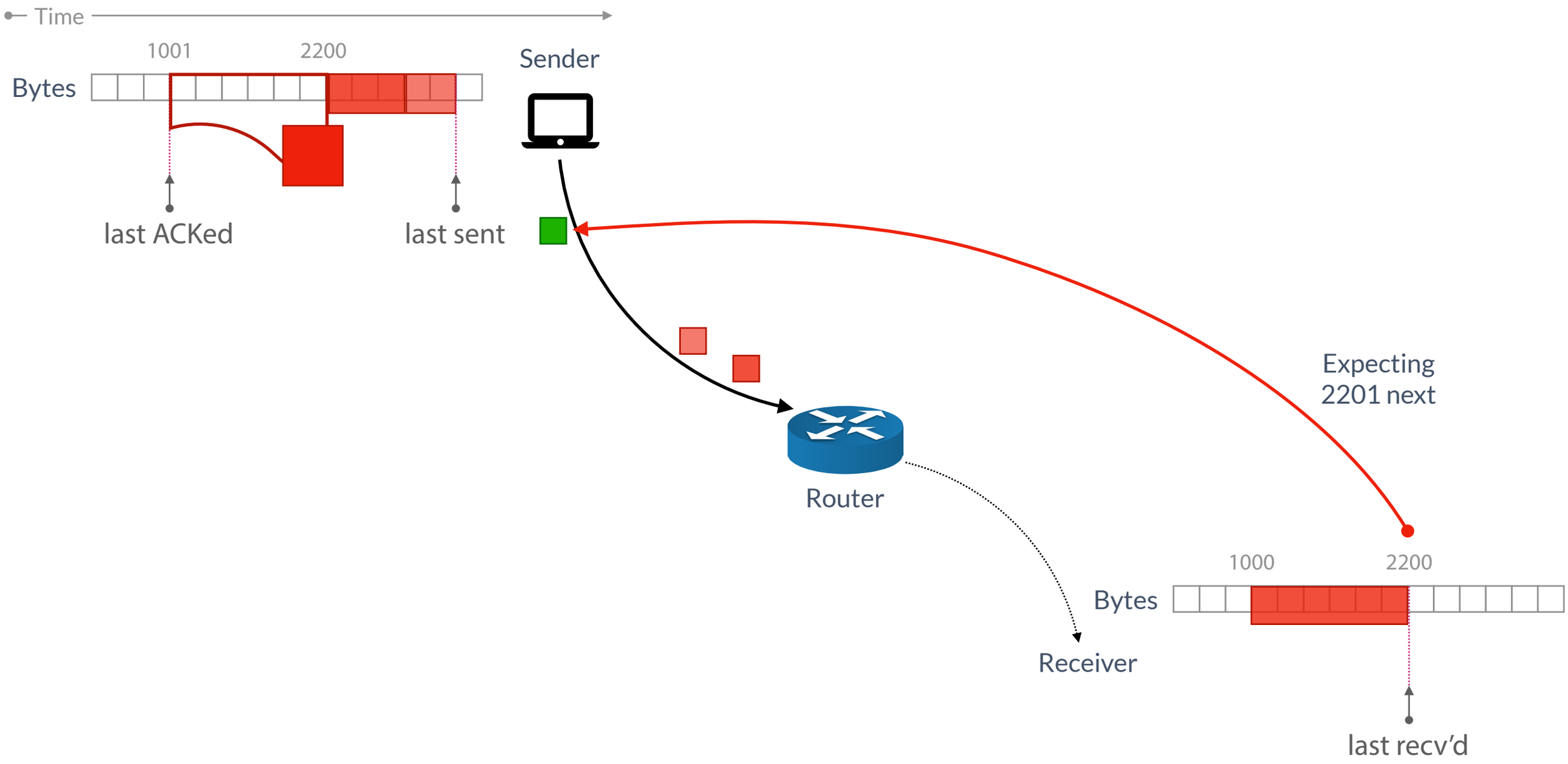

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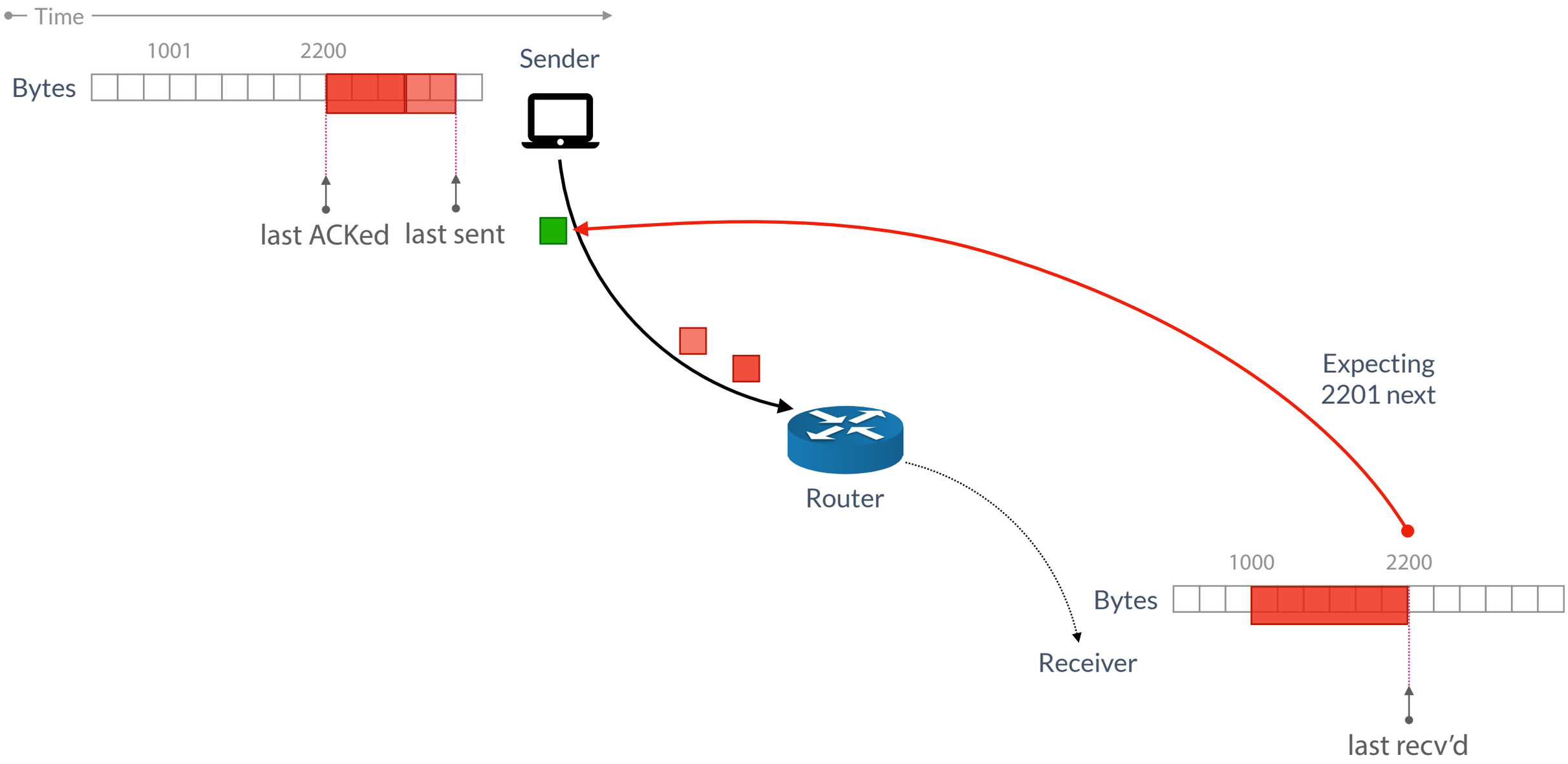

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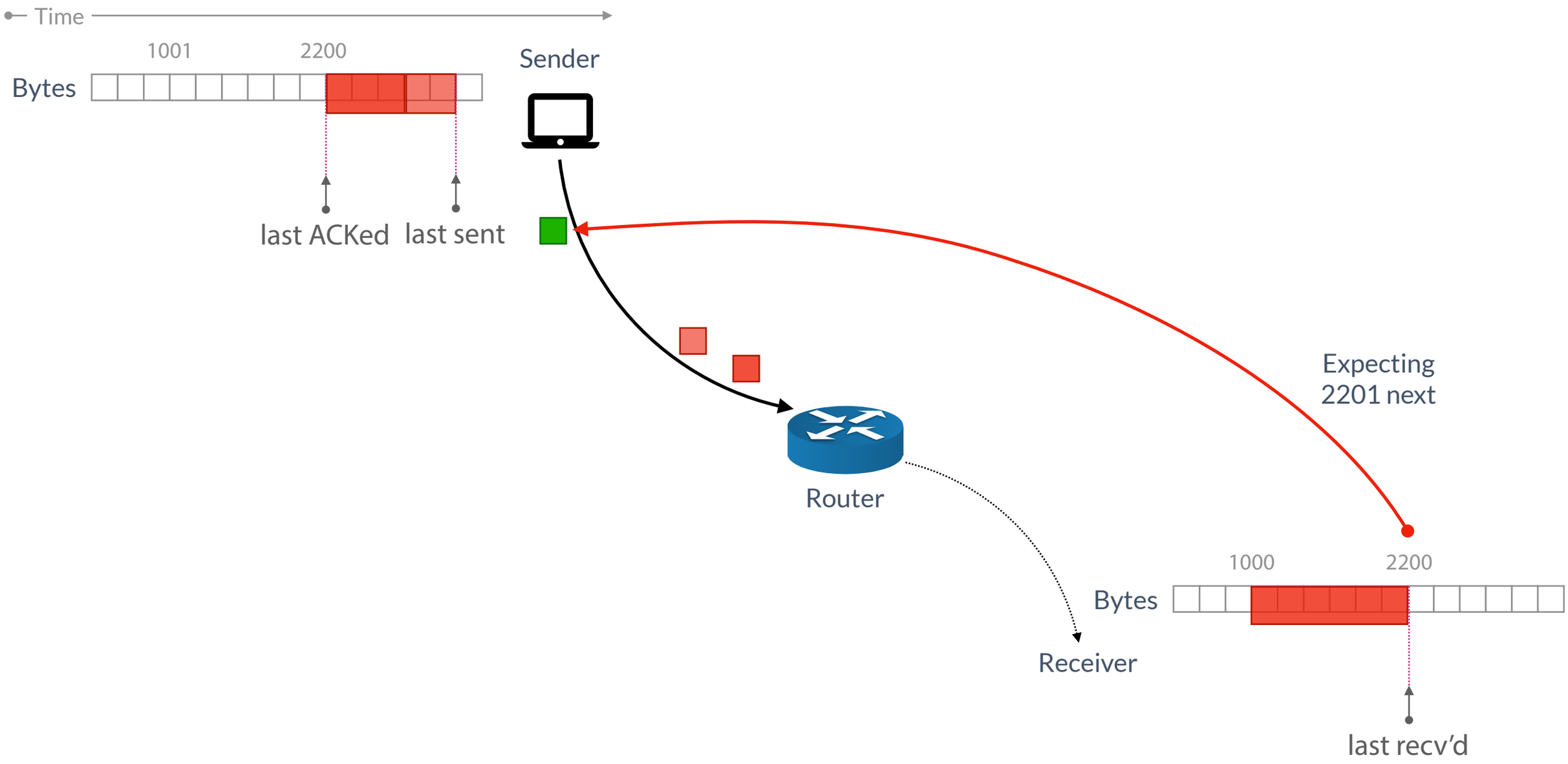
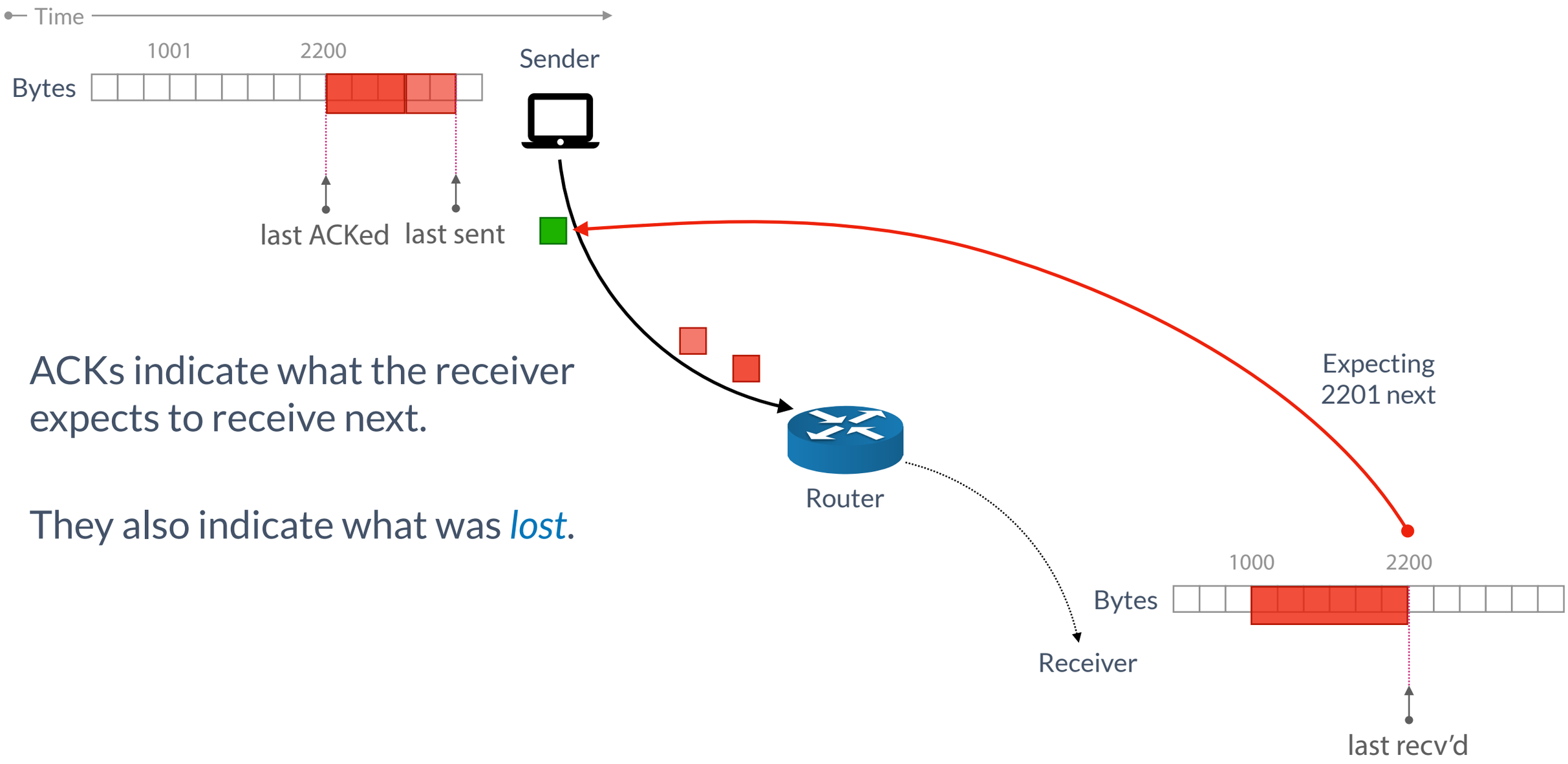


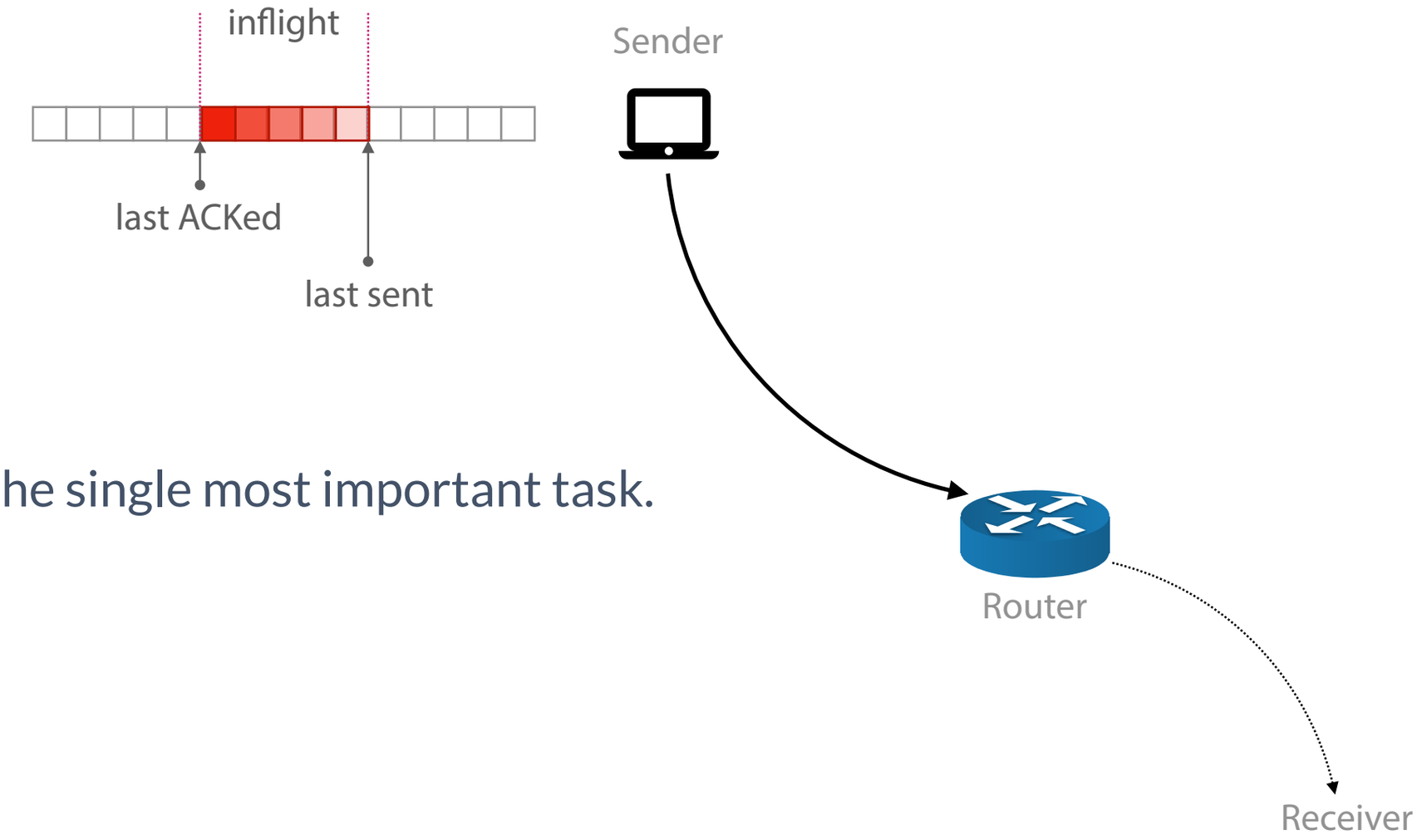
Stream of Bytes Service

ACKs indicate what the receiver expects to receive next.

They also indicate what was *lost*.

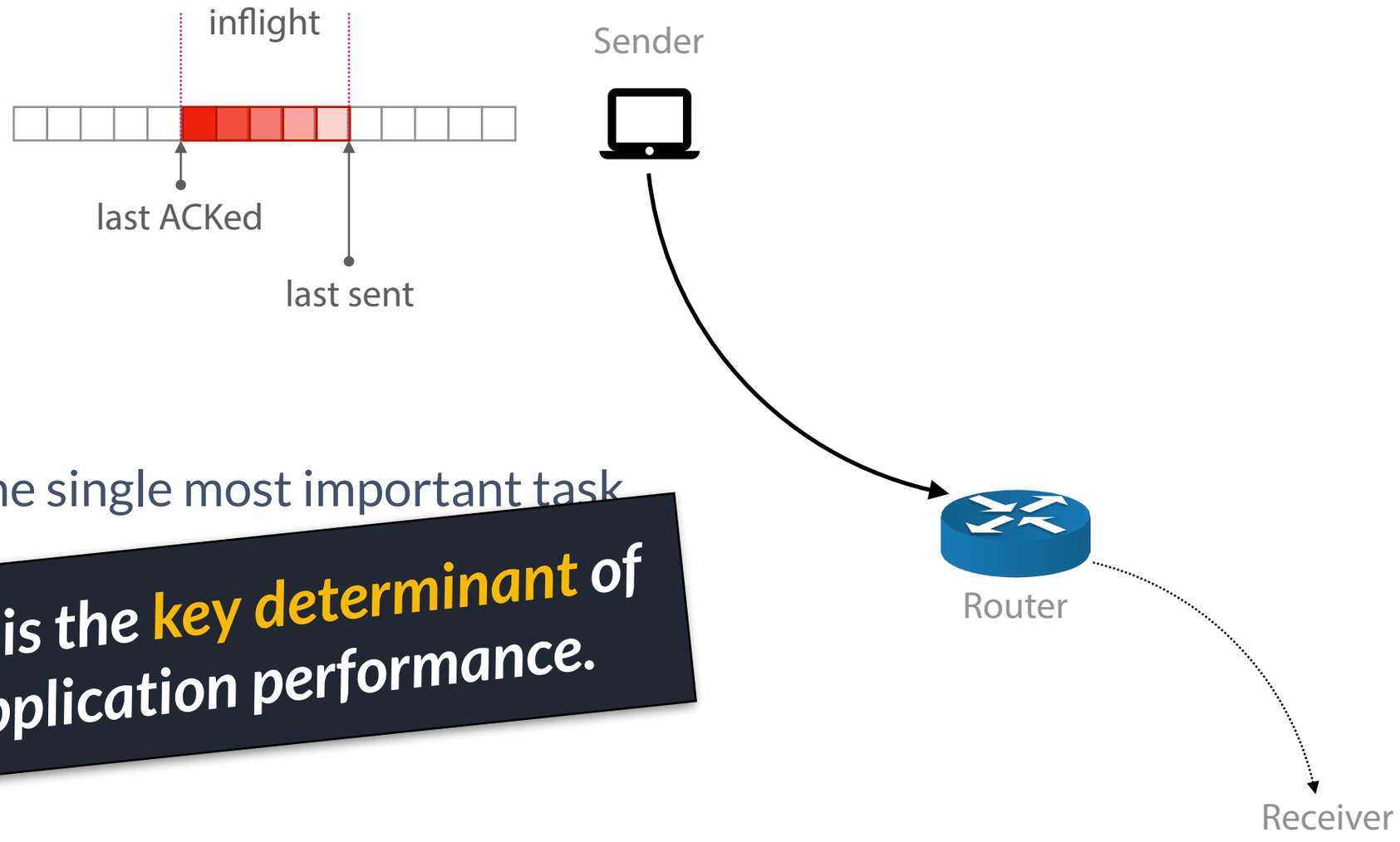


Round-trip time (RTT)



Estimating RTT is the single most important task.

