Introduction to Computer Networks

CS640

TCP Reliability Support (II)

https://pages.cs.wisc.edu/~mgliu/CS640/S25/index.html

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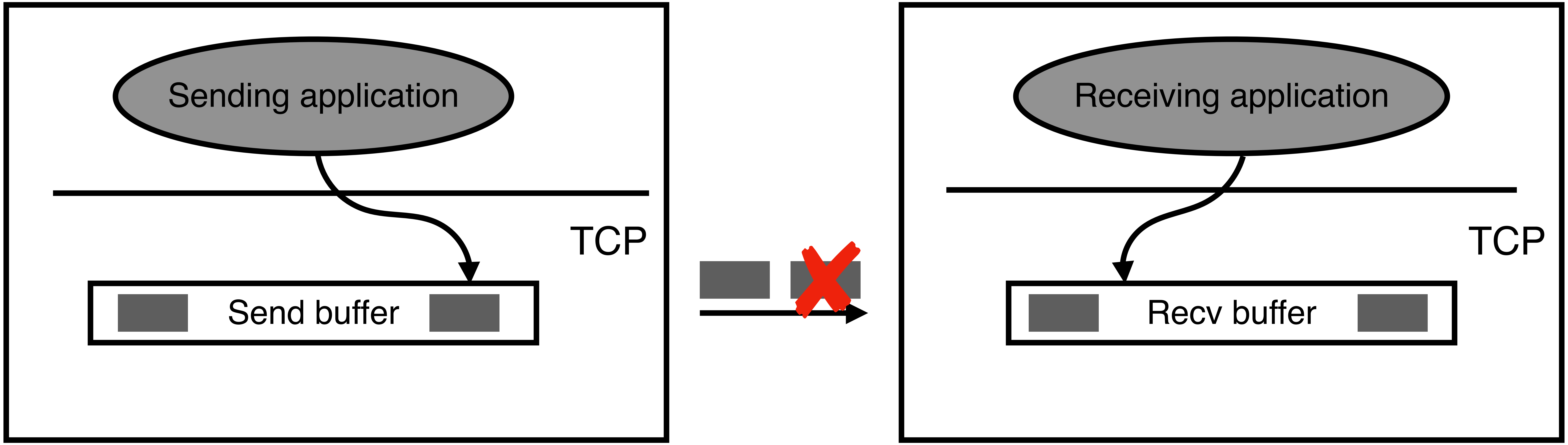
Outline

- Last
  - TCP Reliability Support (I)

- Today
  - TCP Reliability Support (II)

- Announcements
  - Lab 4 due date 05/01/2025 12:01PM

Issue #1: Segment Loss



- How do we know a segment is missing?
- How do we recover a missing segment?

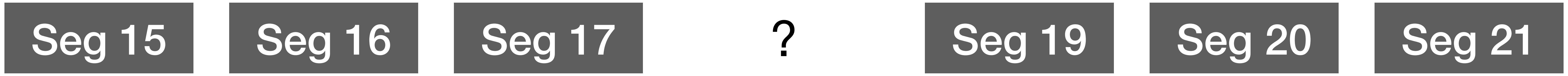
Sender-side Detection

- Acknowledgment
  - Ask the receiver to send back an ACK when a segment is received
  - A missing ACK indicates a missing segment

- Timeout
  - A signal that a segment that was sent but has not received its ACK within a specified time frame (threshold)
  - EWMA = Exponentially Weighted Moving Average

Receiver-side Detection

- Sequence number
  - Ask the sender to assign a unique sequence number for each segment
  - A missing sequence number indicates a segment loss



Seg 15 Seg 16 Seg 17 ? Seg 19 Seg 20 Seg 21

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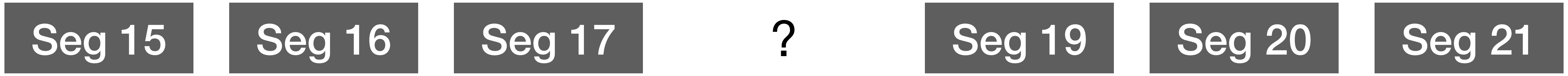

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Is this good enough?

Receiver-side Detection

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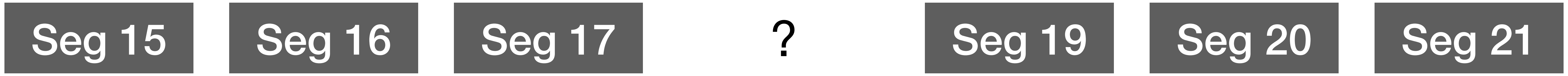

Seg 15 Seg 16 Seg 17 ? Seg 19 Seg 20 Seg 21

How can we differentiate between a missing segment and a slow-arriving (out-of-order) segment?

Receiver-side Detection

- Sequence number
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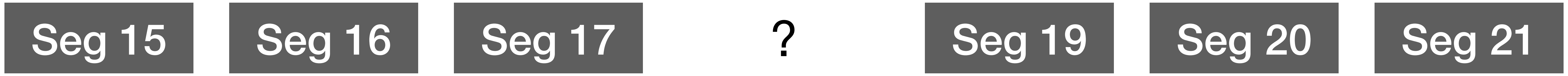

Seg 15 Seg 16 Seg 17 ? Seg 19 Seg 20 Seg 21

- Approaches
  - #1: view out-of-order segments as missing
  - #2: apply timeout again

How should we recover the missing segment?

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Just send it again!

How should we recover the missing segment?

Just send it again!

↓

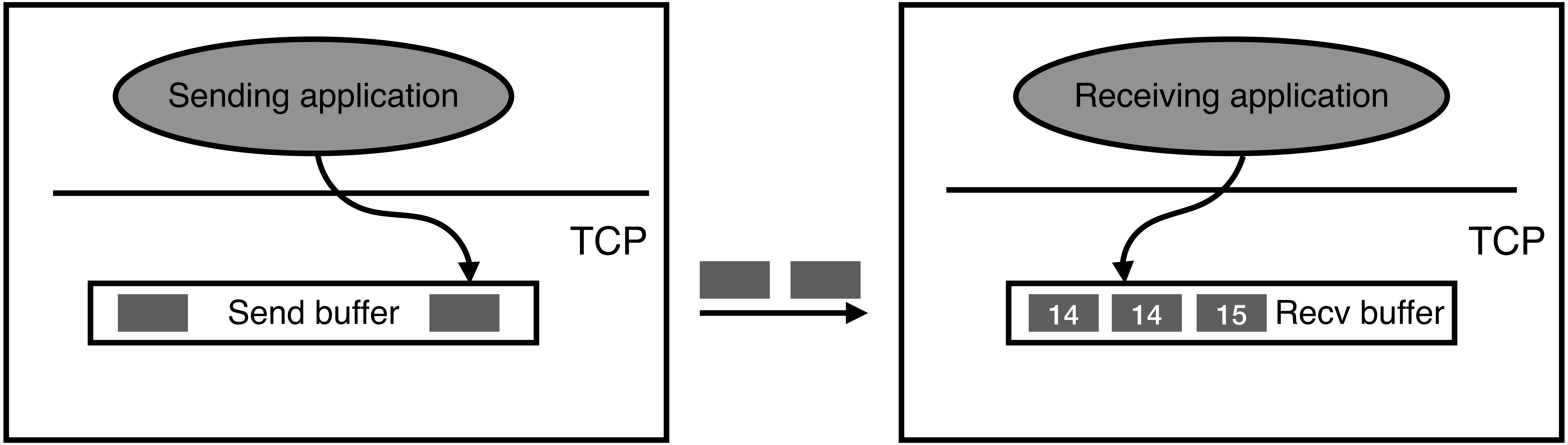
The sender must keep the segment until receiving the ACK.

Recover a Missing Segment

- Sender logic
  - Retransmit a segment when its local timer is triggered
  - Retransmit a segment when receiving an explicit ask from the receiver

- Receiver logic
  - Send an explicit ask to fetch the missing segment
  - Co-leasing or piggyback optimizations are possible to save bandwidth

Issue #2: Duplicated Segment



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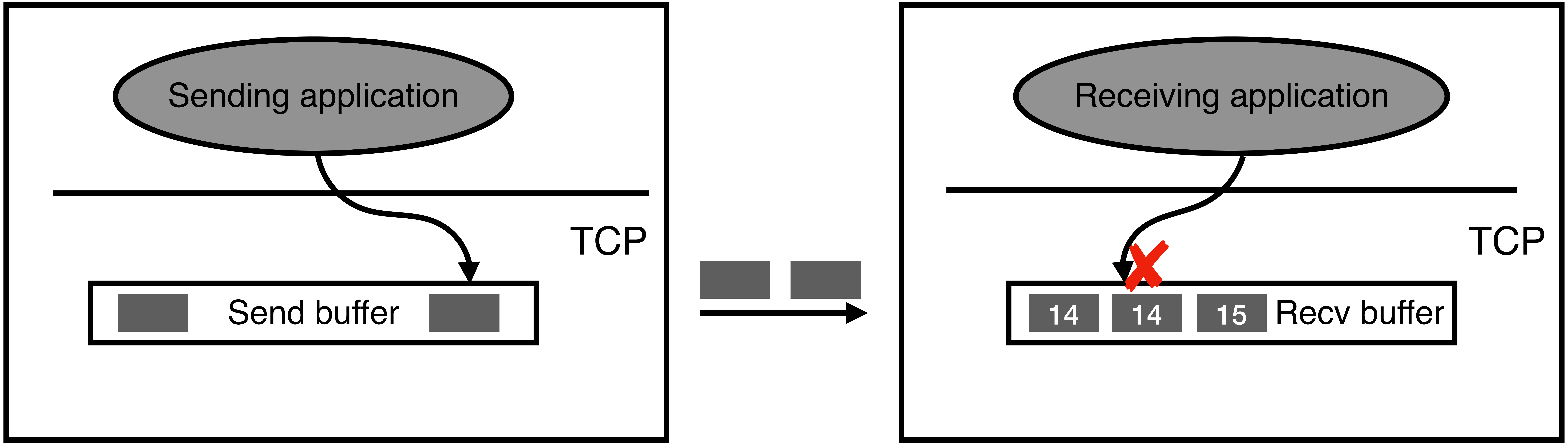

- How do we know a segment is duplicated?
- How do we handle segment duplication?

Receiver-side Detection and Fix

- The segment holds the same sequence number as a prior one
  - Seems simple, but how?

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Duplication is an important signal!

Understanding Duplication

- Why can the receiver receive a duplicated segment?

