Lecture 6:

The Transport Layer

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Outline (from last lecture)

- Interaction with application layer
  - UDP
  - TCP
- Reliable data delivery
  - Imaginary protocol
  - UDP & TCP at the next lecture

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UDP: reliability elements

- UDP does not really offer reliable data delivery
- Checksums to detect corruption

TCP: reliability elements

- Checksums to detect corruption
- ACKs to signal successful reception
- SEQs to disambiguate segments
- Timeouts to detect loss
- Retransmissions to recover from corruption+loss

TCP: reliability elements

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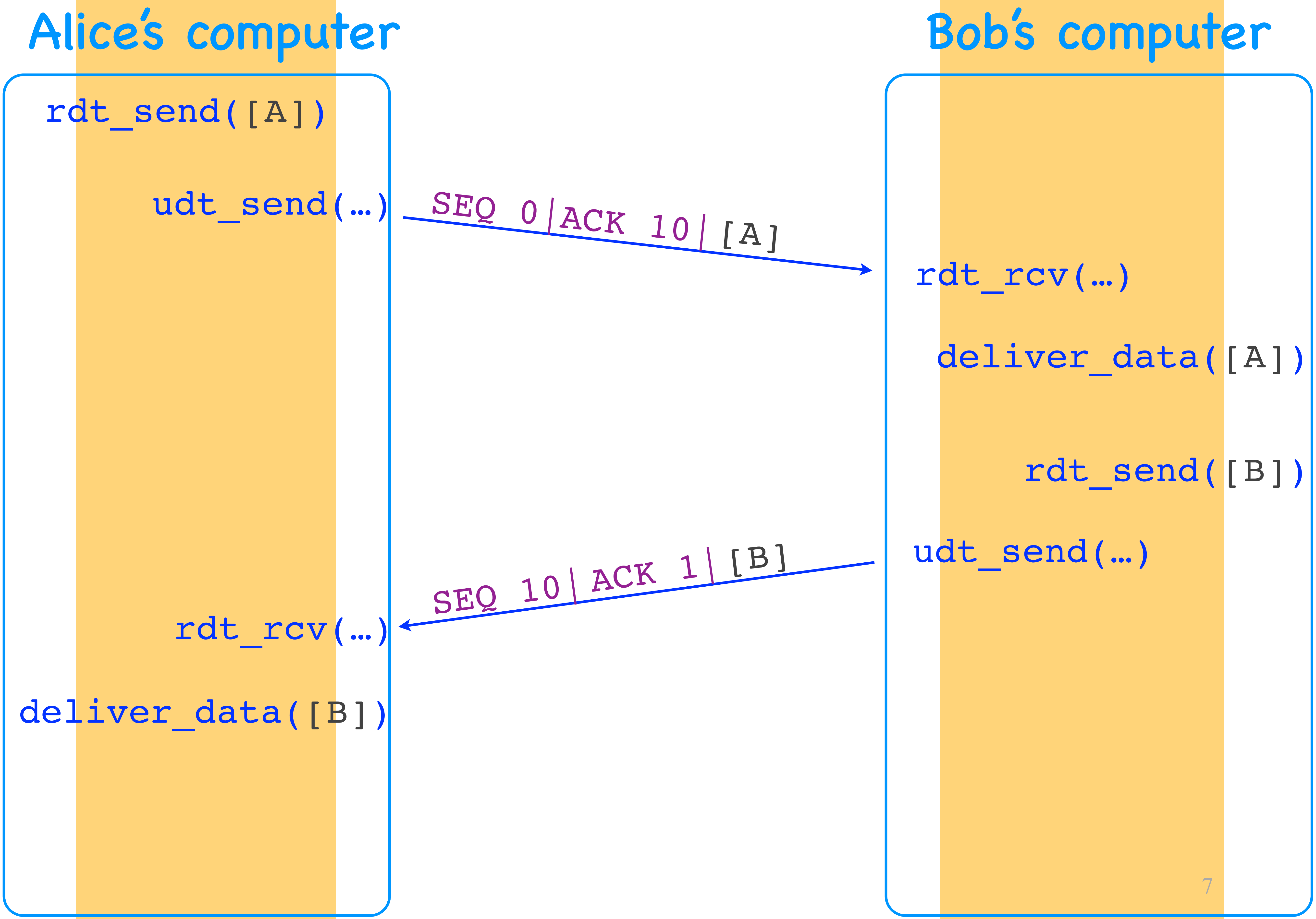
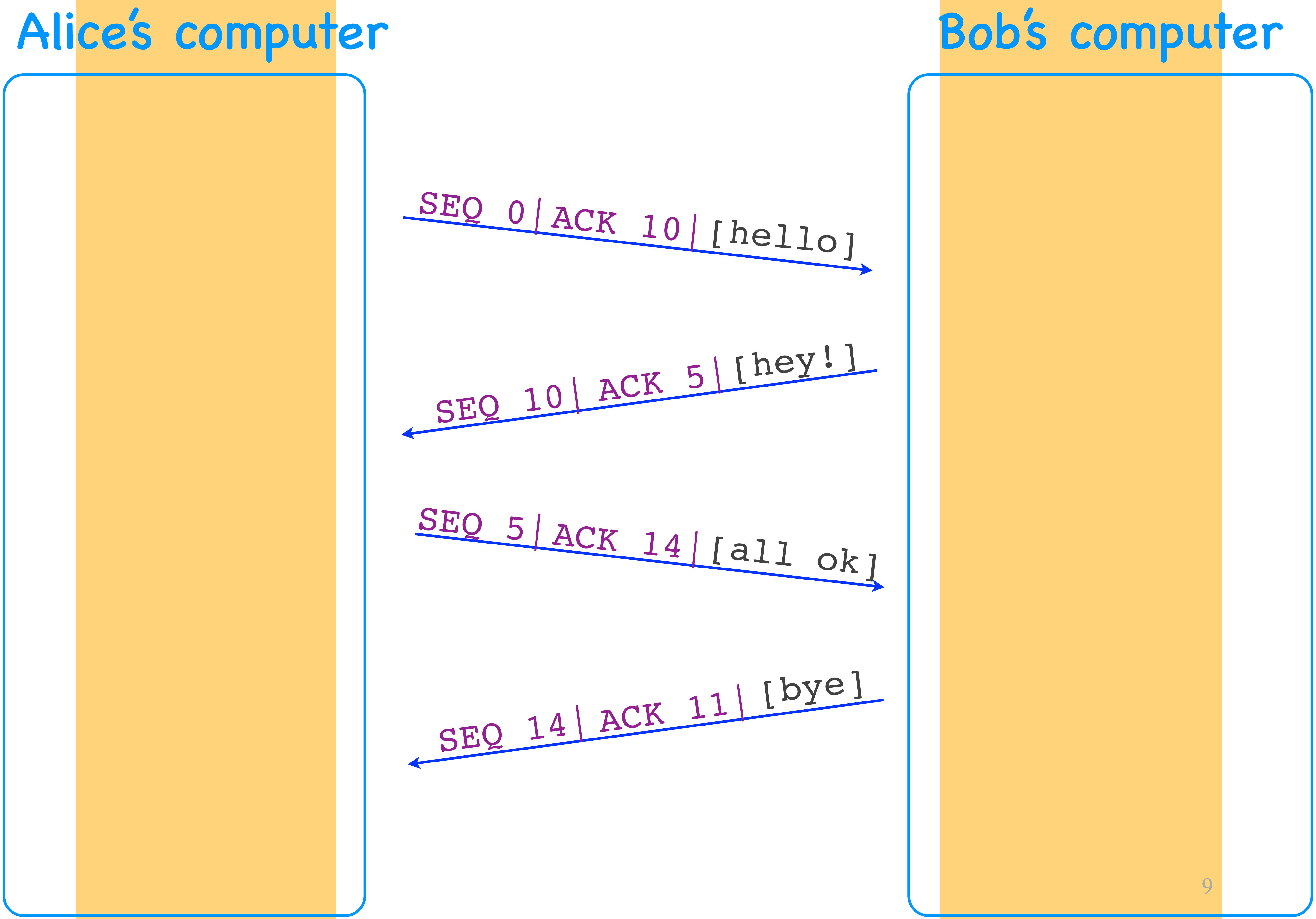
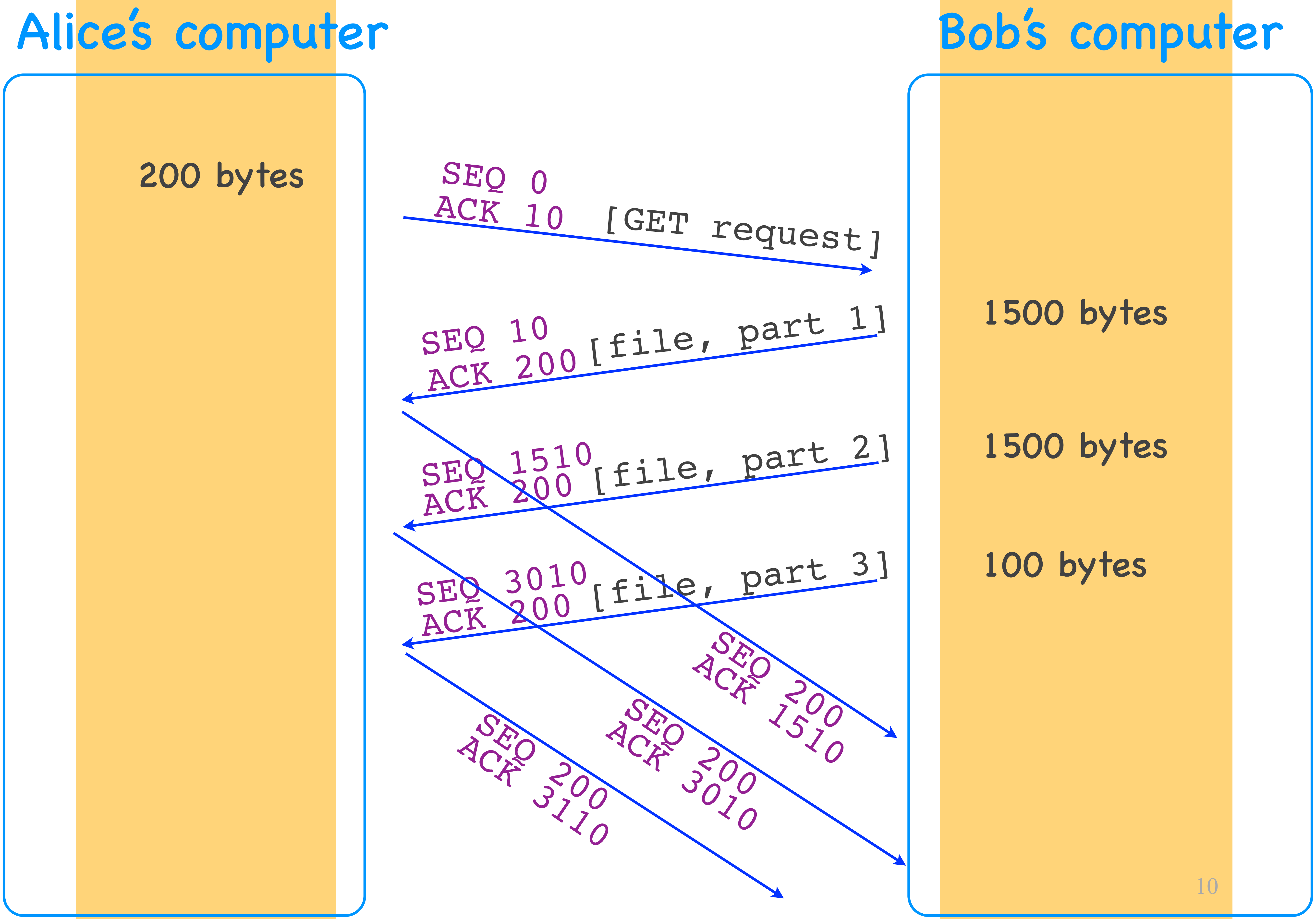

Alice's computer
Bob's computer
rdt_send([A])
udt_send(…)
SEQ 0|ACK 10|[A]
rdt_rcv(…)
deliver_data([A])
rdt_send([B])
udt_send(…)
SEQ 10|ACK 1|[B]
rdt_rcv(…)
deliver_data([B])

SEQs & ACKs

- Data bytes are implicitly numbered
- SEQ: # of the first data byte
- ACK: # of the next data byte that is expected (cumulative)
- Both always present, even if it appears unnecessary


Alice's computer
Bob's computer
SEQ 0 | ACK 10 | [hello]
SEQ 10 | ACK 5 | [hey!]
SEQ 5 | ACK 14 | [all ok]
SEQ 14 | ACK 11 | [bye]