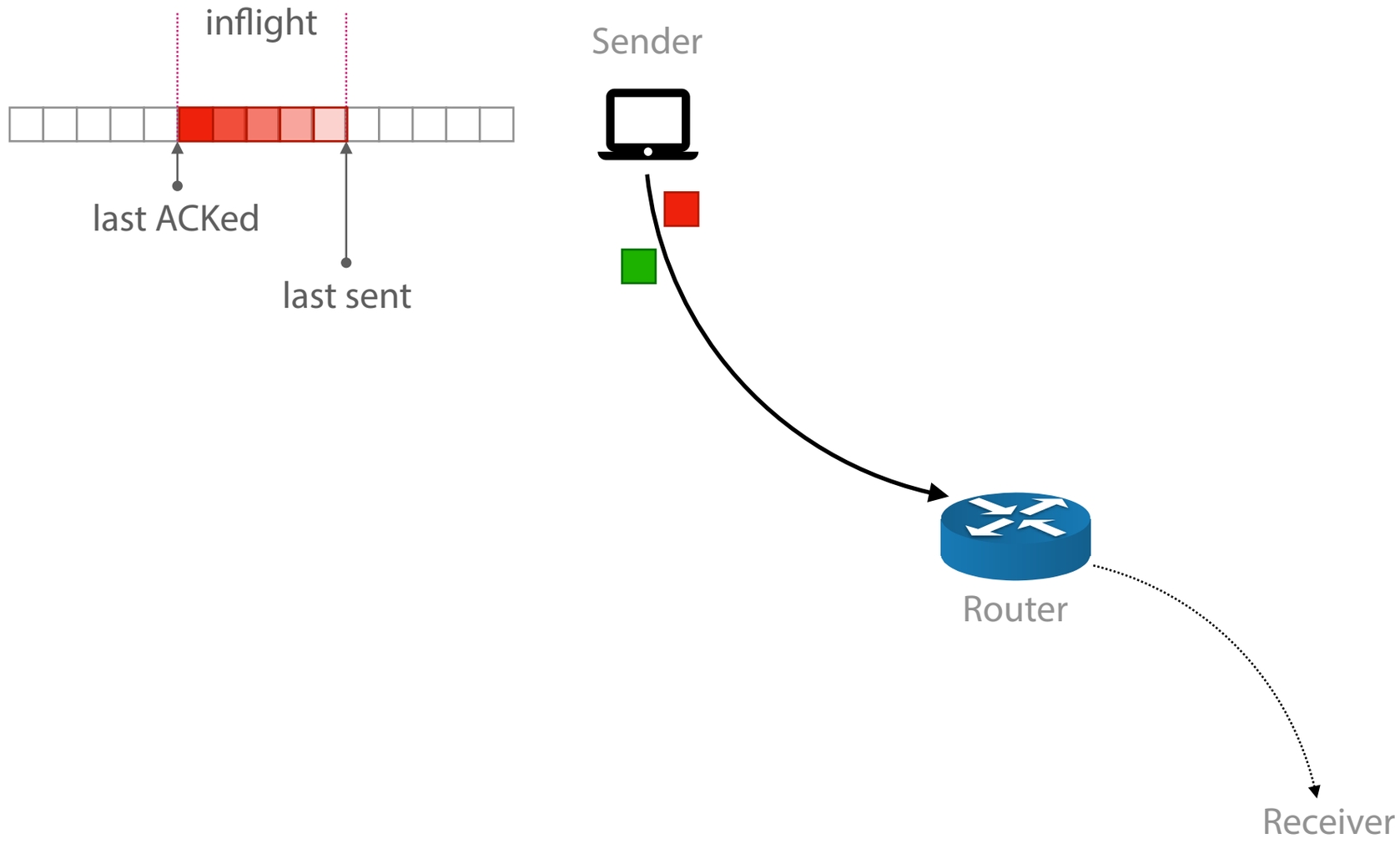
Round-trip time (RTT)



Estimating RTT is the single most important task

RTT is the *key determinant* of *application performance.*

Round-trip time (RTT)



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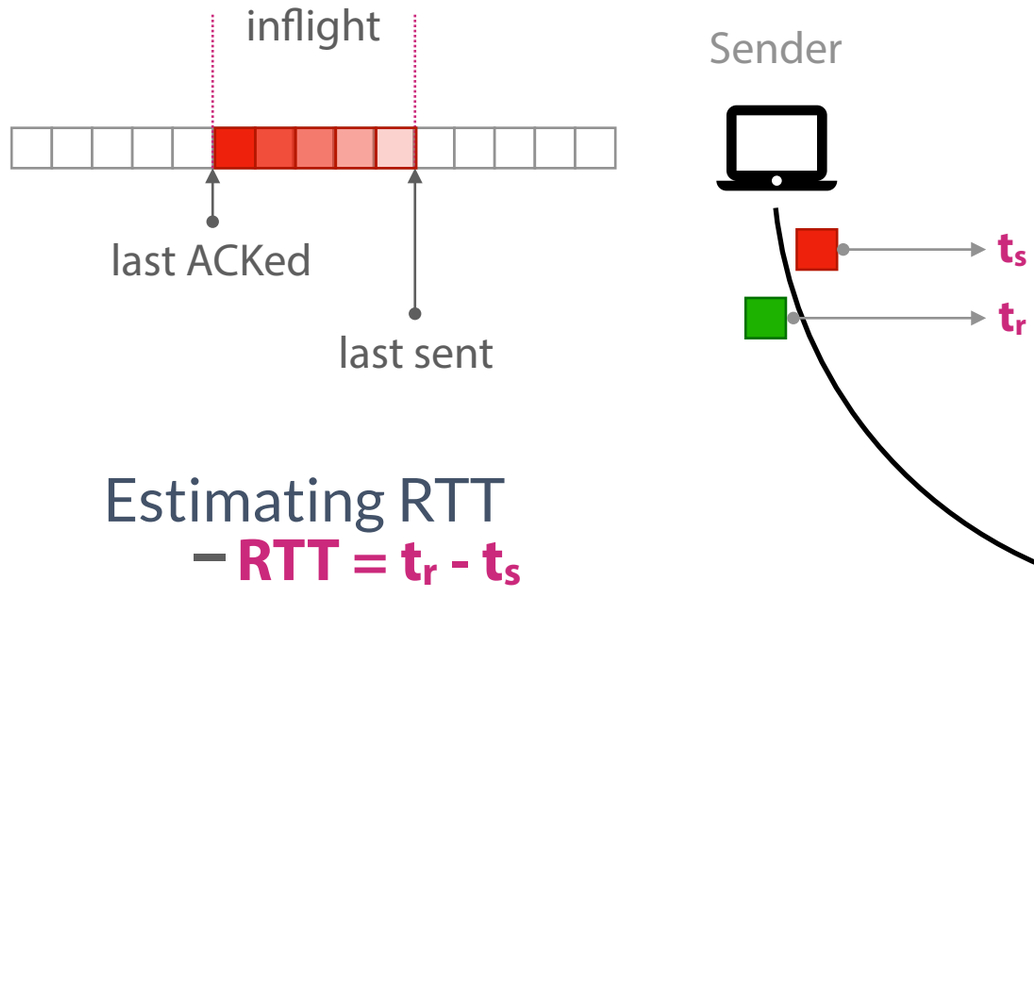
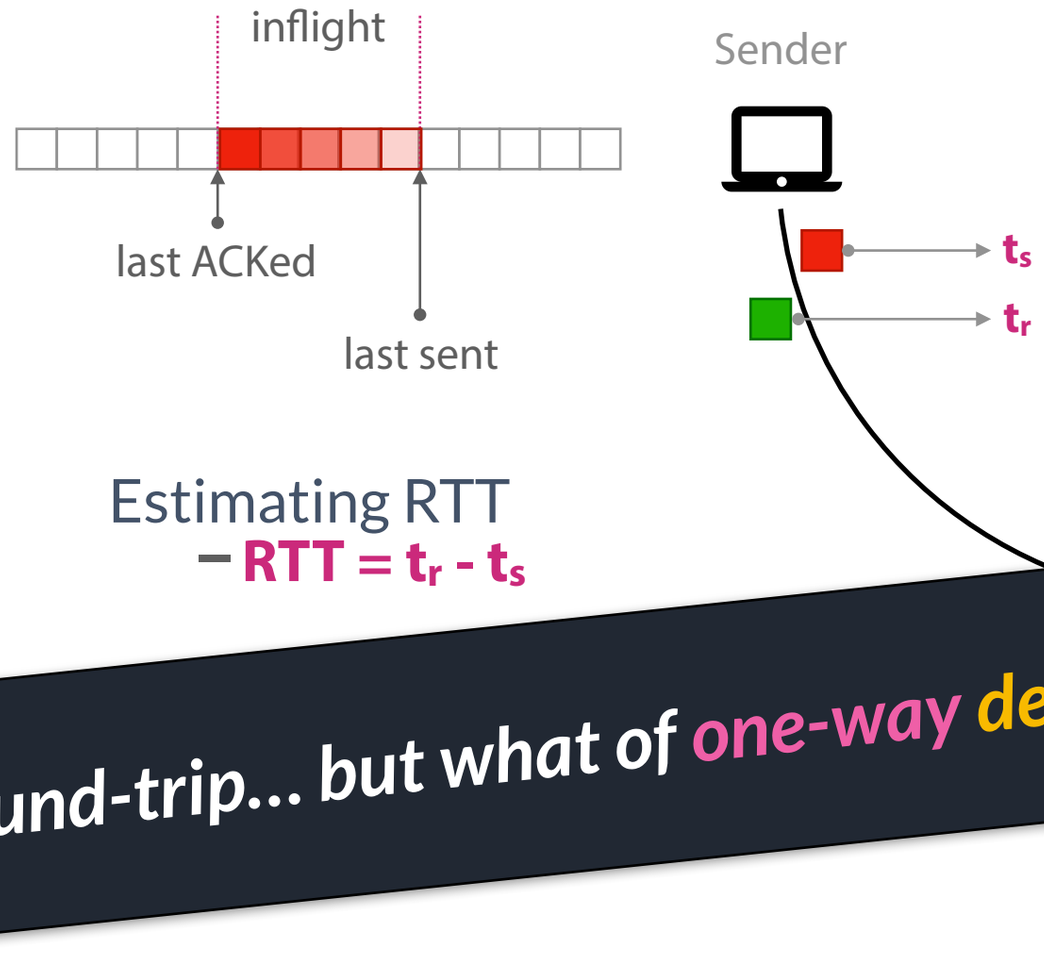


Estimating RTT

- **$RTT = t_r - t_s$**

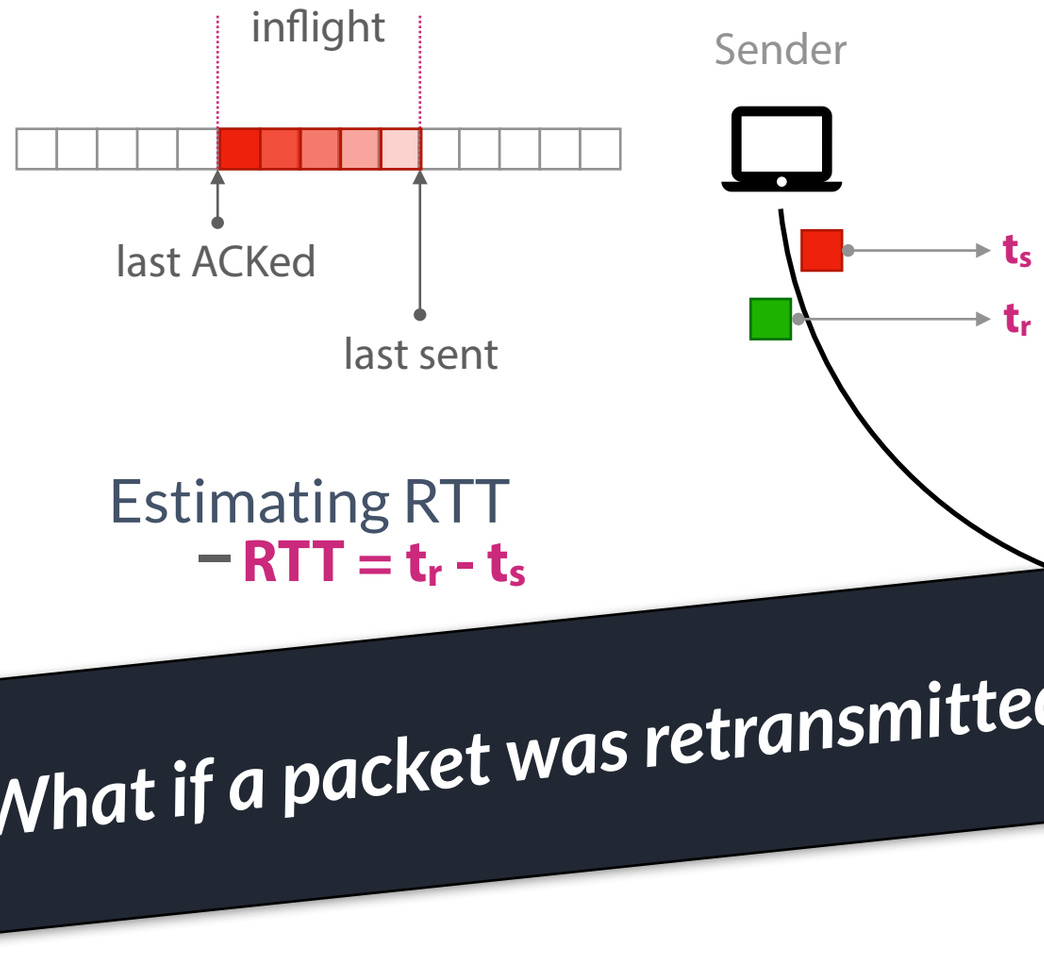
Round-trip time (RTT)



Estimating RTT
- **RTT = t_r - t_s**

Round-trip… but what of one-way delay?

Round-trip time (RTT)

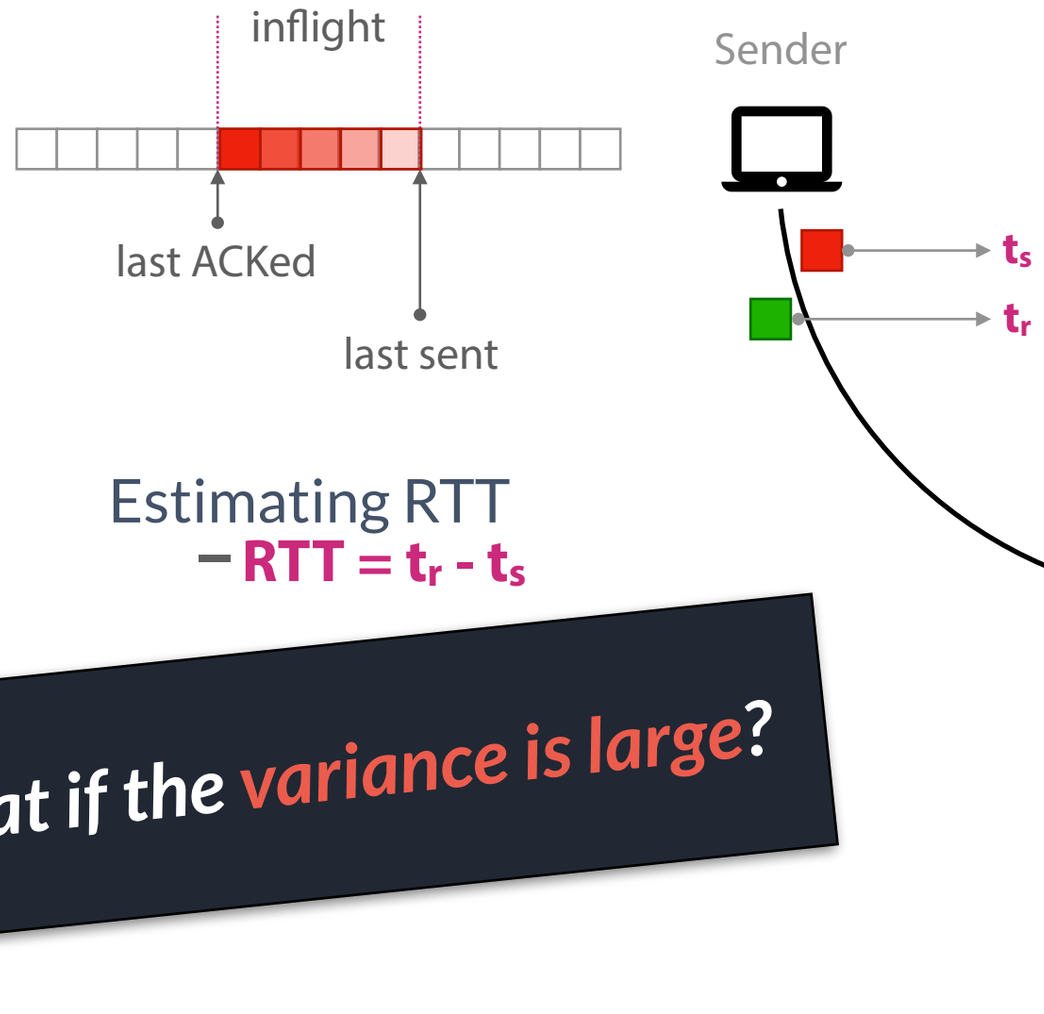


Estimating RTT

- **$RTT = t_r - t_s$**

What if a packet was retransmitted?

Round-trip time (RTT)

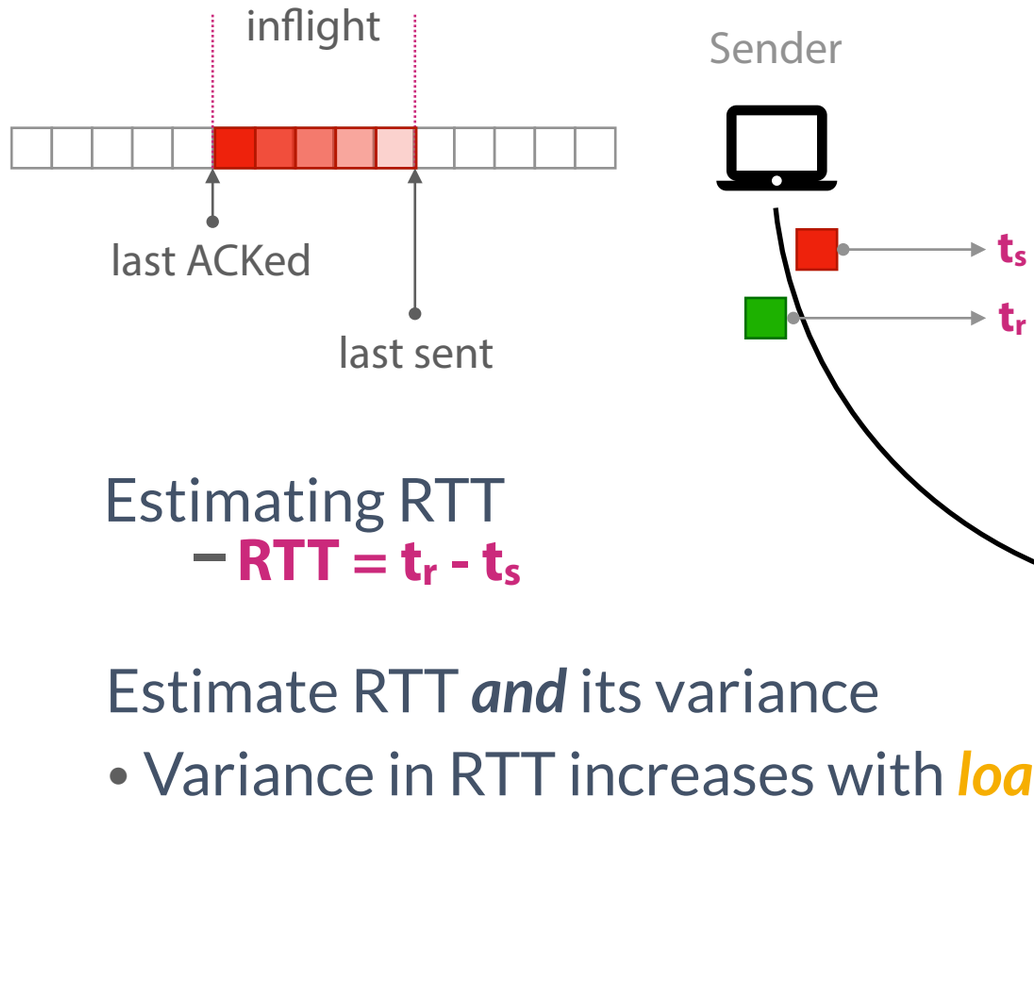


Estimating RTT

- **RTT = t_r - t_s**

What if the *variance is large*?