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Understanding Duplication

- Why can the receiver receive a duplicated segment?
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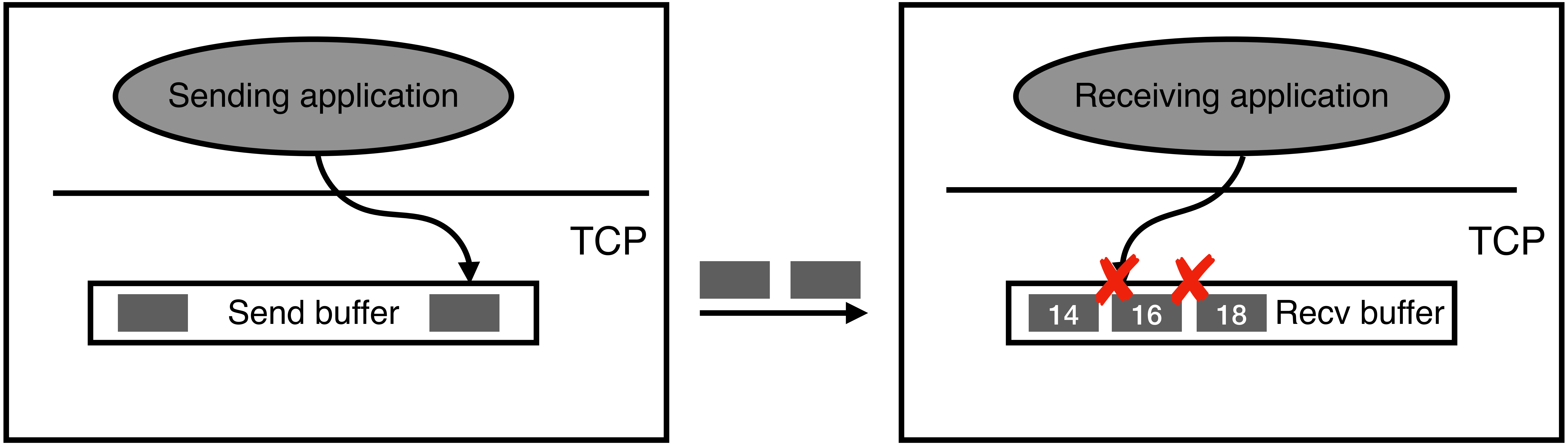
- Why can the sender send the segment again?
  - Case #1: my local timeout is triggered
  - Case #2: the receiver sends an explicit ask
- The network is slow
  - The sender should slow down

Issue #3: Out-of-order Segment



- How do we know a segment is out-of-order?
- How do we handle out-of-order segments?

Receiver-side Detection and Fix

- There is a segment hole in the data stream
  - The receiver should know what the next expected segment is
  - A hole happens when the receiving segment number is not as expected

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  - Pro: simple logics
  - Con: waste bandwidth and hurt performance

Receiver-side Detection and Fix

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  - A hole happens when the receiving segment number is not as expected

- Solution #1: just drop it and wait for the retransmission
  - Pro: simple logics
  - Con: waste bandwidth and hurt performance

- Solution #2: take it and reconstruct the stream until the hold fills
  - Pro: reduce retransmission and improve performance
  - Con: complex logics

Understanding Out-of-order

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  - #1: multiple transmission paths
  - #2: segments are dropped

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  - Sometimes they are the same since the indicator is a segment hole
  - But missing segments can also triggered by timeout

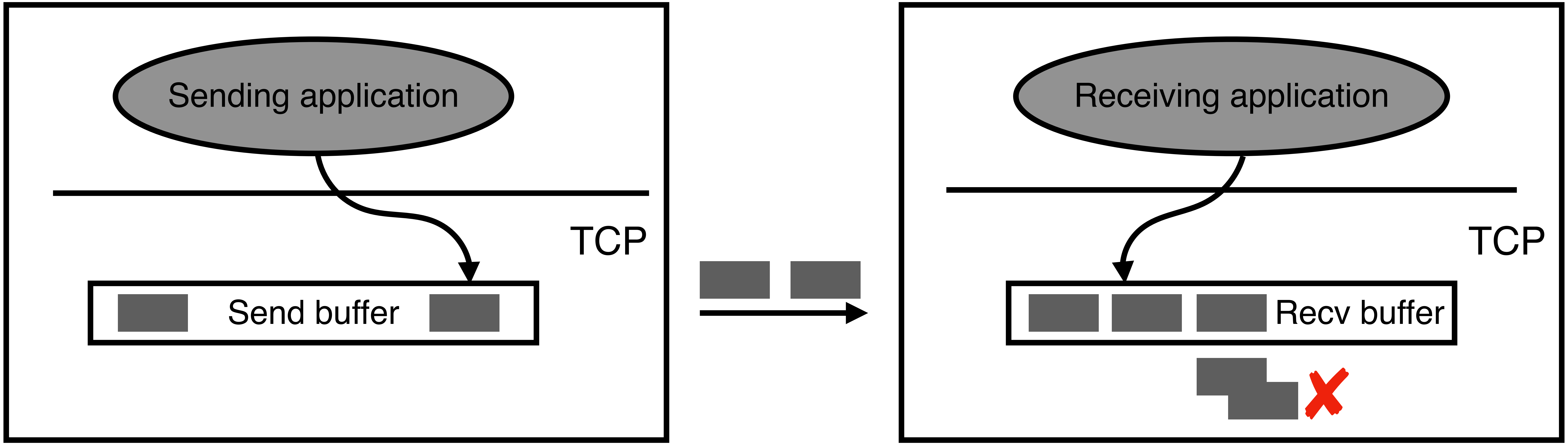
Understanding Out-of-order

- Why can the receiver receive an out-of-order segment?
  - #1: multiple transmission paths
  - #2: segments are dropped

- Missing v.s. Out-of-order
  - Sometimes they are the same since the indicator is a segment hole
  - But missing segments can also triggered by timeout

- The network is unstable
  - Congestion happens during the transmission
  - Communication paths become heterogeneous

Issue #4: Receiver Overwhelming



- How do we know the receiver is overwhelmed?
- How do we handle the receiver overwhelming?

Detection and Fix

- Receiver-side
  - The receiver buffer is full
  - *More advanced, the receiver cannot pull the NIC buffer fast enough*

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  - Ask the sender to slow down explicitly

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  - But, by how much?

Detection and Fix

- Receiver-side
  - The receiver buffer is full
  - *More advanced, the receiver cannot pull the NIC buffer fast enough*

- Solution
  - Ask the sender to slow down explicitly
  - But, by how much? => Tell the sender my buffer availability

What is the goal of TCP reliability mechanisms?

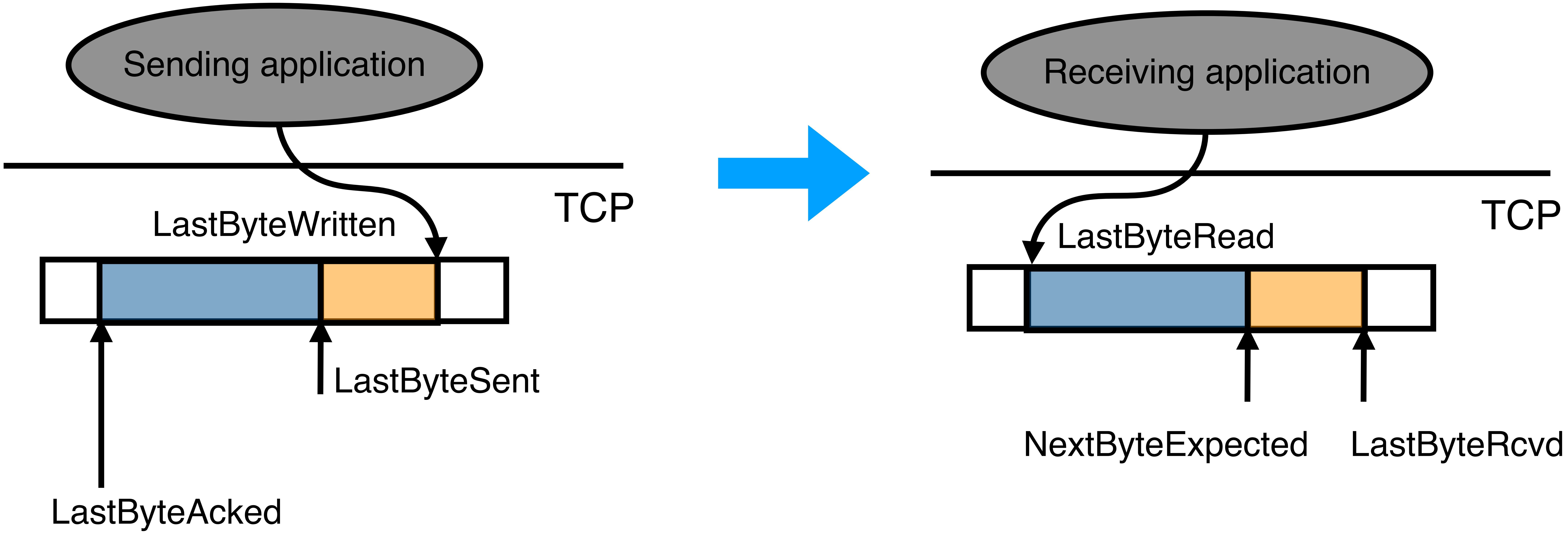
Byte stream @sender = Byte stream @receiver

↓

- #1: TCP segments are delivered with no loss/duplication
- #2: TCP segments are delivered in order
- #3: The sender is not over-running the receiver capability

Combine Everything Together — TCP Sliding Window

- Continuously coordinate sender and receiver during transmission



TCP Sliding Window—Sender

- Four state variables
  - The last byte written by the application (**LastByteWritten**)
  - The last byte being acknowledged (**LastByteAcked**)
  - The last byte sent (**LastByteSent**)
  - The sender buffer size (**MaxSendBuffer**)

TCP Sliding Window—Sender Logics

- Three variables manipulations:
  - Advance **LastByteWritten** when an app writes
  - Advance **LastByteAcked** when a consecutive ACK arrived
  - Advance **LastByteSent** when the segments are sent

- Invariants:
  - **LastByteSent** <=**LastByteWritten**
  - **LastByteAcked** <= **LastByteSent**

- Buffered bytes:
  - **|LastByteWritten - LastByteAcked|** <= **MaxSendBuffer**

TCP Sliding Window—Receiver

- Four state variables
  - The last byte read by the application (**LastByteRead**)
  - The last byte received (**LastByteRcvd**)
  - The next byte supposed to be received (**NextByteExpected**)
  - The receiver buffer size (**MaxRcvBuffer**)

TCP Sliding Window—Receiver Logics

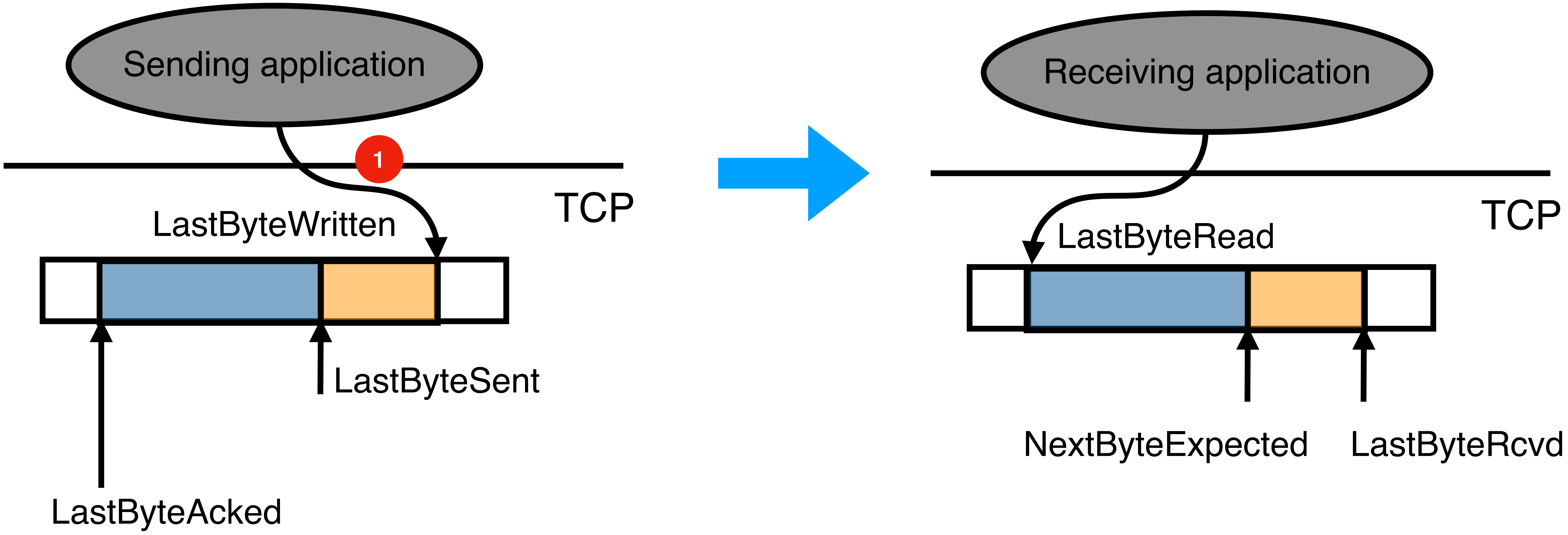
- Three variables manipulations:
  - Advance **LastByteRead** when an app reads
  - Advance **LastByteRcvd** when the segment is received
  - Advance **NextByteExpected** when the next expected segment is received