Alice's computer
Bob's computer
200 bytes
SEQ 0
ACK 10 [GET request]
1500 bytes
SEQ 10
ACK 200 [file, part 1]
1500 bytes
SEQ 1510
ACK 200 [file, part 2]
100 bytes
SEQ 3010
ACK 200 [file, part 3]
SEQ 200
ACK 1510
SEQ 200
ACK 3010
SEQ 200
ACK 3110

Simple things to remember

- A TCP connection may carry bidirectional communication
- A segment may or may not carry data (but it always carries a SEQ)
- There exists a maximum segment size (MSS), dictated by network properties

TCP: reliability elements

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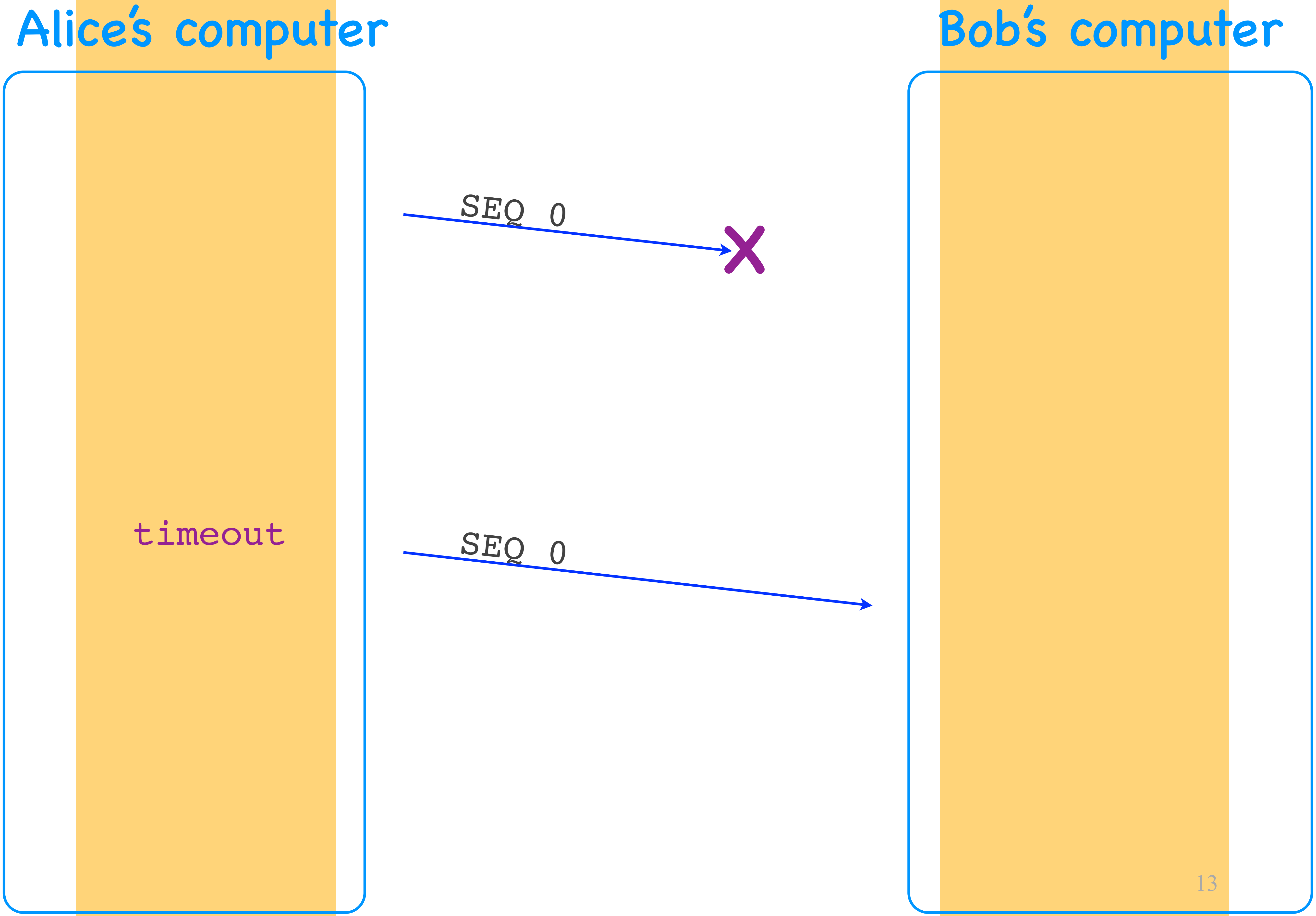
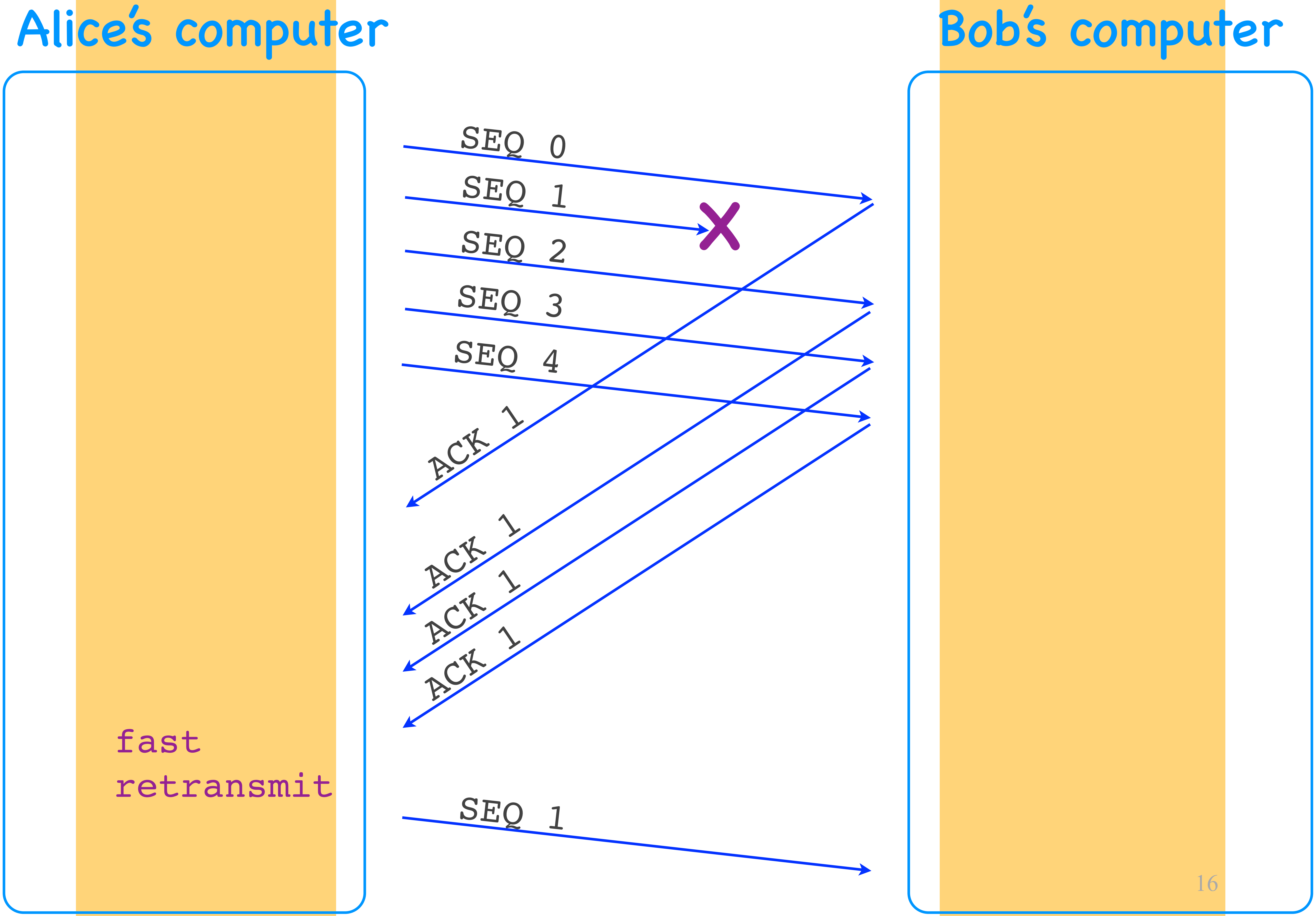

Alice's computer
Bob's computer
SEQ 0
timeout
SEQ 0

How long should the timeout be?

Timeout calculation

- EstimatedRTT =
  0.875 EstimatedRTT + 0.125 SampleRTT
- DevRTT = function(RTT variance)
- Timeout = EstimatedRTT + 4 DevRTT

Empirical, conservative prediction of RTT


Alice's computer
Bob's computer
SEQ 0
SEQ 1
SEQ 2
SEQ 3
SEQ 4
ACK 1
ACK 1
ACK 1
ACK 1
fast
retransmit
SEQ 1

Two retransmission triggers

- Timeout => retransmission of oldest unacknowledged segment

- 3 duplicate ACKs => fast retransmit of oldest unacknowledged segment
  - avoid unnecessary wait for timeout
  - 1 duplicate ACK not enough <= network may have reordered a data segment or duplicated an ACK

TCP: reliability elements

- Checksums to detect corruption
- ACKs to signal successful reception
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- Timeouts to detect loss
- Retransmissions to recover from corruption+loss

Is TCP Go-back-N or SR?

- Go-back-N: cumulative ACKs,
  retransmits multiple segments
- SR: selective ACKs,
  retransmit 1 segment on timeout
- TCP: cumulative ACKs,
  retransmits 1 segment => Go-back-N/SR mix

TCP elements

- Connection setup and teardown
- Connection hijacking
- Connection setup (SYN) flooding
- Flow control
- Congestion control