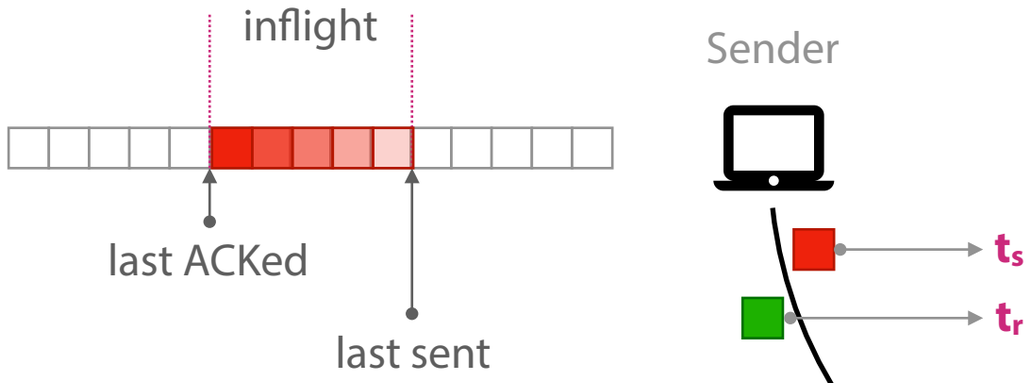
Round-trip time (RTT)

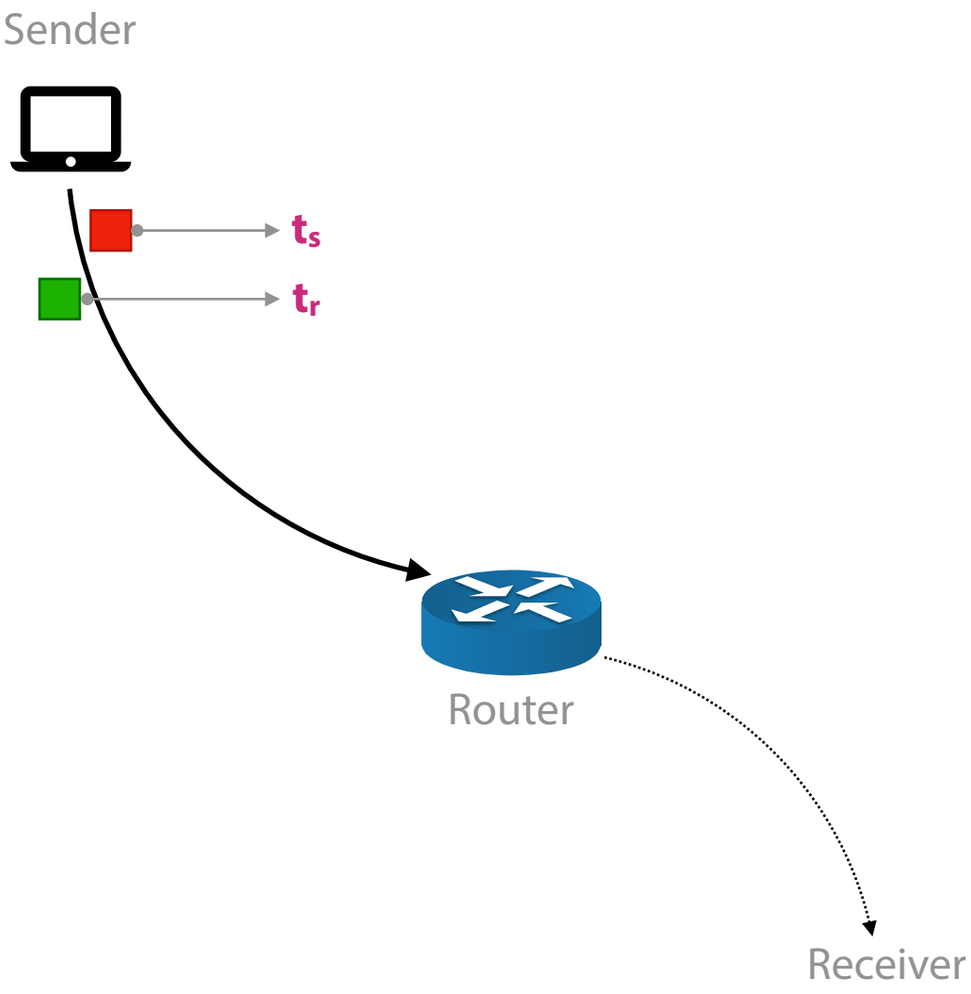


Estimating RTT
- **RTT = t_r - t_s**

Estimate RTT ***and*** its variance
- Variance in RTT increases with ***load***

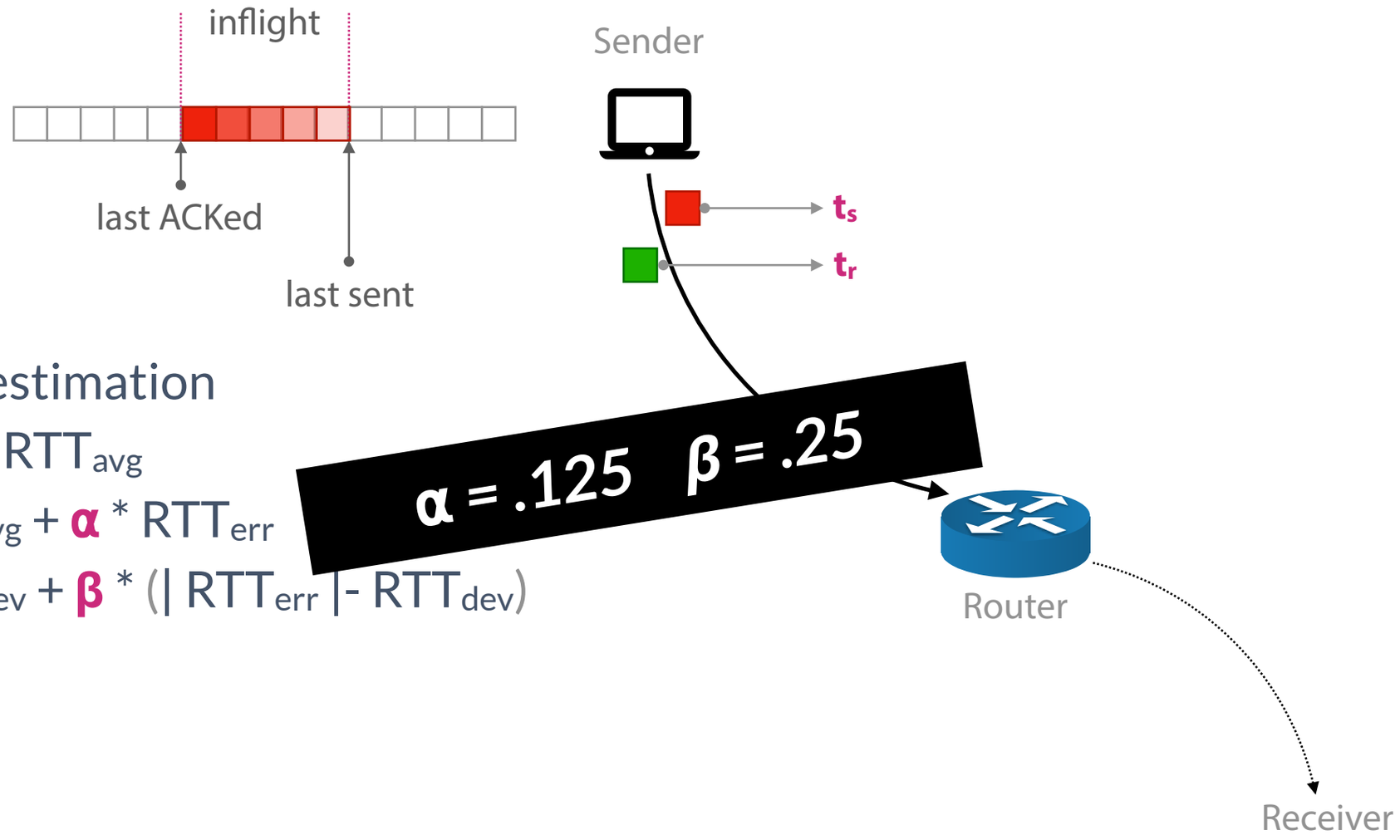
Round-trip time (RTT)





- **Round-trip** time estimation
  - $RTT_{err} = RTT - RTT_{avg}$
  - $RTT_{avg} = RTT_{avg} + \alpha * RTT_{err}$
  - $RTT_{dev} = RTT_{dev} + \beta * (|RTT_{err}| - RTT_{dev})$

Round-trip time (RTT)



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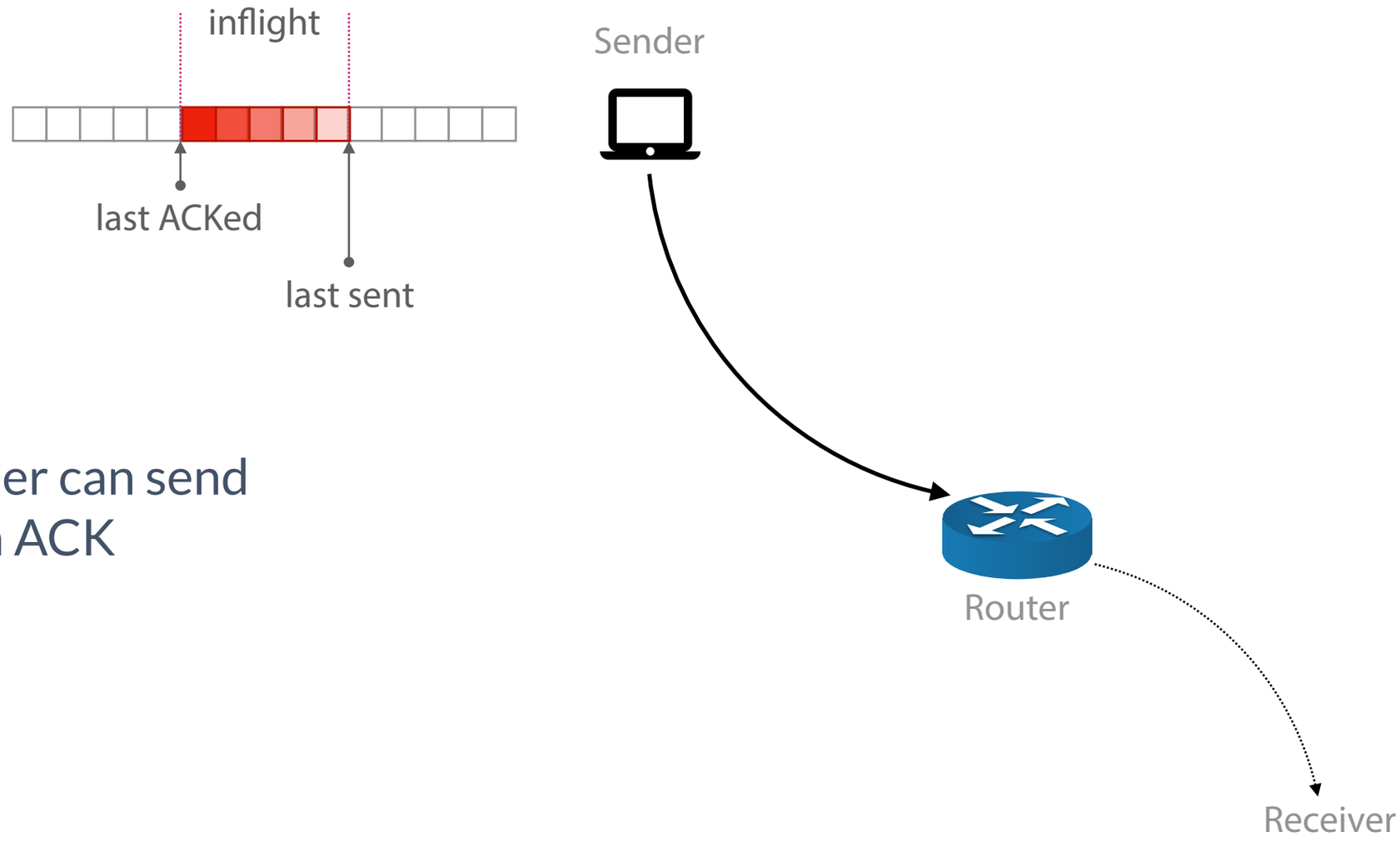
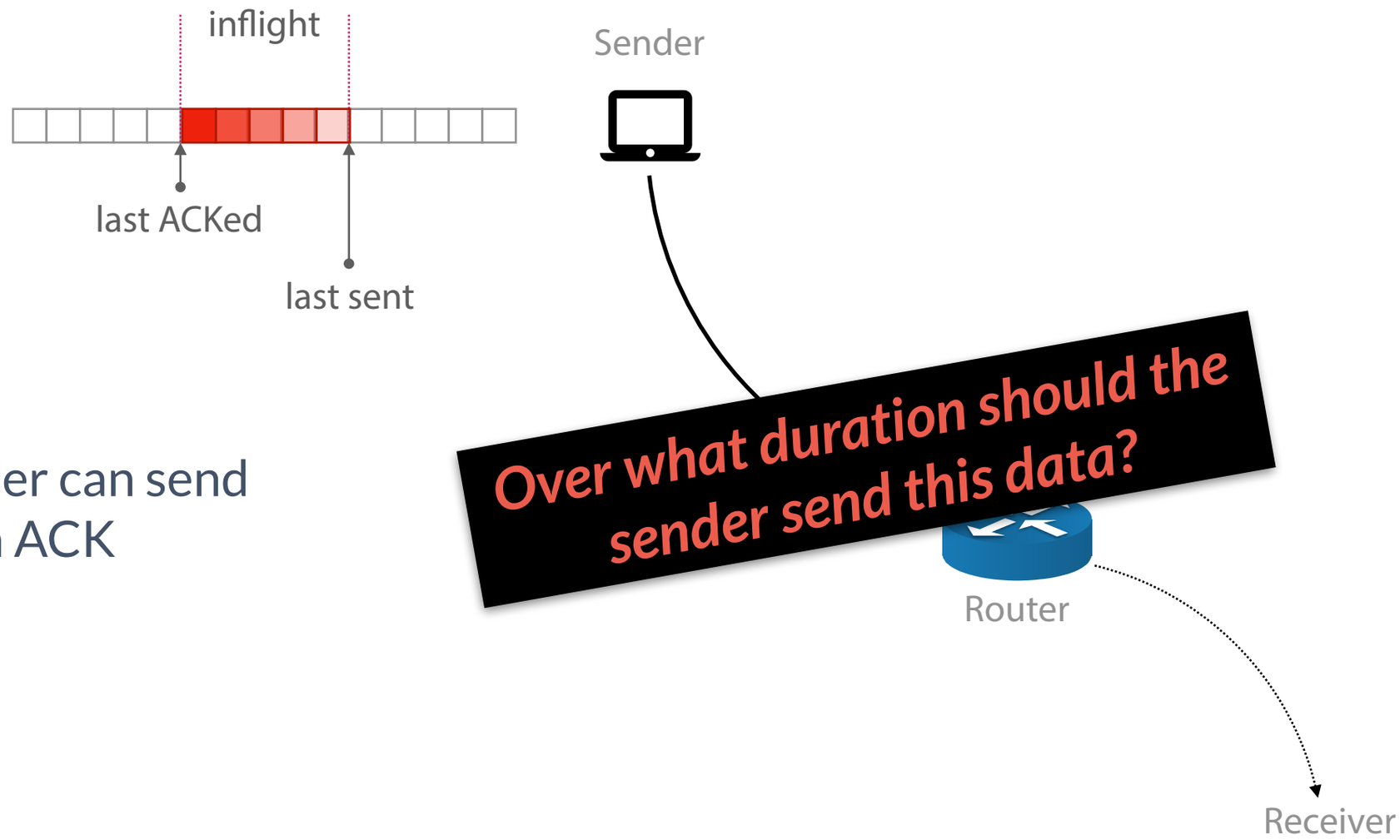
Flow Control



inflight

amount of data a sender can send without waiting for an ACK

Flow Control



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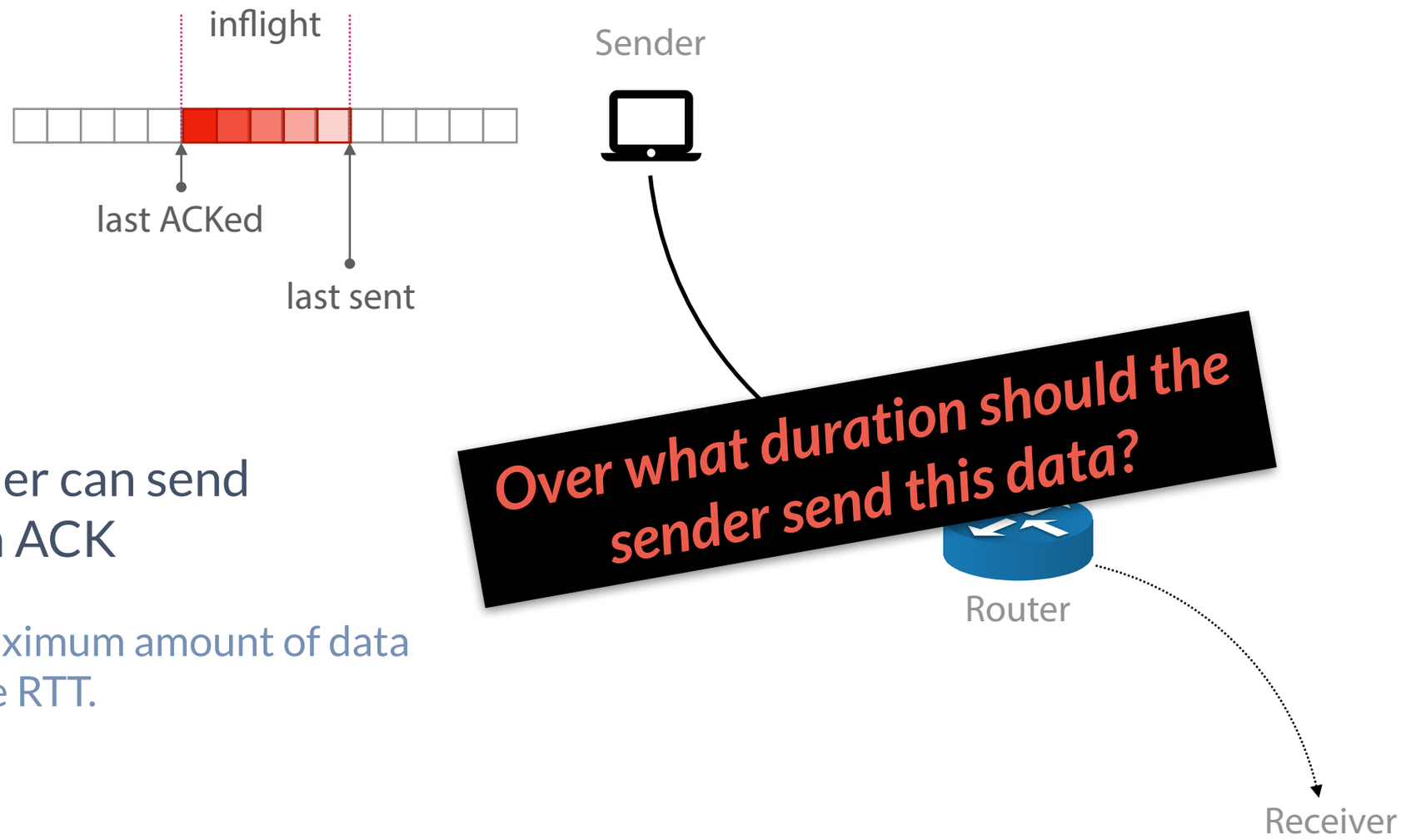
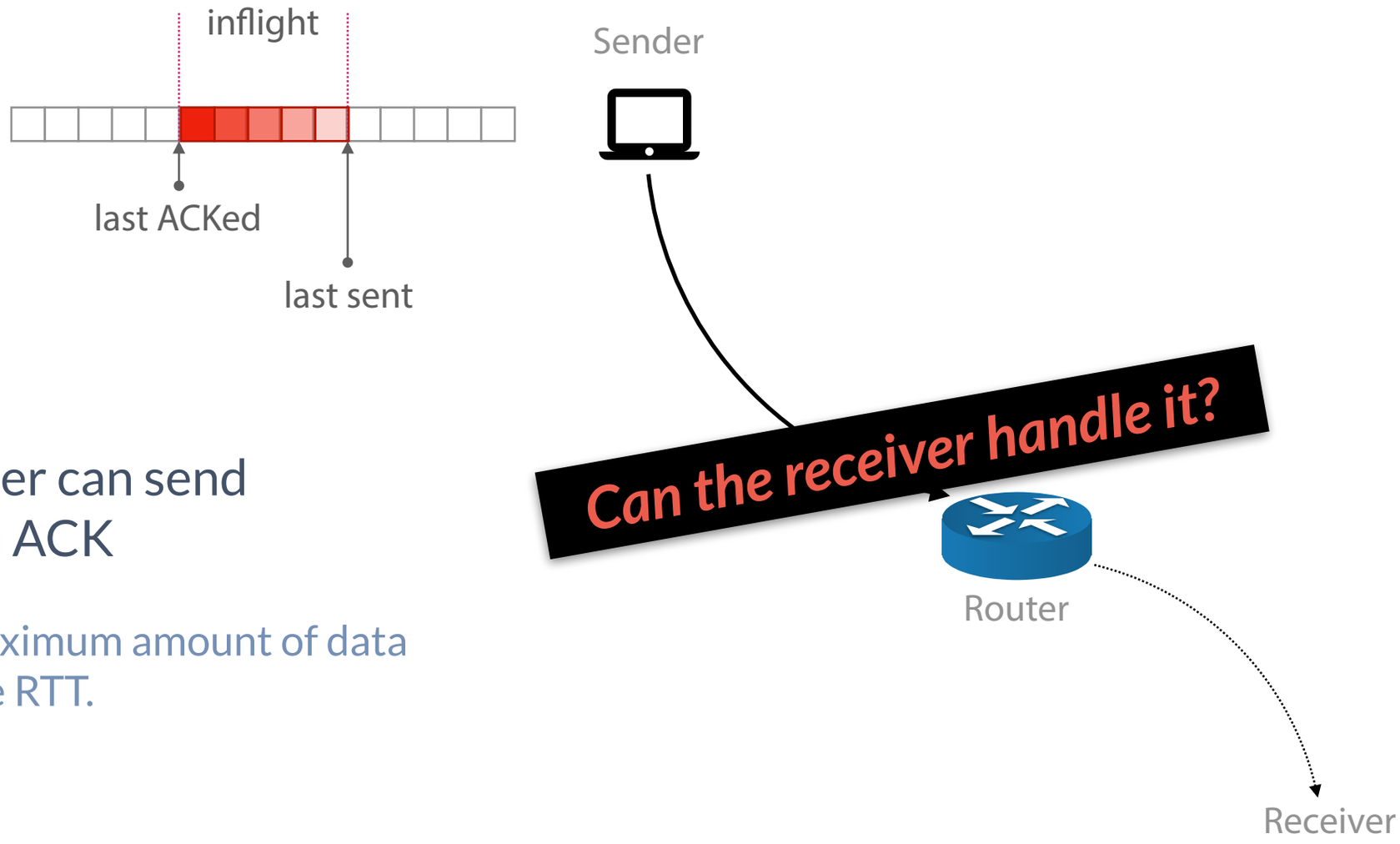


inflight

amount of data a sender can send without waiting for an ACK

Assume that this is the maximum amount of data the sender can send in one RTT.