- Invariants:
  - **LastByteRead** < **NextByteExpected**
  - **NextByteExpected** <= **LastByteRcvd** + 1

- Buffered bytes:
  - **|LastByteRcvd - LastByteRead| <= MaxRcvBuffer**

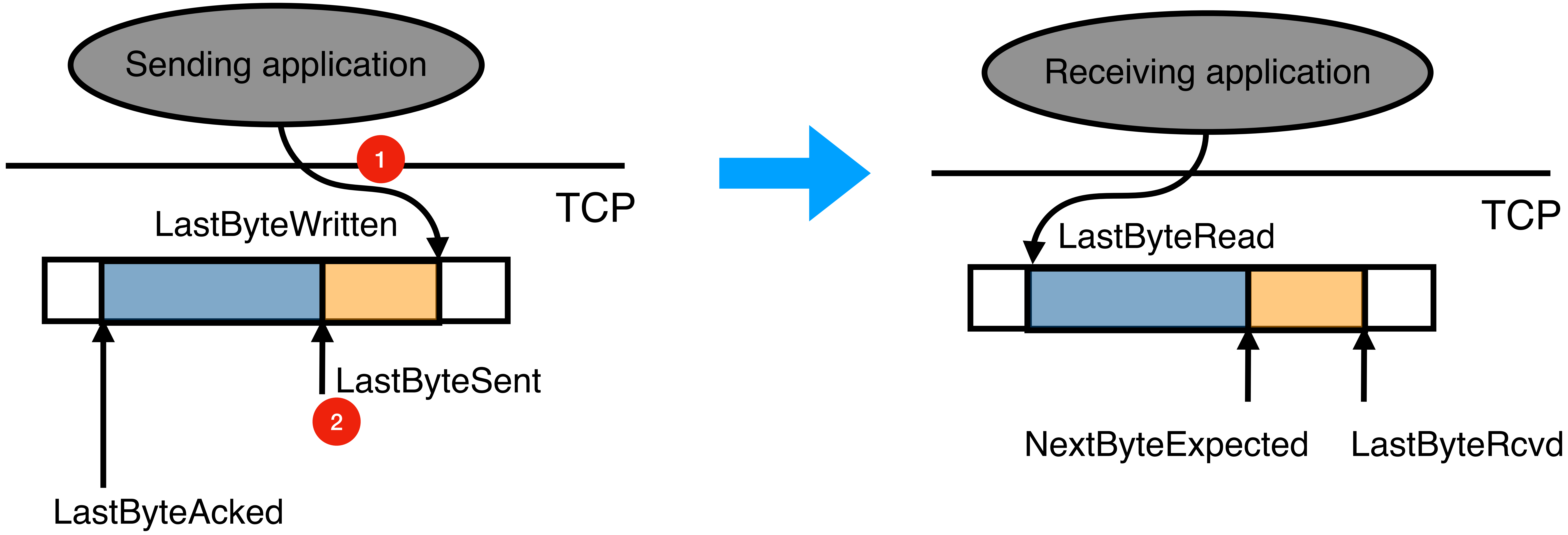
How it works

- Step #1: The sending application writes data to the send buffer
  - **LastByteWritten += sizeof (written data)**



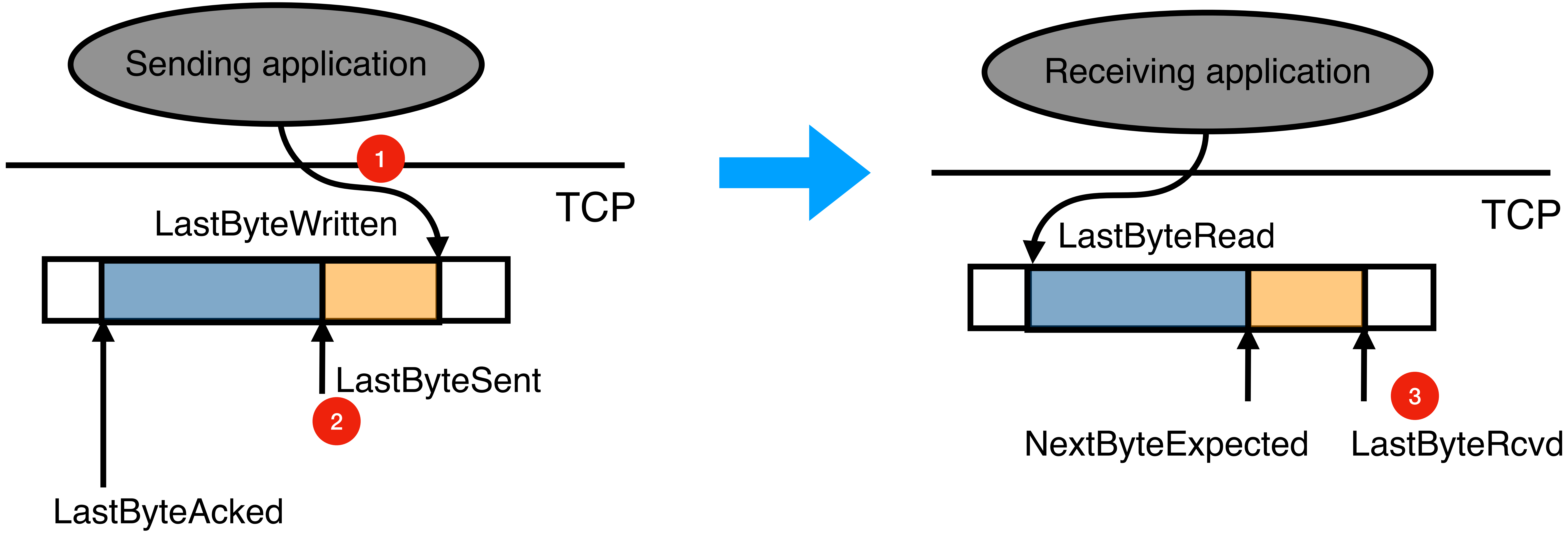
How it works

- Step #2: The buffered data is sent out by OS/NIC
  - **LastByteSent += sizeof (sent data)**



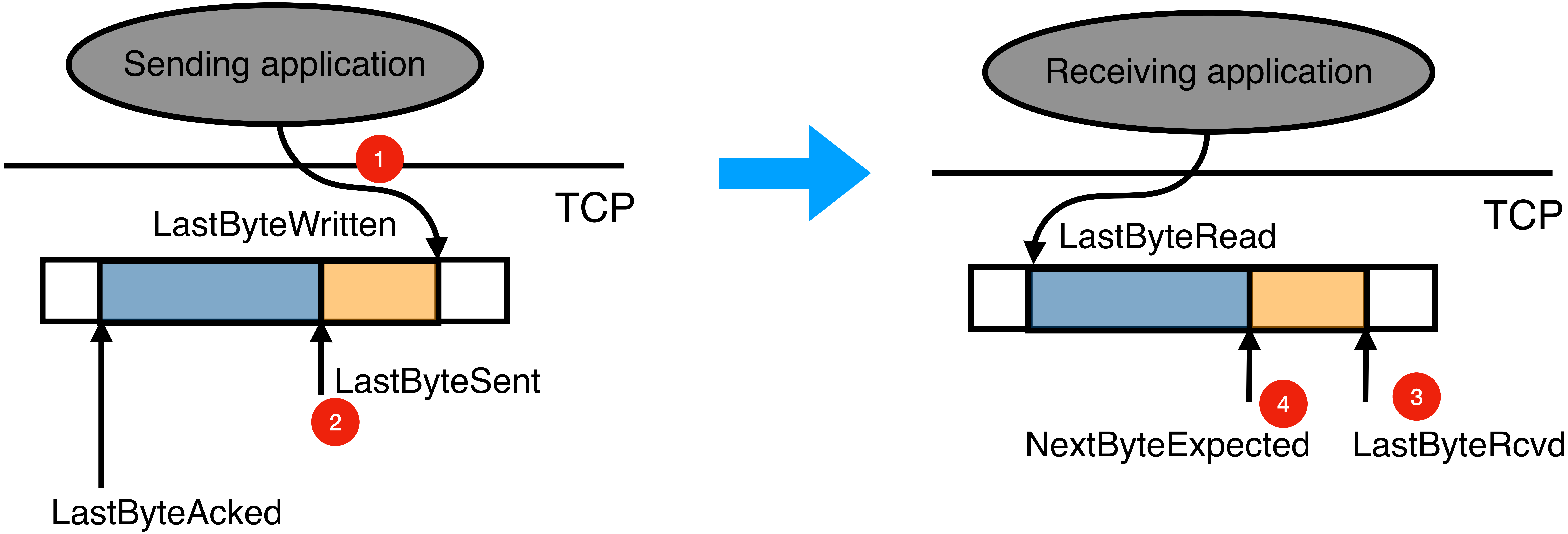
How it works

- Step #3: The data is by the received host and put into the buffer
  - **LastByteRcvd += sizeof (received data)**
  - Advance **NextByteExpected** depending on if there is a hole



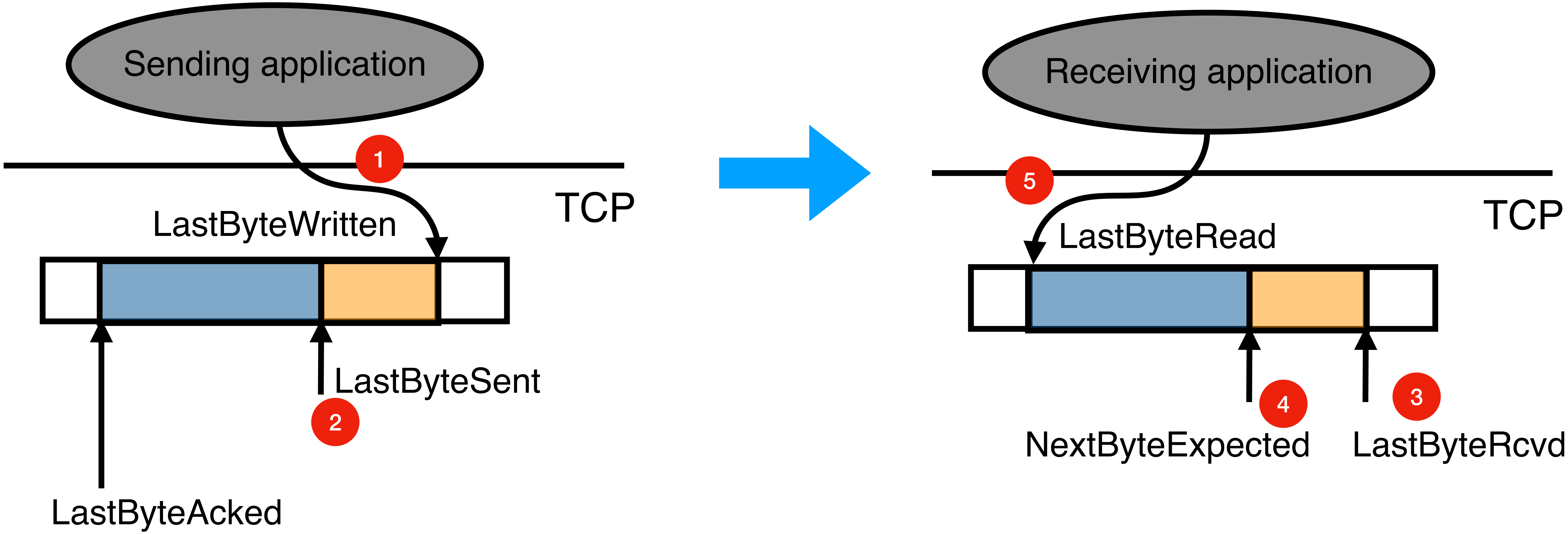
How it works

- Step #4: Received data is sequenced in the buffer
  - Advance **NextByteExpected** when necessary