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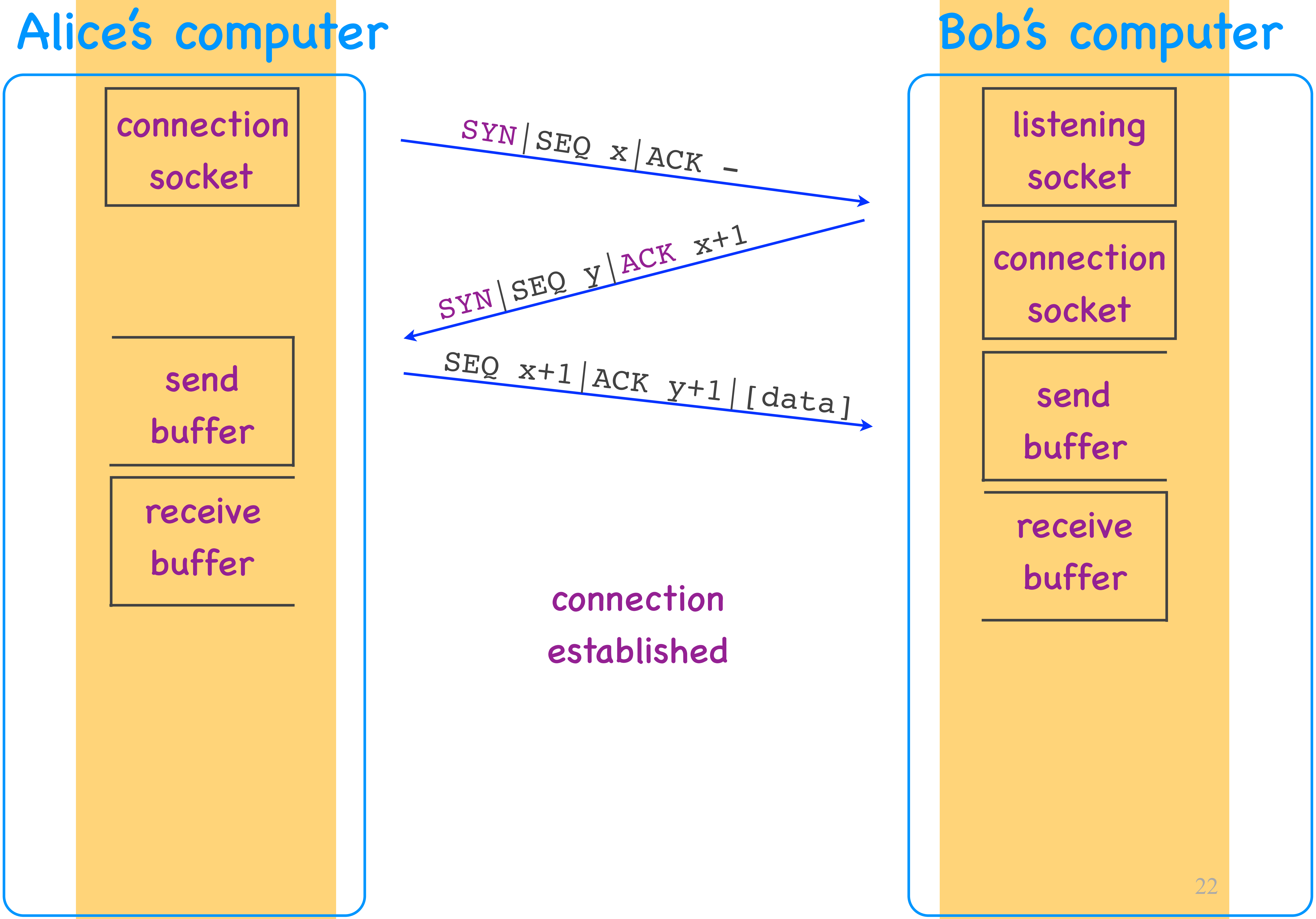
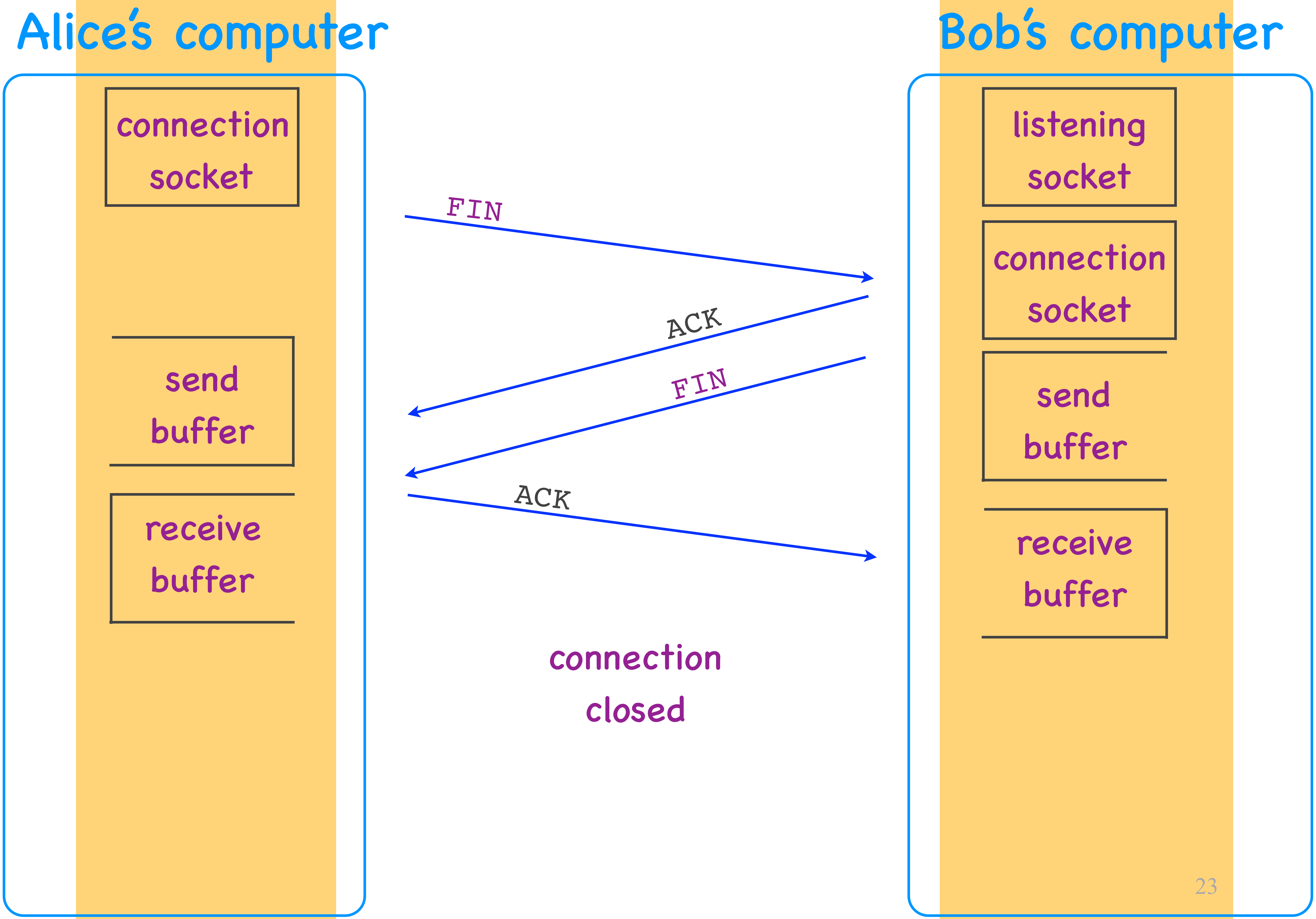


Alice's computer
connection socket
send buffer
receive buffer
Bob's computer
listening socket
connection socket
send buffer
receive buffer
SYN | SEQ x | ACK –
SYN | SEQ y | ACK x+1
SEQ x+1 | ACK y+1 | [data]
connection established


Alice's computer
connection socket
send buffer
receive buffer
FIN
ACK
FIN
ACK
connection closed
Bob's computer
listening socket
connection socket
send buffer
receive buffer

Connection setup

- 3-way handshake
  - "TCP client": end-system initiating the handshake
  - "TCP server": the other end-system
- First 2 segments carry a SYN flag
  - 1-bit field in the TCP header
- "TCP connection" = resources (sockets, buffers…) allocated for communication

TCP elements

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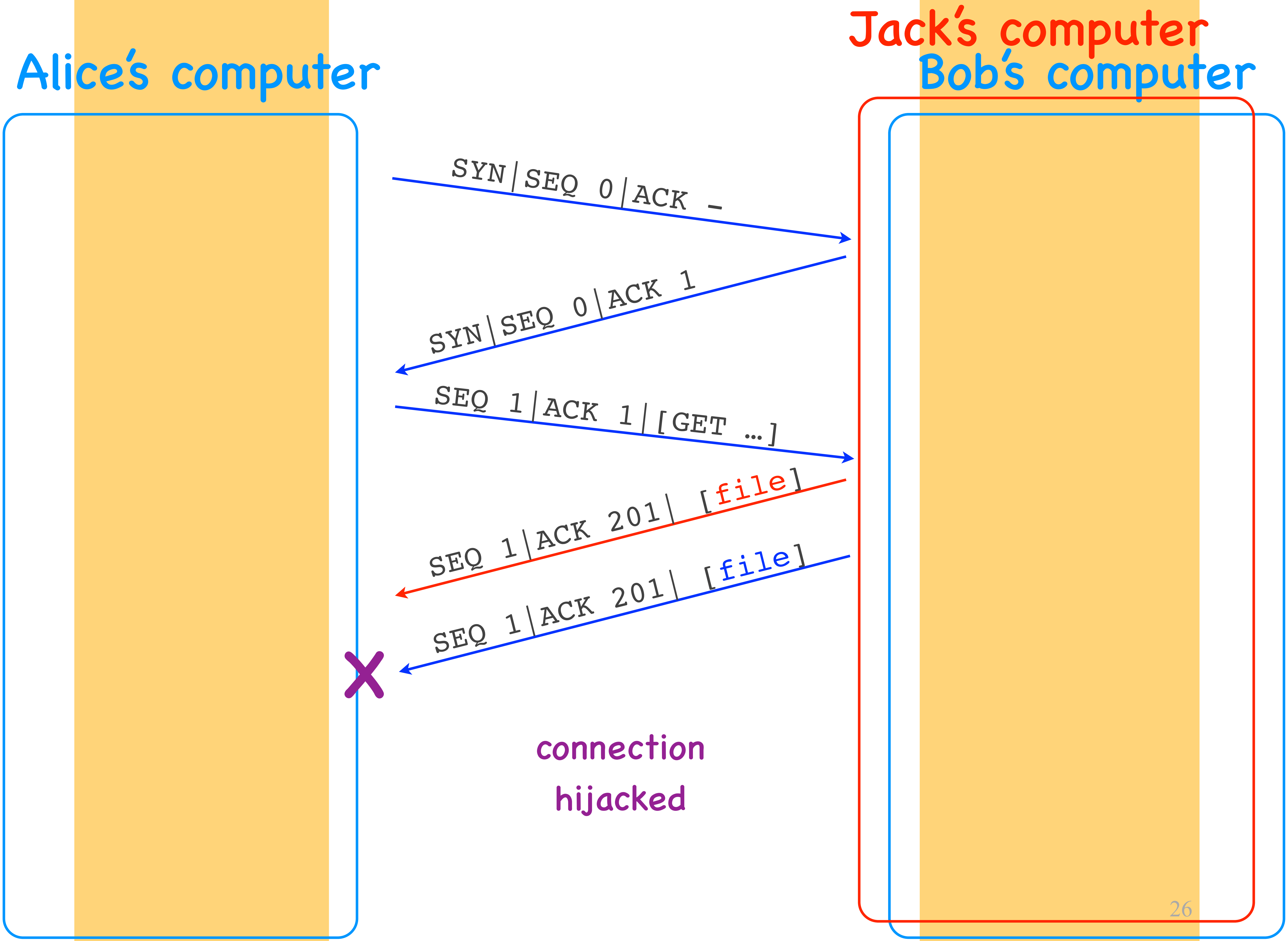
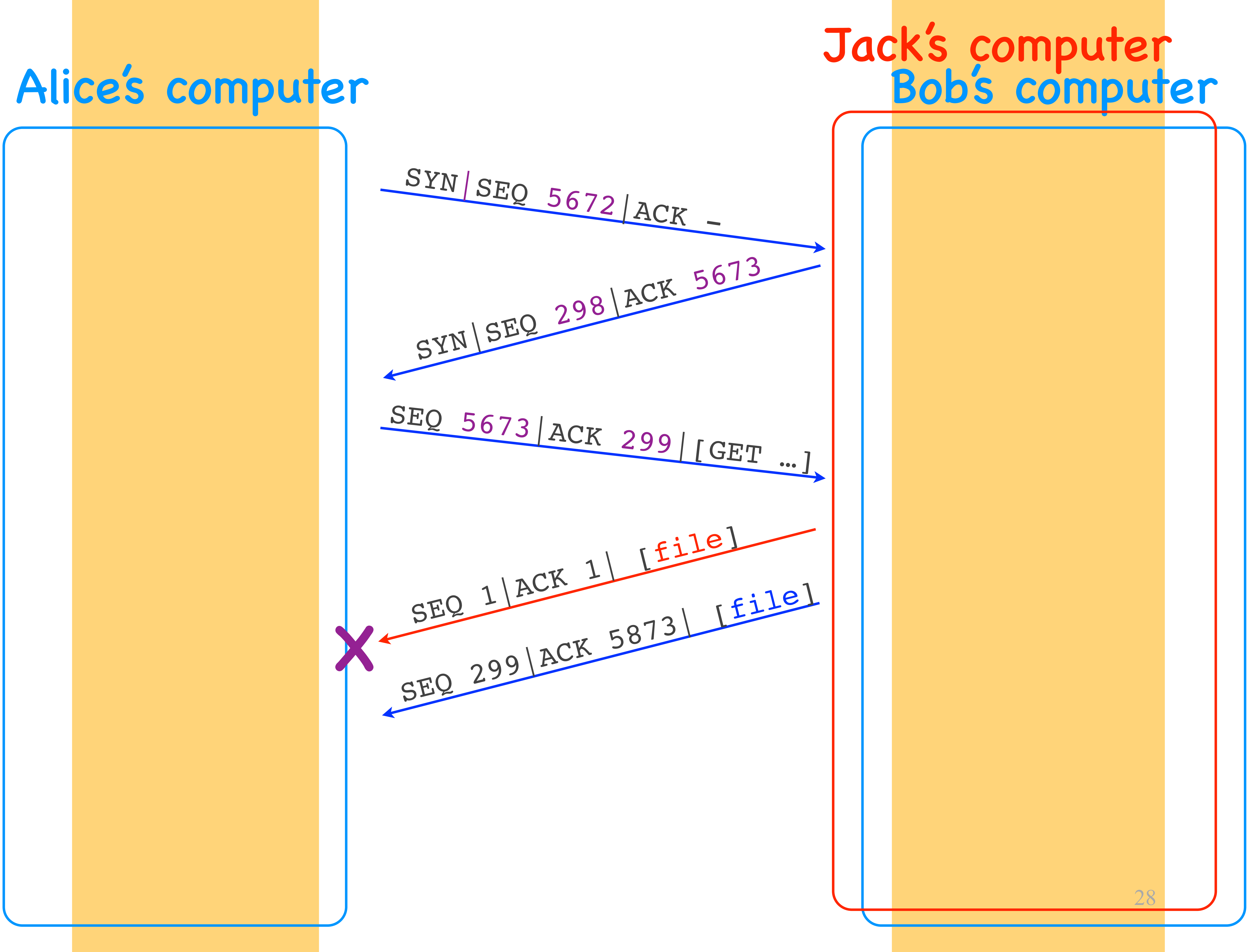


Jack's computer
Alice's computer
Bob's computer
SYN|SEQ 0|ACK –
SYN|SEQ 0|ACK 1
SEQ 1|ACK 1|[GET …]
SEQ 1|ACK 201| [file]
SEQ 1|ACK 201| [file]
connection
hijacked

How to prevent connection hijacking?