Flow Control



inflight

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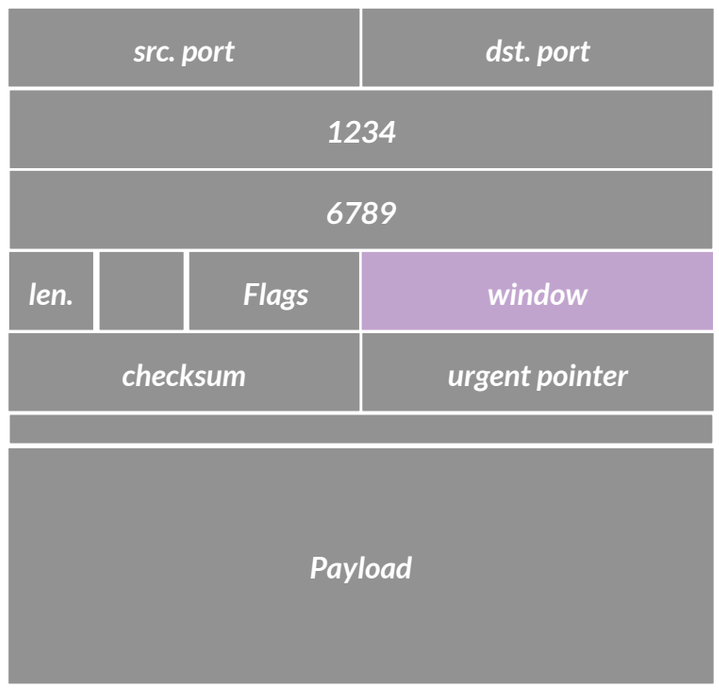
Flow Control

- *Window*
  - Receiver announces its receive window size in this field
  - 16 bits



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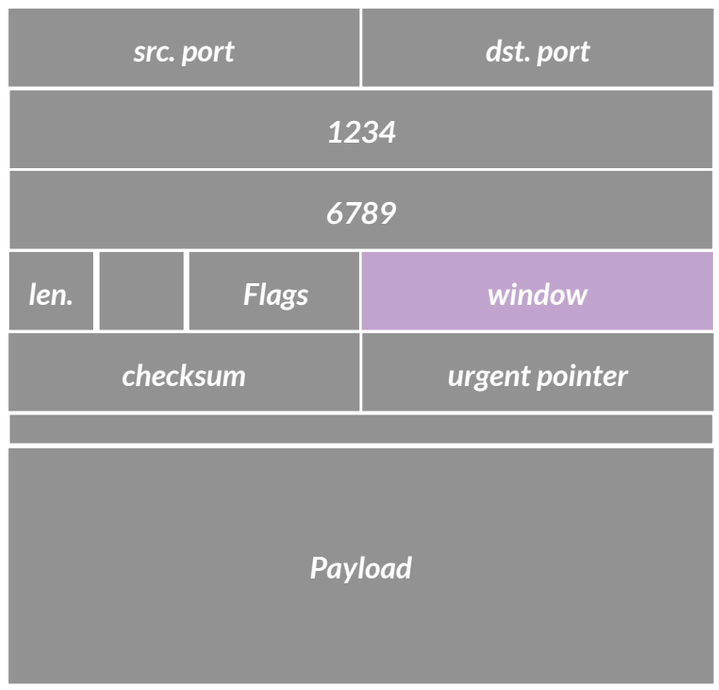

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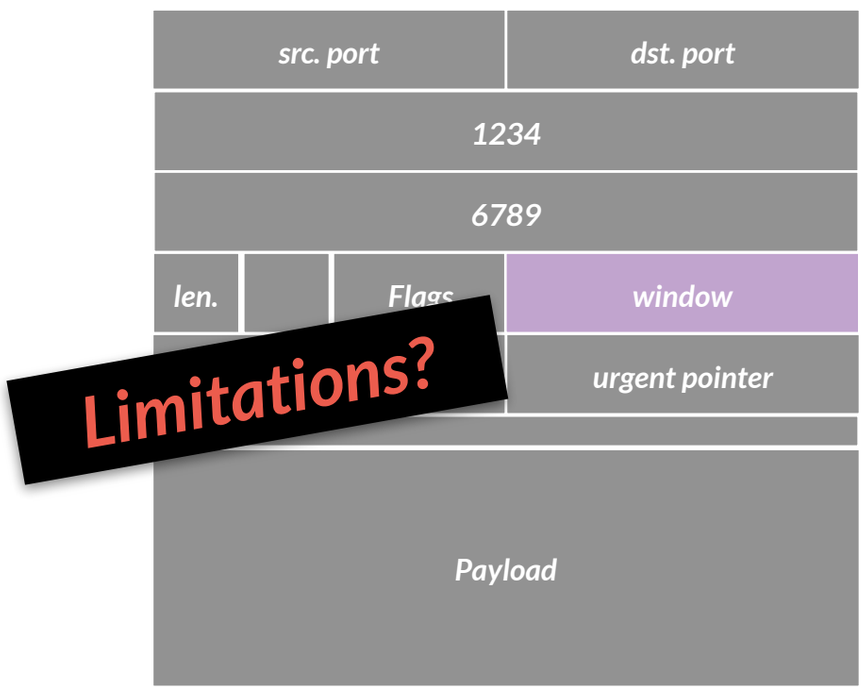

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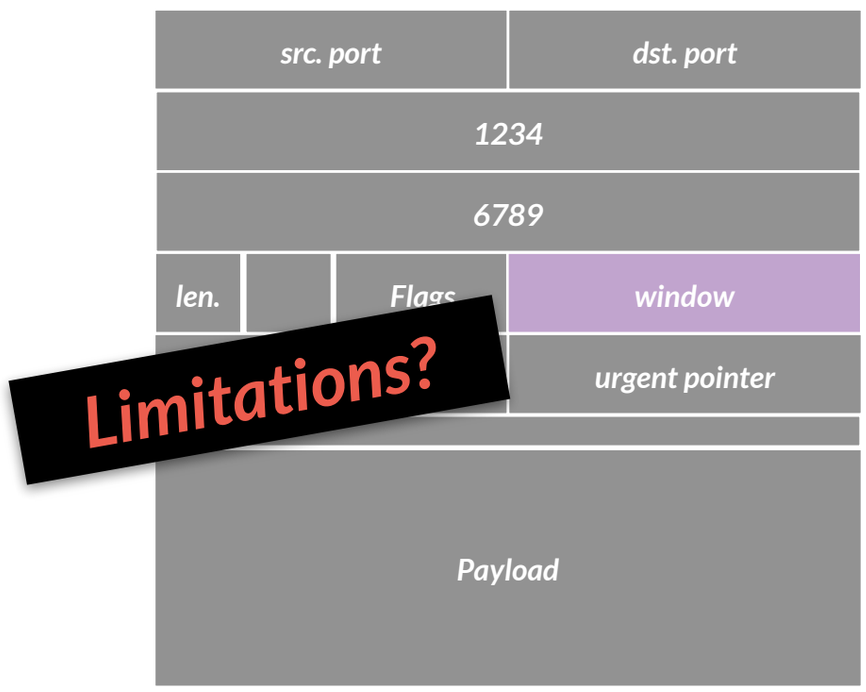

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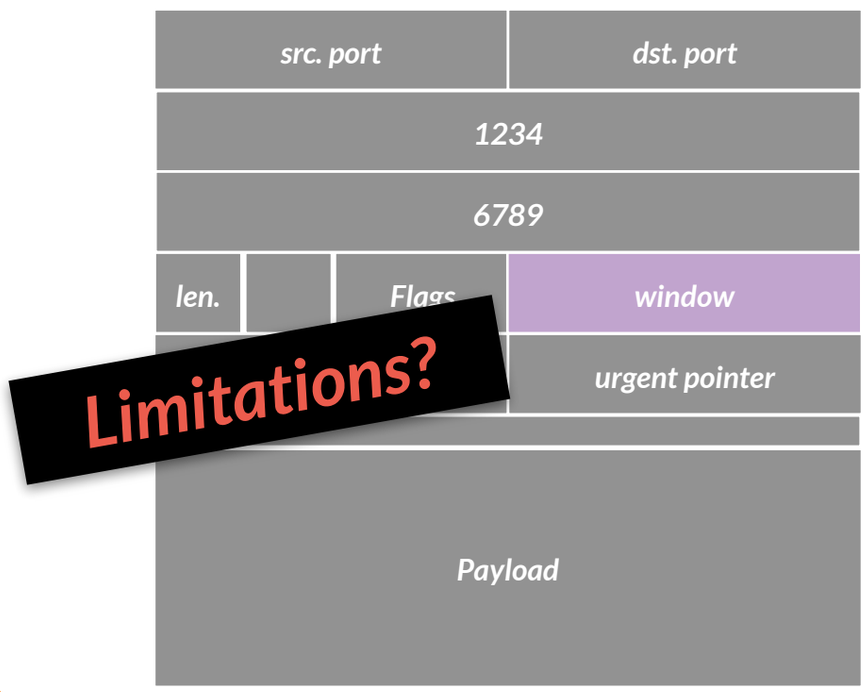
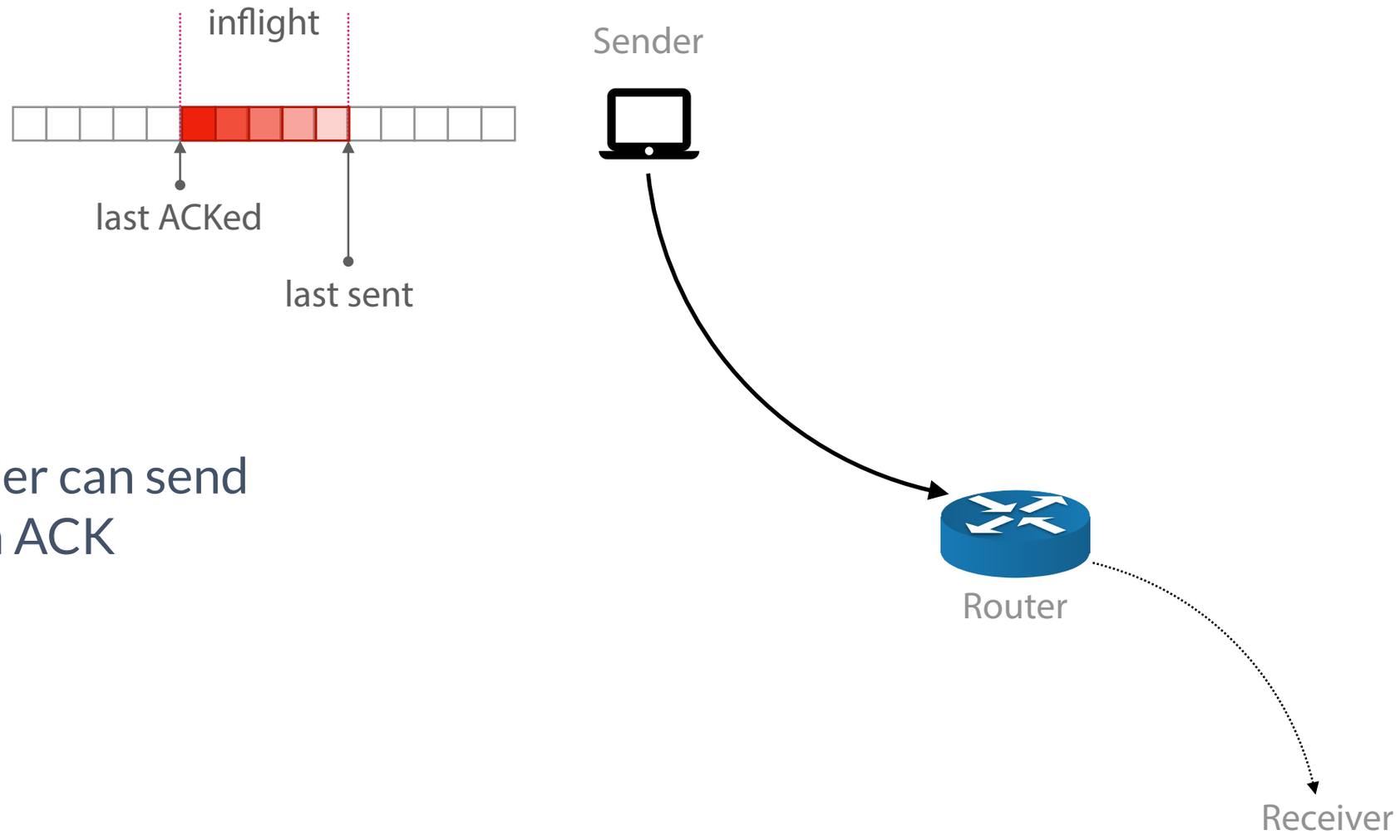


- *Window scale factor*
  - a TCP **option**; left-shift multiplier
  - Enlarge window size to ~1 GB

Congestion Control



inflight

amount of data a sender can send without waiting for an ACK


CARPOOLS ONLY
2 OR MORE PERSONS
PER VEHICLE
Slauson Ave
Sepulveda Bl
1 MILE

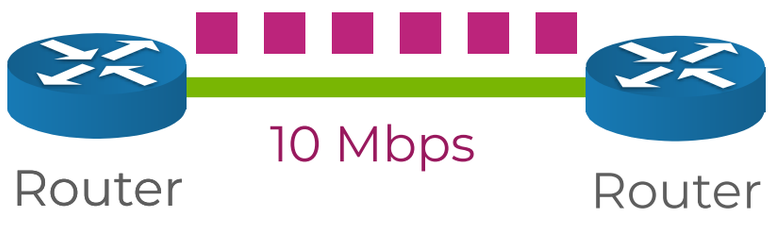

CARPOOLS ONLY
Slauson Ave
Sepulveda Bl
1 MILE

[www.fleetowner.com, secure.i.telegraph.co.uk, abbtakk.tv, www.itv.com]

Router

Router

System has finite **capacity**.



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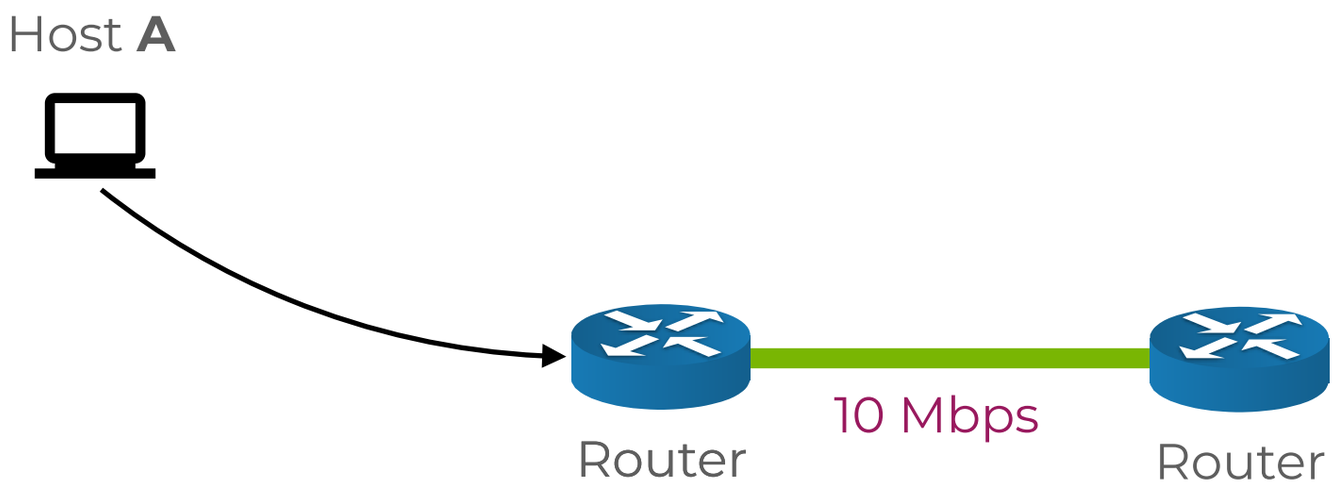
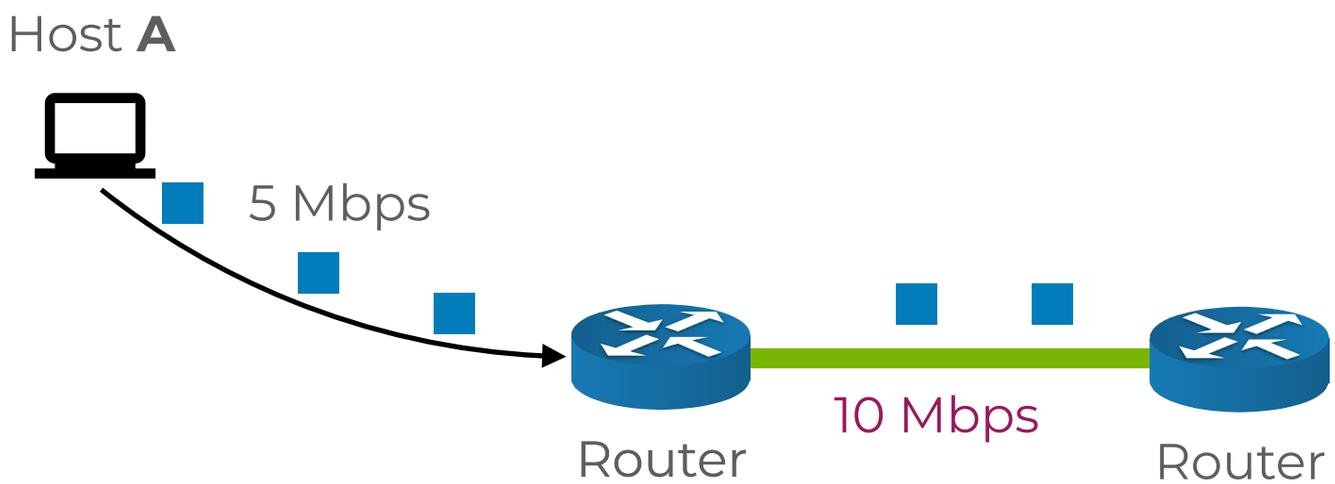
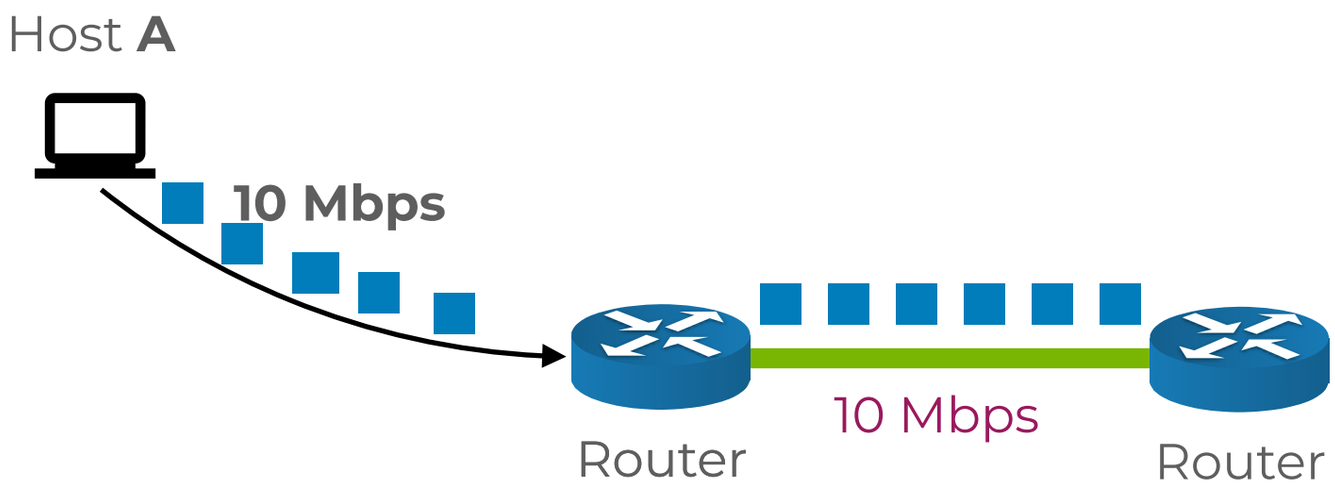




System has finite **capacity**.

Offered **load** is at or below capacity.

Assume UDP, or TCP with no congestion control



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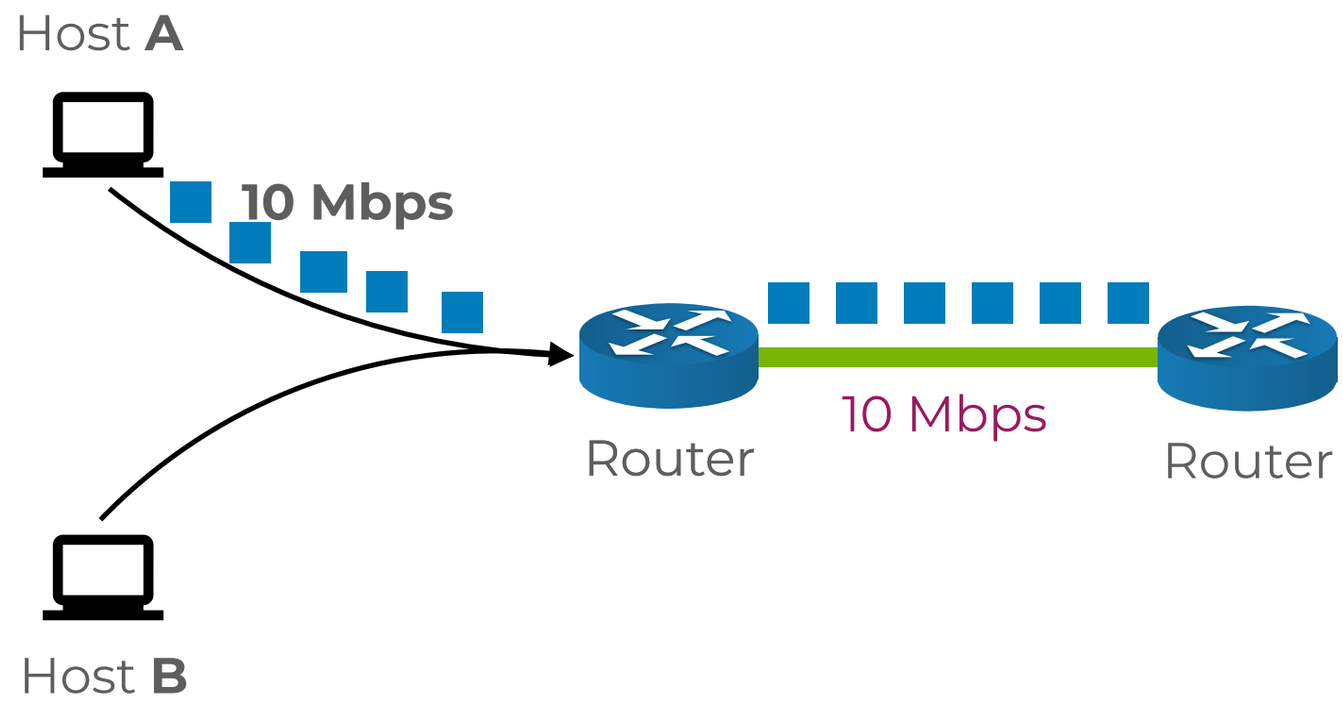

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Offered **load** is at or below capacity.