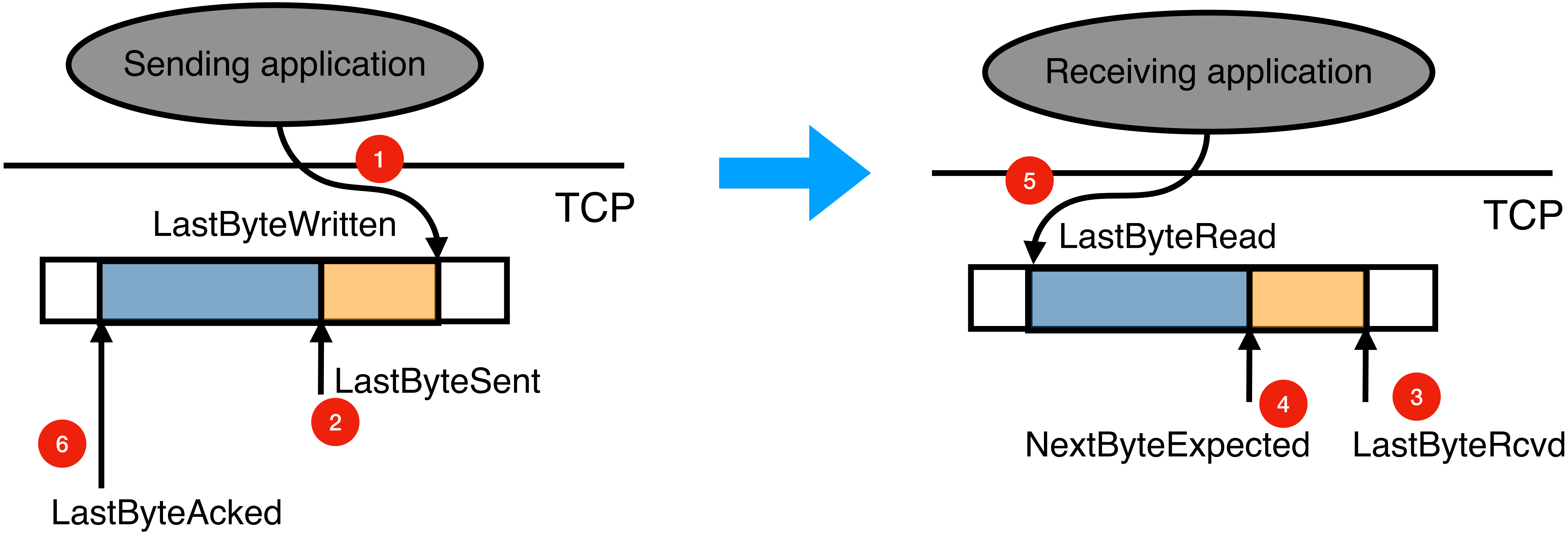
How it works

- Step #5: The receiving application reads data from the buffer
  - **LastByteRead += sizeof (read data)**



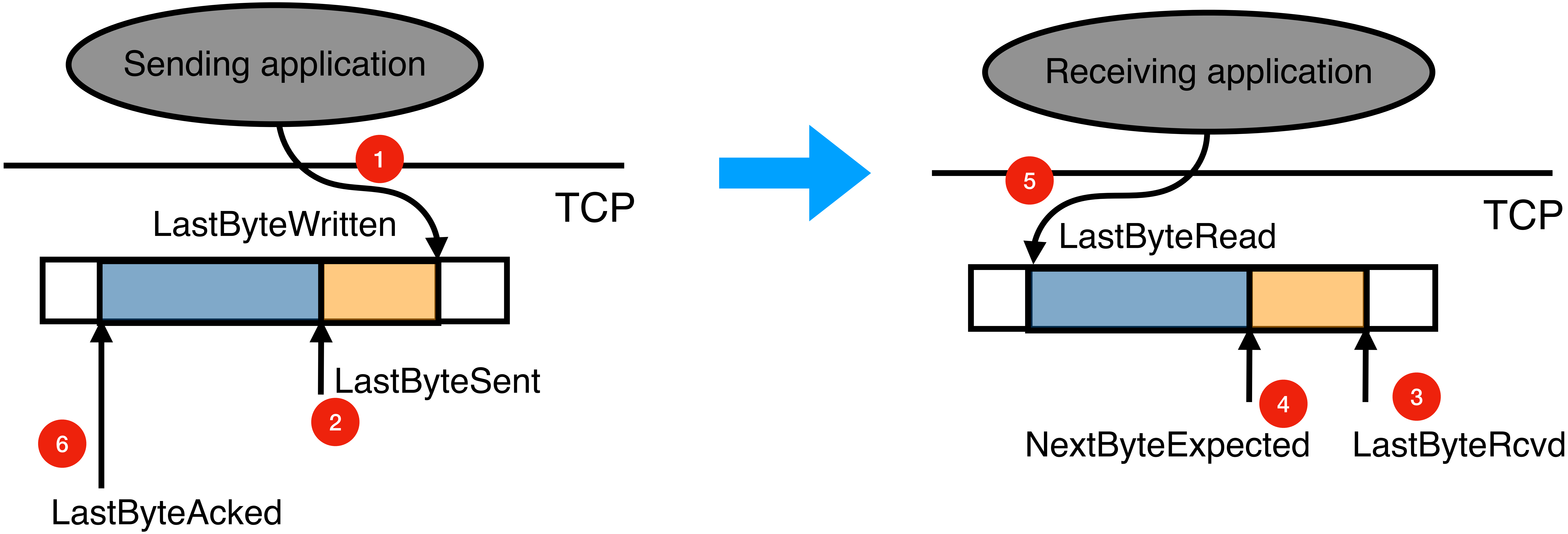
How it works

- Step #6: The receiving application sends ACKs to the sender
  - Advance **LastByteAcked** when necessary



Why Sender Invariants

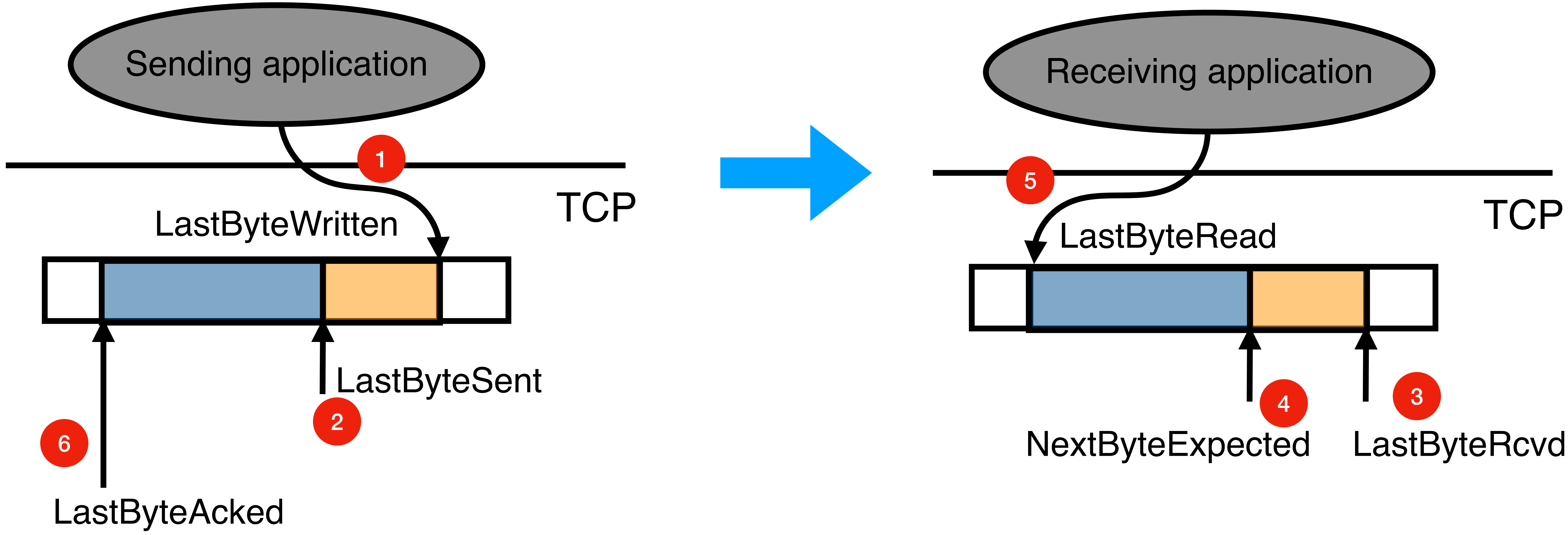
- **LastByteSent** <=**LastByteWritten**
- **LastByteAcked** <= **LastByteSent**



Why Receiver Invariants

- LastByteSent <=LastByteWritten
- LastByteAcked <= LastByteSent

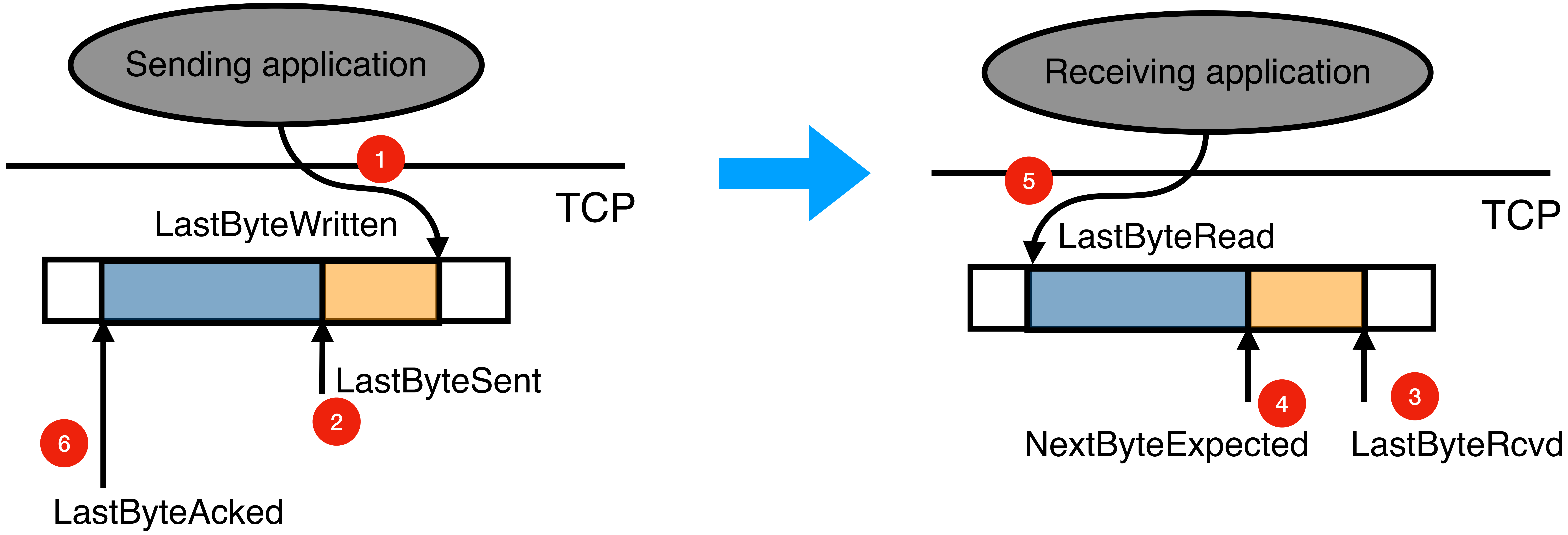
- LastByteRead < NextByteExpected
- NextByteExpected <= LastByteRcvd + 1