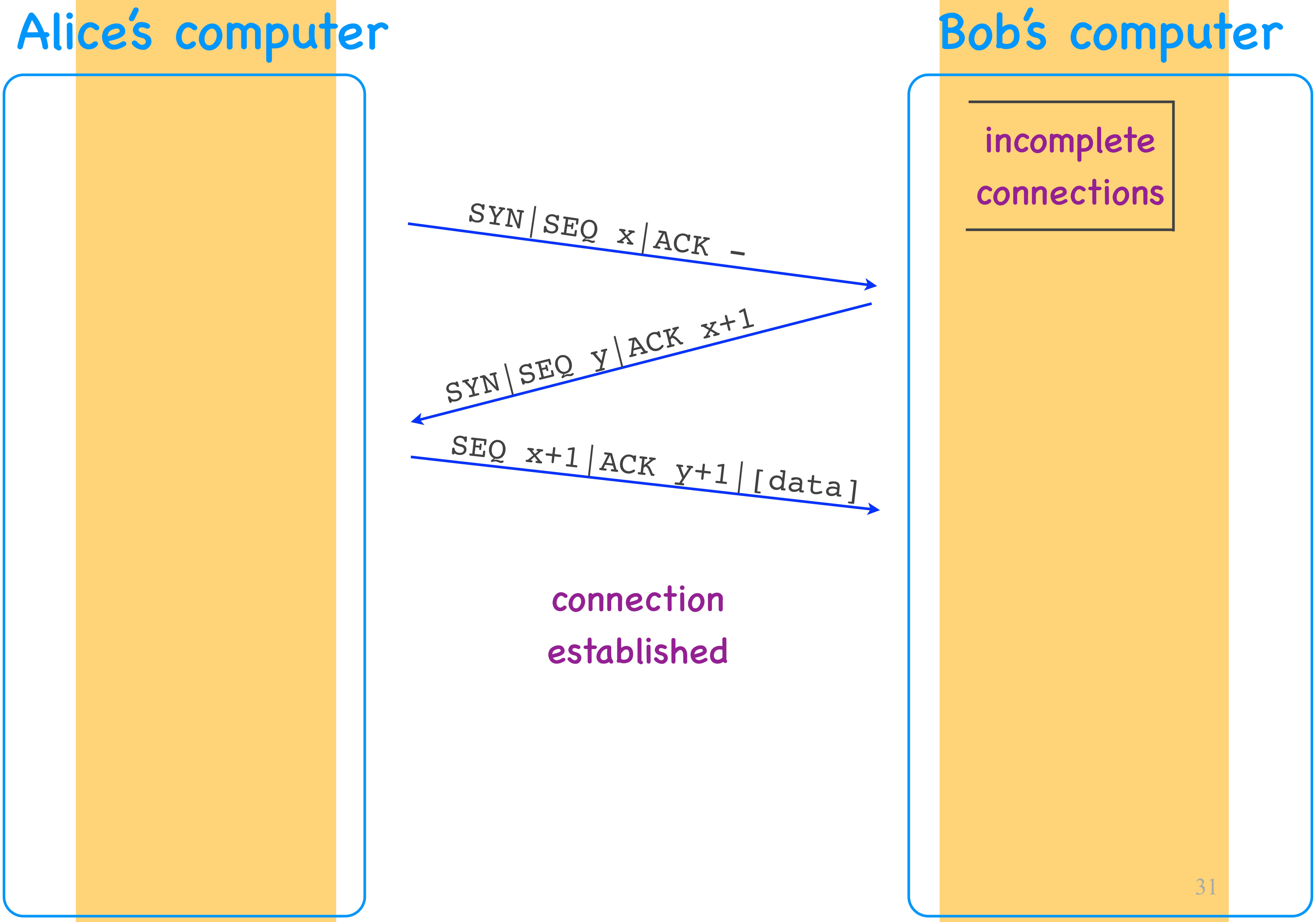

Jack's computer
Alice's computer
Bob's computer
SYN|SEQ 5672|ACK –
SYN|SEQ 298|ACK 5673
SEQ 5673|ACK 299|[GET …]
SEQ 1|ACK 1| [file]
SEQ 299|ACK 5873| [file]

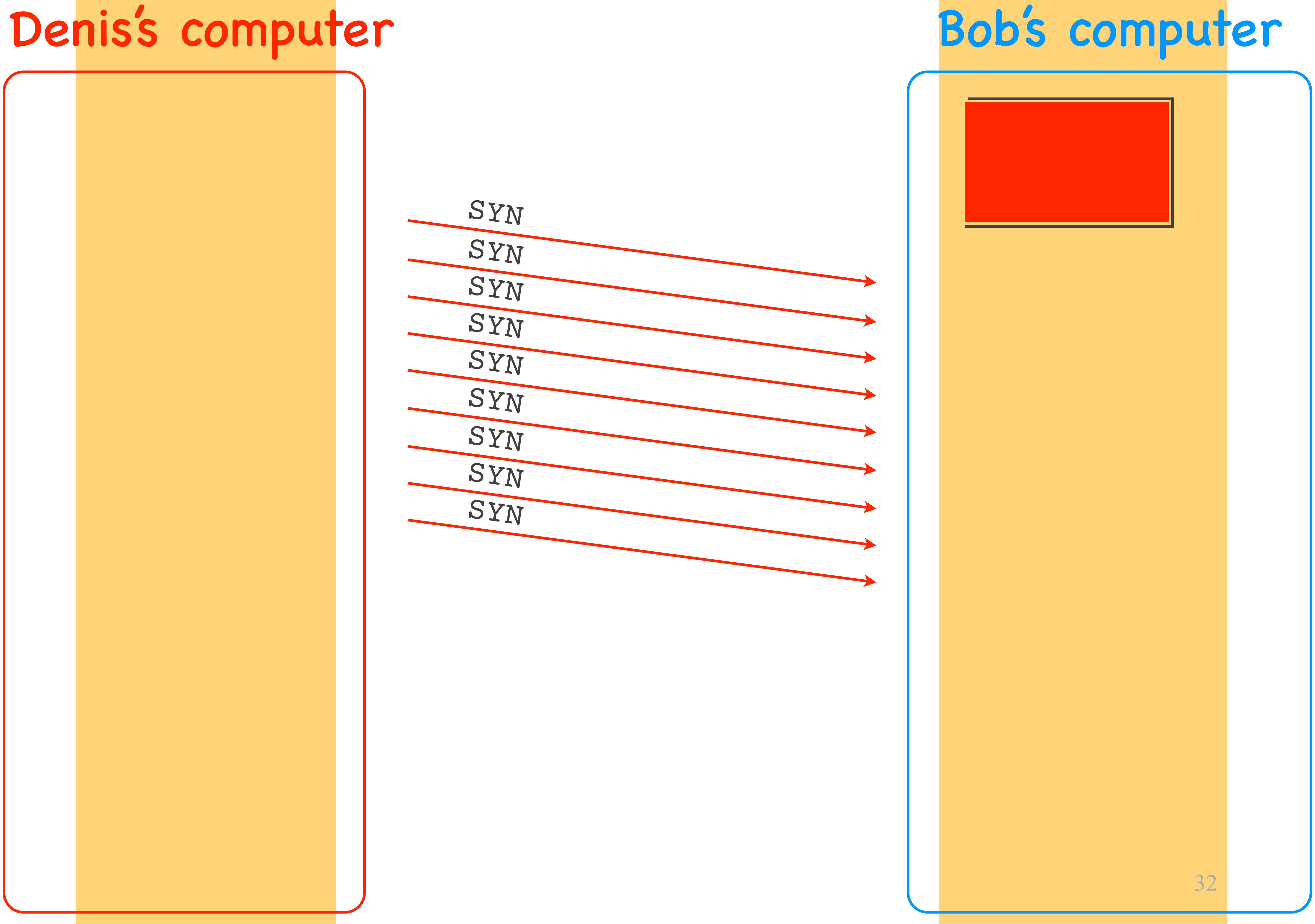
Connection hijacking

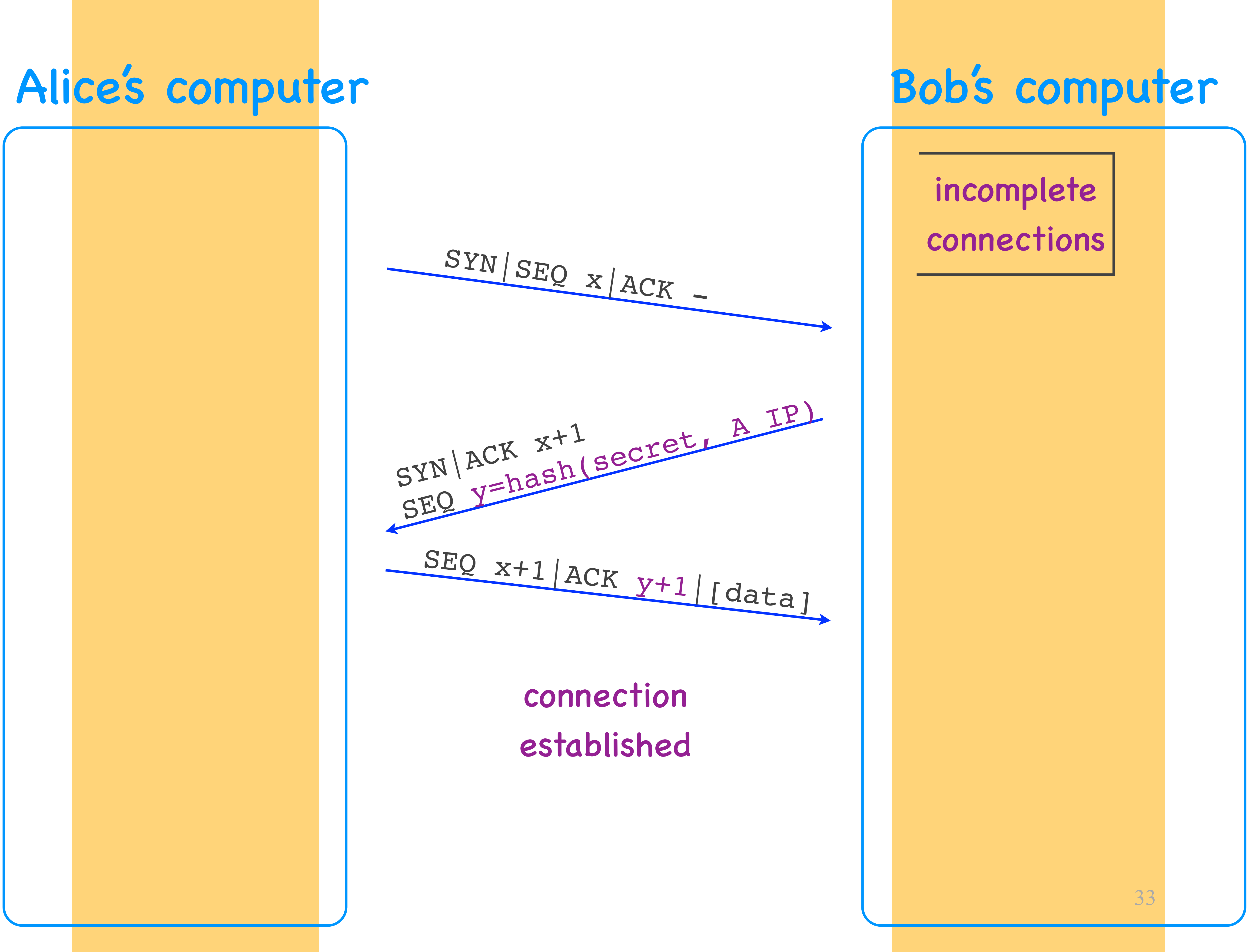
- Attacker impersonates TCP server (or client)
  - sends segment that appears to be coming from the impersonated end-system
- Approach: fake valid segment
  - if the TCP header predictable
- Solution: make TCP header (SEQs) unpredictable