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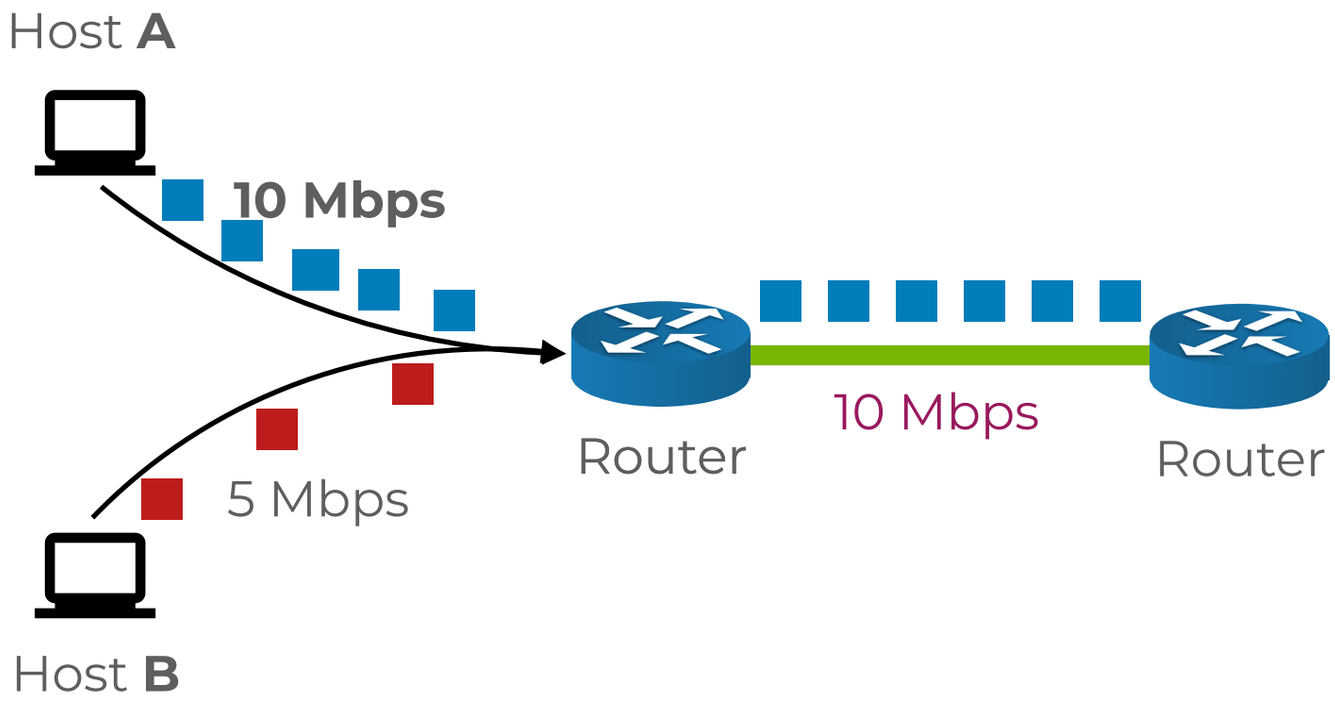
Congestion



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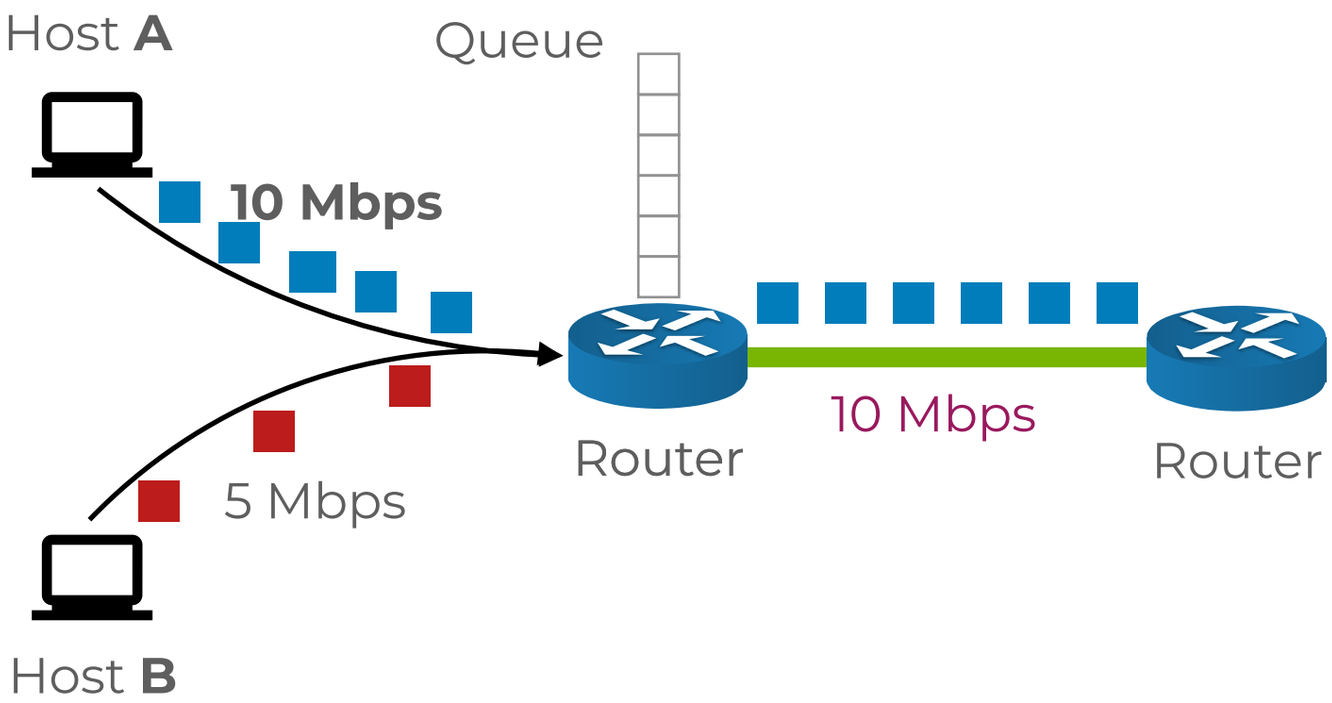

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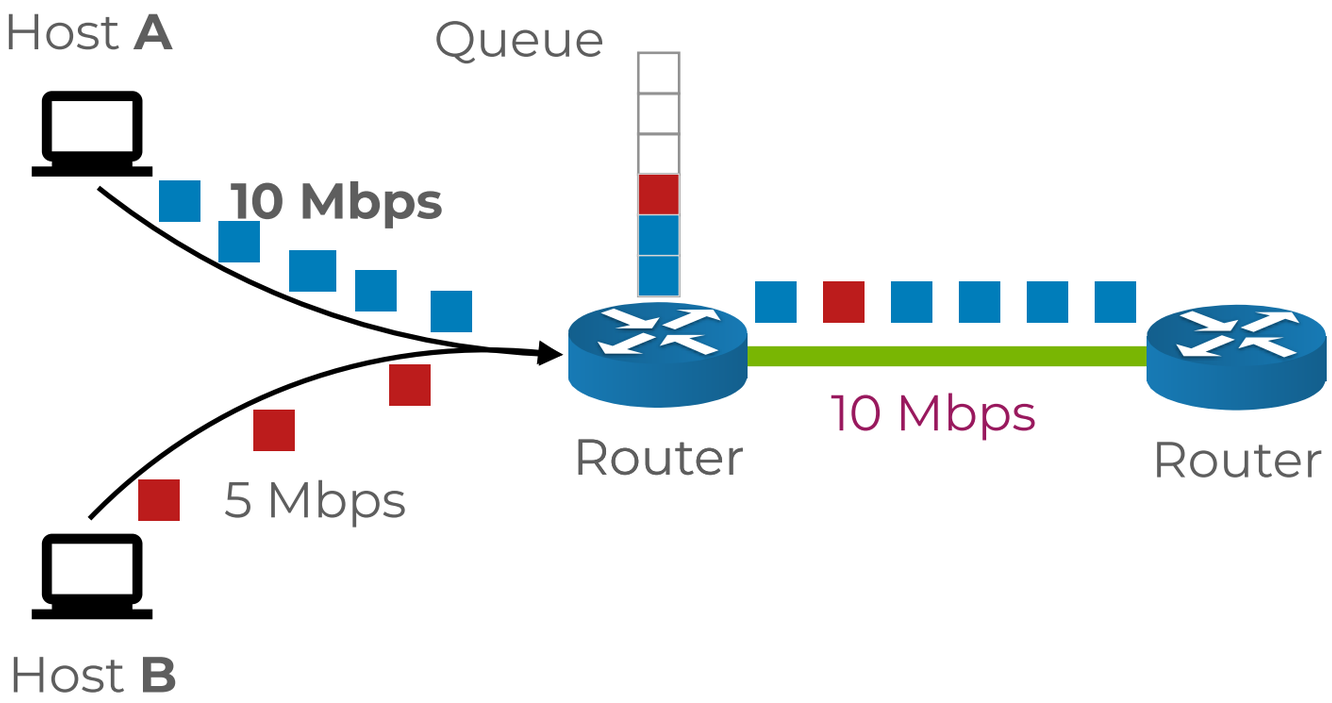

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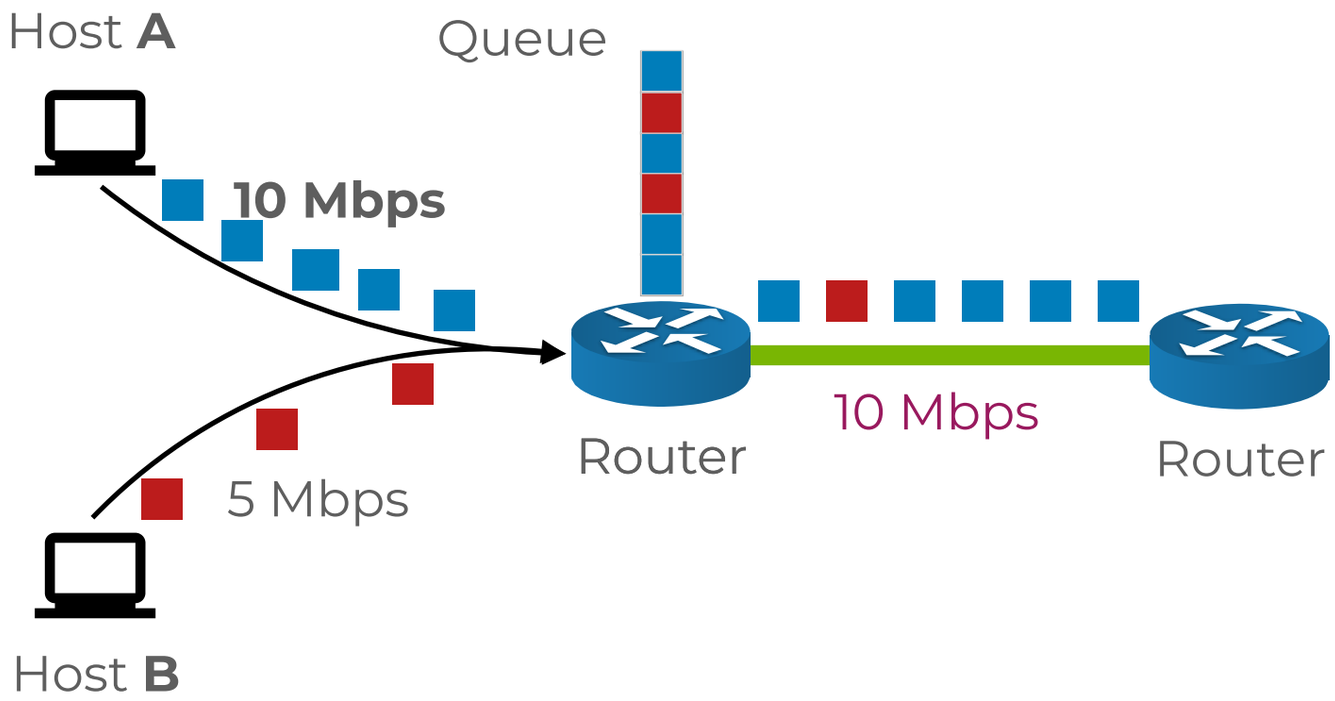

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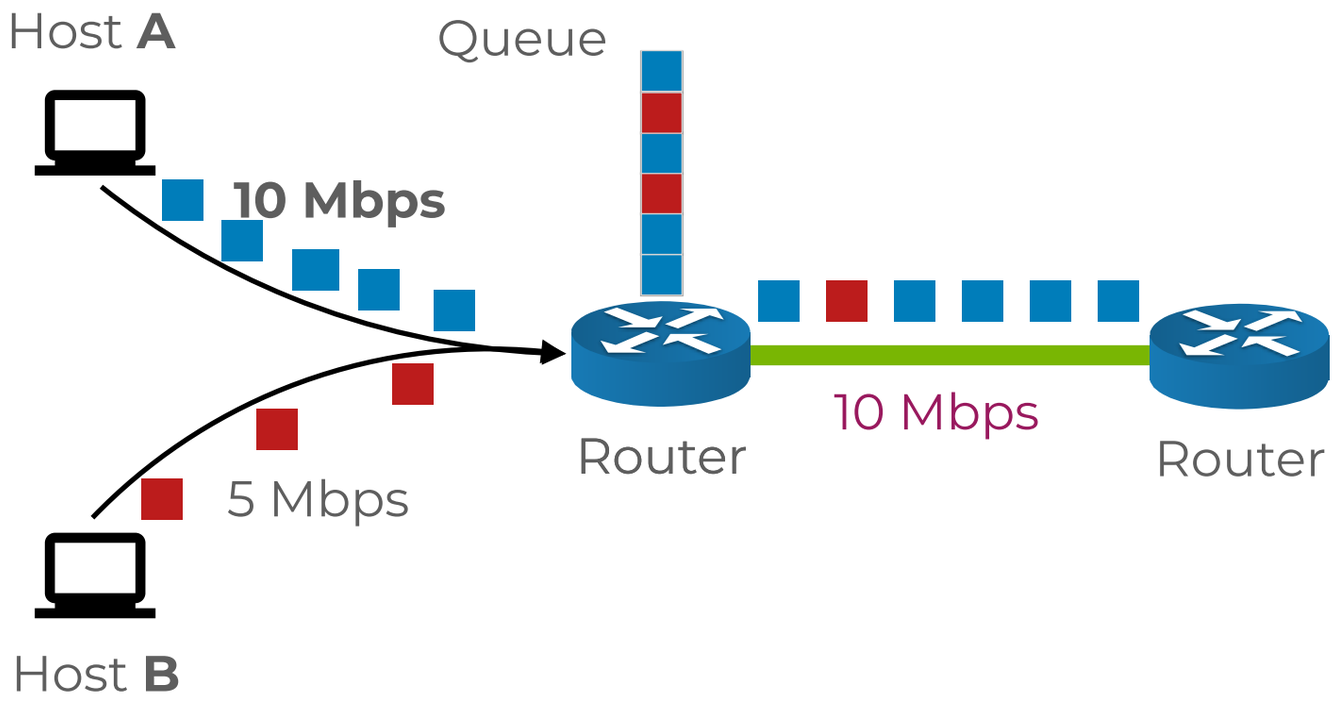

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System performance

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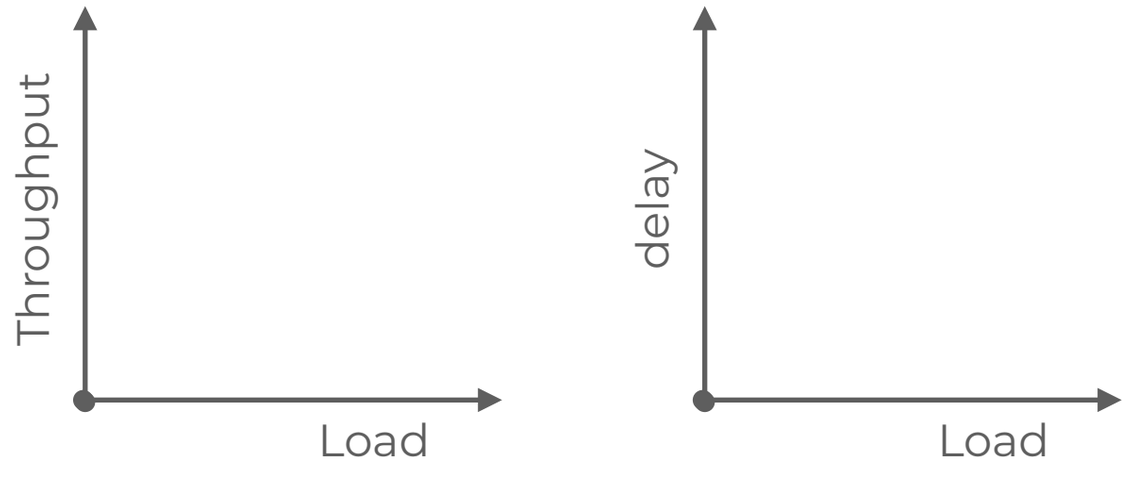
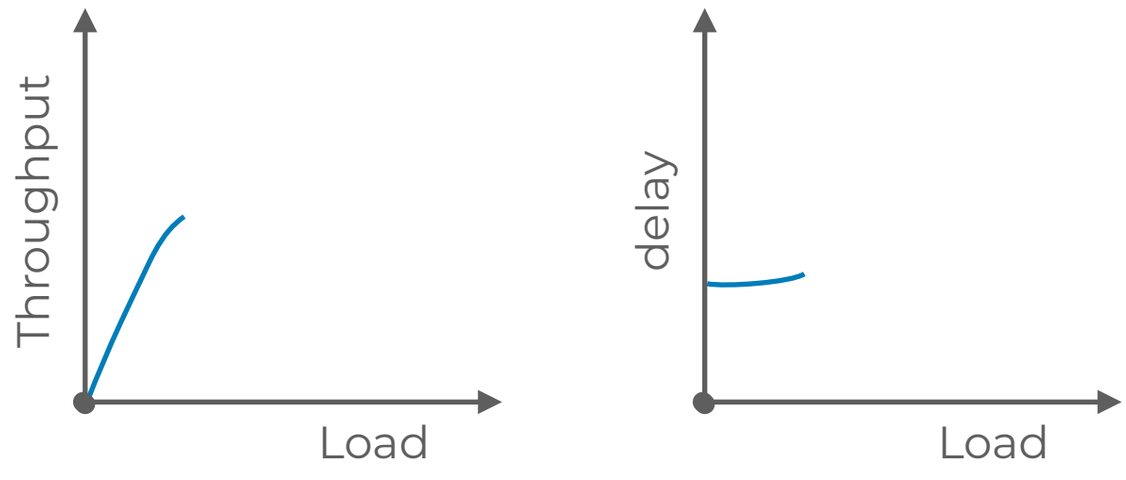


System performance



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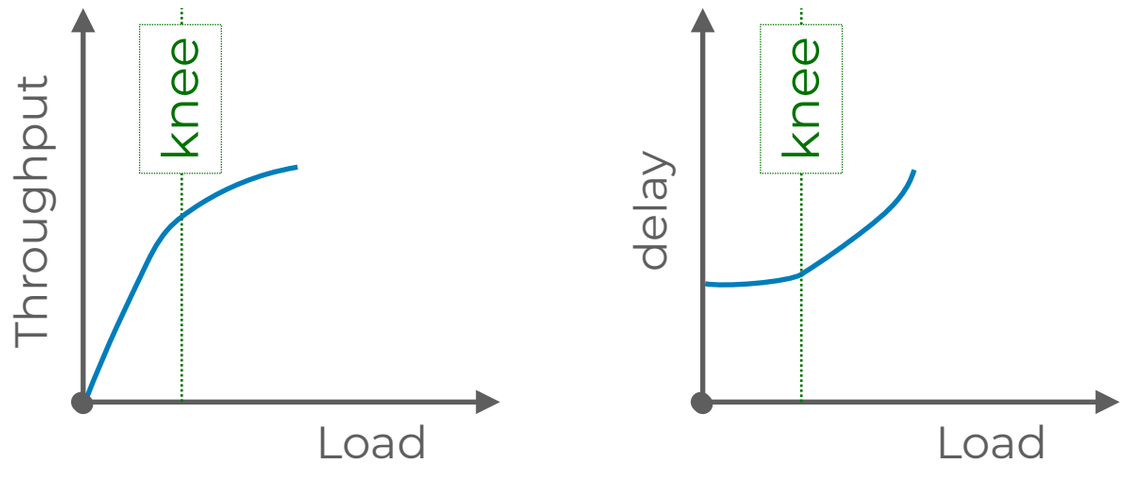