Understanding the Sender Buffer

- **LastByteSent** <=**LastByteWritten**
- **LastByteAcked** <= **LastByteSent**

- **LastByteRead** < **NextByteExpected**
- **NextByteExpected** <= **LastByteRcvd** + 1



- **|LastByteWritten - LastByteAcked|** <= **MaxSendBuffer**

Understanding the Receiver Buffer

- LastByteSent <=LastByteWritten
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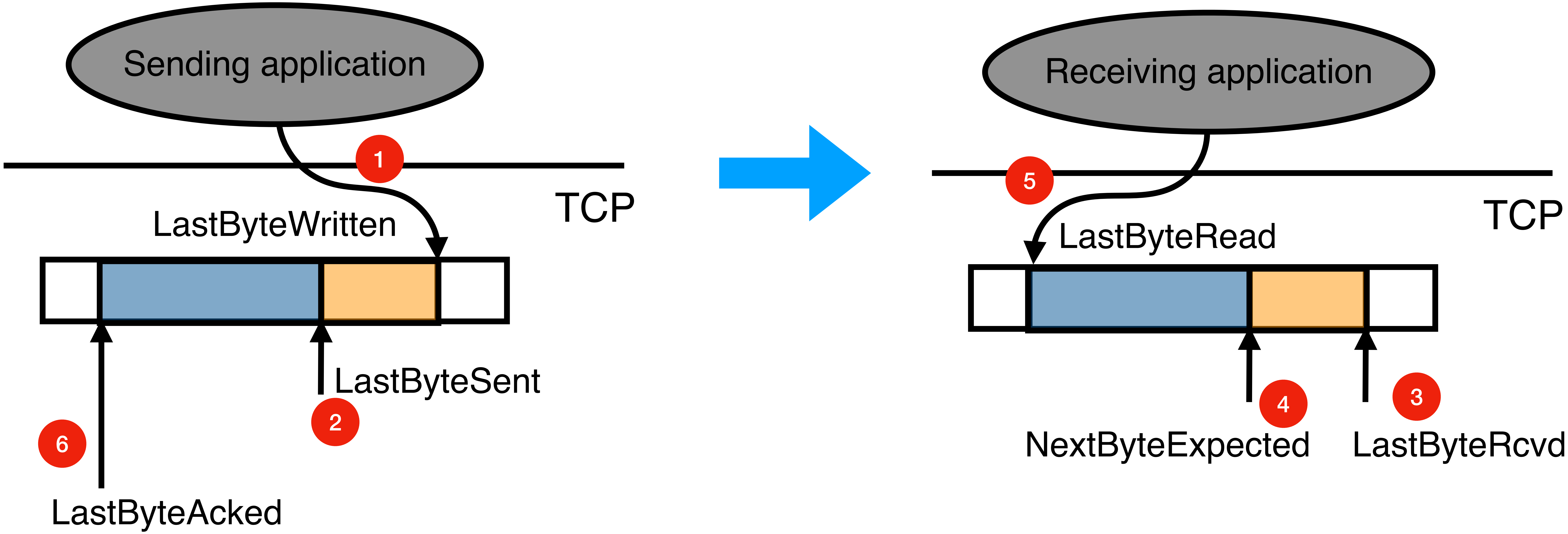
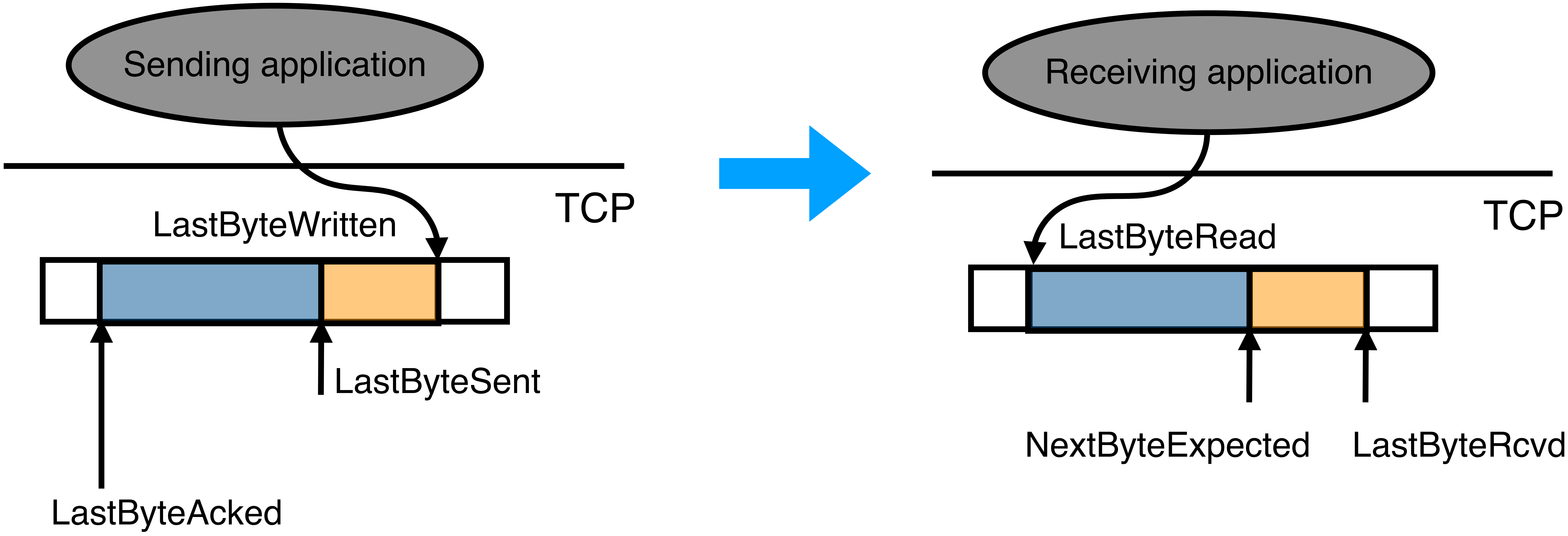
- LastByteRead < NextByteExpected
- NextByteExpected <= LastByteRcvd + 1



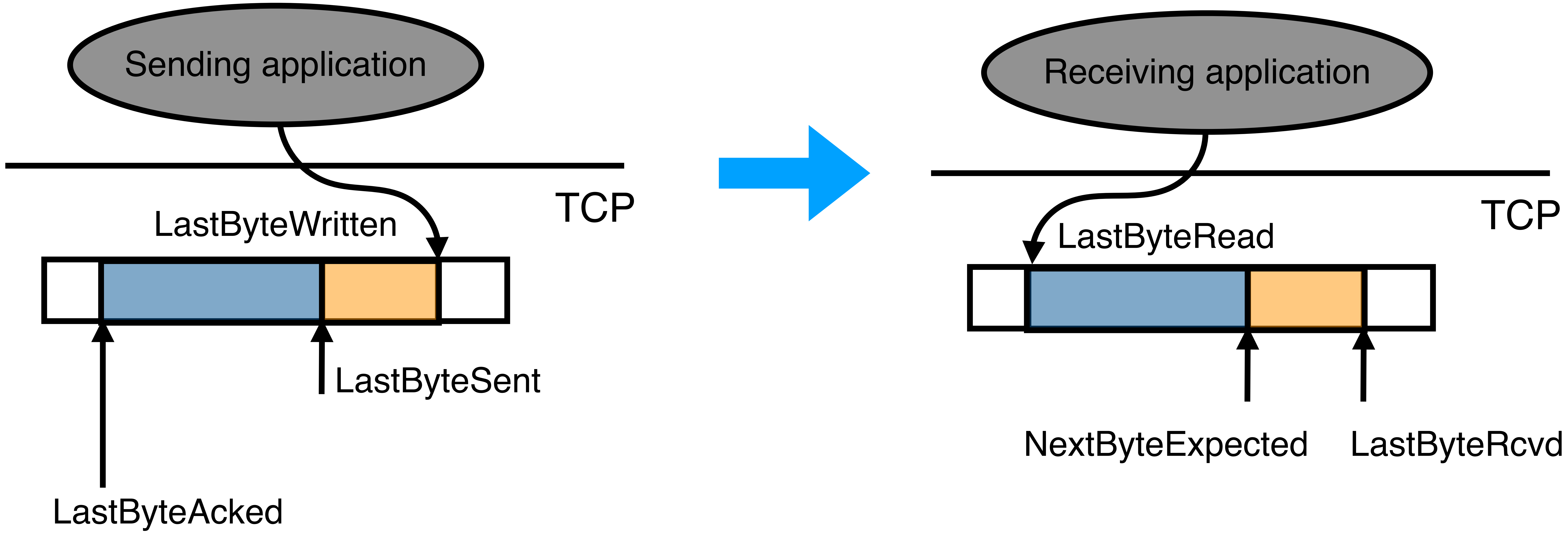
- |LastByteRcvd - LastByteRead| <= MaxRcvBuffer

Tackling Issue #1 (Missing Segment)

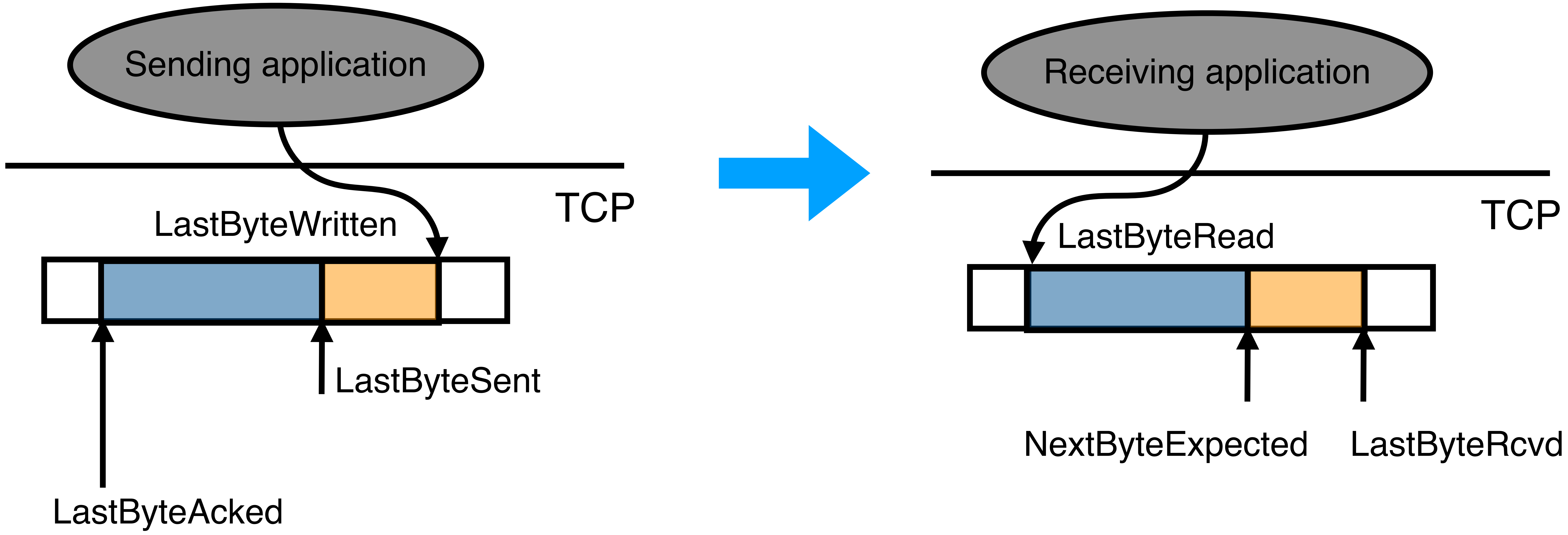


Tackling Issue #1 (Missing Segment)