TCP elements

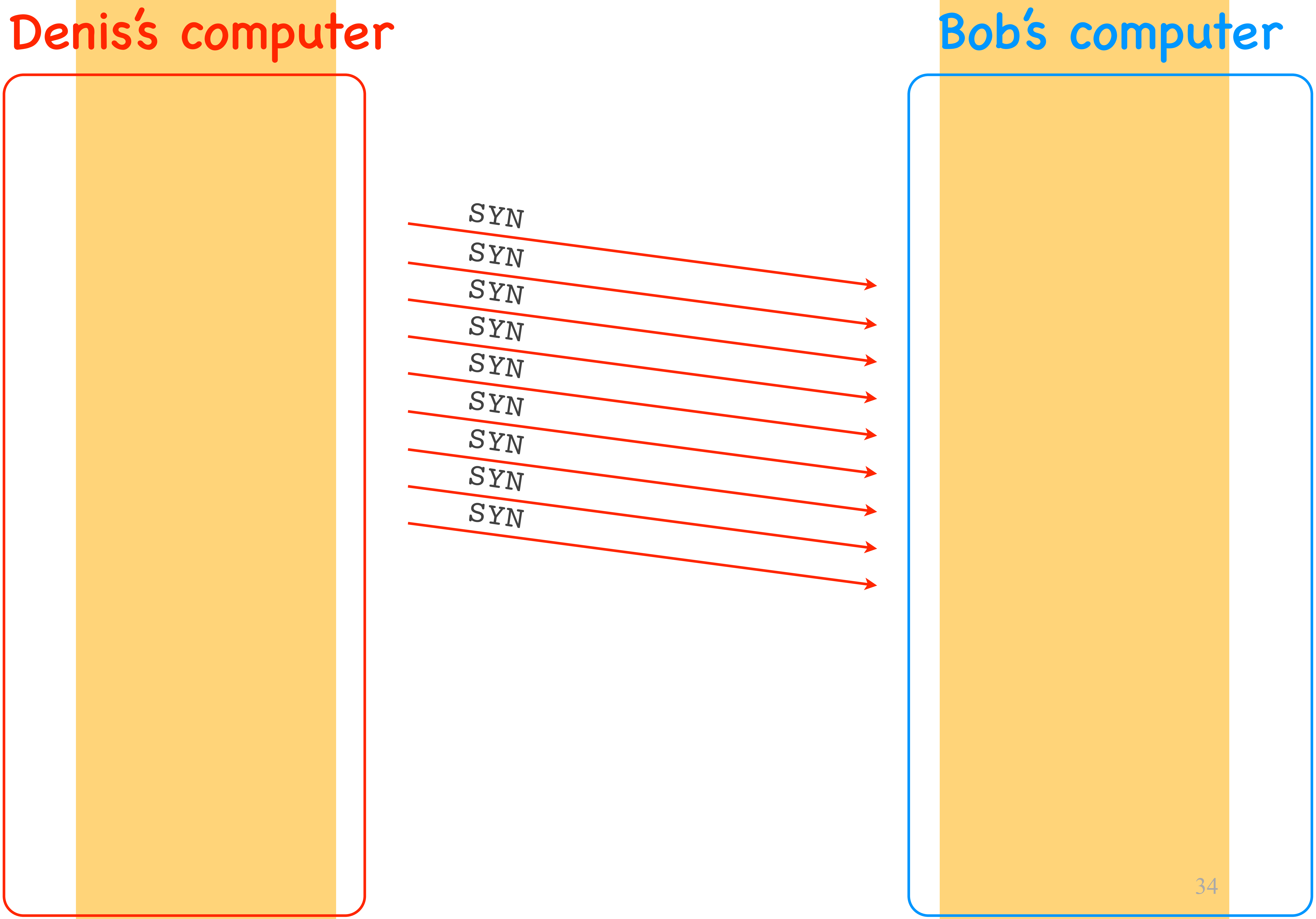
- Connection setup and teardown
- Connection hijacking
- Connection setup (SYN) flooding
- Flow control
- Congestion control


Alice's computer
Bob's computer
incomplete connections
SYN|SEQ x|ACK -
SYN|SEQ y|ACK x+1
SEQ x+1|ACK y+1|[data]
connection established


Denis's computer
Bob's computer
SYN
SYN
SYN
SYN
SYN
SYN
SYN
SYN
SYN



Alice's computer
Bob's computer
incomplete connections
SYN|SEQ x|ACK -
SYN|ACK x+1
SEQ y=hash(secret, A IP)
SEQ x+1|ACK y+1|[data]
connection established


Denis's computer
Bob's computer
SYN
SYN
SYN
SYN
SYN
SYN
SYN
SYN
SYN

SYN flooding

- Attacker exhausts buffer for incomplete connections
  - sends lots of connection setup requests
- Problem: one small resource affects all TCP communication
- Solution: remove the resource
  - pass the state to the TCP client

TCP elements

- Connection setup and teardown
- Connection hijacking
- Connection setup (SYN) flooding
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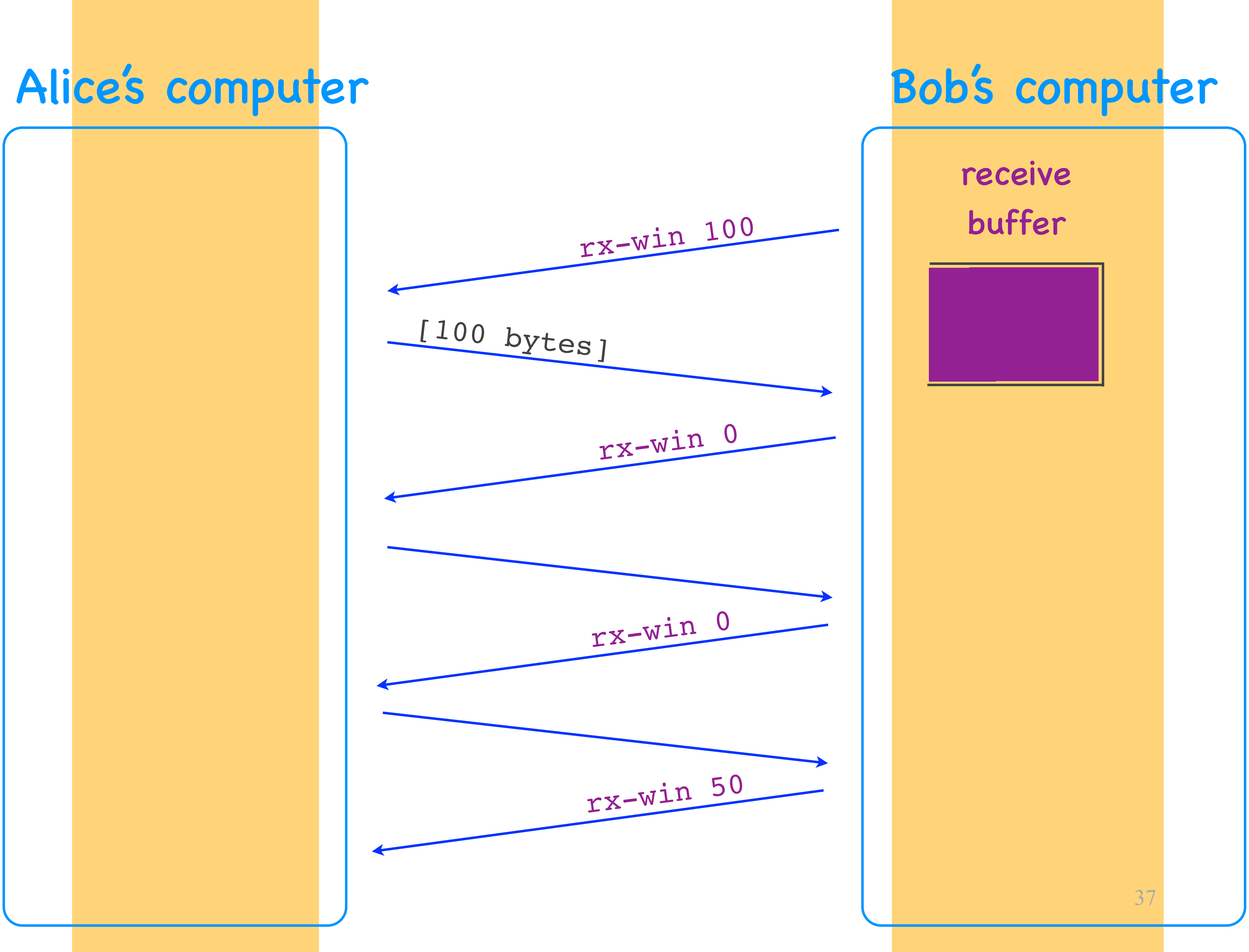
- Congestion control


Alice's computer
Bob's computer
receive
buffer
rx-win 100
[100 bytes]
rx-win 0
rx-win 0
rx-win 50

Flow control

- Goal: not overwhelm the receiver
  - not send at a rate that the receiver cannot handle

- How: "receiver window"
  - spare room in receiver's rx buffer
  - receiver communicates it to sender as TCP header field

TCP elements

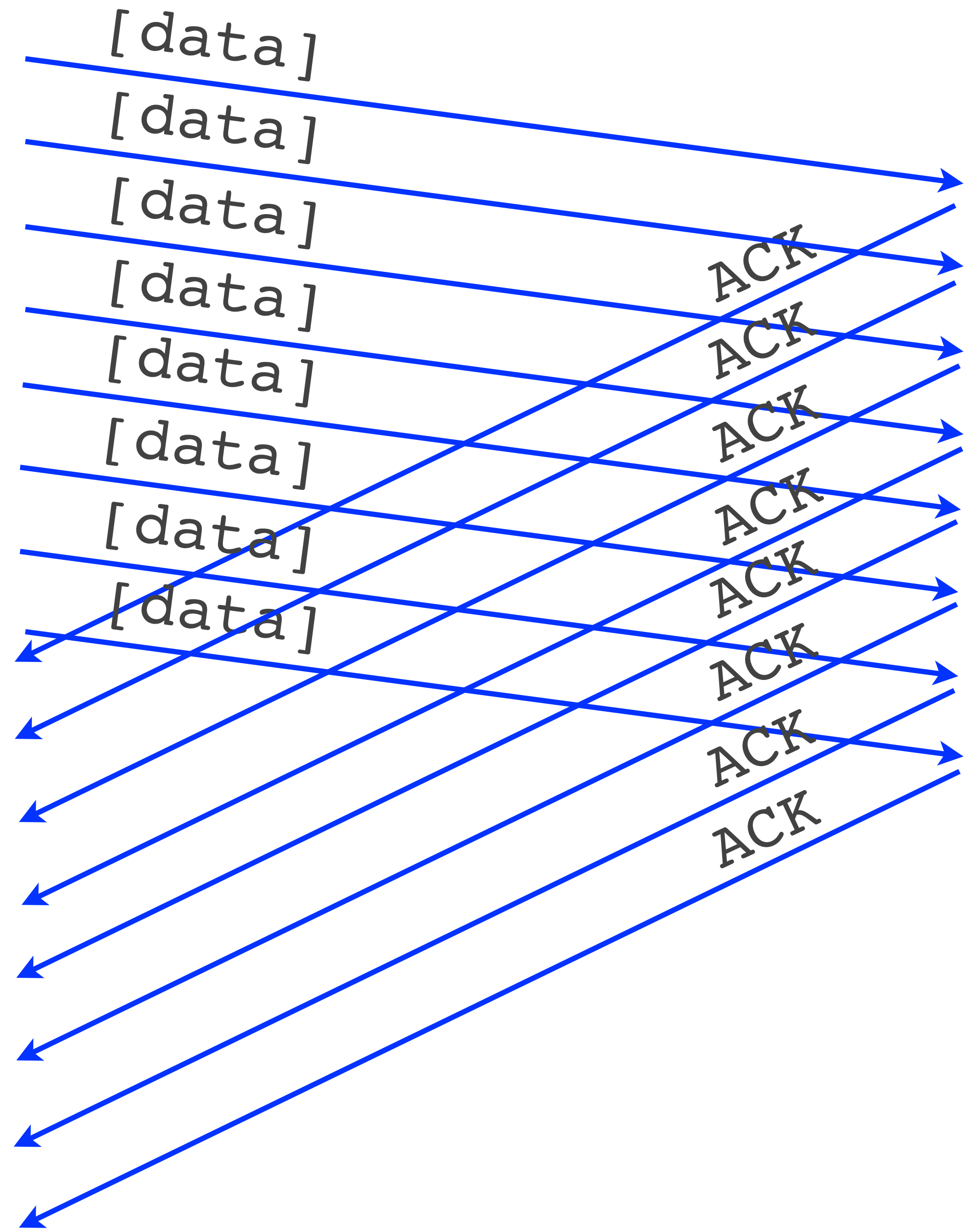
- Connection setup and teardown
- Connection hijacking
- Connection setup (SYN) flooding
- Flow control
- Congestion control

Congestion control

- Goal: not overwhelm the network
  - not send at a rate that the would create network congestion
- How: "congestion window"
  - number of unacknowledged bytes that the sender can transmit without creating congestion
  - sender estimates it on its own