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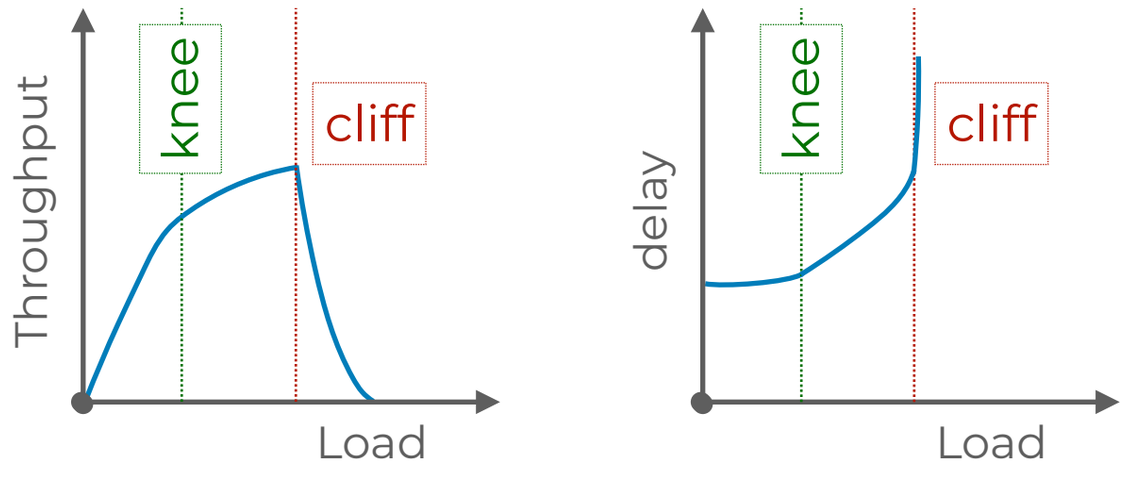

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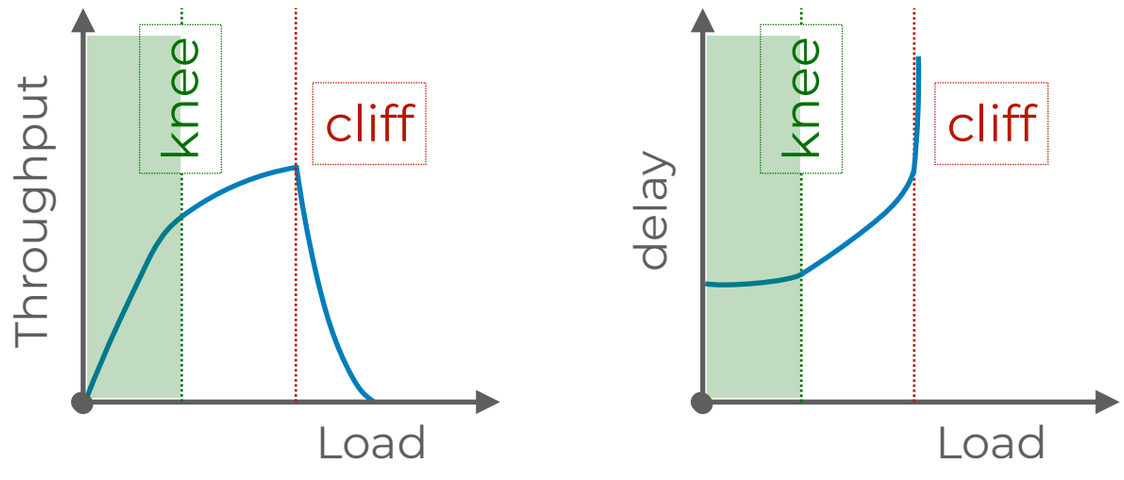
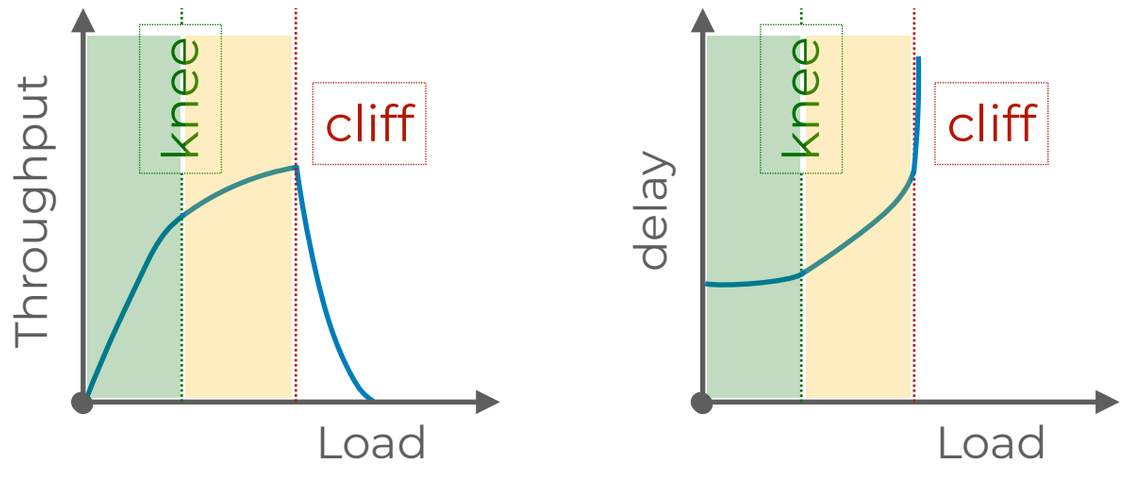


» **Congestion avoidance** Stay left of “knee”

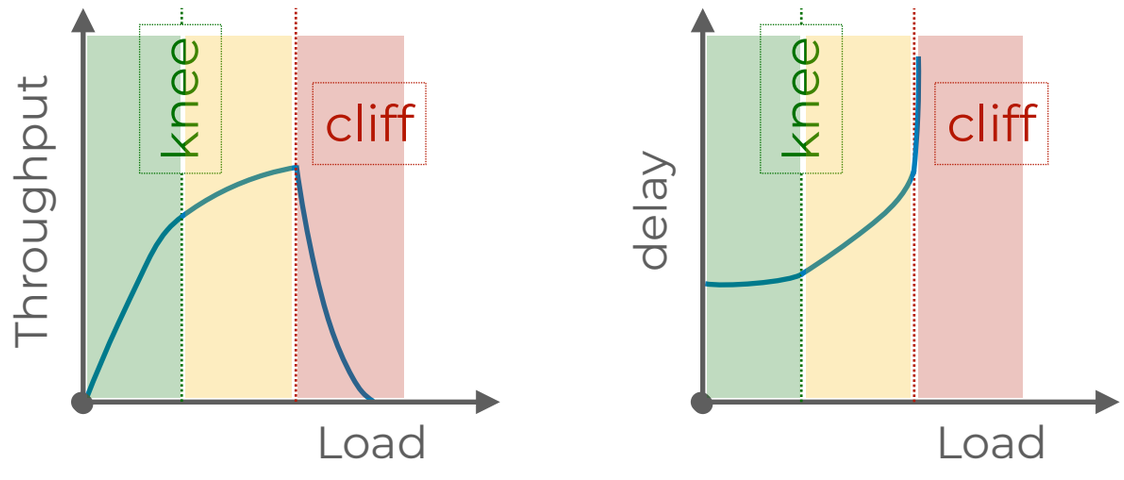
System performance



» **Congestion avoidance** Stay left of “knee”

» **Congestion control** Stay left of “cliff”

System performance



» **Congestion avoidance** Stay left of “knee”

» **Congestion control** Stay left of “cliff”

» **Congestion collapse** Avoid at all costs

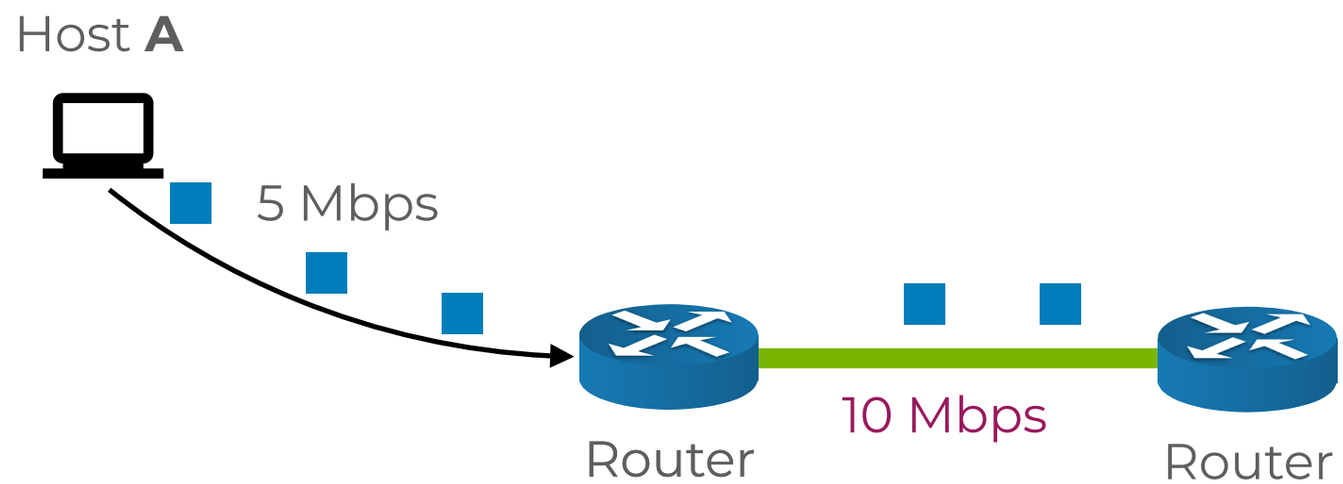
Did you know?

- Congestion collapse is real, and was first observed in 1986 in NSFnet.
- TCP initially did not have congestion control!

Congestion Control: Challenges & Goals

- What are the key challenges and objectives for congestion control?

Why is it a hard problem?



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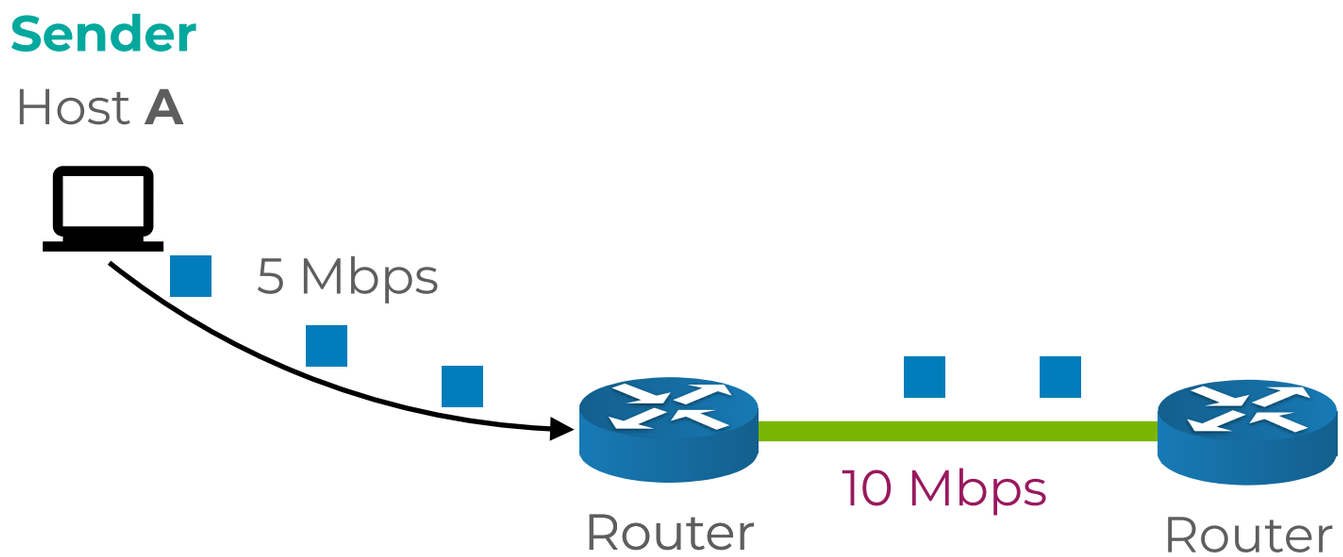

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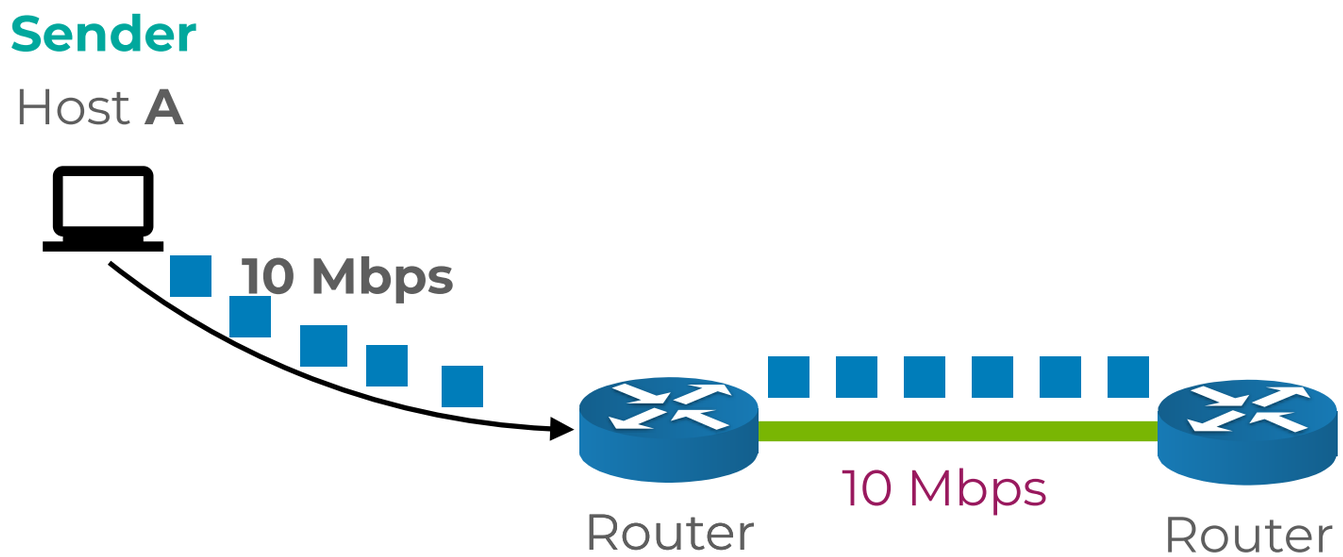

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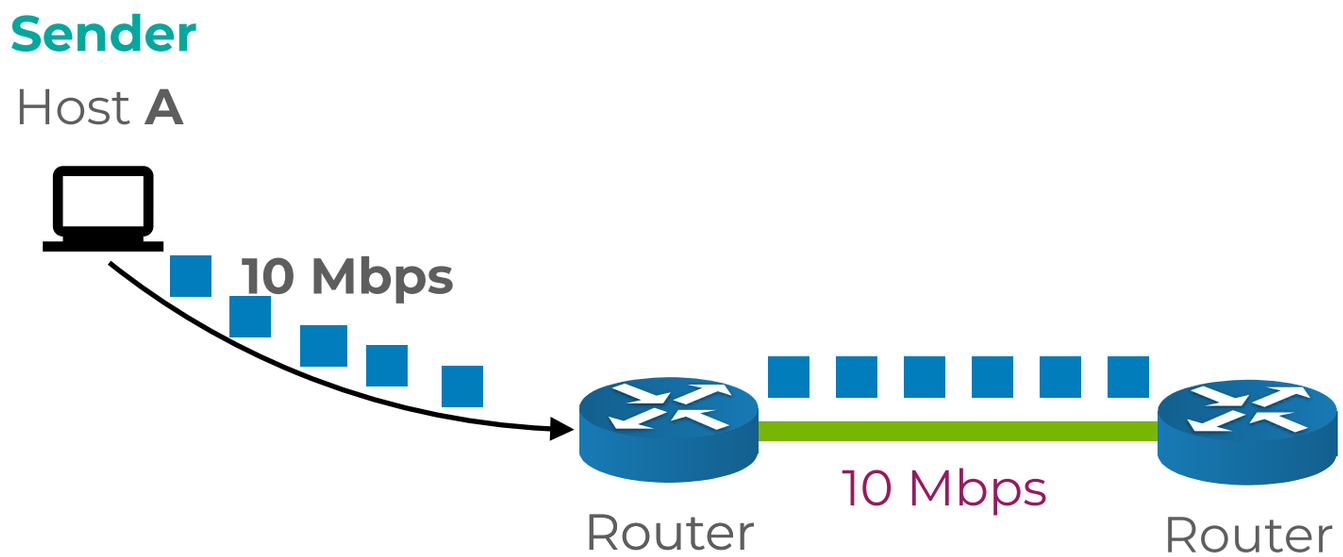

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- Use network resources **“efficiently”**

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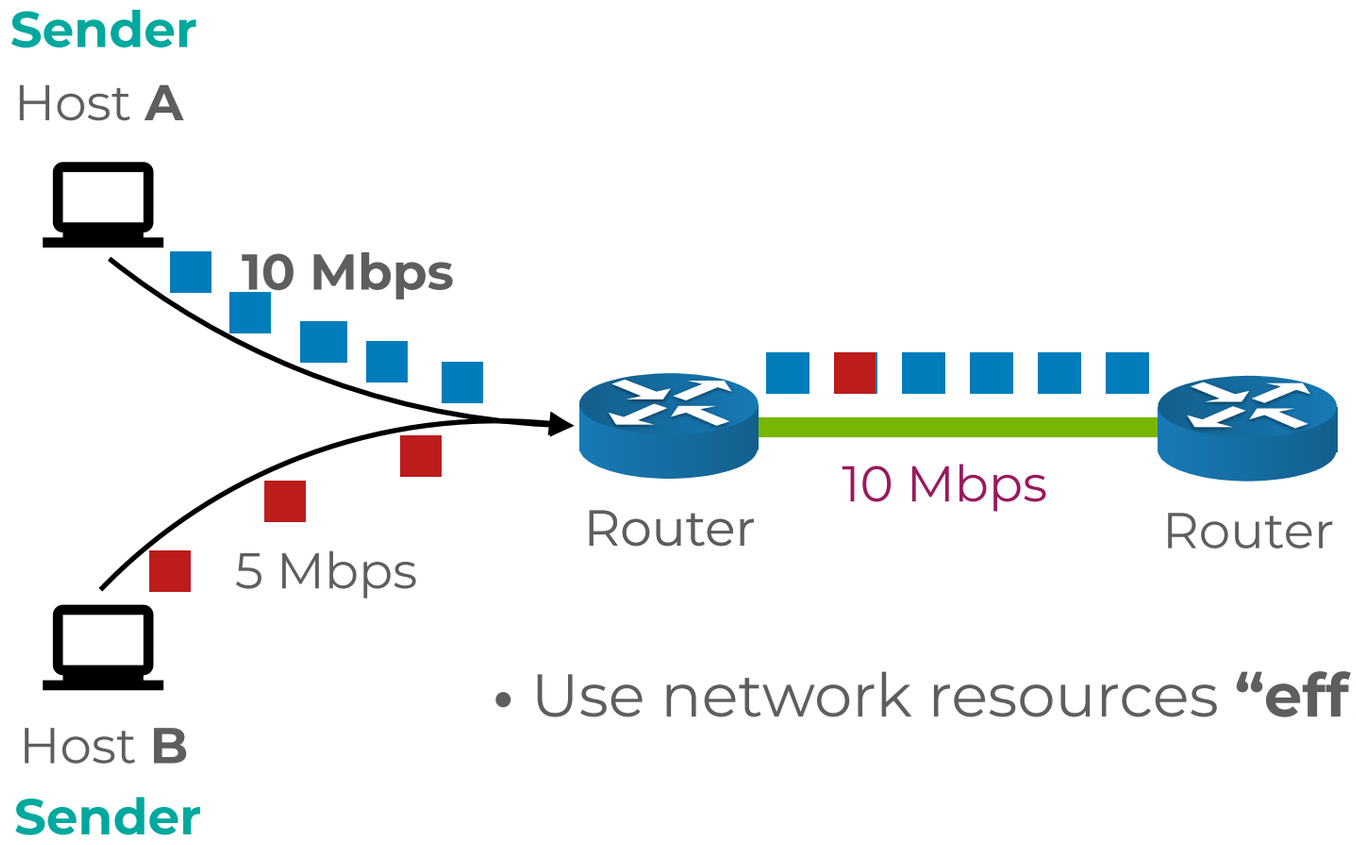

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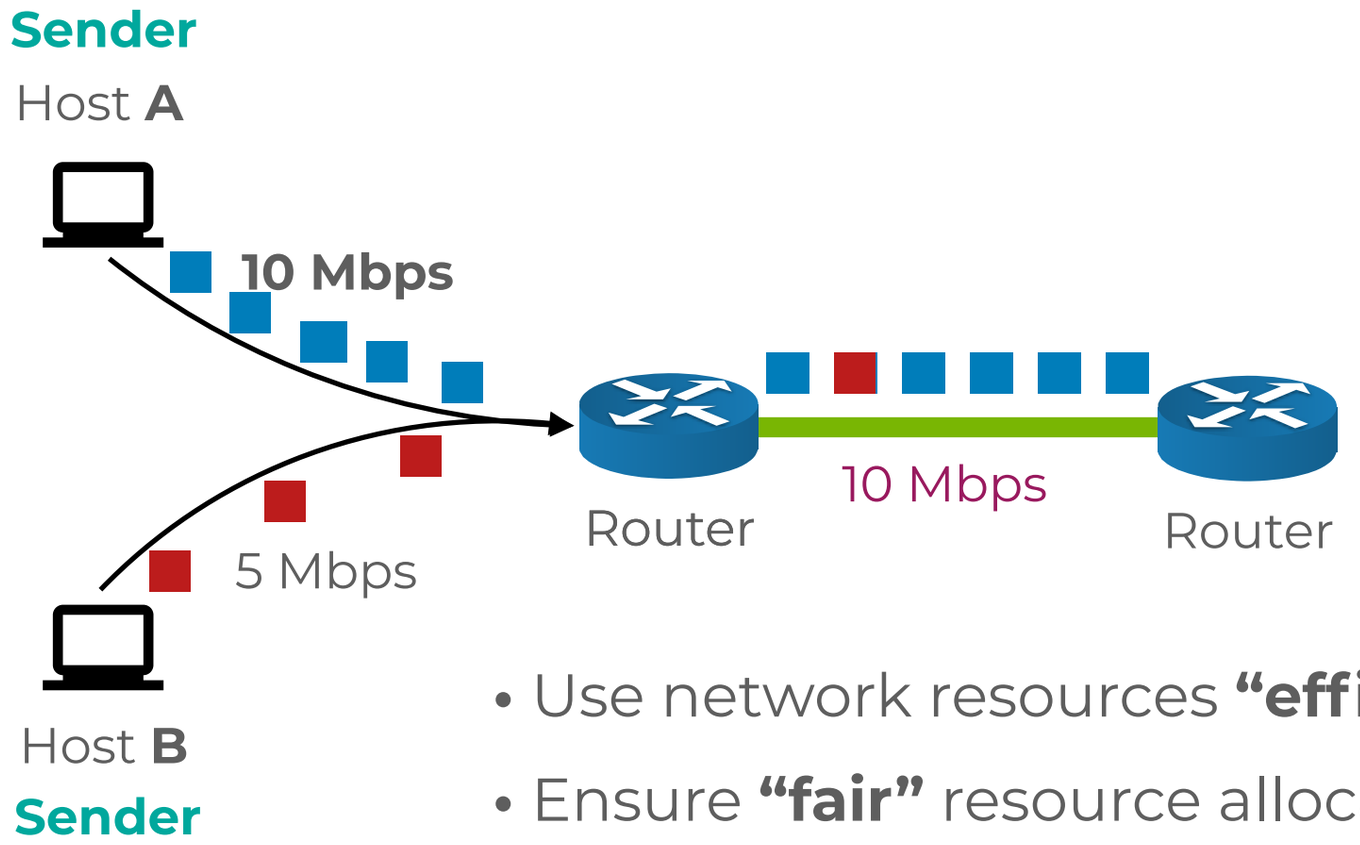