- Receiver-side detection: [**NextByteExpected**, **LastByteRcvd**]
- Sender-side detection: [**LastByteAcked**, **LastByteSent**]
- Fix: buffered bytes are only freed before **LastByteAcked**

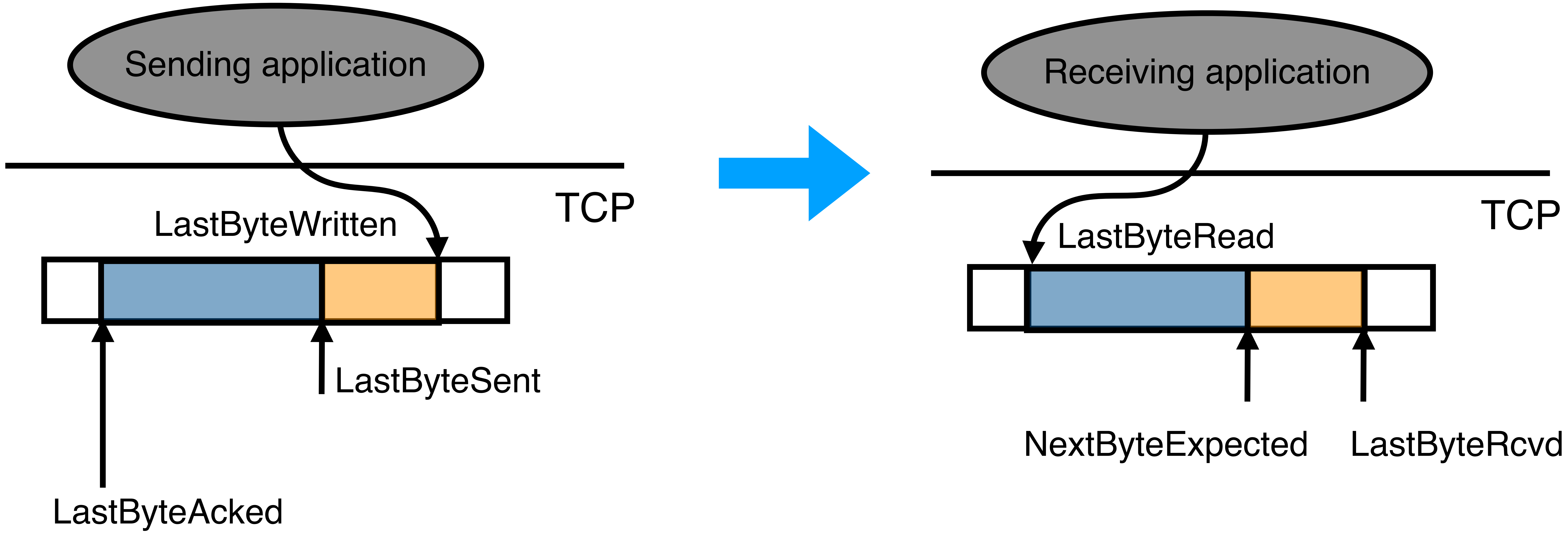


Tackling Issue #2 (Duplicated Segment)

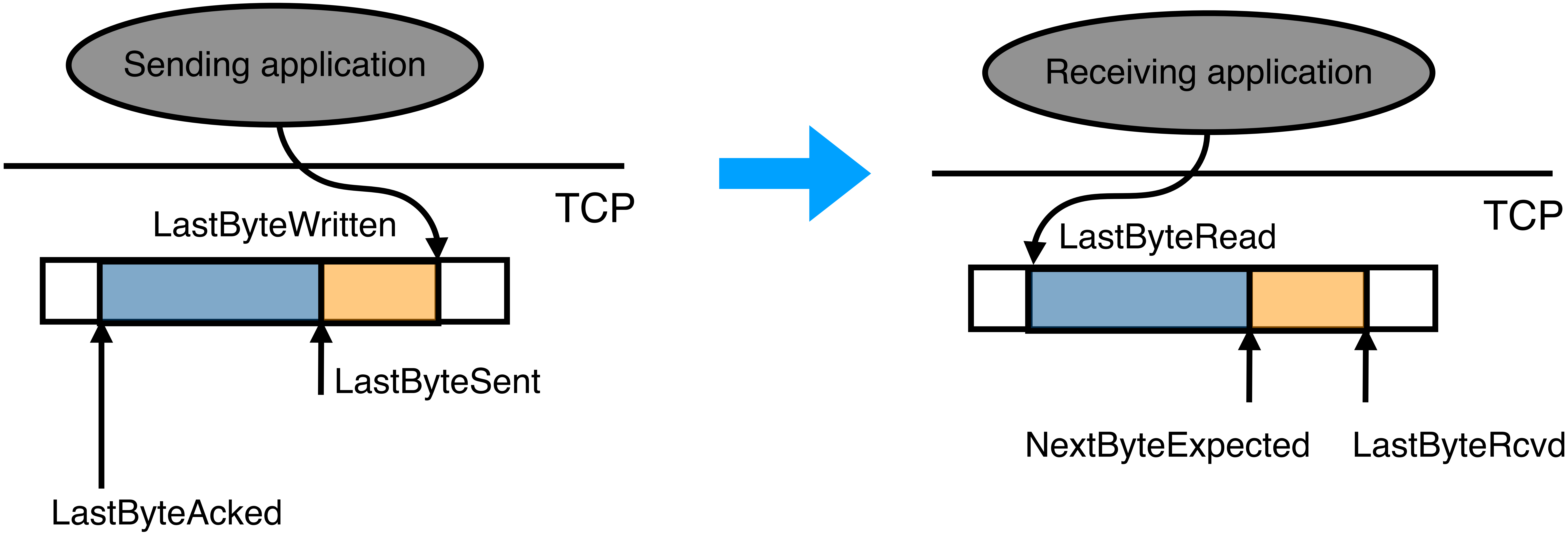


Tackling Issue #2 (Duplicated Segment)

- Detection: [**LastByteRead**, **NextByteExpected**]
- Fix: drop

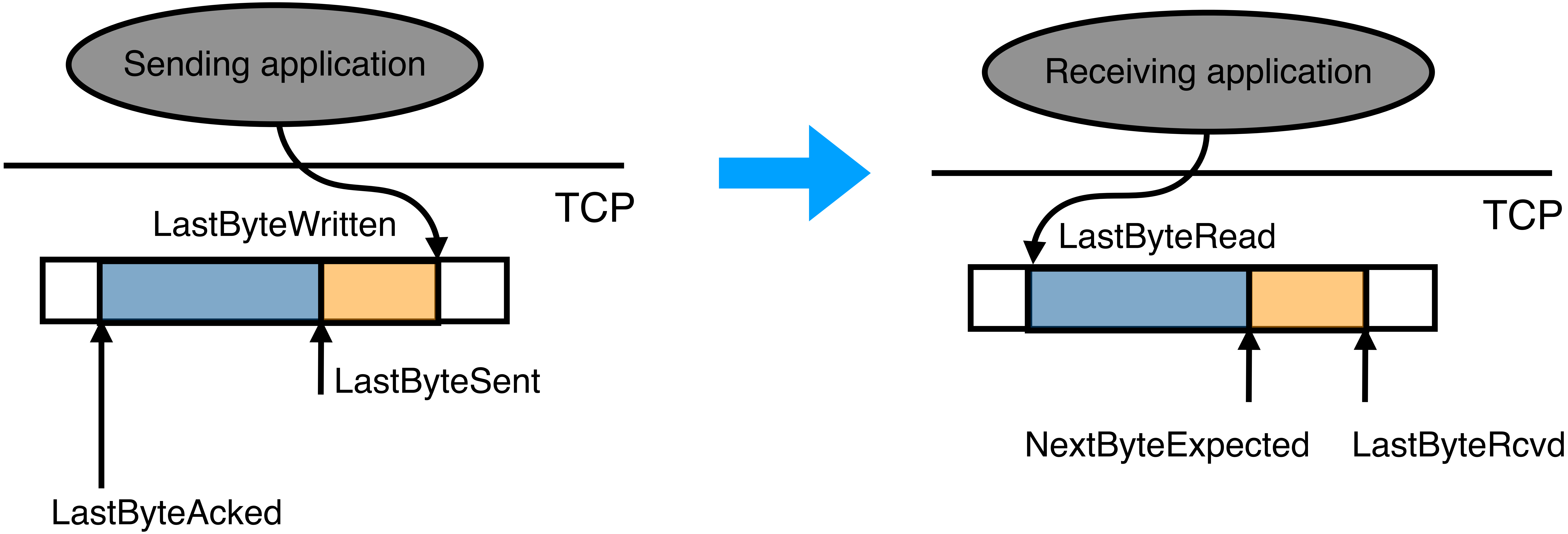


Tackling Issue #3 (Out-of-order Segment)

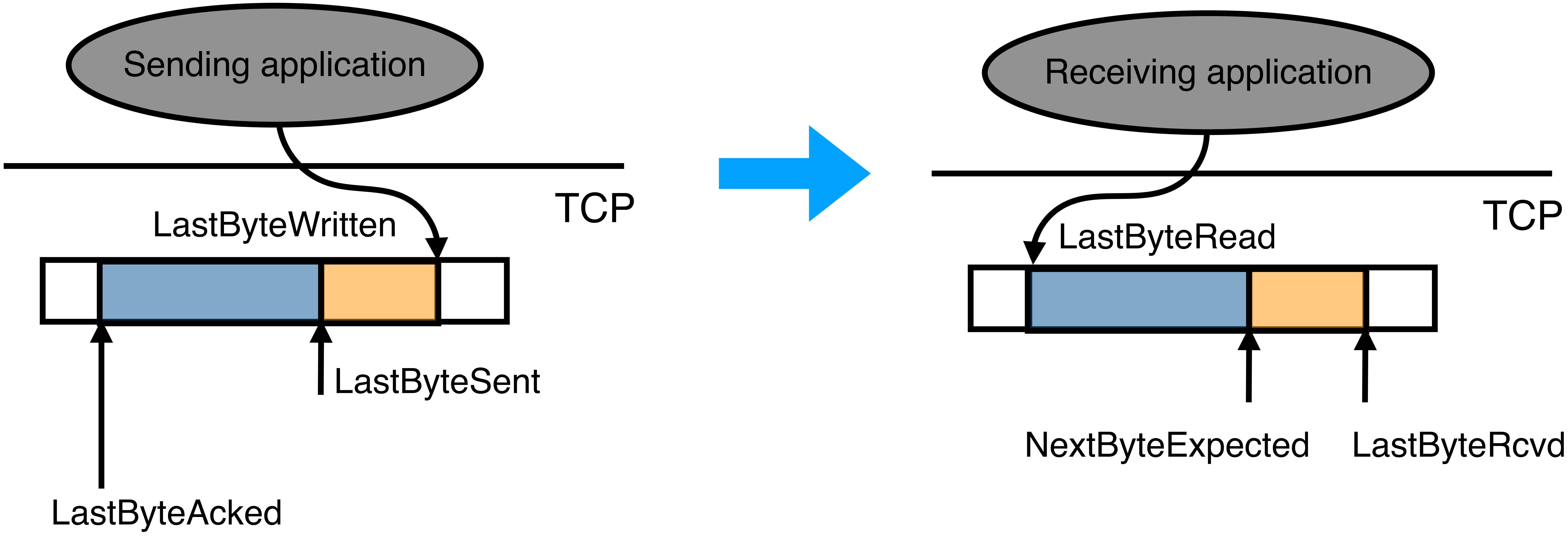


Tackling Issue #3 (Out-of-order Segment)