Alice's computer

Bob's computer

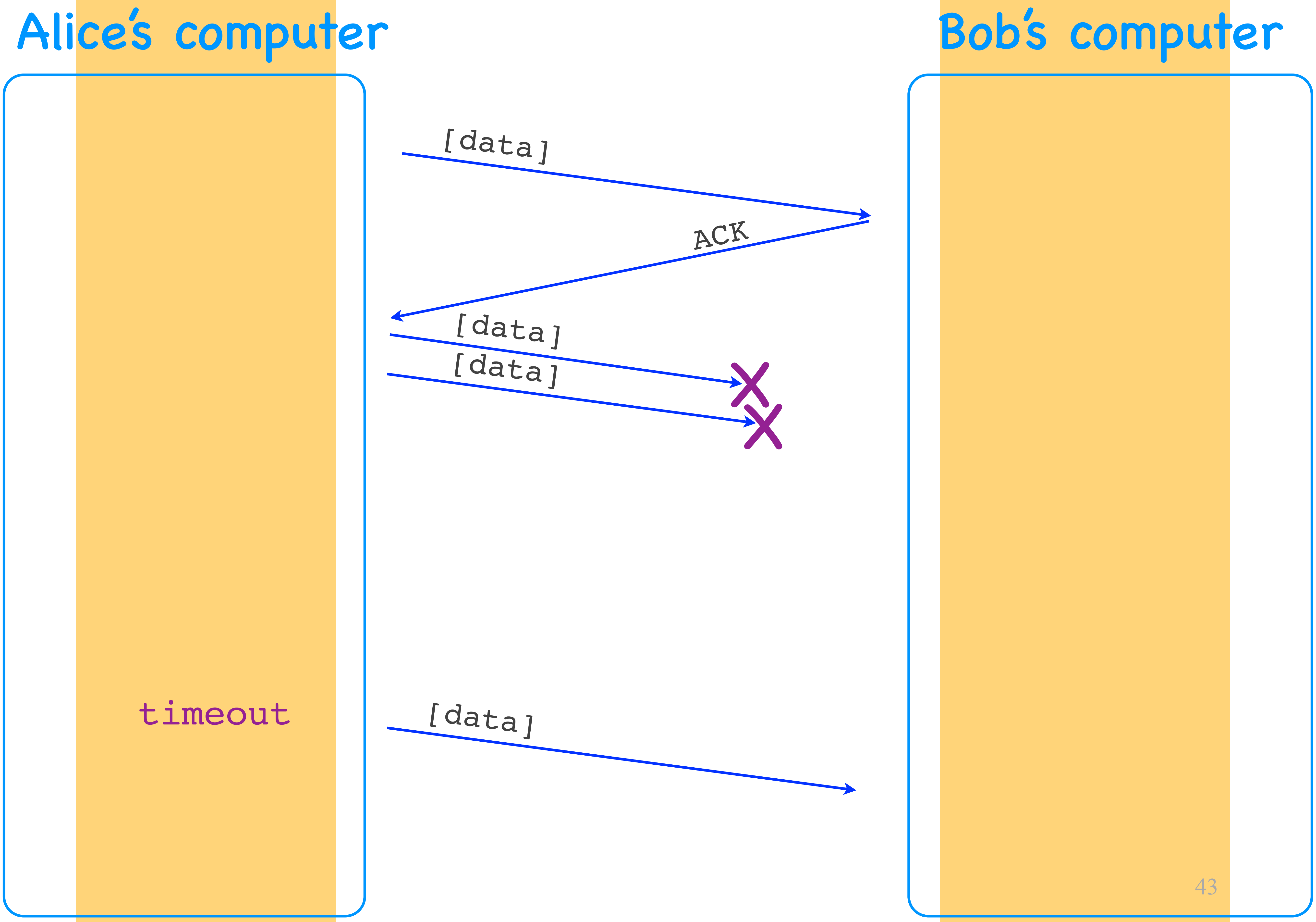


R bps x RTT sec

bandwidth delay product

Bandwidth-delay product

- Max amount of traffic that the sender can transmit until it gets the first ACK
- = the maximum congestion window size that makes sense


Alice's computer
Bob's computer
[data]
ACK
[data]
[data]
timeout
[data]

Self-clocking

- Sender guesses the “right” congestion window based on the ACKs
- ACK = no congestion, increase window
- No ACK = congestion, decrease window

Alice's computer

Bob's computer

N=100 bytes

~~0 - 99~~

N=200 bytes

~~100 - 199~~

~~200 - 299~~

N=300 bytes

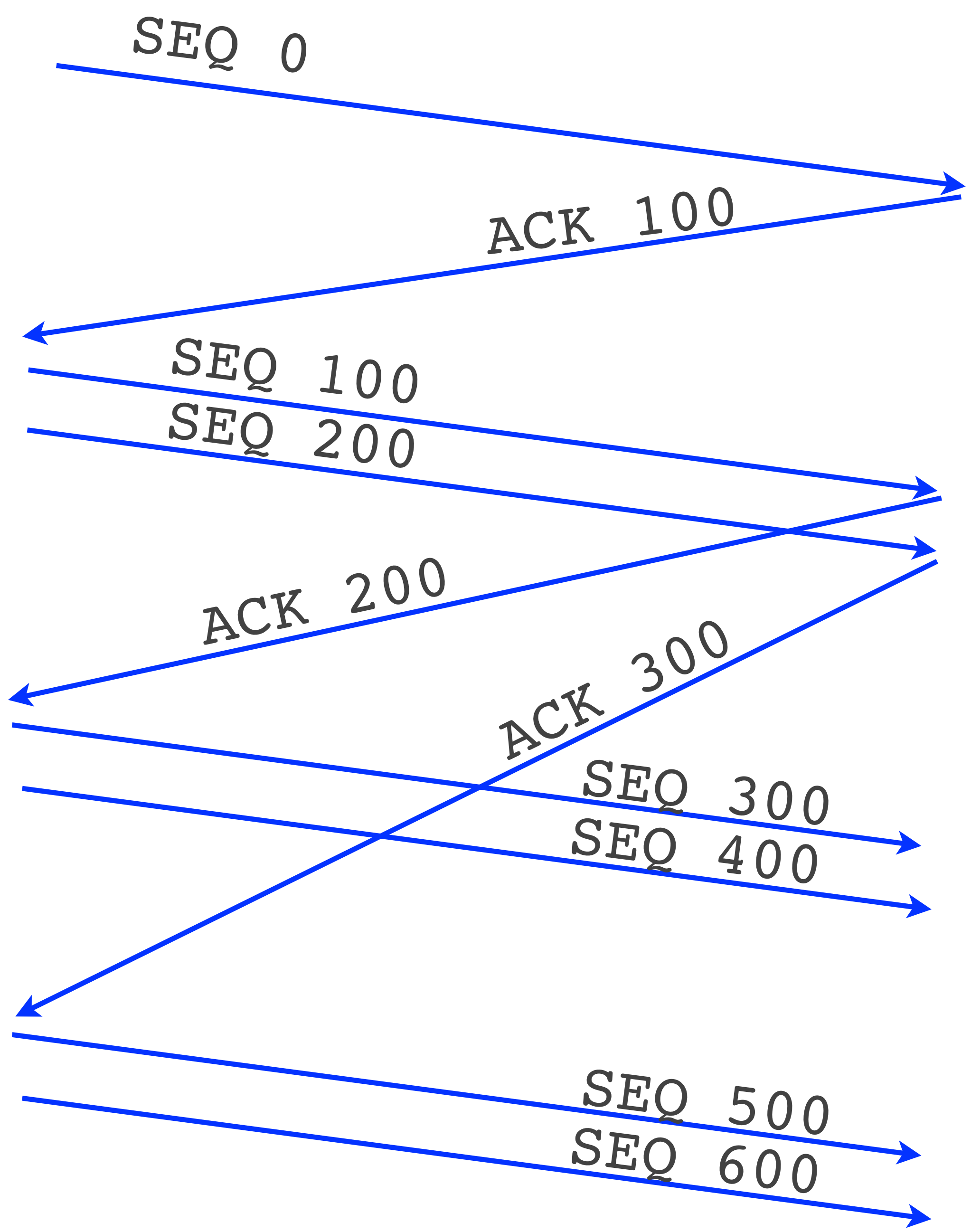
300 - 399

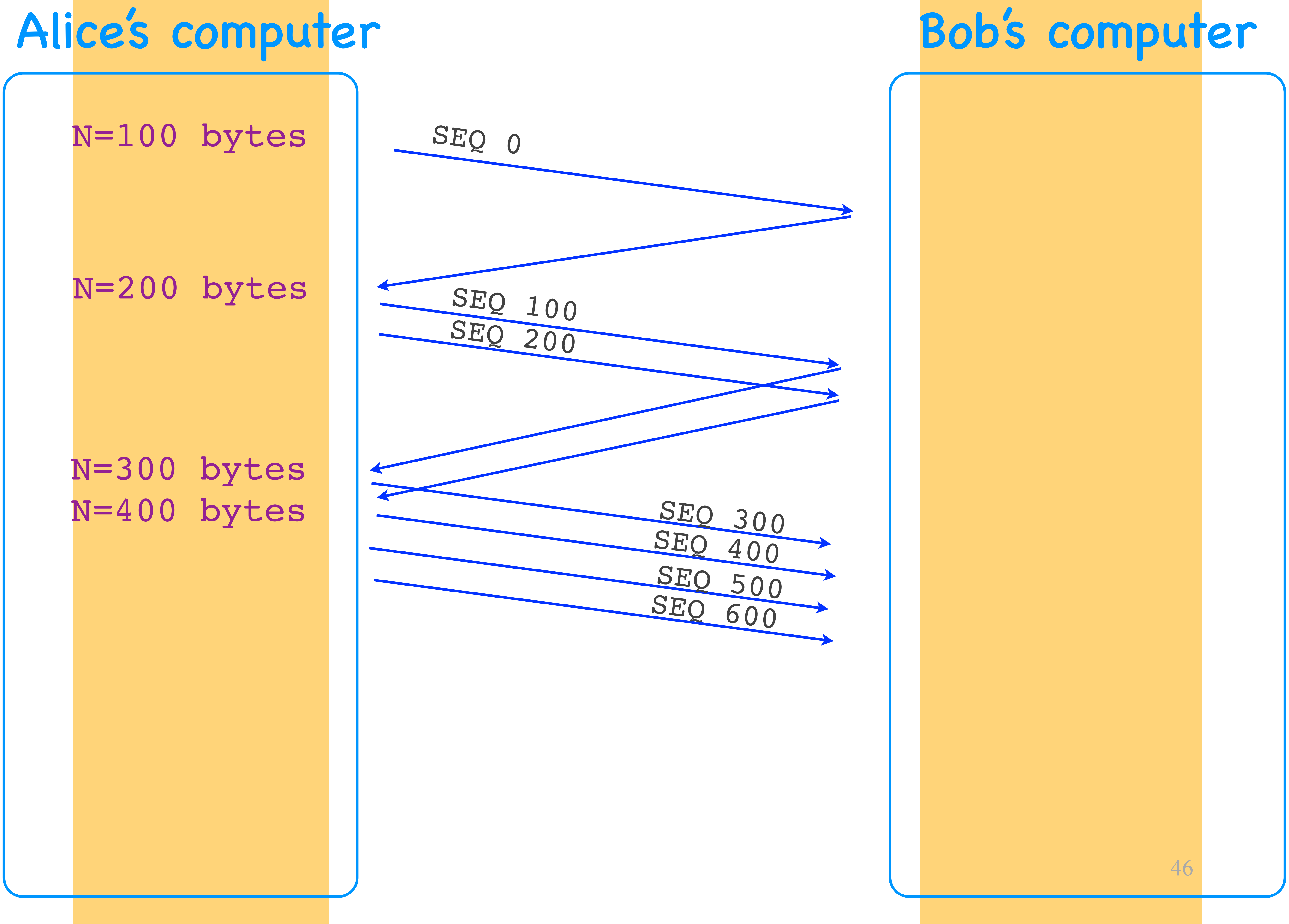
400 - 499

N=400 bytes

500 - 599

600 - 699




Alice's computer
Bob's computer
N=100 bytes
SEQ 0
N=200 bytes
SEQ 100
SEQ 200
N=300 bytes
N=400 bytes
SEQ 300
SEQ 400
SEQ 500
SEQ 600

Increase window size

- Exponentially
  - by 1 MSS for every ACKed segment
  - = window doubles every RTT
  - when we do not expect congestion