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- Use network resources **“efficiently”**
- Ensure **“fair”** resource allocation

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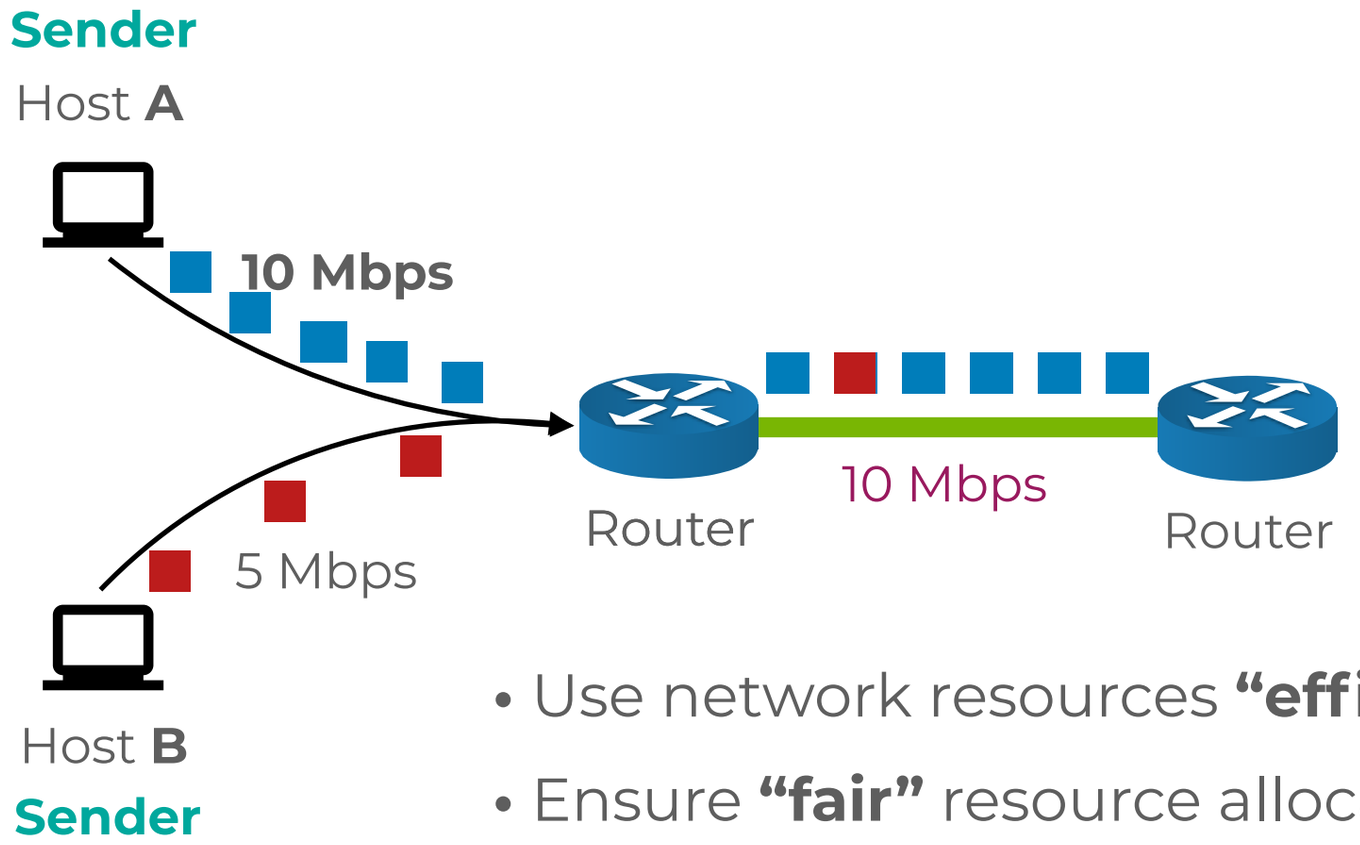

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- Adapt **“quickly”**

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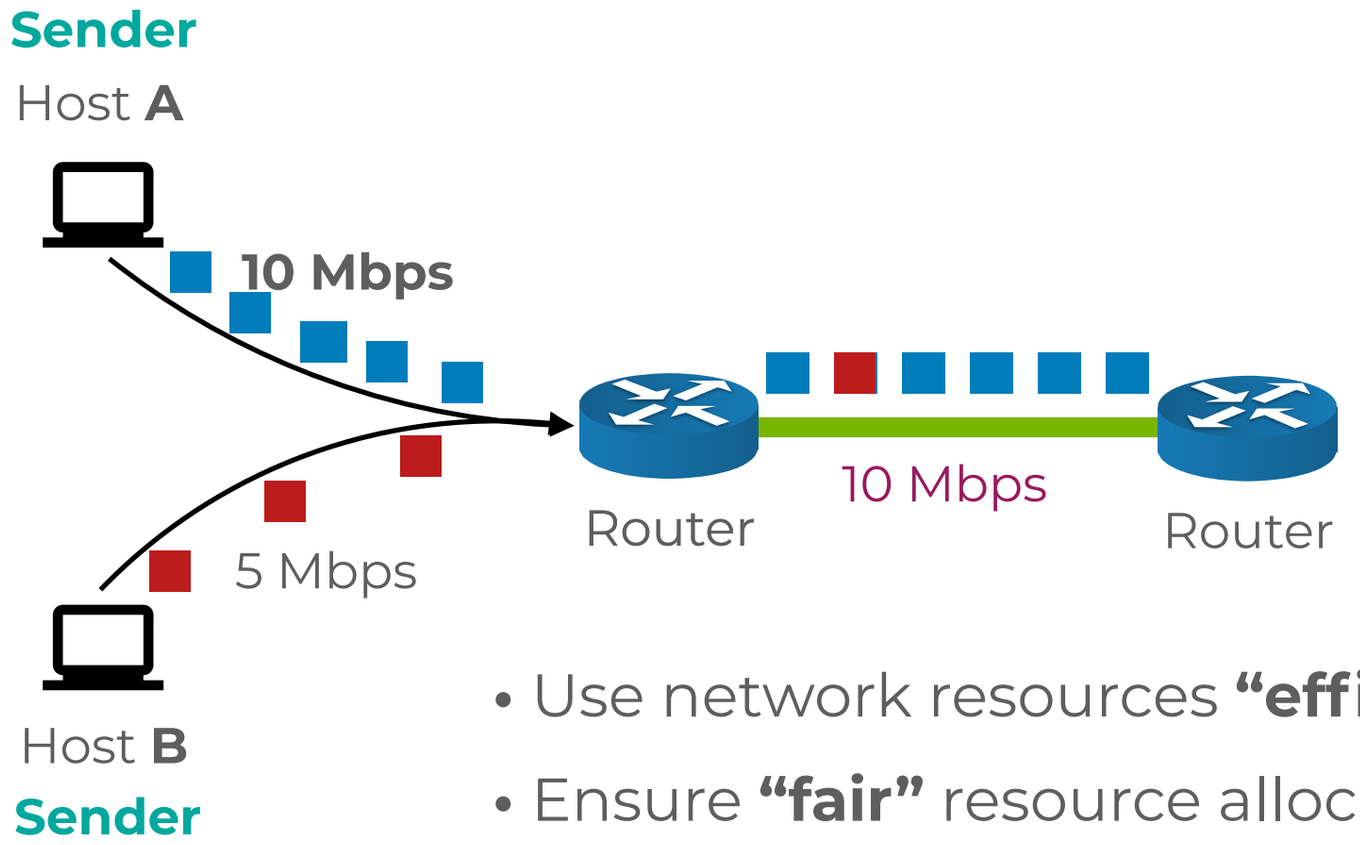

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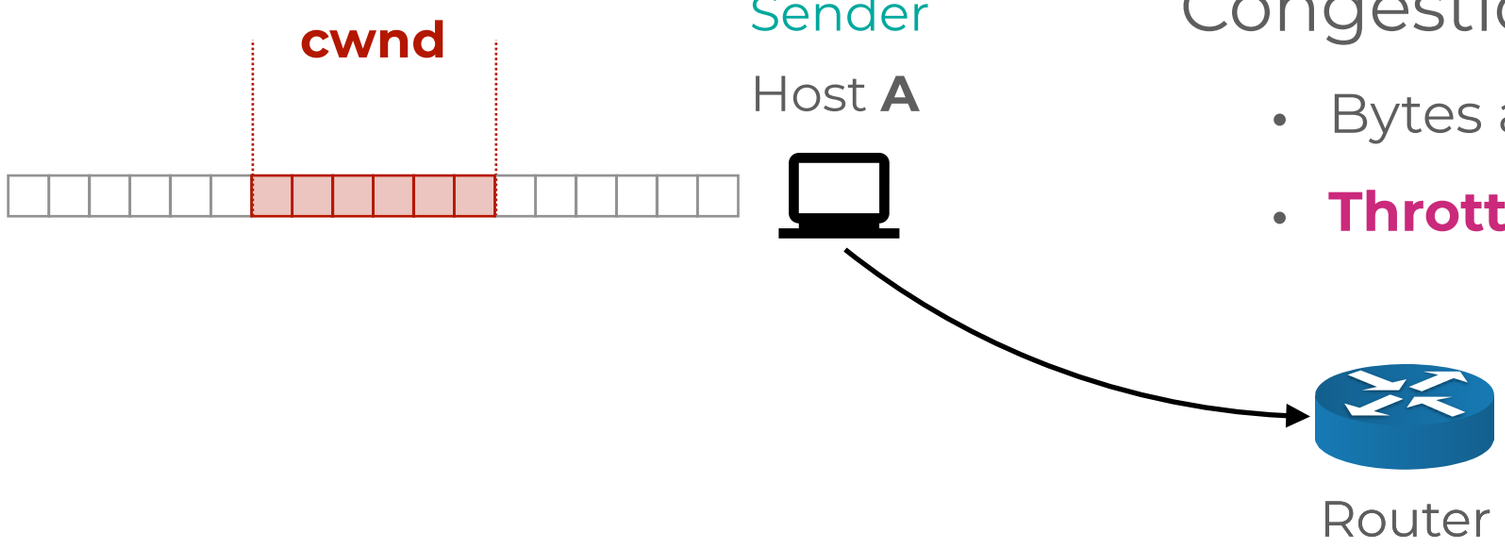
Offered **load** exceeds capacity.

- Use network resources **“efficiently”**
- Ensure **“fair”** resource allocation
- Adapt **“quickly”**
- No **“explicit coordination”**

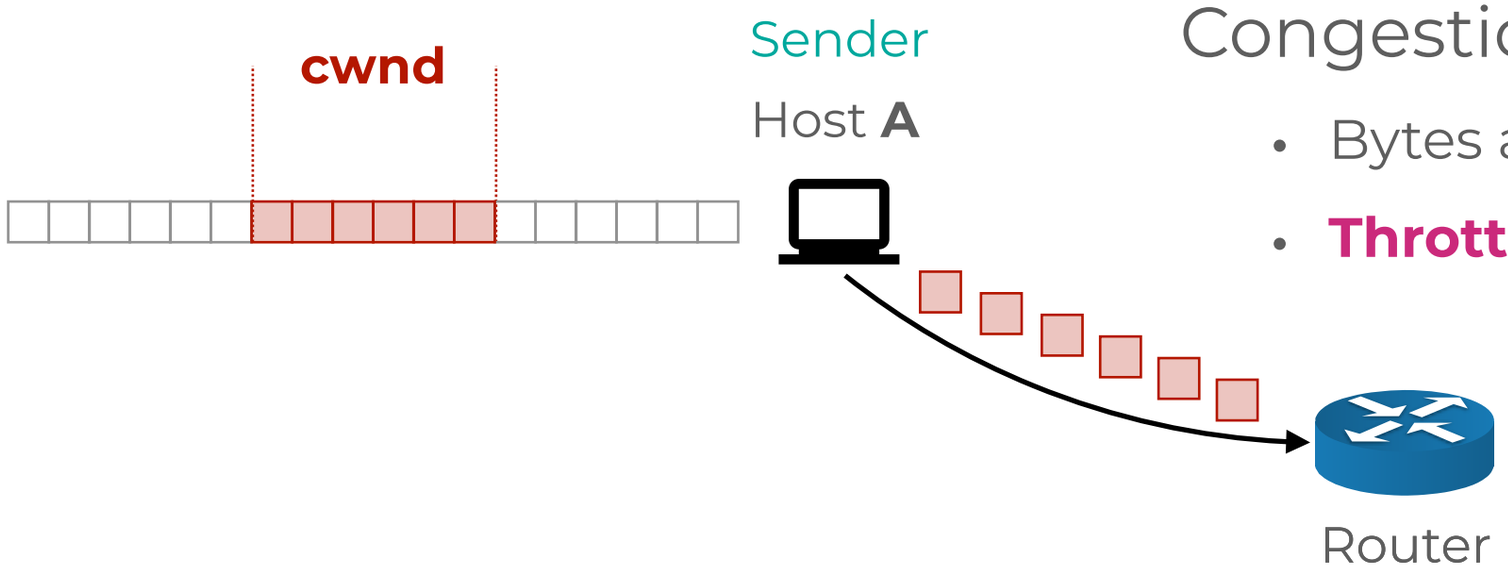
Window-based control



Congestion window (cwnd)

- Bytes awaiting acknowledgement
- **Throttles** sender

Window-based control



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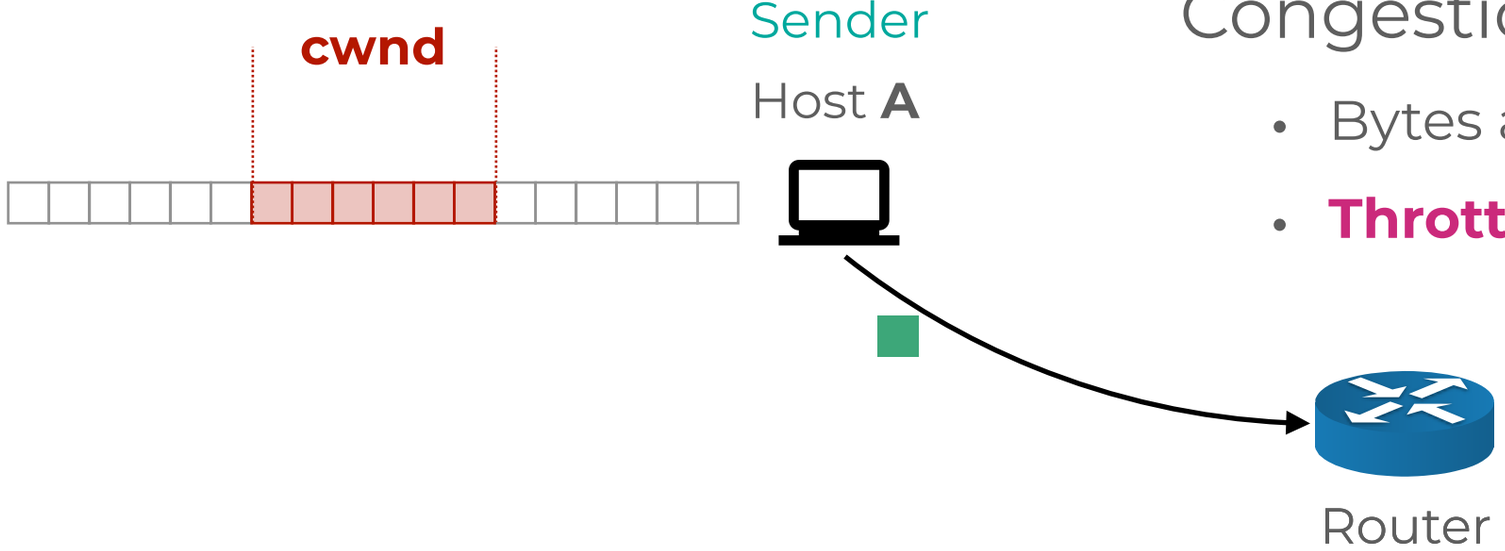

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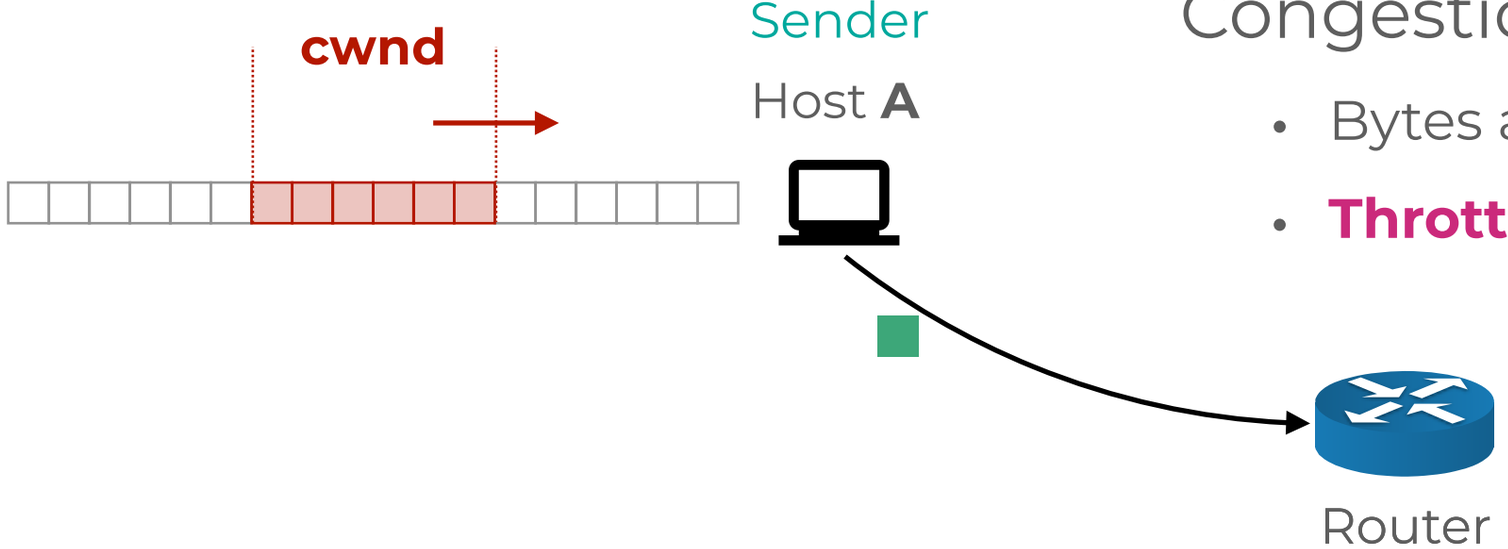

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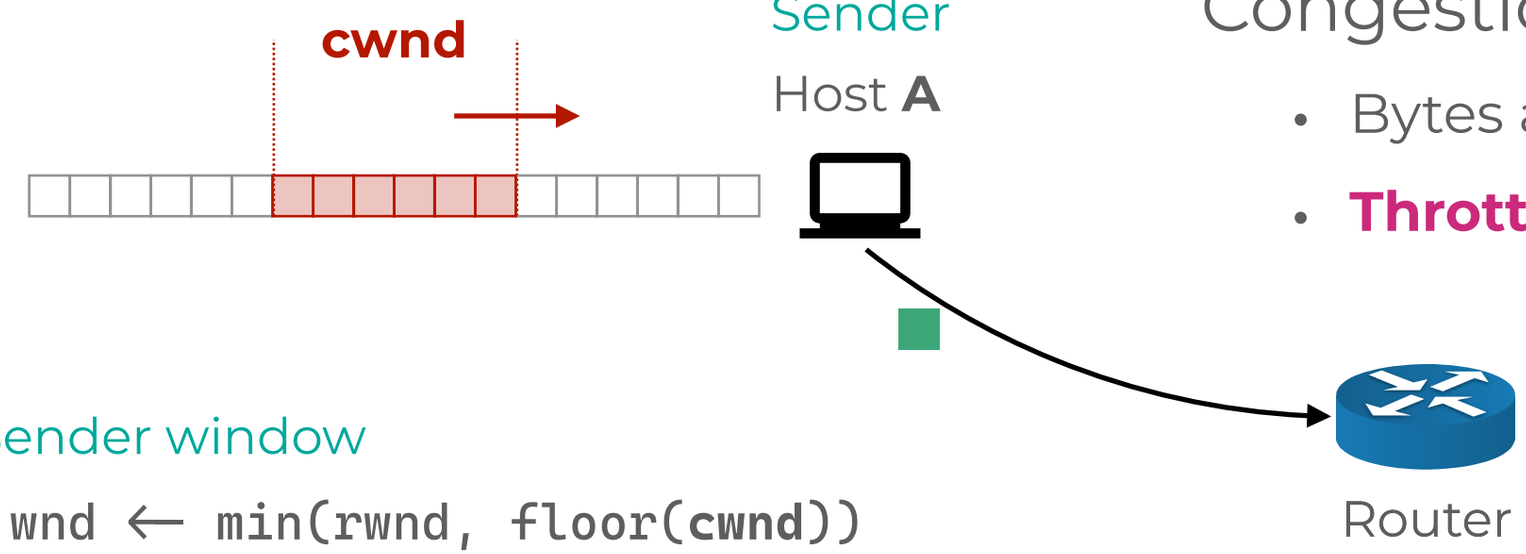