- Detection: [**NextByteExpected**, **LastByteRcvd**]
- Fix: take if **|LastByteRcvd - LastByteRead| <= MaxRcvBuffer**

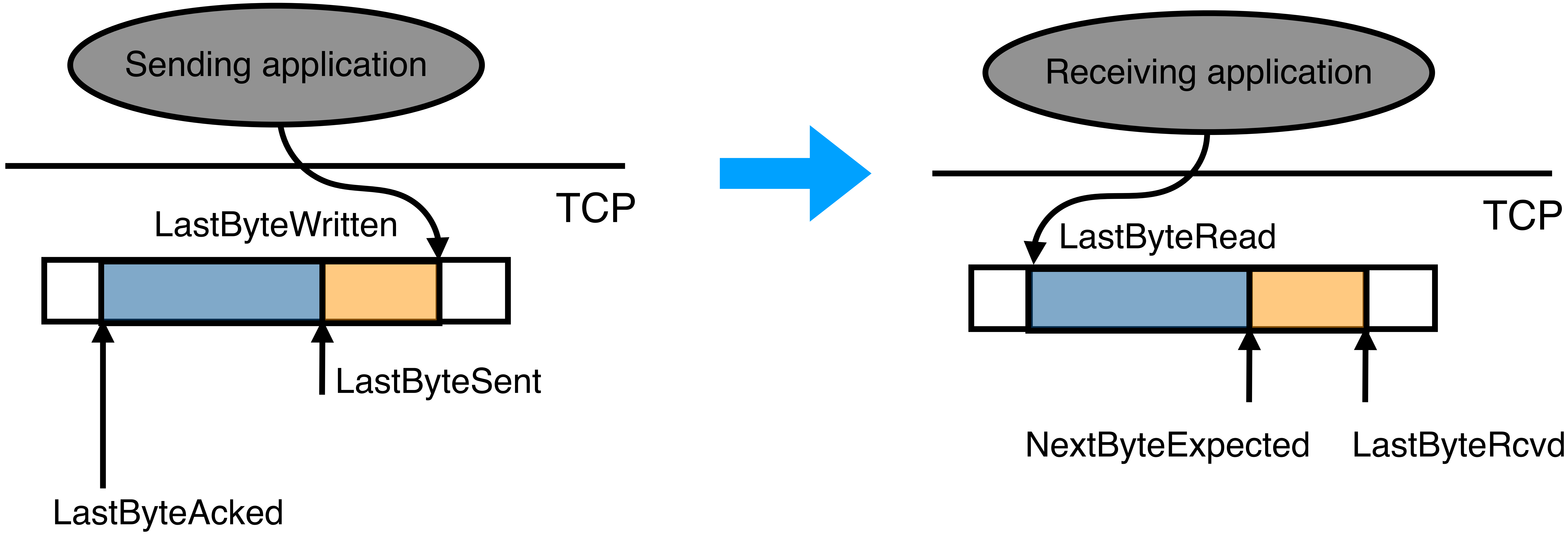


Tackling Issue #4 (Receiver Overwhelming)



Tackling Issue #4 (Receiver Overwhelming)

- Detection: **lLastByteRcvd - LastByteReadl <= MaxRcvBuffer**
- Fix: tell the sender the available space (**AdvertisedWindow**)



Tackling Issue #4 (Receiver Overwhelming)

- Detection: **lLastByteRcvd - LastByteReadl <= MaxRcvBuffer**
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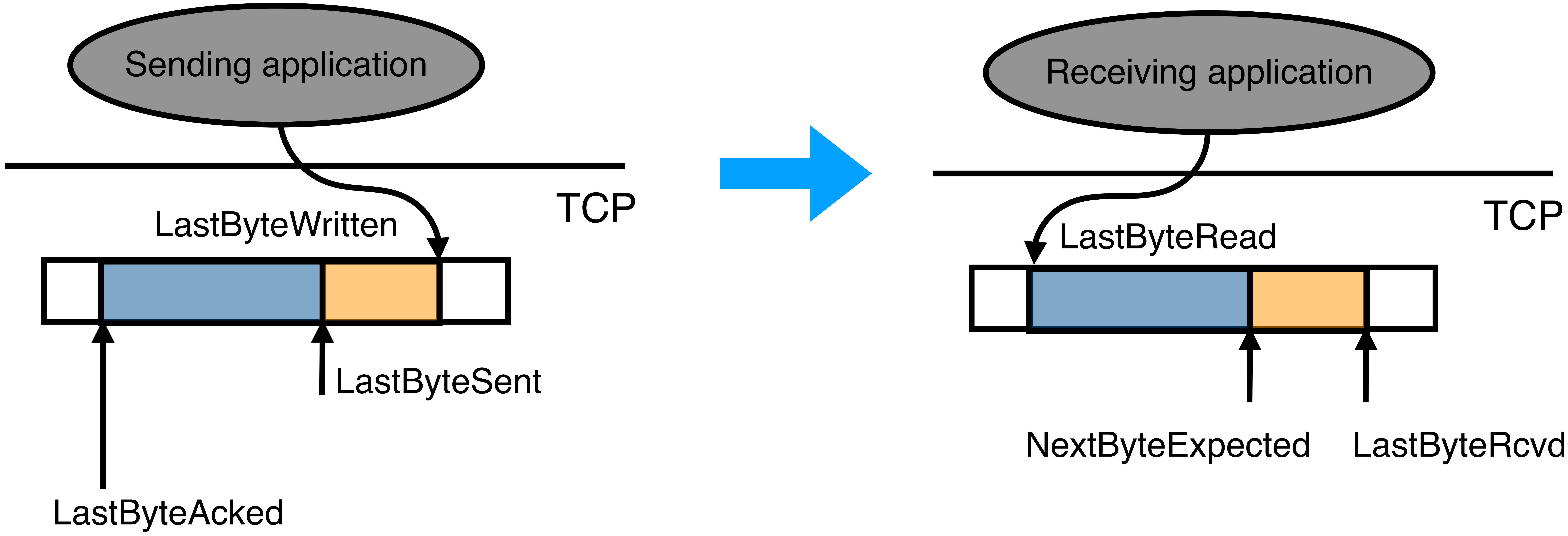
AdvertisedWindow = MaxRcvBuffer - (LastByteRcvd - LastByteRead)

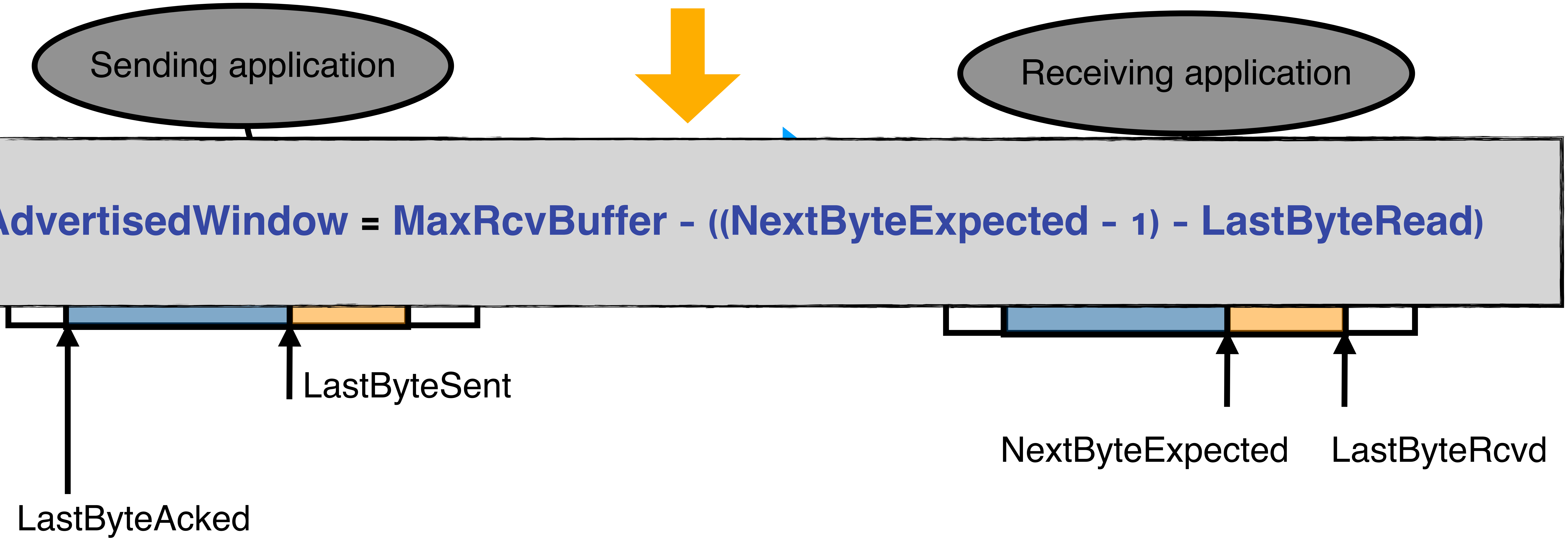


Tackling Issue #4 (Receiver Overwhelming)