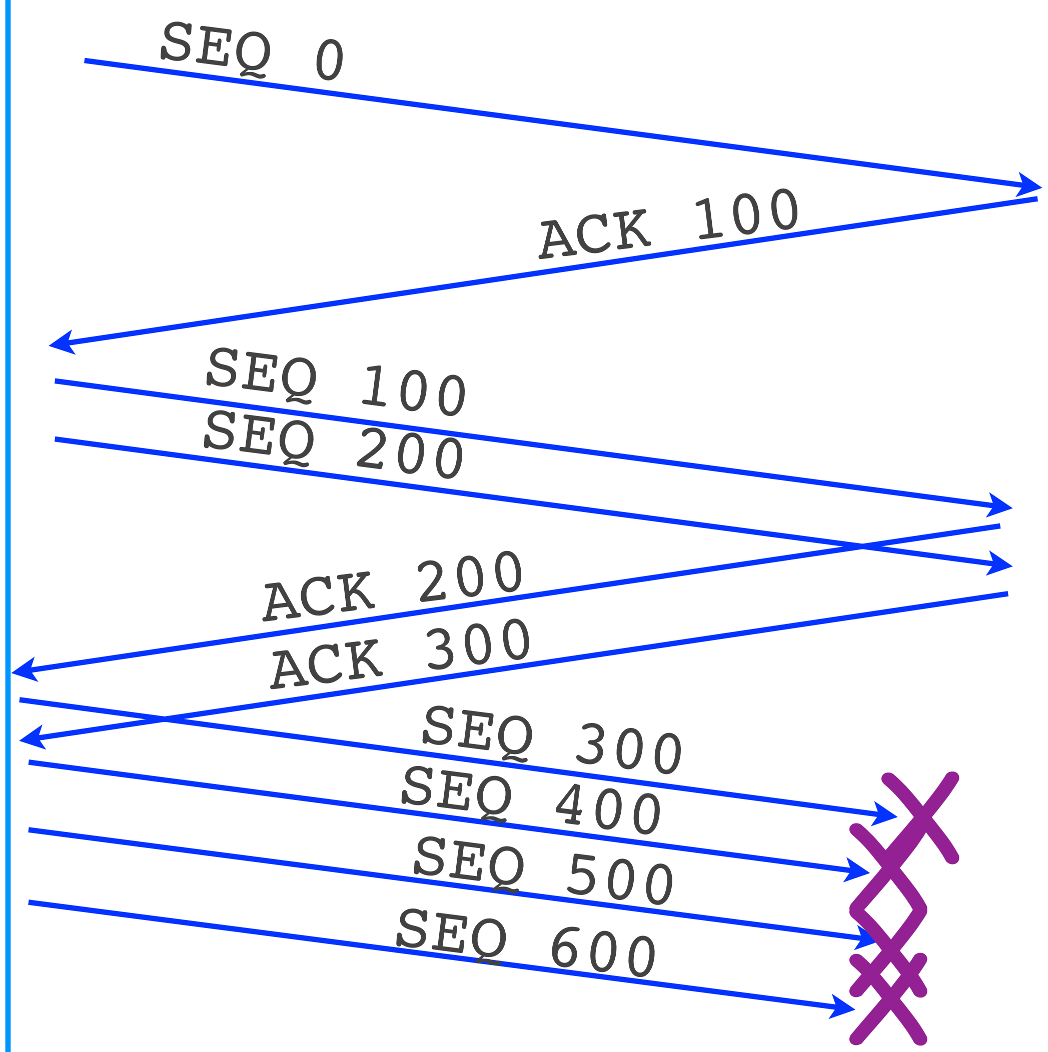
Alice's computer

Bob's computer

N=100 bytes

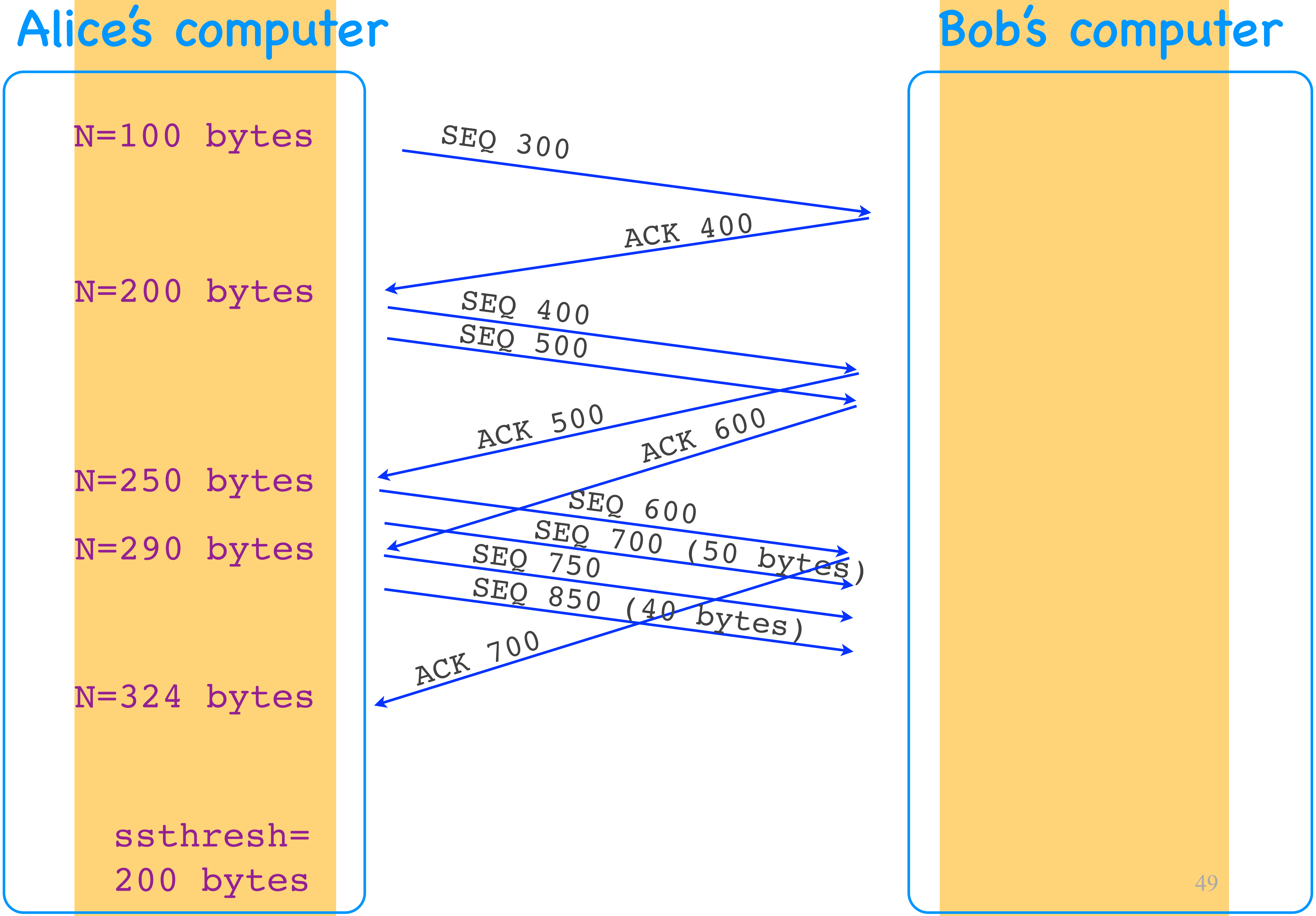
N=200 bytes

N=300 bytes
N=400 bytes



timeout

ssthresh=
200 bytes


Alice's computer
Bob's computer
N=100 bytes
SEQ 300
ACK 400
N=200 bytes
SEQ 400
SEQ 500
ACK 500
ACK 600
N=250 bytes
SEQ 600
N=290 bytes
SEQ 700 (50 bytes)
SEQ 750
SEQ 850 (40 bytes)
ACK 700
N=324 bytes
ssthresh=
200 bytes

Increase window size

- Exponentially
  - by 1 MSS for every ACKed segment
  - = window doubles every RTT
  - when we do not expect congestion
- Linearly
  - by MSS*MSS/N for every ACKed segment
  - = by 1 MSS every RTT
  - when we expect congestion

Goal: increase N by MSS bytes per RTT

Alice sends N unack-ed bytes per RTT

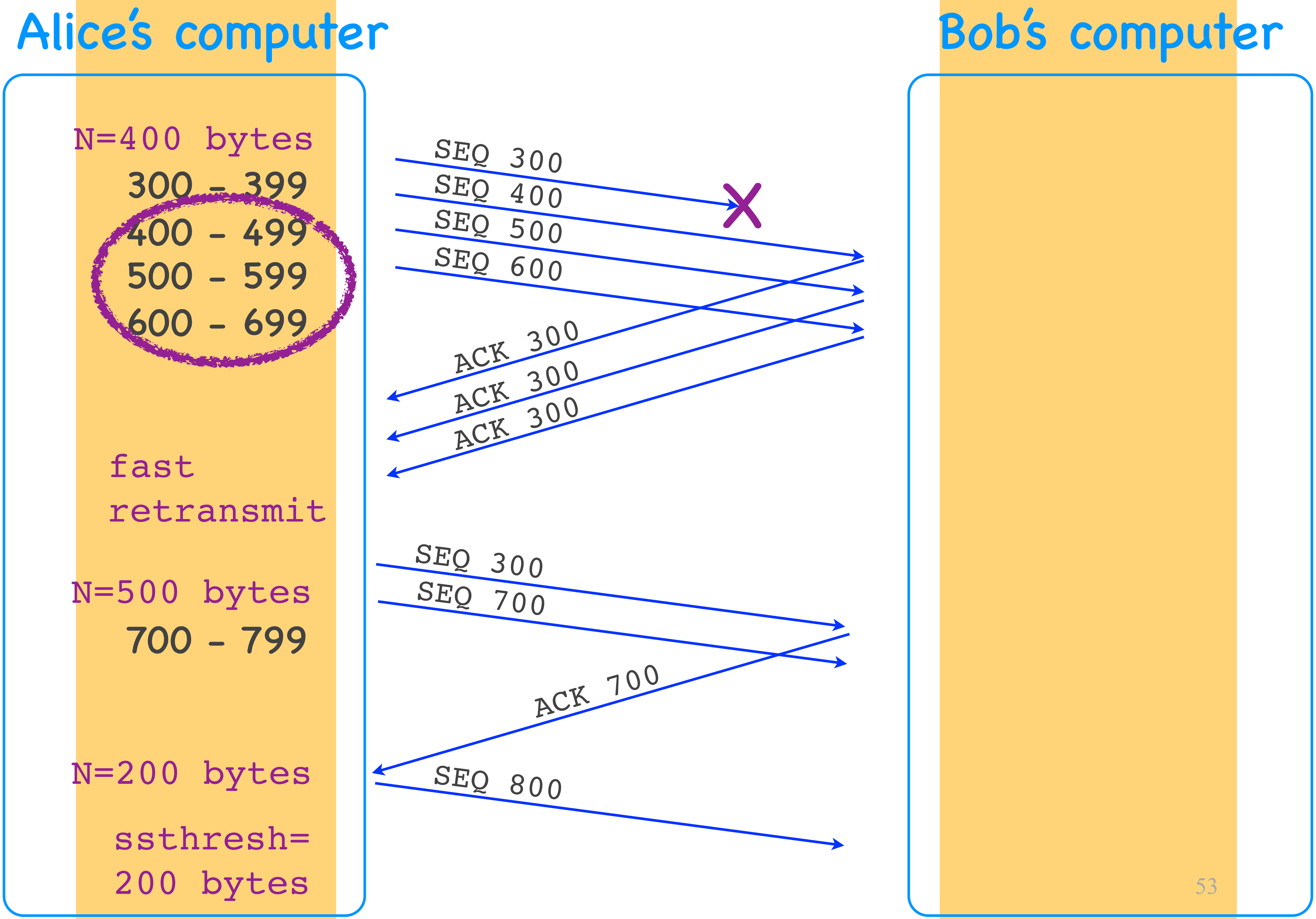
$$= \frac{N}{MSS} \text{ data segments per RTT}$$