Congestion window (cwnd)

- Bytes awaiting acknowledgement
- **Throttles** sender

Sender window

```
wnd ← min(rwnd, floor(cwnd))
```

Window-based control

Congestion window (cwnd)

- Bytes awaiting acknowledgement
- **Throttles** sender

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wnd ← min(rwnd, floor(cwnd))
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If there’s no congestion

- **Increase** cwnd

On detecting congestion

- **Decrease** cwnd

Window-based control

Congestion window (cwnd)

- Bytes awaiting acknowledgement
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If there's no congestion

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wnd ← min(rwnd, floor(cwnd))
```

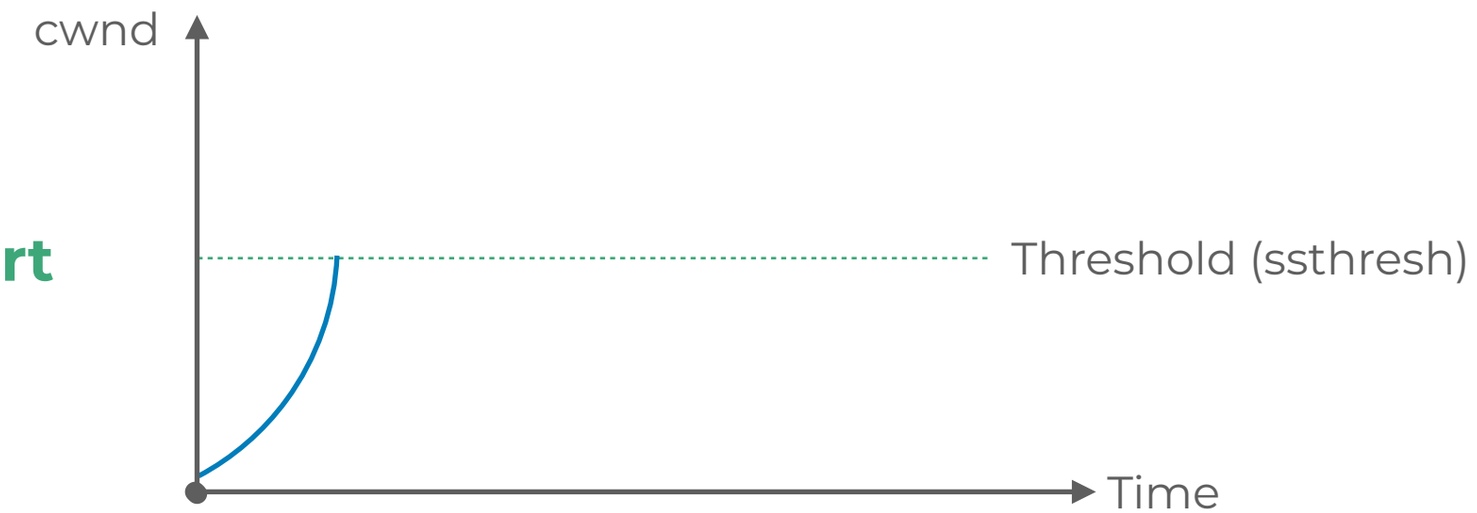
Adaptation

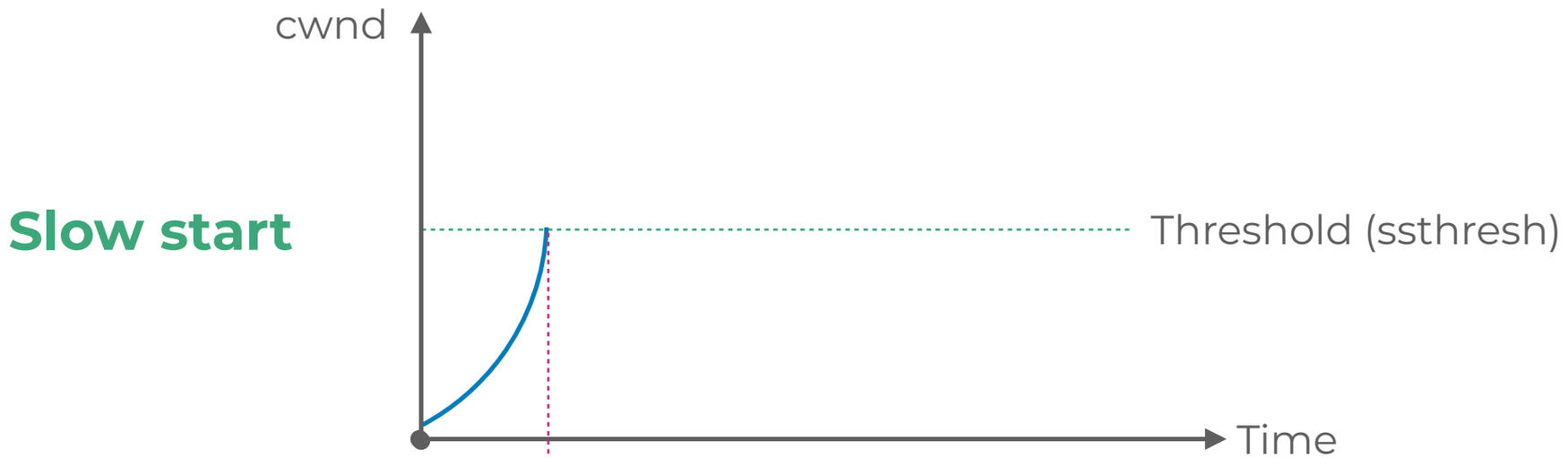

Time

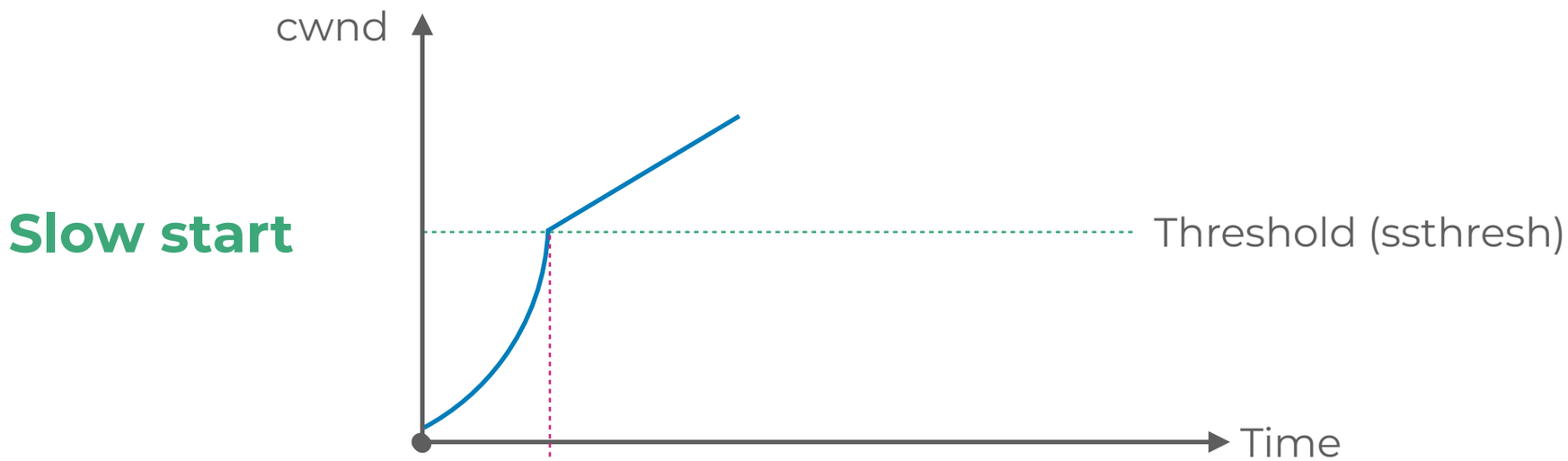

cwnd
Time

Slow start

Slow start

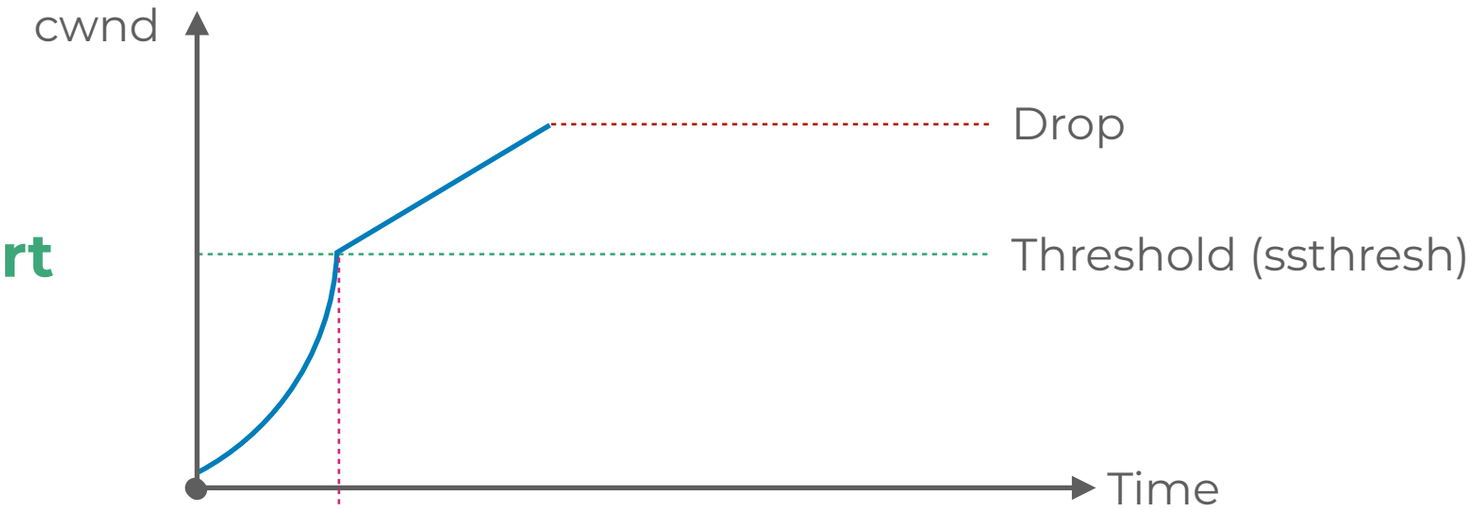



cwnd
Slow start
Threshold (ssthresh)
Time
Quickly probe path bandwidth



Quickly probe path bandwidth

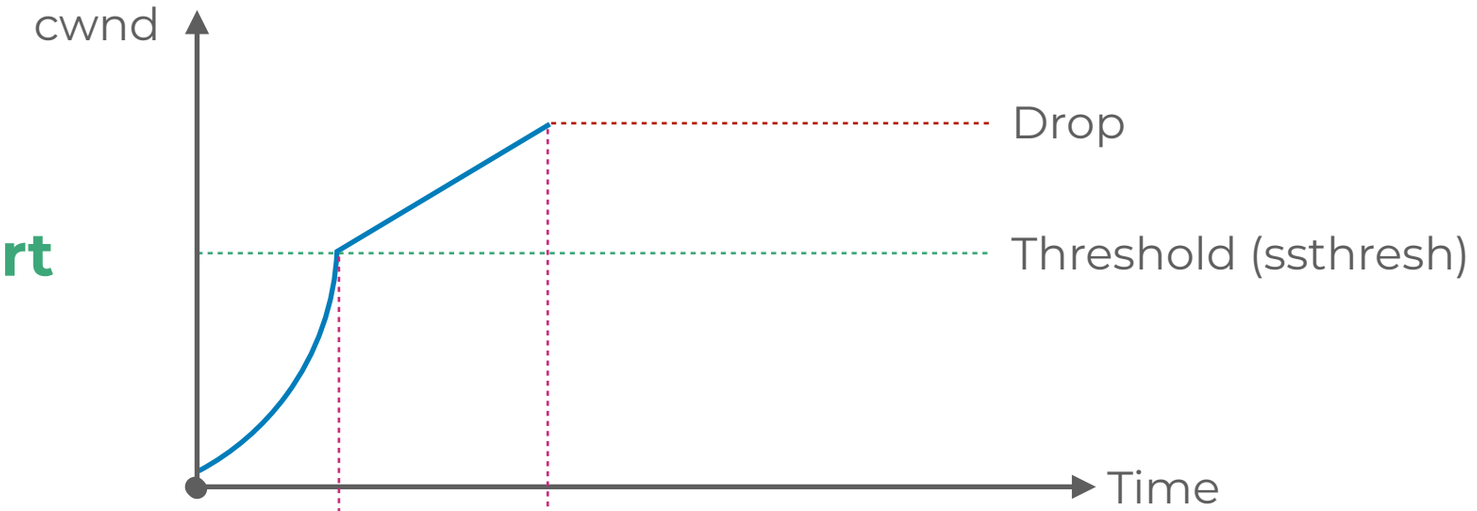
Congestion avoidance



Slow start

Quickly probe path bandwidth

Congestion avoidance

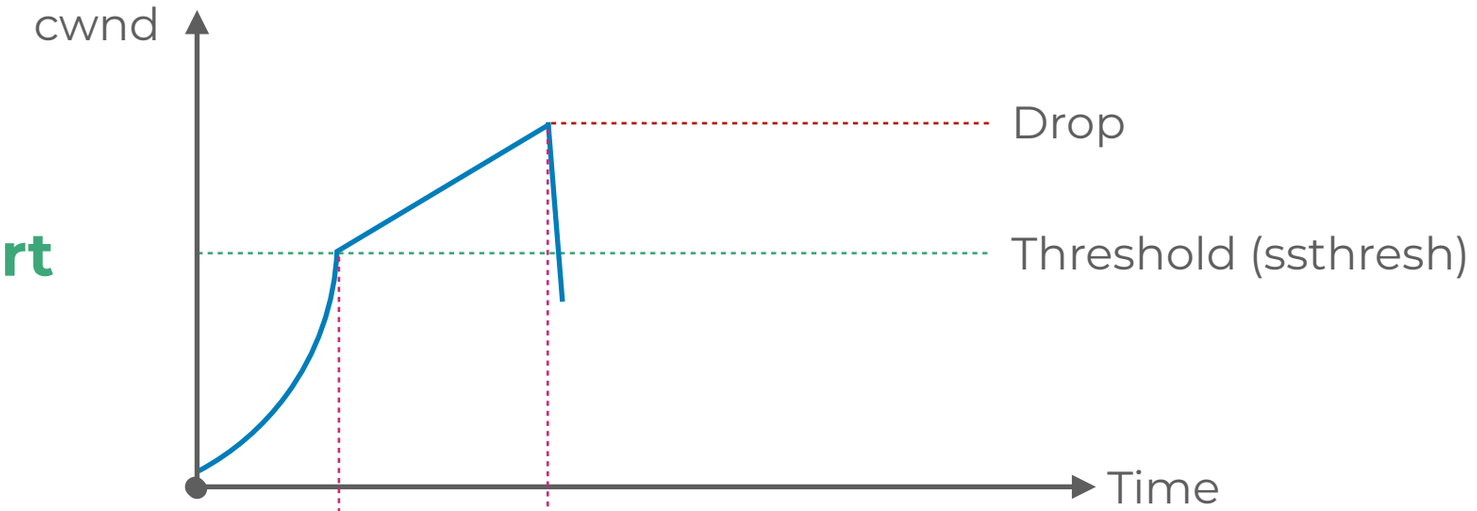


Slow start

Quickly probe path bandwidth

Cautiously probe available bandwidth

Congestion avoidance



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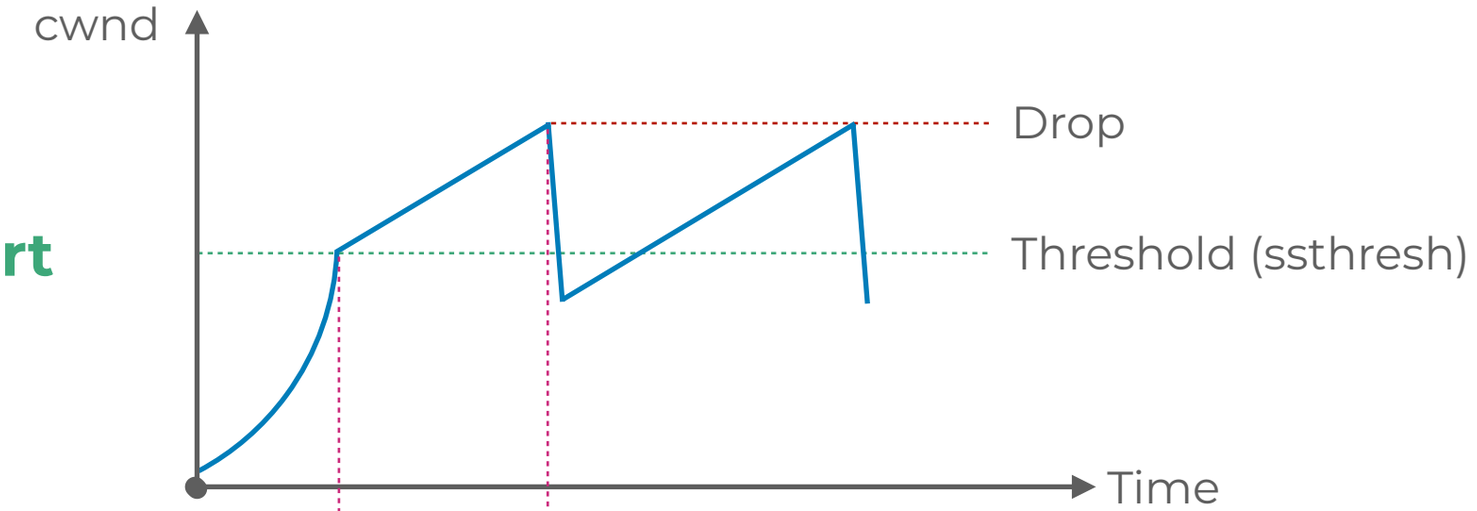

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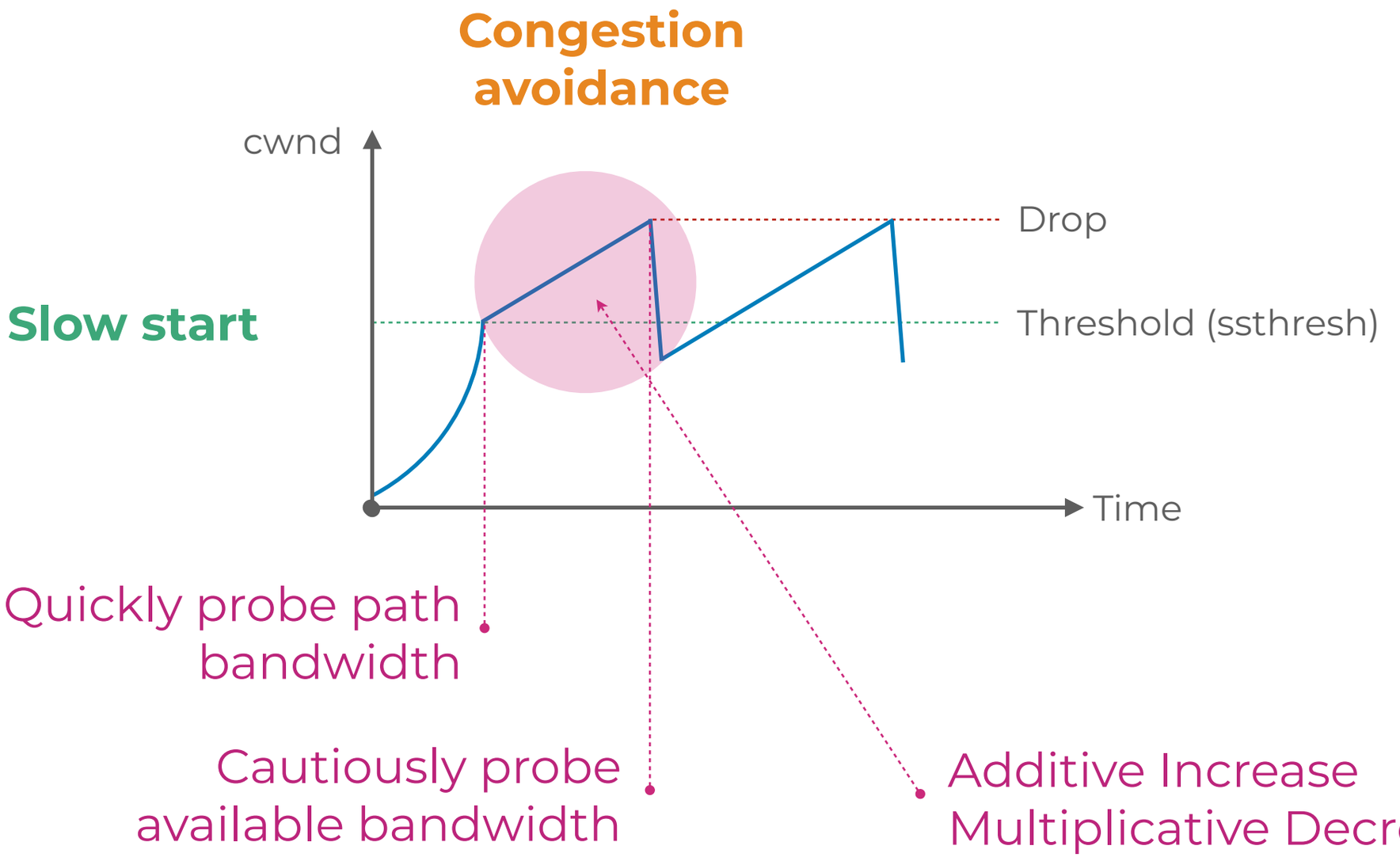
Congestion avoidance
cwnd
Drop
Slow start
Threshold (ssthresh)
Time
Quickly probe path bandwidth
Cautiously probe available bandwidth
Additive Increase Multiplicative Decrease