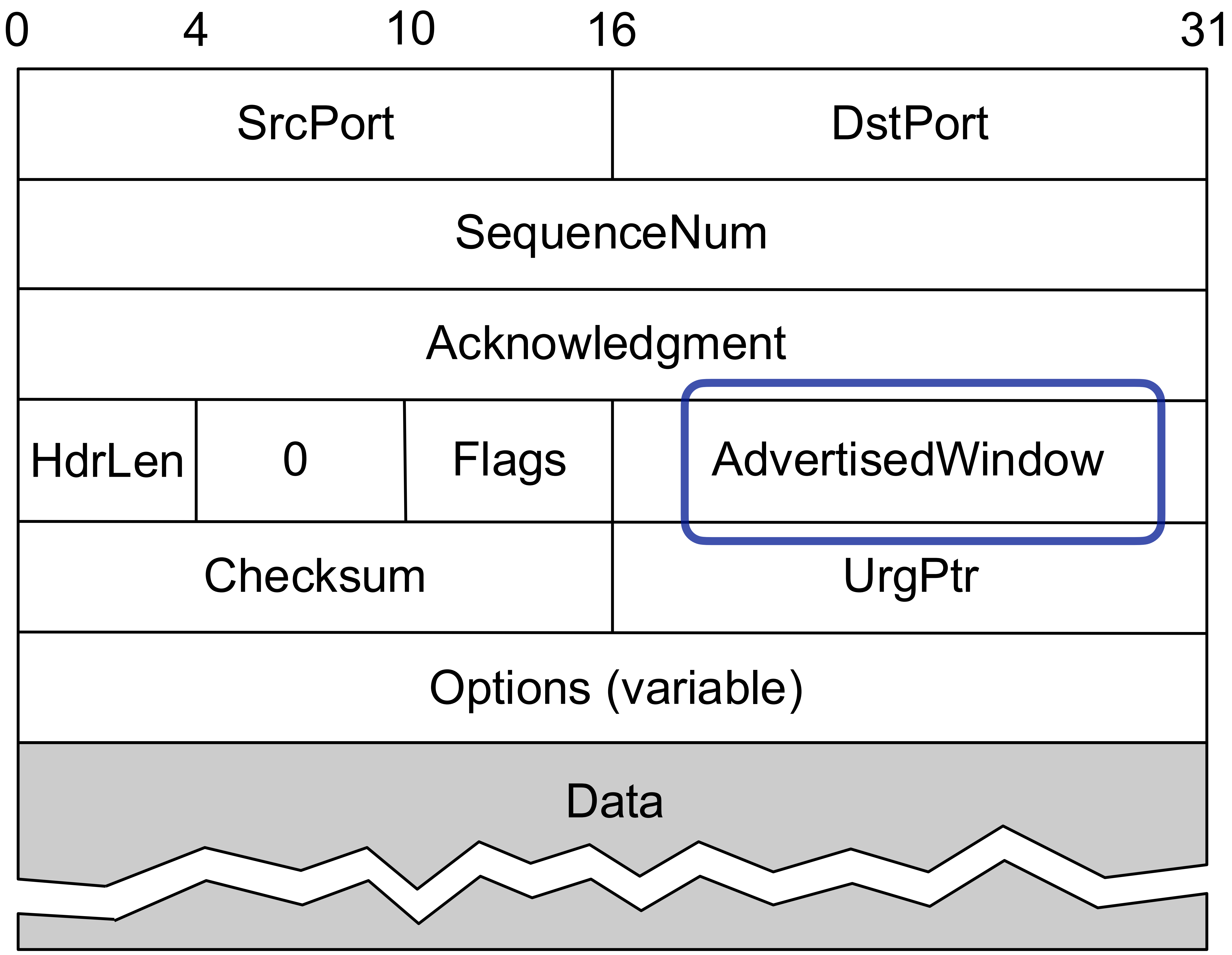
- Detection: **|LastByteRcvd - LastByteRead| <= MaxRcvBuffer**
- Fix: tell the sender the available space (**AdvertisedWindow**)

AdvertisedWindow = MaxRcvBuffer - (LastByteRcvd - LastByteRead)

AdvertisedWindow = MaxRcvBuffer - ((NextByteExpected - 1) - LastByteRead)



Revisiting TCP Header



0 4 10 16 31

SrcPort DstPort

SequenceNum

Acknowledgment

HdrLen 0 Flags AdvertisedWindow

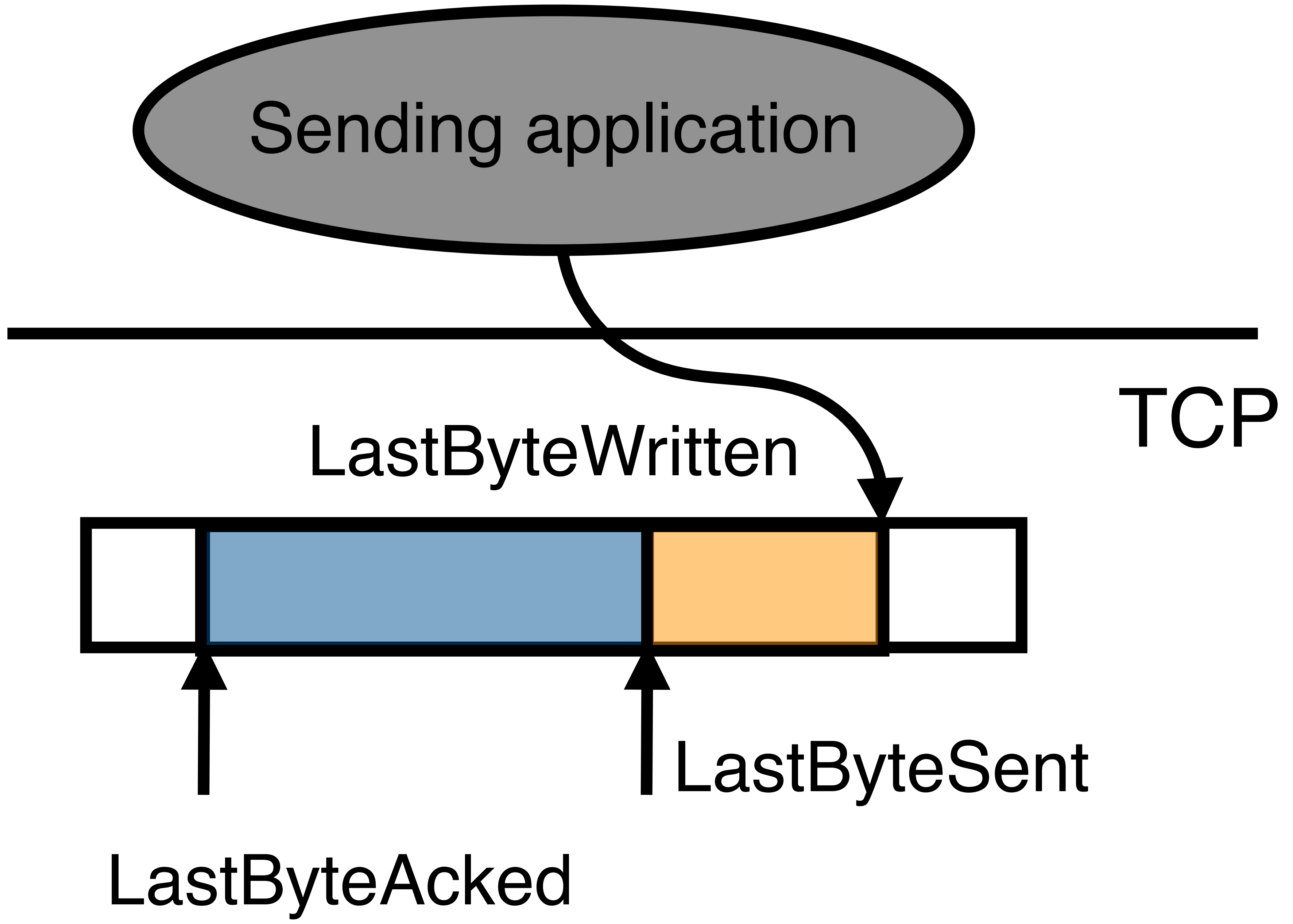
Checksum UrgPtr

Options (variable)

Data

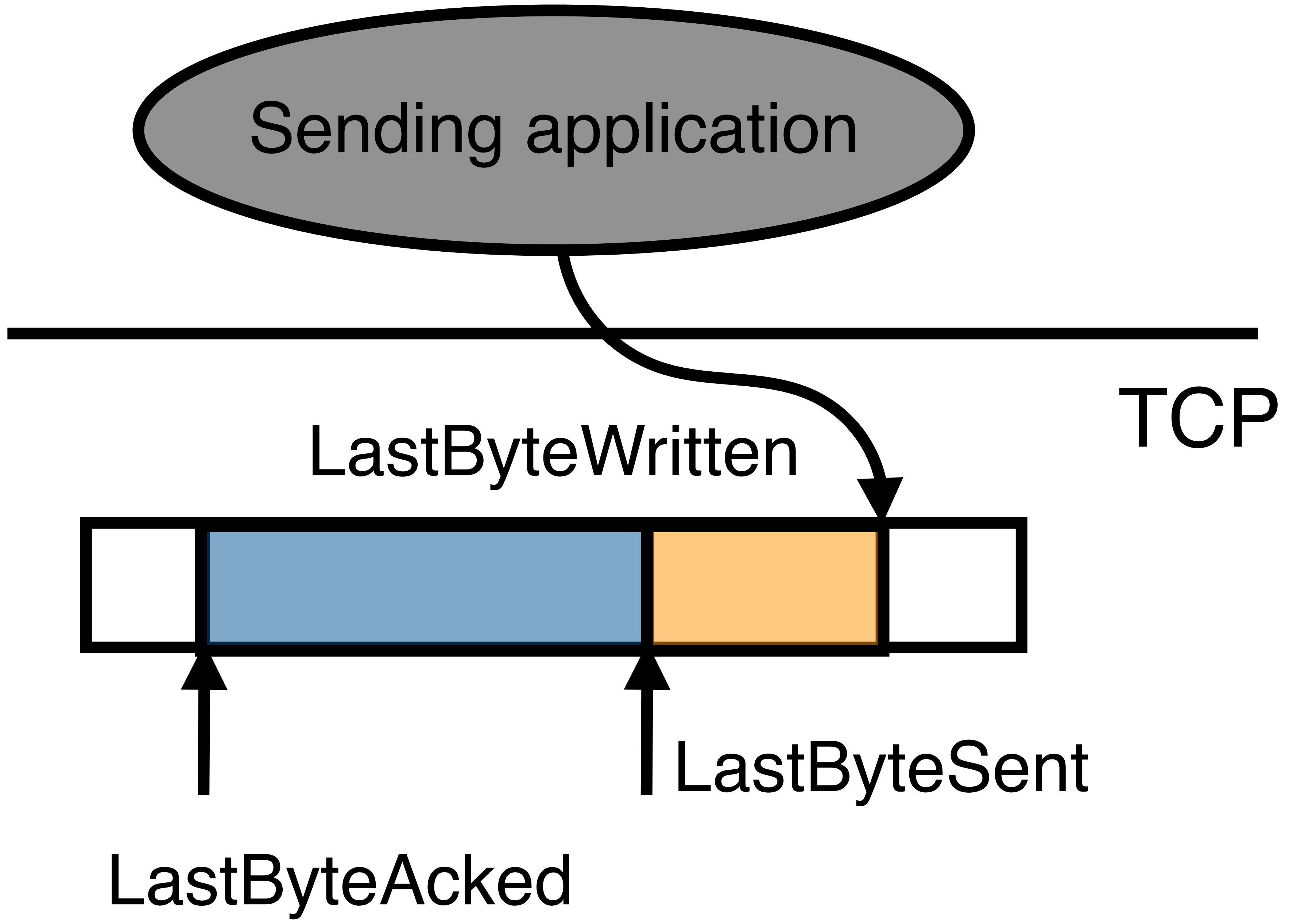
TCP Flow Control

- The sender controls the transmission rate
  - LastByteSent - LastByteAcked <= AdvertisedWindow
  - EffectiveWindow = AdvertisedWindow - (LastByteSent - LastByteAcked)



TCP Flow Control Affects Application Performance

- The application speed is throttled
  - LastByteWritten - LastByteAcked <= MaxSendBuffer
  - Block sender if (LastByteWritten - LastByteAcked) + y > MaxSendBuffer



Flow Control More

- The receiver
  - Always send ACKs in response to arriving data segments

- The sender
  - Persistent sending at least one byte when AdvertisedWindow = 0

How does TCP solve the second issue?

- #1: Arbitrary communication
  - Senders and receivers can talk to each other in any ways

- **#2: No reliability guarantee**
  - **Packets can be lost/duplicated/reordered during transmission** ✓
  - **A checksum is not enough**

- #3: No resource management
  - Each channel works as an exclusive network resource owner
  - No adaptive support for the physical networks and applications

Summary

- Today
  - TCP reliability support (II)

- Next lecture
  - TCP congestion control