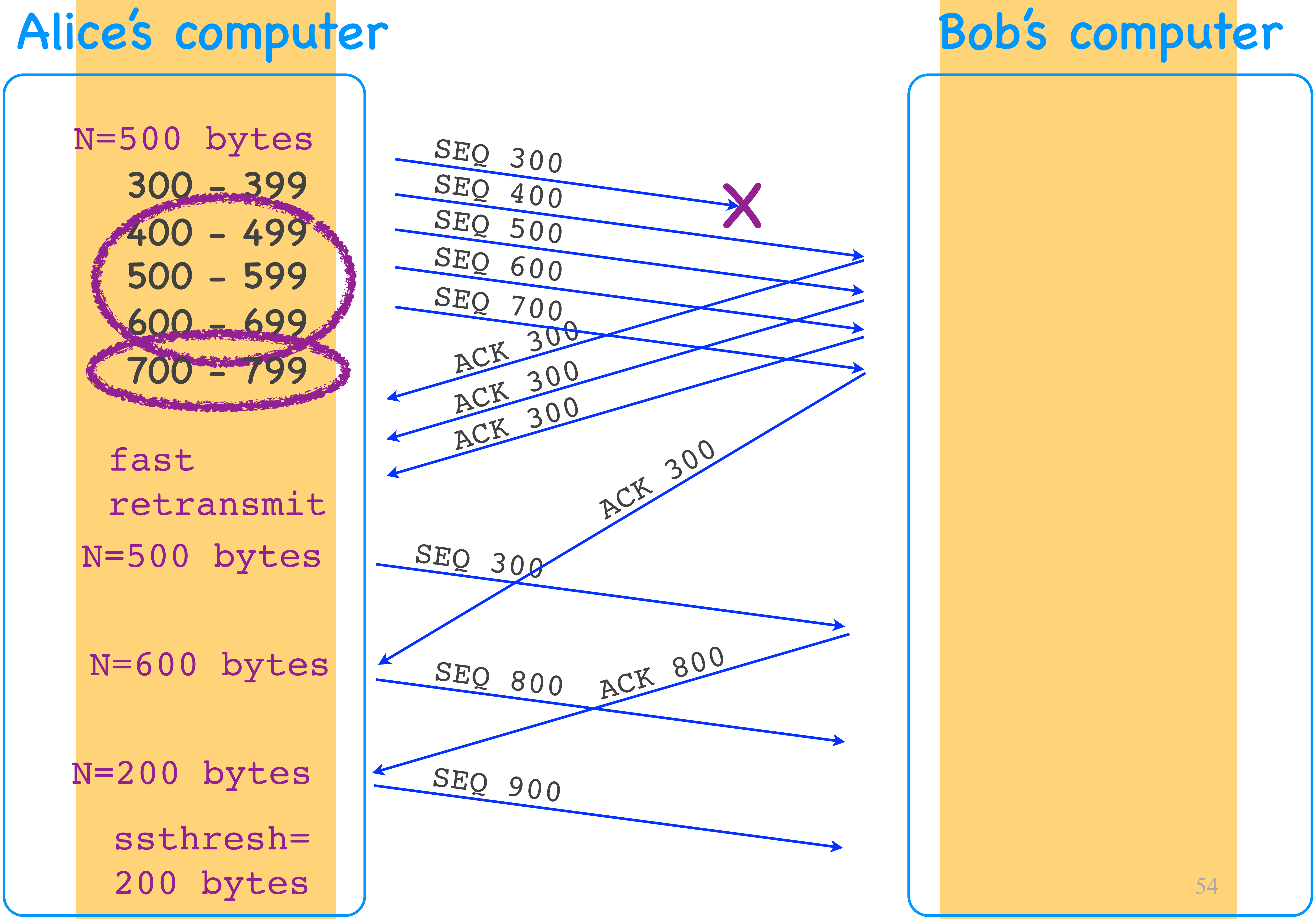
She expects $\frac{N}{MSS}$ ACKs per RTT

$$\frac{N}{MSS} * \frac{MSS*MSS}{N} \text{ bytes } = \text{ MSS bytes}$$

Basic algorithm (Tahoe)

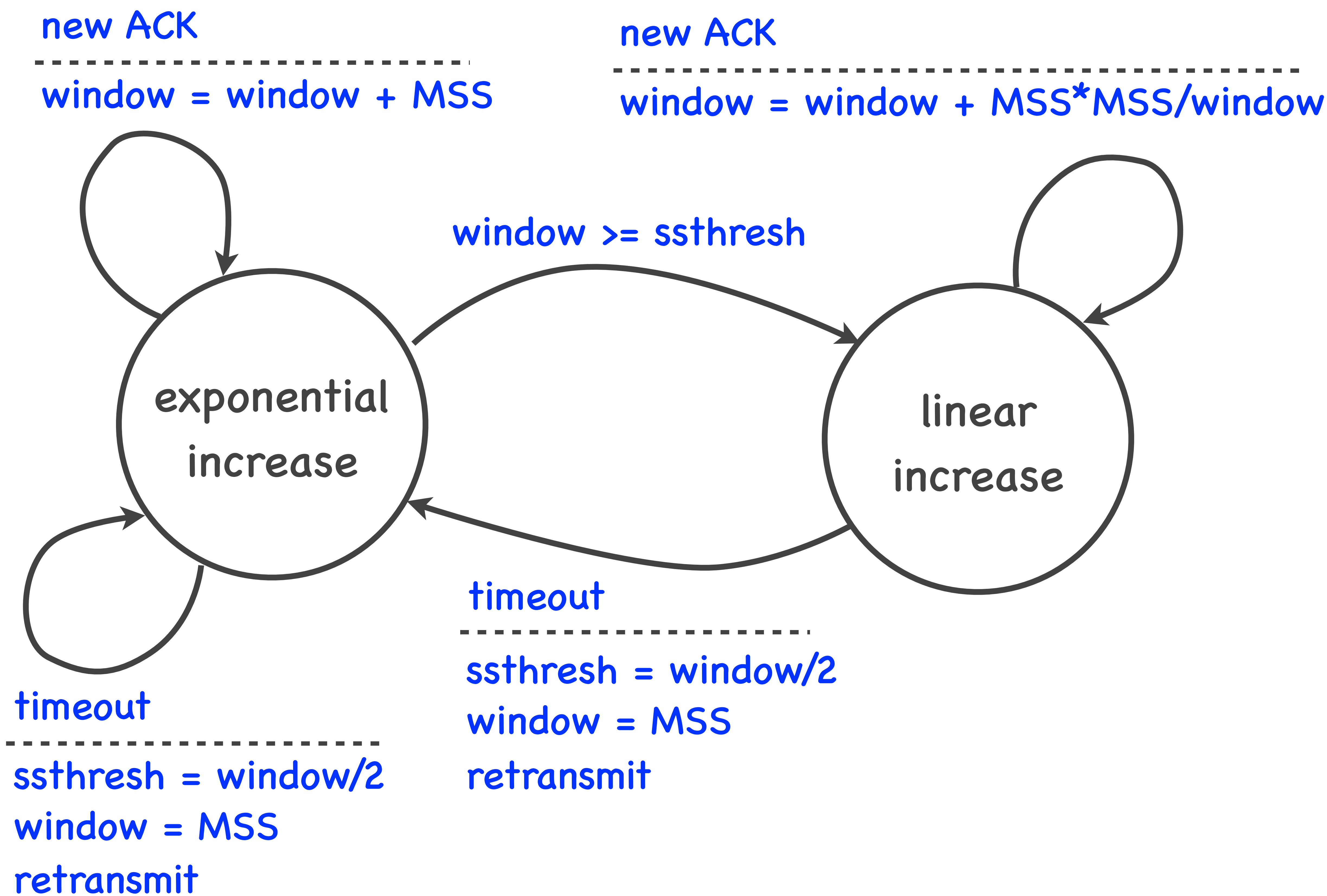
- Set window to 1 MSS,
  increase exponentially
- On timeout, reset window to 1 MSS,
  set ssthresh to last window/2
- On reaching ssthresh,
  transition to linear increase

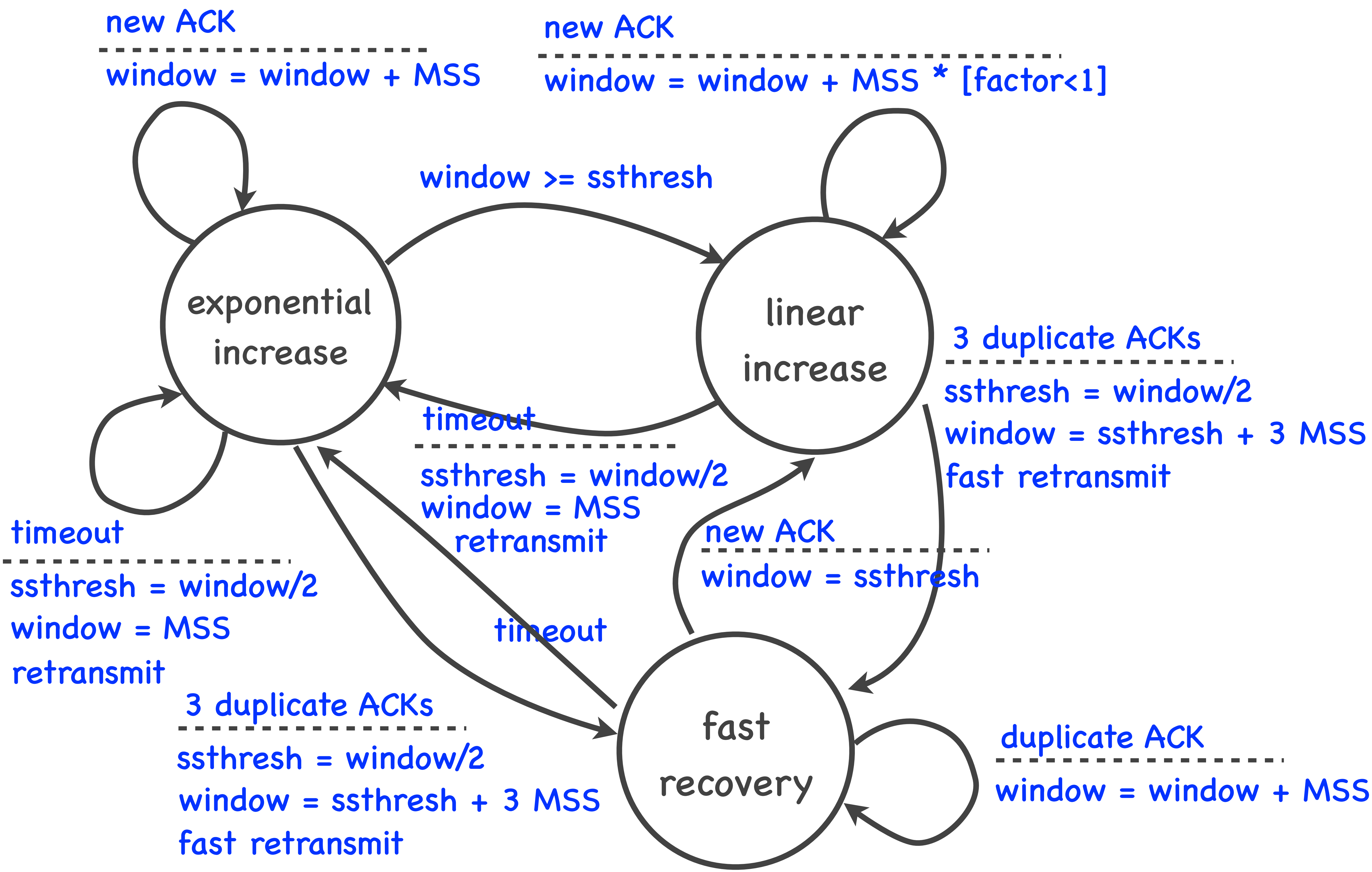

Alice's computer
Bob's computer
N=400 bytes
300 - 399
400 - 499
500 - 599
600 - 699
SEQ 300
SEQ 400
SEQ 500
SEQ 600
ACK 300
ACK 300
ACK 300
fast
retransmit
SEQ 300
SEQ 700
N=500 bytes
700 - 799
ACK 700
N=200 bytes
SEQ 800
ssthresh=
200 bytes


Alice's computer
Bob's computer
N=500 bytes
300 - 399
400 - 499
500 - 599
600 - 699
700 - 799
fast
retransmit
N=500 bytes
N=600 bytes
N=200 bytes
ssthresh=
200 bytes
SEQ 300
SEQ 400
SEQ 500
SEQ 600
SEQ 700
ACK 300
ACK 300
ACK 300
ACK 300
SEQ 300
SEQ 800
ACK 800
SEQ 900

Basic algorithm (Reno)

- Set window to 1 MSS, increase exponentially
- On timeout, reset window to 1 MSS,
  set ssthresh to last window/2, retransmit
- On receiving 3 duplicate ACKs,
  set window to ssthresh (+inflation), retransmit
- On reaching ssthresh transition
  to linear increase


new ACK
window = window + MSS
new ACK
window = window + MSS*MSS/window
window >= ssthresh
exponential increase
linear increase
timeout
ssthresh = window/2
window = MSS
retransmit
timeout
ssthresh = window/2
window = MSS
retransmit



new ACK
window = window + MSS
new ACK
window = window + MSS * [factor<1]
window >= ssthresh
exponential increase
linear increase
3 duplicate ACKs
ssthresh = window/2
window = ssthresh + 3 MSS
fast retransmit
timeout
ssthresh = window/2
window = MSS
retransmit
timeout
ssthresh = window/2
window = MSS
retransmit
new ACK
window = ssthresh
timeout
3 duplicate ACKs
ssthresh = window/2
window = ssthresh + 3 MSS
fast retransmit
fast recovery
duplicate ACK
window = window + MSS

TCP terminology

- Exponential increase = slow start
  - it's called slow, because it starts from a small window; but it's not really slow, the window increases exponentially
- Linear increase = congestion avoidance
  - this term does make sense; it means that TCP expects congestion, so it increases the window more cautiously

Flow + congestion control

- Goal: not overwhelm receiver or network
- How: sender window
  - sender learns receiver window from receiver
  - sender computes congestion window on its own
  - Sender window = min{ receiver w, congestion w }